THEORETICAL STUDY REFINEMENT OF THE DESIGN SCHEME "STRUCTURE-PILE FOUNDATION-FOUNDATION" WORKING UNDER DYNAMIC INFLUENCES

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Annotation. In this work, oscillations of pile foundations are studied, taking into account soil conditions for various types of pile fastening to structures, and rational methods for choosing the parameters of piles and their quantities in earthquake-resistant construction are developed. Based on the results of theoretical studies, resonance curves were constructed for three types of fixings of the "structure-pile group" system. A special technique was proposed to determine the amplitude-frequency characteristics of the system.

In the course of research, we will consider two types of the problem under consideration. In the first task, transverse vibrations of a system of groups of piles elastically clamped with a rigid body at the level of floors are considered. In the second task, the joint work of the above-ground and underground parts of frame-pile structures under dynamic influences is studied.

In the article, solutions of a linear system of differential equations describing the deformations of elements of structures on pile foundations, dynamic, stiffness, geometric parameters, roots of the frequency equation, calculation of the numerical values of displacements, bending moments, shear forces, etc.
Key words: grillage; dynamic impact; seismic platform; amplitude-frequency characteristic; bending moment; cutting force; calculation model; bed rate.

Introduction. At present, when developing the theory of seismic resistance, it is necessary to take into account the factors that primarily affect the result of determining the bearing capacity of a structure: the behavior of the structure under intense seismic impacts; taking into account the accumulation of damage in the structure under repeated seismic impacts and the corresponding change in the strength and stiffness parameters of structures; the spatial nature of the movement of the building and its foundation during an earthquake and the corresponding redistribution of forces in the structure; taking into account the features of the seismically hazardous zone of the region.

The solution of the problem of seismic stability depends on the chosen calculation model. The complication of the calculation model with the inclusion of a large number of structural and earthquake parameters makes it possible to more accurately assess the seismic

Submitted: 17/10/2022 **Accepted**: 14/11/2022

resistance of the structure, but, as a rule, such calculations are so cumbersome that their application to real objects is associated with great difficulties. On the other hand, a significant simplification of the calculation models simplifies the calculation methods, although the accuracy of the calculations is significantly reduced in this case. It follows that the task of the researcher is to choose such a calculation model and develop, accordingly, such a mathematical apparatus that would allow, with a fairly small amount of computational work, to obtain a satisfactory assessment of the seismic resistance of structures.

In recent years, pile foundations have been widely used in housing construction. By transferring the load to deeper and more durable soils, they provide the structure with greater uniformity of settlement and, as a result, the absence of primary stresses in structural elements associated with uneven settlement. Consequently, on pile foundations and structures without primary stress, seismic effects will be more easily tolerated. This is also evidenced by the analysis of the results of earthquakes in the works of Yu.G. Trofimenko [12].

The paper [4] considers the possibility of constructing large-panel houses on pile foundations in seismic regions on subsidence soils of low thickness. A brief analysis of the behavior of such buildings during earthquakes is given, a summary of the results of studies on the strength, rigidity and stability of both the most piled foundations from short driven piles-racks, and large-panel buildings under seismic conditions. In conclusion, the main conclusions are given about the possibility of using pile foundations for large-panel buildings built in seismic areas on subsidence soils of low thickness, the methods and calculations of these pile foundations and their comparison with strip foundations.

It has been established by construction practice that pile foundations are used with the greatest effect in conditions of weak soils, when the ends of the piles rest on solid soils. In such frequently occurring cases, piles, having a slight compliance, do not allow for the transfer of pressure from the grillage rigidly connected to the piles to the ground, therefore, friction forces cannot occur on the area of the grillage foot when horizontal seismic forces act on the pile foundations.

According to the results of the analysis of the consequences of earthquakes and experimental work, it can be seen that in a number of cases, buildings on pile foundations turned out to be more earthquake-resistant compared to buildings on strip foundations.

Apparently, in this, as already noted, the lower initial tension of building structures on pile foundations is of great importance due to the uniformity of their settlement. In addition, the frontal area of the pile foundation is about three times less than the frontal area of the strip foundation.

