UNDERGROUND RAILWAY VIBRATION MEASUREMENT, ANALYSIS AND REDUCTION IN ADJACENT RESIDENTIAL BUILDINGS

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This work presents results of thorough investigations of vibration propagation from underground trains on Kalugsko-Rigskaja line of Moscow Underground. The main aim of the work was to develop effective countermeasures that reduce both the floor vibration and structure-induced noise inside scheduled closely adjacent residential compound. The distance between the residential compound and the tunnel casing varies from 15 to 52 m. Field investigations were performed to measure the ground velocity during underground train passes both on the ground surface and on the foundations of existing buildings. Transfer functions from ground to building foundation were calculated based on those measurements and the prediction of vibration inside the building was performed. Prediction analysis is conversion from the measured vibration levels on the ground surface to the vibration levels of the floors that consists of the following steps: 1) determination of the transfer function between the ground surface and the foundation of the residential buildings; 2) determination of the vibration transmission losses through the building structure; 3) calculation of the resonant increase of oscillations in the center of the floor compared to its contour. The paper presents calculated and averaged over the time of measurements transmission coefficients of vertical vibrations between the said groups of structural elements. The calculated transfer coefficients can be used to predict vibration levels in similar buildings subjected to underground traffic impact. Further analysis allowed for calculation of structural members' vibration velocity that were compared to valid sanitary standards. Vibration reduction measurements were proposed and their efficiency calculated.

Keywords: vibration analysis, finite-element method, Femap, structural-borne sound, underground trains, ground-borne noise, prediction analysis.

1. Introduction

Transport infrastructure of large cities is impossible without the presence of the most efficient type of mass transport –the underground, with its greatest people-carrying ability. The development of the underground transport network "bites" into the existing planned urban areas together with the decrease of the areas for new construction, not affected by anthropogenic activity from the subway.

It is well known, that the shallow metro lines appear to be the sources of significant vibrations that spreads through the soil and transfers to the building's foundation that are located inside the technical zone of the underground lines [1,2]. These vibrations then spread through the load-bearing structures of a building and produce vibrations of walls and floors, that influence both the technical state of the building and sanitary-hygienic conditions of human stay. The vibration generated inside the premises of residential and public areas due to underground train traffic has unsteady discontinuous character with a marked predominance of signal in the frequency band of 22.5 – 90 Hz [1,2, 3], and repeats with a period determined by the schedule of underground train passes. Currently available regulatory documents [4] allows estimating of tolerable vibration velocities inside residential premises. However, valid standard SP [1] afford predicting vibration levels only on the ground surface at any distance from the tunnel axis. Nevertheless, the main challenge facing an engineer when performing vibration and noise level forecast inside residential premises is the lack of scientifically grounded methodology that can estimate the compliance of vibration level with the allowable criteria stated in Sanitary Norms [1, 4] on the design stage of the building.

Recent works [5-7] concerning the problem of vibration transition calculations from underground tunnel to the floors of residential buildings utilizes the latest finite-element analysis software packages to solve the wave problem of vibration transmission from the tunnel through the soil-layered media to the building and derive the vibration velocities of floors and walls of that building. In [5] the authors utilize the combination of FEM and BEM that accounts for semi-infinite volumes, stratification of soil media with different elastic and damping characteristics and solve the problem of vibration levels calculation on the ground surface above the underground train station. Papers [6, 7] present 2D and 3D, respectively, solution of vibration propagation problem in layered media and show the vibration levels both at the ground surface and on the floors of existing buildings. The above-noted works are devoted to detailed theoretical and numerical investigations and vibration level forecasts inside residential buildings. But they lack for experimental demonstration of calculated results. Presented work fills specified gap between numerical or analytical solutions and experimental results by presenting and analysing field-derived behaviour of vibration propagation characteristics in different media. Notwithstanding the large recent progress in the development of finite-element, boundary-element and combined numerical models for railway-induced vibration assessment inside buildings, they are still lots of empirical ones, successfully applied in practice [8]. Examples of empirical methods include the procedures developed by the Federal Railroad Administration (FRA) and the Federal Transit Administration (FTA) of the U.S. Department of Transportation [9, 10], the method developed by the Swiss Federal Railways (SBB) [11]. The procedures developed by FRA and FTA distinguish between the three different levels of assessment of the ISO 14837-1 standard [12]. Most of before mentioned works investigates ground borne noise arising from high-speed trains, but not the underground trains (travelling with up to 72 km/h).

