Modeling of the complex “Ground Base - Foundation - Construction - External Influences” taking into account the cyclic technogenic vibrational loads

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Abstract. The article is devoted to the development of a mathematical model of the complex "ground base - foundation - construction - external influences" taking into account the cyclic technogenic vibrational loads. The mathematical model is used in automated systems of geotechnical monitoring. The coefficients for a qualitative separation of the types of vibrational technological impact and its quantitative presentation are introduced into the model. These coefficients provide the implementation of the criteria for safe and efficient operation of the foundation and the structure as a whole. At the computer modeling, the dependence of the strength parameters in the complex "ground base - foundation - construction - external influences" was evaluated. It is established that the calculation using the developed mathematical model allows increasing the sensitivity to early detection of a decrease in the strength characteristics of the foundation structure by an average of 24%.

1. Introduction

In the process of designing any geotechnical system, certain conditions are laid down within which the given system will be stable and functional [1]. The calculations, as a rule, take into account wind, climatic, and also technogenic load lying within the limits of current and maximum average values for the construction period [2-4]. However, in the process of functioning of urban geotechnical systems, a general redistribution of stress fields and a change in the parameters of the external load occur due to the construction of the buildings, development of above-ground and underground communications of the city, as well as transport networks [5]. In this case, the boundary functional conditions of stability of geotechnical systems, incorporated in the design calculations, lose their adequacy and do not allow to fully predicting stability and functionality.

Existing mathematical models widely used in automated monitoring systems are described the interaction of structural elements of the building foundation with its soil base mainly use standard factors of technogenic vibrational noise and do not take into account the effect of cyclic loading [6-10]. This fact necessitates special studies of the response of geotechnical systems to cyclic disturbances, which in the future should be the basis for building rules and projects, as well as the basis for processing data in the automated systems and complexes of geotechnical monitoring.

Separate class impacts on the complexes “ground base - foundation - construction” are cyclical effects of anthropogenic nature [11]. Technogenic cyclic disturbances are periodic vibrational influences, various combinations of which have a greater impact on the stability of geotechnical
systems than single dynamic influences [12]. During the operation of production halls and structures, considerable attention must be paid precisely to cyclic influences, which has a rigid connection with the foundation elements to ensure stability and safety of operation. In this case, to the external cyclic load on the structures is also added from inside the structure.

The combination of these factors leads to the accumulation of residual stresses in the soil mass, and the development of deformations of the destabilization and vibration creep at local points of the geotechnical system. Under the cyclic influence underground and above-ground structures of buildings, which are a geotechnical system, receive vibrations close to resonant. In this case, there is a danger of collapse of structures. The conditions of a nonequilibrium state lead to the formation of ordered geomechanical deformation structures caused by the influence of self-organization of the geological environment [13]. In the process of vibration distribution, a change in the state and strength properties of the soil base occurs, and then in the external structure of the foundation elements.

In this case, cyclic loads creates favorable conditions for the concentration of tension at the weakest points, not only in the soil base, and in the elements of the reinforced concrete structure of the building foundation, which leads to destruction as a result of lower cyclic loads than under static conditions, which leads to construction design models. This phenomenon leads to the formation of microcracks and is due to the unloading of tension at the points of weakening of the foundation material. Such points are local points of geotechnical systems, since they are the most informative indicators of the development of deformation processes in the geotechnical system “ground base-foundation-construction”.

The actuality of the studies is determined by the need to increase the sensitivity of automated systems for geotechnical monitoring and early detection of structural geomechanical changes that lead to irreversible geodynamic destruction of the elements of the complex “ground base - foundation - construction”. The aim of the work is to build a model of the complex "ground base - foundation - construction - external impact" for use in geotechnical monitoring systems, take into account the influence of technogenic vibrational disturbances of a cyclic nature.

2. Modeling of cyclic technogenic vibrational disturbances in the geotechnical complex

Modern buildings are complex constructive multi-element geotechnical systems with a heterogeneous structure with various strength and deformation characteristics of structural elements and the connections between them. The complex “ground base - foundation - construction” consists of components (subsystems): construction - structures of the aboveground part, foundation - structures of the underground part of the building, ground base - geological structure of the site. With further dismemberment of the system, individual elements can be distinguished: in the aerial part and the foundation - structures, nodes, joints, parts, simple and complex, but interconnected and determining, ultimately, the strength and stability of the structure as a whole; in the soil base - soil layers [14].

