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The Algorithm for Detecting Negative Changes at the Local Point in the Geotechnical System Using Bifurcation Diagrams of Vibration Factors

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Abstract.

The article is devoted to the possibility of detecting negative changes at the local point in the geotechnical system using bifurcation diagrams of the vibration factors. The main vibration factors and their parameters affecting the stability of structures are described. Vibration, acting on the structure, leads to the emergence of additional forced vibrations characterizing changes in the stability of the geotechnical system site. The possibility of using external vibrational noise as a source of a probing signal for monitoring of the building state is noted. A nonlinear model of the stability of the structure is given taking into account the impact of vibration factors. The dynamic behavior of the elements of the building structure with one degree of freedom was modeled, taking into account the load. A bifurcation diagram of the process of deformation of the building structure under the action of the load was constructed. It was found that under vibration exposure, the static load, which is the mass of the floors of the building, can have a significant effect on reducing the stability of structures. The effectiveness of the proposed algorithm is proved when comparing the values obtained in the calculation of the mechanical rigidity of the structure according to the standard method based on the use of a dynamic coefficient.

Keywords: geotechnical system, stability, vibration effect, bifurcation diagram

1. Introduction

As known, the stability of complex geotechnical systems is associated both with the reliability of their individual elements, and with the reliability of their interaction in the system. Moreover, the reliability of geotechnical systems should be laid, formed and changed in the process of their design, construction and operation.

Considering the dynamic process of transition of the initial stability parameters of a complex geotechnical system (ground base - foundation - construction) to the limiting levels in the form of a stationary process and using the methods of the correlation theory of stationary processes, the reliability (stability) forecast can be carried out by solving the linear forecasting task. However, such a forecast, based on the legality of a linear-singular stationary process, can be satisfied in accuracy only over a relatively small time interval (for one to three years of operation of a complex geotechnical system) (Gabibov et al., 2013). This is due to the fact that the linear-spectral approach does not allow to estimate the probability of deviation of the calculated reaction values from the actual values, as well as to reveal the structural strength reserves associated with the physically nonlinear properties of structural materials

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that manifest themselves under dynamic loading. In this regard, further research and development of methods for analyzing and predicting the stability of geotechnical systems, taking into account the nonlinearity of the structural rigidity parameters over time, is relevant.

Particular prospects for solving the task of determining the stability of non-linear geotechnical systems are bifurcation analysis, which consists in assessing changes in the behavior of the geotechnical system with a small variation of the influencing factors.

One of the most common impact factors on operated buildings is the vibrational impact, which is caused by the external technogenic load (auto transport stream, railway overground and underground transport, etc.) (Gerasimov et al., 2017). Vibrational impact has a negative impact on the operational parameters of structures, leading to the development of stress-strain state, cracking and fatigue in structural elements. However, external vibrational noise can be used as a source of a sounding signal, which, acting on the building structure, leads to the appearance of additional forced vibrations in it, and their concentration in weak sections of the structure. In this case, using the methods of chaos theory and knowing the frequency model of the building's stable state that describes the reaction to external vibrational influence, we can determine the initial stage of the building's transition to an unstable state (bifurcation points) by the output of the sum of natural and forced frequencies beyond the model parameters.

In this regard, the aim of the work is to describe an algorithm (stages of the approach) for detecting negative changes at a local point in a geotechnical system using bifurcation diagrams of the dependence of the vibrational displacement parameters of the structure on the external vibrational impact.

2. Vibration factors in geotechnical systems

As noted earlier, the dominant part of the vibrational impact on the structural elements of the building is due to the external technogenic load (auto transport stream, railway overhead and underground transport, etc.).

In it study, the total effect of vibrations from passing vehicles in time is take as a source of vibrational effects in urban infrastructure. Such an effect manifests itself in the form of propagation of longitudinal, transverse, and surface Rayleigh waves over the soil base, the sum of which is a complex time function (Brekhovsky, 1973). Based on the analysis of spectrograms of the vibrational background of the road, the presence of frequencies from 0 to 4000 Hz in the spectrum of the signal of a passing car was noted, but most of the energy is concentrated in the frequency band from 750 Hz to 1850 Hz (Ivaschuk et al., 2018). It is also known that as a result of traffic flow reaching high speeds (more than 100 km/h), actual accelerations in the soil, which go into the structural elements of the foundation of the structure, can approach critical values, and for vehicles developing moderate speeds (60-70 km/h) at a speed of up to 1500 in 1 min, oscillations with acceleration up to 0.2 g are characteristic (Lagerrev & Zedgenizova, 2010). Moreover, in buildings located near the highway, vibrations with accelerations up to 0.1 g can occur (Kuzichkin et al., 2018).

