TECHNICAL TRANSACTIONS 1/2017
CZASOPISMO TECHNICZNE 1/2017
CIVIL ENGINEERING
DOI: 10.4467/2353737XCT.17.005.6102

Krystyna Kuźniar
Institute of Technology, Faculty of Mathematics, Physics and Technical Science, Pedagogical University of Cracow

Tadeusz Tatara (ttatara@pk.edu.pl)
Institute of Structural Mechanics, Faculty of Civil Engineering, Cracow University of Technology

Simple models for determination of the differences of ground and building foundation response spectra in LGC region

Proste modele do wyznaczania różnic w spektrach odpowiedzi od drgań gruntu i drgań fundamentów budynków w LGOM

Abstract

The paper deals with the transmission of mine-induced vibrations in the LGC region from the ground to the foundations of typical buildings. The simple, easy-to-use models have been proposed for the determination of the differences (relations) between ground and foundation acceleration response spectra. Experimentally obtained acceleration response spectra from vibrations occurring simultaneously on the ground near the building and the building foundation were the basis for the verification of the accuracy of the proposed models.

Keywords: mining tremors, transmission of ground vibrations to building foundation, response spectra transmission

Streszczenie

Praca dotyczy przekazywania drgań pochodzenia górniczego w LGOM z gruntu na fundamenty typowych budynków. Zaproponowano proste, wygodne w stosowaniu, modele do wyznaczania różnic (relacji) w przyśpieszeniowych spektrach odpowiedzi od drgań gruntu i drgań fundamentów budynków. Weryfikacji dokładności proponowanych modeli dokonano, bazując na przyśpieszeniowych spektrach odpowiedzi od uzyskanych eksperymentalnie, jednocześnie mierzonych drgań gruntu obok budynków i fundamentów budynków.

Słowa kluczowe: wstrząsy górnicze, przekazywanie drgań z gruntu na fundament budynku, transmisja spektrów odpowiedzi

1. Introduction

Surface vibrations originating from mining rockbursts belong to the most intense, so-called paraseismic vibrations. Their random occurrence is one of the features of this type of vibrations, which causes significant problems in the analysis. Additional difficulties in assessing and forecasting the effect of mining related vibrations on buildings result from dynamic soil-structure interaction (SSI), including the significant differences that can be observed between simultaneously recorded free-field motion near the building and building foundation vibrations [5, 8, 12, 13, 18]. However, very often in practice, vibration measurements are conducted only on free-field (e.g. at the design stage of the building), while the use of building foundation vibrations allows for a more accurate assessment of the harmfulness of vibrations for the buildings [11]. Therefore, it is necessary to assess and predict the transmission of free-field motion to the building foundations. In the paper [2], response spectra of surface vibrations recorded in three mining areas of the Upper Silesian Coalfield (USC) were also established, indicating that the local ground properties may have a significant impact on the shape of the standard spectra.

In the works referring to the experimental examination of the soil-structure interaction, a comparison of the maximum values of ground motion near the building and the building foundation vibrations, recorded simultaneously, is often made in order to evaluate the transmission of free-field motion to the building foundations. This very simple way in the case of mining-related vibrations was used in e.g. [6, 8, 17].

A comparison of the curves of response spectra, obtained on the basis of mining origin vibrations, recorded simultaneously on the free-field near the buildings and on the building foundations, allows for a more advanced analysis of vibration transmission from the ground to the building foundations [5, 7, 13, 18]. A modification of this method, involving a calculation of the Ratio of Response Spectra (*RRS*), with respect to the free-field and the building foundation vibrations caused by rockbursts, is proposed in [9]. Such a method of assessing the SSI is commonly used for vibrations caused by earthquakes [3, 4, 16]. Simple approximate models for practical uses in the evaluation of the transmission of seismic vibrations from the ground to the building foundation are proposed in [3, 14–16]. The suitability (accuracy) of these models, proposed in the literature for vibrations of seismic origin, in the case of vibrations due to rockbursts in the Legnica-Głogów Copper District (LGC), was analysed in [10].

The paper proposes similar, simple empirical models in order to determine the differences (relationship) in acceleration response spectra, calculated on the basis of the free-field and building foundation vibrations, prepared for use in conditions of the LGC region. Separate models were established for the dimensionless acceleration response spectra (β) – model $RRS(\beta)$, and dimensional spectra (S_a) - model $RRS(S_a)$. Variants of the model were designed for use regardless of the type of building (universal models), as well as models intended for use separately in each of the groups of typical residential buildings in the mining region: low-, medium- and high-rise. All of the proposed models are based on the acceleration response spectra obtained using experimentally recorded free-field and building foundation vibrations in the LGC region.

