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INVESTIGATION OF VIBRATION OF THE UNDERGROUND RAILWAY TUNNEL LINING IN CASE OF ELASTIC FASTENING OF THE RAILWAY TRACK

ABSTRACT

The results of experimental investigations of vibration of the underground railway tunnel when lying the railway track on the elastic fastening blocks of the BV2-M grade according to TU BY 100261791.003-2017. Investigation objective: evaluation of the vibration vibration-isolation capacity of the elastic fastening system of a railway track.

The investigations have been performed on the section of the third line of the Minsk Underground Railway being constructed. The dynamic load was applied to the railway track by driving a diesel locomotive at the speed of ≈40 km/h. The diesel locomotive had two two-axle flat wagons with the total weight of 90 and 150 kN.

The efficiency of the vibration isolation of the railway track was evaluated from the vibration level (vibrational accelerations) transmitted to the rail and vibration response occurring in the tray, arch and lateral face of the tunnel lining. The vibrational accelerations were measured in two cross sections of the tunnel, in one of which there was a rail bond joint.

It has been ascertained that the maximum levels of the vibration being transmitted to the rail and vibration response occurring in the tunnel lining structures are fixed in the reference points of the tunnel cross section with the rail bond joint. So the maximum root-mean-square *values of the accelerations being transmitted to the rail in the octave bands with the geometric mean frequency 31.5 Hz and 63 Hz were 130–135 dB that corresponds to the level of the vibration occurring during the run of the typical electric train set. The values of the vibration response accelerations values occurring in the tray and arch as well as at the level of the horizontal diameter of the tunnel lining was less that in similar structures of the first line of the Minsk Underground Railway with ballastless rail track on wooden sleepers by 7–10 dB.*

The fragments of the vibration records (in m/s2) were presented to allow determining the natural frequencies of oscillation of the tunnel lining structures and comparing them with the frequencies of natural oscillations of the slabs of buildings to prevent the resonance vibration.

Keywords: underground railway track, vibration-isolation blocks, vibration tests of the tunnel lining, vibrational accelerations, vibration records, natural frequencies of oscillations.

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ИССЛЕДОВАНИЕ ВИБРАЦИИ ОБДЕЛКИ ТОННЕЛЯ МЕТРОПОЛИТЕНА ПРИ УПРУГОМ КРЕПЛЕНИИ РЕЛЬСОВОГО ПУТИ

АННОТАЦИЯ

Приведены результаты экспериментальных исследований вибрации тоннеля метрополитена при устройстве рельсового пути на блоках упругого крепления марки БВ2-М по ТУ BY 100261791.003-2017. Цель исследований – оценка виброизолирующей способности системы упругого крепления рельсового пути.

Исследования выполнены на строящемся участке третьей линии Минского метрополитена. Динамическая нагрузка на рельсовый путь создавалась путем прогона тепловоза со скоростью ≈40 км/час. Тепловоз имел две двухосные платформы общим весом 90 кН и 150 кН.

Оценку эффективности виброизоляции рельсового пути производили по уровню вибрации (виброускорений), передаваемой на рельс и вибрации-отклика, возникающей в лотке, своде и боковой грани обделки тоннеля. Виброускорения измеряли в двух поперечных сечениях тоннеля, в одном из которых имелось стыковое соединение рельсов.

Установлено, что максимальные уровни вибрации, передаваемой на рельс и вибрации-отклика, возникающей в конструкциях обделки тоннеля, зафиксированы в контрольных точках сечения тоннеля со стыковым соединением рельсов. Так, в октавных полосах со среднегеометрическими частотами 31,5 Гц и 63 Гц максимальные величины среднеквадратичных значений ускорений, передаваемых на рельс, составляли 130–135 дБ, что соответствует уровню вибрации, возникающей при прохождении типового состава электропоезда. Величины виброускорений отклика, возникающих в лотке, своде и на уровне горизонтального диаметра обделки тоннеля, оказалась меньше на 7–10 дБ, чем в аналогичных конструкциях первой линии Минского метрополитена с безбалластным рельсовым путем на деревянных шпалах.

Приведены фрагменты виброграмм (в м/с^2), позволяющие определить собственные частоты колебаний конструкций *тоннельной обделки и произвести их сравнение с частотами собственных колебаний перекрытий зданий, для предотвращения резонансной вибрации.*

Ключевые слова: рельсовый путь метрополитена, виброизоляционные блоки, виброиспытания обделки тоннеля, виброускорения, виброграммы, собственные частоты колебаний.

