DE GRUYTER OPEN

CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

ISSN 2080-5187

CEER 2017; 26 (3): 059-068

DOI: 10.1515/ceer-2017-0035

Original Research Article

RESEARCH OF THE INTERACTION OF PILES WITH DIFFERENT LENGTHS AND THE GRILLAGE IN THE FOUNDATIONS OF HIGH-RISE BUILDINGS

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A b s t r a c t

The interaction of piles with different lengths and the grillage in the foundations of high-rise buildings is considered. The numerical modeling of the «base – foundation – superstructure» system is performed. The redistribution of the efforts in piles depending on the sizes of a foundation slab and the parameters of piles (length and location) is investigated. Typical zones of a foundation such as central, lateral, and angular ones are separated. The redistribution of efforts between piles and a grillage is revealed.

Keywords: pile foundation, pile base, piles with different lengths, numerical modeling, high-rise buildings

1. INTRODUCTION

High-rise buildings are widely spread in the urban development. Pile foundations are often used for high-rise buildings due to a heavy load of superstructures on the base. In those cases, engineers are faced with a number of tasks: a) modern methods of calculation of structures should be developed; b) computer aided design (CAD) systems should be used to solve various problems of geotechnics;

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c) various calculation models involving the nonlinear laws of deformation of materials and the soil base should be applied.

A promising direction of the design of pile foundations is an increase in the economic efficiency and the reliability of design solutions due to the use of a rational number of piles and the efficient use of their supporting ability.

For this purpose, changes in a stress-strain state of the «base – foundation – superstructure» system with different numbers of piles, their different locations, and their different lengths must be simulated with regard for the actual parameters of a soil base.

2. PURPOSE

We will study the redistribution of the efforts in piles depending on the sizes of a foundation slab and the parameters of piles (length and location). Changes in the stress-strain state of a pile foundation with short and long piles will be determined. The interaction of the pile foundation with the base within a model taken for calculations will be analyzed.

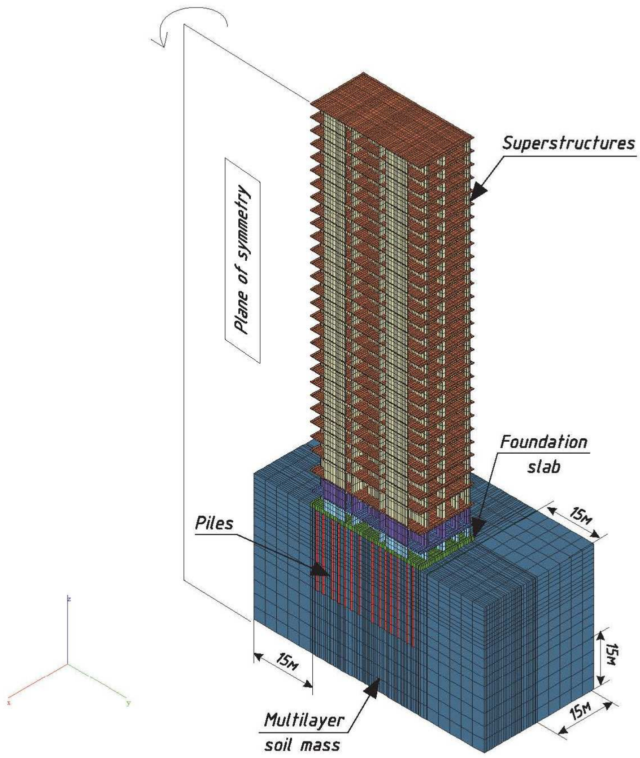

Fig. 1. Finite-element model of a high-rise building

3. DESIGN SCHEME AND THE MODEL OF A SOIL FOUNDATION

The design scheme includes all elements of the building as a «base – foundation – superstructure» system. The finite-element model includes the volumetric soil massif described according to geological studies, pile foundation, and bearing superstructure of the building (Fig. 1).

The soil massif bottom is limited by a plane without vertical displacements (it is assumed that settlements of soil can be ignored at this depth). On the lateral planes, we took the boundary conditions that prevent normal displacements.

The location, capacity, and mechanical properties of soil layers correspond to the data of geotechnical studies. Calculations of a stress-strain state of bearing structures of the building together with the soil base are performed by the finite-element method (FEM) in the three-dimensional statement with the use of the software «VESNA».

