An indirect method for determining the dynamic properties of soils at modeling the vibrating effects of technological equipment on the building structures

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Abstract. The results of experimental studies of the elastic characteristics of soil bases are presented in the simulation of dynamic loads from machinery and equipment to building structures. In the course of work on the inspection of the technical condition of building structures, the authors developed an experimental and theoretical method for determining the elastic characteristics of soil bases. The proposed method involves carrying out full-scale dynamic tests in the mode of natural and forced oscillations.

Keywords. Foundations of machines, dynamic effects, structural vibration, dynamic properties of soils, full-scale dynamic tests.

1. Introduction

While inspecting the technical condition of buildings and structures, it is necessary to study the propagation of oscillations from the foundations of machines with dynamic loads that cause vibration of building structures and foundations [1–4]. The period and logarithmic pitch decrement of the building's natural oscillations are important calculation parameters for conducting surveys and monitoring the technical condition of buildings and structures [5–7].

Under certain conditions, resonance oscillations of bearing and enclosing building structures cause a decrease in their serviceability. One of the reasons for the increased vibration of foundations with dynamic loads and adjacent building structures is an inaccurate determination of the initial dynamic characteristics of the base soil.

Currently, the main normative document regulating the determination of dynamic properties of soils is [8]. This standard is relatively new and establishes three methods of laboratory testing of soils to determine their dynamic properties: dynamic triaxial compression, low-amplitude dynamic tests by resonance column and torsional shear. All three methods require specialized expensive equipment and certain skills to work on it [9–11].

In addition, during the inspection of existing buildings and structures, laboratory methods for determining the elastic characteristics of the soil base have a number of drawbacks, which include not taking into account the actual technical condition of the foundation slabs under equipment and soil bases. In this regard, the development of field methods for assessing the dynamic properties of soil bases of existing buildings and structures by the full-scale tests is a vital task [12–13].

The complexity of this problem is one of the reasons for the use of empirical methods in other normative documents [14–17]. According to [14], the main elastic characteristic of the soil bases is the...
coefficient of elastic uniform compression $C_z$, which is determined by the results of tests or on the basis of data on the velocities of longitudinal and transverse waves. In the absence of experimental data, the value for foundations with a sole area of not more than 200 m$^2$ can be determined by the empirical formula:

$$C_z = b_0E \left[1 + \left(\frac{A_{10}}{A} \right)^{1/2}\right],$$  

where $b_0$ – coefficient for sandy soils taken equal to 1.0; $E$ – the deformation modulus of the soil under the foundation bed; $A_{10} = 10$ m$^2$; $A$ – area of the foundation bed.

According to [14], the coefficients of elastic non-uniform compression, elastic uniform shear, and elastic non-uniform shift are derived characteristics and are determined by the coefficient of elastic uniform compression. Thus, one of the main factors that can affect the results of determining the elastic characteristics of soil base is the value of the modulus of deformation of the soil. According to [18], the soil deformation modulus is a variable value depending both on the stress level in the soil bases and on the method of its determination [19–20].

2. The Essence of the Method
The essence of the method is to establish the dynamic properties of soils in full-scale tests under the conditions of the operating load. Tests are carried out by changing the inertial properties of the foundation in the modes of natural and forced oscillations. Varying inertial properties is accomplished by changing the mass of the foundation. On the basis of the obtained natural frequency values, the elastic characteristics of the soil bases are calculated, and the reaction of building structures is determined. With this approach, empirical methods are used in combination with the results of measurements obtained by field tests.

3. Object of Research
The object of the study is a one-story industrial building with a metal frame. Two technological lines for drying and classification of sand are mounted in the building (Fig. 1). In the process of visual inspection, it was found that all the building structures of the building are affected by the harmonic dynamic load from the technological equipment. According to the results of instrumental surveys, it was found that the amplitude of oscillations of wall sommers and profiled flat for wall fencing exceeds the normative values.