Construction practice has established that pile foundations are used with the greatest effect in adverse soil conditions. Domestic and foreign experience in the design and calculation of piles confirms the relevance of the problem and the need to obtain new experimental data characterizing the behavior of piles under horizontal and vertical seismic impact, in order to develop simple, reliable and reliable methods for calculating and issuing recommendations for the design and construction of pile foundations in seismic regions.

As can be seen from the above, in practice, the possibility of systematization and generalization of materials of previously performed studies that differ in methodology, types of foundations tested, soil conditions, methods of processing and interpretation of the results of theoretical and experimental data is excluded. In this regard, it became necessary, using the experience of the work carried out, to develop a calculation method and propose a methodology for testing buildings and structures on pile foundations under horizontal seismic impact as the most appropriate for the actual operating conditions of buildings and structures on pile foundations during earthquakes.

The main purpose of this work is to show the effectiveness of the use of pile foundations in earthquake-resistant construction on the basis of theoretical studies.

To achieve this goal, it is necessary to solve the following tasks:

- select and justify typical design schemes;
- develop a calculation method;

The objects of research were buildings and structures on pile foundations, which are being built in areas with partially occurring seismic effects.

The main task in this case is to protect buildings from earthquakes and ensure the integrity and performance of structures.

The object of research was studied experimentally and theoretically. For a theoretical study, an analytical solution of the problem was chosen, and for experimental studies, a six-component seismic platform was chosen, which was built on pile foundations.

The seismic platform is represented by: the size in plan is 13 x 13 x 6 m, the size of the foundation shaft is 8 x 8 x 3.5 m, the volume is 800 m3, and the weight is 2000 tons.

The foundation design provides for a built-in manhole in the form of a metal box. At the ends of each of the four branches, holes are provided for ventilation. The base of the foundation rests on piles with a cross-sectional size of 30 x 30 cm and a length of 10 m, the total number is 144 pcs. The piles driven into the clay-sand soil have a three-row arrangement around the shaft, i.e. located along the bases of the wall (Fig. 1). It is assumed that the reaction force of the pile under the dynamic load created by the seismic platform is mainly due to the friction of the side surfaces of the piles and the soil and the distribution of the acting force. Consequently, the change in elastic deformation has a linear character along the length of the pile [2,3,10].

The coefficient of elastic stiffness of the pile foundation for the case of elastic uniform compression is presented in the following form;

$$K_Z = f \cdot C$$

where: f - the number of piles under the base of the foundation;

C-coefficient of elastic stiffness of the pile foundation.

The coefficient of elastic stiffness of the pile foundation with elastic uniform shear has the form

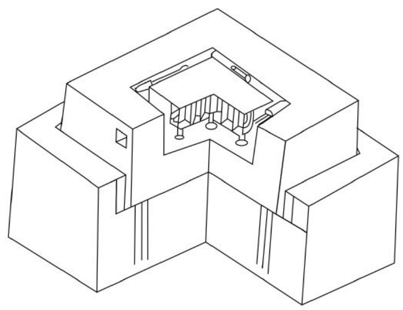
$$K_X = C_X \cdot F$$

where: C_X - coefficient of elastic uniform shear; F - area, soil

The coefficient of elastic stiffness of the pile foundation relative to the horizontal axis is determined as follows:

$$K_{\varphi} = C \cdot \sum C_l^2$$

where: C_l^2 – distance from each pile to the axis of rotation of the base plane;



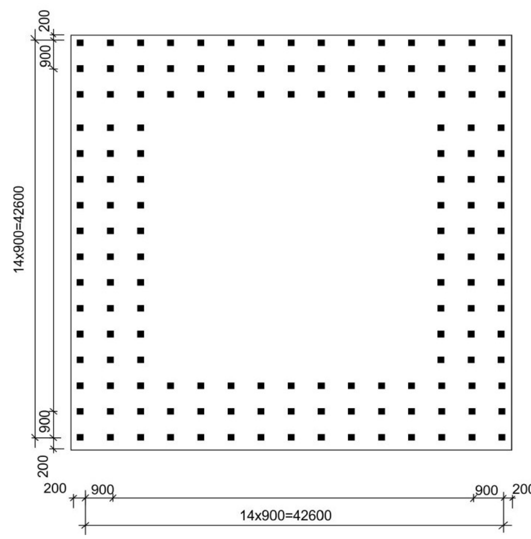


Fig.1. a) platform foundation.
b) pile placement plan

The current stage of development of the dynamic theory of seismic stability is characterized by further refinement of the design scheme of structures, refinement of the parameters of the seismic impact itself - soil movement and the study of the issue of interaction between the structure and the foundation.