Under the influence of industrial vibration, the frequency of forced vibrations of buildings and structures in a stable state can vary from units to tens of hertz, depending on a number of characteristics (Grecheneva et al., 2018):

- Type of construction frame;

- The numbers of degrees of freedom of construction;

- Properties of materials included in the structure;

- Type of foundation;

- Parameters of elasticity of the soil base, etc.

At the same time, there is a relationship between the frequencies of natural vibrations, the limiting values of the acceleration of the vibrational movements of buildings from altitude, defined in the regulatory documents of the Russian Federation and European countries (GOST R ISO 10137-2016; Smirnov, 2018) (table 1). Therefore, the acceleration spectrum is also an informative parameter for controlling the stability of a structure.

Table 1: Acceleration spectrum of building height for maximum design earthquake

Height, meters	Spectrum	Natural transverse frequencies			
		f1=1,0 Hz	f2=2,3 Hz	f3=3,8 Hz	f4=4,2 Hz
		a, cm/s2	*a*, cm/s2	*a*, cm/s2	*a*, cm/s2
44,8	*a1*	160,6	93,3	96,4	138,8
	a2	180,6	76,5	44,0	46,2
33,6	*a1*	114,4	20,7	35,2	35,5
	a2	129,6	16,9	16,0	11,7
16,8	*a1*	64,2	-20,7	-26,6	-65,0
	a2	72,6	-16,9	-12,2	-21,6
0,0	*a1*	30,1	-34,5	-36,5	-51,9
	a2	34,1	-28,4	-16,7	-17,3

The vibrational effect that occurs at one point in the local area of the geotechnical system has a different effect on other points of the analyzed local area. The degree of impact depends on the distance of the vibration source, the hydrogeological parameters of the soil base, the presence of heterogeneities in it, the parameters of the structure, etc. Taking into account the physical nonlinearity of the stiffness parameters of structural materials, using the methods of chaos theory and knowing the frequency model of the steady state of buildings that describes the reaction to external vibration exposure, the initial stage of transition to an unstable state (bifurcation points) can be determined by estimation of paramter output beyond the permissible model parameters of the sum of natural and forced frequencies oscillations, as well as movement parameters. In this case, according to the use of the modular principle of organizing the information-analytical system of geotechnical monitoring, it is possible to localize not only the sites with the least stability, but also places of development of adverse processes (for example, the initial stages of the development of geodynamic processes) (Grecheneva et al., 2017; Dorofeev et al., 2018).

3. Non-linear model of the stability of the structure taking into account the impact of vibration factors

Under the influence of a vibrating external load, in addition to natural vibrations, forced vibrations arise in the structural elements of the building. In this case, the equation of motion of the system can be written as (Savovich, 2005):

$$m\ddot{v} + c\dot{v} + kv = p(t),$$ (1)

where m is the mass matrix; c is the attenuation matrix; k is the stiffness matrix; v is the displacement vector; $p(t)$ is the vector of vibrational impact.

When modeling the buildings is represented by objects with a finite number of degrees of freedom, for example, horizontal displacement y; vertical movement z; angle of rotation α. For such a system, the displacement vector will have the following form:

$$v(t) = [y_1, z_1, \alpha_1, \ldots, y_n, z_n, \alpha_n] , \qquad (2)$$

where $n = 1, 2, \ldots$ is the number of floors of the building.

As part of the solution to the task of detecting negative changes at a local point in the geotechnical system using bifurcation diagrams of vibration factors, the displacement vector will contain only horizontal displacement parameters that are indirectly manifested in the change in the acceleration of structural elements:

$$v(t) = \iint a(t) = [y_1, \ldots, y_n] , \qquad (3)$$

where $a(t) = [a_1, \ldots, a_n]$ is the acceleration vector of the structural elements of the building.