2. Characteristics of experimental data

The work deals with the transmission of mining-related vibrations in the LGC region from the free-field to the building foundations. The analysed buildings can be treated as typical residential buildings in the mining region and as buildings that are representative in their classes. These are: low-rise, one-family, two-storey, masonry dwelling house (N); medium-rise, typical prefabricated (large-block), multiple-segment, five-storey building (S) and high-rise prefabricated (large-plate), two-segment, twelve-storey building (W). All of the considered buildings have basements and are founded on continuous footings. They are situated within a residential complex, at a short distance from each other. The free-field stations are located approximately 5 m from the N, S and W buildings in order to eliminate the influence of buildings' vibrations on the vibrations of the ground points. The epicentral distances of measurement stations N, S and W fluctuated between 913–1224, 614–1430 and 938–1163 m, respectively.

Rockbursts with energies of at least 10^6 J, which generated free-field vibrations, characterised by the measured maximum values of acceleration equal to at least 0.1 m/s^2, were the sources of vibrations.

Simultaneously measured pairs of acceleration records of horizontal vibrations of the free-field vibrations next to the building (a few meters from the building) and the building foundation vibrations (parallel to the transverse and the longitudinal axis of the building respectively) are taken into account in the case of each of the hundreds of considered mining rockbursts. The number of measured pairs of acceleration records of the free-field and the building foundation vibrations considered in the studies is as follows: in the case of N-type building – 111, in the case of the building S – 205, and for the W-type building – 181. The installed measuring equipment records the vibrations in the frequency range from 0.5 Hz to 100 Hz, and the maximum acceleration range is 3 m/s^2.

Dimensionless and dimensional acceleration response spectra (β and S_a respectively) have been calculated using the above-mentioned vibration records. A fraction of critical damping ξ was adopted to be equal to 3%, according to the experimental studies of damping of the considered types of buildings [1]. It can be stated that the response spectra calculated using the free-field and the building foundation records differ considerably, which is the result of a dynamic SSI.

For each pair of response spectra (ground - building foundation), corresponding ratios $RRS(\beta)$ for the dimensionless acceleration response spectra (β) and $RRS(S_a)$ for dimensional acceleration response spectra (Sa) are calculated according to formulae (1) and (2).

$$RRS(\beta)=\frac{\beta_f}{\beta_g} \tag{1}$$

$$RRS(S_a)=\frac{S_{af}}{S_{ag}} \tag{2}$$

where:

$RRS(\beta), RRS(S_a)$ – the ratio describing the transmission of response spectra from the ground to the foundation of the building, in the case of dimensionless and dimensional spectra respectively,

β_f, S_{af} – dimensionless and dimensional acceleration response spectrum from building foundation vibrations,

β_g, S_{ag} – dimensionless and dimensional acceleration response spectrum from free-field vibrations near the building.

Using the ratios *RRS* for particular rockbursts, averaged relationships (*RRS*) were computed for all pairs of the vibrations recorded on the free-field and on the foundations of the buildings N, S and W as well as the averaged relations *RRS* for the considered types of buildings.

Averaged ratios *RRS*(β) and *RRS*(S_a), determined on the basis of the acceleration records of the free-field and buildings foundations for all types of the considered buildings, are shown in Fig. 1. On the other hand, Fig. 2 contains averaged ratios *RRS*(β) and *RRS*(S_a) prepared separately for buildings corresponding to the classes of low-rise buildings (N), medium-rise buildings (S) and high-rise buildings (W).

It is visible that the average graphs *RRS*(β) corresponding to the dimensionless response spectra (β) differ from the corresponding average curves *RRS*(S_a), which were prepared on the basis of the dimensional response spectra (S_a). This observation applies to both the average relations *RRS* for all pairs of the ground-foundation determined in the case of all buildings of type N, S and W, as well as separately for each of the considered types of buildings (N, S, W). The values of the average relations *RRS*(S_a) are significantly smaller (especially in the range of the lower frequencies) than the corresponding values of the *RRS*(β). Therefore, there is clearly a greater reduction of ordinates of response spectra Sa compared with the response spectra β [9].

It is also observed that the averaged curves of the *RRS*, prepared separately in the cases of buildings of different types (N, S, W), are different. This applies to both the relations of *RRS*(β) and *RRS*(S_a) [9].

It is evident that for frequencies higher than 15 Hz, the relations *RRS* are practically constant for all variants of *RRS* shown in Fig. 1 and Fig. 2.

