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Rockburst induced ground motion—a comparative study

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Abstract

While rockbursts from underground copper mining in Western Poland normally produce surface peak ground accelerations (PGA) and velocities of 0.05–0.1 g and 1–3 cm/s, occasionally these peak motions may exceed 0.15 g and 10 cm/s, respectively. These larger motions are of considerable concern and an investigation has been undertaken to define the nature of these larger induced ground motions. This paper compares these rockburst motions with low intensity earthquakes. Various strong motion parameters such as PGA, peak ground velocity (PGV) and displacements as well as strong motion duration, Arias intensity, Fourier and response spectra are compared with those from earthquakes. It is concluded that although short duration is the most obvious parameter that differentiates rockbursts from earthquakes, in fact their high dominant frequencies, which result in high PGA/PGV ratios differentiate them the most. Two types of rockburst-induced ground motions are indicated in this paper: typical—with 3–6 months return period and characteristic, high frequency content—as well as rare events similar to shallow, low intensity earthquakes.

Keywords: Mines; Rockbursts; Ground motion; Response spectra

1. Introduction

Nowadays structural vibrations induced by ground motion can be caused not only by earthquakes but also by the activity of man. On the one hand, traffic vibrations and industrial explosions may be regulated to control the potential for cosmetic cracking (Dowding [3]). On the other hand, rockbursts and reservoir-induced ground quakes are random events with respect to their time, magnitude and place although this randomness is not as obvious as for earthquakes. The event from March 13th 1989 in Germany near Merker ($M_L = 5.4$), which caused injuries to three people and substantial damage to buildings proved that these problems should be treated seriously by civil engineers. Rockbursts belong to a broader category of ground failures caused by human activities. These ground failures together with typical chemical explosions are subject of detailed studies to differentiate them from underground nuclear explosions. The research in this field is sponsored by various governmental and international organizations for the benefits of proper implementation of the Nuclear Test Ban Treaty [1]. This research is concentrated at teleseismic (>2000 km) or regional (>1000 km) epicentral distances whereas the surface effects of the mine-induced ground quakes can usually be observed only at near field distances of less than 10–20 km around mines.

With respect to surface intensity, rockbursts should be classified right after underground nuclear explosions, but before surface mine explosions and construction blasts. The latter two phenomena were studied extensively by Duvall and Fogelson [17], Siskind et al. [2] as well as by Dowding [3]. It was concluded that surface particle velocity was the parameter directly correlated with the amount of damage observed for buildings located in the vicinity of blast activity (coal surface mines, quarries). It was also noted that the spectral content of blast-induced ground vibrations was shifted towards higher frequencies as compared to earthquakes or nuclear explosions.

Rockbursts occur when accumulated stresses fracture intact rock, usually ahead of an advancing mine face (Fig. 1). Johnston [10] gives more precise definition describing six various mechanisms of rockbursts. She also divided rockbursts into two general categories: Type I—directly correlated with mining activity with low to medium magnitude and type II—only loosely correlated with mining activity and with focus in wider area around the mine, but with potentially higher magnitude. From civil engineering point of view, particular attention should be paid to the events of type II which occur randomly, with return period of a few months to a few years.