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INTRODUCTION

When designing the new underground lines, it is necessary as a rule to take various measures to prevent higher-than-normal vibration of dwelling structures from occurrence during the passage of trains. There are various vibration prediction methods (including SP 23.105-2004), however their accuracy is far from perfect [1–2]. In cities, where subsurface underground railway is constructed, such as Minsk there are always dwelling houses, for which it is necessary to take additional measures to reduce the slab vibration. So the installation of so-called floating floors and taking of a number of other measures were required in some apartments when constructing the first line of the Minsk Underground Railway with railway tracks on wooden sleepers.

The world experience of construction of underground railways has shown that the most efficient and economically justified way to reduce the vibration effects on the buildings consists in the use of various methods of vibration isolation of the railway track. Here the so-called systems of elastic fastening of the with the use of reinforced-concrete blocks became a frequent practice:

– Low Vibration Treck (LVT) system consisting of a concrete block, vibration insulator and rubber boot embedded in track concrete (applicable in Russia and a number of European countries);

- Embedded Block System (EBS) system, in which a concrete block is installed into a ready made tray (or niche in concrete), on the bottom of which a vibration isolator is placed and the gap between the tray and the block is filled with filling compound (applicable in Ukraine, Poland, etc.);
- 300 UTS system manufactured by Vossloh company comprising a concrete block and a rail fastening kit with a vibration isolator (applicable in cases where no high vibration isolating capacity is required).

When constructing the third line of the Minsk Underground Railway, the system of elastic fastening of the railway track using reinforced-concrete vibration-isolation blocks of BV2-M grade according to TU BY 100261791.003-2017 "Vibration-isolation blocks for elastic fastening of the underground railway track. Specifications" (analogue of the EBS system blocks) was applied. The working drawings and technical specifications for the blocks are developed by the BelNIIS Republican Unitary Scientific-Research Enterprise for Construction and the production of the blocks was organised at the Subsidiary of the Reinforced-Concrete Structure Plant of Metrostroy OJSC.

The following investigations of the vibration-isolation capacity of the following three railway track fastening systems were preliminarily performed: on the vibration-isolation blocks of the BV2-M grade; on the blocks with the 300UTS fastening system and on wooden sleepers. The fragments were subjected to the dynamic load applied by means of a special vibration exciter fastened to the rails of the fragments. It has been ascertained that the blocks of the BV2-M grade have the highest vibration-isolation capacity. So the reduction of the root-mean-square values of the vertical accelerations of the reinforced-concrete base plate is up to 7 dB in the octave geometric mean frequency band of 31.5 Hz and up to 11 dB in the frequency band of 63 Hz in comparison with the fragment on wooden sleepers. To obtain more accurate figures as to the vibration-isolation capacity of the elastic fastening blocks, the investigations of the operation of this system in the underground railway tunnel were performed.

General characteristic of the object of investigation

The investigations have been performed in the tunnel of the section of the third line of the Minsk Underground Railway being constructed. The section under investigation (≈15 m long) of the tunnel lining is located at the distance of ≈100 m from the Vokzalnaya station of the underground railway in the direction of the F. Bogushevich station. The tunnel was bored by the shield-driving method with the use of the Alesya tunnel boring of METROSTROY OJSC.

The outer diameter of the tunnel (to the outer edge) is 6 m. The tunnel depth (from the top of the lining to the earth surface) on this section is 6–7 m. The surrounding soil mass consists of sandy soils (fine- and medium-grained sands and clay sands). Ground waters are absent.

The tunnel lining is made of five-leaved rings of high-precision reinforced-concrete tubbings (with elastomer seals) interconnected by means of tie bolts screwed into the embedded stud. A tubbing ring is 1,400 mm wide and 300 mm thick. The space between the outer surface of the tubbing support and the soil mass is filled with sand-cement mortar by the method of injection through the open-end holes in the tubbings. The average thickness of the external (cement and sand) layer of the tunnel lining is ≈100 mm (the measurements were performed in the chamber of the ventilation shaft being constructed at the distance of ≈200 m from the section under investigation).

