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Impact of metro induced ground-borne vibration on urban development

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Abstract. Metro trains are a source of increased noise and vibration, whose negative impact on residential development and production processes can lead to a deterioration in the quality of life or products. Fluctuations from metro trains spread with a certain frequency, depending on the operating train quantity. The level of recorded fluctuations depends mainly on the geological structure of the site, the depth of the line, and the distance to the observer. Instrumental study of the vibration levels on the ground surface is of practical interest in terms of assessing the impact of vibration on the projected buildings or structures, as well as scientific interest in terms of analyzing the spectrum of RMS values of vibration accelerations for each octave band on the ground surface. A four-channel vibrometer was used to measure the levels of vibrations in the overpass between the Belomorskaya and Khovrino stations on the Zamoskvoretskaya line of the Moscow metro, and then the frequency spectra were analyzed. The conclusion is made that the impact at the rail junction significantly contributes to the overall vibration load when the train enters the station, which is confirmed by a sharp increase in vibration levels at the corresponding observation points. The calculation of the natural vibration forms of the tunnel fragment is performed. Analysis of the measurements showed that a moving train excites vibrations in all octave bands, but the maximum levels of vibration acceleration were registered in octaves 16, 31.5 and 63 Hz. This is consistent with the results of the numerical simulation since the calculated natural vibration frequencies of the tunnel fragment are close to those measured on the ground surface.

1. Introduction

There has been an increase in new construction in large cities in recent years and, as a result, the intensive development of the transport network. The metro is the only modern mode of transport, the route of which can be laid regardless of the existing buildings on the surface. As a result, it is necessary to take into account the impact of noise and vibration acting on buildings and structures located within the sanitary zone of the subway (40–45 m from the outer walls of the tunnel), both from the movement of trains in its normal operation [1], so and from the sinking shields during the construction of the line [2] at the design stage. The object of research in this work is the rolling stock of the metro in a tunnel of shallow laying, located in the middle of urban development. The subject of the study, respectively, is the vibrations registered on the ground surface.

Vibration transmitted to building structures can worsen the quality of life of people [3, 4], as well as affect sensitive technological processes in modern production. [5, 6], for example, special electron microscopes, which are equipped with some research centers, are sensitive to the vibration amplitudes of the foundation less than 1 μm [5, 6]. It is also necessary to consider that the Central part of large cities mostly consists of cultural heritage sites. In some cases, the subway lines in close (less than two meters) from the foundations of the architectural monuments, which can adversely affect its technical condition

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without special measures [2, 7–10]. In connection with the above, there is an important and actual scientific and technical problem of measurement, analysis of experimental data and subsequent minimization of the impact of increased structural noise and vibration on people and buildings [7–15]. The purpose of this work is to study the vibration background on the ground surface near residential buildings above the new metro line of shallow Foundation. To achieve this goal the following tasks were completed:

1. Long-term vibration measurements were made using a special device at various points above the crossing and the station.

2. The files recorded by the device are processed and converted into visual graphs – vibration acceleration spectra.

3. The data obtained were analyzed and compared with current national and foreign sanitary standards.

4. Numerical modeling of a tunnel fragment was carried out to determine its own vibration modes.

2. Methods

The dynamic load from the moving subway trains is characterized by its discreteness, i.e. at the studied point, the registration of vibration accelerations is possible only for about 10 seconds, which corresponds to the time of the train passing through the measurement range. Further fluctuations almost instantly fade up to the moment of the beginning of passing of the next train [16]. This process – 10 seconds of increased vibration and noise and a subsequent break for 1.5–2 minutes – continues every day for 22 hours. Therefore, the only way to measure vibration levels, which allows the most complete analysis of the vibration background – spectral method [12, 13], without any averaging for 30 minutes of movement. The reliable average maximum of vibration accelerations is determined from the analysis of the full spectrum of the maximum number of trains.

Measuring oscillations of the surface of the soil was performed by a four-channel vibration meter SVAN 958. The device is designed for multi-channel measurement of vibration and noise. Three channels were used, the sensitive elements of which were in three perpendicular directions for registration:

- Vertical oscillations along the Z axis;
- Horizontal oscillations along the subway line (along the X-axis);
- Horizontal oscillations across the subway line (along the Y-axis).