In order to forecast vibration and noise levels inside premises of a building on the design stage subjected to the vibration from underground train traffic we have to make field measurements on the ground surface at the construction site and calculate the vibration parameters and structural noise levels inside those premises accounting for vibration losses on the "ground-to-foundation" transition, floor's panel resonances and noise emission from envelope structures (walls, floors and ceilings). This work was done in [6]. Field vibration measurements were performed with accordance to a method, stated in SP 23-105-2004 [1], that accounts for abovementioned characteristics of vibration source. The key aspect of underground train vibration characteristic is that it has significant values only in the three octave bands [1] with average compound frequency – 16, 31.5 and 63 Hz, which can be seen from the measurement results in Fig. 1b, but in the lower bands, the vibration does not exceed the values of background oscillations. However, the estimation of structural noise levels in residential premises must be carried out also in octave bands with average compound frequency starting from 63 Hz and up to the frequency, when the signal from underground moving train becomes dusky compared to the background oscillations.

Whether the exceedance exist there is a need in calculation of vibration isolation system. The article presents the most economical and effective solution – mixed cell polyurethane slabs located under the foundation. This work is based primarily on paper [6], where more accurate analysis of transfer function was made. This paper presents further studies aimed at calculation of vibration isolation system and proving its effectiveness.

2. Field measurements

The measurements were performed at the construction site near the main line tunnel of Kaluzhsko-Rizhskaja line. Relative position of the residential building and underground train tunnels is plotted on Fig. 1a that also shows the location of six measurement points (a' – f').

a) b)

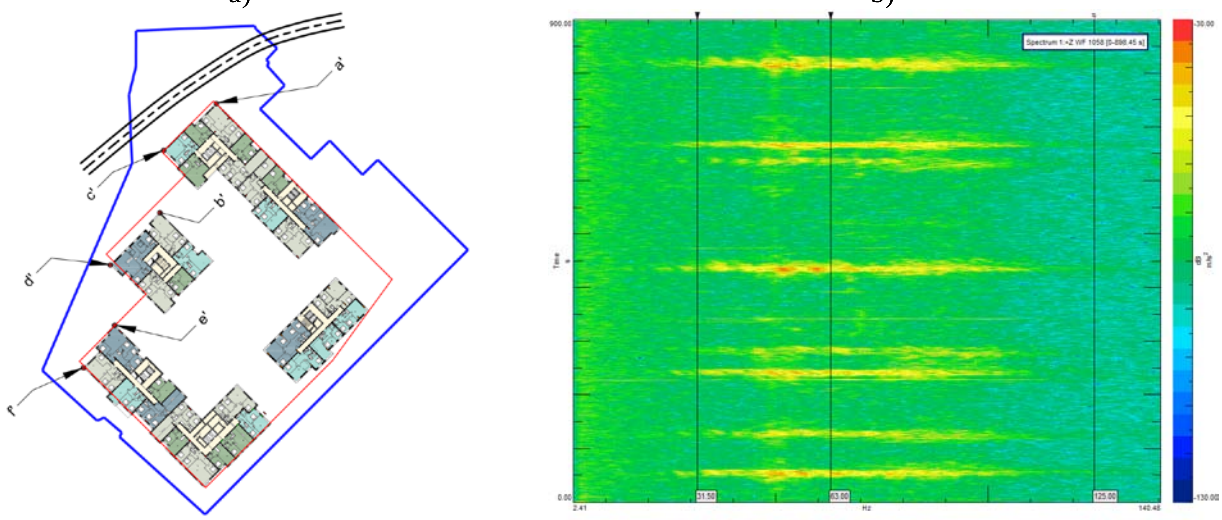


Figure 1. Relative position of the residential building and underground train tunnels. Measurement points (a); Vibration time history at measurement points (b).