The railway track superstructure is constructed with the use of the vibration-isolation blocks of the BV2-M grade. The blocks are embedded in the concrete base of the tunnel. The appearance of the railway track and of the tunnel lining structures on the section under investigation is presented in the photograph (Fig. 1).

Figure 1. Appearance of the railway track and tunnel lining

The peculiarity of the design of the unit of the BV2-M grade consists in the fact that it is fitted with a “soft (M)” (having the static stiffness of 10–15 kN/mm) shock-absorbing pad of the Sylodyn-NC mark with the thickness of 20 mm and the rail (type P55) is fastened by means of the screw and stud sets of the Vossloh-21 mark, see Figure 2.

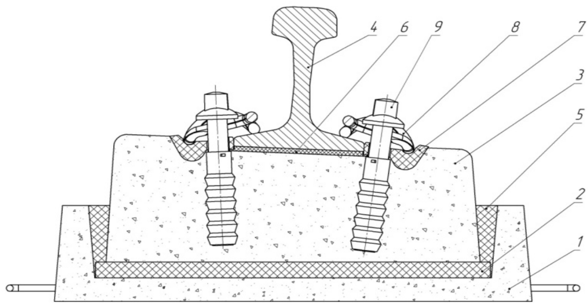


Figure 2. Design concept of the BMV-2 unit
1 – tray; 2 – shock-absorbing pad; 3 – supporting block; 4 – rail; 5 – isolation layer; 6 – rail pad; 7 – plate; 8 – clamp; 9 – self-driving screw

Investigation objective: determining the vibration-isolation characteristics of the elastic fastening system of the underground railway track on the blocks of the BV2-M grade and comparing the obtained values with the known investigation results.

INVESTIGATION TECHNIQUE

The investigation technique has been developed by the BelNIIS RUE and based on measuring the vibration accelerations in the reference points of the railway track superstructure and vibration response occurring in the tunnel lining structures under the action of the dynamic load from the rolling stock. When developing the technique, the recommendations of GOST 31185-2002 [3].

The dynamic load was created by the AGTM diesel locomotive used for delivery of concrete mix when constructing the monolithic tunnel invert. The diesel locomotive consists of two bogies, the first of them accommodating the concrete mixer ("mixer") and the second being the diesel locomotive itself. The standard values (dead weight) of the static component of the first and second bogies of the diesel locomotive are P_1 = 90 kN; P_2 = 150 kN, respectively.

The investigations have been performed on the railway track section located in the tunnel at the distance of 100 m from the station in the rail bond zone (with the gap of ≈15 mm). The railway track section has the curvature in plan with the radius R ≈1 000 м. The reference points (place of fastening the sensors) were arranged in the two tunnel sections arranged at the distance of 15 m from one another. The appearance of the sensors for picking up the vibration signal on the structural members of the railway track and tunnel lining is presented in the photograph (Fig. 3).

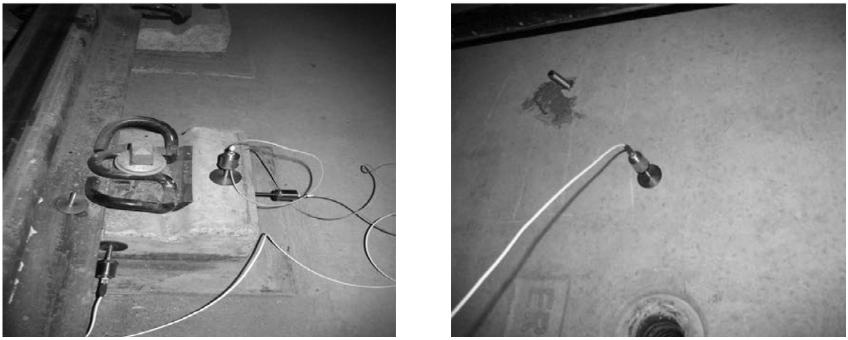


Figure 3. Appearance of sensors No. 1, 2, 5, 9 and 7 on the block and tunnel tubbing

The arrangement diagram and sequential numbers of the reference points on the railway track members, tunnel lining and the direction of picking up the signal by the vibration sensors are presented in Figure 4.

