

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING



This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

<https://www.issmge.org/publications/online-library>

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

The paper was published in the proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering and was edited by Mizanur Rahman and Mark Jaksa. The conference was held from May 1st to May 5th 2022 in Sydney, Australia.

A new design of a combined pile raft foundation for a multi-storey building with determination of its main parameters

Une nouvelle conception de la fondations mixte radier-pieux pour les bâtiments à plusieurs étages avec la détermination de ses paramètres principaux

Oleksandr Samorodov

Department of Geotechnics, Underground and Hydrotechnical Structures, Kharkiv National University of Civil Engineering and Architecture, Ukraine, osamorodov@ukr.net

Dmytro Mulyar

LLC "Engineering company professor Katzenbach and partners – Ukraine", Ukraine

Sergii Tabachnikov & Oleg Krotov

Department of Geotechnics, Underground and Hydrotechnical Structures, Kharkiv National University of Civil Engineering and Architecture, Ukraine

Yuriy Vynnykov

Department of Oil and Gas Engineering and Technology, Educational and Research Institute of Oil and Gas, National University "Yuri Kondratyuk Poltava Polytechnic", Ukraine

Mykola Zotsenko

Department of Organization and Technology of Building and Health Safety, National University "Yuri Kondratyuk Poltava Polytechnic", Ukraine

Volodymyr Shapoval

Department Construction, Geotechnics and Geomechanics, National Technical University "Dnipro Polytechnic", Ukraine

ABSTRACT. A new design of a combined pile raft foundation, which is devoid of the shortcomings of similar existing design solutions and installation methods, and an engineering method for determining its main parameters, are proposed. This technical solution has been implemented at one of the construction sites in Brovary (Kyiv region, Ukraine). The proposed design makes it possible to efficiently use the load-bearing capacity of the soil base by involving the slab part in the response to the loading in a controlled manner with transfer of up to 50% of the total load to this without going beyond the allowable strains of the soil base. The remaining 50% of the load are taken up by piles. After determining the multiplicity of the pile spacing and their parameters costs can be reduced by up to 35% in comparison with other design solutions for combined pile raft foundations.

RÉSUMÉ. Une nouvelle conception d'une fondation mixte radier-pieux, qui est dépourvue des inconvénients inhérents aux solutions de conception et des méthodes d'installation similaires existantes, ainsi qu'une méthode d'ingénierie pour déterminer ses paramètres principaux, sont proposées. Cette solution technique a été mise en œuvre sur l'un des sites de construction à Brovary (région de Kiev, Ukraine). La conception proposée permet d'utiliser efficacement la capacité portante de la base du sol en impliquant la partie dalle dans la réponse au chargement de manière contrôlée avec le transfert de jusqu'à 50% de la charge totale vers celle-ci sans dépasser les déformations admissibles de la base du sol. Les 50% restants de la charge sont repris par des pieux. Après avoir déterminé la multiplicité de l'espacement des pieux et leurs paramètres, les coûts peuvent être réduits de jusqu'à 35% par rapport à d'autres solutions de conception pour les fondations mixtes radier-pieux.

KEYWORDS: combined pile raft foundation, new design, soil base, negative friction forces, implementation.

1 INTRODUCTION.

In the construction of multi-storey and high-rise buildings in the last twenty years in the world practice, one of the advanced developments has been a combined pile raft foundation (CPRF), where the loads from the building are distributed between the piles and the raft slab, allowing up to 50% of the structural load being taken by the raft slab. (Katzenbach, Leppla & Choudhury 2016).

The choice of effective solutions for such foundations depends on many factors, such as the features of soil conditions,

the parameters and spacing of piles, the rigidity of the slab, the model of the base and the nature of the interaction between the piles, slab and soil, and others. Therefore, the design of the "base – foundation – structure" system is possible only with the help of numerical methods implemented in powerful computer systems such as ANSYS, SOFISTIK, etc. taking various individual approaches to modeling such systems with a significant number of assumptions which, as a rule, do not have a full-scale experimental base in terms of the actual resistance of the soil base under the raft slab.

