Computational and Approximate Analysis of the Impact of Mining Vibrations on People Staying in Buildings

Tadeusz Tatara, Małgorzata Fedorczak-Cisak, Alicja Kowalska-Koczwara, and Filip Pachla

Abstract Mining shocks are dynamic phenomenon induced by underground and surface mining activities. In Poland, human activity generates rockbursts. They are the most intense so-called paraseismic sources. They refer to exploration of copper ore, hard and brown coal, gold, diamonds, non-ferrous metals and also originating from pile driving, driving sealed walls, and car, train, tram traffic and subway traffic. The mining-related surface vibrations can not only cause significant damage to buildings but they can also have a negative influence on people-occupied buildings. In Poland, mining tremors referring to hard coal and copper ore exploration occur at the Upper Silesian Coalfield (USC) and the Legnicko–Głogowski Copper District (LGCD), respectively. Rockbursts are not subject to human control, and they are random events concerning time, place of occurrence, and magnitude. There are many significant differences between earthquakes and mining tremors. The significant differences are magnitude, intensive phase of duration, peak ground accelerations (PGA), the range of predominant frequencies, frequency of occurrence, and depth of hypocenter. Mining-related vibrations stand out by having the highest intensity of all forms of paraseismic vibrations. It is, therefore, essential to assess the impact of this type of vibration on buildings and occupants. The study concerns impact evaluation of surface mining-related vibrations on occupants of dwelling masonry buildings using: (a) the RMS method according to British and Polish standards and (b) new version of empirical-measurement scale GSIS-2017. This scale is the base for estimating the level of vibration intensity. Intensity levels correspond to the effects of vibrations on people.

Keywords Mining rockbursts · Surface vibration records · Perception threshold · Comfort limit · RMS method · GSIS-2017 scale

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E. J. Sapountzakis et al. (eds.), *Proceedings of the 14th International Conference on Vibration Problems*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-8049-9_75

1 Introduction

Mechanical vibrations cause influence on the human body. Human vibration is the effect of mechanical vibrations on the human body. Many people are exposed to vibrations during work, for example, vibrations produced by vibrators, machines, or heavy vehicles. As a result of the research, international standards regarding the so-called exposure of people to vibrations are established [1–3]. Two basic types of vibrations acting on the human body are distinguished: (a) vibrations that influence on the whole body [4–6] and (b) vibrations that mainly have effect on the hands and arms through work tools [7, 8]. The first is called whole-body vibrations, and the second is called hand-arm vibrations. They influence a human as a whole, usually by supporting surfaces (feet, loins, back, and chest).

The second type of vibration is mainly exposed to operators using work tools. Both types of vibration are mechanically different and are analyzed separately. The whole-body vibration could be percept actively and passively. The first kind of perception of whole-body vibration occurs in various types of vehicles [9, 10]. The second kind of perception is encountered in the building and in the place where people work and rest. In the passive perception of vibration, the dominant is transport vibrations [11–13]. In this work, we study only the second type of perception, that is, the influence of mechanical vibrations on people in buildings and passively receiving vibrations, and therefore are not related to the vibration generation itself. Vibrations from external sources, similarly as from internal sources, reach the building, and then come to the place of perception. External causes of vibrations are the so-called paraseismic vibrations, which in the case of mining shocks are also sometimes called seismic. ISO standards on vibrations related to influence on people assume that the measured quantity used to assess the annoyance mostly is the velocity or the acceleration of vibrations, and more precisely, the effective value of them (RMS) [1, 2].

Surface vibrations caused by mining exploitation and their impact on people staying in buildings are a new research subject. In the case of mining vibrations, the main focus is on the evaluation of dynamic resistance of buildings in mining areas [14, 15]. It refers to the necessity of providing dynamic resistance of buildings in the operation plans of mines. The comments were not devoted to the effects of mining vibrations on people in buildings, as there has been no experimental research in buildings in this manner. So far, the measurements of mining vibrations are referred to the determination of vibration parameters and their connection to damages in structures. It directly relates to the requirements of the GSIS-2017 scale [16]. These scales describe the dependence of the measured vibration parameters and the building damages. The influences of vibrations on people have been previously determined based on the correlation between vibration parameters and the residents' perceptions. It is worth noting that different scales should assess the harmfulness of vibrations for buildings.