In the simulation of a deformation of soils, we used a model of nonlinear elastoplastic soil medium based on the theory of dilatancy [5]. The non-associated law of plastic flow is used to determine the increment of plastic strains. The Mises-Huber criterion modified by Professor I. Boyko [1] is used as the condition of a plastic flow, which provides the agreement of the results of simulation with experimental data in a wide range of loads on the soil medium.

4. INTERACTION OF PILES AND A GRILLAGE

High-rise buildings are often constructed on a pile foundation joined by a grillage. The interaction of these buildings with the soil base has a number of specific features. It depends, in the first turn, on the ratio of the grillage width and the pile length, on the dimensions of the grillage plate, and on the number and arrangement of piles in the foundation.

4.1. Effect of the dimensions of piles and a grillage on a stress-strain state of the soil base

It is expedient to distinguish two types of the foundations with piles: pile foundations and pile bases. In the case of pile base, the deformations of a building are determined by its width, and piles only improve the properties of soil in the top part of the base (Fig. 2).

The calculation results show that, in the case of pile base, the zone of normal stresses in soil under the grillage overlaps the area of stresses in soil under the sole of piles, whereas this overlap zone is absent in the case of pile foundation (Fig. 3). In the case of pile base, the redistribution of efforts between piles and the grillage is as follows: the grillage accepts about 45% of the total load, and piles accept about 55%. In the case of pile foundation, this redistribution varies: about 15-20% of the load are referred to the grillage and 80-85% to piles, which was observed under different soil conditions.

Our studies indicate the necessity to consider, in calculations, the dimensions of a grillage and piles and their interaction with the soil base.

a) b)

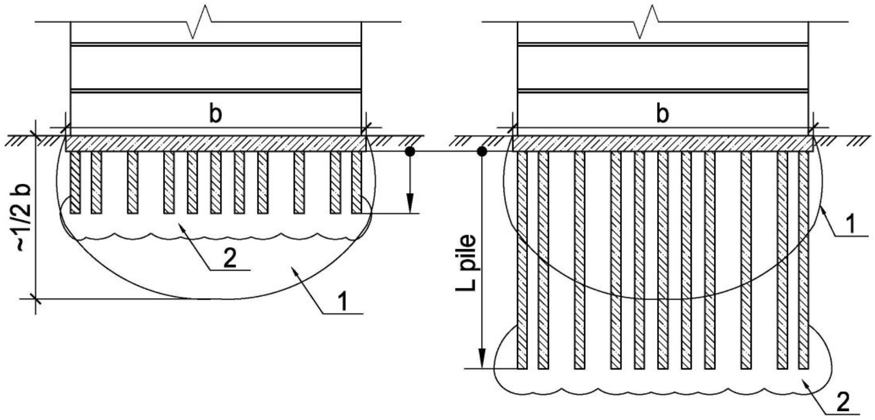

Fig. 2. Schemes of the interaction of a building with soil: a) pile base, b) pile foundation; 1 – deformation zone under the grillage, 2 – deformation zone under the sole of piles

a) b)

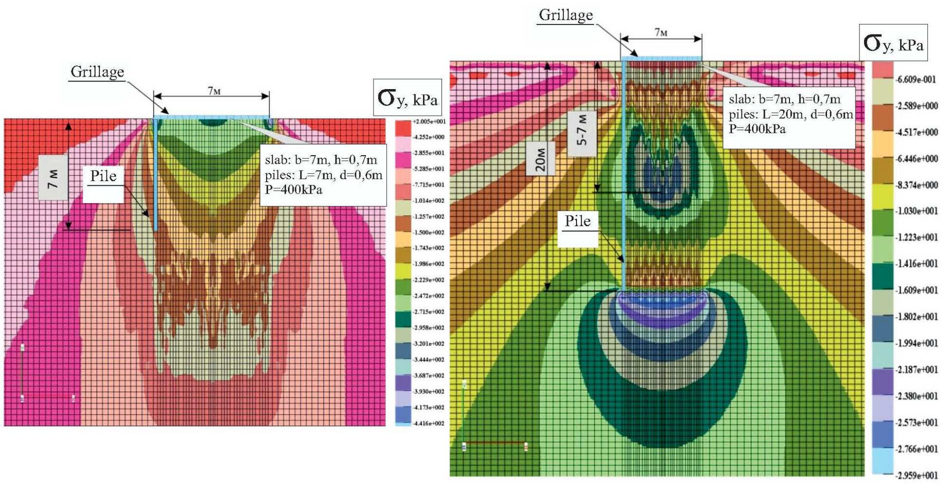

Fig. 3. Stresses in soil: a) pile base, b) pile foundation

The application of a model of nonlinearly deformed soil base results in the complexity of determination of many parameters of soil that change during a deformation. The standard methods of geotechnical investigations do not provide a complete collection of parameters of soil. Therefore, it is necessary to carry out additional studies and to implement the interpretation of parameters. To this end, we present the results of tests of piles as a «load – settlement» plot. According to it, we executed the modeling of the tests of piles, as well as the identification of parameters for the accepted model of deformation of the soil medium. This allowed us to obtain the specified values of stresses in soil and the redistribution of efforts in the foundation.