During the experiment, 5 points along the route between the stations Belomorskaya and Khovrino of the Zamoskvoretskaya line of the Moscow metro were examined (Fig. 1). All measurements have a duration of at least 12 minutes for the collection of reliable data and their subsequent analysis. The average interval of train traffic during the study ranged from one to one and a half minutes.

Point number 1 is located above the station Belomorskaya, point number 2, 3, 4 – directly above the overtake, and point number 5 – above the station Khovrino.

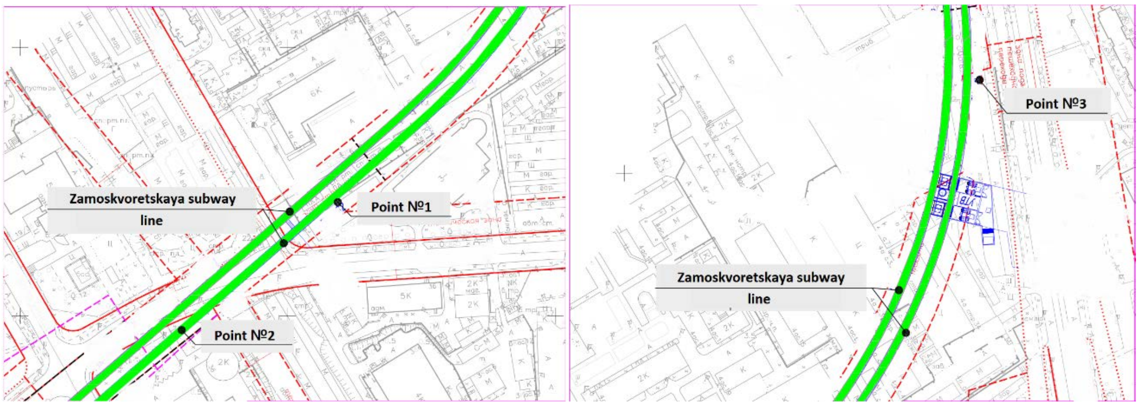

Figure 1. Schemes of location of measurement points No. 1, 2, 3 on topographic survey.

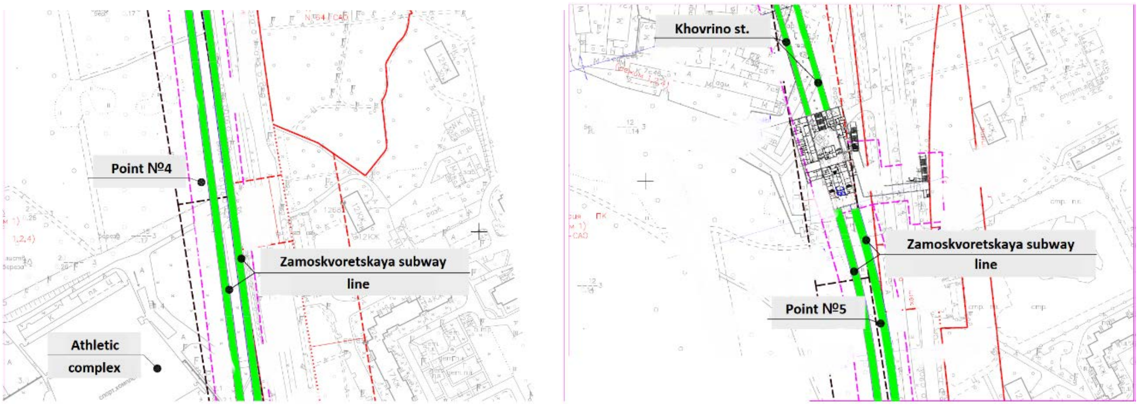

Figure 2. Schemes of location of points No. 4, 5 on topographic survey.

3. Results and Discussion

The device was used to register the vibration accelerations recorded the data separately on three channels into a special file, which was then converted into a graphical form using Svantek PC++ software (Fig. 3–8). The graphs show the vertical and horizontal components of vibration accelerations for different octave bands (4 Hz, 8 Hz, 16 Hz, 31.5 Hz, 63 Hz).

