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IMPACT ASSESSMENT OF EPICENTRAL DISTANCES AND ENERGIES OF MINING SHOCKS ON THE TRANSMISSION OF FREE-FIELD VIBRATIONS TO THE BUILDING FOUNDATIONS

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Abstract. *The study analyses the results of measurements of mining related surface vibrations in the Legnica-Glogow Copper Region (LGCR) to assess the impact of mining tremor epicentral distances as well as mining tremors energies on a curve relationship (ratio) of response spectra (RRS) from simultaneously measured free-field vibrations and building foundations vibrations. The sources of considered vibrations were mine-induced rockbursts resulting from underground exploitation of copper ore. Only records induced by rockbursts with energy higher than* 10^6 *J and horizontal components of peak ground accelerations larger than* $10 cm/s^2$ *are analysed. Epicentral distances of considered mining shocks are in the range* $re = 270 – 5839$ *m and energies are in the range* $En = 1{\cdot}10^6 – 2{\cdot}10^9$ *J. Dimensionless acceleration response spectra (β) as well as dimensional acceleration response spectra* (S_a) *from the horizontal vibrations were taken into account. The focus is on residential buildings – medium-rise building and high-rise building. The results of analyses show that the epicentral distance of mining shock can have a significant impact on the transmission of response spectra from the free-field to the residential building foundations (medium-rise building and high-rise building). This effect is more visible in the case of curves RRS(β) determined using dimensionless acceleration response spectra β than curves* RRS(S_a) *calculated for corresponding pairs for dimensional spectra* S_a*. The appropriate conclusions regarding the influence of mining tremors energies also have been achieved.*

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1 INTRODUCTION

Soil-structure interaction problems are extensively studied with respect to earthquake excitations. However the ground motion can be induced not only by earthquakes, but also by so-called paraseismic sources resulted from human activity. Surface vibrations originating from mining rockbursts belong to the most intensive such vibrations. Although the intensity of mining tremors is smaller than in the case of natural earthquakes, mining-induced ground motion also can result in damage of surface structures.

During the transition of vibrations from the free-field to the building there is the phenomenon so-called dynamic soil-structure interaction. A comparison of a huge number of records of accelerations of vibrations induced by mining tremors measured at the same time on the ground near the building and on the building foundation level leads to conclusion that they can differ significantly [1].

The paper analyses the results of measurements *in-situ* of mine-induced surface vibrations in the most seismically active mining area in Poland – Legnica-Glogow Copper Region (LGCR), to assess the impact of mining rockbursts parameters (epicentral distances as well as mining tremors energies) on a curve relationship (ratio) of response spectra (*RRS – Ratio of Response Spectra*) from simultaneously measured free-field vibrations and building foundations vibrations in the cases of typical actual apartment medium-rise and high-rise buildings.

2 SCOPE OF THE STUDIES OF EXPERIMENTAL DATA

Mine-induced rockbursts resulting from underground exploitation of copper ore in Legnica-Glogow Copper Region in Poland were the sources of considered vibrations. Only records induced by rockbursts with energy higher than 10^6 J and horizontal components of peak ground accelerations larger than $10 cm/s^2$ are analysed. Epicentral distances of considered mining shocks are in the range re=270–5839 m and energies are in the range En=$1{\cdot}10^6$–$2{\cdot}10^9$ J.

The focus is on actual residential buildings – medium-rise (5-storey) building denoted as building M, and high-rise (12-storey) building denoted as H building. The M and H buildings are wall-bearing walls, prefabricated objects. They have basements, continuous footings as foundations and they are located close to each other in one housing estate.

Fundamental frequencies of natural vibrations (f_1) experimentally determined in horizontal directions of the buildings are equal respectively: 2.9–3.3 Hz in a direction parallel to the transverse axis (x) and 2.9–3.1 Hz in a direction parallel to the longitudinal axis (y) in the case of building M, as well as 1.44–1.50 Hz in a direction parallel to the transverse axis (x) and 2.06–2.17 Hz in a direction parallel to the longitudinal axis (y) in the case of building H [1].

