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Analysis of Ground Vibrations Caused by the Shallow Subway

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Abstract. The article presents an analysis of the results of vibration accelerations measurements on the surface of the ground above the shallow subway line. Amplitudes of vibration accelerations, obtained with the help of special equipment, can be used at the design stage of buildings and structures for the prediction of vibration levels in residential premises or production facilities. The data was carried out in the area between the stations "Belomorskaya" and "Khovrino" of Zamoskvoretskaya line of the Moscow metro. The process of attenuation of oscillations with increasing distance to the radiation source is considered, a graph of changes in the levels of vibration accelerations for several points within the sanitary protection zone of the subway is given. Numerical simulation of a fragment of a tunnel in the ground is done to define its natural modes of vibration. Conclusions are drawn about the origin of bursts in the vibration spectra in some octave bands at the time of passing the train.

1. Introduction

In the conditions of intensive development of urban areas, designers face a very difficult task of competent placement of new buildings and structures among the existing buildings and the existing transport infrastructure. Also, the compaction of the urban environment leads to the need for reconstruction of entire neighbourhoods, and, consequently, the ways of communication between them. One of the most attractive means of transportation in this regard is the subway, since its construction is possible in a relatively unoccupied space – underground. Like any mechanism, the underground emits vibrations during operation [1-3], propagating in the complex structure of the soil layers. Depending on the relative location of engineering-geological elements, their thickness and characteristics, the depth of the tunnel and many other factors produced by moving trains noise and vibration can be very adverse factors affecting located within the sanitary protection zones of the subway residential buildings [4-7] or sensitive devices, for example, medical equipment or some high-tech production [8-10]. It is known that special electron microscopes cannot provide the required accuracy of measurements under the influence of oscillations with very small amplitudes of the order of 1 µm. Rather strict requirements to the vibration background should also be made in the vicinity of cultural heritage sites, the materials of which (in particular, preserved paintings, frescoes, lime plaster, etc.) may suffer as a result of exceeding the level of fluctuations from nearby transport lines. In accordance with the above, an important research challenge is the analysis of vibration measurements of the background near buildings and structures, development of methods for the assessment of the impact of the projected tracks of the subway on the
surrounding buildings, their verification (comparison of theory with experimental data on existing lines with known geological structure of the site), as well as the creation and testing of means of protection from excessive structural noise and vibrations [11-17].

2. Analysis of the vibration measurement of the surface of the soil

The usual speed of a subway train is about 70 km/h or about 20 m/s. Taking into account the length of each car and the number of cars in the composition, it can be calculated that the time of the train passing through the investigated tunnel is on average no more than 10 seconds. Registration of vibration accelerations is possible only in this period, since the oscillatory process almost instantly fades (this is also confirmed by measurements of vibration accelerations directly on the rails [7]). The only method that can characterize the vibration background most correctly for the case of periodic bursts of vibration over a long period of time (the period of train movement per day on average 1.5-2 minutes) is the spectral method [15, 16]. A reliable average maximum of vibration acceleration should be determined from the analysis of the full spectrum of vibration for a sufficiently long time (usually 10-20 minutes) at each point.

For registering vibrations of the surface of the soil four-channel vibration meter SVAN 958 was used. The device is designed for multi-channel measurements of vibration and noise. The sensors of the vibrometer were arranged in three mutually perpendicular directions for measurement:
- Vertical oscillation along the Z-axis;
- Horizontal oscillation along the route of the tunnel (X-axis);
- Horizontal oscillation across the route of the tunnel (Y-axis).

The experiment involved a survey of five points along the Zamoskvoretskaya metro line of the Moscow metro (in the area of its shallow laying) between the stations "Belomorskaya" and "Khovrino" (Figure 1). Each point contains measurements of at least 12 minutes. The average interval of trains was one and a half minutes.

Figures 1 and 2 show fragments of the topographic survey of the district Khovrino with a plotted route of the metro and the designated measurement points. Point number 1 is located directly above the station Belomorskaya, point number 2, 3, 4 – over the station-to-station block, and point number 5 – over the station Khovrino.

Figure 1. Location of measurement points №1, 2, 3
Vibrometer SVAN 958 was used in three-channel mode and recorded data separately for each channel in a special file. Graphical interpretation of the obtained data can be performed by Svantek PC++ software.