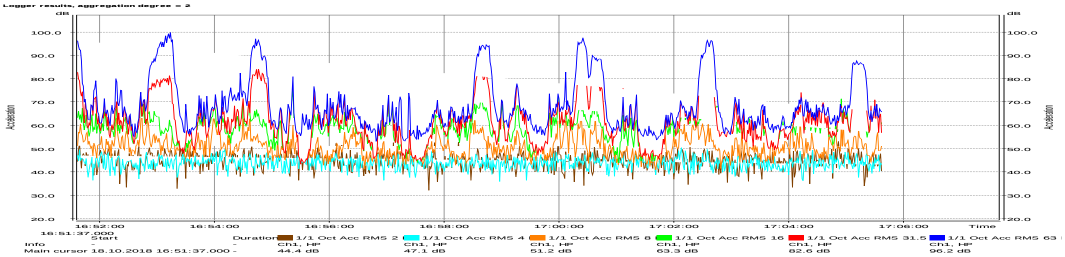

Figure 3. Point No. 1. Vertical component of vibration accelerations (z-axis).

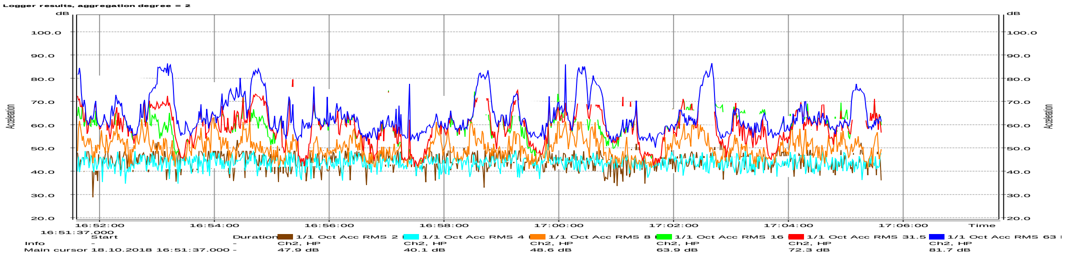

Figure 4. Point No. 1. Horizontal component of vibration accelerations (x-axis).

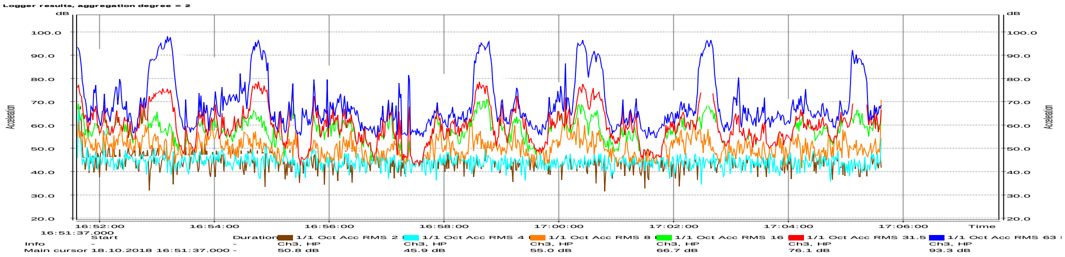

Figure 5. Point No. 1. Horizontal component of vibration accelerations (y-axis).

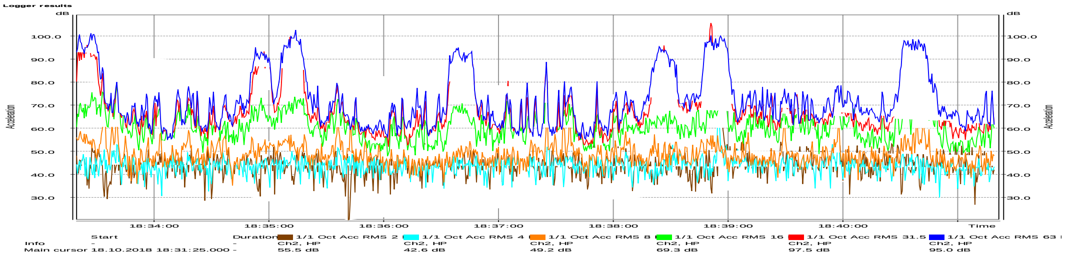

Figure 6. Point No. 5. Vertical component of vibration accelerations (z-axis).