Building structures are less sensitive to vibrations than people. In designing new buildings, human perception of vibrations is a decisive parameter of evaluation. In the case of used buildings, small maintenance is sometimes sufficient to improve vibration comfort for people. It is related to, among others, road investments (construction of a subway, highways, and infrastructure buildings) and the necessity of such evaluations at the investment design stage [17].

The main aim of this article is to point out the essence of not only scientific problem but also social. After the occurrence of mining shocks, residents report not only material damage to residential buildings but also describe their negative feelings during the rockbursts. The article analyzes the recorded vibration patterns in terms of their perceived by people. The analysis used selected evaluation methods as in cases of other vibration sources.

2 Full-Scale Measurements of Free-Field and Building Vibrations

This article uses the results of full-scale long-term experimental monitoring measurements and analyses these records. The ranges of the considered mining tremors energies, epicentral distances, and wave propagation directions are extensive. Rockbursts have energies En = $1.0 \times 10^5 - 4.0 \times 10^9$ J, and epicentral distances of the considered mining shocks are in the range re = 230−2045 m. In the analysis, we applied only horizontal components of PGA larger than 5 cm/s^2.

The measurements concerned several hundred phenomena. We recorded almost 500 pairs free-field and foundation accelerations in horizontal x and y directions. Horizontal directions correspond to the transverse axis (x) and longitudinal axis (y) of the building. Table 1 contains maximal values of resultant ground acceleration (PGA_{H10}, PFA_{H10}) and velocity (PGV, PFV) for the analyzed rockbursts.

Figures 1, 2, 3, and 4 show example records of one of the most intensive rockbursts corresponding to free-field and building vibrations. Table 2 contains maximal values of horizontal components of vibration acceleration and velocity for the analyzed rockbursts presented in Figs. 1, 2, 3, and 4.

Table 1 Maximal values of horizontal components x, y of free-field and foundation vibration acceleration [m/s^2] from all recordings

Location of gauges	x-direction	y-direction
Free-field	1.97	2.0
Foundation	1.52	2.1