The load $p(t)$ acting on the structure is a combination of inertial forces f_u (for example, accelerations obtained from the vibrational effects of vehicles), stiffness forces f_c and damping forces f_s. Then, the vector of vibrational effects can be represented in the form (Doronin et al., 2014):

$$p(t) = f_u(t) + f_c(t) + f_s(t) , \qquad (4)$$

Performing the increment of equation (4):

$$\Delta p(t) = \Delta f_u(t) + \Delta f_c(t) + \Delta f_s(t) , \qquad (5)$$

where $\Delta f_u(t) = m\Delta v(t)$, $\Delta f_c(t) = c\Delta v(t)$, $\Delta f_s(t) = k(t)\Delta v(t)$, $\Delta p(t) = p(t + \Delta t) - p(t)$.

There is a large class of problems in the dynamics of structures in which systems cannot be considered as linearly deformable objects. For example, as a result of exposure to vibrational factors, the presence of defects of various configurations (micropores, microcavities) in the structure of concrete, which is part of the construction foundation of the building, leads to a redistribution of the stress field to the primary, propagating in the thickness of the material, and the secondary, concentrated in areas of localization of microinhomogeneities (Ansari, 1985; Beaudoin, 1985). The secondary stress field is characterized by variability in each of the loading cycles, since microcracks are the most vulnerable areas of stress concentration from the point of view of load distribution. Each cyclic impact below the fatigue limit leads to the accumulation of plastic deformations and the slow growth of microcracks. This process is accompanied by the convergence of the peaks of growing microcracks to a certain threshold (a certain critical distance), beyond which microcracks merge with a further growth of a single crack. Thus, vibrational loading creates favorable conditions for stress concentration at the weakest points of not only the soil base, but also the elements of the reinforced concrete structure of the building's foundation, which leads to its destruction at significantly lower cyclic loads than under the static conditions adopted in construction calculation models. As a result, the stiffness coefficients are able to change due to the appearance of fluidity in structural elements. In this case, equation (1), taking into account (5) and nonlinearity properties, will take the following form:

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$$m\Delta v(t) + c(t)\Delta v(t) + k(t)\Delta v(t) = \Delta p(t) \quad , \qquad (6)$$

In this case, the damping $c(t)$ and stiffness $k(t)$ functions change according to certain laws and can be set at the end of the iteration stage, expressing the nonlinear nature of the materials of the structure:

$$c(t) = \frac{df_c}{dv} \;\; ; \;\; k(t) = \frac{df_s}{dv} \;\; . \qquad (7)$$

In the process of solving the task, the nonlinear nature of the construction materials was determined by a change in stiffness in accordance with the accepted elastoplastic dependence (7). In the numerical integration of equation (6), it was assumed that, within each time interval, the acceleration varies linearly, while the attenuation and stiffness remain unchanged. When considering motion, the change in acceleration was assumed to be linear, and the change in speed and displacement was assumed to be quadratic and cubic. As a result, equation (6) can be written as:

$$\tilde{k}(t)\Delta v(t) = \Delta p(t) \quad , \qquad (8)$$

Wherein:

$$\tilde{k}(t) = k(t) + \frac{a}{t}m + \frac{3}{t}c(t); \; \Delta p(t) = p(t) + m\left(\frac{a}{\Delta t}m + 3v(t)\right) + c(t)\left(3v(t) + \frac{\Delta t}{2}v(t)\right); \quad (9)$$
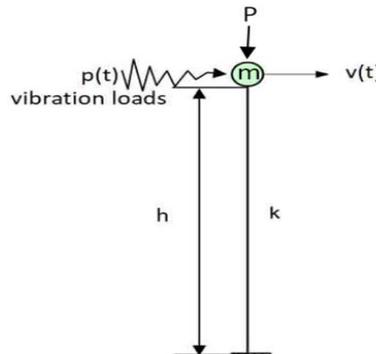
where a is the acceleration of structural elements.

During the vibrational impact on the foundations of structures, the main type of deformations are roll deformations, which are manifested in the loss of stability when the limit value of the angle of inclination of the structure is reached. In this case, the limiting stable value of the angle of inclination is determined by the elastic properties of the material and changes according to the exponential law until the elastic limit of the materials of the structure is reached (Vasilchenko et al., 2019).

4. Simulation results

As a result of the studies, the dynamic behavior of structural elements of the structure with one degree of freedom was modeled (Figure 1). Model parameters *m=200 tons*, *k = 30000 kN*/m, *h = 1.5 m*. This model, as a first approximation, is the simplest link in the structure.