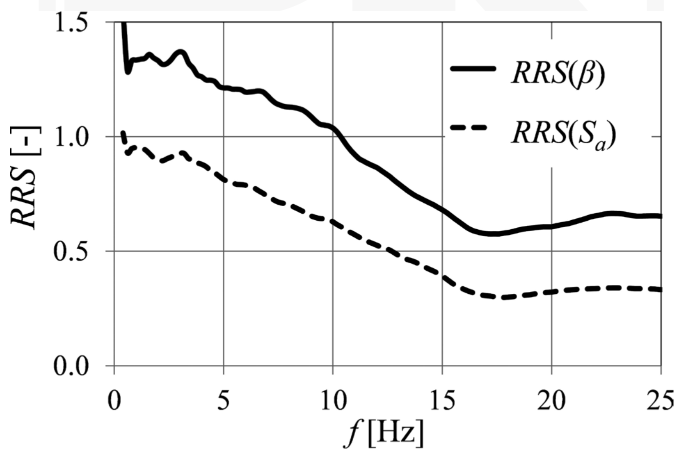

Fig. 1. Averaged relations RRS(β) and RRS(Sa) determined on the basis of vibration acceleration records on free-field near the buildings and foundations vibrations for all types of buildings

Moreover, *RRS* curves shown in Fig. 1 and Fig. 2 confirm the phenomenon that is observed in the dynamic SSI – buildings of all considered types "operate as a low pass filter", and so in the transmission of vibrations from the free-field to the building foundation, dampen vibrations of the ground with higher frequencies [9].

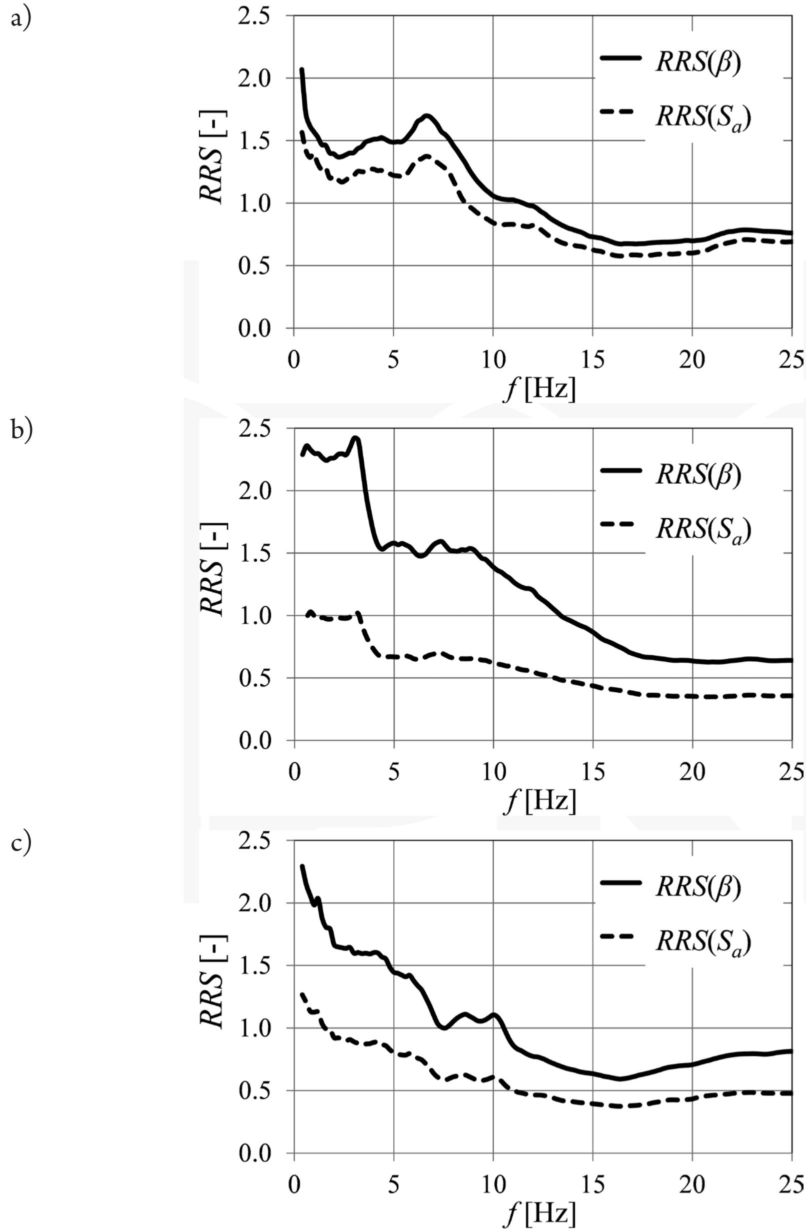

Fig. 2. Averaged relations RRS(β) and RRS(Sa) determined on the basis of vibration acceleration records on free-field and foundation vibration for building: a) low-rise (type N), b) medium-rise (type S), c) high-rise (type W)