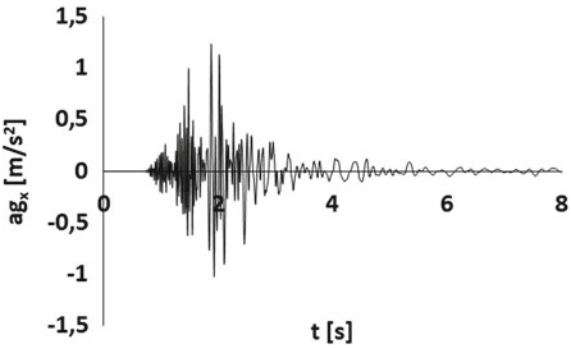

Fig. 1 The horizontal component of ground vibration in the x direction

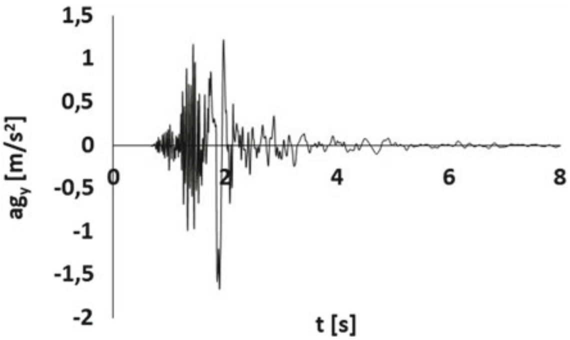

Fig. 2 The horizontal component of ground vibration in the y direction

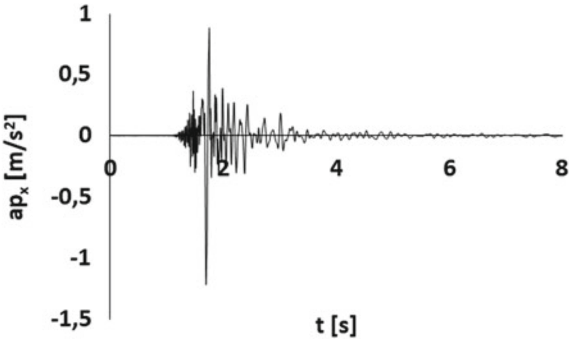

Fig. 3 The horizontal component of foundation vibration in the x direction

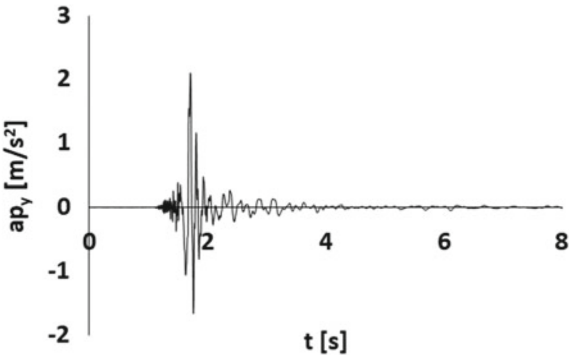

Fig. 4 The horizontal component of foundation vibration in the y direction

Table 2 Maximal values of horizontal components of vibrations acceleration [m/s^2] for the analyzed rockburst

Location of gauges	Direction			
	x	y	x	y
Free-field	1.23	1.67	–	–
Foundation	–	–	1.22	2.1

3 Approximate Evaluations of the Impact of Mining Vibrations on People Staying in Buildings

3.1 The Newest Mining Intensity Scale GSIS-2017 Applied in the USC Area

The new empirical-measurement GSIS-2017 scale, established in 2017, permits monitoring and assessing the influence of mining-related ground vibrations, both for structures and human perceptibility of quakes in the USC region. The GSIS-2017 scale originates from the former GSI-GZWKW-2012 [18, 19]. The GSIS-2017 refers to buildings and significant underground structures (e.g. water, gas, sewage network) whose failure-free functioning provides safety to residents. The GSIS-2017 scale includes buildings made of brick or other small-size elements, having wall bearing systems; concrete and reinforced concrete bearing structure; frame buildings of reinforced concrete, or steel construction. Besides, the scale includes effects of vibrations on buildings in poor technical condition and subject to the influence of continuous deformations characteristic of the III–V category of mining area [20] and effects of vibrations on sensitive of historical buildings. These factors influence on dynamic resistance of structures subjected to rockbutsts and the scale contains developed criteria for empirical evaluation of this resistance.

It also deals with the evaluations of the impact of mining vibrations on people staying in buildings. The GSIS-2017 scale consists of two versions based on velocity

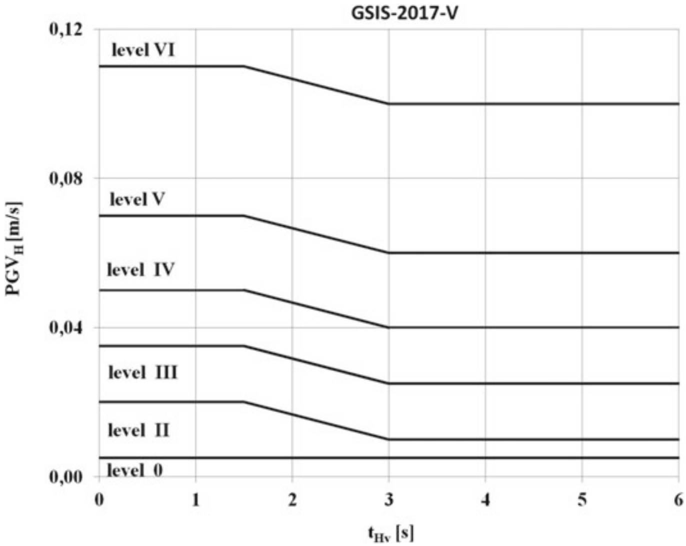

Fig. 5 The GSIS2017 scale in velocity version

and acceleration data. The GSIS-2017 scale associates values of the ground parameters with macro-seismic effects in structures and their perceptibility by people. The maximum values of the resultant ground velocity PGV_H and duration of the intensive phase of vibrations t_{Hv} are the base for evaluation of rockburst impact. In auxiliary acceleration GSIS-2017 scale version, these parameters are the resultant free-field acceleration calculated using the filtered components of the horizontal vibration in the range to 10 Hz (PGA_{H10}) and duration of the intensive phase of oscillations t_{Ha} [16, 21]. Figures 5 and 6 present two versions of GSIS-2017 scale.