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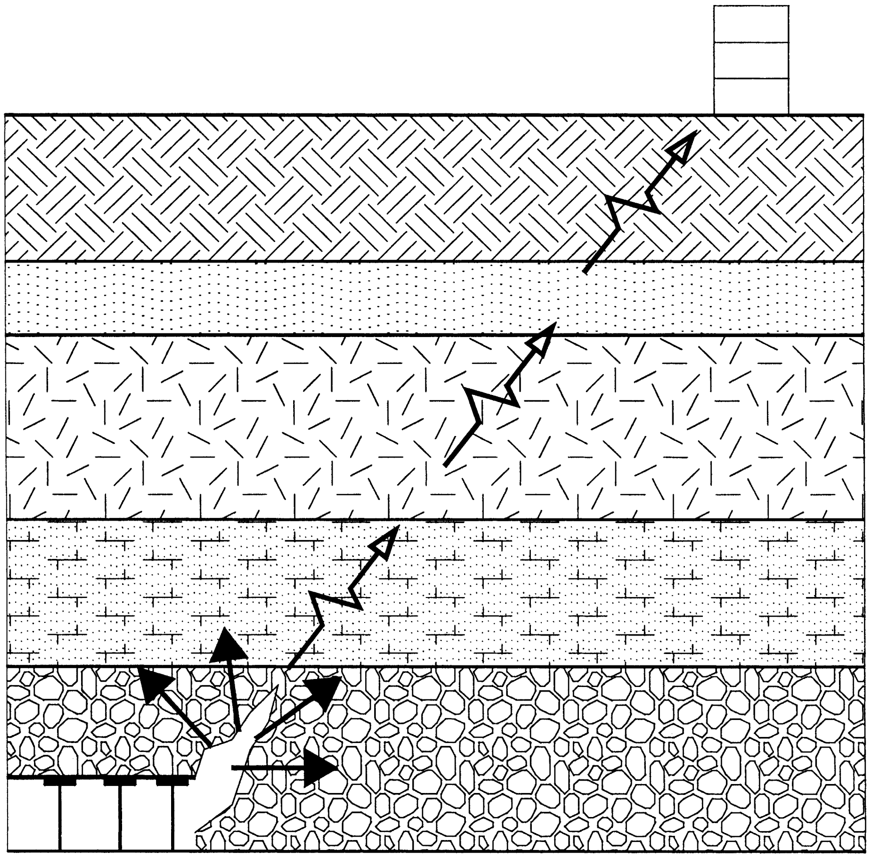

Fig. 1. Sketch schematically showing mine-induced rockburst.

Mine-induced rockbursts can occur in many countries. When mines are located in the vicinity of cities, rockbursts may affect life of ordinary people and at the extreme may cause some damages to buildings or equipment. Rockbursts are usually carefully monitored by special geophysical services of mines, which are primarily interested in the safety of the crews working below the surface of the earth, so networks of measuring devices are installed below the ground and at selected places on the surface. These problems are extensively studied from seismological point of view [4,5]. From the results of seismological research, one may see that almost every mine has its own specifics, generating particular type of ground motion, depending on the type of ore, technology and local geology. These local differences are usually much more pronounced compared to regional differences of earthquakes. In spite of substantial seismological research, these studies often do not meet direct civil engineering needs as they are concentrated on physics of the events and on statistical models of their occurrences rather than on spectral and peak ground parameters [4].

The purpose of this paper is to present results of an analysis of recorded ground motions during rockbursts taking place in the vicinity of a copper mine from Western Poland. Classic seismic strong motion parameters like peak ground accelerations (PGA), velocity (PGV), displacements (PGD), strong motion duration as well as Fourier and response spectra of the mine tremors are calculated and compared with the same parameters from earthquakes. The main aim of this study is to better assess the intensities of mine seismic events and investigate the differences and similarities of rockbursts and earthquakes. Such comparison is the first step to adapt methods of seismic engineering to mitigate rockbursts effects on buildings.

2. Ground motion parameters

For the purpose of this study, the ground motion parameters can be divided into four categories

- descriptive intensity parameters (local Mercalli intensities),
- energy measures of ground motion records like Arias [6] intensity,
- measures of peak ground motion (acceleration—PGA, velocity—PGV and displacements—PGD),
- spectral parameters (Fourier and response spectra),
- measures of strong motion duration.

The local Mercalli intensities applied here are Modified Mercalli (MM), Medvedev, Sponhauer Karnik (MSK-64) and Mercalli, Cancani, Sieberg (MCS). The first two of them (MM and MSK-64) can be treated as almost identical for civil engineering purposes [7]. The third (MCS) differs more, though not very substantially [8].

The Arias intensity, as applied in this study, is a direct measure of energy transmitted through the ground surface

$$I_A = \int_0^{t_k} a^2(\tau)\mathrm{d}\tau \quad (1)$$

where $a(t)$ is the acceleration record with total duration t_k. Using this definition and the notion of so called Husid plot

$$H(t) = \frac{\int_0^t a^2(\tau)\mathrm{d}\tau}{\int_0^{t_k} a^2(\tau)\mathrm{d}\tau} \quad (2)$$

the definition of strong motion duration t_d as the time for the Husid plot to stay between 5 and 95% can be formulated. This definition of strong motion duration has been proposed by Trifunac and Brady [9].

