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Application software system SolidWorks to study dynamic behaviour of pile foundations

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ABSTRACT: The choice of software for calculating pile foundations with dynamic loads was made in the course of special comparative studies. As a result, SolidWorks package with CosmosWorks and CosmosMotion modules was adopted for development. The dynamic calculation of pile foundations was carried out in a volumetric formulation and included: an adjustment of the dividing of the computational domain into the grid of FE (finite element) with regard to the considered foundation design and the ground conditions of the site; input and processing of information for the finite element analysis; modal analysis of the problem to determine the natural frequencies of the system; harmonic analysis (to obtain the oscillation amplitudes of the pile foundation). To solve special problems that sometimes arise during the design, static and dynamic stresses (longitudinal forces and bending moments) in piles were determined. A numerical analysis of the applicability of the proposed approach to predicting the execution behavior of pile foundations was carried out by rated verification of numerous physical experimental data.

1 INTRODUCTION

One of the promising areas of practical geotechnology can be numerical methods for analysing the execution behaviour of foundations, including the prediction of the parameters of the excited oscillations from various types of dynamic loading. However, they are not widely used. The main reason for this is the lack of accounting complexes available for engineering use. Practically all the main geotechnical software systems do not allow considering dynamic problems in a volumetric formulation. The greatest problems in this regard arise when calculating vibrations of pile foundations, the design features of which in all cases require volumetric modelling.

The choice of software for calculating pile foundations with dynamic loads was made in the course of special comparative studies (Nuzhdin & Serdakova 2009). As a result, SolidWorks package with CosmosWorks and CosmosMotion modules was adopted for development (Nuzhdin & Serdakova 2011a, Nuzhdin et al. 2015). The advantages of this rated complex are the combination of powerful capabilities that allow to operate with more than a million finite elements, with an intuitive structure and relative ease of use. It is characterized by the possibility of creating a pile foundation - a soil foundation - quite close to the actual conditions of the system and conducting its modal and harmonic analysis in spatial formulation.

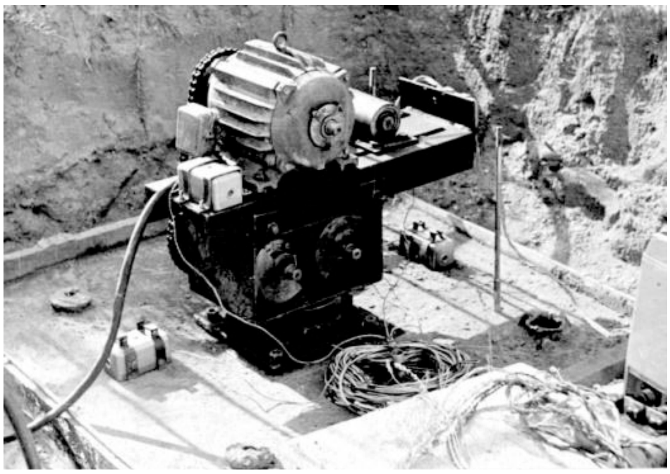

Figure 1. Studies of oscillations of tested pile foundation at the test site.

2 COMPUTATIONAL INVESTIGATION

For correct modelling of the foundations and obtaining a reliable picture of their execution behavior using test problems, an analysis of the size of the computational domain, the nature and density of its partition, the type of finite elements used, layering and other heterogeneity of the soil base, ground conditions of the foundation framework with the ground, soil models, etc. were performed. The results obtained are in good agreement with the experimental data and allow us to carry out a numerical analysis of various aspects of the execution behavior of pile foundations (Nuzhdin & Serdakova 2012, Nuzhdin et al. 2015).

To study the features of oscillations of pile foundations, the design model was square in the plan of foundation framework of 4-9 floating piles. The computational models almost completely coincided with the designs of experimental reinforced concrete foundations (Fig. 1), previously experimentally investigated in the laboratory of the dynamics of foundation soil and foundations of the NSUACE (Novosibirsk State University of Architecture and Civil Engineering) under the guidance of L.V. Nuzhdin. The experiments were carried out by Ph.D. candidates P.A. Genze, A.O. Kolesnikov, A.V. Lesin on the test site and in natural conditions. A large amount of experimental data on horizontal oscillations of pile foundations was obtained by S.V. Linovsky.

