MODELS AND CALCULATION METHODS OF THE PILE FOUNDATION IN SCAD OFFICE

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The authors in this article review different approaches to the simulation of pile foundations using finite element methods and analytical methods, developed in SCAD Office and GeoSoft Software. Problems of ensuring the accuracy of calculations with different detailed elaboration of models of pile foundations are discussed. Special attention is paid to the features for implementing described methods of pile foundation modelling under seismic impacts.

Keywords: Pile foundations, Ground base models, Finite element method, Platform models of pile foundations.

1. INTRODUCTION

In the modern engineering there is a huge experience in calculation of file foundations accumulated on the base of finite elements method. Application of one or another engineering method depends on the construction particularities of a foundation including the degree of the detalization of the calculation in relation to forces in the zone under consideration. Methodologies, contained herein, consider soil structure interaction analysis. They are taken from common practice by the companies, which use the SCAD Office and GeoSoft software for computing foundations of civil objects, as well as specialized programs for the nuclear industry.

We can select three groups of calculation methods for file foundations shown in Table 1. The main group include the analytical methods, which are realized in technical standards of Russian Federation Numerical calculations of file foundations with the use of software, which founded on the method of finite elements, could be divided in two independent groups: bearing static loads and bearing dynamic loads (Table 1). Such division is essential due to foundations the rigidities of which can be changed by the short time dynamic actions. It is also useful to study the singular stress-deformed state of a multistorey building in operation stage with account of the genetically nonlinear history of its construction work.

The analytic methods used in the SCAD Office are founded on the results of scientific experiments and theoretic substantiating states. The probable calculation inaccuracies of such methods are connected with admissions in fundamental research and imprecisions of site investigation. If using numerical finite element methods, the maximum possible errors in the form of the absolute extreme deviation from analytic theoretic solutions can be estimated in correspondence with the results of the Table 2. These data were provided during recent certification for solving problems of designing objects of nuclear industry. Examination of the software complex was carried out by A. M. Belostotskii, V.I. Golyakov, A.G. Tyapin, S.A. Toporkov, S.S. Nefedov, S.V. Prokopovich, A.V. Esenov.

There are extreme deviations set out in Table 2, which can be seen in various tests of different types. The given values of the enveloping deviations give an estimate picture, which confirms that the use of direct physical models with solid finite elements for modelling of a soil foundation has the maximal risk of errors accumulation. Due to dynamic calculation the error level of numerical solutions can either increase or decrease depending on the number of minus-plus signs. The compensation of the accumulating error in the direct static and dynamic models of beds in the form of solid finite elements should be carried out with the use of more accurate multi-node finite elements. It is also can be done by doubling the spectrum method with more detailed dynamic calculations in the mode of the direct integration of motion equations with the use of seismograms.

Table 1. Approaches to classification of methods for calculation of pile foundations

Classification of calculation methods	Method for calculation of pile foundations
1. On detalization degree of analytic models	1.1. The discrete model of a pile group.
	1.2. The discrete model of a pile field on the base of the cell method.
	1.3. The conditional foundation on the natural bed in the form of an support plate on the elastic half-space.
	1.4. The pile reinforced ground base with reduced characteristics.
2. On numerical FEM-models in static conditions	2.1. The Winkler foundation with constant contraction coefficient of the bed C_1.
	2.2. The two parameter Pasternak model with the constant coefficients of the bed for contraction C_1 and for displacement C_2.
	2.3. The bilinear Fedorovskey model with variable coefficients of the bed C_1.
	2.4. The direct physical linearly elastic model of the half-space with solid elements.
3. On numerical FEM-models in dynamic conditions	3.1. The dynamic model with constant coefficient C_1 or with variable coefficient C_1 and single-node dampers in the both types.
	3.2. The direct dynamic model in the form of solid finite elements with nonuniform damping and with reflectionless or remote horizontal boundaries.
	3.3. Numerical-analytical platform models.