Simultaneously measured pairs of records of horizontal vibration accelerations of the free-field vibrations next to the building and the building foundation vibrations (parallel to the x and y axis of the building respectively) were taken into account in the case of each of the considered mining rockbursts. Next, dimensionless acceleration response spectra (β) as well as dimensional acceleration response spectra (S_a) from the horizontal vibrations were calculated. According to the results of experimental analysis relating to damping of considered types of buildings [2], the fraction of critical damping ξ was adopted equal to 3%.

The number of analysed pairs (free-field – building foundation) of acceleration response spectra β and S_a in the successive ranges of epicentral distances are listed in Table 1, whereas the number of analysed pairs of these spectra for the successive orders of magnitude of rockbursts energies are shown in Table 2. The orders of magnitude of rockbursts energies 10^6J, 10^7J, 10^8J, 10^9J are denoted as E6, E7, E8, and E9 respectively. It is worth mentioning that the numbers included in Table 1 and Table 2 refer to the data with precisely verified values of epicentral distance or mining tremor energy and only such data were taken into analysis.

re [m]	Response spectra β		Response spectra S_a	
	Building M	Building H	Building M	Building H
to 500	2	3	2	3
501 – 800	29	12	26	11
801 – 1100	28	51	22	44
1101 – 1700	27	23	25	17
1701 – 2500	44	41	34	24
over 2501	60	47	44	25
whole range	190	177	153	124

Table 1: Summary of the number of analysed pairs (free-field – building foundation) of response spectra (β and S_a) in the successive ranges of epicentral distances.

En [J] – order of magnitude	Response spectra β		Response spectra S_a	
	Building M	Building H	Building M	Building H
E6	41	37	40	24
E7	84	97	67	64
E8	42	41	30	34
E9	8	2	6	2
whole range	175	177	143	124

Table 2: Summary of the number of analysed pairs (free-field – building foundation) of response spectra (β and S_a) for the successive orders of magnitude of rockbursts energies.

3 THE IMPACT OF ROCKBURSTS PARAMETERS ON THE TRANSMISSION OF GROUND MOTIONS TO THE BUILDINGS

3.1 Relationship between building foundation input and free-field ground motions

The response spectrum enables the evaluation of the maximum response of a given structure to seismic-type ground motion. The application of response spectra is well known in earthquake engineering, for instance, in the design process of buildings [3 – 5].

Comparison of the response spectra curves obtained on the basis of mining origin vibrations simultaneously recorded on free-field near the buildings and on building foundations allows for analysis of the one of the soil structure interaction effects – vibration transmission from the ground to the building foundations [1, 6, 7].

Modification of this method involves the calculation of the Ratio of Response Spectra (*RRS*) with respect to free-field and building foundation vibrations [8 – 11].

For each pair of response spectra (free-field – building foundation) corresponding ratios $RRS(\beta)$ for the dimensionless acceleration response spectra (β) as well as $RRS(S_a)$ for dimensional acceleration response spectra (S_a) are calculated according to formulae (1) and (2) respectively:

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

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

where:

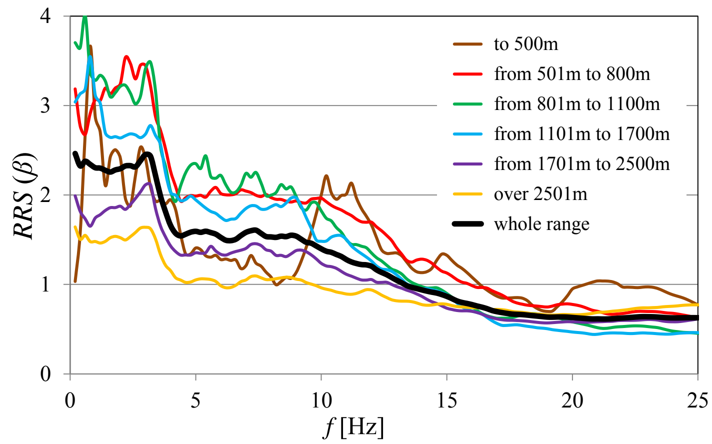
$RRS(\beta)$, $RRS(S_a)$ – relationship (ratio) describing the transition of response spectra from the free-field to the building foundation in the case of dimensionless and dimensional acceleration response spectra respectively,
β_f, S_{af} – respectively dimensionless and dimensional acceleration response spectrum originating from the building foundation vibrations,
β_g, S_{ag} – respectively dimensionless and dimensional acceleration response spectrum obtained on the basis of free-field vibrations next to the building.