**Changing vibration levels with increasing distance to the emission source**

Given the constant compaction of urban development, in construction practice there are situations when the projected building is located within the sanitary protection zone of the subway (about 40 m from the axis of the tunnel). Having data on amplitudes of vibration accelerations at any point near the tunnel and characteristics of soils, it is possible to estimate attenuation of amplitudes with increasing distance from the center of vibration radiation with the help of the well-known following asymptotic dependence:

$$A_r = A_0 \sqrt{\frac{r_0}{r}} e^{-\alpha(r-r_0)}$$  \hspace{1cm} (1)

where: $A_r$, $A_0$ – the amplitude of the ground vibration at a distance $r$ and $r_0$ from the source; $\alpha$ – the damping coefficient, m$^{-1}$ or cm$^{-1}$.

The damping factor of oscillations depends on the characteristics of the soil. It was established experimentally that for wet sandy clays and loamy sands the values are within 0.03...0.06 m$^{-1}$.

Using the formula (1) the relationship of the amplitudes of vibration accelerations for the four angles of wave propagation was found (0°, 30°, 60°, 71°). The angle of 71° corresponds to the distance from the center of the tunnel about 40 m. The depth of the tunnel center in the considered point is 14 m.

Using the well-known dependence $L_{ab} = 20 \log_{10} \frac{a_{\text{max}}}{a_b}$ vibration acceleration levels at each point of four selected directions within the limits of sanitary protection zone were found. The distance from the center of the tunnel was calculated by the formula $l = l_0 \frac{1}{\cos \theta}$.

where: $l_0$ – the distance from the center of the tunnel to the desired point in increments of 0.5 m vertically, $\cos \theta$ – the cosine of the angle of inclination of the corresponding line.

With the help of formula (1) it is possible to build graphs of changes in vibration acceleration levels for each section and to estimate the need for vibration damping devices in the first approximation.
Stratification of the soil mass is accounted by using the arithmetic mean of the attenuation coefficient in the calculation.

As can be seen from figure 3, at 8 m (which corresponds to the angle of 30°), vibration damping and a decrease in vibration acceleration levels by 1.19 dB are observed. At the border of the sanitary protection zone (40 m from the tunnel axis, 71° from the vertical), the levels of vibration acceleration are reduced by 12.43 dB.

![Figure 3. Changing vibration levels with increasing distance to the emission source](image)

**The definition of own forms of fluctuations of a fragment of the tunnel**

There are quite a few ways to study the static and dynamic stress-strain state of the tunnel under the action of the load from the movement of subway trains. For example, in [19] the tunnel is considered as a beam of constant cross-section on an elastic-viscous basis to assess the effect of the speed of movement of the car in the form of point forces from the wheel pairs on the levels of propagated oscillations. Based on the levels of vibration acceleration and vibration velocity for different modes of repetition made the conclusion about the considerable influence of the speed of passing trains on a vibrating background. In [20] subway cars are presented in the form of a moving pulsating load in a cylindrical shell to solve a wide range of problems related to the radiation of waves in an elastic-viscous half-space.

![Figure 4. Tunnel design scheme](image)

This study involves the determination of the natural vibration frequencies of the tunnel enclosed in the soil massif. In the software package MSC Patran/Nastran was performed a numerical experiment.
consisting in calculating the fragment of the tunnel in a soil medium. The tunnel model consists of beam finite elements with a variable thickness and a constant width of 1 m. In the lower part of the cavity, a local thickening is simulated to imitate a tray. The thickness of most of the ring is set to 0.3 m. The Soil is represented in the model by elastic elements located along the contour of the tunnel (modulus of elasticity – 25 MPa).

**Figure 5.** The first (left, frequency 16.3 Hz) and the second (right, frequency 17.4 Hz) forms the vibrations of the tunnel fragment

**Figure 6.** 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

It is worth noting the characteristic eigenfrequencies of the tunnel oscillations in bands near 16 Hz and 31.5 Hz for further analysis.