3. Empirical transmission models of the response spectra from the free-field to the buildings foundations

In [10], the suitability (accuracy) of simple approximate transmission models of the response spectra from the ground to the building foundations was analysed, which in the literature are proposed for earthquake vibrations [3, 14–16], in application to the vibrations originating from rockbursts in the Legnica-Głogów Copper District (LGC). It can be found that the application of these models (i.e. models designed for taking into account the phenomenon of dynamic SSI in the case of earthquakes) to the prognosis of acceleration response spectra originating from the building foundation vibrations on the basis of appropriate response spectra from free-field motion in the case of rockbursts in the LGC region, results in a relatively high inaccuracy of prediction [10].

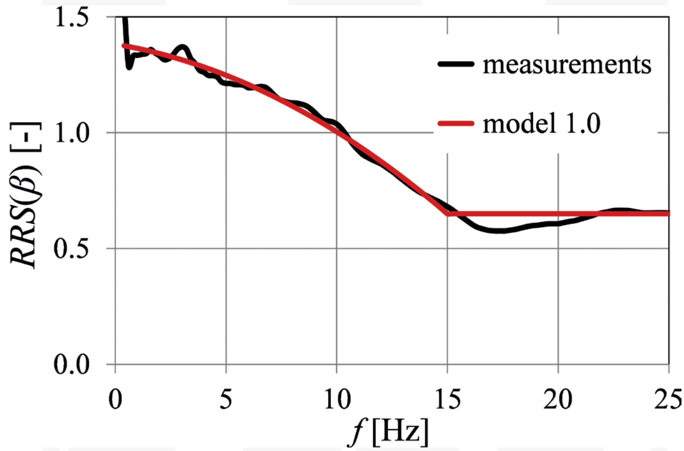

Fig. 3. Averaged relation RRS(β) determined on the basis of vibration acceleration records on free-field and buildings foundations of all types and for model 1.0

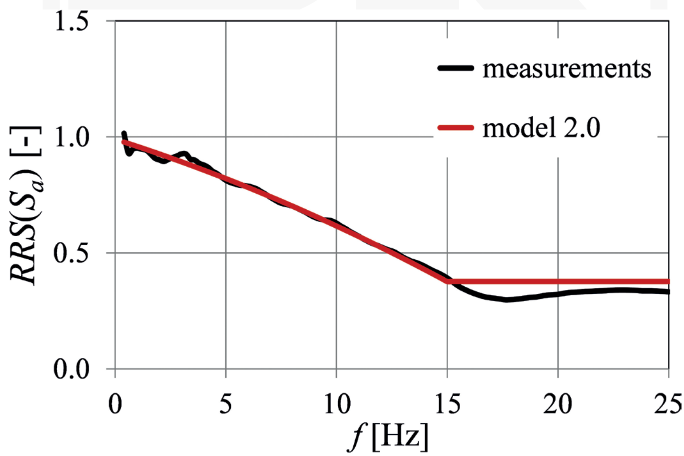

Fig. 4. Averaged relation RRS(Sa) determined on the basis of vibration acceleration records on free-field and buildings foundations of all types and for model 2.0