Thus, the development of a new design of a combined pile raft foundation and a method for determining its main parameters is a relevant objective.

1.1 New design of a combined pile raft foundation

A new design of a combined pile raft foundation is proposed, which is devoid of the shortcomings of similar existing design solutions and methods of arrangement, and engineering methods for determining its rational parameters are proposed. A combined pile raft foundation (as shown in Figs. 1, 2) consists of the slab 1 and the piles 2 with the diameter d , with the gap 3 of the height Δ provided between the slab and the piles, and the distance between the axes of the piles being of $a=nd$. Moreover, for technological convenience to ensure the absence of contact between the slab and the pile heads within the concrete bed installation under the plate 4, the gap can be filled with a low-modulus material such as foamed palstic.

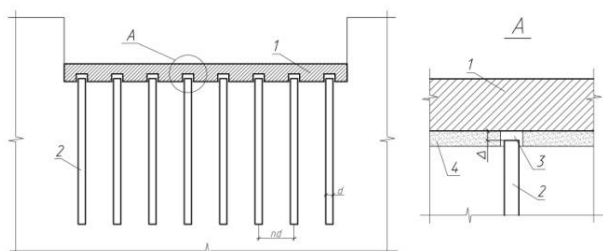


Figure 1. Combined pile raft foundation.

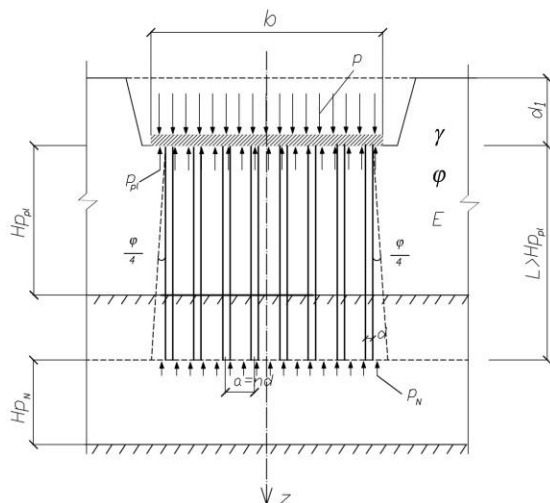


Figure 2. Design model for the interaction between a large-size pile raft foundation and the soil mass.

Further, it is proposed to consider the development of an engineering method for designing a pile raft foundation proceeding from the maximum allowable settlement of a structure s_u , taking into account the design model for the interaction between a nominally solid foundation and a linearly deformed soil environment (see Fig. 2).

1.1.1 Engineering methodology for the optimal design of a combined pile raft foundation

Let us put forward a number of justifications and assumptions (see Fig. 2.2):

- The total pressure p on the bottom of the foundation is taken as evenly distributed over the entire area of the foundation slab measuring $b \times l$, while in the course of erection of a building the slab part of the foundation is the first to be involved in the response to the loading, which takes up the allowable pressure p_{pl} , and then the pile is involved in the response, the intensity of reactions N of which is shown as a

uniformly distributed pressure p_N at the elevation of their bottoms to be laid. Therefore, two compressible layers H_{ppl} and H_{pn} are successively formed both under the slab and under the lower ends of the piles respectively;

- The lower limit of the compressible layer H is set proceeding from the condition (DBN V.2.1-10:2018): $k \cdot \sigma_{zg,H} = \sigma_{zp,H}$ (where $k = 0.5$ at the width of the bottom of the foundation making $b > 20m$);

- To determine the settlements, we use the known formula obtained from the generalized Hooke's law for a uniformly loaded layer of soil:

$$s = \beta \frac{p \cdot H}{E}, \quad (1)$$

where $\beta = 1 - [2\nu^2 / (1 - \nu)]$.