![Figure 1. Fragment of building structures and technological equipment.](image-url)
The framing of the building is made according to the wall-frame scheme and is the main supporting structure, which perceives and transmits to the foundations all vertical and horizontal loads. Elements of the frame are steel through two-branch columns, rafter trusses, vertical and horizontal links and spacers. The conjunction of trusses with steel columns is made in a hinged variant. The cross frames of the framing provide the rigidity of the building in the transverse direction, and the vertical links and spacers between the columns – in the longitudinal direction. The structures of working platforms and cover are leaned to the columns on different labels. Wall fences and roof coat are made of profiled flat bed, which is attached to the sommers. Wall sommers and binding rafters are designed for installation of profiled flat bed, which provide transmission to the framework of snow and wind loads, increase the rigidity and stability of the entire structure. The profiled flat bed is attached to the sommers of the coating and walls by self-tapping bolts with joint washers.

The construction site is composed of the following soils: filled-up ground with depth 0.8 m, medium-sized sand, average density with depth 2.3 m and medium-sized sand, dense with depth 7 m. Separately standing isolated footing for steel columns are made of concrete class B25. The height of the first stage and the bases of columns of all foundations is 600 mm, and the height of the middle stage, depending on the location of the foundations ranges from 100 to 3700 mm. The depth of the foundations, respectively, ranges from 2.2 m to 4.9 m. The foundations are prepared from concrete class B10 with a thickness of 100 mm.

Each production line consists of two types of equipment: a furnace-drying unit and a vibrating pneumatic classifier. The main characteristics of the process equipment are presented in Tables 1–2.

### Table 1. Technical characteristics of the furnace-drying unit.

| Position | Parameter                             | Value |
|----------|---------------------------------------|-------|
|          | **Vibro-duct**                        |       |
| 1        | Oscillation amplitude, mm             | ≤ 4   |
| 2        | Oscillation frequency, Hz             | 12.5–16.7 |
| Drive (Electromechanical vibrator MVE 13000/1) |       |       |
| 3        | Amount                                | 2     |
| 4        | Capacity, kW                         | 10    |
| 5        | Oscillation frequency, Hz             | 16.7  |
| Overall dimensions |                                 |       |
| 6        | Length, mm                            | 11228 |
| 7        | Width, mm                             | 2308  |
| 8        | Height, mm                            | 13950 |
| 9        | Weight, kg                            | 13950 |

### Table 2. Technical characteristics of the vibrating pneumatic classifier.

| Position | Parameter                             | Value |
|----------|---------------------------------------|-------|
|          | **Vibro-duct**                        |       |
| 1        | Oscillation amplitude, mm             | ≤ 4   |
| 2        | Oscillation frequency, Hz             | 12.5–16.7 |
| Drive (Electromechanical vibrator MVE 13000/1) |       |       |
| 3        | Amount                                | 2     |
| 4        | Capacity, kW                         | 10    |
| 5        | The driving force of one vibrator, kg | 13009 |
| 6        | Oscillation frequency, Hz             | 16.7  |
| Overall dimensions |                                 |       |
| 7        | Length, mm                            | 7123  |
| 8        | Width, mm                             | 1838  |
| 9        | Height, mm                            | 3365  |
| 10       | Weight, kg                            | 7503  |

The equipment of technological lines is installed on the Foundation slab of reinforced concrete. The monolithic slab with a thickness of 400 mm is made of concrete of class B25 and reinforced with two flat grids of reinforcing bars with a diameter of 12 mm (A400). The step of bars in both directions is 200 mm. Under the monolithic plate a concrete blinding coat is made with class B10 and 100 mm thick.

### 4. Testing

Before the measurement of vibrations, structures with increased amplitudes were identified. Measurements were carried out in the modes of natural and forced oscillations. The frequencies of the natural oscillations of the system "Foundation-Machine" were determined with stopped technological machines. In order to fixate large dynamic displacements of building structures, forced oscillations...
were carried out in resonance regimes. Measurement points were selected in the immediate vicinity of the reference nodes, at the interface of structural elements and in the middle of the spans of beam structures.

To determine the extent of influence of driving forces that arise during operation of the furnace-drying unit and pneumatic classifiers on the amplitude of the oscillation, measurements have been carried out in the operating and idle modes. In order to establish a connection between the fluctuations of the building structure and the operation of specific equipment, measurements were carried out by alternately disconnecting and turning on two production lines.

During the test, in addition to fixing the dynamic movements of building structures, measurements of vibrations of the frame and slab parts of the foundations for the equipment were carried out. In order to identify the separation of the frame part of the foundation and the loosening of the anchor bolts, measurements are made for two points of the foundation plate located in opposite directions.