3. Results and discussions
The data obtained by vibrometer can be presented in graphical format as it shown in figures 7-12.
Figure 7. Point №1. Vertical component of vibration accelerations (Z-axis)

Figure 8. Point №1. Horizontal component of vibration accelerations (X-axis)
**Figure 9.** Point №1. Horizontal component of vibration accelerations (Y-axis)

**Figure 10.** Point №5. Vertical component of vibration accelerations (Z-axis)
Figure 11. Point №5. Horizontal component of vibration accelerations (X-axis)

Figure 12. Point №5. Horizontal component of vibration accelerations (Y-axis)
By comparing the vibration accelerations with a certain reference value of vibration, with the help of the formula \( L_{dB} = 20 \log_{10} \frac{a_{\text{max}}}{a_0} \), the measurement data can be converted to graphs of the vibration acceleration levels (dB) and then tabulate the average maximum values of the recorded vibration acceleration levels (table 1) for each measurement point.

The data shown in the table are the average values of the maximum vibration levels for the entire number of measurements obtained as a result of the analysis of the spectrum of mean square values of vibration accelerations for each octave band on the ground surface at each of the measurement points.

The study of spectra allows us to identify the predominant frequencies of external influence, as well as to understand the nature of the attenuation depending on the distance to the source.

The only known method of analysing the impact of subway trains on buildings and structures, which allows you to reliably select from the entire set of experimental data the maximum mean square values of vibration accelerations during the movement of one train [13] without taking into account the "period of silence", is a method of frequency analysis. This approach is generally accepted in most States [16, 18], as it makes it possible to assess the impact on people and the surrounding buildings of vibration from the discrete effects of periodically passing trains.

Analysis of the spectra obtained as a result of the experiment allows us to conclude that the vibrations registered on the ground surface (in octaves of 31.5 and 63 Hz – see the values highlighted in table 1) can lead to exceeding the normalized vibration parameters in the buildings planned for construction near the metro line. In addition, it is noted that at points №1 and №5 levels of acceleration is much higher than at points №2, 3, 4. This can serve as a confirmation of the contribution to the overall vibration background from a moving train [5] wheel impact at the junction of the rails at the entrance of the station [7].

| Measurement point No. | Direction | 2 Hz | 4 Hz | 8 Hz | 16 Hz | 31.5 Hz | 63 Hz |
|-----------------------|-----------|------|------|------|-------|---------|------|
| 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 |
|                       | Z         | 50.7 | 44.7 | 57.2 | 65.4  | 85.0    | 81.3 |
| 3                     | X         | 47.7 | 49.0 | 59.6 | 66.9  | 83.7    | 84.8 |
|                       | Y         | 47.3 | 47.8 | 61.7 | 67.6  | 89.4    | 85.1 |
|                       | Z         | 53.1 | 47.9 | 53.5 | 57.9  | 88.0    | 87.6 |
| 4                     | 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 |
|                       | Z         | 48.2 | 48.2 | 57.6 | 69.2  | 83.4    | 93.7 |
| 5                     | 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 |
|                       | Z         | 53.1 | 48.2 | 59.3 | 71.2  | 88.0    | 100.8|
| Max.                  | 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 |
Returning to the obtaining of natural frequencies of tunnel, the presence of characteristic bursts at frequencies in octaves of 16 Hz, 31.5 Hz and 63 Hz can be noticed, which can be explained, among other things, by the characteristic eigenfrequencies of the tunnel fragments located in the soil massif (the result of a numerical experiment).

4. Conclusions
The conducted research within the framework of the task allows us to formulate the following conclusions:

- the shock at the junction of the rails induces all forms of vibrations, but the greatest are vibrations with frequencies close to 31.5 Hz and 63 Hz;
- formation bursts at frequencies of 16 Hz, 31.5 Hz and 63 Hz occur in part because of the characteristic eigenfrequencies of the vibrations of the metro tunnel, the prisoner in elasto-viscous half-space;
- vibration levels measured in octaves of 31.5 and 63 Hz, at points located above the subway track, significantly exceed the permissible sanitary standards of the Russian Federation. To account for the overlap of resonances the vibration levels of the soil, you should add 3.5 dB [6, 16];
- as the distance increases, vibration levels decrease. At 40 m from the central axis of the tunnel there is a decrease in the level of vibration acceleration by 12.43 dB.
- the decision on the need for vibration damping devices should be made using the spectral method based on the assessment of the expected vibration levels in individual octave bands, as it allows to determine the "response" of individual structures to vibration at a given frequency.

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