

<https://doi.org/10.32762/eygtec.2025.45>

METHODOLOGY OF SOIL MODEL SIMULATION FOR COMBINED RAFT-PILE FOUNDATION CALCULATION

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ABSTRACT

The paper theoretically justifies an improved model of the soil foundation for the combined raft-pile foundation (CRPF), accounting for the non-linear behaviour of the elements both "before" and "after" the connection between the raft and the piles (structural non-linearity). This model allows the analysis of the stress-strain state using the finite element method in modern calculation software. By using the improved model, it is possible to accurately simulate the behaviour of the CRPF, considering the structural non-linearity. The result of using the proposed methodology with the structural nonlinearity of the foundation showed the reduction of moment forces in the raft by 15% compared to the full load applied to the pile instantaneously and simulating the behaviour of the raft with a permanent connection between the raft and the piles.

Keywords: soil base, non-linear model, combined raft-pile foundation, stress-strain state.

INTRODUCTION

In modern geotechnics, with advances in information technology and powerful software for calculating the base-foundation-building (BFB) system, a key research focus is developing and improving soil base models to ensure proper interaction between system components during construction and operation. To obtain reliable stress-strain results for foundation designs in the BFB system, it is essential to choose a soil base model with parameters that closely match the actual soil behavior, based on two criteria: distribution capability and deformability of building foundations.

REVIEW OF RECENT RESEARCH SOURCES AND PUBLICATIONS

In the past century, engineering calculations for foundations often used a soil base model as a continuous linear elastic layer, widely accepted in practice and outlined in building codes (Comodromos, 2016). This model required specifying layer thickness (H) and soil properties like strain modulus (E) and Poisson's ratio (ν), with no plan dimension limitations. Today, advanced numerical software such as SOFISTIK, ABAQUS, Plaxis, SCAD, and Lira employs a 3D approach for simulating the BFB system, with a new model representing the soil base as a continuous layer with finite distribution capabilities (Fig. 1) (Samorodov, 2022). This model, in addition to the vertical strain constraints at a

specified depth H , also includes horizontal strain constraints within a specific area of the load in plan ($L_x \times L_y$).

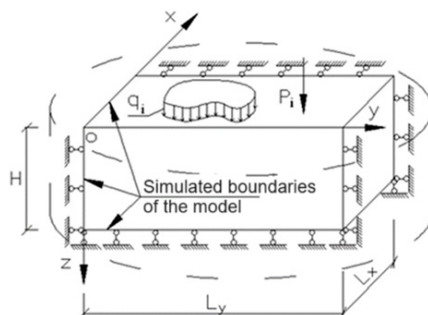


Figure 1 Soil base model in the form of a continuous layer of finite distribution capability (for three-dimensional problems)

These boundary conditions assume external loads on the soil base create a stress-strain region, beyond which strains are negligible. The load at the boundaries does not exceed the soil's strength (Cunha, 2001). Soil strain patterns, including time-dependent ones, can be defined in the model.

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IDENTIFICATION OF UNRESOLVED ISSUES

A key limitation of current approaches to simulating building-soil interaction with classical models is their inability to capture the structural nonlinearity of the BFB system. This is especially important for high-performance, large-scale combined raft-pile foundations (CRPFs) used in multi-story and high-rise buildings (Katzenbach, 2016), where no initial contact occurs between the piles and the raft during the first loading stage. A Utility model (2020) for CRPFs has been patented. (Fig. 2). This foundation consists of a raft (1) and piles (2) with a diameter d , and a gap (3) of height Δ between the raft and the piles. For practical purposes, a low-modulus material can be used to fill the gap beneath the raft, ensuring no contact between the raft and pile heads within the concrete bed (4). The soil base is denoted as (5).

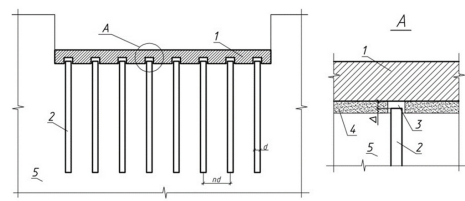


Figure 2 General Arrangement of a Combined Raft-Pile Foundation (CRPF)

METODOLOGY OF SOIL MODEL SIMULATION

An improved model of the soil base in the form of a combination of a continuous linear strain layer of finite distribution capability and a Winkler-Fuss layer is shown in Fig. 1.

The methodology for simulating the base-CRPF subsystem includes the stages as follows:

1. Is simulated the soil base of the CRPF with the physical and mechanical properties of soil layers and model dimensions such as compressible thickness H_{ppl} and overall dimensions $L_x \times L_y$ in plan, and corresponding vertical and horizontal strain constraints on the boundaries of the model.
2. Is simulated the interaction between the soil base and a single pile separately (or using a built model). Based on the calculations and results of soil tests with piles at the construction site, we iteratively determine the connection stiffness G_p under the lower end of a single pile. In this case, the connection stiffness G_p of a single pile can be either linear or nonlinear (for example, bilinear). To determine the stiffness of piles in the pile field, we should consider their interaction; therefore, the stiffness G_{pf} under the lower ends of the piles will be equal to:

$$G_{pf} = G_p \cdot \zeta [kN/m] \quad (1)$$

where G_p is the stiffness of the connection under the lower end (bottom) of a single pile, kN/m;

ζ is the coefficient of transition from the settlement of a single pile to the settlement of the pile field, units. Is accepted the normative value of $k=0.2$; when justified, the value of $k = 0.25 \div 0.33$ can be taken (Samorodov, 2017).