4.2. Location of piles in typical areas of a foundation

As is known, piles in a pile foundation are not equally loaded. This is confirmed by experimental data [2, 3] and the results of numerical modeling [4, 6]. In those works, it was noted that the piles of marginal zones are loaded most of all, and the load on the piles of central zones is the least. This depends on many factors, one of which is the location of piles within the grillage. In practice, we can observe very often the location of piles on a regular grid with a given step. This choice is proper only at first sight. In fact, it has several drawbacks: peripheral piles are overloaded by 1.5-3 times as compared with the design load on a single pile, whereas the load on central piles, whose share is about 50% in the foundation, is 50-60% of the design one on a single pile. This leads to a significant overspending of materials (concrete and reineffortment) in piles and, consequently, increases the cost of a construction. The account for a nonlinear deformation of the soil base allows one to simulate a redistribution of efforts between piles, which are working up to the limit of their bearing capacity. The task of a designer is to find the optimal position of piles in the foundation. The typical zones of a foundation are angular, contour, and middle ones, where its piles work differently. The angular and contour zones together constitute the peripheral zone, which includes piles with the same name. In the middle zone, the middle piles and piles of the rigidity core are located (Fig. 4). We note that the lateral surface of peripheral piles works most efficiently. As for the middle piles, soil is clamped between the lateral surfaces of piles, which reduces or eliminates the lateral friction. Therefore, the middle piles are underloaded, and the peripheral piles are overloaded. In this case, the question arises about the efficient use of the bearing capacity of piles. This can be achieved by a rational geometric arrangement of piles in the foundation (Fig. 4). The criterion of rational location of piles is a more uniform redistribution of efforts between the piles, providing the efficient use of a material of piles. Therefore, it is advisable to move the piles from the middle zone to the contour of the building and to dispose them under the load-bearing structures. This approach requires one to increase the number of piles in peripheral zones and to reduce it in the middle zones. This increases the average distance between the piles, which leads to a more complete work of their lateral surface. An example of the problem and the main indicators are presented in Table 1.

a) b)

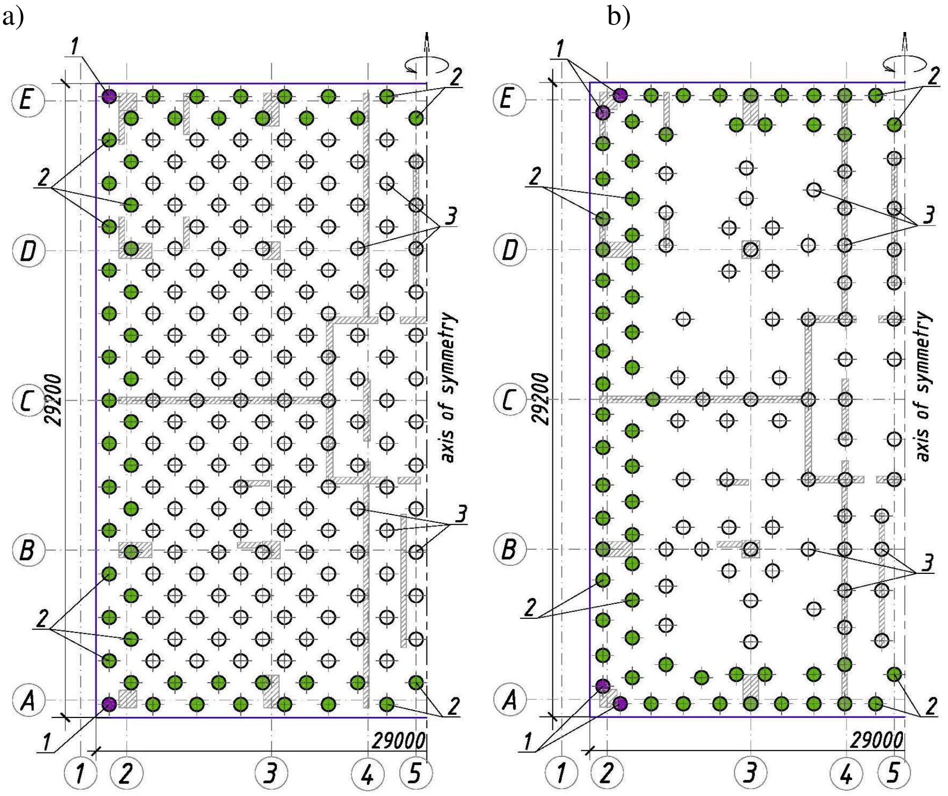

Fig. 4. Location of piles on a regular grid (a) and rationally (b) according to the zones: 1 – angular; 2 – contour; 3 – middle; (1+2) – peripheral