To measure variations in spectral content of the accelerograms, one may need not only to see plots of Fourier and response spectra, but also to formulate some quantitative parameters. The simplest parameter of this kind can be formulated as mean, or central frequency calculated here in Hz as follows

$$f_{\mathrm{centr}} = \frac{1}{2\pi} \frac{\int_0^\infty \omega S(\omega)\mathrm{d}\omega}{\int_0^\infty S(\omega)\mathrm{d}\omega} \quad (3)$$

where $S(\omega)$ is the power spectral density (Fourier spectrum) of the analyzed record. The integral in the numerator is a spectral moment. So the result of Eq. (3) can be interpreted as value of abscissa of center of gravity of the figure described by the plot of spectral density $S(\omega)$.

Except for descriptive Mercalli intensities, all the other ground motion parameters are separately defined for each of three Cartesian axes x, y, z. To apply these parameters independently of the instrument orientation, they should be reformulated separately for one horizontal and the vertical direction. The latter one remains the same as there is only one vertical axis, whereas from two horizontal records along x and y axes, one measure should be derived. From civil engineering point of view, the role of horizontal and vertical excitations is different, as buildings differ with respect to their horizontal and vertical properties. In particular, vertical building stiffness is usually much grater than the horizontal one.

The peak ground motion parameters (PGA, PGV and PGD) are formulated as vertical and horizontal, with the latter ones being just surface maxim: $\max\sqrt{x^2 + y^2}$.

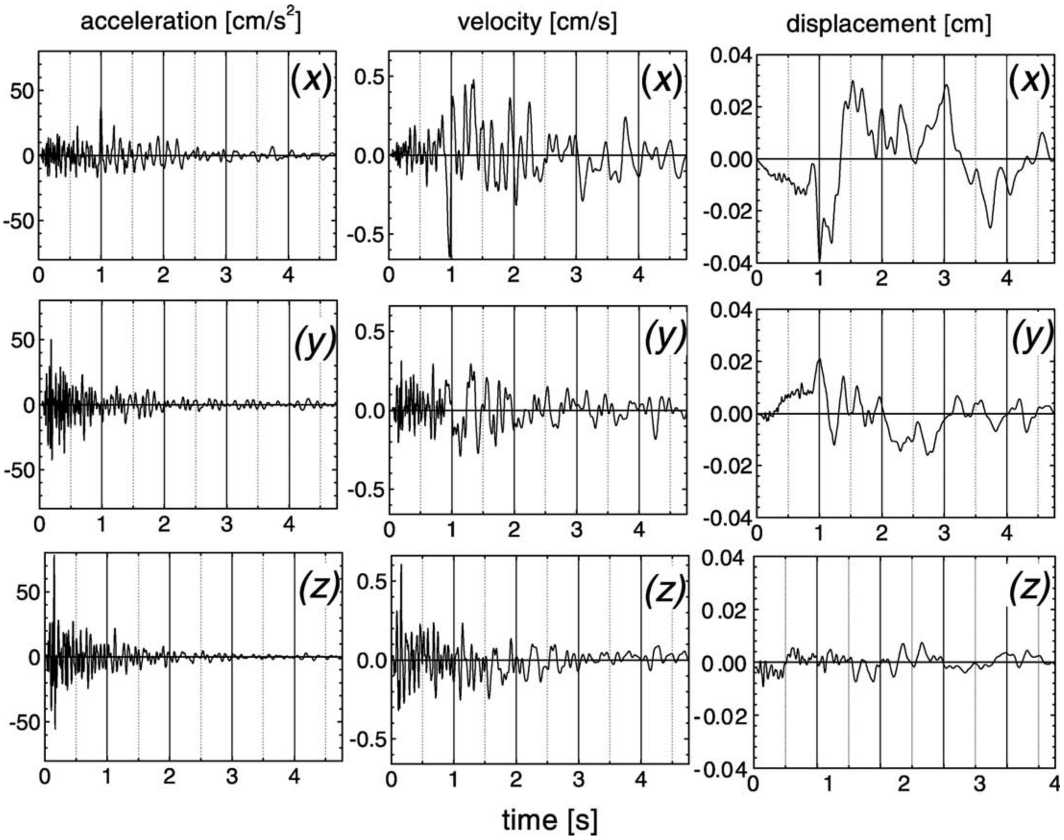

Fig. 2. Time history measurements of a rockburst from February 2nd 2001 (station '3 Maja', g03), horizontal x, y and vertical z.