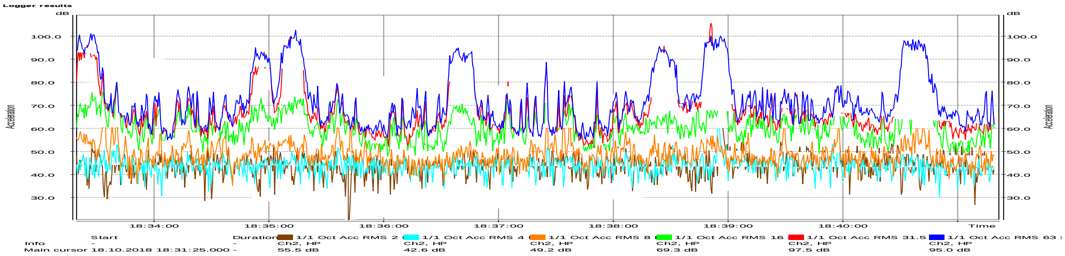

Figure 7. Point No. 5. Horizontal component of vibration accelerations (x-axis).

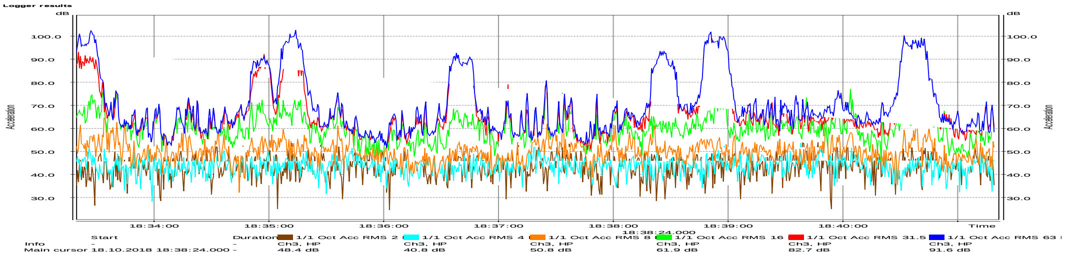

Figure 8. Point No. 5. Horizontal component of vibration accelerations (y-axis).

The study of graphs allows to select and tabulate the average maximum values of the recorded levels of acceleration in these octave bands (Table 1).

Table 1. Maximum levels of vibration acceleration.

		Vibration acceleration levels (dB) in (1/1) octave bands					
		2 Hz	4 Hz	8 Hz	16 Hz	31.5 Hz	63 Hz
Measurement point No.	Direction	Value	Value	Value	Value	Value	Value
1	Z	51.5	44.8	59.3	71.2	83.9	100.8
	X	47.6	48.0	62.9	75.3	78.2	86.5
	Y	54.6	44.9	57.1	69.2	77.6	97.5
2	Z	50.4	47.8	52.6	67.1	78.2	75.3
	X	47.9	47.0	58.9	68.3	73.2	86.0
	Y	53.7	50.1	52.5	58.1	75.6	82.4
3	Z	50.7	44.7	57.2	65.4	85.0	81.3
	X	47.7	49.0	59.6	66.9	83.7	84.8
	Y	47.3	47.8	61.1	67.6	89.4	85.1
4	Z	53.1	47.9	53.5	57.9	88.0	87.6
	X	45.9	48.4	58.9	65.5	88.5	99.8
	Y	48.6	50.4	55.5	63.9	90.4	96.4
5	Z	48.2	48.2	57.6	69.2	83.4	93.7
	X	50.0	45.8	56.8	68.8	95.3	98.0
	Y	50.9	51.4	54.7	71.9	92.2	99.1
Maximum	Z	53.1	48.2	59.3	71.2	88.0	100.8
	X	50.0	49.0	62.9	75.3	95.3	99.8
	Y	54.6	51.4	61.1	71.9	92.2	99.1

The values shown in the Table are the average values of the highest vibration levels for all measurements, determined by analyzing the spectrum of RMS values of vibration accelerations for each octave band on the ground surface using the following formula:

$$L_{\mathrm{dB}} = 20\lg {a \big/ a_0}, \mathrm{dB} \qquad (1)$$

From these spectra it is possible to distinguish the dominant frequencies of external influence, as well as to understand the nature of attenuation depending on the distance to the source. The method of frequency analysis is suitable for determining the influence of metro trains on a structure, since it can be used to select the average maximum of the mean square values of vibration accelerations from the entire ensemble of measurements during the passage of one train [9]. The train interval is not considered. This approach is adopted in most States as the main [13, 17], as it allows to assess the greatest negative effect of vibration on people and buildings, taking into account the discrete nature of the impact and guided by the principle of "no significant concern" (Sanitary code of Russian Federation, p. 3.2).