The executed studies showed that the angular piles and some contour ones, which are located on a regular grid, get loads that exceed their bearing capacity by ground and by material, which is unacceptable. The optimal arrangement of piles in plan resulted in a more uniform redistribution of the efforts over foundation structures. In this case, the maximum effort in a pile decreases by 10-20%, and the minimum effort increases more than twice.

Therefore, the efficiency of the use of the bearing capacity of each pile increases. The total number of piles can be reduced by 15-30% at their rational location, settlement of the foundation slab varies within 5%, and bending moments are changed within 10%. With such changes, the total bearing capacity of the foundation is not reduced.

Thus, the rational arrangement of piles makes it possible to efficiently distribute the load between the piles, to detect the zones of extreme internal efforts, and to make decision aimed at their reduction. This allows one to design the reliable foundation constructions with optimum number of piles.

Table 1. Comparison of the results of calculations with different locations of piles

№	Indicator	Location of piles		Com-parison
		on a regular grid with given step	rational	
1	Total load of the building on the foundation, kN (%)	456 200 (100)		-
2	Load on the grillage, kN (%)	63 282.7 (13.9)	60 163.9 (13.2)	<1 %
3	Load on the piles, kN (%)	392 917.3 (86.1)	396 036.1 (86.8)	<1 %
4	Total number of piles, pcs (%)	392	252	↓ 140 pcs (↓ 35%)
5	Maximum effort in a pile, kN	3 729.6	3 470.0	↓ by 1.08 times
6	Average effort in a pile, kN	1 002.5	1 571.6	↑ by 1.57 times
7	Settlement of the grillage, cm	51.2	52.8	~3 %

4.3. Interaction of the grillage and piles with different lengths

The investigation of stress-strain states of the «base – foundation – superstructure» system shows that the rational location of piles within the scope of a grillage gives the desired redistribution of efforts in piles not in all cases. The peripheral piles (especially, angular ones) remain problematic. In this connection, we propose to change the length of problematic piles for the regulation of efforts in them. This allows one to efficiently use the bearing capacity of piles and to get optimal internal efforts in foundation structures. Indeed, the smaller the length of piles, the less their bearing capacity.

For this purpose, we considered two variants with the variable lengths of piles: a foundation with shorter peripheral piles and a foundation with shorter middle piles (Fig. 5). These variants of foundations are compared with the foundation on piles with identical length.

The results of calculations show a decrease in efforts in shorter piles as compared with piles with identical length, which is logical. Therefore, short piles in the middle zone of a grillage are not recommended, because the peripheral piles are already overloaded. It is more efficient to reduce the length of piles in the peripheral zone. An example of such variant of a pile foundation is given by the high-rise building in Frankfurt-am-Main proposed by Professor R. Katzenbach et al. [2]. In the homogeneous basis, they offered to arrange a pile field with significant increase in the length of piles to the center of the building.

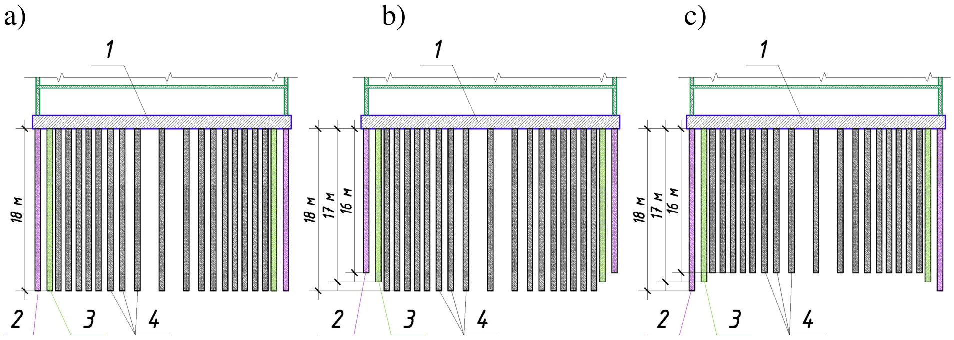

Fig. 5. Changing the length of piles within the typical zones of the foundation: a) piles with identical length, b) shorter peripheral piles, c) shorter middle piles; 1-grillage, 2-peripheral piles of the 1st line, 3-peripheral piles of the 2nd line, 4-middle piles