Table 2. Calculation deviation ratios in using various types of the SCAD finite elements

Types of engineering calculations	Maximum deviations of calculation results in SCAD in verification tests of analytic solutions	
Static calculation of the parameters of the stress-deformed state in the linear option	7%	for rod elements
	10%	for plate elements
	21%	for solid elements
Dynamic calculation of the stress-deformed state	8%	calculation of natural frequencies
	14%	calculation of forces and stresses from dynamic loads

2. 2 ANALYTIC MODELS OF PILE FOUNDATIONS

The discrete model of a pile group, regulated by paras 7.4.4-7.4.5 of the SP 24.13330.2011, based on the research papers of V.G. Fedorovskey, S.N. Levachyova, S.V. Kurillo, Y.M. Kolesnikova. There is a constraint in the SP 24.13330.2011, which said that we should not use more than 25 piles in one group. Nevertheless, in the originating works that methodology was intended to be for the foundations of hydro engineering structures, in which, as distinct from regularly loaded pile fields, unbalanced loading can be seen without constraints of the number of the piles in a group.

In the present methodology a group foundation is regarded as a discrete set of separate piles with unique rigidity characteristics of the bed accounting the horizontal and vertical influences on neighboring piles (Fig. 1). The advantage of this approach is the maximal detailed calculation of forces in each point along the length of any pile and also the clear manifestation of the marginal pile effect on the boundary pile rows and on the corner piles of the group (Fig. 2, a).

As a peculiarity of the pile group method is the necessity to carry out a nonlinear iterative calculation with the account of the vertical mutual influence of the piles in the group and the rigidity of the pile raft. This peculiarity also includes the necessity of carrying out a nonlinear calculation to provide the allowable horizontal normal stresses of soil in the zone of side surfaces contact. Another matter in dispute of the calculation method for the pile foundation as for a pile group is the convention of the linear increasing of the horizontal reduction of a pile shaft by soil. In calculations with long piles it leads to over-estimation of the reactive forces with the increasing reduction of the pile shaft. In addition to that, the horizontal influence of the piles in a group, which decreases the side soil pressure, is verified by the scientific experiment only for cases of the orthogonal mutual alignment of piles and only for sandy soil.

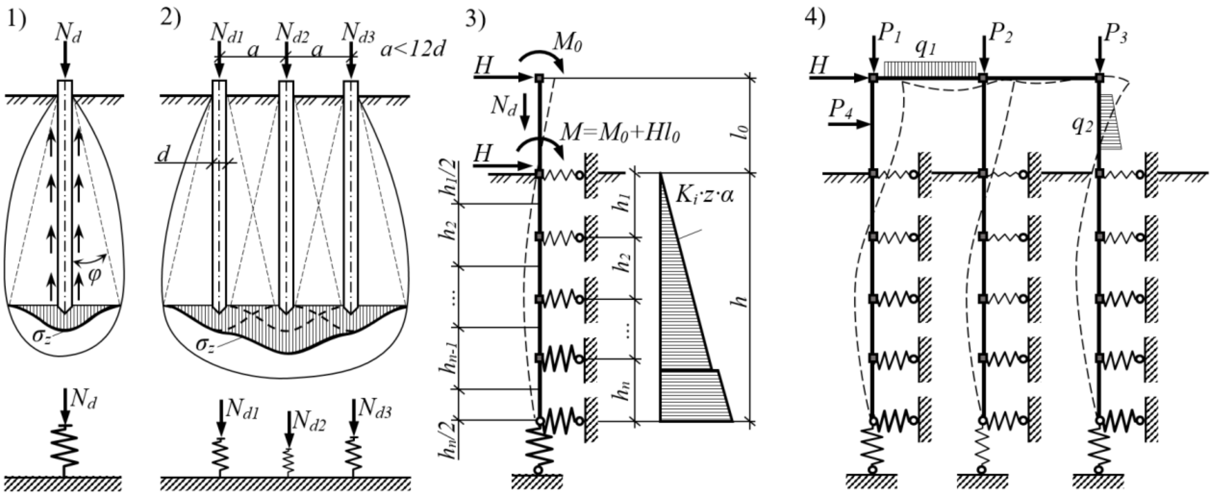
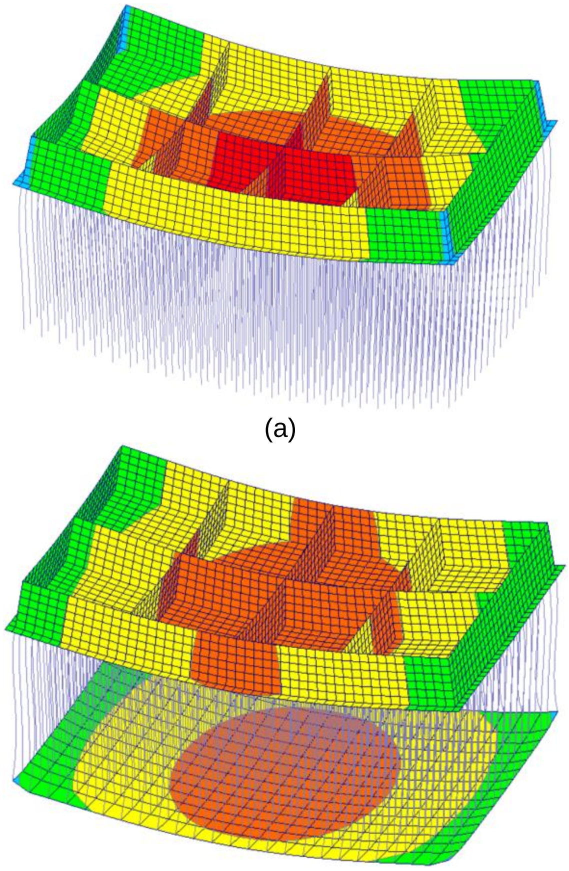