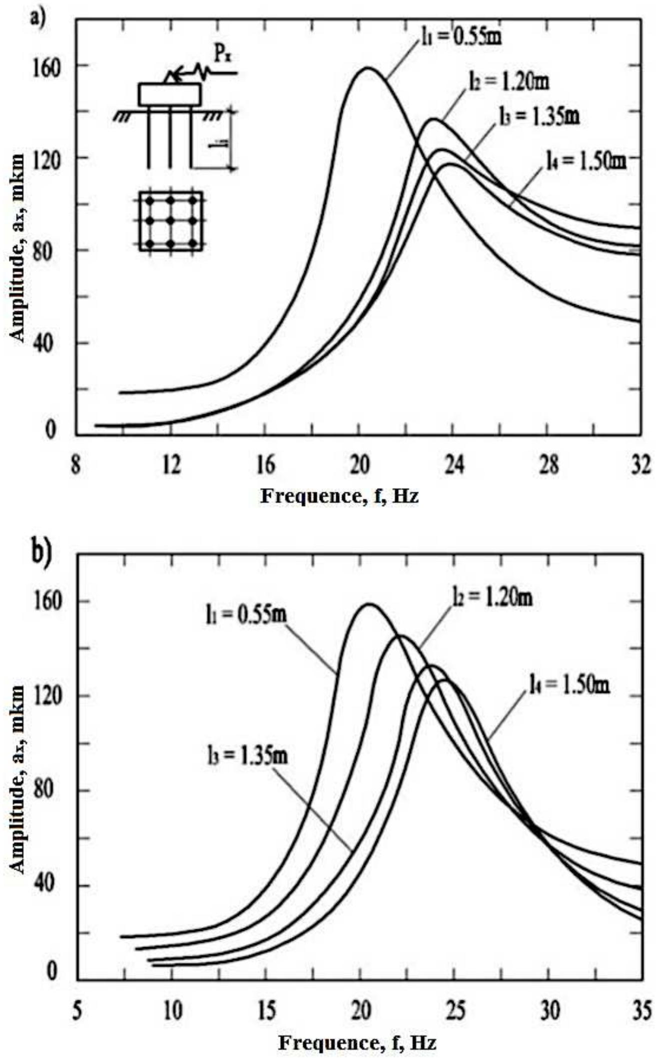

Figure 2. Flow diagrams of horizontal oscillations of pile foundation models with piles of various lengths under experimental data (a) and numerical simulation results (b).

In addition, the results of model studies in a large ground tray on fine sand with an inventory metal foundation framework of 0.5 m2, supported by 1–9 metal tubular strain gauge piles from 0.65 m (15d) to 1.75 m (40d) were calculated. The oscillations of the experimental foundations and models were created with the help of two-shaft directional vibrators. The ratio of loads and the scheme of their application to the foundation fully corresponded to machines with dynamic loads.

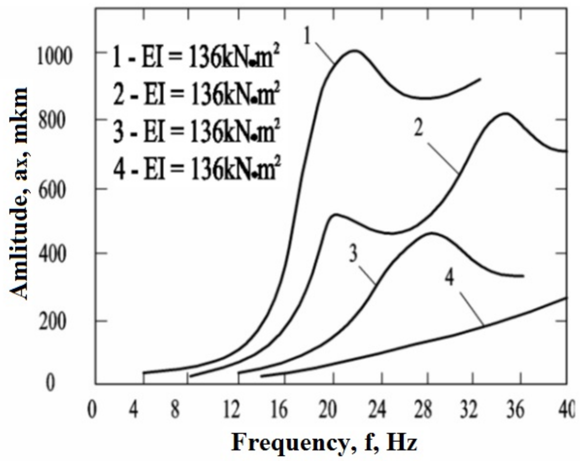

Figure 3. Flow diagrams of horizontal oscillations of the tested pile foundation with different flexural rigidity of piles and with a change in the modulus of elasticity of the soil 1, 2 - at E_0 = $3.8 \cdot 10^5$ kPa; 3 - at E_{01} = $3.8 \cdot 10^5$ kPa (up to 8d), E_{02} = $164.6 \cdot 10^5$ kPa (from 8d to 21d); 4 - at E_0 = $164.6 \cdot 10^5$ kPa (up to 20d).