The horizontal and vertical Arias intensities can be formulated as follows:

$$I_A^{hor} = \frac{1}{2}\int_0^{t_k} [a_x^2(\tau) + a_y^2(\tau)]d\tau \quad (4a)$$

$$I_A^{ver} = \int_0^{t_k} a_z^2(\tau)d\tau \quad (4b)$$

The horizontal and vertical strong motion durations are formulated from appropriately modified Husid plots

$$H^{hor}(t) = \frac{\int_0^{t} [a_x^2(\tau) + a_y^2(\tau)]d\tau}{\int_0^{t_k} [a_x^2(\tau) + a_y^2(\tau)]d\tau} \quad (5a)$$

$$H^{ver}(t) = \frac{\int_0^{t} a_z^2(\tau)d\tau}{\int_0^{t_k} a_z^2(\tau)d\tau} \quad (5b)$$

Analogously, the horizontal and vertical central frequencies may be defined as follows

$$f_{centr}^{hor}(\omega) = \frac{1}{2\pi}\frac{\int_0^{\infty} [\omega S_x(\omega) + \omega S_y(\omega)]d\omega}{\int_0^{\infty} [S_x(\omega) + S_y(\omega)]d\omega} \quad (6a)$$

$$f_{centr}^{ver}(\omega) = \frac{1}{2\pi}\frac{\int_0^{\infty} \omega S_z(\omega)d\omega}{\int_0^{\infty} S_z(\omega)d\omega} \quad (6b)$$

Both horizontal Arias intensity and horizontal central frequency can be viewed upon as averaged values of these quantities derived from respective values measured on x and y axes.

