Joint work of a flat frame and pile foundations under dynamic impacts

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Abstract. In this paper, the basic data of theoretical and experimental studies of a flat frame on pile foundations are presented. Based on theoretical and experimental studies, methods for conducting experimental studies have been developed, the dynamic parameters of the system have been determined, the dynamic calculation scheme has been refined, and a method for calculating a flat frame with a pile foundation under dynamic loads has been developed. Calculation and comparative analysis of the results on the application of pile foundations following building standards are made and the advantage of the work of pile foundations under the condition of dynamic effects is established. Research results allow us to obtain the dynamic characteristics of a flat frame on pile foundations, necessary for subsequent calculations. An analysis of the modes of natural vibrations shows that for a system the 1st form of vibrations is apparently qualitatively different from the vibration form of a conventional single-mass system. To determine 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 field tests for structures. The parameters used were adopted on the basis of theoretical calculations. Quantitatively, the discrepancy near the resonant frequency was about 15% in moving micron vs frequencies curves. The maximum amplitude of oscillations on this grillage very closely coincides with each other. With an increase in frequency in both cases, it leads to a decrease in the amplitude of oscillations of the grillage. The discrepancy between the theoretical and experimental values was about 16%.

1. Introduction

Improving the efficiency and quality of construction largely depends on the correct assessment of the properties of soil foundations and the choice of the foundations of buildings and structures. Particular difficulties arise when designing foundations on specific, structurally unstable soils, which include loess subsidence soils. Reliable construction of buildings on these soils is one of the most important and complex problems of modern construction.

In Uzbekistan, most of the built-up territories are composed of loess and other structurally unstable soils. Their peculiarity lies in the tendency to subsidence, quick-flowing phenomena, liquefaction phenomena, etc., which can often disable the structure.

In connection with these phenomena, in the design and construction under these conditions, appropriate measures are required to ensure the stability of the soil base.

Research, calculation, and design of earthquake-resistant buildings and structures with high reliability and efficiency, still remains a very difficult and critical task. There are various, sometimes controversial, hypotheses about the state of buildings during earthquakes. This is explained not only by the complexity of the processes that occur during seismic vibrations of buildings but also by insufficiently complete data on the nature and magnitude of seismic effects. Therefore, the study and
provision of seismic resistance, as well as seismic protection of buildings and structures is relevant [1, 2], [14-22].

One of the main sources for solving this urgent problem is the development and implementation of the construction of new, most rational designs of earthquake-resistant buildings and structures.

The seismic vibrations of the structure primarily depend on the nature of the transmission of seismic waves by the soil to the structure, i.e., on the interaction with the soil. An important role is played by the conditions of embedding the structure into the base, the type of underlying soil, changes in the properties of soils and the development of residual deformations in the base during strong earthquakes, and the transmission mechanism of various types of foundations of soil vibrations to the structure [3, 4].

At the same time, the seismic resistance of buildings and structures can be achieved not only by increasing the strength of the bearing elements of the foundation but also by improving the designs of the foundations themselves, which can dissipate part of the seismic energy without transferring it to the foundation of the structures.

In this paper, we study the possibility of reducing inertial horizontal forces in the supra-foundation part of the building with a rigid structural scheme using pile foundations with increased dissipative properties.

The presence of pile foundations is taken into account when assessing the dynamic properties of structures. Pile foundations of various designs (high or low grillage, conditions for pairing piles with grillage, cross-sectional dimensions of piles) can have a certain effect on the frequencies and forms of natural vibrations of the structure and, therefore, on the loads that arise in the structure during these vibrations [5].

It should be noted that the methods for calculating pile foundations in complex engineering and geological conditions are still not sufficiently developed. In this regard, the relevance of the development and refinement of design schemes for the interaction of foundations with the ground and the building remains to provide an appropriate basis for the design. The main problems include the following:

- development of the design scheme for determining the displacements and stress-strain state of the pile under the action of horizontal and moment load;
- development of a design scheme for the mechanical interaction of piles and grillages;
- compilation of algorithms and computer programs that implement the above calculations;
- conducting experimental experiments, their analysis, and issuing practical recommendations.

The article presents a calculation method developed by the author, which allows one to take into account the combined work of the aboveground and underground parts of frame-pile structures, obtain the frequencies of natural oscillations and construct their shapes, determine the amplitude-frequency characteristic of the system. According to this technique, the calculation is made according to the design scheme of flat design; wall panels are accepted as absolutely rigid weightless rods; only translational longitudinal and transverse vibrations without torsional vibrations are considered. The nature of soil resistance is not provided.

The main structural elements of the “flat frame-grillage-group of piles” system are the upper structure, including the grillage with a superstructure, and piles connecting the upper structure with the soil base. Usually, the concepts of the upper structure and grillage are identified. On the upper structure (grillage), static and dynamic loads can act. Under the action of the former, the upper structure undergoes static displacements, while dynamic, it oscillates. Piles perceive the effects of the upper structure and transfer them to the soil base.