The escalation in the weight of the foundation was achieved by loading the frame part of the foundation with sandbags (Fig. 2–3). During the test, five stages of loading were provided. All stages of the test were carried out under the same conditions and in the absence of snow loads to cover the building.

![Figure 2. General view of the unit and change of own weight of the frame part of the foundation by the test load.](image)

5. Results and Discussion
According to the results of the research, the values of the natural frequencies of the system "Soil Base-Foundation-Machine" and the amplitude of oscillations of building structures were obtained. Determination of elastic characteristics was carried out by solving the inverse problem by the method described below.
Figure 3. Design model of the system "Soil Base-Foundation-Machine".

It is known that for a one-mass system (figure 3) the eigen frequency is determined by the formula:

$$\omega = \left( \frac{K_s}{m + \Delta m} \right)^{1/2}, \quad (2)$$

where $K_s$ – the stiffness coefficient of the soil base under uniform compression; $m$ – the weight of the system "Foundation-Machine"; $\Delta m$ – testing weight.

The stiffness coefficient for the earth foundation is determined in accordance with clause 6.1.4 [9] as for the model of Winkler:

$$K_s = C_z \cdot A, \quad (3)$$

where $C_z$ – the coefficient of elastic uniform compression; $A$ – area of the foundation bed.

With the help of formulas (2) and (3), taking into account the change in the mass of the system, we obtain an expression for determining the eigen frequencies of the system "Soil Base-Foundation-Machine":

$$\omega = \left( \frac{K_s}{m + \Delta m} \right)^{1/2} = \left( \frac{C_z \cdot A}{m + \Delta m} \right)^{1/2}. \quad (4)$$

From the obtained formula we express the coefficient of elastic uniform compression:

$$C_z = \frac{(m + \Delta m) \cdot \omega^2}{A}. \quad (5)$$

From the obtained ratio taking into account (1) determine the modulus of deformation of the soil:

$$E = \frac{\omega^2 \cdot (m + \Delta m)}{b_0 \cdot A \cdot \left[ 1 + \left( \frac{A_{10}}{A} \right)^{\frac{1}{2}} \right]} \quad (6)$$

Some results of tests and determination of characteristics according to the above procedure are given in the summary Table 3.
Table 3. Results of tests in the mode of natural oscillations at work of the furnace-drying unit of the first line.

| Stage | Test load $Δm, t$ | Frequency of the system "Soil Base-Foundation-Equipment" $ω, \text{sec}^{-1}$ | Coefficient of elastic uniform compression $C_z, \text{kN} \cdot \text{m}^{-3}$ | Deformation modulus of the soil $E, \text{MPa}$ |
|-------|-------------------|---------------------------------|---------------------------------|-------------------|
| I     | 0 (idle mode)     | 128.3                           | $32.66 \cdot 10^3$              | 18.29             |
| II    | 1.5               | 128.5                           | $34.35 \cdot 10^3$              | 19.24             |
| III   | 3.0               | 132.1                           | $37.98 \cdot 10^3$              | 21.27             |
| IV    | 5.0               | 138.7                           | $44.33 \cdot 10^3$              | 24.83             |
| V     | 8.0               | 143.4                           | $51.34 \cdot 10^3$              | 28.75             |

According to the test results, the increase in the values of the deformation modulus as the test load increases at high frequencies was established. The difference between the strain modulus values is due to different stress values at different stages. At low frequencies, no significant changes in elastic characteristics were observed.

According to the results of testing the foundation of the first line furnace-drying unit, it was found that the increase in the mass of the foundation at low frequencies leads to an increase in the amplitude of vibration fluctuations of building structures.

According to the results of the research it was decided to change the stiffness of the wall sommers in order to withdraw them from the resonance zone.

6. Conclusion
- The proposed method makes it relatively quick and easy to obtain a clear relationship between the vibration effects on the building and the dynamic characteristics of the soil bases.
- All vibrations to determine the elastic characteristics of soil bases are caused by the action of existing equipment, so in the process of testing additional dynamic effects on the soil bases are not made.
- The dynamic properties of soils, in particular, the coefficient of elastic uniform compression are variable, which depends on both the level of stresses in the bases and the parameters of external dynamic effects.
- An increase in the weight of the foundation at low frequencies leads to a raising in the amplitude of vibratory oscillations of building structures.

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