The dynamic calculation of pile foundations was carried out in a volumetric formulation and included: adjustment of the dividing of the computational domain into the grid of FE (finite element) with regard to the considered foundation design and the ground conditions of the site; input and processing of information for the finite element analysis; modal analysis of the problem to determine the natural frequencies of the system; harmonic analysis - to obtain the oscillation amplitudes of the pile foundation.

2.1 *Influence of pile length*

The first of the main factors affecting the vibrations of the foundation, considered the length of the piles. The results of the numerical analysis and their comparison with the experimental data on the modelled problem are shown in Figure 2.

The general nature of changes in the execution behaviour of the pile foundation in numerical and physical experiments coincides. With an increase in the length of the piles, an increase in the frequency of resonant (free) oscillations of the basement occurs with a simultaneous decrease in displacement amplitudes. The numerical values of the vibration parameters are almost the same. In both cases, we can talk about the effective length of the pile (about 20d ... 25d - with hard pile embedment in the foundation framework), but the change in the amplitude of the oscillations of the foundation framework in the preresonance region is more pronounced in numerical simulation.

2.2 *Pile stiffness and soil properties*

Important factors determining the dynamic behaviour of the pile foundation are the stiffness of the piles and the elastic properties of the foundation soil. Their influence was assessed experimentally when testing the foundation model at an experimental test site (Linovsky 1993). The research results are shown in Figure 3.

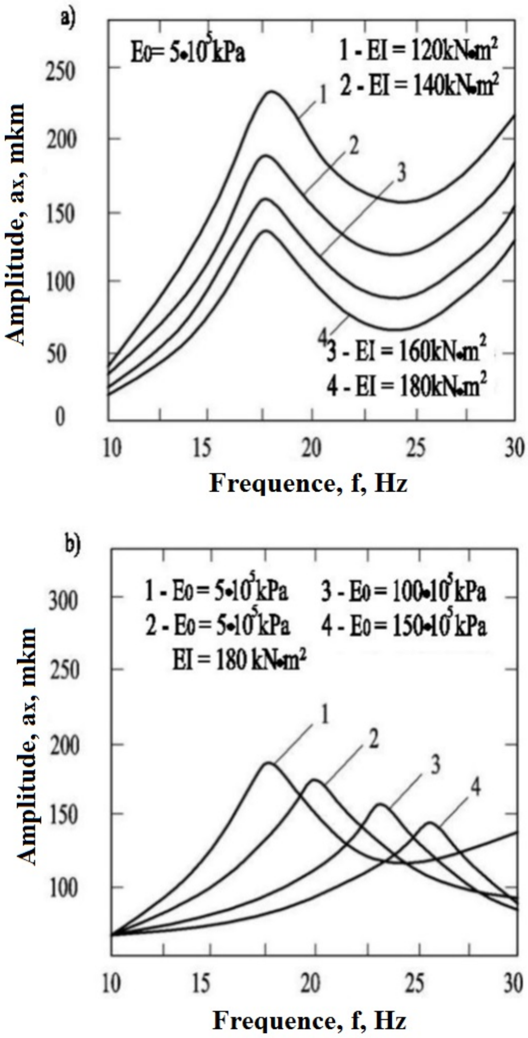

Figure 4. The effect of flexural rigidity of the pile (a) and the modulus of elasticity of the soil (b) on the parameters of the horizontal vibrations of the pile foundation according to the data of numerical simulation in the software package SolidWorks.

The stiffness of the tubular hollow piles was increased by concreting their central holes. The change in the elastic characteristics of the soil was achieved by naturally freezing it in winter conditions and thawing in the spring. First, by freezing to the depth of the zone of the main dynamic bending deformations of the piles (line 4), then by thawing - the upper part of this zone (line 3). Lines 1 and 2 are obtained in completely melted soil. In numerical modelling, the effect of flexural rigidity of piles (Fig. 4a) and elastic properties of the soil (Fig. 4b) were assessed separately. Comparison of the data indicates a good repeatability of the results.