3.2 The influence of epicentral distances of mine-induced tremors on the ratio of response spectra

Ratios $RRS(\beta)$ for the dimensionless acceleration response spectra (β) as well as $RRS(S_a)$ for dimensional acceleration response spectra (S_a) were used to try to assess the impact of epicentral distances of mining tremors on the transition of free-field vibrations to the building foundations.

Separately, for the building M and the building H, each of the relationship $RRS(\beta)$, and the relationship $RRS(S_a)$ defined for each of the considered mining shock, is placed into one of six groups. The criterion for assigning *RRS* relation to the group was the epicentral distance of the mining shock. Successive ranges of epicentral distances which correspond to the established relationship groups *RRS* are presented in Table 1.

a)



b)

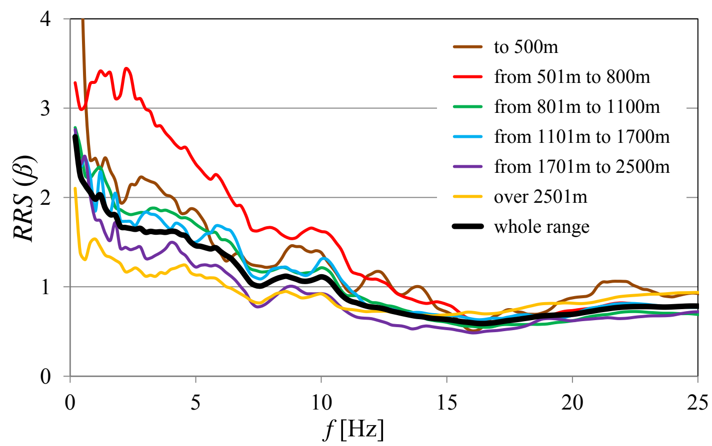
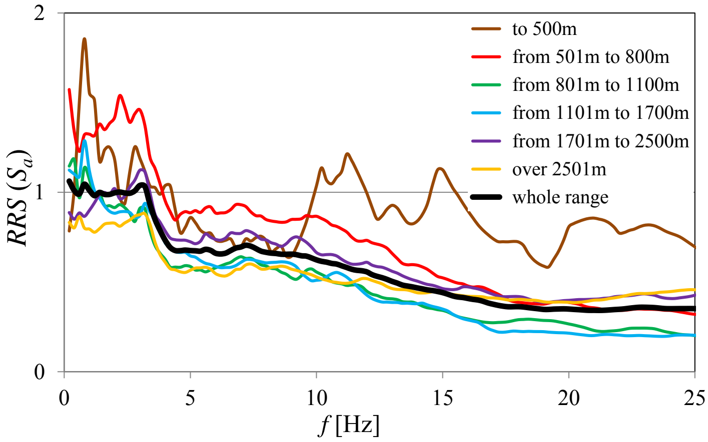


Figure 1: Relations $RRS(\beta)$ averaged in the ranges of mining tremors epicentral distances: a) building M; b) building H.

a)



b)

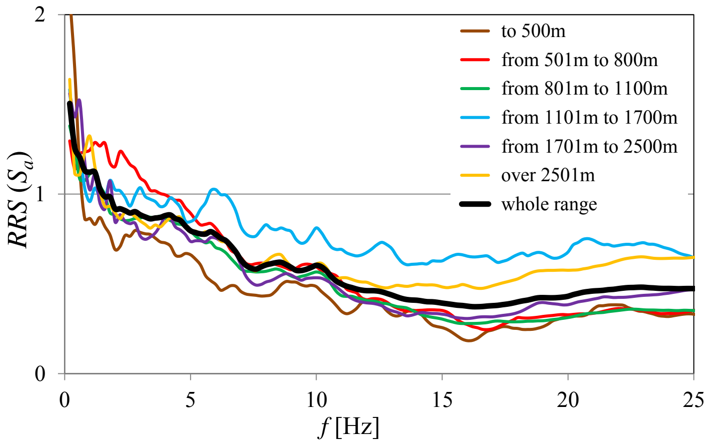


Figure 2: Relations $RRS(S_a)$ averaged in the ranges of mining tremors epicentral distances: a) building M; b) building H.