To find the seismic load by the method of dynamic calculation, it becomes necessary to consider the dynamic design schemes of structures, since the magnitude and distribution of seismic forces depend not only on external influences, but also on the dynamic features of the structure itself. In principle, dynamic calculation schemes should make it possible to determine the deformation of the system under the action of inertial forces; therefore, they are represented as a distributed mass of the system, taking into account its rigidity and the mutual influence of the movement of concentrated masses.

When structures vibrate, serious factors affecting the nature of the vibrations are the conditions for embedding the foundation of the structure in the ground and the elastic properties of the foundation. The actual conditions for embedding the foundation into the ground are difficult to mathematically analyze. In this regard, in the formulation of the problem of seismic effects, first of all, it is necessary to consider the problem of the interaction of the structure with the soil.

Methods. Many years of experience in calculating and designing parts of buildings and structures has shown that the consumption of materials depends on the accuracy of the calculation, while the latter is directly related to the correct choice of the design scheme, which takes into account the factors that significantly affect the structure when exposed to an external dynamic load.

In the course of research, we will consider two types of the problem under consideration:

1. Movement of a platform with a pile foundation under dynamic influences for groups of piles elastically clamped with a rigid body at the level of floors.

2. Joint operation of above-ground and underground parts of frame-pile structures under dynamic influences.

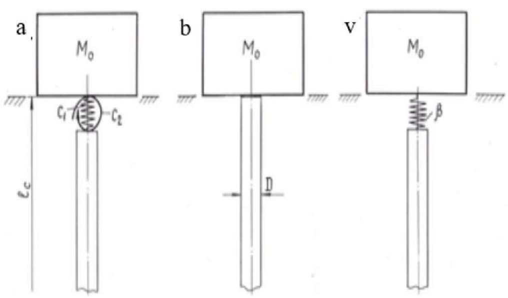
Further we will consider in a separate form the above mentioned tasks.

1 task. Movements of a platform with a pile foundation under dynamic influences for groups of piles elastically clamped with a rigid body at the level of floors.

The differential equations of motion of a platform with a pile foundation under dynamic influences will be for three types of pile attachment to a structure. Elastic pinching of a building with a pile foundation, rigid pinching of a building with a pile foundation and hinged ends of the pile to the building (Fig. 2).

The calculation scheme is a group of piles located along the contour of the platform foundation, driven into sandy soil (other types of soil are possible, and piles of various lengths).

During an earthquake, seismic loads enter the pile field, in turn, the pile field transfers the loads to the structure. At the same time, piles absorb a significant part of the energy.



Thus, the choice of the calculation scheme consists in the analysis of the process under study and the quantitative assessment of the influence of individual factors on the calculation results. It should be noted that the secondary factors taken into account in the calculation scheme cannot always refine the results of the calculation, since in this case it is necessary to have a large number of constant parameters, the specific values of which are often known only approximately.

Fig.2. Typical types of fixing structures with pile foundations:

a). Combined elastic fastening; b). Rigid fastening; c). Elastic fastening.

On the other hand, mathematical tabs become more complicated, and this, in turn, leads to additional operations and errors in calculations.

It is desirable to have the calculation scheme as simple as possible, however, the accepted simplifications must be sufficiently substantiated and confirmed experimentally [10].

In the future, in the course of research, systems were studied according to the type of pinched pile foundations with a rigid body.

Let us consider the transverse vibrations of a system of groups of piles elastically clamped with a rigid body at the level of floors.

