Foundations design and construction for high-rise buildings in seismic areas

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Abstract. Due to the unusual architectural forms of modern high-rise buildings, as well as an increase in design loads on their bases, geotechnics is developing. Experts in the field of bases and foundations solve increasingly complicated problems, as a result of which methods for calculating, designing and building hidden from the eyes, but very responsible and costly elements of the buildings that are the foundations, are improved. Hazardous natural processes, high seismicity, the risk of developing landslide processes complicate the task and make the problem of foundation engineering in such conditions even more urgent. The methods being developed for the construction of effective foundations have made it possible to erecting a number of high-rise buildings in seismic areas in recent years.

1. Introduction

The variety of various hazardous processes characteristic of the territory of the Krasnodar region leads to the need for systematic monitoring over these processes, which in turn determines the initial parameters for the calculation and design of essential structures in difficult soil conditions. The ongoing tendency to increase the height and number of floors of the buildings complicates the task of choosing the type of foundation and predicting its behavior during the phased transfer of loads from the above-ground structure, while taking into account such adverse factors as seismic impact and landslide processes. In many cases, during construction on such sites, the cost of performing foundations in the amount of 30-35% of the cost of construction and installation work for the entire building turns out to be familiar ratio.

It should be noted that the high cost of foundations is most often accompanied by the need to use specialized construction equipment and significant time costs for the performance of work [1]. But a higher cost of foundations and a multiple increase in their material intensity does not always lead to a more reliable solution. The impact on the soil mass or on the slope during work changes its natural initial state and significantly complicates the prediction of the work of soils and foundations over time.

Technical solutions aimed at improving the efficiency of the foundations lead to a significant reduction in the costs and time required to complete the high-rise building. Theoretical, laboratory and field studies of the proposed methods of foundation construction make it possible to obtain a justification for the possibility of using the proposed foundation structures not only for difficult soil conditions of the Krasnodar Territory, but also for similar sites with significant heterogeneity of the massif and intense external impacts [2].

2. Theory of evaluation of base deformability taking into account rigid elements made
Evaluation of the soil massif deformability with made piles can be presented in the form of two main approaches:

- Accounting of piles, element by element, inside the soil mass with actual layering;
- Use of the above properties of the massif by averaging the properties of soils and piles.

Each approach has its own advantages and disadvantages [3]. So, when averaging the properties of the soil massif and the elements made in it, a simple model of the slab foundation on an improved base is obtained, which makes it possible to quickly perform the calculation of deformations. However, this approach does not reflect the real structure of the soil massif, does not take into account the non-linear processes of interaction between piles, as well as the interaction between a group of piles and a foundation slab.

If using a detailed approach when calculating reinforced bases, the task becomes more complicated, it becomes more labor-intensive, requiring correct work modeling of the soil interacting with piles, as well as the use of appropriate calculation algorithms to analyze the entire geotechnical model.

It is necessary to take into account the diameter, length, number, pitch of piles and their manufacturing technologies, which can not only make it possible to find rational solutions, but also to develop a methodology for regulating stress-strain state (SSS) during the construction and operation of the facility.

In the approach with a detailed representation of the reinforcing elements included in the massif, several important modelling stages can be distinguished, which include considering the interaction of a single pile with the surrounding soil [4,5], the interaction of a group of piles with a foundation slab [6-14], as well as modelling the operation of transfer layers [3]. As a result of studies [15,16], the phases of development of linear and non-linear deformations of single piles under the influence of gradually increasing vertical load were determined on the basis of field and laboratory experiments. Information about the operation of single piles makes it possible to evaluate the work of the soil, having previously calculated the specific load perceived by individual elements at different stages of loading the foundation. Further, the force in the head of the reinforcing element determines the structure, material and thickness of the intermediate pad based on the analysis of the Prandtl fracture pattern, or the

**Figure 1.** Averaging properties of soils and reinforcing elements.

**Figure 2.** Element-by-element accounting of piles with detailed modelling of soil layers.
formed surface of the shear cone. However, all the above-mentioned calculation prerequisites should be compared to the results of verification spatial calculations made using up to date software complexes. The analytically and numerically validated result provides a solid basis for developing general technical recommendations for this type of foundation design.