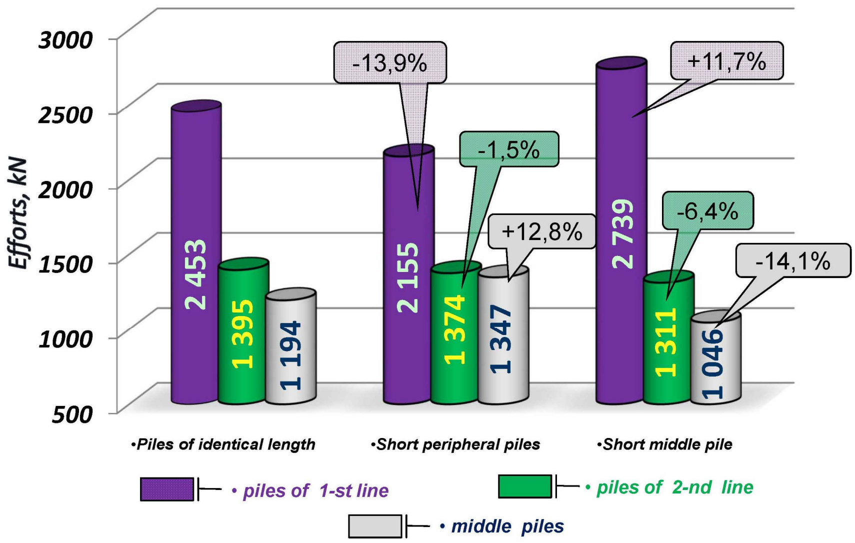

Fig. 6. Redistribution averaged efforts between piles depending on their length

The pile foundation with shorter peripheral piles allows one to reduce the effort in them up to 15% as compared with the foundation with piles with identical length (Fig. 6). The redistribution of efforts between the grillage and piles in two variants of foundations with shorter piles is almost unchanged on the whole or increases by about 1%. The change in the length of piles causes the increase in the settlement of a foundation plate within 5-6%. In general, the bearing capacity of the pile foundation remains unchanged. This suggests that the rational choice of a location of piles in plan and of their lengths makes it possible to decrease the extreme values of internal efforts in the foundation structures and to reduce the total number of piles.

5. CONCLUSIONS

1. The reliable results of numerical modeling of the «base – foundation – superstructure» system can be obtained with regard for the identified parameters of a model of soil base.
2. The correlation of the grillage sizes and the lengths of piles defines the separation of a foundation with piles into two types: pile foundation and pile base.
3. The redistribution of efforts in piles between typical zones such as the angular, contour, and middle ones should be considered. We have established that the values of efforts in piles differ by three times in the angular and middle zones. Therefore, it is advisable to carry out complex calculations aimed at the determination of a rational location of piles in the pile foundation. This will give the economic effect concerning the consumption of materials.
4. It is found that the rational location of piles in a foundation allows one to uniformly load the piles and to decrease their total number by 15-30% as compared with the case of piles on a grid with regular step.
5. To adjust the efforts in the angular piles, it is proposed to change their lengths depending on the combination of loads. It is established that the pile foundation with shorter peripheral piles is more uniformly loaded, more efficiently uses its bearing capacity, and is more reliable as compared to the foundation with shorter middle piles.

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BADANIA INTERAKCJI PALI O RÓŻNEJ DŁUGOŚCI I RUSZTÓW W FUNDAMENTACH BUDYNKÓW WYSOKICH

S t r e s z c z e n i e

W pracy rozważa się wzajemną interakcję pali o różnej długości i rusztów w fundamentach budynków wysokich. Wykonano analizę numeryczną systemu "grunt - fundament - budynek". Analizowana jest redystrybucja wykorzystania nośności poszczególnych pali w zależności od wymiaru płyty fundamentowej i parametrów pali (długość i położenie). Wydzielone są typowe strefy fundamentu - centralna, boczne i kątowe. Sprawdzone redystrybucję wytężenia pomiędzy palami a rusztem.

Słowa kluczowe: pale fundamentowe, modelowanie numeryczne, wysokie budynki

Editor received the manuscript: 5.07.2017