The influence of the shape of high-rise buildings on the design features and methods of making foundations in difficult soil conditions

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Abstract. The methods of calculation and design of foundations considered in the article are applied in the construction of high-rise buildings of complex shape in heterogeneous soil conditions, leading in each case to minimizing costs. Considered in the article multi-storey and high-rise buildings have a complex geometry, which is further complicated by the location of objects in particularly difficult soil conditions - on construction sites with a significant difference in the marks of natural relief, at risk of developing landslide processes, as well as seismic impacts with an intensity of 8-9 points. For each of the examples under consideration, the final technical solution of the foundations is described, which made it possible to minimize the totality of complicating factors. To achieve the result, original methods of staged construction of foundations were used, based on previously carried out full-scale tests. To confirm the reliability of the developed methods, geotechnical monitoring was carried out during the construction and operation of facilities. Further development of methods for designing foundations in difficult soil conditions will make it possible to achieve greater efficiency in the consumption of material for the construction of foundations and buried structures.

1 Introduction

Difficult soil conditions are commonly referred to as significant non-uniform compressibility of the base, caused by the geometric and physical non-linearity of the elements within the compressible thickness. For such construction sites, a common solution is to use a pile foundation, which allows transferring the load from a heavy building to dense and homogeneous deep soils. Numerous studies in the field of pile foundation engineering lead to the increasing efficiency of such foundations in terms of material consumption for the manufacture of piles and the timing of the work [1-3]. Taking into account the underestimated reserves of the actual bearing capacity of piles in comparison with the calculated values, including the slab part of the foundation in joint work, regulating the sequence of construction stages make it possible to significantly reduce the

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cost of building foundations and buried structures. However, in some cases, when choosing a technical solution for the foundation, the shape of the above-ground structure is one of the most important parameters, which determines the stress fields transmitted to the foundation spot. In the case of buildings that are very irregular in terms of plan and height, it is possible to solve the issue of reducing construction costs and achieving the required operational safety of the facility under construction by using effective and original methods for designing and building pile-and-slab foundations. The original combination of irregular three-dimensional forms of high-rise buildings, non-uniformly compressible soil foundations, variable relief and complex combinations of external influences made it possible to develop the structure of construction methods for the foundations of high-rise buildings. The results of the implementation of some of the developed methods [4-6] are considered in this article. The objects of study are the foundations of high-rise buildings built over the past 20 years in difficult soil conditions of Krasnodar Krai, in most cases at construction sites with high design seismicity and the risk of landslide processes. In this paper, the influence of a given architectural form on the justification of the foundation design and the choice of the sequence of its construction are considered.

2 Materials and methods

Below are some of the forms of constructed high-rise buildings, which, in combination with soil conditions, determined approaches to the calculation and design of the foundations of these objects (Figure 1).