- Since for large-size foundations the compressible layer H does not usually exceed $0.5 \div 1.0b$, the pressure intensity along the depth can be taken to be constant (Guidelines for designing pile foundations. NIIOSP named after N. M. Gersevanov 1980);

- To simplify the conclusions, we take the physical and mechanical characteristics of the soil layer as the average values: γ , ϕ and E , ν .

Determine the value of the allowable pressure p_{pl} based on the allowable settlement s_{pl} of the slab part of the building.

According to Fig. 2 and the accepted assumptions write the normative equality of stresses at the boundary of the compressible layer H_{ppl} in the form of $k \cdot \gamma(d_1 + H_{ppl}) = p_{pl}$, so the depth of the compressible layer will be equal to

$$H_{ppl} = \frac{p_{pl}}{k \cdot \gamma} - d_1. \quad (2)$$

On the other hand, the value of the compressible layer can be obtained by the formula (1) based on the amount of strain s_{pl} , which is allowed for the soil base of the slab part. Equating the formulas (1) and (2), we obtain the value of the pressure under the raft slab p_{pl} in the form

$$p_{pl} = \frac{d_1 + \sqrt{d_1^2 + \frac{4 \cdot s_{pl} \cdot E}{k \cdot \gamma \cdot \beta}}}{2} k \gamma \quad (3)$$

Assigning the design load N on the pile with the diameter d and length $L > H_{ppl}$, we find the multiplicity of the spacing n . According to the design model in Fig. 2, it is seen that the total load from the structure p is separately taken by the slab part of the foundation p_{pl} as part of a solid raft slab measuring $b \times l$ and the pile N based on the load area $(nd)^2$. Then we can write a simple formula:

$$p = \frac{N}{(nd)^2} + p_{pl},$$

or

$$n = \sqrt{\frac{1}{d^2} \cdot \frac{N}{p - p_{pl}}}, \quad (4)$$

where p is the total pressure under the bottom of the slab part from the building, kPa;

p_{pl} is the part of the total pressure p , which is allowed only on the soil base under the slab part of the foundation, kPa;

N is the part of the total load $p(nd)^2$, which is taken by the pile, or the design load on the pile, kN;

d is the diameter or the cross-sectional side of the piles, m;

in addition, the condition must be met

$$nd = a \leq 2L \cdot tg \frac{\varphi}{4} + d. \quad (5)$$

The resistance (pressure) p_N at the elevation of the lower ends of the piles will be equal to

$$p_N = p - p_{pl}, \quad (6)$$

then the value of the compressible layer H_{p_n} is written as

$$H_{p_n} = \frac{p_N}{k \cdot \gamma} - d_1 - L, \quad (7)$$

and the additional average settlement of the foundation with the piles involved in the response to the loading will be defined by the formula (1) at $H = H_{p_N}$

$$s_N = \beta \frac{p_N \cdot H_{p_N}}{E}. \quad (8)$$

If the distance between the piles does not satisfy the condition (5), it is required to consider the local downward pushing of the base by the piles according to the methodology adopted in the Russian regulatory document SP 50-102-2003 when determining the settlements according to the formula (8).

The condition for the design of a combined pile raft foundation for the second group of boundary conditions will be written as

$$s_{pl} + s_N \leq s_u. \quad (9)$$

A special feature of the design of the combined pile raft foundation is also to take into account the initial settlement of piles $S_{pile}^{P_n}$ due to the additional loading friction forces P_n acting on their lateral surface within the compressible layer $H_{p_{pl}}$ during the settlement of the soil base due to the initial load p_{pl} . To this end, consider the pattern of formation of additional loading friction forces acting to a single pile of the length L and diameter d (Fig. 3) in a two-layer base with the parameters (deformation modulus and Poisson's ratios: E_1, ν_1 and E_2, ν_2).