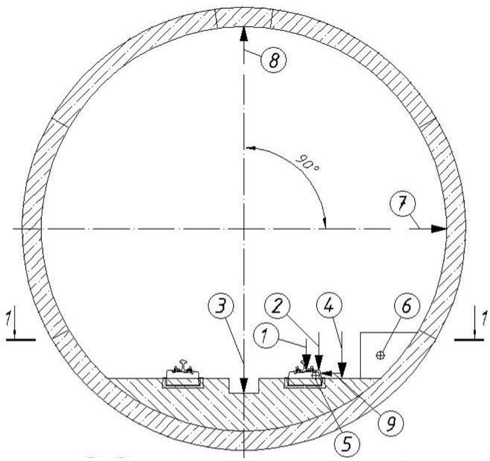


Figure 4. Places of installation and directions of the vibration sensors

The vibration levels (root-mean-square value of the vibration accelerations) were measured by means of the Octave 101-V three-channel vibration meter with the following measuring ranges: from 1 to 1

000 Hz as to the frequency and from 77 to 175 dB as to the vibration level (relatively to 10^{-6} m/s^2) with the measuring error of ± 0.5 dB. The recording was performed in the octave bands with the geometric mean frequencies of 31.5 and 63 Hz with averaging for 1 s. The measurements were performed during the three runs of the diesel locomotive for each variant of connection of the sensors in the following order:

- placing the diesel locomotive at the distance of ≈70 m from the measuring section and stopping the engine;
- connecting the sensors according to variant 1 (sensors 1–3) and checking the operability of the vibration meter and recording apparatus;
- switching on the signal recording in the mode of recording the spectrum of vibration levels for each frequency band and starting (after 10–15 s) the diesel locomotive engine and acceleration the diesel locomotive on the measuring section to the speed of ≈40 km/h;
- stopping the diesel locomotive (at the distance of ≈70 m from the measuring section) and its engine followed by stopping the signal recording;
- checking the signal recording quality and background vibration level.

In cases of malfunctioning of the instrument or low level of the vibration being transmitted to the rail, the testing was repeated. Then the sensors were re-installed to other reference points (next variant) and the vibration levels were measured in the above order.

RESULTS OF THE VIBRATION TESTING

The testing of the tunnel lining of the third line of the Minsk Underground Railway on the railway track consisting of the vibration-isolation blocks of the BV2-M grade.

Tables 1–2 present the maximum values of the root-mean-square vibrational accelerations (in dB) occurring in the characteristic points of the railway track structures and tunnel lining during the passage of the AGMT diesel locomotive for different variants of connection of the vibration sensors for the reference tunnel sections: Section No.1 (with the rail bond) and No.2 (without rail bond).

Table 1

Vibrational accelerations in dB in the reference points of section No.1

Sensor number (place of installation)								
1 (rail Z)	**2 (block Z)**	**3 (tray Z)**	**4 (base Z)**	**5 (block X)**	**6 (tunnel X)**	**7 (lateral face, Y)**	**8 (arch Z)**	**9 (block Y)**
Variant No.1 of connection of the sensors								
Frequency band 31.5 Hz								
122.7	–	76.3	–	–	–	72.7	–	–
119.7	–	76.0	–	–	–	73.2	–	–
126.1	–	77.0	–	–	–	74.0	–	–
Frequency band 63 Hz								
130.4	–	89.7	–	–	–	86.5	–	–
130.4	–	89.8	–	–	–	86.6	–	–
128.2	–	92.3	–	–	–	89.3	–	–
Variant No.2 of connection of the sensors								
Frequency band 31.5 Hz								
–	122.2	–	–	–	–	73.5	71.7	–
–	120.5	–	–	–	–	72.3	68.7	–
–	123.0	–	–	–	–	74.5	72.5	–
Frequency band 63 Hz								
–	127.7	–	–	–	–	91.5	88.5	–
–	126.2	–	–	–	–	90.8	87.0	–
–	127.9	–	–	–	–	91.5	88.2	–

Table 2

Vibrational accelerations in dB in the reference points of section No.1

Variant No.10 of connection of the sensors								
Frequency band 31.5 Hz								
1 (rail Z)		3 (tray Z)				7 (lateral face, Y)		
114.5	–	74.0	–	–	–	71.2	–	–
108.8	–	75.7	–	–	–	72.0	–	–
108.4	–	76.6	–	–	–	73.2	–	–
Frequency band 63 Hz								
123.9	–	80.9	–	–	–	73.9	–	–
117.2	–	84.9	–	–	–	79.5	–	–
115.7	–	84.7	–	–	–	78.4	–	–