The GSIS-2017 scale is an improved version of the GSI-GZW$_{KW}$-2012 scale. The results of recordings and observations of several most substantial rockbursts occurring in the USC region in the years 2015–2016, with the magnitude of energies exceeding 10^8 J and the maximum values of vibration velocity PGV > 0.05 m/s, and acceleration with PGA > 1.0 m/s^2, were additionally included in the scale.

The GSIS-2017 scale also presents the impact of the rockburst, expressed by measuring the level of seismic intensity. The recorded or predicted free-field vibration parameters are the base for classification of these levels. These parameters are correlated with macro-seismic observations in buildings described by levels of vibration harmfulness. The parameters of the rating are the same as the parameters used in the case of GSI-GZWKW-2012 scale.

The GSIS-2017 scale contains seven levels of seismic intensity (from 0 to VI) related to assigned effects of free-field vibrations on buildings, linear underground infrastructure, and human perceptibility on vibrations and the discomfort of using structures in correlation with parameters of free-field vibration (see Figs. 5 and 6). The level of vibration intensity—IV, V, and VI—corresponds to the structural damage

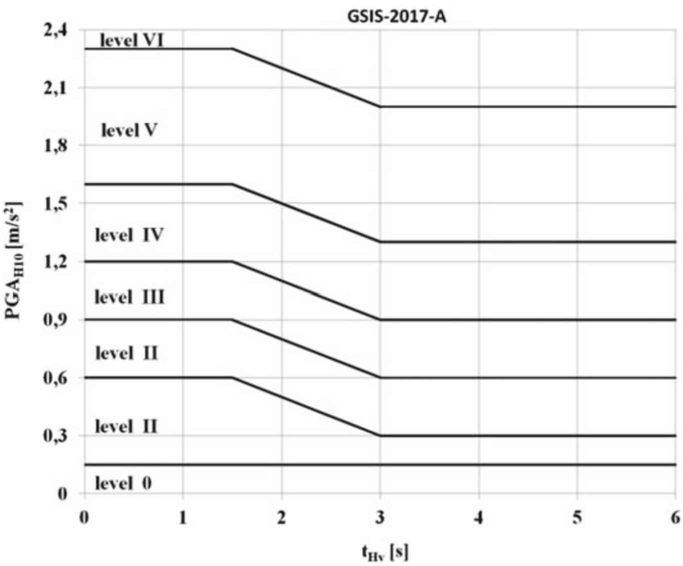

Fig. 6 The GSIS2017 scale in acceleration version

of buildings that may occur. We emphasize that measurements have not been verified for the VI-level intensity. Table 3 contains a description of results corresponding to human perception according to the GSIS-2017 scale.

3.2 The Results of Analysis Using GSIS-2017 Scale

As an example, Table 4 presents basic parameters of vibration records shown in Figs. 1, 2, 3, and 4 used in evaluation using GSIS-2017 scale. Figure 7 shows the results of evaluations of the surface vibrations intensity using velocity and acceleration versions of the GSIS-2017 scale for whole set of data.

Results presented in Figs. 7 and 8 indicate that parameters of whole analyzed records remain in level IV of the GSIS-2017 scale. It means that all people very strongly felt the vibrations, people are terrified, many scared people run outside, and some lose their balance.

3.3 The Basics of the Evaluation of the Impact of Mining Tremors to People According to Standards

In 2017, a new version of the Polish standard [22] appeared, which included the problems of evaluation of the impact of building vibrations on people passively receiving

Table 3 Results of mining-related corresponding to levels of intensity given in the GSIS-2017 scale

Level of vibration intensity *I GSIS*	Specification of results corresponding to human perception according to the GSIS-2017 scale
0	Imperceptible by people or weakly felt
I	Perceptible by people inside buildings, poorly felt by people outside. Hanging objects are swinging
II	Inside buildings, the vibrations are very much felt. The whole building is swaying slightly
III	Strongly felt by most people outside and inside buildings. Furniture can move. the whole building is rocking
IV	Very strongly felt by all people. People very scared. Many scared people run outside. Some lose their balance, especially on the upper floors. Small items fall from the shelves
V	The powerful and nagging sense of vibration. People have problems maintaining their balance in the upper threshold of vibration intensity. Large items fall from shelves and tables
VI	Widespread fear and panic. Turning and moving heavy objects such as furniture, unprotected TV sets etc

Table 4 Values of horizontal components parameters used in GSIS-2017 scale

Location of gauges	PGA_{H10}	t_{Ha}	PGV_H	t_{Hv}	PFA_{H10}	t_{Ha}	PFV_H	t_{Hv}
Free-field	1.69	1.54	0.06	1.3	–	–	–	–
Foundation	–	–	–	–	2.29	1.51	0.09	1.68

vibrations. The standard specifies formal criteria and evaluation methods. These vibrations may cause the reduction of people's quality of life and the effectiveness of their work. The ISO standards [1, 2] contain the weighting functions referring to people's reaction to building vibrations used in the Polish standard [22].