2.3 *Number of piles*

The effect on the vibrations of pile foundations on the number of piles in the foundation framework was also checked. As it was noted earlier by a number of authors, given the seeming unambiguity of the question of an increase in the shear stiffness of the base (and, consequently, a decrease in the oscillation amplitudes of the foundation) with an increase in the number of piles, this aspect of the execution behavior of the pile foundation requires complex consideration. The latter is due to the influence of the conditions of interaction of the foot of the foundation framework with the soil on the stiffness of the foundation.

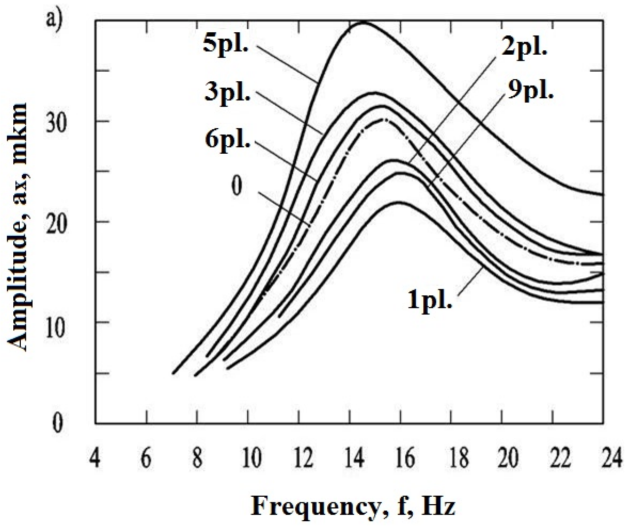

Figure 5. Flow diagrams of horizontal vibrations of pile foundations with different number of piles in the foundation framework according to experimental data.

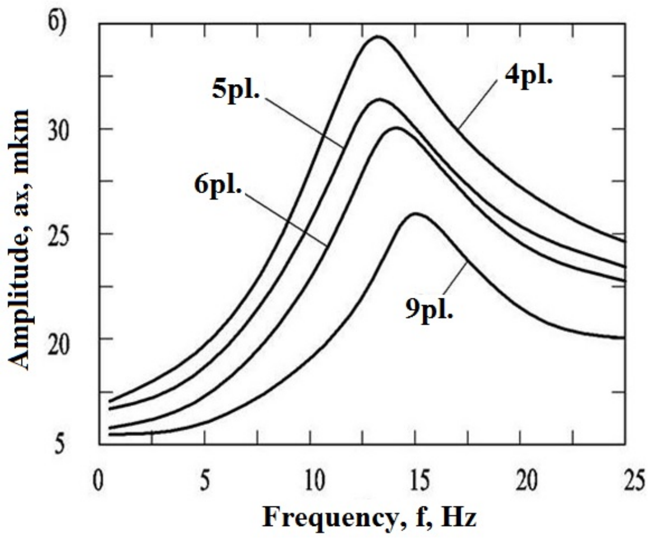

Figure 6. Flow diagrams of horizontal vibrations of pile foundations with different number of piles in the foundation framework according to the results of numerical modelling (b).

The contact between the foot of the foundation framework and the soil may be broken depending on the number of piles and loads on the foundation. In this case, when the total shear stiffness of the piles is less than the stiffness of the soil along the foot of the foundation framework (and sometimes it can be added to the stiffness of the piles), there is no positive effect from the increase in the number of piles and even an increase in the level of oscillations. An illustration of this effect is experimentally obtained resonance flow diagrams of oscillations of the foundation without piles (0) and with the 1 (1pl.), 2 (2pl.), 3 (3pl) and 5 (5pl) piles shown at Figures 5-6.

