Investigation of the Influence of Dynamic Loads of Industrial Equipment on the Occurrence of Prolonged Yielding of their Foundation Soils

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Abstract. The parameters of oscillations of the foundations and structures of the dynamic equipment of the new production workshop located in the Kharkiv region were experimentally investigated. For this purpose, appropriate measurements of the amplitude of oscillations in the vertical and orthogonal horizontal directions were performed. To compare the parameters of the amplitudes of forced oscillations and determine the damping properties of the applied rubber spacers placed between the frame and the slides, as well as the quenching effect of the foundation massif, several measurements of oscillation parameters were performed at the locations mentioned above. The amplitude of oscillations of the vertical component of the vibration load on different sides of the rubber dampers was reduced by 2-3 times, the horizontal component was completely attenuated. It was also established that there was no transmission of vibrations to the foundations of the production workshop. The safety of the measured parameters of oscillations from the point of view of long significant unstabilized subsidence of the foundations, both equipment and building, was determined. Recommendations for monitoring are given from the point of view of the possible deterioration of the properties of the used rubber dampers over time.

1. Introduction

The issue of foundations performance in terms of their perception of dynamic loads from existing industrial equipment remains one of the most serious and least studied issues in industrial construction. Despite a considerable amount of research on this topic, this situation still occurs due to the wide variety of possible machines and mechanisms and as a result the practical impossibility to predict what exactly the size, shape, and direction of dynamic loads will be generated by each machine. Therefore, when installing foundations that will transfer dynamic loads to the base, it is necessary to pay special attention to investigating the parameters of these loads.

The situation can be complicated by the possible water saturation of the base soils during operation due to seasonal or emergency groundwater level rise. When designing foundations for such equipment, in addition to the amount of static load, which must be distributed on the base soils, it is necessary to additionally determine the magnitudes, shapes and directions of forced oscillations that occur in both stationery and emergency modes of dynamic equipment. It is necessary to focus on both the technical specification data of the equipment manufacturer and the actual data obtained during the study of the operating parameters of similar equipment. Also, if possible, measures should be taken to reduce the amount of transmitted dynamic forces, such as balancing the moving and rotating parts, the
installation of dampers, etc. After all, the dynamic loads transmitted to the ground of the foundation, in certain conditions, can lead to unstabilized subsidence lasting years and even decades of the mechanism operation, as well as affect the neighboring foundations of buildings and structures.

2. Definition of unsolved aspects of the problem
When designing foundations for equipment with dynamic loads, it is necessary to consider the effect of vibration on the soil base, especially if its base is composed of sandy soils, because this effect leads to the phenomena known in the literature [1-7] as vibration creep and soil thinning. These phenomena are characterized by a decrease in the strength of the base soils, increasing their compressibility and consequently cause cracks and damage to structural units when exceeding the limit of their strength from a combination of static and dynamic loads. Or they can lead to stoppage or damage of the technical equipment as a result of the offset alignment due to the difference in the yielding of the foundations of the equipment involved in one technical process. In addition to the frequency and amplitude of forced oscillations of the equipment, the vibration level is also affected by the type and size of the foundations, as well as the frequency of natural oscillations of structures and their elements and the presence of dampers. Thus, during designing, it is quite difficult to calculate the operational and non-standard parameters of oscillations of the foundations of dynamic equipment. Therefore, it is recommended to clarify these parameters, as well as post-commissioning monitoring.

3. Review of the latest research sources and publications
In modern research [1 - 2], there are mainly three phases of deformation of the base depending on the dynamics of the deformation of the soil base exposed to vibration loads. Phase 1, as a rule, occurs at relatively small static and dynamic loads, subsidence of the base in it occurs due to the reduction of soil porosity. Phase 2 is characterized by the development of significant plastic deformations in the soil mass which have a slight tendency to attenuate during the entire period of dynamic loads and almost instantly stabilize after their removal [3 - 7]. This subsidence mainly occurs in sandy (including after reaching their maximum density) water-saturated soils, but under certain conditions can occur in non-water-saturated sands and even in clay soils. Phase 3 is characterized as destructive without a tendency to stabilize. The loss of stability of the foundation occurs at a high rate, the soil in this case is considered by researchers as a viscous medium, and the phenomenon itself is called soil thinning [8 - 11].

4. Problem statement
Summing up the above initial data during the construction of a new production workshop of an industrial enterprise, the question arose of the possible adverse impact of technological equipment on the performance of the foundations of the equipment, as well as on the performance of foundations of the workshop under construction, given that there is the need for sand pillows under some foundations of the building as well as under the foundations of dynamic equipment. The purpose of the research is to measure the actual oscillations of the structures of dynamic equipment, their foundations and the foundations of the new workshop in order to determine the possible occurrence of additional to the design stabilized or unstabilized deformations of the soil base in the zone of dynamic influences.