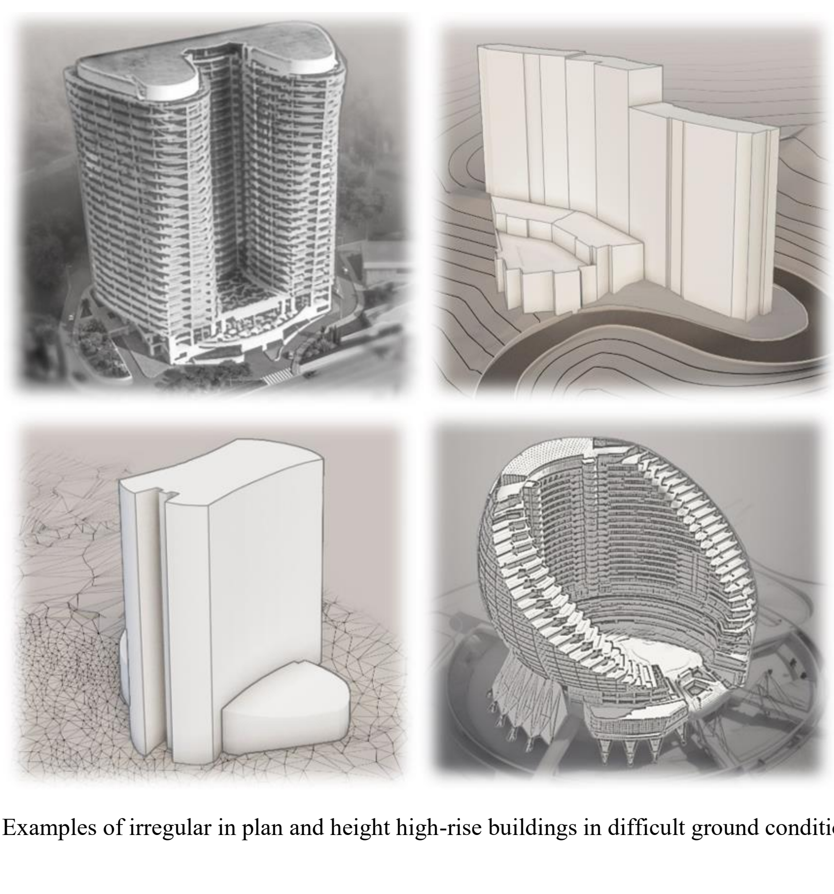

Fig. 1. Examples of irregular in plan and height high-rise buildings in difficult ground conditions.

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The structure of the development of methods for designing the foundations of high-rise buildings in difficult soil conditions is shown in Figure 2. These include:

- methods for calculating and designing pile foundations when dividing the shape of a high-rise building into blocks in accordance with external influences and soil conditions;
- calculation and design of foundations, reinforced with rigid vertical elements, with an intermediate distribution layer;
- development of methods for designing foundations for high-rise buildings in areas with a significant difference in elevation;
- methods for including pile and slab elements in joint work due to their design features and the specified stages of construction;
- regulation of uneven compressibility of the base by increasing the spatial rigidity of the foundation;
- development of methods for designing pile foundations based on the results of a study of the work of the foundation of bored piles and taking into account their group interaction.