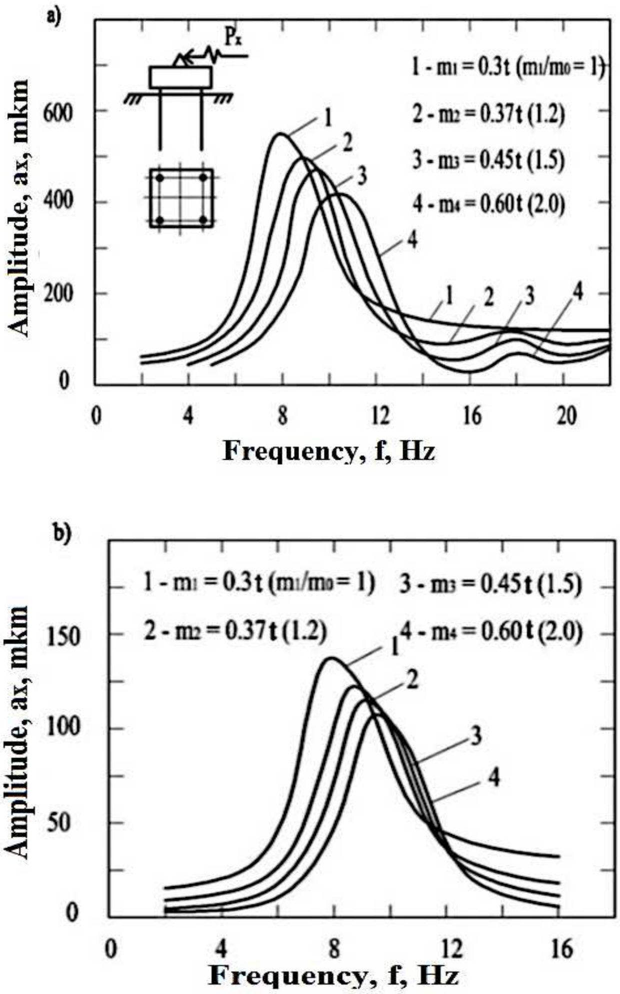

Figure 7. Flow diagrams of horizontal oscillations of pile foundation with foundation frameworks of various mass under experimental data (a) and numerical simulation results (b).

Since during the construction of the design model of the pile foundation for the elemental analysis, the parameters of the interaction of the foundation frameworks with the soil on the foot, as well as on the side faces, are proposed to be independently based on the independent analysis of a particular situation, in the considered numerical experiment, this factor was not taken into account. The results of calculations, shown in Figure 6b, for foundations with 5-9 piles are both qualitatively and quantitatively close to the experimental data.

2.4 *The foundation framework mass*

An important factor influencing the oscillations relatively to lightly loaded pile foundations of machines with dynamic loads is the own weight (mass) of the foundation framework. The mass of the system involved in the oscillations, as well as the foundation parameters considered earlier, can significantly affect the natural frequencies of free and resonant frequencies of forced oscillations, which can significantly change the amplitudes of displacements in a particular (working) frequency range.

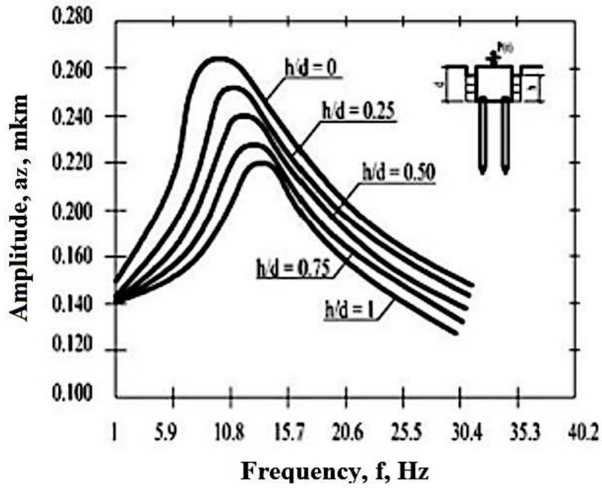

Figure 8. Flow diagrams of vertical oscillations of a pile foundation with an in ground foundation framework when changing the contact area of its side surfaces with the ground.