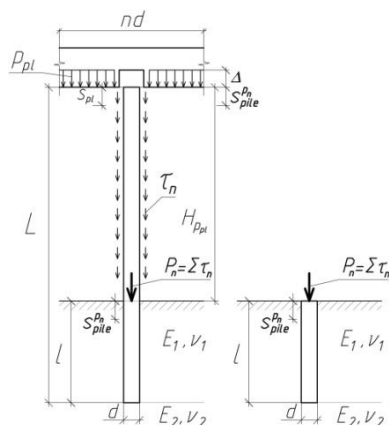


Figure 3. Design models for determining the initial settlement of piles in the combined pile raft foundation in the course of deformation of the base under the slab.

For the theoretical determination of the value of the additional loading soil friction forces P_n , the prerequisites proposed by O.V. Samorodov and confirmed by laboratory tests (Samorodov, Tabachnikov & Naydenova 2019) that the additional loading friction force P_n acting on the pile develops due to additional deformations of the near-pile area and cannot be greater than the resistance force on the lateral surface of the pile at rest T_0 , which is formed due to the own weight of the soil

base.

Preliminary calculations show that for the design model (Fig. 3) the maximum settlement of the pile $S_{pile}^{P_n}$ for the action of the total friction force p_{pl} (formula 10) can be obtained by the formula by V.G. Fedorovsky given in the Guide (Guidelines for designing pile foundations 1980), for the case when $\frac{G_1 L_d}{G_2 d} \approx 1$ and without taking into consideration the deformation of the pile body:

$$S_{pile}^{P_n} = \frac{0.22 P_n}{G_2 d}, \quad (10)$$

The following is the method of calculation and assignment of rational parameters of the combined pile raft foundation:

- Determine the value of resistance (pressure) under the raft slab p_{pl} according to the formula (3) at a given allowable value of the settlement s_{pl} of the slab part;
- Determine by calculation or experimentally the design load N to the pile of the length $L > H_{p_{pl}}$, where $H_{p_{pl}}$ is calculated by the formula (7);
- Determine the multiplicity of the spacing n between the axes of the piles according to the formula (4) while checking the condition according to the formula (5);
- Determine the resistance (pressure) p_N at the elevation of the bottom of the piles according to the formula (6) and settlement according to the formula (8);
- Check the fulfillment of the condition by the formula (9);
- Perform the calculation of the initial settlement $S_{pile}^{P_n}$ of the piles due to the action of the additional loading friction forces on their lateral surface P_n according to the formula (10) and adjust the value of the gap between the slab and the pile heads:

$$\Delta = s_{pl} - S_{pile}^{P_n}$$

1.2 Example of designing a combined pile raft foundation

By means of a specific example, consider the possibility of designing a combined pile-raft foundation of a 28-storey building with a cast in-situ reinforced concrete frame in Brovary, Kyiv region.

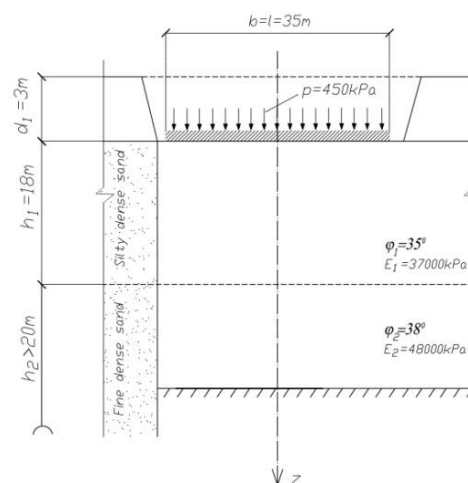


Figure 4. Model of laying a raft slab on the geotechnical cross-section

Consider the initial data for an example of design of the pile raft foundation:

- The plan dimensions of the slab are $b \times l = 35 \times 35$ m;
- The average pressure under the bottom of the slab is $p = 450$ kPa;
- The average specific weight of soil is $\gamma = 20$ kN/m³;

- The allowable settlement with consideration for the increasing factors is $s_u = 27.0 \text{ cm} = 0.27 \text{ m}$;
other values are given in the design model (Fig. 3).

Preliminary calculations show that the use of a slab type foundation will lead to a significant settlement of the building $s = s_{pl}$, which will be greater than the maximum allowable value: $s_{pl} \approx 0.36 \text{ m} > s_u = 0.27 \text{ m}$.

