The industrial buildings settlement foundations calculation made taking into account the soils vibro-creep

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Abstract. The present study focuses on the interaction of soil and the foundation under vibration and cyclic loading arising from the operation of dynamic machinery of industrial buildings. The paper presents the methods for predicting the behavior of sand under vibration loads on the example of testing in a triaxial compression device with the possibility of creating dynamic loading. During the final stage of testing, the values of the sample’s additional deformations were obtained due to the vertical vibration load action of a given frequency under conditions of consolidated-drained triaxial compression. The vibro-creep coefficient was obtained, which makes it possible to determine the reduced Young's modulus, which makes it possible to use it in the sediment calculations by the layer-by-layer summation method. The dependence graphs of the Young's modulus on the pressure of the all-round reduction and vertical deformation on the number of cycles "load – discharge" are given. Analytical and numerical calculations of vertical deformations on the elastic base with vibration load are performed. The possibility of obtaining the coefficient of vibro-creep for different types of sandy soils in tabular form with the aim of simplifying the foundations additional movements calculation of the machines with dynamic loads is presented.

Introduction
The machines foundations design with dynamic loads is associated with the nature of the forces that have a complex mechanical effect on the base, as they vary in time in magnitude and direction, causing a complex tension-strain state in soils.

From the building practice experience, it is known that there is a need to arrange separate foundations with various damping devices for dynamic equipment. Such a constructive solution allows reducing the impact on the building as a whole, but there are cases in which increased demands are placed on the foundation deformations under a dynamic installation. These types of installations include, for example, hydroelectric turbines. Thus, this task is relevant in the design of the industrial buildings’ foundations.

Russian and international design standards, such as - BC 22.13330 "Ground bases and foundations of buildings and structures", BC 26.13330 “Foundations of machines with dynamic effects" and EN 1997-1: Eurocode 7 "Geotechnical design" [2-4] prescribe to calculate the long-term additional deformations from the joint action of static and dynamic loads (vibro-creep - the accumulation of volume and shear deformations in dispersed soils under prolonged vibration loads). This calculation is possible to be made, while accepting the reduced values of the soil deformation modulus (Young's modulus), which should be determined, as a rule, from the test results. This technique is simple for use in engineering practice and is available to a wide range of specialists. According to the authors, this technique is suitable for the preliminary analysis of soil vibro-creep, however, the difficulty of its use is the need to determine the lower values of the Young's modulus using the soil samples laboratory tests for each case.

The main objective of this work is to demonstrate the possibility of obtaining tabulated averaged coefficients for different types of soils, which will allow to obtain the lower values of the Young's modulus for the calculation of the 2nd limit state. This is quite a convenient way to obtain the deformations preliminary values without time-consuming tests.
Review

This work is devoted to the ground environment under vibration loads study from the point of view of the deformed solid mechanics, it is rather complicated, since the soil properties and effects on them cannot be set in advance; therefore, it is impossible to predict the initial and effective stress-strain states of the soil strata formed for various reasons.

General questions on the topics studied in this paper were considered in the works of many Russian and foreign authors: Voznesensky Ye.A. [5], P.L. Ivanov [6], Ter-Martirosyan Z.G. [7, 8], Ter-Martirosyan A.Z. [9], Lushnikov V.V. [10], Tsytovich N.A. [11], Ishihara K. [12], Seed H.B. [14], Idriss I.M. [13] and many others.

In the works of the above-mentioned scientists, the basics of describing the mechanical properties of soils in the pre-limiting and limiting states under static and dynamic effects are developed, the importance of a quantitative assessment of additional soil deformations under various vibration effects is noted.

Under laboratory conditions, studies of the rheological and vibro-rheological properties of soils for various kinds of dynamic loads are reproduced by applying various installations, for example, vibratory triaxial instruments, vibrating tables, etc.

