Vibration Data Probability Analysis Inside Residential Premises Adjacent to Underground Train Lines

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Abstract. It is well known, that the shallow underground train 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. 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, and repeats with a period determined by the schedule of underground train passes. This article deals with probability analysis of vibration data measured inside residential dwelling adjacent to shallow underground railway line. Measurements were acquired using 24-bit resolution digital multichannel acquisition system. Measurement were performed simultaneously in the basement, on the 4th and 5th floors of the dwelling. The duration of the measurements was set as 2 weeks of continuous recordings in order to obtain maximum data for probability analysis.

1. Introduction

The popularity of the metro as public transport is due to a number of features: isolation from large traffic flows on the surface of the earth, small interruptions in the movement of trains during rush hours and, as a result, the ability to transport a large number of people [1]. But despite these advantages, the metro is a source of vibration, the effect of which occurs when the wheel and the rail track interact, and then transmitted through the ground to the surrounding buildings and affects the structure of buildings and the condition of the people inside them [2].

In addition to assessing vibration and structural-borne noise in existing buildings, special attention should be paid to the prediction of vibration in scheduled buildings and during construction of new underground lines. Neglecting this issue at the project stage can result in high costs associated with countermeasures development to improve the sanitary-hygienic situation in the building, operation of equipment and life support systems, and the prevention of structural destruction of the dwelling. Therefore, the amount of funds necessary to protect buildings from the underground train impact depends on the accuracy of the forecast. The more accurate the forecast is, the more efficient (and in most cases the cheapest one) solution can be designed and implemented.
2. Recent research
Currently available regulatory documents [3, 4] allow estimation of tolerable vibration velocities inside residential premises. However, valid standard SP [5] afford predicting vibration levels of the ground surface at any distance from the tunnel axis. Prediction methods in [5] use normalized maximum and equivalent vibration velocities as design parameters. However, questions arise about the applicability of the indicators to characterize such a complex phenomenon as vibrational effects, because its distribution is influenced by many factors: the quality of the wheelset, the load of train car, the speed of train, soil parameters, structural system of the building and many others according to ISO 14837-1. As a result of random factors influence, an unambiguous prediction of the system behavior is impossible. In order to understand the laws that govern the process, it is necessary to take into account its probabilistic nature.

The excitation and propagation of vibration is a complex random process which depends on many factors. Thus, the axle load of the car varies from 78 to 148 kN depending on the car’s occupancy, the train speed varies from 40 to 90 km/h depending on the track type (straight or curved) and the roughness of the rail varies randomly. In view of this, the constructed models in [5] do not always reflect reality in full, but the study of the process itself allows us to identify the statistical features of the set of realizations and analyze what is happening “from the inside”. Importance of pure understanding of the vibration propagation phenomena is visible when making a forecast. An analysis of what is happening in the source allow us to determine the input parameters of the external influence. Their knowledge as well as transfer function characterizing the features of the transmission of vibration to the building, allows to determine the required output characteristics of the system.

The issue of predicting vibration and structural noise in buildings is reflected in VSN 211-91 [6], as well as in [7] and [5]. In [5 – 6], a method for predicting vibration for soil is presented, but it is not described how to perform it for indoor premises. In [7], questions of modeling the transmission of influence from a source to an object are touched upon in detail, and the characteristics of the “source – propagation path – object” system are described, which must be taken into account in the forecast.

But in the regulatory documentation, existing and current at the moment, there are some gaps associated with the issues of methods for assessing and predicting vibration in residential and public buildings. Meanwhile, these problems are already being investigated in the scientific community. In particular, vibration estimation methods are considered in [8], forecasting issues are considered in [2], [9–10].

3. Problem statement
The main objective of this work is to perform probability analysis of vibration data due to underground train traffic and determine the indicators necessary to assess its impact on urban development with prescribed confidence level. These indicators should be then verified with the measurements performed in a dwelling located near the underground line.

4. Experimental set-up
Vibration velocity measurements were performed inside the 5th story residential brick building located 10 meters off the main tunnel of red line of Moscow Underground. Vibration data was acquired using 24-bit resolution digital multichannel acquisition system with a sample rate of 2000 Hz. Measurements were performed simultaneously in 3 points: at the basement, on the 4th and 5th floors of the dwelling (in the center of the room). The duration of the measurements was set to 2 weeks of continuous recordings in order to obtain maximum amount of data required for probability analysis.

5. Probability analysis
The study of mass phenomena, regardless of the exact behavior of individual events, is considered by the theory of random processes [11]. Its mathematical apparatus makes it possible to estimate the mathematical expectation, variance, distribution density, correlation function, and spectral density. It is these nonrandom functions that allow us to describe the basic properties of a random process.
To assess the random process in the framework of this work, we study the behavior of the peak values of the vibration velocity at the moments of each train pass. During each day from 560 to 680 train passes were recorded. It is these data that will make it possible to obtain such a characteristic by which it is possible to judge the fulfillment of the requirements of sanitary norms. Under similar conditions, the level of vibration during the passage of trains along the far and near tunnels will change in time approximately uniformly and make random fluctuations relative to some average value. This allows us to consider the process stationary with mathematical expectation and dispersion, not depending on time, and a correlation function that does not depend on the choice of the origin, but only on the difference of the arguments.