The underground train line consists of two tunnels. The depth of each tunnel vary from 8 to 10 m and has a 5.4 m diameter circular cross-section concrete tunnel vaults 0.2 m thick. The soil characteristics with their geological data, thickness and depth from the surface can be found in [6]

Fig. 1a shows the contour of a 5 to 13-storey residential compound resting on a single stylobata, marked with the red curve. There were some existing buildings inside the construction side, where the measurements were also performed and transfer functions were calculated. In this respect acceleration of specified points were measured synchronously using 5 PCB accelerometers and 8-channel vibration recording system. According to SP 23-105-2004 [1], the RMS of the acceleration signal was measured with the integration period of 1 s. The measurement time was set up to 15 minutes, during which more than 10 train passes through the closest to the building tunnel and the distant one were detected. Fig. 1b shows the recorded spectrogram of vibration at point c'. This figure plots a 3D graph with 3 axes: time, frequency and acceleration level in dB.

The spectrogram plotted on Fig. 1b is typical for such type of excitation. Moving trains in underground tunnels excite the measurement points mainly in octave bands with average compound frequencies from 31.5 to 125 Hz. The background vibration is 20 to 30 dB lower, than the vibration during each train pass.

Each train pass excites the ground for 15 – 20 seconds with the amplitude depending on the distance from the source, the speed of train and the load of a carriage, which is a function of amount of passengers. It is clearly observed, that there are small amplitude peaks (coloured with yellow) on the spectrogram as well as high amplitude ones (coloured in red). The first ones correspond to the train passes through the distant tunnel and the last – to the closes one. The difference between amplitudes of vibration from those tunnels occurs because the closest one acts as a baffle on the path from the distant tunnel to the measurement points. Moreover, the frequency of train passes through the tunnels is slightly different which is notable by inconstant appearance of signal peak groups with high and low amplitudes. In addition to that Fig. 1b shows that the closest train pass excites the ground surface in a wider frequency range – from 20 to 130 Hz, against 30 – 100 Hz frequency range for the distant one. This is because the high-frequency components of vibration damp faster, then the low-frequency ones. The maximum measured amplitude spectra during each train pass lies between 50 and 67 Hz, which falls in octave band with compound frequency 63 Hz.

The vertical vibration transfer factor is calculated as the ratio between corresponding vibration velocities at different measurement points (e.g., ground surface – basement) calculated as rms velocity value averaged over each train pass in octave bands with average compound frequency 16, 31.5, 63 and 125 Hz.

3. Transfer function calculation

There are many factors that influence the vibration level in different points between the tunnel casing and the building floor. Some of them are arranged in appendix A of [12]. The detailed implementation of all these factors inside a numerical or analytical model results in high complexity or even impossibility of solution. In order to reduce vast uncertainty in the nature of vibration transfer factors, the best solution is to measure them in field. Further processing is needed to get statistical data and apply them in calculations. Therefore, the field investigations were performed on the construction site.

Fig. 2a shows a measurement set-up. Measurements were performed using simultaneous recording of acceleration on the ground surface and the foundation of existing building located inside the construction side with the same distance from the track as point a'. Fig. 2b shows acceleration data within octave bands with average compound frequency 8 – 4000 Hz at two different points in X (horizontal) and Z (vertical) directions. By dividing their peak values or time averaging them by the train pass interval (10 – 15s) it is possible to obtain peak or time averaged transfer factor. More detailed procedure is discussed in [18].

As the results analysis revealed, the average vibration reduction between the ground surface and the foundation is 17 – 18 dB in octave bands 31,5 – 125 Hz. To get a statistical distribution of transfer factor, more train passes are used in calculations.