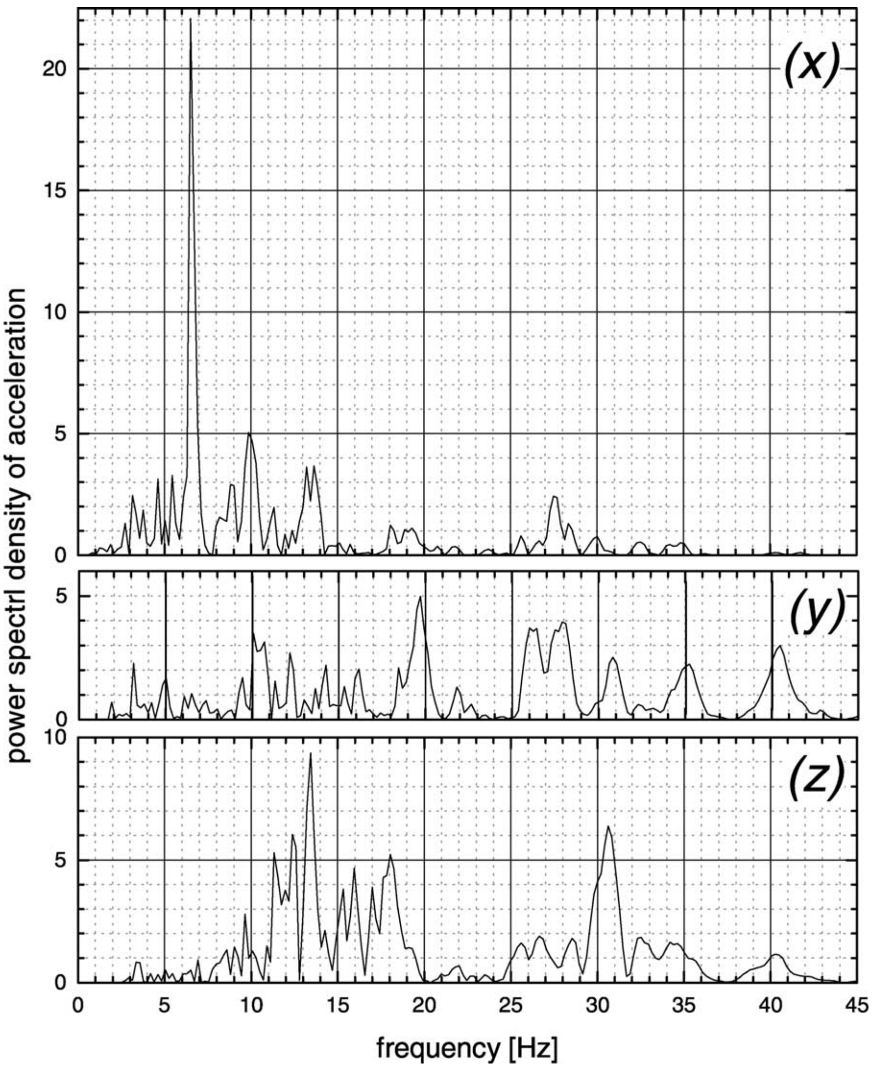

Fig. 3. Fourier spectra of a rockburst from February 2nd 2001 (station '3 Maja', g03), horizontal x, y and vertical z.

3. Comparative study

The copper mine 'Rudna' is situated close to a small town Polkowice (about 20,000 inhabitants). It is a part of a copper 'LGOM' basin consisting of also a few other, smaller mines. Typical buildings of the Polkowice are small, residential masonry buildings and prefabricated reinforced concrete residential buildings of 6 and 11 stories with natural periods of 0.5–0.9 s. The mine operates at depths of 600–1000 m practically below the whole town and neighboring villages. For this reason, the surface network of measuring devices is located within the radius of about 6–8 km inside and around the city. The instruments are installed at the foundations of some buildings as well as on the ground. Most of the instruments measure three components of accelerations. Some devices measure also velocity. The measurements are triggered by events with PGA exceeding 10 cm/s^2. Stronger mine tremors occur with return period longer than 3–6 months causing usually only minor damage, mostly to non-structural elements of the buildings. The local magnitude (M_L) of the strongest rockbursts reach 4–4.5 for Lubin–Polkowice region. It is rather high value as compared with other mining regions of the world (Table 2 in Ref. [10]). The largest rockbursts in the region belong to type II, i.e. they are strong and occur randomly. The geologic conditions of the mine and its neighborhood favor accumulation and sudden releases of energy in the calcium–dolomite and anhydrite rocks overlying the exploited deposit [11] and do not cause greater static ground deformations met in many coal mine regions. On the other hand, the surface layers of soil are not particularly susceptible to amplification phenomena as the shear wave velocity in the upper soil layer equals about 400–600 m/s [12]. For each detected rockburst, the geophysical services calculate approximate energy release and location of epicenter. Typical energies of strongest rockbursts equal for this mine 10^6–10^9 J. It should be noted, however, that the greatest surface effects (e.g. PGA or PGV) are not directly correlated with the maximal energies.

The main purpose of the reported research was to assess the intensity and destructive capacities of the rockbursts as compared to earthquakes. The investigations were motivated by unusually high peak ground accelerations as for rockbursts, often exceeding 0.1 g as well as controversies regarding the assessments of local intensities of the measured events. These problems are important for the mine authorities when responding to numerous claims of local residents for damages to buildings or equipment.

Fig. 2 presents typical time history record of surface ground motion caused by a rockburst. As it can easily be seen, the characteristic feature of the mine tremor is its very short duration. But this is not the only difference. Observing the velocities and displacements reveals their small values as compared to earthquakes with similar values of PGA. Another difference can be seen in Fig. 3, which shows respective Fourier spectra of the accelerations from Fig. 2. It can be seen from this figure that the spectral content display clear shift of the dominating parts of the plots into higher frequencies as compared with the earthquakes. Fig. 4 presents respective response spectra which show in turn