Note. Tables 1 and 2 present the values of the vibrational accelerations to be used for comparison with the results of the investigations performed by the Belarusian National Technical University (BNTU)

The vibrational accelerations were obtained from decoding the signal record with the use of the program "R110 Version 1.20". Prior to beginning the movement of the AGMT diesel locomotive, the vibration level was 60.1–63.6 dB and its effect was not considered. It has been ascertained that the presence of the gap in the rail bond joint (section No.1) increases considerably the vibration effects on the rail and tunnel lining during the passage of the diesel locomotive. So the levels of vibration effect on the rail for section No.1 in the octave frequency band of 63 Hz during the movement of the AGTM diesel locomotive exceed the similar values for section No.2 (without rail bond) by ≈15 dB and the respective values of the vibration of the tray and lateral face of the tunnel increase by ≈10 dB.

In the frequency bands of 31.5 and 63 Hz, the maximum rail acceleration values were 120–130 dB, here the respective accelerations of the rail pad of the vibration-isolation block were 120–128 dB and the accelerations of the monolithic base near the block were 75 to 90 dB.

The testing results confirm a high vibration isolating capacity of the blocks of the BV2-M grade. The presence of a bond joint in the railway track allowed reaching the vibration effects on the rail commensurable with those from typical underground railway trains or even exceeding them.

Table 3 presents the values of the vibration effect on the rail and tunnel lining of the third line from the AGTM train and similar values for the first line of the Minsk Underground Railway on the section from the Petrovshchina station to the Malinovka station during the movement of the typical electric trains of the underground railway. On the above section of the first line, the vibration-isolation blocks of the system manufactured by Tinnes Company (Poland) are laid. The investigations of vibration on the first line of the underground railway were performed under the leadership of professor Y. V. Vasilevich (BNTU) accordint to order of Minsk Underground Railway Municipal Commercial Unitary Enterprise.

The BNTU's reports (the data of the reports are provided by the customer) only present the vibrational acceleration values for the three points: rail, tray and lateral face of the tunnel that does not allow the comparison of the efficiency of the vibration insulation of the railway track for the said systems with sufficient accuracy.

Table 3

Vibrational accelerations, in dB in the reference points of the railway track systems

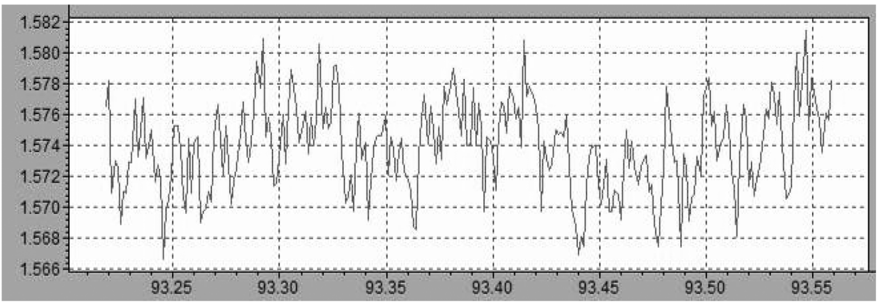
	1 (rail)	3 (tray)	7 (lateral face)
Track on BV2-M blocks			
Frequency band, Hz 31.5			
Vibrational accelerations, dB	122.7	76.3	72.7
	119.7	76.0	73.2
	126.1	77.0	74.0
	63		
	130.4	89.7	86.5
	130.4	89.8	86.6
	128.2	92.3	89.3
Track on EBS blocks			
Frequency band, Hz 31.5			
Vibrational accelerations, dB	128.1	87.0	83.2
	127.4	86.7	83.1
	63		
	130.3	98.3	93.3
	129.2	96.8	91.9
Track on wooden sleepers			
Frequency band, Hz 31.5			
Vibrational accelerations, dB	118.7	84.0	80.8
	118.9	86.5	82.8
	63		
	125.2	101.1	97.5
	125.7	101.8	98.0

The analysis of the testing results shows that lower levels of vibration of the railway track base is reached when using of the BV2-M grade should it be chosen from the said two types of the elastic fastening blocks.