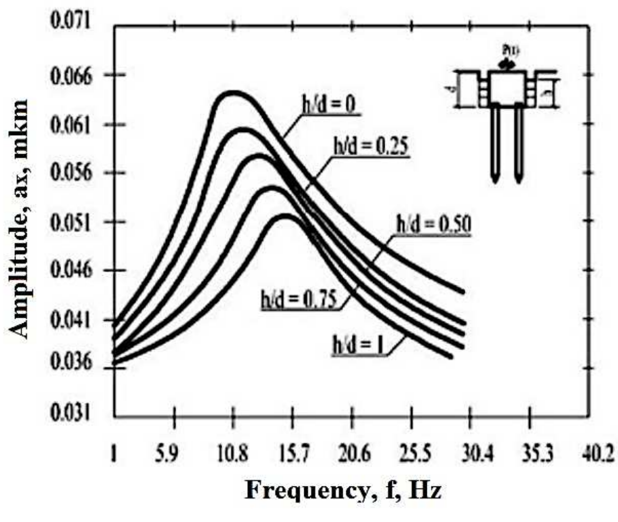

Figure 9. Flow diagrams of horizontal oscillations of a pile foundation with an in ground foundation framework when changing the contact area of its side surfaces with the ground.

Comparison of the results of numerical analysis and experimental studies of the effect of the mass of the foundation framework on the parameters of the horizontal oscillations of the foundation is shown in Figure 7. The obtained data demonstrate the complete coincidence of the qualitative changes in the resonant frequencies and amplitudes of the oscillations of the foundation. They once again confirm the conclusion that an increase in the mass of the foundation framework with the machine can serve as a rather effective way to reduce the parameters of induced oscillations.

Figure 10. Dynamic testing of a production pile foundation on 4 precast reinforced piles C10-30, 10 m long.

2.5 *The interaction of the foundation framework with the soil*

One of the least studied factors affecting the oscillations of pile foundations is the interaction of the inground foundation framework with the soil. To assess the interaction of the foundation framework with the surrounding soil, we studied the execution behavior of the pile foundation when the conditions of the contact of the side faces of the foundation framework with the soil change (Nuzhdin & Serdakova 2011b). This was done by setting the gap between them. The gap on the side surfaces of the foundation framework with the ground was carried out from top to bottom in steps of 1/3 or 1/4 of the height of the foundation framework, which corresponded to the conditions of physical experiments. The appearing of a gap in SolidWorks software corresponded to the assignment of zero characteristics to the corresponding ground elements under contact with the side surface of the foundation framework.

From the calculated flow diagrams Figures 8-9 it can be seen that the digging in of the foundation framework can have a significant impact on the oscillation parameters of the pile foundation. Increasing the digging in of the foundation framework leads to an increase in the rigidity of the foundation, which results in a slight increase in the resonant (free) frequencies and a noticeable decrease in the amplitudes of the oscillations. More significantly, this affects the horizontal component of the oscillations of the foundation. The degree of influence of the soil interacting with the side faces of the foundation depends on its density and modulus of dynamic deformation, as well as the parameters of stiffness and damping of the pile foundation. In general, the results of numerical analysis qualitatively correspond to the peculiarities of the real process of oscillation of pile foundations and respond well to the available materials of experimental studies.

3 COMPARISON OF THE RESEARCH MATERIALS

The calculation of a separate standing foundation was performed (Fig. 10) for the integral estimation of the accuracy of prediction of horizontal oscillations of the pile foundation using the SolidWorks software system. The foundation framework that is not embedded bore against the four precast reinforced piles 10 m long each. The ground base within the pile length was layed with: water saturated peat, 3.4 m; soft sandy loam saturated with water, 3.8 m; sandy silt, 1.0 m; and gravel sand.

