Modeling a “pile-soil array” system under the seismic load action taking into account shock-absorbing properties of the soil

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Abstract. In this article, in a spatial setting, the modeling technique for a reinforced concrete pile immersed in the soil array under the seismic load action has been considered. Modeling of the “pile-soil mass” system elements is performed by the volumetric finite elements. The calculation includes the shock-absorbing properties of the soil mass model (“transparent boundaries”). A comparison of the proposed methodology with the known solutions has been performed. The prospects of further development and practical application of the pile operation proposed model together with the soil under the seismic load action has been given.

1. Introduction

In many regions of Russia, including seismically hazardous areas, weak soils, construction on which is impossible or extremely difficult, are common. To solve this problem, a special case of artificial foundation is used - a pile bases or pile foundations. This type of foundations has established itself as one of the most reliable and cost-effective.

At the same time, the complexity of calculating and modeling the pile foundation, especially in the spatial setting, should be noted. The problem of studying the actual operation of piles in the soil under the dynamic loads action remains poorly understood. Recently, the computer technologies and techniques, that can more accurately simulate the pile foundation work, have appeared but they need constant development and improvement. Even current software systems and calculation methods cannot give an unambiguously accurate prediction of the behavior of piles under the seismic loads action. In this regard, further study of the pile foundation operation under seismic conditions is one of the most urgent issues of earthquake-resistant construction.

This article presents a methodology that describes the operation of not only piles, but also soil that has fallen into the seismic impact zone. The experience and recommendations of other authors [1, 2, 3] dealing with this issue are taken into account.

In the classical statement of the pile foundation designing problem, a separate pile in the form of a short length rod with a single-node finite element at the end modeling the entire pile rigidity is considered. That is, a pile is a generalized stand that operated exclusively in the vertical direction. However, under the seismic load action, the building-pile foundation system operates as a single spatial system, characterized by a complex stress-strain state with separate local damage and destruction zones. Therefore, the real work of the system in question can be obtained only through the spatial computational models’ use.
2. The spatial system “pile-soil array” modeling

When conducting the research at the initial stage, the task was set to select a mathematical model of piles and soil. Currently, there are two engineering methods for calculating piles. The first technique is the classic “manual” piles’ calculation according to the generally accepted formulas of existing regulatory documents. The second method involves computer calculation using the finite element method, where the pile is represented by a chain of bar elements, and the nature of the work according to the beam and linearly deformable medium type is provided by a variable coefficient of subgrade resistance \( C_x \) [4]. To simulate the vertical operation of piles in the soil at the pile edge, a single-node finite element, which essentially represents a spring is used, the rigidity of this element characterizes the value \( R \).

To justify the calculated spatial model of the “pile-soil mass” system and to analyze its compliance with the generally accepted methods, a quantity that has the minimum discrepancy for all methods — pile settlement \( S \) is used, cm. The model should include not only the pile operation, but also the soil falling into the seismic impact zone. According to the numerical experiments’ results, it was found that the maximum convergence of the reference value \( S \) with the generally accepted methods, it has a circuit composed of volumetric finite elements with node-by-unit conjugation of pile elements and soil mass. For modeling the body of the pile, spatial eight-node iso-parametric finite elements (arbitrary hexahedron) are used.

The soil massif modeling was carried out using the physically non-linear parallelepipeds designed to describe the one-sided compression work of the soil with the shear possibility.

When calculating the soil mass, the shear strength condition was accepted according to the Coulomb – Mohr theory.

The study of the three-dimensional system “pile - soil massif” was performed using the LIRA SAPR 2019 calculation complex. The elements of the pile and soil were crushed by the equilateral parallelepipeds with geometric characteristics 100 × 100 × 100(h), mm.

For the study, a reinforced concrete pile with a cross section of 300x300 mm and a length of 9 m is considered. The pile body is immersed in soil at 8 m, the cantilever section above the ground is 1 m. \( N = 150 \text{ kN} \). The accepted dimensions of the soil mass model are 2.1 × 2.1 × 9 (h), m. According to [5], the soil vibrations’ acceleration is reduced to 2 times at a depth of 8 m compared to soil acceleration on the day surface. In order to analyze the displacements and forces in the soil at the pile immersion depth, the calculated depth of the massif was taken to be 9 m. \( E = 23 \text{ MPa} \); the internal friction angle \( \varphi = 17 \text{ hail} \); the specific grip \( C = 61 \text{ kPa} \).

![Figure 1. Reference design schemes (physical and finite element)](image-url)

1 - soil massif.
Figure 2. The design scheme of the model “pile - soil massif”

- a - volumetric view; b - section; c - vertical movements of the model; g – efforts’ distribution in the model

The precipitation values’ comparison was carried out with two generally accepted methods: according to regulatory documents (“manual” calculation) and the finite element method (FEM) using the coefficient of subgrade resistances and a single-node element. The results obtained using the three calculation methods are shown in Table 1.