Therefore, consider the option of a combined pile raft foundation with the initial pressure p_{pl} being transferred to the soil base of the slab, for example, with the expected (allowable) average settlement of about 10 cm, i.e. for ease of completing the gap Δ within the thickness of the concrete bed: $s_{pl} = \Delta = 0.1 \text{ m}$, then

$$p_{pl} = \frac{3 + \sqrt{3^2 + \frac{4 \cdot 0.1 \cdot 37000}{0.5 \cdot 20 \cdot 0.8}}}{2} \cdot 0.5 \cdot 20 = 230 \text{ kPa};$$

$$H_{p_{pl}} = \frac{230}{0.5 \cdot 20} - 3 = 20 \text{ m}.$$

Take the design load $N = 2700 \text{ kN}$ on the augercast pile with the diameter $d = 0.63 \text{ m}$ and the length $l = 21.0 \text{ m}$, which is obtained on the basis of static tests, and find the optimal multiplicity of the spacing n

$$n = \sqrt{\frac{1}{0.63^2} \cdot \frac{2700}{450 - 230}} = 5.56.$$

Further, the condition $nd = 3.5 \text{ m} < 7.2 \text{ m}$ (5) is fulfilled, and the settlement of the pile base will be equal to zero due to the lack of the compressible layer H_{p_N} :

$$H_{p_N} = \frac{p_N}{k \cdot \gamma} - d_1 - L = \frac{220}{0.5 \cdot 20} - 3 - 21 = -2 \text{ m}.$$

In this case, the condition (9) is written as: $0.1 \text{ m} < 0.27 \text{ m}$. Fig. 5 below shows a design model for determining the additional settlement $S_{pile}^{P_n}$ of the piles under the effect of additional loading friction forces.

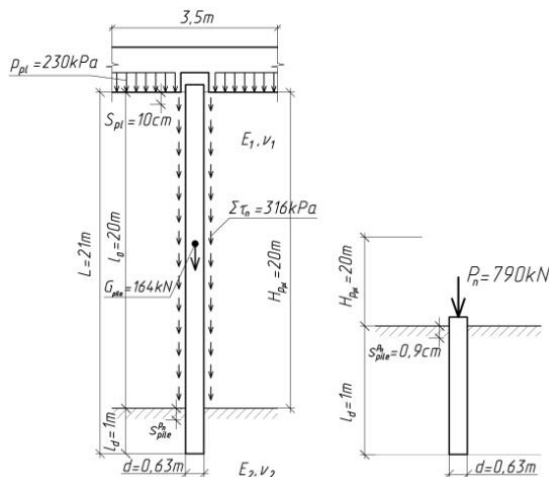


Figure 5. Design models for determining the settlement of the pile $S_{pile}^{P_n}$ under the effect of the additional loading friction forces P_n along its lateral surface

Since the piles are embedded below the compressible layer $H_{p_{pl}}$ by 1.0 m in the bearing layer with the deformation modulus $E = 48000.0 \text{ kPa}$ (kN / m^2), the shear modulus of this layer within the length of the pile and under the lower end according to the design model in Fig. 7 will be equal to:

$$G_{1,2} = \frac{E}{2(1+\nu_2)} = \frac{48000}{2(1+0.3)} = 31200 \text{ kN}.$$

Due to the fact that the ratio $l/d = l/0.63 \approx 1.6 < 5$, the additional settlement from the additional loading soil friction forces can be approximately calculated by the formula by V.G. Fedorovsky::

$$S_{pile}^{P_n} = \frac{0.22 P_n}{G_2 d} = \frac{0.22 \cdot 790}{31200 \cdot 0.63} \approx 0.009 \text{ m} \approx 9.0 \text{ mm}.$$

The adjusted value of the gap between the slab and the pile heads should make

$$\Delta = s_{pl} - S_{pile}^{P_n} = 0.1 - 0.009 = 0.091 \text{ m} \approx 90.0 \text{ mm}.$$

In this alternate design of the foundation with a regular pile spacing, the approximate number of piles in the pile field will be equal to

$$x = \frac{b \cdot l}{a^2} + \frac{l}{a} = \frac{35 \cdot 35}{3.5^2} + \frac{35}{3.5} = 110 \text{ pc}.$$

Fig. 6 shows a design model for the interaction between the base and the design case of the combined pile raft foundation.