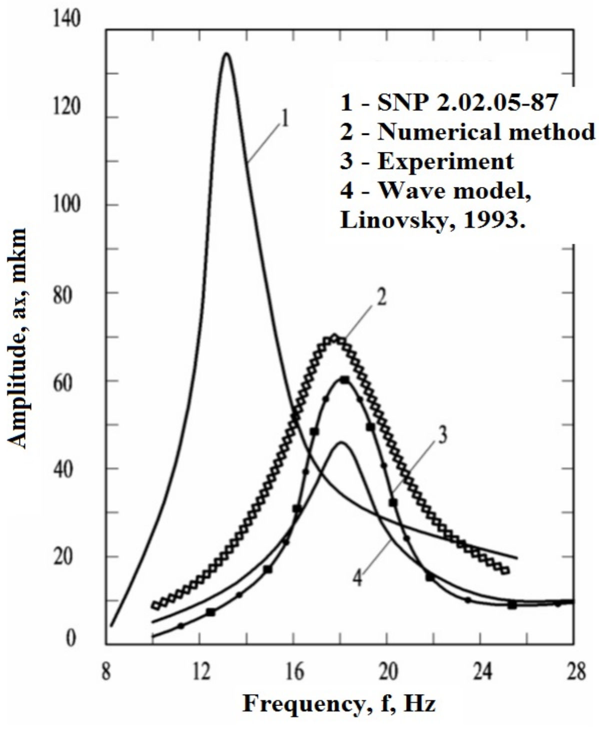

Figure 11. Amplitude-frequency flow diagrams of horizontal oscillations of a production pile foundation, obtained experimentally (3), by a numerical method in the SolidWorks package (2), calculated by the Linovsky wave model (4) and by SP 26.13330.2012 (SNiP 2.02.05-87) (1).

The results of the numerical analysis of the parameters of the horizontal oscillations of the described foundation and their comparison with the experimental data and the results of the calculation by the method of SP 26.13330.2012 (SNiP 2.02.05-87) and the wave model (Linovsky 1993) are given in Figure 11.

Calculations of the tested in the field large-scale model with a grid foundation 1.0×1.0×1.0 m, based on 4 floating piles 2.25 m long, that were immersed in hard sandy loam were also carried out. The obtained data was compared with the results of the calculation using SP 26.13330.2012 (SNiP 2.02.05-87) and the wave model (Nuzhdin 2004), which takes into account the interaction of the foundation framework with the soil (Fig. 12).

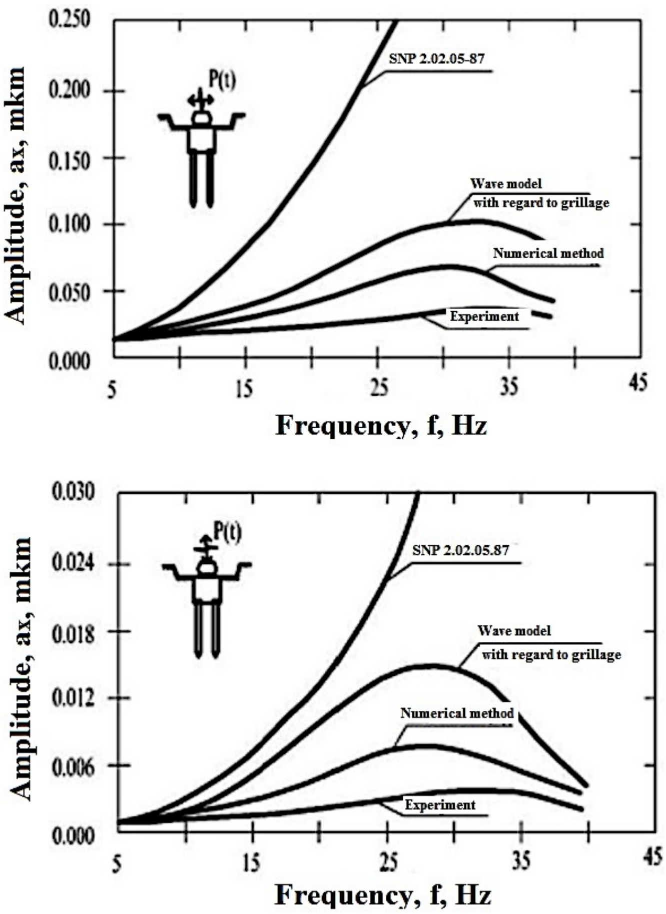

Figure 12. Flow diagrams of vertical (a) and horizontal (b) oscillations of a pile foundation with a ingrounded foundation framework, obtained experimentally (4), by a numerical method in SolidWorks package (3), calculated by the wave model (2) and by SP 26.13330.2012 (SNiP 2.02.05-87) (1).

4 CONCLUSION

Analysis of the obtained data shows that the SolidWorks software package, provided that the required accuracy of the design schemes is ensured, allows reliable analysis of the executive behaviour of pile foundations and the creation of a universal method for calculating the oscillations of foundations taking into account all the main influencing factors.

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