Modelling of the complex "ground base - foundation - construction" belong to the class of difficult formalized tasks, due to the nonlinearity of the processes of interaction of its components.

To modelling the mechanics of the processes occurring in the complex "ground base - foundation - construction - external influences" as a result of the impact of a cyclic technogenic load of a vibrational nature, we introduce the following:

- The available cyclic disturbances under vibration technogenic loads in the form of equations are sum of the waves of oscillations from all external sources [15];
- The soil base models a set of infinitely thin independent plates, which has the following characteristics: – Poisson's ratio, – soil density, – shear modulus, – shear wave velocity in soil [16];
- Each soil layer has its own elastic modulus, on which the amplitude and vibration damping coefficient depend. In most cases, it is determined by laboratory research of samples using various compression methods or can be approximately taken from standardized tabular values, which show the elastic module of the main types of soil and materials of pavements.
The lower and upper parts of the buried pile foundation during oscillations are in continuous contact with the soil base;

The structure is represented as a combination of structures, nodes, joints connected together.

In the process of the impact of cyclic technogenic vibrational disturbances, propagated from various vibration sources in the soil foundation of the structure, vertical, horizontal and rotational vibrations of the pile type foundation are distinguished (Figure 1) [17, 18].

![Figure 1. a) Vertical vibrations of the pile foundation; b) Horizontal vibrations of the pile foundation.](image)

It is known that the acceleration of vibrations in the process of propagation in the soil decreases exponentially:

$$\omega = \omega_0 e^{-0.1z},$$  \hspace{1cm} (1)

where $\omega_0$ is the acceleration of vibrations near the source of vibration exposure; $z$ is the distance from the bottom of the foundation to the $i$-th source of oscillation.

The total cyclic vibrational load on the foundation is presented in the form of harmonic oscillation:

$$N(t) = N_0 e^{i\omega t} = N_0(\cos \omega t + i \sin \omega t),$$  \hspace{1cm} (2)

where $N(t)$ is the disturbing force, $\omega$ is the oscillation frequency.

The dynamic reaction of the foundation to cyclic impact, taking into account the parameters of stiffness and damping, can be represented as an integral [19]:

$$S(w, t) = \int_0^d S(w, t)dw$$  \hspace{1cm} (3)

where $d$ is the pile penetration, $S_w(t) = G_0 (S_{w1} + iS_{w2})$ is the dynamic reaction of a layer of unit thickness, acting along the side face, in which $S_{w1}$ and $S_{w2}$ soil stiffness and damping functions.

In harmonic oscillations with a frequency $\omega$:

$$w(t) = e^{i\omega t}$$  \hspace{1cm} (4)

The kinetic (thermofluctuation) theory of the destruction of solids is based on the fact that in solids, as a first approximation can be represented by a soil base, under the influence of cyclic loads, the process of damage accumulation is continuously going on, which leads to the complete destruction of bodies. The time of the non-critical deformable state of the soil base under cyclic loading is determined by the following formula:
\[ t = t_0 \exp \left( \frac{U_0 - \sigma V}{kT} \right), \]  

where \( t_0 \) is the constant that coincides in order with the period of cyclic vibrations and does not depend on the chemical composition and structure of the body, \( U_0 \) is the activation energy of the destruction process; \( V \) is the activation volume, depending on the structure of the body and amounting to 103 ... 104 atomic volumes; \( kT \) is the measure of the energy of thermal fluctuations; \( k \) is the Boltzmann constant; \( T \) is the absolute soil temperature.

As a result of calculating the integral (3), the expression is obtained:

\[ S_w(t) = G_0 d(S_{w1} + iS_{w2})w(t) \]  

To assess the stress-strain state of soils at the base of the structure, we use the Mora-Coulomb elastic plastic model, which describes the behavior of soil under load by Hooke's law and uses the definition of the ultimate state of destruction of a soil base by the Coulomb strength condition [20]. It takes into account the basic properties of the soil, such as elastic behavior at low loads, low rigidity of the material during failure, and the failure condition [21, 22]. The main problems of using this model are simplification when determining soil resistance to shear near the limiting state, which is practically accepted Young's modulus and Poisson's number constants.