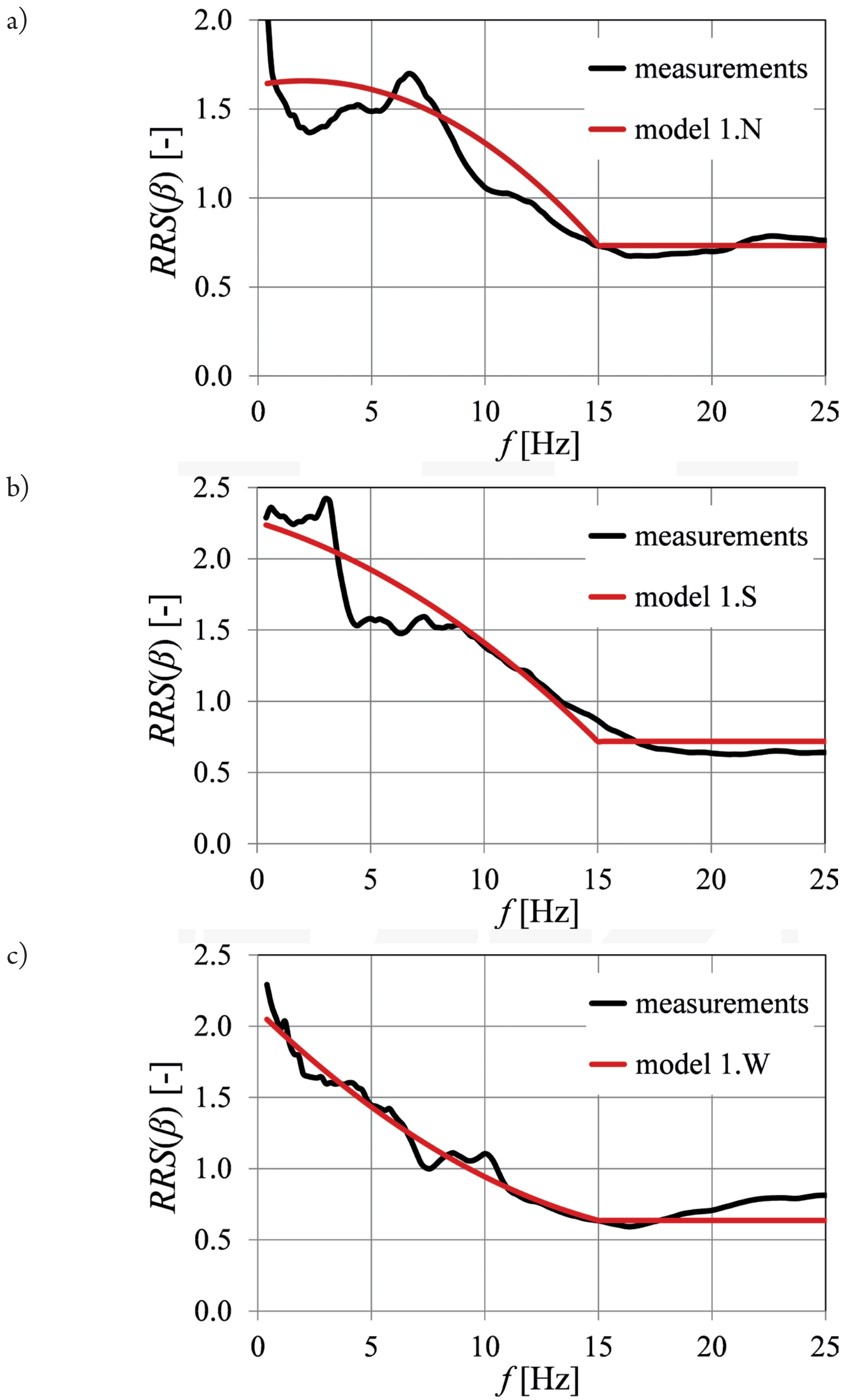

Fig. 5. Averaged relations RRS(β) determined on the basis of vibration acceleration records on free-field and buildings foundations vibrations and the proposed models for buildings: a) low-rise (type N), b) medium-rise (type S), c) high-rise (type W)