After analyzing the spectra obtained as a result of measurements within the framework of the task, it can be concluded that vibration acceleration recorded on the surface of the soil (these values in octaves of 31.5 and 63 Hz are highlighted in the tables) can cause exceeding the normalized vibration parameters in the designed buildings, the construction of which is planned in close proximity to the existing or projected sections of the subway route. The spectra analysis also showed that the vibration acceleration levels at points 1 and 5 are higher than at other surveyed points, which can serve as a confirmation of the contribution to the overall vibration load from a moving train of a wheel impact at the inevitable "parted" junction of the rails at the station at the entrance and exit of the train [16].

For completeness, the study should consider ways to assess the levels of vibration acceleration, presented in international, as well as some foreign regulatory documents, namely, the interstate standard ISO 2631 and the recommendations of the US Department of transportation.

The ISO 2631 document, developed by the international organization for standardization, establishes a methodology for calculating parameters that, applicable to national legislation, determine the permissibility of vibration values, as well as the degree of impact of vibration on human health using health criteria, comfort level, sensitivity to vibration and susceptibility to motion sickness.

The main measured value in the document is vibration acceleration, the formula for calculating the RMS value of which has the form:

$$a_w = \left[\frac{1}{T} \int_0^T a_w^2(t)\, dt \right]^{1/2}, \ \text{м}/\text{c}^2. \tag{2}$$

It is assumed that the human body is affected by the average (smoothed) vibration. It should be noted that the calculation uses a weighted value of vibration acceleration obtained from the entire set of measured data [18]. It should be noted that ISO 2631 does not contain limit values for the defined vibration parameters, but only provides methods for calculating them for further comparison with existing national hygiene regulations, which may set appropriate limits for different conditions and different types of vibration.

The recommendations of the US Department of transportation (USDT recommendations) define the frequency (spectral) method as the main approach to assessing the impact of vibration on a person, calculating logarithmic levels of vibration speeds as follows:

$$v_{\text{dB}} = 20 \lg \frac{v_{rms}}{5 \times 10^{-8}}, \tag{3}$$

where v_{rms} is the mean square values of the vibration velocity, and the denominator is the reference value of the vibration velocity.

In addition, the recommendations use the concept of PPV (peak particle velocity) – the maximum vibrational speed, that is, the maximum instantaneous positive or negative value of the vibration velocity. This value is often used to analyze the effects of explosive impacts.

For residential buildings with so-called "frequent events" (more than 70 "events" of vibration from a single source per day), USDT recommendations set the maximum value of the vibration level at 72 dB.

The Russian Federation sanitary code set logarithmic levels of vibration velocity L_v and vibration acceleration L_a as normalized parameters, which can be calculated using the following expressions:

$$L_v = 20 \lg \frac{v}{5 \times 10^{-8}}, \tag{4}$$

$$L_a = 20 \lg \frac{a}{1 \times 10^{-6}}, \tag{5}$$

where the numerators of formulas (4) and (5) contain, respectively, the root mean square value of vibration velocity, m/s and RMS acceleration, m/s^2; in the denominators of the recorded reference value of vibration velocity, m/s acceleration m/s^2.

The total vibration is considered as an octave or 1/3 octave bands with average geometric frequencies from 0.8 Hz to 80 Hz. The main difference between the method used in the codes of the Russian Federation and the United States from the ISO standard is the fact that no weighing is applied to the measured signal [18].

It should be also noted that there is a common approach to assessing the impact of vibration on a person or building structures in applicable legislation of the Russian Federation and the United States.