3. Is simulated a CRPF with no contact between the raft and the piles with the gap Δ between them.
4. Is simulated special inserts with the thickness Δ between the raft and the piles, the stiffness of which should be not less than that of the foundation elements (by convention, "concrete" inserts).

Next, is simulated the superstructure with the appropriate effective, wind and other loads to obtain a model of the entire "base-CRPF-structure" system (Fig. 3).

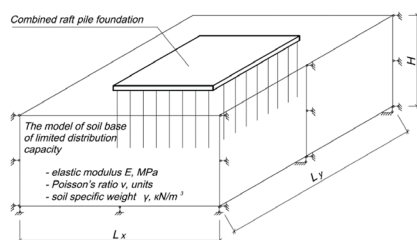


Figure 3 General arrangement of an improved model of the soil base for the CRPF

To calculate the structural nonlinearity of the combined raft pile foundation, the main calculation steps are as follows:

- is determined the stress-strain state of the **raft** of the foundation "before" the connection to the piles. It is determined for the part of the vertical load p_{pl} , which is taken by the raft of the foundation "before" the connection to the piles;
- is determined the stress-strain state of the **raft** of the foundation "after" the connection to the piles to find the most unfavorable combination of loads on it. It is determined for the additional (effective) vertical load p_{ad} after developing the stress-strain state at the previous stage.

To examine the impact of the proposed soil base model on the stress-strain behavior of the CRPF, a straightforward calculation example will be considered, using the initial data from a real construction project in a two-dimensional context:

- The overall normative vertical average load under the raft of the combined raft pile foundation is $p_{tot} = p_{pl} + p_{ad} = 167$ kPa;

- The gap between the raft and the piles is $\Delta=0.05\text{ m}=5.0\text{ cm}$;
- The soil base takes the average vertical load under the raft of $p_{pi}=119\text{ kPa}$ (approximately of the weight of the total building volume) "before" the connection to the piles (Stage 1);
- The soil base takes the additional average vertical load under the raft of $p_{ad}=48\text{ kPa}$ (effective load) "after" the connection to the piles (Stage 2);
- The linear stiffness under the ends of the piles is $G_{pp}=32000\text{ kN/m}$, determined through numerical iterative calculations of the interaction between the soil mass and a single pile under a vertical force $F=1200\text{ kN}$ on the single pile with the stiffness under the lower end of $G_b=160000\text{ kN/m}$ (determined iteratively) and its settlement $\approx 5\text{ mm}$, which corresponds to the results of field tests of soils with bored piles (Samorodov O., 2017).

The conditional calculation patterns of the base-CRPF system are shown in Figures 4 and 5.

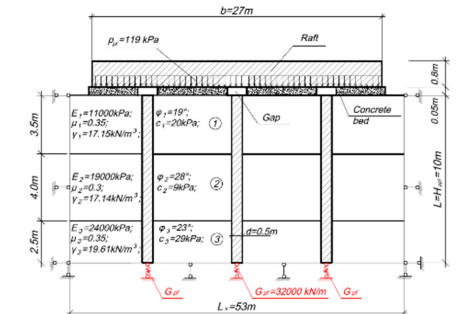


Figure 4 Conditional calculation pattern of the base-CRPF system "before" the connection to the piles (Stage 1)

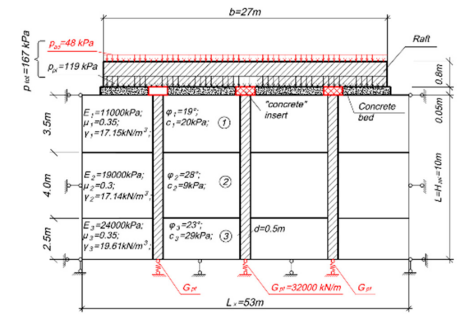


Figure 5 Conditional calculation pattern of the base-CRPF system "after" the connection to the piles (Stage 2)

To evaluate the performance of the proposed soil base model, a finite element model of the base-CRPF subsystem, including the soil base and a combined raft pile foundation, was developed using the PLAXIS 3D software, following the calculation patterns outlined in Figs. 4 and 5 (Fig. 6) (Samorodov, 2022).