The bases for evaluation of the impact of mechanical vibrations on people staying in buildings are:

- measurement of the corrected acceleration (or velocity) of vibration in the entire frequency band
- measuring the spectral acceleration (or velocity) of vibration in one-third octave bands.

The vibrations excited by mining tremors do not entirely fall into the vibration classification given in the standard [22]. The duration of such vibrations is a few seconds, and they can happen once every few days or less frequently, although they can occur exceptionally in the same building and vibrate from two shocks during the day. Duration of mining-related vibration concerning the length of vibrations

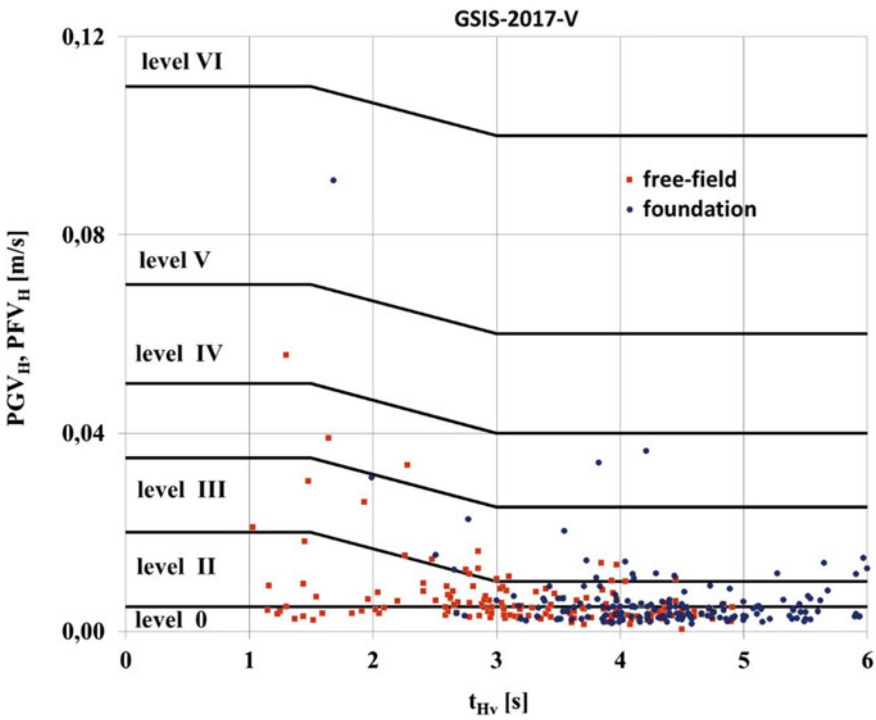

Fig. 7 Evaluations of the surface vibrations intensity using velocity version of the GSIS-2017V scale

defined in [22] as sporadic determines the difference of even in two powers. The vibration distribution given in the British standard [3] is more useful in the case of mining-related vibrations because, in this standard, it was adopted:

- continuous vibrations lasting 16 h a day and 8 h a night,
- "explosive" vibrations, rapidly increasing to the "peak" value and then diminishing due to damping and which may contain several vibration cycles (or not). These vibrations may also consist of suddenly operating several cycles of approximately the same amplitude, provided that their duration is short, less than 2 s. Besides, intermittent vibrations are determined. The so-called dose vibration value (concerning continuous vibrations occurring during 16 h a day and 8 h at night) is the base for evaluation of annoyance of intermittent vibrations.