Hooke’s law in differential form connects the tensors of increments of stresses \( \Delta \sigma_{ij} \) in the medium and deformations of the soil base \( \Delta \alpha_{ij} = \left( \Delta \alpha_{xy}, \Delta \alpha_{yx}, \Delta \alpha_{zz} \right) \):

\[ \Delta \sigma_{ij} = D_{ij} \Delta \alpha_{ij}, \quad \Delta \sigma_{ij} = D_{ij}^{-1} \Delta \sigma_{ij} \]  

where \( D_{ij} \) is the stiffness tensor.

The model of the foundation vibrations, taking into account the lateral reaction, can be written as:

\[ m \frac{\partial^2 w}{\partial t^2} + C \frac{\partial w}{\partial t} + Kw = N(\cos \omega t + i \sin \omega t), \]  

where \( C \) is the damping coefficient equal to the total damping of the foundation structure with vertical and horizontal vibrations; \( K \) is the stiffness coefficient equal to the total rigidity of the foundation structure with vertical and horizontal vibrations.

In real conditions, the patterns of the effect of changes in the loads acting on the structural elements of the foundation are, as a rule, more complex. When adding vibration effects on the linear part of the foundation, it is necessary to qualitatively separate these effects. The coefficients for a qualitative separation of the types of vibrational technological impact and its quantitative presentation are needed introduce into the mathematical model. These coefficients provide the implementation of the criteria for safe and efficient operation of the foundation and the structure as a whole.

Thus, to obtain a better idea of the effect of each individual loading cycle, it is necessary to take into account its effect on the strength characteristics of the structural material, introduction to (6) a modified stiffness coefficient:

\[ K_{mod} = \left[ \left( \frac{\sigma_{ae}}{\sigma_{ae}} \right)^n - 1 \right]^{1/k} \]  

where \( \sigma_{ae} \) are the amplitude equivalent voltages, MPa; \( \sigma_{ae} \) are standard amplitude equivalent voltages, MPa; \( \sigma_{ae} \) are the amplitude equivalent stresses determined at the values of the maximum loading cycle, MPa; \( n \) and \( k \) are the minimum and maximum load value in the cycle.
To determine the difference in the $K_{mod}$ values in each of the cycles, it is proposed to assign discharges from 1 to 10 to the differences in the amplitudes of the vibration effect, that is, for different cycles at a different speed, a correction factor will be introduced, which will be determined from the conditions of the task for each specific section of the foundation.

3. Results and conclusions
In the computer modeling, the dependence of the strength parameters in the complex “ground base - foundation - construction - external influences” was estimated on the basis of the proposed mathematical model that takes into account the vibrational cyclic effect and the model of mechanics of a deformable solid used traditionally for solving problems of this class [23].

In modeling, the foundation was a monolithic reinforced concrete block completely buried in the ground with dimensions of 100.0x20.0x1.0 m, supported by 40 piles with a diameter of 1.14 m and a working length of 5 m. The frequency spectrum of vibration exposure is in the range 1-60 Hz, the maximum vibration speed 2.2 mm/s, constant load 2MPa.

Figure 2 present the results of modeling changes in the strength parameters $K$ of the foundation over time with vertical and horizontal vibrations, taking into account the effects of cyclic loading, without taking into account this effect.

![Figure 2](image)

Figure 2. a) Line 1 - Modelling curve of strength parameters at constant load; Line 2 - Modeling curve of strength parameters at constant and cyclic loads; b) Line 1 - Modeling curve of strength parameters at constant load; Line 2 - Modeling curve of strength parameters at constant and cyclic loads.

As a result of computer modeling, it was found that when using any developed mathematical models, a decrease in early (24% earlier) detections of a decrease in the strength characteristics of the building foundation structures (reach critical 80%) is detected compared to a technique that takes into account only constant load. The proposed calculation methods make it possible to more accurately describe the dynamic behavior of buried pile foundations and taking into account interactions in the complexes “soil foundation - foundation - construction - impact” allows more accurately assess the parameters of the geotechnical system.

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