5. Basic material and results
Studies of the parameters of dynamic oscillations were conducted on the production site of the existing yacht and boat manufacturing enterprise in the Kharkiv region. Since this type of production involves the use of polyester resins, other volatile substances and welding, the building was equipped with powerful ventilation systems that are driven by powerful industrial radial fans.

The building of the new production unit has a total size of 78.0 x 36.0 m. The objects of research are powerful radial fans placed along the rear facade of the building are installed on their own foundations (see Figure 1).
During the design of this building while performing engineering-geological surveys, the following engineering-geological elements were installed:

- engineering geological element EGE 1 - bulk soils are represented by loams with admixtures of construction and household waste from 10% to 20%, non-sedimentary. Layer thickness is 0.5-2.6 m;
- engineering geological element EGE 2 - soil-vegetation layer - loams with admixtures of plant remains. Layer thickness is 0.6-0.8 m;
- engineering geological element EGE 3 - semi-hard, soft-plastic, subsidence loams. Layer thickness is 3-3.2 m;
- engineering geological element EGE 4 - semi-hard, soft-plastic loams.

Groundwater at the search area as of August was not recorded to a depth of 7.0 m.

For the physico-mechanical characteristics of the base soils see Table 1.

EGE 3 was chosen as the bearing EGE for the foundations of the production building, and the foundations for radial fans were made according to the shallow structural scheme on a sand pillow (see Figure 2).

![Figure 1. Layout of the ventilation systems along the front 1–14.](image)

![Figure 2. Installation of workshop foundations and radial fans on the engineering geological section of the construction site.](image)

A set of equipment consisting of a VIP-2 vibrometer with a D21A displacement sensor and an Oscill digital oscilloscope connected to the vibrometer for spectral and visual analysis of oscillations,
as well as for recording the oscillogram was used to determine the oscillation parameters. While performing the measurements, the parameters of oscillations along all 3 main axes of the orthogonal coordinate system were recorded. The Z axis was taken as vertical to the earth surface, and the X and Y axes form the conditional plane of the earth surface. Therefore, when indicating the direction of vibration measurement below, these assumptions should be kept in mind.

While performing the measurements, the following oscillation parameters were set: the amplitude of the forced oscillations of the support part of the fan (above the dampers) in the orthogonal directions X, Y and Z, the amplitude of the forced oscillations of the foundation in the orthogonal directions X, Y and Z, spectral analysis of oscillations with determination of their prevailing frequencies and determination of possible transmission of oscillations on the foundations and workshop structure.

During the development of the Heating and ventilation section of the project for the construction of a new production building, standard solutions proposed by the manufacturer of dynamic equipment were used, such as schemes of support of ventilation system elements on the foundation, installation and nomenclature of damping gaskets, placement of embedded parts, etc. Separately, metal frames were developed to support the exhaust pipes, which rest on the same slab foundations as the radial fans. All these structures are interconnected by pipelines and are in some interaction.

**Table 1.** Physico-mechanical characteristics of the base soils.

| Engineering-geological elements (EGE) according to GOST 25100-95 | Specific weight of soil, kN/m³ | Specific adhesion, kPa | The angle of internal friction, degree | Estimated modulus, E (MPa) | Estimated resistance, R₀ (kPa) |
|---|---|---|---|---|---|
| Bulk soil with admixtures of construction and household waste, loose | 15.2 | 12.1 | - | - | - | - | - | 100 |
| Soil and vegetation layer - loams with admixtures of plant remains | 18.3 | 16.2 | - | - | - | - | - | 100 |
| Semi-hard, soft-plastic, sagging loams | 26.7 | 18.9 | 14.9 | 0.02 | - | - | 17 | 16 | 14 | 10 | 110 |
| Semi-hard, soft-plastic loams | 26.7 | 19.2 | 15.1 | 0.02 | - | - | 18 | 17 | 16 | 14 | - |

When determining the amplitudes of oscillations, the reference values were the readings of the scale of the device VIP-2. The calibration was performed for this device by the state enterprise “Kharkivstandartmetrologiya”.

The operating frequency range of the device (with guaranteed constant error) is from 10 to 1000 Hz. The range of vibration velocity measurement is from 0.1 to 100 mm/s, vibration of oscillations – from 2 to 1000 μm.

The main element of the vibrometer is a vibration transducer which perceives mechanical oscillations and, by converting them into electrical signals, transfers them to the input of the measuring device.