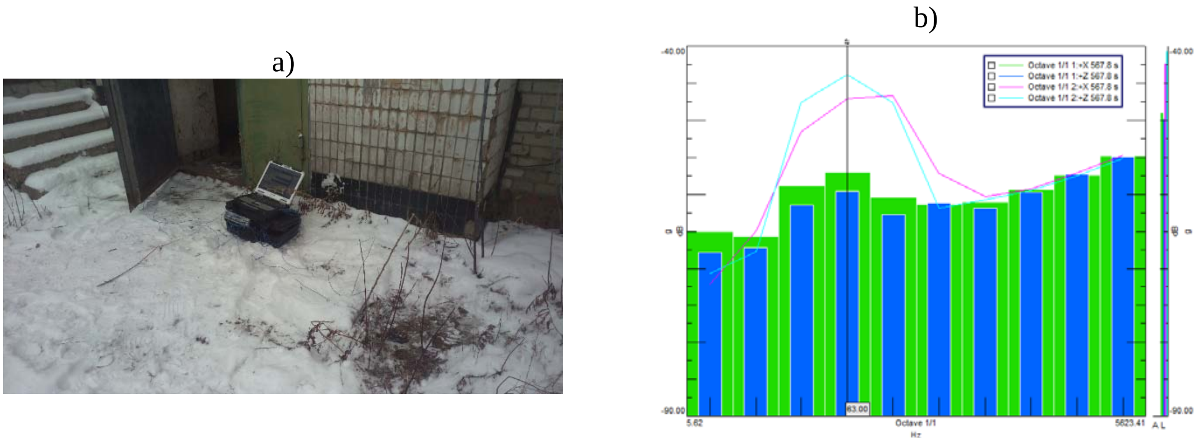


Figure 2. Measurement set-up (a); Acceleration during train pass (b).

4. Vibration amplification analysis

Paper [6] suggests an engineering approach to calculate vibration velocity in m/s (or vibration velocity level in dB) at the center of the floor inside the residential premises using transfer factors (that can be calculated analytically or measured):

$$v_{floor}(t) = v_{g.s.}(t) \cdot k_1 \cdot k_2 \cdot k_3, \quad (1)$$

where $v_{floor}(t)$ – vibration velocity at the center of the floor; $v_{g.s.}(t)$ – velocity of the ground surface on the expected contour of the building; k_1 – k_3 – transfer factors according to [6].

This approach takes into account both the characteristics of the soil and real transfer factors at the discontinuity surfaces (e.g. ground – foundation) and presents quite easy and reliable method of vibration level estimation in residential or public buildings.

To reduce the model uncertainty, we apply transfer factors k_1, that were measured in field. But other transfer factors – k_2 & k_3 will be calculated numerically, because the span of the measured slab differs from the one in project. Floor vibration amplification was calculated using FEA package PLM Femap.

4.1 Modal analysis

The first step in dynamic analysis of floor slab's amplifications is modal analysis of the slab that produces important for understanding its behaviour modal parameters – natural frequency and associated mode shape. The common practice is to simulate the floor slab using plate elements with its thickness according to design project and material parameters (Young's modulus and Poisson coefficient) according to national concrete standards. The outer edge was fixed according to the design project. The results of modal analysis are plotted in Fig. 3a – d and show, that the floor slab's first four natural frequencies lie inside the range of underground train excitation frequencies, which will definitely result in high vibration amplification due to slab's resonance.

4.2 Dynamic analysis

The amplitudes of resonant amplification were found using frequency response analysis of floor slab subjected to broadband excitation. The range of external kinematic excitation was established from 1 to 150 Hz. The slab was fixed by its edge and external acceleration was applied to its boundary. The mode shapes acquired from modal analysis are then used in frequency response analysis. The results of the analysis – acceleration of middle span point subjected to unit edge acceleration – are shown in Fig. 3e. The results plotted in Fig. 3e can be considered as transfer factor k_3.

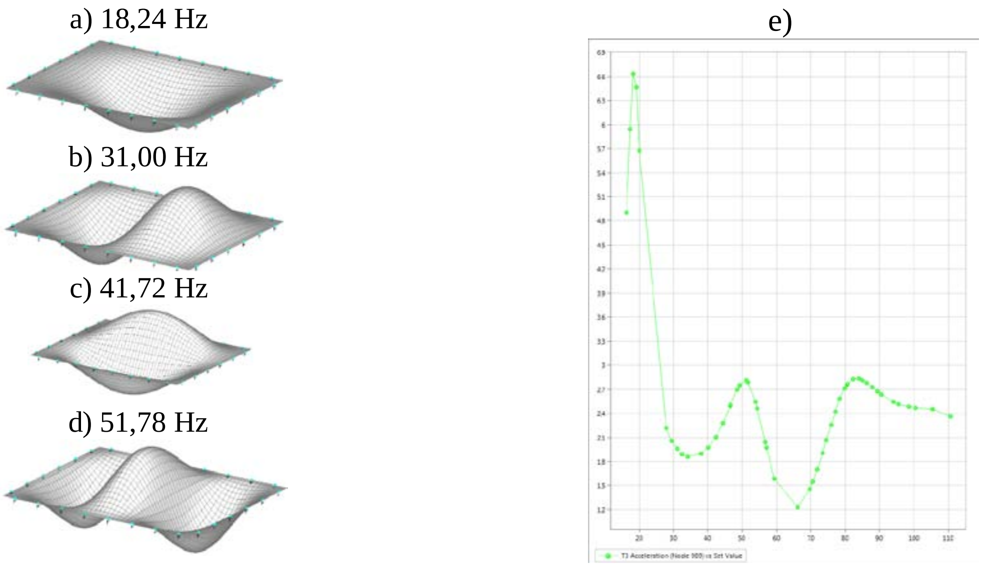


Figure 3. Modal analysis results (a); Floor slab's response spectra (b).