Figure 1. Vertical and horizontal stiffness properties of neighbouring piles

The discrete model of the pile group is more investigated and widely represented in normative documents for dynamic calculations. The account of the decreasing pile capacity on vertical loads is carrying out by introduction of decreasing coefficients in accordance with the SP 24.13330.2011. The partial contact loss of the side surface of a pile with soil in horizontal direction is accounting in accordance with the SP 14.13330.2014. The account of the dynamic properties of soils for pipe foundations in such a quasi-static state is very easy to check by simple equations. The abovementioned decreasing coefficients have been reduced significantly in the research made by V.A. Ilichejv, Y.V. Mongolov, V.M. Shayevich. However, their extended fundamental methodology is more interesting in terms of the maximal detailed computerized calculation and removal of the existing constraints for dynamic calculations. In these calculations the difference of the pile loading level is not accounted in various points of the foundation with the use of uniform coefficients. In addition to that, there is no possibility to use nonlinear calculations with the redistribution of the supporting loads between the field piles or group piles. In this case we take in the account the pile raft flexibility due to inapplicability of the superposition principle for dynamic calculations.

The discrete model of a pile field on the cell method is described in paras 7.4.6-7.4.9 of the SP 24.13330.2011. The authors of that methodology are the staff under the charge of V.G. Fedorovskii. The advantage of the methodology is the easy for programming with regular disposition of piles and in the account of axial actions in the discrete model of the pile field. Nevertheless, that methodology does not allow to check the strength of the boundary piles, when bending moments arise in them. It should also be taken into account, that the layer summation method does not account the rigidity of the foundation plate in calculation of the mean settlement of the conditional foundation on the central and corner points. As a result, the account of the pile raft rigidity in the model of elastic half-space shall reduce the average settlement, and that can be seen in the methodology. This problem can be solved in the software Geo-Set in shared use with SCAD. In Geo-Set the method of elastic half-space is not solved in a table style but in an explicit form by the spacial integrating of the Boussinesq task (Fig. 3).