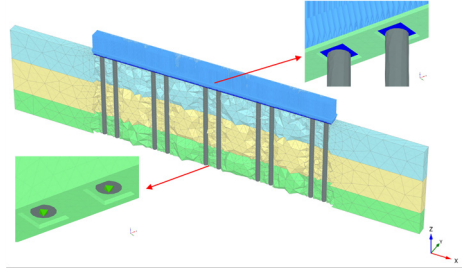


Figure 6 General view of the base-CRPF system in a two-dimensional formulation

The soil base and piles were modeled using a linear-elastic material model based on Hooke's law for isotropic elasticity. These were represented by solid finite elements with consistent stress-strain properties, including Young's modulus (elastic modulus) E in kN/m^2 and Poisson's ratio ν in dimensionless units.

The raft is simulated by plate finite elements using an elastic material model with the parameters as follows: specific weight γ in kN/m^3 , elastic modulus E in kN/m^2 , and Poisson's ratio ν in units.

Fixed-end anchor elastic elements with the elastic modulus E (kN/m^2), cross-section A (m^2), and thickness Δ (m), that is, with the linear stiffness of $G_{pf}=E \cdot A / \Delta=32000\text{ kN/m}$, are used as the connection of finite stiffness under the lower ends of the piles.

A two-row arrangement of the piles with the spacing $3d$ at a distance of 6.0 m between the rows was adopted.

The load is assumed to be evenly distributed over 1 (one) running meter of the raft.

Fig. 7 below shows the results of the preliminary simulation of the interaction between the soil base and the single pile to determine iteratively the connection stiffness G_p under the bottom end of the single pile. Iterative calculations were performed for both the linear-elastic model and the nonlinear Mohr-Coulomb model for soil. The difference was not more than 2%.

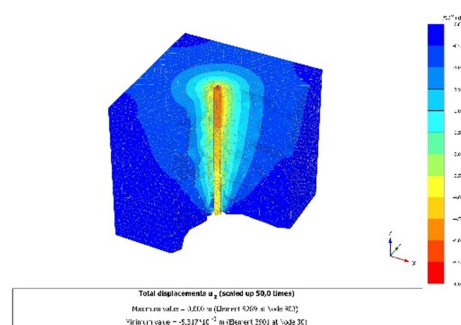


Figure 7 General view and straining of the base-single pile system

Fig. 8 shows the bending moment curves along the raft of different foundations:

- CRPF (2 stages) L-E model: calculation pattern for the base-CRPF system "after" the connection to the piles (Stage 2), where the soil base is simulated using a linear-elastic material model;
- CRPF (2 stages) M-K model: calculation pattern for the base-CRPF system "after" the connection to the piles (Stage 2), where the soil base is simulated using the nonlinear Mohr-Coulomb material model;
- RPF L-E model: calculation pattern for the base-RPF system with the full load p_{tot} being applied and the behaviour of the raft as a raft with the permanent
- connection between the raft and the piles, where the soil base is simulated using a linear-elastic material model;
- RPF M-K model: calculation pattern for the base-RPF system with the full load p_{tot} being applied and the behaviour of the raft as a raft with the permanent connection between the raft and the piles, where the soil base is simulated using the nonlinear Mohr-Coulomb material model.

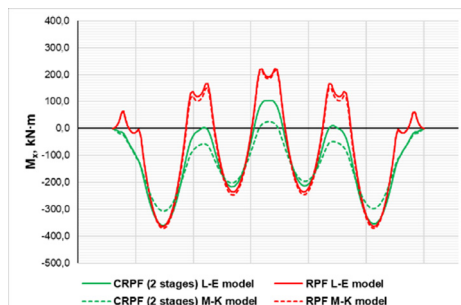


Figure 8 Bending moment curves M_x along the raft, kNm.

It should be noted that the calculation of a 2-stage development of the stress-strain state of the CRPF reduces the moment forces in the raft at the 2nd (last) stage to 15% in comparison with the application of the full load $p_{tot}=p_{st}+p_{per}=167$ kPa and the behaviour of the raft as a raft with the permanent connection between the raft and the piles. The analysis of the stress-strain state of the combined raft pile foundation at various stages of interaction with the proposed soil base model helps to validate the physical significance of the structural nonlinearity in the behaviour of the foundation elements. It is important to note that comparing the stress state of the raft with other soil base models is not relevant in this case, as this is currently the only model capable of qualitatively simulating the behaviour of the CRPF with structural nonlinearity.

CONCLUSIONS

The investigations lead to the following conclusions:

1. The soil base model combining a continuous linear strain layer and a Winkler-Fuss layer has been improved and justified. A methodology for simulating the base-CRPF subsystem was developed to determine the CRPFs stress-strain state, effectively simulating structural nonlinearity in the raft and piles.
2. Numerical studies show a 15% reduction in bending moment forces in the raft when considering the structural nonlinearity of foundation elements, compared to applying the full load at once and treating the raft as permanently connected to the piles.
3. Test results show that when the raft carries 100% of the load, moment forces in the raft are lower than in the pile-raft connection, reducing force concentration in corner and peripheral piles.
4. The improved model can also be used for classical piled raft foundations to reduce force concentration, requiring further research into the proposed soil base model.

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