Denote $\vartheta_n(\mathrm{x,t})-$ displacement of the n-th pile, $\vartheta_0(t)$ - movement of the floor mass. These displacements satisfy the following system of differential equations

$$E_n I_n \frac{\partial^4 \vartheta_n}{\partial x^4} + m\frac{\partial^2 \vartheta_n}{\partial t^2} + \mu\frac{\partial \vartheta_n}{\partial t} + K\vartheta_n = 0 \qquad (1)$$

where μ is the coefficient of viscous friction, which characterizes the attenuation of oscillations during the interaction of piles with the soil medium.

It is required to find a solution to the system of differential equations (1) that satisfies the following boundary conditions:

$$E_n I_n \frac{\partial^4 \vartheta_n}{\partial x^4} = K_n(\vartheta_n - \vartheta_0), \qquad \frac{\partial^2 \vartheta_n}{\partial t^2} = 0 \quad \text{at} \quad x = 0 \qquad (2)$$

$$\vartheta_n = 0, \qquad \frac{\partial \vartheta_n}{\partial x} = 0 \qquad \text{at} \qquad x = l_n \qquad (3)$$

where: E_n - elastic modulus; I_n- moment of inertia; $m-$ linear weight of the pile; - coefficient of lateral repulse of soil; K_n - coefficient of rigidity of the connection of the mass (platform) with n - pile.

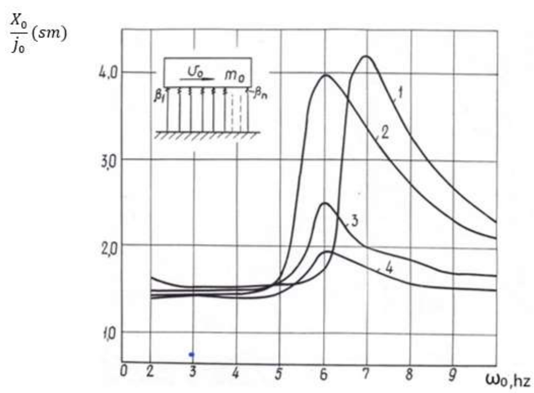
After some transformations, we obtain the amplitude of oscillations of the floors in the form

$$X_0 = -\frac{\alpha_1 j_0}{\alpha_0 \tilde{\omega}_0^2 + \sum_{n=1}^{N} \chi_n \frac{a_n \beta_n \lambda_n^3}{b_n \beta_n - \lambda_n^3 \chi_n a_n}} \qquad (4)$$

Including the expression for determining the shear force for the n-th pile can be written in the following form:

$$X_0''' = -\frac{\alpha_1 j_0 a_n \beta_n \lambda_n^3}{(b_n \beta_n - \lambda_n^3 \chi_n a_n)(\alpha_0 \tilde{\omega}_0^2 + \sum_{n=1}^{N} \chi_n \frac{a_n \beta_n \lambda_n^3}{b_n \beta_n - \lambda_n^3 \chi_n a_n})} \qquad (5)$$

Results and Discussion. On the basis of calculated by formulas 4 and 5, the results of the amplitude-frequency characteristic and the shearing force were obtained for various numbers of piles and they are presented in fig. 3 and 4.



Rice. 3. Graph of the change in the amplitude-frequency characteristic of the system depending on the number of piles with elastic fastening: 1- N =144, 2 -N=120, 3 -N=50, 4-N=30

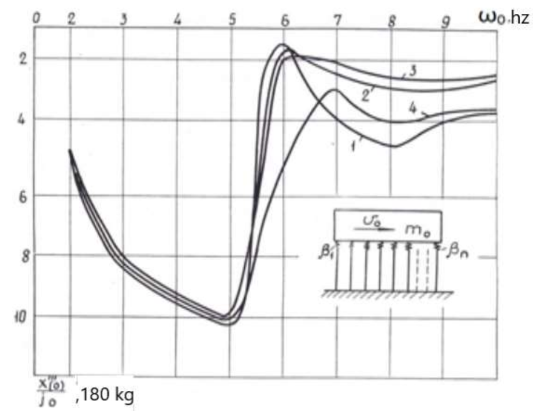


Fig.4. Graph of the change in the magnitude of the shearing force of the system from 1- *N* =144, 2 -*N*=120, 3 -*N*=50, 4- *N*=30

2-problem. Joint operation of the above-ground and underground parts of frame-pile structures under dynamic influences.