The conditional foundation method for a pile field on natural bed (Fig. 2, b) is recommended in para 6.1. of the SNiP 2.02.03-85. In the modern technical standard SP 24.13330.2011 the model of conditional foundation was integrated in the cell method. However, in the engineering practice the modeling method of conditional foundation in the form of a support plate with soft rigidity on an elastic half-space is still popular. This numerical approach is not in conflict with the cell method and it uses the elastic half-space on the border of the contact of the support plate with application of the Pasternak model with two proportionality coefficients. For such a pile foundation model on a support plate at the level of the bottom of the piles at first glance may seem a simple task, the dynamic properties of the base due to making the static stiffness of the Foundation soil to the dynamic stiffness by multiplying by a common factor, regulated in SP 22.13330.2014 in the absence of other data. However, this approach dramatically overestimates the bearing capacity of the piles is observed in experiments decrease, which limits the applicability of the model.



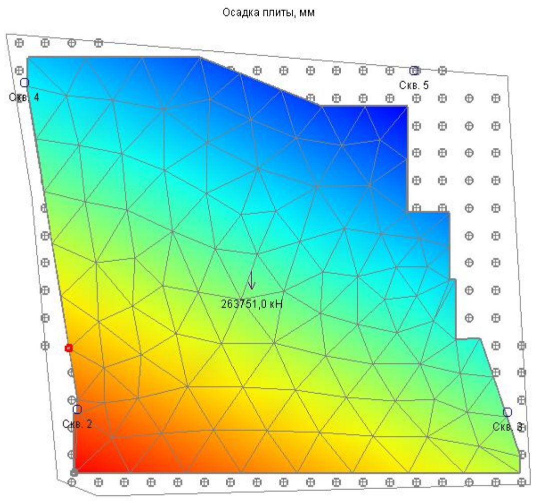
(a)

(b)

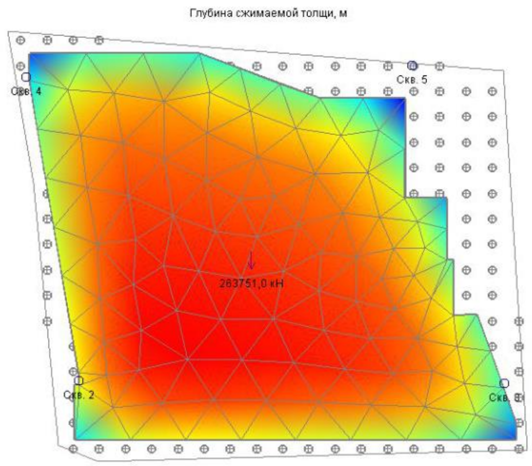
Figure 2. The settlement analysis of a pile foundation with the use of the discrete model described in paras 7.4.6-.9 of the SP 24.13330.2011 (a) and conditional foundation model by para 6.1. of the SNiP 2.02.03-85 (b)

A less accurate calculation method is the pile reinforced bed with reduced characteristics. According to the recommendations of the instruction paper “Designing and calculation plate foundation beds with soil-cement columns”, published by the Moscow State Building Construction University, the reduced deformation module of the reinforced bed should be calculated in the form of the direct mean value on the specific area of the soil piles and soil bed in relation to the plate area on the reinforced bed. The model in such a simple form of a pile bed does not allow to receive information about forces in a single pile. Nevertheless, this approach allows to avoid error accumulations in calculation models due to the stress concentrators which take place under the lower pile ends and on the side surface of physic models with solid finite elements. JSC Atomenergoproekt has similar views in designing atomic reactors with pile foundations on weak sub-bases.

According to the soil mechanics the reduced characteristics method can be applied to both pile foundations and combined pile-plate foundations, when it is necessary to prove the state by the result comparison of other prescribed and approved methods. The advantage of the bed model with reduced characteristics is the possibility of stress control in any point of the elastic half-space by the way of special integrating of the Boussinesq task. This method also allows to model beds with heterogeneous soil layers by the way of accounting the corresponding deformation module. An example of calculation of the plate foundation on a pile bed in the Geo-Set Pro software is shown at Figure 3.