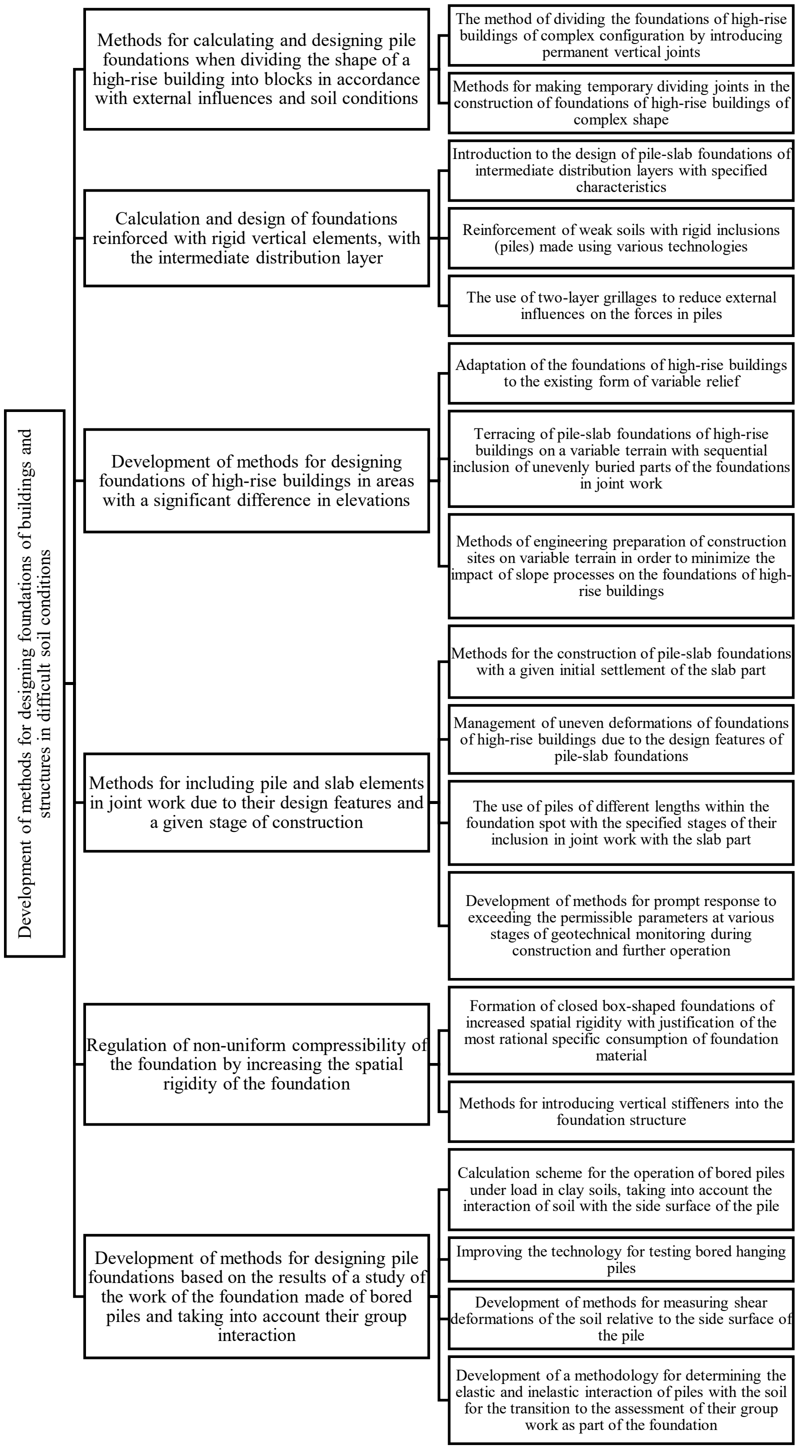

Fig. 2. The structure of design methods for the foundations of high-rise buildings in difficult soil conditions.

3 Results

3.1 Peculiarities of dividing the form of the above-ground part of a high-rise building into blocks to reduce forces in the foundation elements

The introduction of vertical joints in the volume of the above-ground structure helps reduce or eliminate stress concentrations in the above-ground structures and foundations due to the significant differences in the number of storeys and the height of the above-ground part. In this case, the mutual influence of individual blocks on each other arises, and this manifests itself in uneven settlements of the foundations of adjacent blocks, as well as in the forces transmitted to the piles. When absorbing dynamic, wind and seismic loads, the perimeter piles of adjacent blocks experience horizontal loads, which can often exceed the bearing capacity of the pile in terms of material and soil. In such cases, when choosing the places for the introduction of vertical joints, it is important to correlate the design features of the high-rise volume with the places where the division sections are arranged, including those that do not lead to significant architectural changes.

More complex cases include situations in which a high-rise building with an irregular scheme of above-ground structures is located on a construction site with irregular in plan and depth alternation of soil differences.

Each individual block as part of a single architectural complex can be located in different conditions and cause uneven compressibility of the base, which inevitably leads to different solutions for the foundations of each of the blocks. The studies carried out to assess the interaction of piles in the composition of the soil, as well as unevenly loaded adjacent piles [7, 8], make it possible to assess the mutual influence of the extreme piles of adjacent foundation slabs within the common spot of the building, to develop recommendations for setting the distance between piles, taking into account joint work with the foundation slab [9].

As an example of the practical implementation of the principle of dividing a complex shape of a high-rise building into blocks in order to reduce the effort in the foundation elements, two realized objects of high-rise buildings are given below.

3.1.1 Marriott hotel complex in Krasnodar

The high-rise building was originally located on a limited area surrounded by existing architectural monuments with significant physical deterioration of building structures (Figure 3).

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a)

b)

Fig. 3. Marriott hotel complex in Krasnodar: a) three-dimensional shape of the building surrounded by adjacent architectural monuments and an adjoining multi-storey building is highlighted in red; b) the building after completion of construction.

The form set by the architect initially provided for the greatest functionality of the building volume and did not imply any significant adjustments. However, the geotechnical calculations, taking into account dynamic and seismic effects for the undivided form, led to places of multiple excess of forces in piles and stresses in the foundation slab. As a result, the foundation was divided into blocks, and a through vertical atrium was inserted into the volume of the building for the entire height of the building, serving as the boundary between adjacent high-rise block sections of the hotel complex.

As a result, due to the introduction of the atrium and vertical joints, the shape of the building was preserved. The forces in the piles, taking into account all combinations of loads, were brought to an acceptable value, as were the values of additional deformations of neighboring architectural monuments. The final division of the given form into blocks is shown in Figure 4.