The results show that the biggest amplification is at the first resonance frequency (16,4 dB at 18 Hz). The higher the frequency, the lower the amplification is – the second resonance amplification is at the third slab's natural frequency (12,04 dB at 51 Hz).

This is due to the fact, that the point of interest was the point in the centre of the slab where the 2nd and 3rd mode shape nodes lie. However, if we take the point in the 1/3 of the slab, the resonant amplifications on higher frequencies are still less than in the centre (11,6 dB at 18Hz and 11,8 dB at 51 Hz).

5. Floor velocity estimation

Using the above procedure, both the velocity level of vertical and horizontal floors oscillations were calculated. The maximum and equivalent corrected vibration velocity exceedance is presented in Table 1 compared to Sanitary Norms [4] calculated in accordance with [1].

Table 1: Maximum vibration level exceedance

Section number	Vibration level exceedance in dBv in octave bands			Equivalent corrected vibration level exceedance, dBv
	16	31,5	63	
1	-	14,2	2,3	14,5
6	-	3,0	-	4,0
5	-	2,6	-	3,8
3, 4 and basement	-	-	-	-

The results show that the vibration level is 14,2 dB higher in the design building, then the regulatory value, stated in [4] and the building requires vibration isolation.

The above analysis shows, that the vibration isolation system has to reduce vibrations at 14,2 dB in octave band of 31,5 Hz.

6. Vibration isolation calculation procedure

Among other vibration isolation solution available in the market, the contractor selected application of vibration isolation pads Sylomer. In order to select appropriate type of vibration isolation material, the loads under the foundation slab were calculated. Fig. 4a plots the values of surface load under the foundation pad. The colormap underneath it shows the surface loads in kN/m^2.

Fig. 4a shows, that the surface loads vary from 220 to 850 kN/m^2, which results in different settlement of the foundation slab. The designer has to solve two different task simultaneously. The first one is the reduction of vibration transmission, which results in lowering the stiffness of vibration isolation pad. Nevertheless, the settlement of different parts of the foundation slab has to be equal. In order to comply for both of the tasks, the surface under the foundation slab was divided into four zones (load at zone 5 equals load at zone 1) with equal load pressure and different types of vibration isolation material were applied there (see Figure 4b).

Assuming the vibration isolation system as a single DOF system, we can find according to Table 1, that the required natural frequency of the system is has to be lower than 12,5 Hz.

Depending on the stiffness and load-bearing characteristic of different material types the foundation vibration isolation pad layout was made. The stiffness of isolation material for each zone was selected to obtain the same natural frequency as stated above. The overall efficiency plot (made by "Getzner" software), showing isolation region and vibration reduction values in dB (in one-third octave band) is shown on Fig. 5.

a) b)