Very topical tasks at present are the refinement of design models of structures consisting of structures on pile foundations, the study of their dynamic characteristics and the development of recommendations for their determination, taking into account the actual operation of structures during oscillatory processes of the system.

Therefore, when calculating structures erected on pile foundations for dynamic effects, one of the most important tasks is to select such a dynamic calculation scheme that would take into account all the main deformed properties of both the material of structures and the foundation soil, and the structure of the structure itself. At the same time, it should be simple and universal from the point of view of its acceptability for calculations of a vast class of structures and computer implementations.

Of all the currently most common calculation models used to study the operation of structures in conjunction with pile foundations under dynamic impacts, apparently, the second model is best suited for studying the operation of the “flat frame-grillage-group of piles” system. It allows you to take into account almost all the factors necessary for this case.

The view of the accepted calculation model of the system "flat frame - grillage - group of piles" is shown in Fig. 5 and Fig. 6. This model is the best fit for the study of this system and it allows you to take into account almost all the factors necessary for this case [2,3].

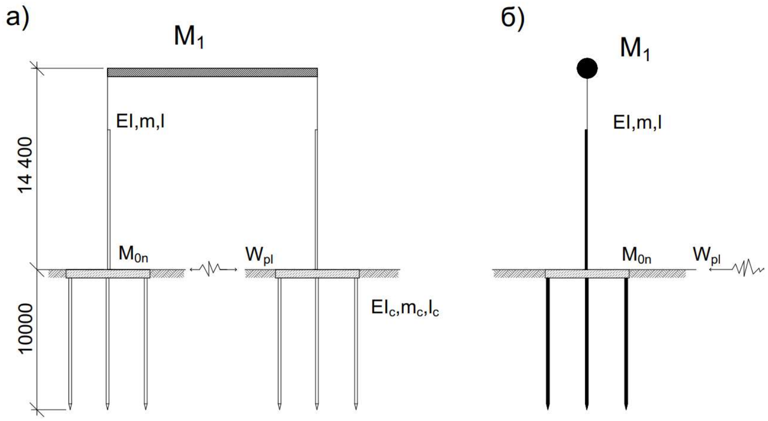


Fig. 5. Scheme of a flat frame on a pile foundation: a-frame scheme, b-dynamic calculation model.

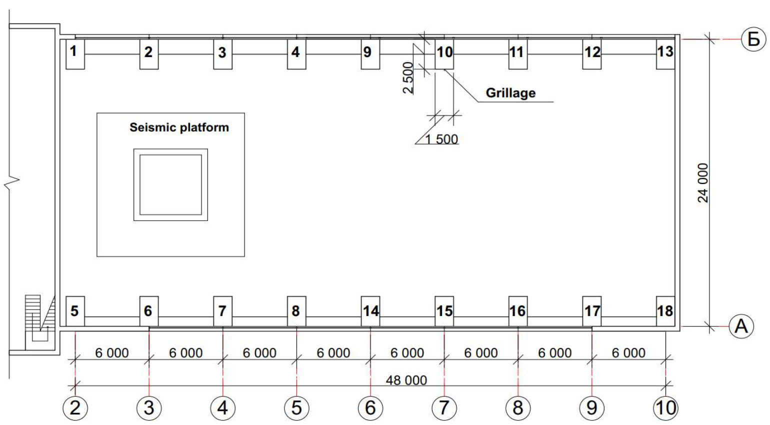


Fig. 6. Scheme of the sequence of location of the grillages of the system "flat frame - grillage - a group of piles".

The calculation scheme is a flat frame resting through the grillage on the k-th number of piles - racks driven into the loess soil. The calculation scheme provides for the work of grillages independently of each other and joint work, as a single plate uniting the pile heads. Only translational transverse vibrations are considered without taking into account torsional vibrations.

Solutions of a linear system of differential equations describing the deformations of elements of structures on pile foundations, finding dynamic, stiffness, geometric parameters, the roots of the frequency equation, calculating the numerical values of displacements, bending moments, shear forces, etc., in a closed form with an analytical description of the dynamic impact - allows with sufficient accuracy to simplify on a computer.