In the scientific literature, various methods of modeling the static and dynamic behavior of the tunnel under the action of the load from the movement of metro trains are considered, which allows us to consider the problem from different sides. For example, in [19] to assess the effect of the speed of movement of the point load from the wheel pairs of cars on the levels of induced vibrations, the tunnel is represented as a beam of constant cross-section on an elastic-viscous base. The train speed was consistently assumed to be 10, 20, and 30 m/s. The resulting calculations the highest levels of vibration velocity and vibration acceleration of tunnel meet train speed of 30 m/s. For the maximum speed of trains on the railway haul, usually not more than 80 km/h (22.2 m/s), calculated vibration level of the surface of the tunnel is 62 dB. Actual measurements of vibration on the ground surface, although performed under different conditions, differ in a large way by an average of 30 %, and with increasing distance from the observer, as is known, vibrations in the ground fade. Thus, the representation of the tunnel as a beam on an elastic-viscous base, loaded with concentrated forces from the wheel pairs of cars, allows only preliminary estimation of the vibration levels of the tunnel lining with some error.

In M.A. Dashevsky's doctoral thesis, a wide range of problems related to the radiation of waves in the ground (elastic–viscous half-space) during the movement of a pulsating load of the metro type in a cylindrical shell (tunnel) is considered. In [20] is published a solution of the problem in a flat statement about the radiation of vibrations by a circular tunnel from moving metro trains. The tunnel is represented as a cavity soldered into an elastic semi-infinite plane, and the load is modeled by periodic averaged forces that change according to the harmonic law. The results of calculations are qualitatively consistent with full-scale experiments. In [21], numerical modeling is used to consider the propagation of vibrations in the ground mass from impacts when damaged wheels and rails interact with defects of various types, including the joint of rails with a break. Rolling stock, rail support and ballast are modeled as a complex interacting multi-mass system located on an elastic base. To verify the model, measurements were made of ground surface vibration from a passing train at 12 m from the track. It is shown that any connection of rails with artificial irregularities during the passage of the train leads to an abrupt increase in the levels of vibration acceleration.

As part of this study, the MSC Patran/Nastran software package performed a numerical calculation of a tunnel fragment in a ground environment to determine its own vibration patterns. The tunnel is modeled by beam end elements with a variable thickness and a constant width of 1 m. the Thickness in the upper part of the tunnel is 0.3 m, and a local thickening is created in the lower part to represent the tray. The soil is modeled using elastic elements located along the contour of the tunnel (the modulus of elasticity is set to 25 MPa).

When performing the calculation to determine the natural frequencies of vibrations, the tunnel structures were modeled using generalized beam finite elements that allow for shear to be considered, that is, they correspond to Timoshenko rods. The tunnel diameter is 6 m. Each of the finite elements of the tunnel is adjacent to the finite element of finite stiffness, which simulates the elastic properties of the subgrade. The tunnel thickness is assumed to be 300 mm. The stiffness of each of the finite elements that simulate the soil surrounding the tunnel is determined based on the average stiffness of the subgrade of 25 MPa. The width of the finite elements of a beam with concrete stiffness parameters is 1 m. The finite elements simulating the elastic properties of the soil are rigidly fixed at their farthest ends from the center of the tunnel, and the other end is connected to the elements simulating the tunnel. That is, in fact, the problem of determining the natural frequencies of vibrations of an elastic ring in an elastic medium is being solved. There are no external loads, additional stiffness and mass from the track concrete is modeled by local thickening of the beam elements within the tunnel element located under the half sleepers.

Fig. 10–11 show the first few variations of the tunnel fragment.

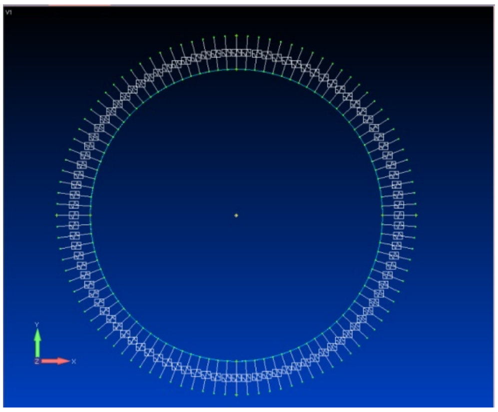

Figure 9. Tunnel design scheme.