(a)



(b)

Figure 3. The settlement analysis of a pile foundation with the use of the discrete model described in paras 7.4.6-.9 of the SP 24.13330.2011 (a) and conditional foundation model by para 6.1. of the SNiP 2.02.03-85 (b)

3. DIRECT PHYSICAL MODELS

It should be mentioned, that physical models are numerical models of the finite element method, in which piles together with soil bed layers are modelled by solid finite elements. Such models have the abovementioned risk of error accumulations on the one hand, but on the other hand they have the pictorial presentation of calculation results and can be used as an auxiliary analytical model for the detailed analysis of a stress-deformed soil state. The auxiliary type of this model is explained by the necessity in calibrations of such models with reduction of settlements and stresses in accordance with expected results provided by proved analytic methods in technical standards. In addition, in the process of performing numerical studies of direct physical models of pile Foundation, it was revealed that they lead to incorrect results, without increasing the horizontal stiffness of the soil in connection with the increase in compression of the body of the pile in the lateral surface of the piles with increasing depth.

If the direct physical model of the pile foundation should experience dynamic impacts, it is necessary to adhere to a number of technological requirements. First, the oscillation damping in soils is much higher than in the concrete. Therefore, in the current version of SCAD functions to account for the inhomogeneous damping of different materials were implemented. Solving such dynamic problems is possible using the module «Direct integration of motion equations». Secondly, during the analysis of vibrations of the base the effect of the reflected waves should eliminated. It could be done by increasing the dimension of the model to the extent when the distance to the boundary edges will be sufficient to fade the reflected waves. Alternatively, it could be done by introducing non-reflecting boundary edges with one-node dampers, implemented in the latest version of SCAD. In terms of dynamic effects direct physical models can have high inaccuracy, as it was previously mentioned in the first paragraph of the article.

4. NONPHYSICAL PLATFORM MODELS

Platform models have now become the international standard for calculations of foundations for the most important facilities of nuclear industry, operating in conditions of seismic effects. This was preceded by numerous experiments, showing high precision of the platform models in the process of predicting the behavior of real objects in comparison with previous approaches on the use of direct physical models, wave models and the contact dynamic models. Technology create platform models based on the modified asymptotic method combined with the use of four software systems are described in detail in the monographs of A. G. Taypin, chief specialist of JSC "Atomenergoproekt". Integrated translational and rotational springs at the nodes of the foundation base are calculated as the result. These elements of finite stiffness do not have any physical interpretation, but accurately describes the interaction of Foundation and structure.

The combined asymptotic method can be divided into five main stages. In the first stage using the program SHAKE, you move from the original base exposure on the earth's surface with the available accelerograms by deconvolution to the underlying basalt basement of the tectonic plate. Then the engineer executes the reverse convolution to a new designed level of the ground contact with the deepened foundation. In the second stage FEM-calculation of superstructures on a rigid ground base is performed with the definition of the dynamic matrix of inertia in the frequency range. The dynamic matrix of inertia in a single node located at the center of gravity under the sole of foundation slab. In the third step, you should calculate the impedances and transfer functions to seismic loads impacting the foundation on a uniform layered basis, held motionless. The third stage is carried out using software CLASSI for surface foundations or SASSI for deepened foundations. In the fourth stage, using the software AGA new accelerograms are synthesized for the modified and reinforced ground base, allowing to calculate the response of a rigid foundation under a structure with modified properties of soils. In the final step in a finite element analysis program the engineer generates a platform model with transfer functions from foundation vibrations to the impact on the non-physical platform.

5. CONCLUSIONS

In this paper, the authors reviewed five methods of pile foundation modelling in terms of static loads. In the presence of significant seismic effects on structure it is recommended to use the following methods: the discrete model of a pile group or the model of a pile field; the simplified model of the pile reinforced ground base with reduced characteristics; the direct physical model using solid FEM elements, the inhomogeneous damping of different materials and non-reflecting boundary edges; the nonphysical platform model.

On authors` opinion, the combined asymptotic method, based on platform models, deserves the most attention as it was approved for designing foundations under seismic effects for the structures of nuclear industry, attracting the best scientific and engineering technologies. This method should be adapted for mass use in engineering calculations for civil and industrial purposes. In this case the software has to be facilitated to one complex program on the one hand, and the theory as well should be simplified on the other hand.

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