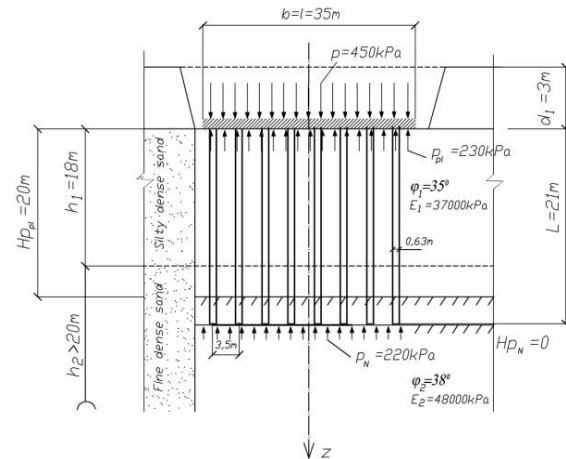


Figure 6. Design model for the interaction between the soil base and the adopted design of the combined pile raft foundation.

If we take as a criterion of efficiency the total concrete consumption V per a pile field, for the proposed design of the combined pile raft foundation we get a reduction in concrete consumption for pile installation by 35% (with an actual taking up of 50% of the total load by the raft slab) compared to the primary solution to the pile raft foundation (with conditional inclusion of the slab in the work up to 15%).

It should be noted that preliminary calculations show that the transfer by the raft slab of a larger share of the total load (over 50%) does not have, despite the established opinion, the desired effect, as it leads to overconsumption of concrete per piles due to the need to embed the piles below the intended compressible layer under the slab: $L > H_{p_{pl}}$.

2 CONCLUSIONS

A new design of a combined pile raft foundation has been developed, which is able to distribute in a real and controlled manner the resistance between the slab part and the piles by arranging a gap between them, where the slab and then the piles are fully involved in the response to the loading from the

building. An engineering method and method for determining the main parameters of the combined pile raft foundation for multi-storey buildings have been developed: the gap between the slab and the piles, the length of piles and the pile spacing depending on the allowable pressure (resistance) under the raft slab or slab settlements. In addition, it has been found that depending on the maximum allowable settlement the actual taking up of the full load by the slab part can be up to 50%. For this example of calculation, we have a 35% reduction in the cost of the foundation of a building compared to the alternate design of the traditional combined pile raft foundation.

3 REFERENCES

- DBN V.2.1-10:2018 Osnovy Ta Fundamenty Budynkiv I Sporud. Osnovni Polozhennia. Bases and foundations of buildings. GBC V.2.1-10:2018. Kyiv, Ministry of Regional Building in Ukrain, 2018
- Katzenbach R., Leppla S. and Choudhury D. 2016; *Foundation Systems for High-Rise Structures*, published by CRC Press, Taylor & Francis Group, USA and UK
- Rukovodstvo po proyektirovaniyu svaynykh fundamentov. Guidelines for designing pile foundations. NIIOSP im. N.M. Gersevanova Gosstroya SSSR. M.: Stroyizdat, 1980
- Samorodov O., Vinnikov Yu., Tabachnikov S., Naydenova V. and Novsky V. 2019. Improvement of the method for determining the bearing capacity of bored piles in view of additional load friction forces of soil. *Proceedings of the XVII ECSMGE-2019*, Reykjavik, Iceland, 1-6.
- SP 50-102-2003 Proektyrovanye Y Ustroistvo Svainykh Fundamentov. Design and construction of pile foundations. - M .: Gosstroy of Russia, 2004.