The purpose of the calculation is to ensure the normal operation of structures exposed to dynamic loads excited by various industrial machines, in particular, a seismic platform, to prevent resonance phenomena and to lead it away from this position.

Thus, the task of dynamic calculation of the system "flat frame - grillage - a group of piles" is formulated as follows: calculate natural frequencies and build vibration modes, determine bending moments, shear forces at the points of fastening of the system elements, obtain the amplitude-frequency characteristics of the system at a different level of action loads generated from the seismic platform and during separate operation of the grillages connecting the pile heads, including in the position of their fastening (grillages) to a single slab in plan.

In this case, eight grillages located nearby receive the greatest impact. In this case, the differential equation of the transverse oscillation of the beam of the type:

$$E_cJ_c\frac{\partial^4 W_{ic}}{\partial x^4}+m_c\frac{\partial^2 W_{ic}}{\partial t^2}+k\left(W_{ic}-W_{pl}\right)=0, i=\overline{1,8} \quad (6)$$

$$E_cJ_c\frac{\partial^4 W_{ic}}{\partial x^4}+m_c\frac{\partial^2 W_{ic}}{\partial t^2}+kW_{ic}=0, i=\overline{9,18} \quad (7)$$

$$EJ\frac{\partial^4 W_i}{\partial x^4}+m\frac{\partial^2 W_i}{\partial t^2}=0, i=\overline{1,18} \quad (8)$$

Where: m and m_c — linear masses of the column and pile-rack;

E_c and E — modulus of elasticity of concrete piles and metal columns;

J_c and J — moment of inertia of the section of the pile-rack and metal column;

W_i, W_{ic} and W_{pl}— movement of the column, pile-rack and seismic platform;

k-coefficient of the bed at the level of the pile-rack.

Using dimensionless parameters, after some transformations of equations (6)-(8) we can write**:**

$$\frac{\partial^4 Y_{ic}}{\partial \xi^4}+\gamma_c\sigma_c\frac{\partial^2 Y_{ic}}{\partial \tau^2}+\beta\left(Y_{ic}-Y_{pl}\right)=0, i=\overline{1,8} \quad (9)$$

$$\frac{\partial^4 Y_{ic}}{\partial \xi^4}+\gamma_c\sigma_c\frac{\partial^2 Y_{ic}}{\partial \tau^2}+\beta Y_{ic}=0, i=\overline{9,18} \quad (10)$$

$$\frac{\partial^4 Y_i}{\partial \xi^4}+\frac{\partial^2 Y_i}{\partial \tau^2}=0, i=\overline{1,18} \quad (11)$$

where: $Y_{pl}=\alpha_0\sin\alpha\tau$ - harmonic impact from seismic platform; a_0— seismic platform displacement amplitude; α— vibration frequency of the seismic platform.

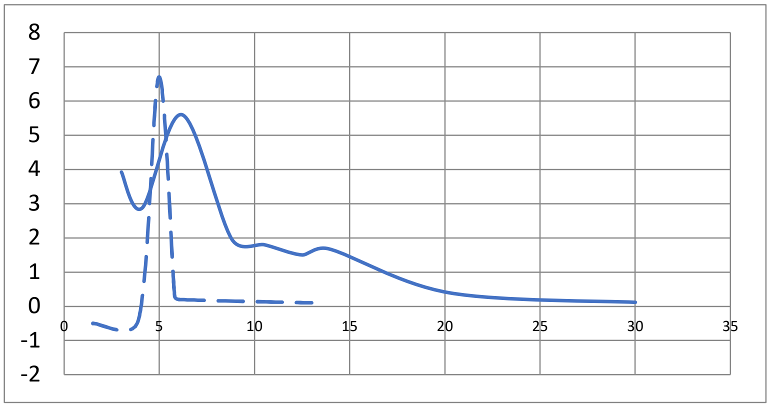
Based on the boundary conditions and conjugation conditions at the ends of the elements of the system and some transformations, a transcendental high-order equation is finally obtained to determine the eigenvalues of the system.

$$\mu\alpha^2\Phi_9-N\Phi_{10}=0$$

where: N — number of flat frame posts. Φ_9 and Φ_{10} – accepted notation in the resulting expressions.