According to standard [22], the measurement is carried out at the point where human percept vibration. Unfortunately, practically no vibrations from rockbursts are carried out in buildings, which can currently be used to assess their annoyance on people. Standard [3] allows making vibration measurements outside the structure or on the surface at points that are not vibration perception points for human. In

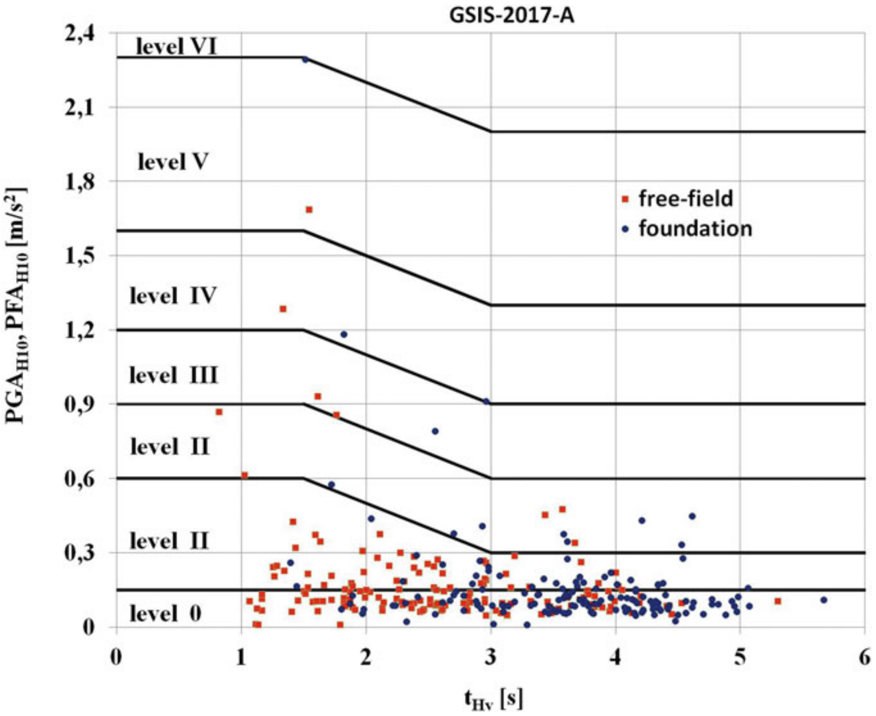

Fig. 8 Evaluations of the surface vibrations intensity using acceleration version of the GSIS-2017-A scale

such cases, the so-called transition functions, between the measuring point and the vibration perception point by a human, should be used.

In the case of "explosive" vibrations in the standard [22], it is proposed to treat the vertical components of vibration as the dominant one. In single-family houses, it is assumed that the vibrations measured at the building can be treated as vibrations on the ground floor of the building. Vertical components of vibrations (except buildings with wooden floors) in low and high buildings are similar to those at the bottom of the building. Such an approach is a significant simplification which may lead to incorrect evaluation results.

The root mean square (RMS) method is the base for evaluation of the impact of vibrations on humans given in the standard [22]. The RMS method has a physical interpretation that allows the evaluation of vibration energy. RMS is also a basic method of evaluation according to ISO standard [2]. The RMS method averages acceleration values in duration and the effective value of a_{RMS} of vibration acceleration a(t) is calculated according to the formula:

$$a_{RMS} = \sqrt{\left[\frac{1}{T}\int_0^T a^2(t)\mathrm{d}t\right]} \tag{1}$$

where:

a(t)—record of vibration acceleration, m/s^2

T—duration of measurement, s.

3.4 The Results of Analysis Using Standard Procedure

Following the regulations contained in the British Standard, in further analyses, these were used for vibration measurements outside the structure or on the surface at points that are not vibration perception points for human. The results of such analyses will be used to compare with the results obtained based on the GSIS scale. The examples of acceleration records shown in Figs. 1, 2, 3 and 4 were used for analysis by the RMS method in one-third octave frequency bands. The results allow assessing the human perception of horizontal ground vibration in the x and y directions—comp. Figs. 9 and 10. Figures 11 and 12 show the results of RMS analysis obtained based on lateral building vibration records in the x and y directions.