Table 1. Pile draft calculation results

| Name of calculation procedure                                                                 | Precipitation, cm |
|---------------------------------------------------------------------------------------------|-------------------|
| “Manual” calculation for regulatory documents \[S = \beta \frac{\bar{N}}{G * L}\]               | 0.162             |
| FEM using coefficient of subgrade resistances and a single-node element                      | 0.159             |
| FEM with volumetric model “pile - soil massif”                                              | 0.159             |

According to the calculation results given in the Table 1, the pile settlement according to all three methods is ≈ 0.16 cm. Thus, the model under consideration in terms of precipitation is in good agreement with the known models and adopted for the further studies to analyze the piles’ operation in the soil mass under the seismic forces’ action.

3. Modeling the shock-absorbing properties of the soil and their inclusion in the model “pile - soil mass” operation

At the second stage of the study, the problem of modeling the shock-absorbing properties of the soil, the so-called “transparent borders”, is solved. According to [6], we accept a number of statements:
- elasticity theory and Hooke’s law are not applicable for soils;
- heterogeneous natural strata of soils contradict the anisotropy theory of the soil massif, and the calculation methods based on soil homogeneity cannot be true.
The analysis of the “pile-soil mass” model should be carried out in compliance with the certain sizes (boundaries) of the soil mass and, when modeling the seismic effects, it is necessary to exclude the Rayleigh surface waves’ reflection from the boundaries of the massif under consideration. The kinetic energy caused by the seismic forces is not infinitely mirrored and should fade from the soil model boundaries’ source [7]. Therefore, the shock-absorbing properties of the soil (transparent boundaries) are included in the calculation. In the framework of this study, the task of the soil shock-absorbing properties’ modeling is divided into two stages.

At the first stage, a check calculation of the flat soil mass was carried out with the shock-absorbing properties’ inclusion. At the second stage, the transparent boundaries were connected to the considered volumetric finite element model (Fig. 3).

Further calculation was made taking into account the dead weight of the pile and soil. In the calculation, a strictly consistent mass matrix was used. A model integration step of 0.01 s and an integration time of 10 s were set. In addition, the coefficients \( \alpha = 0.25 \) and \( \delta = 0.5 \), characterizing parameters determining the accuracy and stability of integration by the Newmark method, were introduced [8].

Figures 4–5 show the displacements and propagation of kinetic energy within the considered soil mass boundaries. The energy in the array is spread from the center of influence and fades to the boundaries of the considered area.

**Figure 3.** The design scheme of the model “pile - soil mass” taking into account the shock-absorbing properties of the soil
1 - pile; 2 - soil massif; 3 - transparent borders.
Figure 4. Changes in the “pile-soil mass” model under the seismic forces influence
a - model before seismic impact;
b - model at the time of seismic impact;
c - model at the time of maximum seismic impact;
d - model after seismic impact.

Figure 5. Kinetic energy distribution in the pile-soil mass model, taking into account the shock-absorbing properties of the soil

4. Summary
Based on the materials and conclusions presented in this paper, we can conclude that the three-dimensional model of the pile work together with the soil under the seismic loads action gives adequate results, good convergence and demonstrates the nature of the work close to reality. It is
worth noting that this technique is labor intensive and time consuming for machine counting. At this stage, it is advisable to use such a calculation in relation to theoretical and scientific research problems. To introduce this technique into practical tasks, a number of further studies are necessary.

In the future, the authors set the task to optimize the methodology presented in the article for modeling the “pile – soil mass” system under the seismic loads action. In addition, the further goal of the study is to develop the methods for modeling the complete pile foundation and the transition from the “pile-soil array” system to the more complex “building-pile foundation” system.

References
[1] Uzdin A M, Sandovich T A, Al-Nasser-Mohomad Samih Amin 1993 Fundamentals of the theory of earthquake resistance and seismic construction of buildings and structures (Publishing House VNIIG them. B.E. Vedeneeva, St. Petersburg).
[2] Birbraer A N 1998 Calculation of structures for earthquake resistance (Science, St. Petersburg).
[3] Nikolenko N A, Nazarov Yu P 1988 Dynamics and earthquake resistance of structures (Stroyizdat., Moscow).
[4] Nurieva D M 2014 Numerical study of models of piles and pile foundations under seismic loads Bulletin of KSACEU. Foundations and foundations, underground structures 4 (30) 214-221.
[5] Gaipov S K 2015 Research and calculation of the seismic-isolating adaptive pile-in-pipe system with disconnecting connections taking into account soil characteristics (dis. to that. tech. Sciences: 05.23.01. - JSC “Research Center Building” Central Research Institute of Building Structures named after V.A. Kucherenko, Moscow).
[6] Dzhincvelashvili G A 2015 Nonlinear dynamic methods for calculating buildings and structures with a given seismic resistance (dis. Dr. tech. Sciences: 05.23.17. - Moscow State University of Civil Engineering, Moscow).
[7] Under the general editorship of Sorochan E A, Trofimenkova Yu G 1985 Designer reference. Foundations, foundations and underground structures (Stroyizdat, Moscow).
[8] Gorodetsky A S, Batrak L G, Gorodetsky D A, Liznyuk M V, Yusupenko S V 2004 Calculation and design of structures of high-rise buildings from monolithic reinforced concrete (Fact, Kiev).