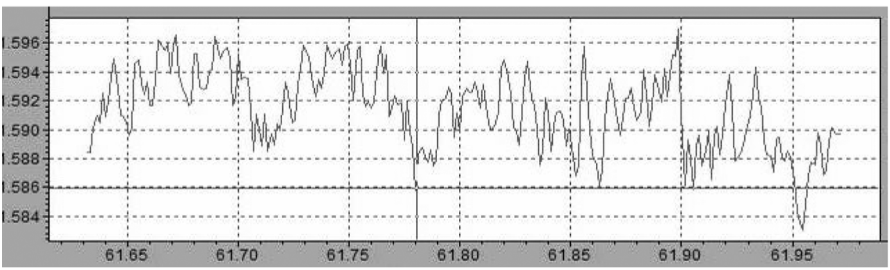
So the reduction of the vertical vibration level in the tunnel tray from 9.7 to 11 dB in the frequency band of 31,5 Hz and from 4.5 dB to 8.6 dB in the frequency band of 63 Hz is reached. The level of vibration over the lateral face of the tunnel (in the horizontal direction) in the frequency band of 31.5 Hz is reduced by 9.1 to 10.5 dB and from 2.6 dB to 6.8 dB in the frequency band of 63 Hz. It should be also noted that the railway track on wooden sleepers does neither ensure the required reduction of the level of vibration in the frequency band of 31,5 Hz (for this underground railway section taking account the apartment blocks) nor meet the requirements for operational reliability due to poor durability of wooden sleepers.

Figure 6 presents the typical (stable) time areas of the vibration records for the tunnel lining parts under investigation: tray (point 3); lateral face (point 7) and arch (point 8), the oscillations of which are caused by the passage of the AGTM diesel locomotive. The vibration records allow determining both the minimum values of the vibrational accelerations (in m/s^2) and the natural frequencies of oscillations of the said tunnel lining parts. So the natural frequencies of oscillations of the arch (vertical direction) and lateral face (horizontal direction) of the tunnel lining are approximately equal and located within the range 12–14 Hz. The natural frequency of oscillations of the tunnel tray (vertical direction) is 7–9 Hz that is caused by a considerable thickness (mass) of monolithic concrete.

a)



b)



c)

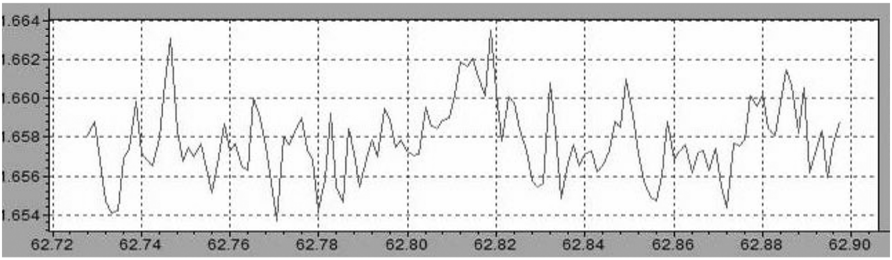


Figure 6. Vibration records of oscillations of typical sections of the tunnel lining; a – tray; b – lateral face; c – arch

It should be noted that the level of vibration of the tunnel lining affects considerably the values of the resonance vibration occurring in the dwelling slabs. The BNTU's reports contain no vibration records of oscillations of typical parts of the tunnel lining that prevents evaluation of the influence of the lining design on the measurement results. So the tunnel lining of the third line of the Minsk Underground Railway consists of high-precision tubbings with the thickness of 300 mm while the thickness of the tunnel lining on the first and second is 250 mm.

CONCLUSION

On the basis of the investigations, it was ascertained that the construction of the railway track on the elastic fastening blocks of the BV2-M grade according to TU BY 100320367.002-2017 ensures the considerable reduction of vibration of the underground railway tunnel lining in comparison with the railway track on wooden sleepers. In the octave band with the geometric mean frequency of 31.5 Hz, the reduction of the maximum root-mean-square values of the vibrational accelerations in the tunnel tray is at least 7 dB and that at the level of the horizontal diameter of the tunnel is at least 6 dB. In the octave band with the geometric mean frequency of 63 Hz, the reduction of the maximum root-mean-square values of the vibrational accelerations in the tunnel tray and at the level of the horizontal diameter of the tunnel is at least 8 dB.

The proposed technique of evaluation of the vibration insulation of the railway track may be used in the process of construction of the underground railway that will allow the efficient application of various methods of vibration-insulation of the railway track, including the accounting of the existing urban area and geological engineering conditions at the place of location of the underground railway tunnel.

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