3. Regulation of stress-strain state of reinforced soil mass by stage of foundation erection

To regulate the SSS of the base of the pile (pile and slab) foundation, it is possible to use various methods related to introducing improved design patterns, as well as using various effective methods of foundation construction in seismic areas, on unevenly compressible bases and difficult ground conditions [17-19].

A method is known, in which piles can be made of different lengths, thus it is possible to achieve a reduction in the material capacity of the pile (pile and slab) foundation due to the inclusion in the operation and transfer of a significant load to the soil through the foundation slab (see Figure 3, a).

Efficiency of this structure is achieved by step-by-step inclusion of piles in the footing operation taking into account the sequence of building construction (see Figure 3, b-e) [2].

![Figure 3. Method of construction of CPRF with inclusion of piles of different length; a - installing short piles, b - installment of longer piles with design clearance; c - erection of foundation slab rigidly combined with short piles; d - process of erection of above-ground structures of a high-rise building and compaction of soil in the area of short piles; e - exhaustion of design clearance during application of operational loads; f - one of the possible solutions for the inclusion of long piles in the foundation operation is a performing of a niche in the lower part of the foundation slab.](image-url)

In order to increase the share of load transferred to the foundation slab, it is necessary that various settlement values of the slab and piles in the foundation to be provided at the beginning, which can be obtained if the joint work of the slab and long piles begins after part of the design load arrives on the slab, which in turn leads to deformation of the upper layers of the soil.

Due to the initial deformations of the slab with short piles, the ground of the base is compacted, and much considerable share of the load is transferred to the foundation slab. Long piles placed under the
supporting vertical structures are included in the work at the last stage, when the percentage of load perceived by the foundation slab may already be \( \approx 50\% \).

4. Practice of mastering complex soil conditions and developing design methods for reinforced bases for construction of high-rise buildings

As an implementation of such a method of building foundations, we consider a high-rise building, which was built in Sochi. Its design did not initially involve the use of piles as elements of base reinforcement. The site for construction was quite even and according to the survey, no significant capacities of weak soils were revealed. Therefore, a CPRF foundation was designed from bored piles of 20 m long and 630 mm in diameter (Figure 4, a).

However, during the work performance and field tests of soils by piles (No. 20 and No. 99, see Figure 4, a), it was found that the actual bearing capacity of such piles was not more than 1200 kN, which was 1.5 to 2 times less than the required value.

Therefore, additional geotechnical surveys were carried out to determine the reasons for such a low bearing capacity of the foundation piles. As a result of processing the test results, it was found that within the site the elevation of the bedrock roof varies greatly, in some places the thickness of weak soils, that make up the section, is 30 m, which caused the low bearing capacity of the piles (Figure 4, b).

Under such conditions, it was decided to change the length of the piles to 35 m and their diameter by 400 mm. The selection was also dictated by the technological capabilities of the drilling rig.

After completing the piles for the reinforcement of the base, field tests were carried out, which confirmed the high bearing capacity of the reinforcing elements in these soils. At the same time, to reduce the effect of horizontal loads on the reinforcing elements of the base and the building, they were separated at the level of the foundation slab by a transfer layer of granite crushed stone, which is low-compressible material.

![Figure 4](image)

**Figure 4.** Technical solution for reinforcement of the foundation of the high-rise building in Sochi on unevenly compressed soils; a - plan of reinforcing elements (piles Ø400 33-35 m long) and piles made for the initial solution of foundations (piles Ø400 20 m long); b - final design scheme "foundation-reinforced base."

5. Conclusions

As a result of the development of methods regulating the working of foundations in the process of construction and further operation of high-rise and unique buildings, practical recommendations and technical solutions for performing the effective foundation structures are proposed, the implementation of which minimizes construction costs and provides an additional opportunity to control absolute and uneven deformations of underground and above-ground building elements.
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