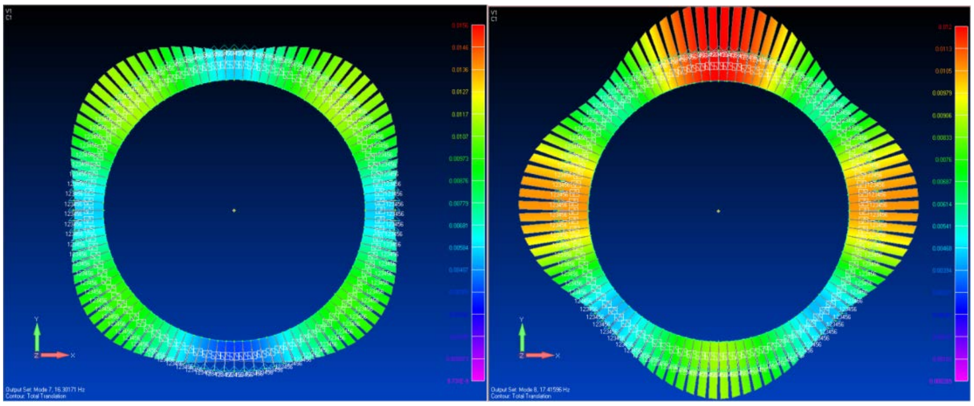

Figure 10. The first (left, frequency 16.3 Hz) and the second (right, frequency 17.4 Hz) forms the vibrations of the tunnel fragment.

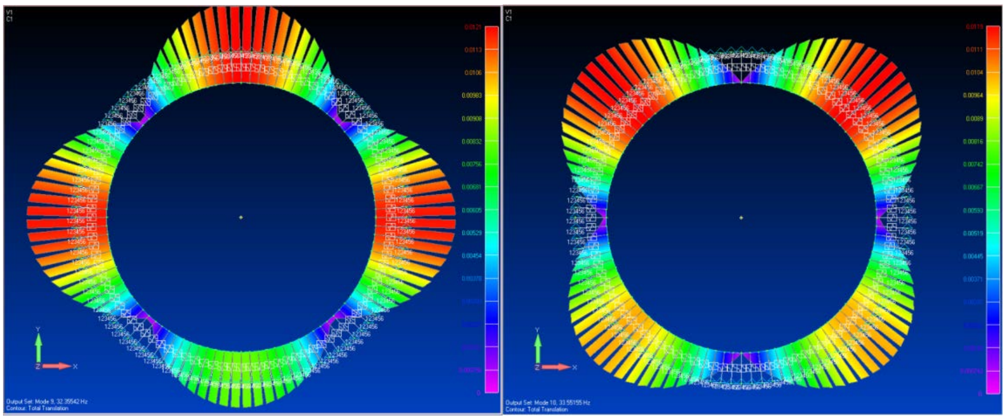

Figure 11. The third (on the left, the frequency of 32.3 Hz) and fourth (right, frequency of 33.5 Hz) mode shapes of the fragment of the tunnel.

The vibration levels of the soil surface obtained during the measurements have characteristic bursts at frequencies in octaves of 16 Hz, 31.5 Hz and 63 Hz, which can be explained, among other things, by the characteristic eigenfrequencies of the tunnel fragments located in the soil massif.

4. Conclusions

The analysis of the results of the measurement of oscillations over the subway track and numerical simulation of the tunnel fragment led to the following conclusions:

- shock at the junction of the rails excites all forms of vibrations, but the predominant are vibrations with frequencies close to 31.5 Hz and 63 Hz;
- bursts at frequencies of 16 Hz, 31.5 Hz and 63 Hz occur also due to the characteristic natural frequencies of the underground tunnel surrounded by the ground;

- the vibration levels measured in octaves 31.5 and 63 Hz, significantly exceeds the allowable by Sanitary code of the Russian Federation. To account for floor resonances, 3.5 dB should be added to vibration levels.
- when determining the need for the device of vibration protection systems, it is necessary to use a spectral method based on the assessment of the expected vibration levels in individual octave bands, since it allows to determine the "response" of individual structural elements to the vibration effect at a certain frequency.

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