The free-field vibration in the x and y directions indicate that the threshold of vibrations perceptibility by people and the limit of comfort are exceeded. The building's foundation vibrations show that the comfort limit is not exceeded in the y-direction during the day, while in the x-direction it is on the edge of the comfort limit for

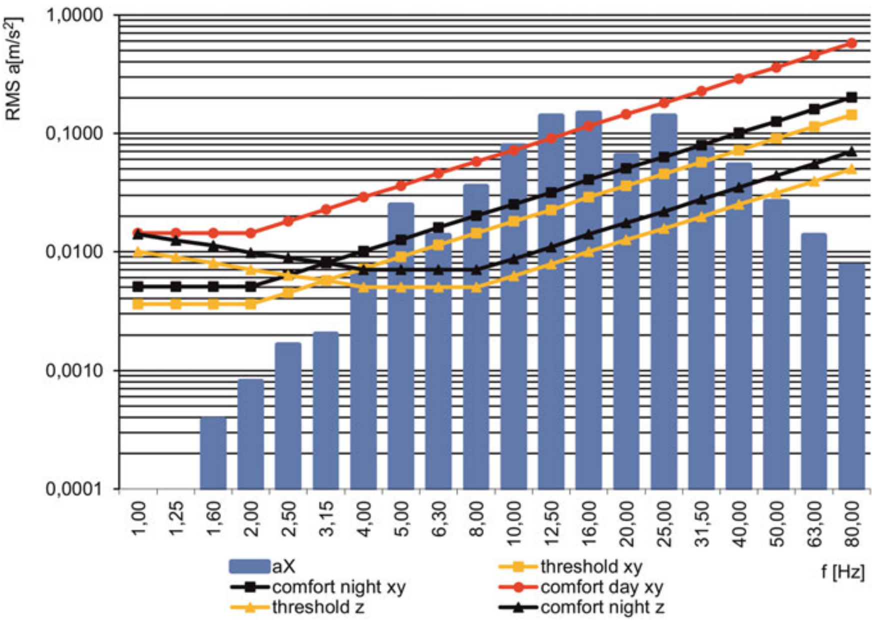

Fig. 9 Human perception of ground vibration in the x direction

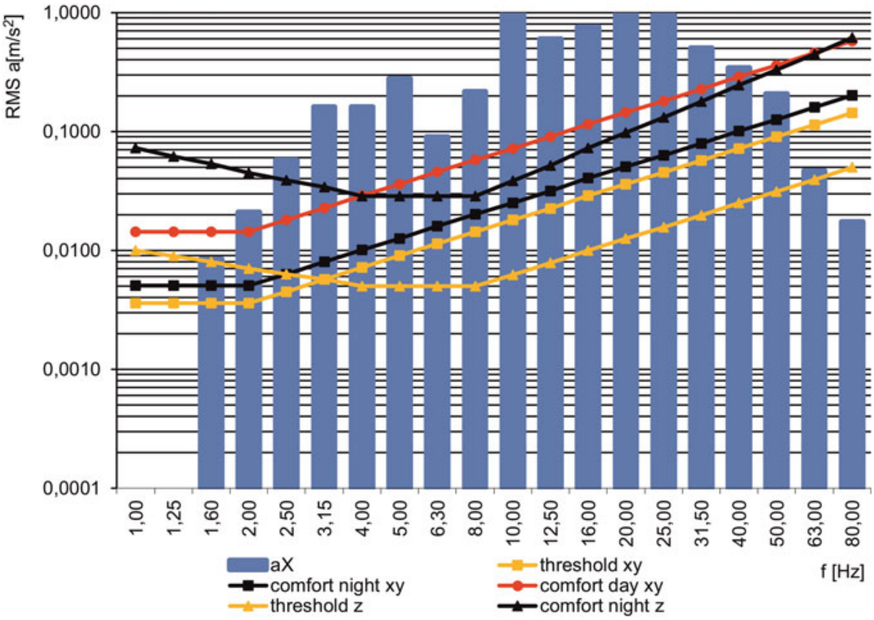

Fig. 10 Human perception of ground vibration in the y direction

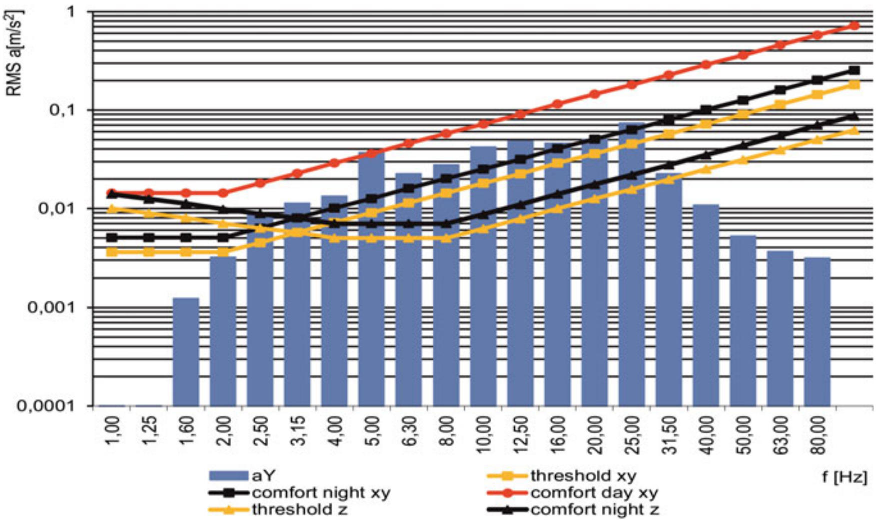

Fig. 11 Human perception of building vibration in the x direction

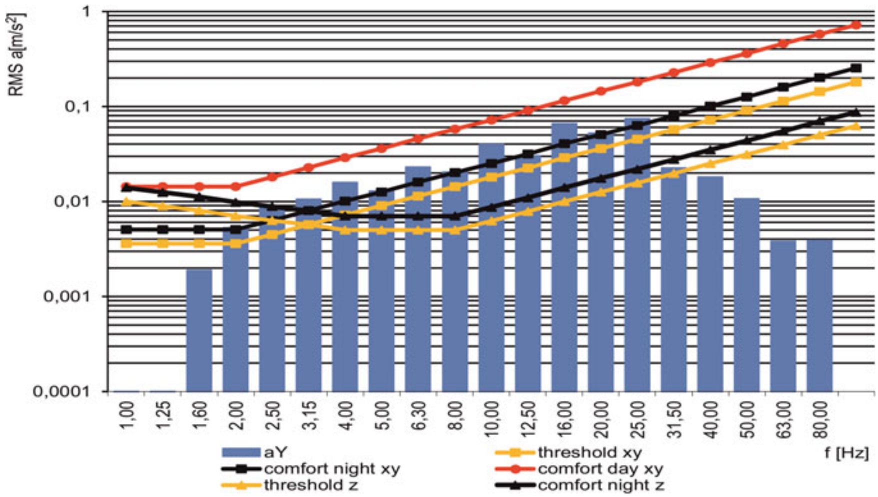

Fig. 12 Human perception of building vibration in the y direction

the day. For the night time, both the perception thresholds and the comfort limit are exceeded.

The analysis of vibrations from Figs. 1, 2, 3, and 4 indicates that the parameters of these vibrations remain in the fourth level of the GSIS-2017 scale. From the description of level IV (see Table 2), it is clear that many people very strongly felt such vibrations, and people are terrified. The results of analyses of assumed vibrations through the values of a_{RMS} and using the GSIS-2017 scale are similar. However, we emphasize that the results using the GSIS scale are very general. Analyses through a_{RMS} indicate frequency ranges in which the threshold of perceptibility and comfort limits are exceeded. These results can be used in the design of vibro-insulation in the field of reducing the level of perceived vibrations by humans.

4 Conclusions

The article undertakes a research problem concerning the impact of mining origin vibrations on people staying in buildings and passively receiving these vibrations. The analysis used the recorded free-field and foundation of the building vibrations in the mining area in the Upper Silesian Coal Basin. Measurements lasted eight years.

The study assessed the impact of horizontal mining vibration components on humans using the RMS method and the new mining intensity scales GSI-2017. The GSIS-2017 scale is an empirical scale. The questionnaire of the feelings of mining shocks by people was the basis for determining the levels of sensibility. Experiments made on people in the twentieth century from early 30s till 80s are the base for the

RMS method. The regulations of the second edition of ISO standard [23] contain the results of these experiments.

The analyses show that the most intense parameters of vibration remain at the fourth level of intensity, which means that such vibrations are strongly felt by people and cause fear. The results obtained using the GSIS-2017 scale and the RMS methods are comparable. The RMS method is more precise because it allows determining the threshold of perceptibility and comfort limits for people in buildings in the one-third octave bands.

The results of detailed analyses provide the basis for undertaking work to reduce the level of vibrations and their perceptibility by people. Such practices should be taken already at the stage of building design. In existing buildings, you can also try to limit the perception of vibrations on people by using vibro-insulation in a building.

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