The tasks set are generally aimed at solving an important scientific and technical problem - the study of the dissipative properties of pile foundations used for buildings and structures subject to dynamic effects.

Thus, the question arises of periods, decrements and forms of free vibrations of structures, since these characteristics are the initial data for calculation according to existing building codes and the rules of seismic loads acting on structures.
The paper discusses issues related to field studies of the system “flat frame-grillage-group of piles”. Of particular importance is the setting of the experiment, where the object of research is a real industrial building, and a sufficiently powerful seismic research stand was chosen as a source of oscillations.

2. Methods
The basis of the seismic testing complex is a six-component seismic platform measuring 6x6 m in size, with a lifting capacity of 50 tons, operating in the frequency range of 3...80 Hz, and providing movement along the X and Y axes within ± 100 mm.

The six-component seismic platform is mounted on a massive concrete block weighing more than 2000 tons, which in turn is based on a pile foundation. The seismic testing complex provides full automation of experimental studies, starting from the formation of the synthesized signal of seismic effects and ending with the issuance of the results in a convenient form for experimenters (Fig. 1).

The building has the following geometric parameters: in the transverse direction – 24 m, in the longitudinal direction the total length of 48 m with a column pitch of 6 m. The total height of the building is 1.6 m, the total height of the column is 14.4 m.

Using the indicated seismic platform, loads were generated in the frequency range 1 ... 30 Hz with the constant acceleration of 3 m/s².

The indicated acceleration value is selected on the basis of the technical feasibility of confidently recording the signal response at the most “insensitive” points. Based on the preliminary test registrations, the author chose the method of "fixed frequencies" in combination with scanning. The latter method eliminates the possibility of a "slip" of the resonance and is implemented first of all, and then, having information about the resonant frequencies, you can more thoroughly study the resonance region using the “fixed frequency” method. In each case, a triple repetition of the load and its registration was carried out.

To conduct experimental research, the following task was posed: to determine the dynamic characteristics at the control points of the building elements of the frame structure on the pile foundation and to refine on this basis the developed calculation method.

As the object of theoretical research was said to be a real industrial building, the source of oscillations is a sufficiently powerful seismic platform located inside the structure.
The calculation was carried out to ensure their reliable performance under the conditions that occur under industrial excitations due to the repeated repeatability of such buildings and structures.

The form of the adopted calculation model of the system “flat frame – grillage – group of piles” is presented in figure 2 and 3. This model is best suited for the study of this system and it allows you to take into account almost all the factors necessary for this case.

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

To solve the dynamic calculation “flat frame - grillage - group of piles”, the following task was posed: to calculate the natural frequencies and build the vibration forms, determine the bending moments, shear forces at the fastening points of the system elements, to obtain the amplitude-frequency characteristics of the system at different levels of the loads excited from the seismic platform and with the separate work of grillages uniting the heads of piles, including in the position of their fastening to a single plate in the plan.

![Figure 2. Scheme of a flat frame on a pile foundation: a-diagram of the frame, b-dynamic design model.](image)

![Figure 3. Scheme of arrangement of grillages of the system “flat frame - grillage - group of piles”.](image)

The greatest impact is obtained near the eight located grillages. In this case, the differential equation of transverse vibration of the pile and the frame rack is represented by the equations of vibration of the...
beam type:

\[ E_J \frac{\partial^4 W}{\partial x^4} + m \frac{\partial^2 W}{\partial t^2} + k(W - W_p) = 0, i = 1.8 \]  \( (1) \)

\[ E_J \frac{\partial^4 W}{\partial x^4} + m \frac{\partial^2 W}{\partial t^2} + kW = 0, i = 9.18 \]  \( (2) \)

\[ E_i \frac{\partial^4 W}{\partial x^4} + m \frac{\partial^2 W}{\partial t^2} = 0, i = 1.18 \]  \( (3) \)

where:

- \( m \) and \( m_c \) are the linear masses of the column and pile stands;
- \( E_c \) and \( E \) are the modulus of elasticity of concrete piles and metal columns;
- \( J_c \), and \( J \) are the moments of inertia of the cross-section of the piles-racks and metal columns;
- \( W_i \), \( W_d \), and \( W_p \) are the moving columns, pile racks, and seismic platforms;
- \( k \) is the coefficient of bed at the level of pile racks.

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

\[ \mu a^2 \Phi_0 - N \Phi_{10} = 0 \]  \( (4) \)

3. Results and discussion

Table 1 shows the results of calculations of the roots of the transcendental equation (4) depending on the change in the coefficient of bed.