The measuring device is made as a separate unit, on the front panel of which there are operating mode switches, the input “Vibrator Inverter” for connecting a vibration transducer and the OUT
connector for connecting an oscilloscope. The measurement of oscillation parameters is performed using an analog scale with an arrow, the maximum deviation of which corresponds to the maximum value of the set measurement limit using the “Measurement Range” switch. Switching of vibration of oscillations and vibration acceleration modes is performed using the “Measurement Type” switch. When the oscilloscope is connected, it is possible to control the frequency for which the amplitude is measured, as well as to perform spectral analysis of oscillations to determine the predominant frequency and, if available, secondary harmonics. And if the scale of the oscilloscope is calibrated on the scale of the vibrometer, it is possible to perceive and analyze information on the magnitude of the amplitude of oscillations directly from its screen (see Figure 3).

Thus, it was determined that the maximum deviation of the arrow of the analog scale of the device in any mode of the switch “Measurement Range”, when measuring the amplitude of oscillations, corresponds to the interval from -2 V to +2 V on the oscilloscope screen. Therefore, when adjusting the oscilloscope to work with the VIP-2 vibrometer, its sensitivity is set to a maximum of 2 V, which corresponds to the maximum of the selected measurement limit. Intermediate values, respectively, can be determined by interpolation.

**Figure 3.** General view of the VIP-2 vibrometer.

When determining the oscillation parameters of the fan design, the vibrometer sensor was mounted on a frame rigidly attached to the fan, and when determining the oscillations of the foundations of this equipment – to the metal support slides welded to the embedded parts of the foundations (below complete rubber dampers) (see Figure 4). Therefore, we further consider the parameters of forced oscillations determined during the research.

**Figure 4.** General view of the research area.
During the research it was found that the maximum vibration of oscillations of oscillations registered by the VIP-2 device is 30 μm (corresponding to the amplitude of 15 μm), so the switch of the measurement limit was set to 30 μm. Accordingly, the indicators displayed on the oscilloscope screen were calibrated, namely: the set limit of vibration of oscillations measurements on the vibrometer 30 μm corresponds to the value of ±2.0 V on the oscilloscope screen. The division value on the oscilloscope screen in voltage units is 0.5 V, so the division value in amplitude units is:

\[
\text{Div. value} = \frac{30(\mu m) \cdot 0.5(V/\text{div.})}{4(V)} = 3.75(\mu m/\text{div.}),
\]

First, the parameters of the forced oscillations of the support part of the radial fan, on which it is rigidly fixed and connected to the design of pipelines, were measured to determine the initial parameters of forced oscillations that occur during its operation in stationary mode (see Figures 5 - 7).

**Figure 5.** Oscillogram of oscillations of the support part along the Z axis. (the division value along the Y axis = 3.75 μm, along the X axis = 0.2 s).

**Figure 6.** Oscillogram of oscillations of the support part along the X axis. (the division value along the Y axis = 3.75 μm, along the X axis = 0.2 s).

**Figure 7.** Oscillogram of oscillations of the support part along the Y axis. (the division value along the Y axis = 3.75 μm, along the X axis = 0.2 s).
Thus, the following was determined: the maximum amplitude of oscillations is 15 μm (corresponds to the vibration of oscillations equal to 30 μm) and is registered in the vertical direction to the earth's surface Z. In the horizontal directions X and Y, the measured amplitude was ~ 2 times smaller, about 7 μm.

To assess the contribution of the fundamental frequency of forced oscillations from radial fans and determine the natural frequency of the entire structure of the ventilation system, as well as its impact on the overall picture of oscillations of all structures combined into a single complex spatial system, spectral analysis of oscillations in the Z direction, the worst in terms of the magnitude of the amplitude of oscillations, was performed, with the installation of a vibration transducer on the fan frame above the damper inserts. The engine speed according to the passport data is 1450 rpm. The radial fan itself is driven by the engine by means of a belt drive with a coefficient of speed reduction equal to 2. The spectrogram (see Figure 8) visualizes two main peaks: at a frequency of ~ 12 Hz and 24 Hz, which are the frequencies of forced oscillations of the radial fan and its motor, respectively. The third small peak at a frequency of 17 Hz most likely corresponds to the frequency of natural oscillations of the entire ventilation structure.

![Figure 8. Spectrogram of oscillations of the support part.](image)

To evaluate the efficiency of rubber spacers, as well as the damping effect of the foundation massif and soil base, the following measurements of similar parameters of forced oscillations below the rubber dampers were performed by placing the D21A vibration transducer on steel slides rigidly welded to the embedded structures in the foundation slab (see Figure 9).

![Figure 9. Oscillogram of oscillations of the foundation along the Z axis. (the division value along the Y axis = 3.75 μm, along the X axis = 0.2 s).](image)
During measurement of the parameters of the foundation oscillations, the following was established: due to the damping properties of the inventory rubber spacers and the foundation massif, the amplitude of forced oscillations is reduced by almost 2-3 times to 7-5 μm. In this case, any significant values of the amplitudes are registered only in the Z direction. In the X and Y directions, vibrations are almost completely absent and are not recorded by the device. The spectrogram of oscillations in this case shows a corresponding decrease in peaks at fundamental frequencies and almost does not affect the magnitude of the amplitude at the assumed natural frequency of ~ 17 Hz, which confirms the previous conclusions in this regard (see Figure 10).