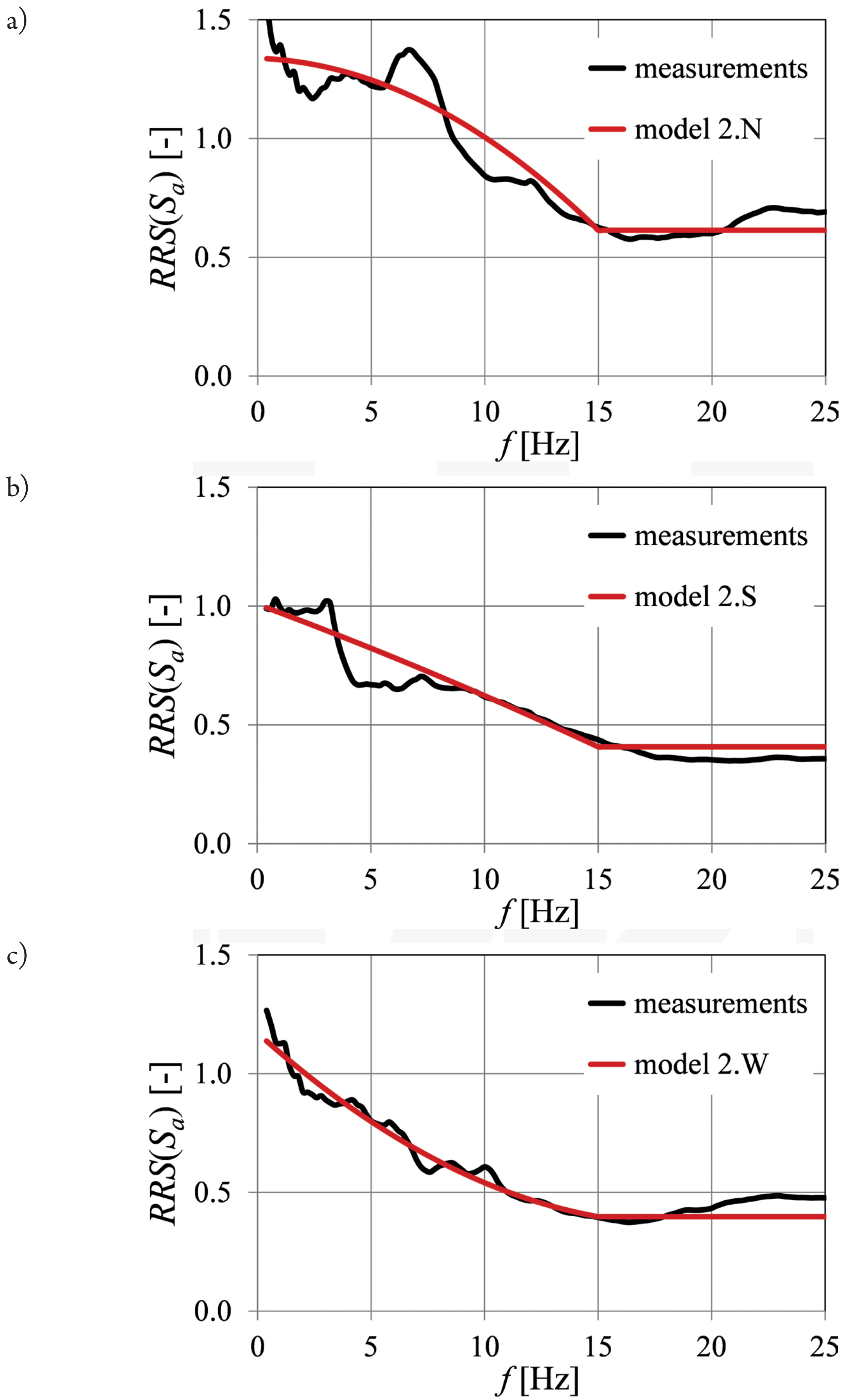

Fig. 6. Averaged relations RRS(S_a) determined on the basis of vibration acceleration records on free-field and buildings foundations vibrations and the proposed models for buildings: a) low-rise (type N), b) medium-rise (type S), c) high-rise (type W)

This paper proposes similar, simple, empirical models in order to determine the differences (relations) in the response spectra from the ground and the building foundation vibrations, prepared with the intention of using them in the LGC region conditions. These models are nearing match position to the nature of rockbursts originating vibrations and the characteristics of substrate in the LGC region.

Separate models were constructed for the dimensionless acceleration response spectra (β) – models $RRS(\beta)$, and dimensional spectra (S_a) – models $RRS(S_a)$.

Variants of the models have been developed for use regardless of the type of building ("universal" models), which are denoted as: model 1.0 for $RRS(\beta)$ and model 2.0 for $RRS(S_a)$.

Also, models intended for use separately in each of the groups of common residential buildings in this mining region: low-rise (N), medium-rise (S) and high-rise (W), have been alternatively treated. They have been denoted consecutively as: model 1.N, model 1.S and model 1.W in the case of modelling of the transmission of non-dimensional spectra (β), and model 2.N, model 2.S and model 2.W in the case of dimensional spectra (S_a) transmission.

A graphical illustration of the above-mentioned models is shown in the red line in Figs. 3–6, and their equations are given in Table 1 and Table 2.

It is worth mentioning that all the proposed models are based on the acceleration response spectra from vibration records measured during dynamic investigations in the free-field situation near the buildings and building foundations in the LGC region.

Table 1. The equations of the proposed models of empirical relation $RRS(\beta)$ for use in the cases of dimensionless response spectra β

Model	Application	Equations of the models	
		$f < 15$ Hz	$f \geq 15$ Hz
1.0	buildings of the type N, S, W	$-0.0022f^2 - 0.0158f + 1.3822$	0.650
1.N	buildings of the type N	$-0.0055f^2 + 0.0223f + 1.6362$	0.733
1.S	buildings of the type S	$-0.0036f^2 - 0.0486f + 2.2577$	0.719
1.W	buildings of the type W	$0.0037f^2 - 0.1537f + 2.1100$	0.637

Table 2. The equations of the proposed models of empirical relation $RRS(S_a)$ for use in the cases of response spectra S_a

Model	Application	Equations of the models	
		$f < 15$ Hz	$f \geq 15$ Hz
2.0	buildings of the type N, S, W	$-0.0007f^2 - 0.0304f + 0.9903$	0.377
2.N	buildings of the type N	$-0.0030f^2 - 0.0033f + 1.3386$	0.614
2.S	buildings of the type S	$-0.0003f^2 - 0.0355f + 1.0078$	0.408
2.W	buildings of the type W	$0.0023f^2 - 0.0861f + 1.1720$	0.398

4. Results of the calculations with the use of proposed models

Fig. 3 compares the averaged relation *RRS*(β), determined on the basis of acceleration vibration records measured on the free-field near the buildings and on the building foundations of all types with the graph for model 1.0. On the other hand, separately averaged relations *RRS*(β) in the cases of buildings type N, type S and type W, and graphs of appropriate models proposed for separate use for each type of the buildings are compared in Fig. 5. A similar comparison corresponding to the average relations $RRS(S_a)$ and graphs for the model 2.0, model 2.N, model 2.S, and model 2.W, is given in Fig. 4 and Fig. 6.