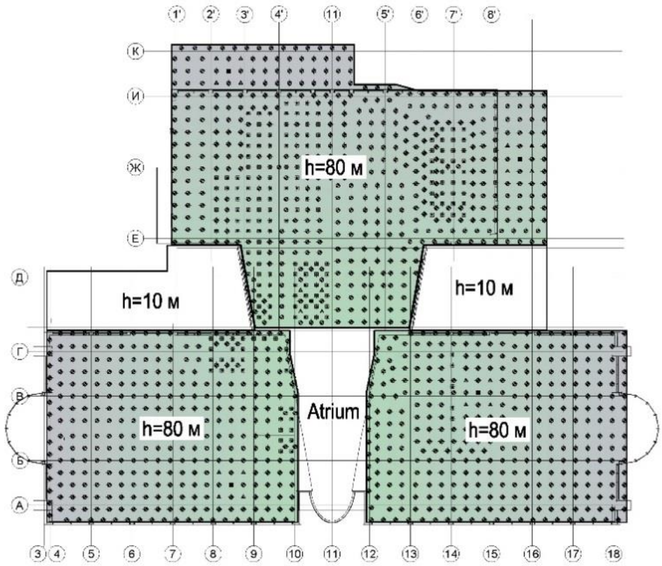

Fig. 4. The final division of the complex shape of the foundation slab into separate blocks.

The pile-and-slab foundation was made using CFA piles having a length of 23 m. The thickness of the foundation slab was 1400 mm. During construction and for 2 years after its completion, monitoring of additional and technological settlements of surrounding buildings was carried out, which confirmed the correctness of the project forecast.

3.1.2 Multifunctional residential complex on Gorky Street in Sochi

A general view below of the completed construction of a high-rise residential complex in Sochi is another example of dividing the volume of a high-rise building into blocks when constructing a pile-and-slab foundation. In this case, in addition to the complex shape of the building in plan (Figure 5), it was necessary to take into account the ancient buried channel within the construction site.

a)

b)

Fig. 5. Multi-storey residential complex in Sochi on Gorky street: a) general view of the building after completion of the construction; b) the layout of the blocks of the building with the allocation of the contours of the buried channel within the construction site.

In view of the difficult engineering and geological conditions of construction, it was decided to conduct a series of tests of piles of various lengths to establish the actual bearing capacity of the foundation soils.

In the process of selecting and substantiating the final version of the foundation, a special test program was developed, the purpose of which was to establish the actual bearing capacity of soils, taking into account the specified stage of load application, the rate of settlement stabilization and the holding time on the steps. The main task was to assess the behavior of piles of various lengths under a constantly increasing load with the piles tied to places with different stratification of engineering-geological elements and, in particular, sections of the ancient channel occurring in plan and in depth.

The influence of the channel was minimized by choosing different design elevations of the bottom of the foundation slabs of each of the adjacent blocks. Figure 6 shows the final deformations of the pile-raft foundations of individual blocks within the common foundation spot.

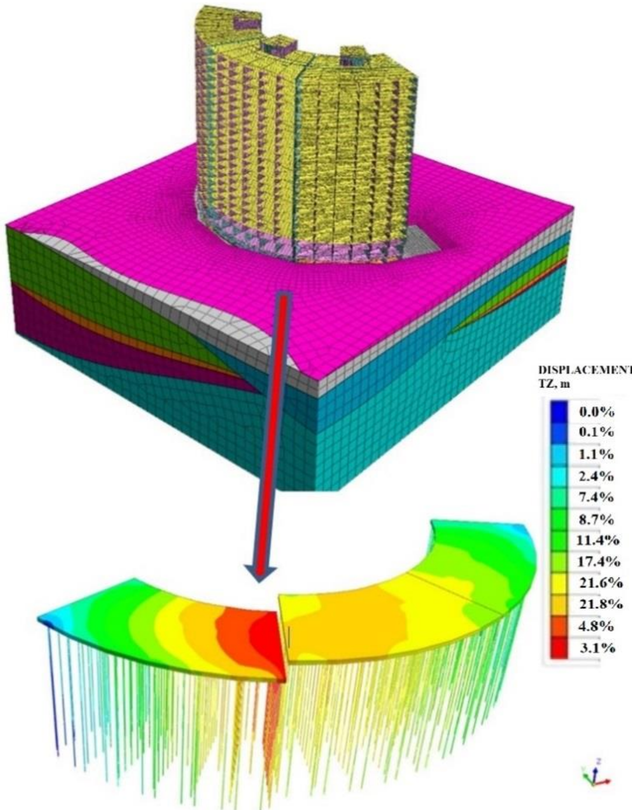

Fig. 6. Engineering-geological section with reference to the foundations of adjacent block sections of the building.