Figure 1: Design model of a frame building model with one degree of freedom

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Moreover, in the case of modeling bifurcations of structures having a more complex design scheme, it is possible to use the modularity method, in which the one shown in Fig. 1 replaces each of the basic structural elements, and the interconnection of structural elements is ensured by the introduction of additional differentials of the type (7).

In accordance with the theory of dynamical systems (Rudiger, 2010; Nazarov, 2015), the bifurcation of codimension 1 is valid for this case — merging. The bifurcation diagram of the change in the overall stability of the structure during displacement Δv obtained during an increase in load P, taking into account the vibration effect $p(t)$, is shown in Figure 2.

Figure 2: Bifurcation diagram of the displacement of the building structure when the load changes
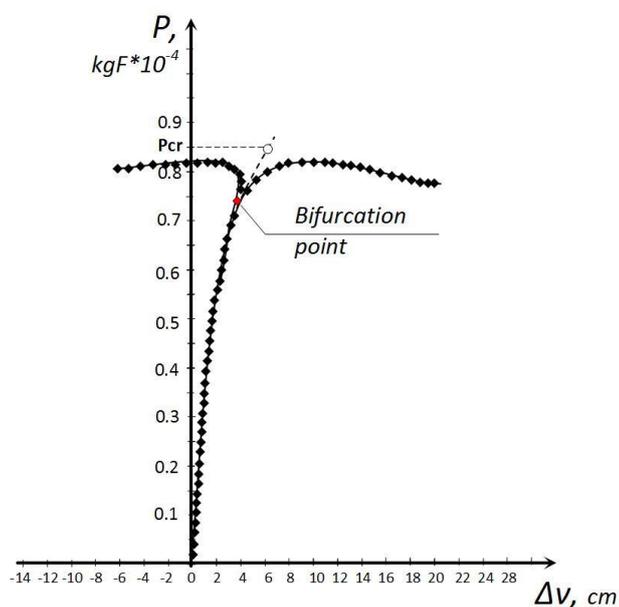
According to the analysis of the bifurcation diagram, the bifurcation point is the displacement value Δv for a structure with a static load of *P≈7500 kgF*. At this point, the displacement of the structural unit Δv is *3.89 cm*. The displacement of the assembly after the bifurcation point $\Delta v = 4.53\ cm$ corresponds to the unstable state of the geotechnical system, which leads to the formation of a roll of the structure. As can be seen from the diagram, the bifurcation process occurs at a load *P <Pcr*. This suggests that under vibration exposure, the static load *P*, which is the mass of the floors of the building, has a greater effect on reducing the stability of structures than in the absence of vibration noise.

To evaluate the effectiveness of the proposed algorithm, the roll of the structure was calculated according to the standard methodology using the dynamic coefficient *Kd* (Kolesnikov et al., 2019). As a result of the design calculations for the action of the static load, taking into account the applied forces, the elastoplastic work of materials and changes in their strength characteristics, the maximum strain ν max was obtained at which the maximum displacement of the structure while maintaining its stability was *5.76 cm*. The difference between the obtained limit values is $\Delta v = 5.76\ \text{-}3.89 = 1.87\ cm$, which is significant in the theory of the stability of structures. This indicates the effectiveness of the application of the algorithm described in the article, which makes it possible to identify negative changes at the local point of the geotechnical system and determine the critical values of the vibration effect,

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which manifests itself in a change in the accelerations of the structural elements of the structure.

5. Discussions and conclusions

As a result of the studies, an approach to identify negative changes in local points of the geotechnical system using bifurcation diagrams of vibration factors was developed and described. Using the described model of the stability of structures and methods of chaos theory when analyzing data on the displacements and vibration frequencies of local points (buildings), it is possible to determine the initial stage of the transition of the geotechnical system to an unstable state (bifurcation points). In this case, according to the use of the modular principle of organizing the information-analytical system of geotechnical monitoring, it is possible to localize not only the sites with the least stability, but also the sources of instability development (the initial stages of the development of geodynamic processes).

As a result of the simulation, the effectiveness of applying the bifurcation analysis algorithm was confirmed in comparison with the traditional methodology for determining the permissible movement of structural elements of a structure. It was established that under vibration exposure, the static load, which is the mass of the floors of the building, has a greater effect on reducing the stability of structures than in the absence of vibration factors. The results obtained in this article correlate well with the results of similar studies presented in (Inozemtsev&Zhestkova, 2016; Inozemtsev& Nashchintsev, 2015), which indicates their adequacy.

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