Averaged relationships were determined in each set of relationship $RRS(\beta)$ and $RRS(S_a)$. They corresponded to the range of epicentre distances. Furthermore, averaged relationships $RRS(\beta)$ and $RRS(S_a)$ were also calculated in the whole range of epicentral distances of the considered mining shocks, both in the case of the building M and the building H.

Fig. 1 shows relationships $RRS(\beta)$ averaged in the considered ranges of epicentral distances of mining tremors, for the building M and the building H. Analogous curves prepared for the ratios $RRS(S_a)$ are presented in Fig. 2.

Significant differences in the curves $RRS(\beta)$ and $RRS(S_a)$ which were obtained by averaging of the collections referring to individual ranges of epicentral distances, are visible (cf. Fig. 1 and Fig. 2) for both of the building cases: the building M as well as the building H, especially for the ratios $RRS(\beta)$.

Moreover the graphs of *RRS* made for the individual epicentral distance ranges clearly distinguish from curves averaged in all over the range of distances.

These differences are especially evident at frequencies important from a practical point of view, namely in the relatively low frequency range (to approx. 10 Hz).

Additionally, Table 3 contains the values of ratios of $RRS(\beta)$ and $RRS(S_a)$ averaged within the adopted ranges of epicentral distances, which correspond to the appropriate mean values of the fundamental frequency of natural vibrations f_1 in the x and y directions of the building M as well as the building H.

re [m]	Building M – f_1 = 3 Hz		Building H – f_1 = 1.8 Hz	
	$RRS(\beta)$	$RRS(S_a)$	$RRS(\beta)$	$RRS(S_a)$
to 500	2.41	1.19	2.18	0.77
501 – 800	3.45	1.46	3.11	1.17
801 – 1100	3.41	0.91	1.89	0.90
1101 – 1700	2.68	0.87	2.05	1.08
1701 – 2500	2.11	1.12	1.72	1.07
over 2501	1.64	0.88	1.30	0.93
whole range	2.45	1.04	1.80	0.98

Table 3: Values of $RRS(\beta)$ and $RRS(S_a)$ corresponding to the frequencies of natural vibrations f_1 of M and H buildings, averaged in the successive ranges of epicentral distances.

It is visible that substantial differences may occur in the values (ordinates) $RRS(\beta)$ and $RRS(S_a)$ corresponding to the natural fundamental frequencies of building vibrations, calculated in the individual ranges of epicentral distances (cf. Table 3). For example, both in the case of the building M and the building H, value $RRS(\beta)$ in the range of epicentral distances within 501 – 800 m is approximately twice greater than calculated for epicentral distances within the range over 2,501 meters. However, the differences in the values *RRS* corresponding to the natural fundamental frequencies of the buildings from the individual intervals of epicentral distances, in relation to the values *RRS* averaged in all over the range of epicentral distances, reach tens percent.

3.3 The influence of energies of mine-induced tremors on the ratio of response spectra

Ratios $RRS(\beta)$ as well as $RRS(S_a)$ were also used to estimate the impact of the order of magnitude of rockbursts energy on the transition of free-field vibrations to the building M and the building H foundations.

Analogously as it was for the case of analysis of the influence of the rockburst's epicentral distance on the ratios of response spectra, the curves of relations $RRS(\beta)$ as well as relations $RRS(S_a)$ averaged for the successive orders of magnitude of rockbursts energies were prepared for the buildings M and H. These graphs are shown in Fig. 3 and Fig. 4, respectively.