The presence of a buried channel with vaguely defined contours led to the use of the final version of the pile-raft foundation using a raft 800 mm thick, piles d = 630 mm of different lengths, spaced in plan to achieve the most complete involvement of the raft part in the perception of external loads from above-ground blocks.

3.2 Introduction of intermediate beds and the use of composite grillages

In cases where the introduction of significant structural changes in the above-ground form is unacceptable due to architectural and technological requirements, a solution for regulating the forces and stresses in the foundation elements can be found by introducing a base reinforced with vertical elements and a separating layer in the form of a bed, with specified strength and deformation properties. Such a technical solution is the basis for a slab of a high-rise building that is not divided into blocks. Features of the characteristics of the intermediate bed, technical solutions for designing the heads of the reinforcing elements, as well as the calculated step of the reinforcing elements (which are often bored piles) reduce the stress concentration for the sections of perimeter and corner piles, and the selection of the length of the reinforcing elements for different sections of the group makes it possible to equalize the compressibility of the base under stress fields of different intensity from different-storey and different-height parts of the upper structure. Studies on the alignment of the movements of the head of the reinforcing element and the point in the lower part of the foundation slab, corresponding to the middle of the span between the reinforcing elements, determine the approach to choosing the geometric parameters of the intermediate layer in combination with the rational consumption of material for the execution of vertical reinforcing elements.

As an example of the implementation of this method, a building 110 m high with a variable elevation of the roof of the bedrocks that make up the base is given.

Figure 7 shows the general view of the object and its shape completed today.

To compensate for the uneven compressibility of the base and regulate the influence of the above-ground form, it was decided to reinforce the base with vertical elements of different lengths with an intermediate bed in the form of crushed granite with a selected fraction and hardness.

Fig. 7. High-rise building of complex shape on Kurortny Avenue in Sochi: the final stage of the construction of the facility.

Figure 8 shows the final decision on the implementation of the foundations of the building.

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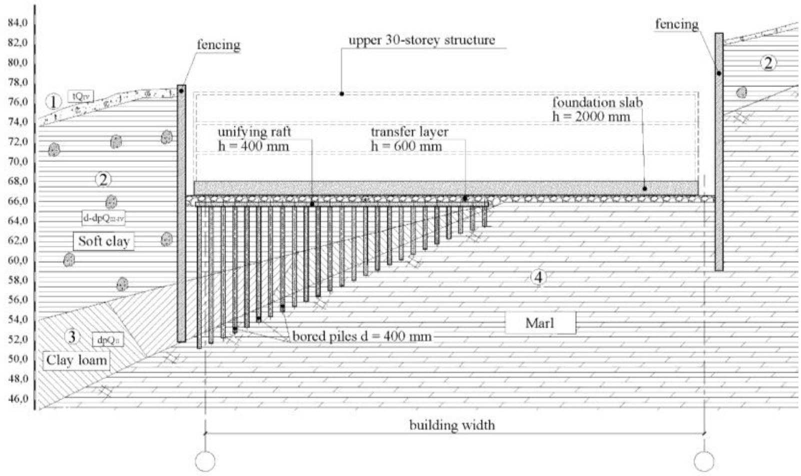

Fig. 8. Section of the building combined with the base reinforced with reinforcing elements and an intermediate bed.

This method for high-rise buildings of complex shape has been repeatedly used in similar soil conditions. The decision to assign the final scheme of reinforcing elements in the plan was based on the data of full-scale tests, previously carried out according to a specially compiled program, taking into account the staging of the load application and the distribution capacity of the foundation slab.

4 Conclusions and prospects

The other principles of designing the foundations of high-rise buildings of complex shape presented in Figure 2 were used in the construction of several dozen projects of high-rise multi-storey buildings in difficult soil conditions. Their further improvement and scientific and practical justification make it possible to significantly increase the efficiency of geotechnical solutions, reduce construction costs and achieve the required reliability and safe operation of facilities.

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