The accuracy of the proposed models for use as a potential tool for the prediction of differences in the free-field and the building foundation mining-related vibrations was assessed using the Pearson correlation coefficient and average values of relative errors.

Table 3 presents the average values of relative errors of the prediction of the average relations *RRS*(β) using the proposed models as well as the corresponding linear Pearson correlation coefficients. Similar results relating to the average relations *RRS*(Sa) are shown in Table 4.

In both tables, the results are given separately for the whole considered range of vibration frequencies ($f \leq 25$ Hz) and for the range of relatively low frequencies of particular importance from a practical point of view ($f \leq 15$ Hz).

A very good fit of models constructed for use in the cases of different types of buildings during the transmission of the dimensionless spectra (β) as well as the dimensional spectra (S_a) is visible. However, also the use of "universal" models (model 1.0, model 2.0) allows to predict the average values of *RRS*(β) and $RRS(S_a)$ with satisfactory accuracy. These applications relate to the whole frequency range and, separately, relatively low frequency range. Moreover, in all the proposed variants of models, the adoption of a constant value *RRS* for frequencies exceeding 15Hz simplifies the structures of the models without loss of their accuracy.

Table 3. Pearson correlation coefficients and average values of relative errors of *RRS*(β) obtained using the proposed empirical models in relation to the results of experimental research

Type of building	Model	Pearson correlation coefficients [-]		Average values of relative errors [%]	
		$f \leq 15$ Hz	$f \leq 25$ Hz	$f \leq 15$ Hz	$f \leq 25$ Hz
N	1.0	0.902	0.955	12.0	13.3
	1.N	0.913	0.957	9.2	11.7
S	1.0	0.909	0.964	28.5	18.8
	1.S	0.918	0.967	8.8	9.5
W	1.0	0.936	0.926	13.1	12.3
	1.W	0.983	0.980	4.8	7.6
N, S, W	1.0	0.989	0.993	1.9	3.3

Table 4. Pearson correlation coefficients and average values of relative errors of $RRS(S_a)$ obtained using the proposed empirical models in relation to the results of experimental research

Type of building	Model	Pearson correlation coefficients [-]		Average values of relative errors [%]	
		$f \leq 15$ Hz	$f \leq 25$ Hz	$f \leq 15$ Hz	$f \leq 25$ Hz
N	2.0	0.919	0.956	33.4	36.2
	2.N	0.932	0.957	7.9	7.4
S	2.0	0.915	0.963	8.1	7.2
	2.S	0.923	0.965	6.8	8.9
W	2.0	0.957	0.942	7.6	9.8
	2.W	0.985	0.981	3.7	6.4
N, S, W	2.0	0.997	0.995	15.3	7.1

5. Conclusions

The study presents empirical models for the evaluation of the differences (relations) in the acceleration response spectra originating from the free-field and the building foundations vibrations. These models have been prepared for use in the case of mining rockbursts in the Legnica-Głogów Copper District.

In practice, the proposed simple, approximate models can be used for prediction of the response spectra from the building foundation vibrations on the basis of response spectra from the free-field motion near the buildings.

The form of the developed models can be treated as the preliminary base proposal. The objective of further attempts of models' modification would be the construction of a common model for different types of buildings, but taking into account the information about the differences in their structure, and therefore also their dynamic properties.

References

[1] Ciesielski R., Kuźniar K., Maciag E., Tatara T., *Damping of vibration in precast buildings with bearing concrete walls*, Arch. Civ. Eng., Vol. 41, 3, 1995, 329–341.

[2] Czerwionka L., Tatara T., *Wzorcowe spektra odpowiedzi z wybranych obszarów GZW (Standard response spectra from chosen mining regions at Upper Silesian Coalfield)*, (in Polish), Czasopismo Techniczne, Vol. 2-B/2007, 11–18.

[3] FEMA 440, *Improvement of Nonlinear Static Seismic Analysis Procedures*, ATC-55 Project, 2005.