![Figure 10. Spectrogram of foundation oscillations.](image)

The study of possible transmission of oscillations to the foundations of the building did not show the occurrence of any vibrations on their surface due to good damping properties of the selected structure of the foundations and the base in the form of vibration damping sand pillow, as well as rather small dynamic forces compared to the building massif. According to studies [7] under the action of dynamic loads with an amplitude of oscillations of 10 - 15 μm on an artificial sand base with layer-by-layer compaction to the standard value of skeletal density $\gamma_d = 1.65 \text{t/m}^3$, which corresponds to the conditions at this site, additional subsidence may occur typical for Phase 1 or Phase 2. That is, with the rapid stabilization of deformations after compaction of the sand base, or with long-term deformations, the development of which is approximated by the logarithmic law.

6. Conclusions
The study of the parameters of forced oscillations of structures and foundations of the ventilation system of a new production building for yachts and boats in Kharkiv region demonstrates that determining the parameters of forced oscillations of complex engineering and geometric systems by analytical methods is often impossible or unreasonably time consuming. Given the potential risks to foundations and associated above-ground structures, provided they are laid on sandy natural or artificial foundations, this issue cannot be ignored. In this case, it is considered most rational to take all available measures to reduce the possible negative impact of vibration, such as balancing rotating and moving parts, installation of dampers between structures and foundations, and, if necessary, installation of anti-vibration screens in the soil mass to prevent vibration on the foundations of neighboring buildings.

In the framework of this study, it was found that the parameters of forced oscillations in the stationary mode of operation of the studied dynamic equipment are within safe limits for this type of basis. It should also be noted that the transmission of vibrations to the foundations of the building does not occur.

However, from time to time the condition of inventory factory dampers should be monitored, due to the deterioration of the properties of which the change in the dynamic mode of operation of the foundations in the direction of deterioration of their performance can occur.
References

[1] Savinov O A 1979 Modern Structures of Foundations for Machines and Their Calculation (Leningrad: Stroyizdat) p 200

[2] Kudryavtsev I A 1999 The Effect of Vibration on the Foundations of Structures (Gomel: Belarusian State University of Transport) p 200

[3] Vynnykov Yu L 2009 Influence of Vibration Regime of Rollers on Compaction of Low Cohesive Overburden Industrial Machine Building, Civil Engineering vol 25, ed S F Pichugin et al (Poltava: National University “Yuri Kondratyuk Poltava Polytechnic”) pp 40–49

[4] Sawicki A and Mierczyński J 2015 Some Effects of Intrinsic Cyclic Loading in Saturated Sands Journal of theoretical and applied mechanics vol 53, ed W Kurnik et al (Warszawa: JTAM) pp 285–293

[5] Sawicki A, Mierczyński J and Sławińska J 2015 Structure and Calibration of Constitutive Equations for Granular Soils Studia Geotechnica et Mechanica vol 36, ed A Różański et al (Warszawa: De Gruyter) pp 35–46

[6] Aleksandrovych V A, Taranov V G, Luchkovskyi I I, Plaschev S A, Kornienko N V, Areshkovych O O 2013 Structure-Soil Massif System Behavior Features Under Static and Dynamic Loads Proc. of the 18th Intern. Conf. on Soil Mechanics and Geotechnical Engineering (Paris) vol 2, ed P Delage at al (Paris: Presses des Ponts) pp 1627–29

[7] Aleksandrovych V A 2012 Concerning the Vibrocreep Issue Proc. of the 22nd European Young Geotechnical Engineers Conf. (Gothenburg) vol 1, ed V Svahn and T Wood (Gothenburg: Chalmers University of Technology) pp 173–178

[8] Lange D and Fanourakis G 2009 Comparing Vibratory and Impact Laboratory Compaction Methods Proc. of 17th Intern. Conf. on Soil Mechanics and Geotechnical Engineering (Alexandria) vol 1, ed M Hamza (Amsterdam: IOS Press) pp 93–96

[9] Kim S I, Park K B, Park S Y, Hwang S J, Lee J H and Choi J S 2005 Effects of Irregular Dynamic Loads on Soil Liquefaction Proc. of the 16th Intern. Conf. on Soil Mechanics and Geotechnical Engineering (Osaka) vol 4, (Amsterdam: IOS Press) pp 2673–76

[10] Areshkovych O, Boyko I and Sakharov V 2011 Determination of the Stress Strain State of Soil Base for the Structures at Static and Dynamic Loads Proc. of the 15th Europ. Conf. on Soil Mechanics and Geotechnical Engineering (Athens) vol 2, ed A Anagnostopoulos (Amsterdam: IOS Press) pp 1225–30