Furthermore, in Table 4, the values of $RRS(\beta)$ and $RRS(S_a)$ corresponding to the fundamental frequencies of natural vibrations f_1 of M and H buildings, averaged for the successive orders of magnitude of rockbursts energies are collected.

It is visible that just as it can be observed in the case of epicentral distance impact, the value of mining tremor energy also plays important role in the transmission of free-field vibrations to the building foundations, in the case of medium-rise building as well as in the case of high-rise building.

Also similar, clear differences between the graphs of *RRS* performed for the individual orders of magnitude of rockbursts energies, and the curves averaged in all over the range of energies, are visible.

Both in the case of the building M, and the building H, in ordinates of relationship *RRS* referring to the dimensionless acceleration response spectra (β) prepared in the individual successive orders of magnitude of rockbursts energies, there are bigger differences than in the analogous relationship *RRS* based on dimensional acceleration response spectra (S_a).

An interesting, very clear trend can be observed in Fig. 3 which concerns the ratio $RRS(\beta)$: the smaller values of mining tremors energies the greater ordinates of $RRS(\beta)$, both in the cases of the M and H buildings.

a)

b)

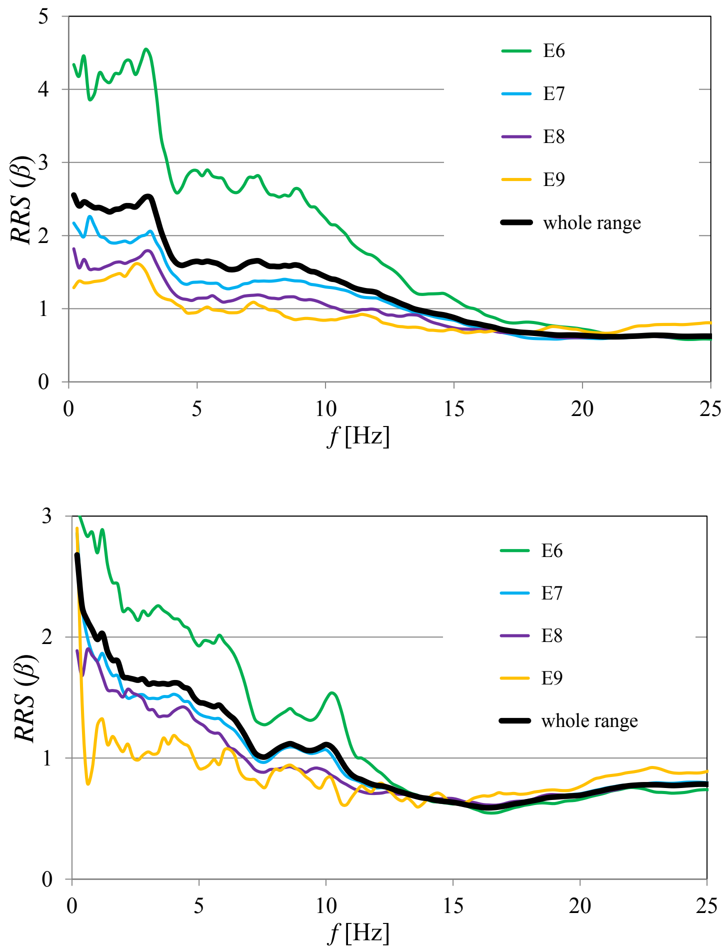


Figure 3: Relations *RRS*(β) averaged for the successive orders of magnitude of rockbursts energies: a) building M; b) building H.