The mechanism used in this work to determine the behavior of a sand sample under cyclic loads in a triaxial compression device was shown by Sid and Lee (Seed, Lee, 1966). In their experience, they compacted water-saturated soil with compressive pressure and applied a series of cyclic loads with a constant amplitude of oscillations before the onset of axial deformations. As a result, they received an increase in the pressure of pore water, which reached the initial pressing pressure, which led to the development of axial deformation (liquefaction).

Also, in the framework of this work, the Russian and international construction norms and rules, in which a separate item spells out the need to take into account dynamic loads from machines of industrial buildings and apply them in calculations for the second limit state (settlement calculation) are analyzed [2,4].

Materials and methods

The accepted procedure for testing: the dry soil of a given density sandy soil samples (1.67 g/cm$^3$), close to natural, were placed in a three-axis device chamber, after which they were completely saturated with distilled water.

After the water saturation completion, a comprehensive pressure equal to the household pressure at a given depth (2.7 m, 5.4 m, 8.1 m) was applied to the sample and a consolidation stage was conducted under conditions of open drainage. Radial pressure was equal to vertical and was for each soil sample - 50, 100, 150 kPa.

After the static load deviator application of 50 kPa (which corresponds to the pressure under the base of the foundation) and the deformations stabilization, a vibration load with a frequency of 100 Hz (such variations for some types of turbo units) and the number of load-unload cycles of 15000 were applied to the sample.

During the final stage of testing, the values of additional deformations of the sample were obtained due to the action of the vertical dynamic load of a given frequency under conditions of consolidated-drained three-axis compression.

After processing the data obtained during the tests, the vibro-creep ($C_{vc}$) coefficient values at the stage of vibration loading for each specimen at a single loading frequency were obtained.

The calculation was carried out taking into account the following dependencies: to take into account the vibro-creep of soils, an additional coefficient [7], which reduces the value of the static Young's modulus is used. This approach to predicting the vibro-creep of soils can be called quasi-static, since it is carried out within the framework of the usual static methods for calculating the structures foundations settlement. The vibro-creep coefficient values for the studied soils were calculated by the following formula:

$$K_{vc} = \frac{\Delta \varepsilon_i}{(\Delta \varepsilon_i + \Delta \varepsilon_d)}$$  \hspace{1cm} (1)

where $\Delta \varepsilon_i$ and $\Delta \varepsilon_d$ – are the increments of deformation from static and dynamic loading in a given stress range, in fractions of a unit;

Young's modulus of soil, taking into account the deformation of vibro-creep, can be determined by the formula:

$$E_{vc} = K_{vc} \cdot E_s$$  \hspace{1cm} (2)
where \( E_{vc} = \sigma / (\varepsilon_s + \varepsilon_d) \); \( E_s = (\sigma / \varepsilon_s) \cdot \beta \); \( E_s \) – is the Young’s modulus according to the results of static tests, in kPa; \( E_{vc} \) – is the adjusted value of the Young’s modulus based on the results of dynamic vibration tests of soils, in kPa; \( C_{vc} \) – is the vibration coefficient, in fractions of a unit; \( \beta \) – is the dimensionless coefficient taking into account the absence of lateral expansion of the soil in determining the sediment, in accordance with the recommendations of [2] is assumed to be equal to 0.8.

**Laboratory Test**

The results of the dynamic tests of the three samples are presented in Figures 1, 2. In addition, a summary table of the results obtained during the tests and the parameters calculations has been compiled (see Table 1).