The assessment was carried out according to the following algorithm:

1. The travel time of trains was determined, taking into account the duration of the stimulated effect (10-15 s) and the maximum level of vibration velocity per passage along one of the frequency bands and one direction, corresponding to the most “clean” (with largest signal-to-noise ratio) record;
2. Determination of exposure levels at the moments of train passage in all octave frequency bands and directions;
3. The allocation of trains passing through the near and far tunnels relative to the building in which the measurements were made, on the basis of the assumption that the level of impact from the distant train is lower 2 – 5 dB than from the nearest. The most reliable information about this can be obtained by having a train schedule on the line. Vibration velocity difference between the near and distant tunnel is shown in Figure 1;
4. Formation of vibration velocity data arrays during train passage for each of the tunnels, as well as for all trains without dividing the tunnels in 3 directions and in all octave frequency bands in which the vibration dominates (more than 6 dB) the background noise;
5. Selection of the most suitable types of distribution for vibration velocity levels data arrays along train aisles. The distribution law selection was made on the basis of the maximum likelihood function. An example is shown in Figure 2;
6. Calculation the values of mathematical expectation, standard deviation and maximum levels provided with probabilities of 95%, 99%, 99.9%, 99.99% in accordance with the selected types of distributions;

In addition, a percentile analysis was carried out for comparison and exposure levels were determined with percentile 95, 99, 99.9 and 99.99%.

The aim of the algorithm considered above is to determine the most probable level of vibration exposure and to select the distribution that most accurately describes these data, the knowledge of which will allow to calculate the characteristics and understand the laws that govern the initial process.

6. Discussion and results
Figure 2 shows difference in probability density function (PSD) between different tunnels. Thus, the variation in velocity values for the near tunnel is less than for the distant one. It is common practice to represent PSD of a vibration signal from underground traffic having normal distribution. As data analysis in figure 2 shows, the better distribution function is not always the normal one, but the t-location scale distribution or loglogistic one. The t location-scale distribution is useful for modeling data distributions with heavier tails (more prone to outliers) than the normal distribution. The loglogistic distribution is a probability distribution whose logarithm has a logistic distribution. This distribution is often used in survival analysis to model events that experience an initial rate increase, followed by a rate decrease.

Comparison of different assessment methods is shown in Figure 3. The analysis carried out in accordance with the presented algorithm showed that the velocity levels provided with probabilities of 95 and 99% cannot serve as an indicator for assessing the maximum probable value of vibration velocity. The level provided with a probability of 99.9% is close to the level of 99.99%, but the data obtained using [5] most closely reflects the 99.99% level and 99.99 percentile.
It is noticeable that in frequency bands from 8 to 63 Hz the values are closely located by all three methods, which indicates the correctness of the results. But at high frequencies, both in the probabilistic assessment and in the percentile assessment, velocity levels are smaller than that, obtained by SP 23-105-2004. This is due to the fact that on the record there are bursts of a random nature that are not related to the impact from the source of exposure. And this circumstance confirms the influence of random impulse actions of a different nature on the normalized indicators.

Comparison of different assessment methods presented in figure 3 also shows that the probability analysis with confidence level 99.99% overestimates the maximum probable vibration level in frequency bands 8 – 31.5 Hz.

Figure 1. Vibration velocity difference between the near and far tunnels.

Figure 2. Probability density function for vibration data.
The measurements show that a vibration velocity data due to underground train traffic is a stationary probability signal, that depends on many factors. In order to make a proper forecast the velocity data with probability variance should be taken into account. The middle ground estimation is to use 99.99% percentile analysis data.

The described analysis technique offers a different mechanism for assessing the vibrational impact than proposed in the regulatory documentation relevant to date. Due to the complexity of the mechanism of vibration propagation on the ground and many factors that affect the process, system modeling is not quite able to reflect all the features. Carrying out full-scale measurements of vibration followed by a probabilistic assessment of the process will allow us to evaluate the characteristics of the impact in specific conditions. In conjunction with knowledge of the structural features of the building (in the form of transfer functions), in which it is necessary to obtain the level of impact, such a technique will give more prominent vibration forecast.

References
[1] Merkin V and Konyukhov D 2016 Proc. Eng. 165 663-672
[2] Smirnov V and Tsukernikov I 2017 Proc. Eng. 176 371-380
[3] SN 2.2.4/2.1.8.566-96 1997 Industrial vibration, vibration in residential and public buildings Sanitary norms p 20
[4] SN 2.2.4/2.1.8.562-96 1997 Noise at workplaces, in residential and public buildings and residential areas Sanitary norms p 21
[5] SP 23-105-2004 Vibration estimation in the design, construction and operation of underground facilities p 45
[6] VSN 211-91 Prediction of soil vibration levels from the movement of metro trains and calculation of vibration protective building devices p 15
[7] GOST R ISO 14837-1-2007 Ground-borne noise and vibration arising from rail systems Part 1 General guidance
[8] Dashevskij M, Mondrus V, Motorin V 2018 ACADEMIA 4 109-115
[9] Tsukernikov I, Smirnov V 2017 J. fac. of Phys. MSU 5
[10] Smirnov V, Philippova P, Tsukernikov I 2017 Bios. comp. 3 87-95
[11] Kallenberg O 2002 Foundations of Modern Probability, 2nd ed. Springer Series in Statistics