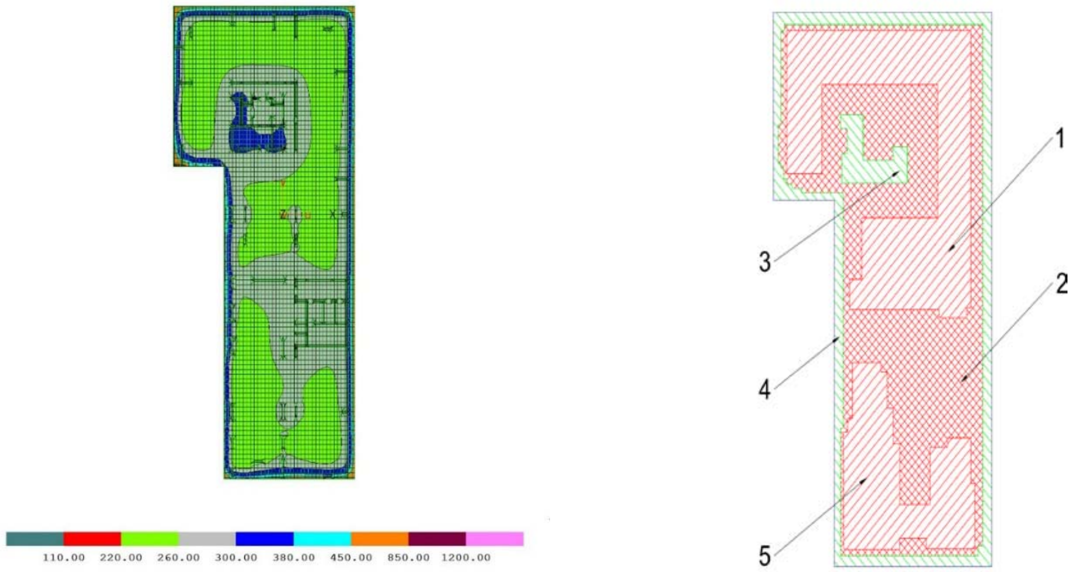
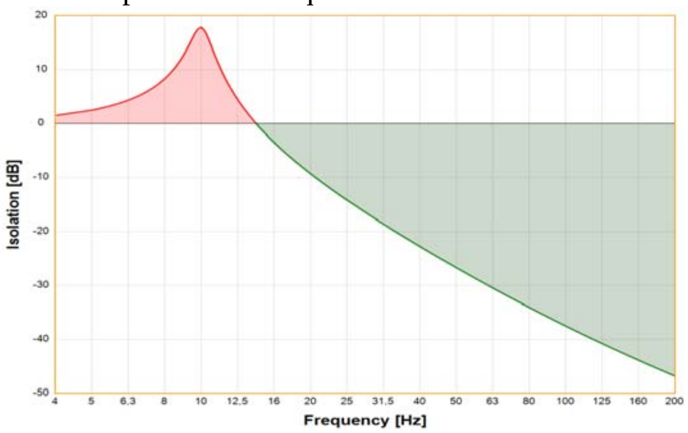


Figure 4. Surface loads under foundation slab (a); zones of different stiffness calculation (b).

The reduction of vibration caused by underground trains in an octave band with central frequency of 31,5 Hz is more than 18,6 dB, which is more than the required efficiency of vibration isolation.

This result fits the engineering practice because there are two drawbacks that reduce vibration isolation efficiency. The first one is the material aging, which can increase the natural frequency of vibration isolation system up to 5%. The latest investigations made in work [13] shows, that Sylomer can withstand long-term loading with an increase in natural frequency less than 0,5 Hz. The second one is the typofication of material thickness. The standard material thickness is 12.5 mm, so only 37.5 mm thick pad fits the requirements.



Frequency	Isolation
4 Hz	1.5 dB / -19%
5 Hz	2.5 dB / -33%
6.3 Hz	4.3 dB / -65%
8 Hz	8.5 dB / -167%
10 Hz	17.8 dB / -676%
10 Hz	17.8 dB / -676%
12.5 Hz	4.8 dB / -74%
16 Hz	-3.8 dB / 35%
20 Hz	-9.3 dB / 66%
25 Hz	-14.1 dB / 80%
31.5 Hz	-18.6 dB / 88%
40 Hz	-22.9 dB / 93%
50 Hz	-26.7 dB / 95%
63 Hz	-30.5 dB / 97%
80 Hz	-34.2 dB / 98%
100 Hz	-37.5 dB / 99%
125 Hz	-40.7 dB / 99%
160 Hz	-44 dB / 99%
200 Hz	-46.9 dB / 100%

Figure 5. Vibration reduction calculation.

7. Discussion and results

This paper present a review of latest woks devoted to the problem of vibration level forecast at the floors of residential buildings. Existing methods mostly exploit theoretical and numerical approach using the finite element analysis software.

Results of field measurements are presented and transfer coefficients that can during the design stage estimate the floor vibration levels and their compliance with the Sanitary Norms are derived. Using those coefficients, the vibration velocity at the center of the floor is founded.

This approach takes into account both the characteristics of the soil and real transfer factors at the discontinuity surfaces (e.g. ground – foundation) and presents quite easy and reliable method of vibration level estimation in residential or public buildings.

The vibration isolation selection procedure is performed and the appropriate type of material selected. The analysis shows that there exist even a 3dB reserve in vibration reduction over the calculated exceedance of 14,2 dB.

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