[4] Kim S., Stewart J.P., *Kinematic soil-structure interaction from strong motion recordings*, Journal Geotechnical and Geoenvironmental Engineering, Vol. 129, 4, 2003, 323–335.
[5] Kuźniar K., *Analiza drgań budynków ścianowych o średniej wysokości podlegających wstrząsom górniczym z wykorzystaniem sieci neuronowych (Analysis of vibrations of medium-height buildings with load bearing walls subjected to mining tremors using neural networks)*, (in Polish), Monografia 310, Inżynieria Lądowa, Wyd. Politechnika Krakowska, Kraków 2004.
[6] Kuźniar K., *Zastosowanie sieci neuronowych w prognozowaniu przekazywania drgań pochodzenia górniczego z gruntu na fundament budynku (Application of neural networks for the prediction of mine-induced vibrations transmission from the ground to building foundation)*, (in Polish), Inżynieria i Budownictwo, Vol. 1, 2014, 43–47.
[7] Kuźniar K., Maciąg E., Tatara T., *Acceleration response spectra from mining tremors*, First European Conference on Earthquake Engineering and Seismology (ECEES), Geneva 2006, Switzerland, Abstract Book, 466–467 (full paper on CD).
[8] Kuźniar K., Tatara T., *Przekazywanie drgań od wstrząsów górniczych z gruntu na fundamenty budynków różnego typu (Influence of building type on the transmission of mine-induced vibrations from the ground to building fundaments)*, (in Polish), Przegląd Górniczy, Vol. 6, 2014, 30–34.
[9] Kuźniar K., Tatara T., *Wpływ typu budynku na transmisję spektrów odpowiedzi od drgań górniczych z gruntu na fundamenty (The influence of building type on the transmission of response spectra of vibrations induced by mining tremors from the ground to building foundations)*, (in Polish), Przegląd Górniczy, Vol. 10, 2015, 31–36.
[10] Kuźniar K., Tatara T., *Zastosowanie przybliżonych modeli SSI w przypadku wstrząsów górniczych (Application of approximate SSI models in case of mining tremors)*, (in Polish), Przegląd Górniczy, Vol. 10, 2015, 25–30.
[11] Maciąg E., *Ocena szkodliwości drgań budynków od wstrząsów górniczych na podstawie drgań ich fundamentów czy drgań gruntu (Evaluation of harmfulness of mining tremors for buildings based on their foundations or free-field vibrations?)*, (in Polish), Inżynieria i Budownictwo, 12, 2005, 670-677.
[12] Maciąg E., *Interakcja układu budynek-podłoże gruntowe w świetle doświadczalnego badania drgań parasejsmicznych (Subsoil-building interaction due to the impact of paraseismic vibrations)*, (in Polish), Inżynieria Morska i Geotechnika, 4, 2006, 240–250.
[13] Maciąg E., Kuźniar K., Tatara T., *Spektra odpowiedzi drgań gruntu i fundamentów budynków od wstrząsów górniczych w LGOM Response spectra of ground and foundations of buildings vibrations caused by mining tremors in LGOM)*, (in Polish), [in:] K. Stypuła (ed.), *Aktualne problemy wpływów sejsmicznych i parasejsmicznych na budowle (Current problems of influence of seismic and paraseismic on buildings)*, Vol. II, *Badania wstrząsów górniczych i drgań komunikacyjnych (The investigation of mining tremors and communication vibrations)*, Monografia 477/2, Seria Inżynieria Lądowa, Wydawnictwo PK, Kraków 2015, 39-66.
[14] Mikami, A., Stewart, J.P., Kamiyama, M., *Effects of time series analysis protocols on transfer functions calculated from earthquake accelerograms*, Soil Dynamics and Earthquake Engineering, Vol. 28, 9, 2008, 695–706.

[15] Mylonakis G., Nikolaou S., Gazetas G., *Footings under seismic loading: Analysis and design issues with emphasis on bridge foundations*, Soil Dynamics and Earthquake Engineering, Vol. 48, 26, 2006, 824–853.
[16] NIST GCR 12-917-21, *Soil-Structure Interaction for Building Structures, prepared by NEHRP Consultants Joint Venture (a partnership of the Applied Technology Council and the Consortium of Universities for Research in Earthquake Engineering)*, 2012.
[17] Tatara T., *Działanie drgań powierzchniowych wywołanych wstrząsami górniczymi na niską tradycyjną zabudowę mieszkalną (An influence of surface mining-related vibration on low-rise buildings)*, (in Polish), Zeszyty Naukowe Politechniki Krakowskiej, seria Inżynieria Lądowa, Vol. 74, Kraków 2002.
[18] Tatara T., *Odporność dynamiczna obiektów budowlanych w warunkach wstrząsów górniczych (Dynamic resistance of buildings in mining tremors conditions)*, (in Polish), Wyd. Politechniki Krakowskiej, Kraków 2012.