The calculated roots of the frequency equation (4) corresponding to the first three forms are: \( \alpha_1 = 4.6; \alpha_2 = 7.64; \alpha_3 = 19.9 \). An analysis of the modes of natural vibrations shows that for a system the 1st form of vibrations is apparently qualitatively different from the vibration form of a conventional single-mass system. This phenomenon can be explained by the fact that if there is a significant concentrated mass at the level of grillages and coatings, the 1-form oscillation of the system “flat frame – grillage - group of piles” for the corresponding numbers, the calculated roots of the frequency equation (4).

| The value of the coefficient of bed, t/m² | 1st form | 2nd form | 3rd form |
|------------------------------------------|----------|----------|----------|
| 0                                        | 0.00     | 0.7537   | 12.5520  |
| 8                                        | 3.5431   | 11.4002  | 18.7534  |
| 10                                       | 3.9526   | 11.4015  | 18.7916  |
| 12                                       | 4.3552   | 11.4084  | 18.8147  |
| 15                                       | 4.8577   | 10.5729  | 18.8308  |
| 20                                       | 5.5345   | 10.6248  | 18.8429  |
| 30                                       | 6.7774   | 12.7264  | 19.8462  |

Next, the construction of the amplitude-frequency characteristics of the system “flat frame - grillage - group of piles” was considered.

To determine 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 field tests for structures. The parameters used were adopted on the basis of theoretical calculations.

Resonance curves from field data were constructed using the “fixed frequency” method, which ensures the accuracy of the results. The compilation was carried out at marks of 10.91 m and 14.4 m - on columns, on the grillage itself, and coatings.
In Figures from 4 to 6, solid lines show resonance curves constructed from field observations, dotted from the results of calculations based on the formulas obtained.

**Figure 4.** Comparison curves for the amplitude-frequency characteristics of the columns at the mark 14.4 m. – experimental; ---- theoretical.

**Figure 5.** Comparison curves for the amplitude-frequency characteristics of the grillage. – experimental; ---- theoretical.
Figure 6. Comparison curves for the amplitude-frequency characteristics of coatings. – experimental, ---- theoretical.

A comparison of these curves shows that the nature of the change in the amplitude of the oscillations of the indicated points of the columns from the frequency is qualitatively close to each other. Quantitatively, the discrepancy near the resonant frequency is about 15%. According to field data, the resonance amplitude is achieved at lower frequencies than theoretical. Also, resonance curves constructed from field data of maximum amplitudes are found to be slightly smaller than the main, which are absent in theoretical calculations.

In figure 5 a comparison of theoretical and experimental data of amplitude-frequency characteristics (AFC) obtained for the grillage is presented. The maximum amplitude of oscillations on this grillage very closely coincides with each other. With an increase in frequency in both cases, it leads to a decrease in the amplitude of oscillations of the grillage.

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

The discrepancy between the results of theoretical calculations and field measurements is explained by the fact that the adopted calculation scheme is quite simplified; in particular, it does not take into account the process of interaction between piles, which creates a certain wave field in the soil environment. The energy transfer of platform oscillations through the soil medium to the pile system is described by a simple law using the force of interaction proportion to the relative displacement. Finally, in the adopted scheme, only transverse vibrations are taken into account. In fact, due to a violation of the geometric features of the structure, the structure performs, in addition to transverse, shear, and vertical vibrations.

As can be seen, from a comparative analysis of theoretical data with field data, the adopted calculation scheme can be used with some approximation to estimate the maximum amplitudes near the resonant frequencies.

We know that when designing and calculating buildings and structures, one of the main tasks is to maximize the use of their geometric, stiffness, and other parameters that affect the formation of the forces acting on the structure. Considering these factors, it can lead to a significant economic effect, opens up many possibilities for buildings, and structures hiding in the structures.

4. Conclusions

Based on the analysis and generalization of the results of experimental and theoretical studies of the vibrations of structures on a pile foundation, the following has been achieved:

- developed a methodology for experimental research in kind;
- based on experimental studies, the dynamic characteristics of a flat frame on pile foundations under simulating effects of a seismic platform are revealed;
- a high-order transcendental equation is obtained for determining the Eigen frequencies of the “flat frame - grillage-pile group” system;
- a computational dynamic model is proposed and a methodology for calculating the system “flat frame - grillage - group of piles” is developed for a different level of action of loads excited from the seismic platform and the separate work of grillages, including in the position of their fastening (grillages) into a single plate;
- based on theoretical studies, differential equations have been derived that describe the behavior of the system “flat frame – reamer - group of piles” under dynamic effects;
- calculation of the system “flat frame - grillage-group of piles” under dynamic impacts allows to identify and use additional reserves of structural strength and thereby design this structure with a high degree of reliability, which leads to lower loads, resulting in saving in building materials and labor costs.

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