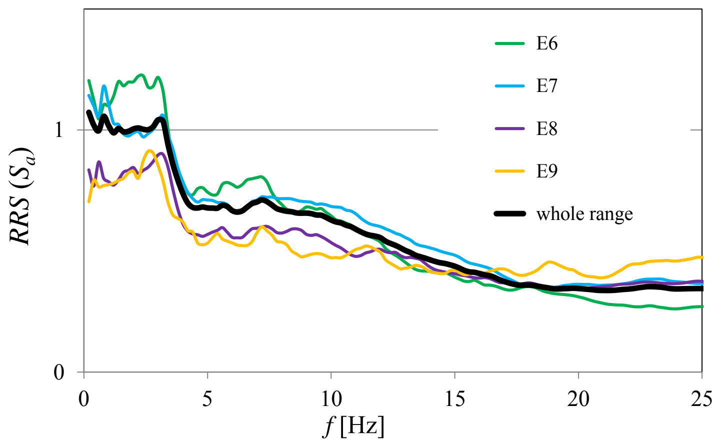
Similarly as in the case of the influence of epicentral distances on the features of *RRS* graphs, practically, in all of the individual successive orders of magnitude of rockbursts energies is not seen significant dependence of differences in the relationship *RRS*(β) referring different building construction of buildings M and H versus values of mining tremor energy.

However, much greater differences than in the previous results of analysis regarding to epicentral distances, may concern the values of *RRS*(β) and *RRS*(S_a) corresponding to the fundamental frequencies of natural vibrations of the buildings averaged in the individual ranges of energies (cf. Table 4).

For instance, in the case the building M, value of *RRS*(β) averaged for the order of magnitude of mining tremor energy equal 10^6 (E6) is three times greater than the corresponding value obtained for the energy with the order of magnitude equal 10^9 (E9). In the analogous proportion for the building H, the value of *RRS*(β) for the energy E9 is approximately twice smaller than the value for the energy E6.

Besides, the differences in the values of *RRS* corresponding to the fundamental natural frequencies of building vibrations, calculated for the individual intervals of energies, in relation to the values *RRS* averaged in all over the range of energies, respectively reach: the building M, *RRS*(β) – approx. 80%, *RRS*(S_a) – approx. 17%; the building H, *RRS*(β) – approx. 36%, *RRS*(S_a) – approx. 3%.

a)



b)

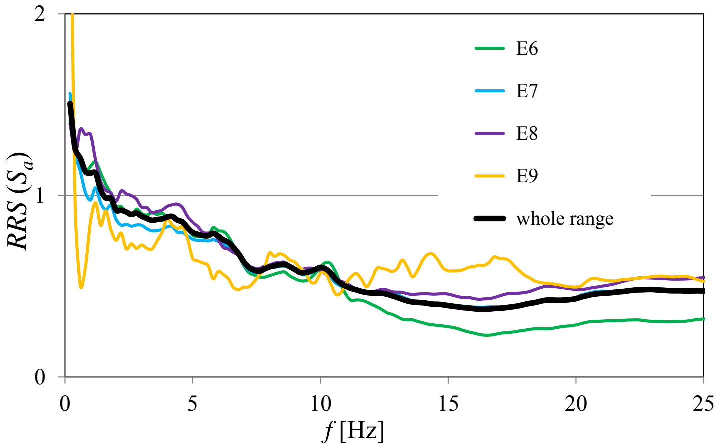


Figure 4: Relations *RRS*(S_a) averaged for the successive orders of magnitude of rockbursts energies: a) building M; b) building H.

En [J] – order of magnitude	Building M – f_1 = 3 Hz		Building H – f_1 = 1.8 Hz	
	RRS(β)	*RRS*(S_a)	*RRS*(β)	*RRS*(S_a)
E6	4.45	1.22	2.44	1.01
E7	2.01	1.03	1.68	0.94
E8	1.79	0.90	1.55	1.01
E9	1.51	0.85	1.11	0.81
whole range	2.53	1.04	1.80	0.98

Table 4: Values of *RRS*(β) and *RRS*(S_a) corresponding to the frequencies of natural vibrations f_1 of M and H buildings, averaged for the successive orders of magnitude of rockbursts energies.

4 CONCLUSIONS

From the results of analyses it can be stated that the epicentral distance of mining rockburst as well as the order of magnitude of the value of mining tremor energy, can have a significant impact on the transmission of response spectra from the free-field to the apartment medium-rise building and high-rise building foundations. This effect is clearer visible in the case of curves *RRS*(β) determined using dimensionless acceleration response spectra β than in the case of curves *RRS*(S_a) calculated for analogous pairs of dimensional response spectra S_a.

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