Next, the construction of the amplitude-frequency characteristic of the system "flat frame - grillage-group of piles" was considered.

To identify the degree of reliability of the developed methodology, the results of theoretical



calculations carried out on the basis of the obtained formulas were compared with the data of full-scale tests for structures. The parameters used were taken on the basis of theoretical calculations [11, 12].

Fig. 7. Graph of comparison of the amplitude-frequency characteristic of the grillage. ___ - experimental value; ---- - theoretical value

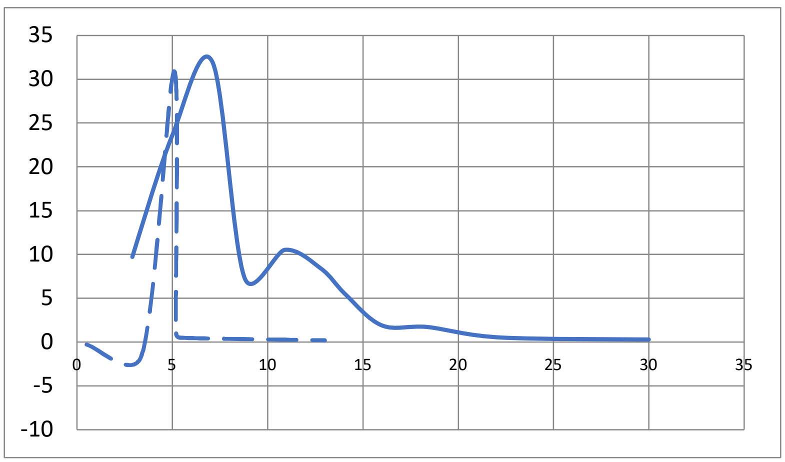


Fig. 8. Graph of comparison of the amplitude-frequency characteristics of coatings. ___ - experimental value; ---- - theoretical value

Figures 7 and 8 show a comparison of the theoretical and experimental frequency response data obtained for the grillage and coatings. The maximum oscillation amplitude on the grillage coincides very closely with each other. With an increase in frequency in both cases, it leads to a decrease in the amplitude of grillage oscillations.

The discrepancy between the theoretical and experimental values is about 16%.

The discrepancy between the results of theoretical calculations and full-scale measurements is explained by the fact that the adopted design scheme is rather simplified, in particular, it does not take into account the process of interaction of piles with each other, which creates a certain wave field in the soil medium. The transfer of platform oscillation energy through the soil medium to the pile system is described by the simplest law through the interaction force proportional to the relative displacement. Finally, the adopted scheme takes into account only transverse oscillations. In fact, due to the violation of the geometric features of the construction of the structure, it also performs shear and vertical vibrations in addition to transverse ones.

The calculation results (force, displacement) practically coincide with the data obtained by calculation according to generally accepted calculation schemes. These results are consistent with the ultimate shear stiffness of the foundation and very high flexural stiffness. Thus, taking into account only the shear stiffness of foundations does not lead to significant differences in forces and displacements.

Conclusions.

1.Based on the results of theoretical studies, resonance curves were constructed for two types of fixings of the "structure-pile group" system. Including, on the basis of the experiments, the resonance states of the system were investigated.

2. A dynamic model of the "platform-group of piles" system is proposed, taking into account the influence of the number of piles, the method of their fastening to the platform, as well as the law of interaction with the surrounding soil on the oscillation parameters of the system.

3. The results of theoretical studies show that when the coefficient of rigidity of the connection between piles and structures is kg/cm2, the displacement amplitude is closer than when to the experimental result at frequencies of Hz. The discrepancies between the results of theoretical and experimental studies are about 20%. Hence, it can be concluded that the accepted design scheme of theoretical studies is chosen correctly and can be used to calculate pile systems for seismic effects with different amplitude-frequency characteristics.

4. The results of theoretical studies are confirmed by the reliability of the operation of structures on pile foundations under seismic and dynamic effects.

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