Table 1 presents the values for the three dynamic tests at different values of radial pressure. The first and second lines are, respectively, the increments of strain from static and dynamic loading in a given stress range, in fractions of a unit; the third line - Young’s modulus according to the results of static tests, in kPa; the fourth is the vibration coefficient calculated by the formula (1); the fifth one is the corrected value of the Young’s modulus based on the results of dynamic vibration tests of soils using the creep coefficient according to the formula (2).

| \( \sigma_z \) [kPa] | 50     | 100    | 150    |
|---------------------|--------|--------|--------|
| \( \Delta \varepsilon_s \) | 3.83×10^-4 | 3.24×10^-4 | 1.78×10^-4 |
| \( \Delta \varepsilon_d \) | 8.32×10^-5 | 4.01×10^-5 | 3.14×10^-5 |
| \( E_s \) | 106302  | 120503  | 223324  |
| \( K_{vc} \) | 0.82    | 0.89    | 0.85    |
| \( E_{vc} \) | 87167.6 | 107247.7 | 189825.4 |

Below is a graph of the static and dynamic Young’s modulus dependence on the pressure of comprehensive compression. In Figure 1, it can be seen that with an increase in pressure of all-round compression, the Young’s modulus increases. The graph also shows the dependence of the dynamic Young’s modulus obtained by the formula (2).

**Figure 1.** Graph of the comprehensive compression pressure static and dynamic Young’s modulus

Below is a plot of the vertical deformation versus the number of load-unload cycles, at three different values of all-round pressure (Figure 2). The graph shows that with increasing cycles of «load-unloading» increases the vertical deformation, which confirms the presence of vibro-creep.
Research results show that with increasing overall pressure on a soil sample, additional vibro-creep deformations decrease. This is characterized by a decrease in the steepness of the graphs of the dependence “vertical deformation - the number of cycles” with an increase in the comprehensive compression value.

Calculation of settlement
When dynamic loads are applied to the foundation, the base deformations increase, as the creep effect of the soil is observed. Using the obtained experimental data of the soil Young's modulus, the sediment was calculated in accordance with the requirements of BC.22.13330 (layer-by-layer summation), as well as FEM in the geotechnical software package PLAXIS 3D in a spatial formulation (the calculated diagram is shown in Figure 3). For the analytical and numerical solution of these two methods, the experimental values of the static and dynamic (taking into account vibro-creep) Young's modulus were used. The pattern of distribution of vertical displacements in the soil mass at the stage of dynamic load is presented in Figure 4. The results of calculations of the deposition of the foundation on an elastic base are presented in Table 2.
Figure 4. Isolines of vertical displacements in the soil mass at the stage of application of the vibration load on the foundation

Table 2. Summary table of sediment taking into account the dynamic and static Young's modulus

| Method                                             | Stamp settlement, mm |
|----------------------------------------------------|-----------------------|
| SP 22.13330 (by the method of layer-by-layer summation) | 0.32                  |
| SP 22.13330, taking into account the vibro-creep of soils | 0.39                  |
| FEM in PLAXIS 3D (soil model - linear-elastic)      | 0.22                  |
| FEM in PLAXIS 3D, taking into account vibro-creep    | 0.30                  |

Summary

Analyzing the results of the research we can draw the following main conclusions.

1. With increasing compression of the soil sample, the Young's modulus increases.
2. With the increase in the number of “load-unload” cycles, with dynamic loading, the vertical deformation increases, this fact confirms that the soil has vibro-creep.
3. Due to the limited number of tests, it was not possible to establish reliable dependencies between the compression pressure and the coefficient of vibro-creep.
4. From the conducted laboratory experiments it can be seen that the deformation modulus, taking into account the coefficient of vibro-creep, decreases on average by 15%.
5. The obtained value of the coefficient of vibro-creep and the reduced Young's modulus can be applied to this type of soil in the calculations of sediment by layer-by-layer summation method in accordance with the requirements of BC 22.13330.
6. The results of deformation calculations using the layer-by-layer summation method with regard to vibro-creep deformations and the FEM in the PLAXIS software show satisfactory convergence.

The main conclusion of the results of the research should be noted that there is a possibility of obtaining the coefficient of vibro-creep for different types of sandy soils in tabular form (for an example, see Table. 1). Having performed similar studies for other varieties of soil, it is possible to create the tabulated values to obtain a lower Young's modulus and, as a result, to simplify the foundations preliminary deformations calculation from the dynamic loads of industrial buildings.

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