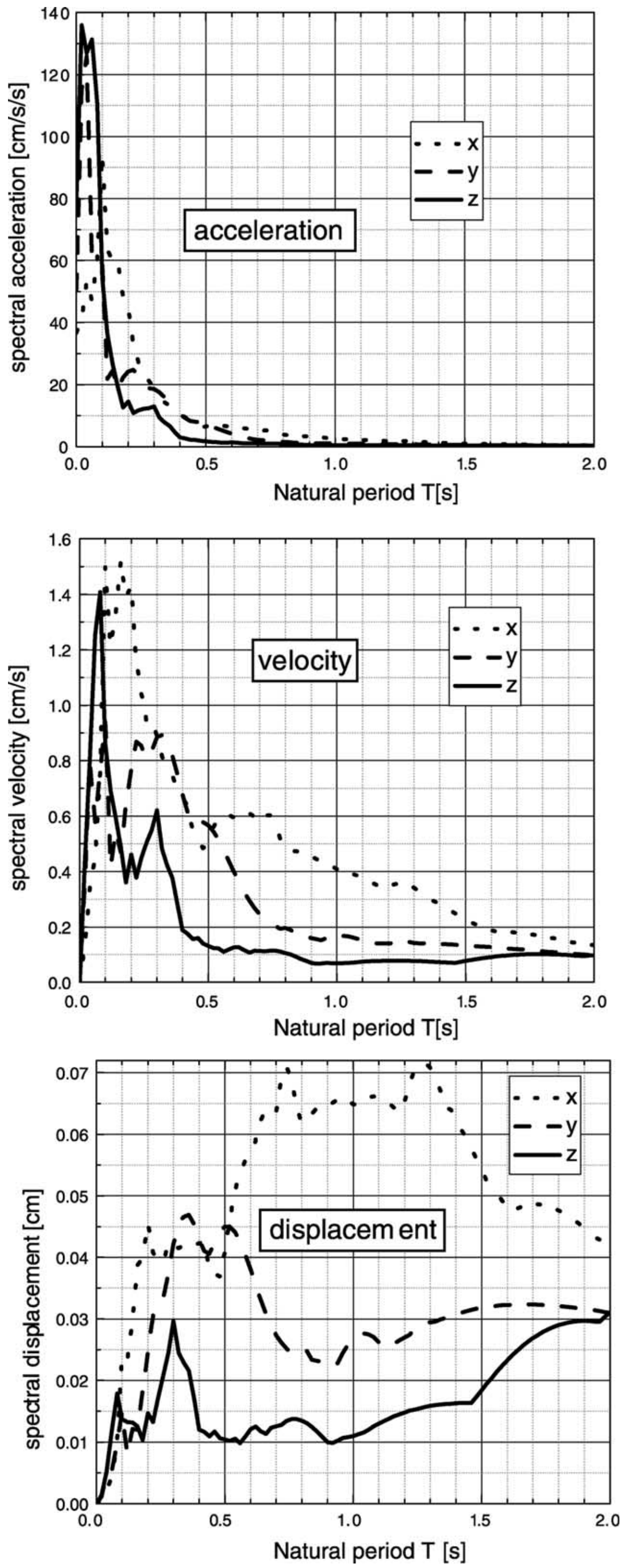

Fig. 4. Response spectra of a rockburst from February 2nd 2001 (station '3 Maja', g03), horizontal x, y and vertical z components ($\xi = 0.05$).

Table 1
Some characteristics of six selected earthquake records

Name of the record and number in Ref. [13] catalogue	Local intensity	Horizontal, vertical				
		Acceleration			Velocity PGV (cm/s)	Displacement PGD (cm)
		PGA (cm/s^2)	$\log_{10} I_A$ (cm^2/s^3)	t_d (s)		
Corinth nr 553	IV MSK	108, 97	3.47, 3.22	5.48, 5.80	4.8, 1.7	0.38, 0.11
Patras nr 446	VI MSK	116, 55	3.50, 3.16	3.47, 3.49	8.4, 3.2	0.88, 0.30
Pyrgos nr 559	VI MSK	128, 57	3.54, 3.29	10.86, 13.88	5.7, 1.3	0.78, 0.18
Lazzio nr 395	VI MCS	131, 46	3.26, 2.59	0.84, 3.03	7.0, 1.8	0.44, 0.20
Campano nr 293	VII + MCS	108, 72	4.54, 4.20	49.93, 50.36	13, 6.5	3.3, 1.4
Alkion nr 335	VIII MSK	139, 44	4.10, 3.39	15.65, 17.49	16, 4.4	4.6, 1.4

characteristic narrow pattern of pseudo-acceleration plots similar to earthquakes with high PGA/PGV ratio and very small induced structural vibrations.

These qualitative observations deriving from Figs. 2–4 are now analyzed in detail on a sample of 31 surface records collected during six events from January 2000 to May 2001. Tables 2 and 3 contain the main parameters of these records. The parameters describing earthquakes are taken from papers by Trifunac and Brady [7,9] and from a database of about 1000 European earthquakes [13].

From the database of Ref. [13], six records were selected with similar PGA as expected for the strongest of the analyzed rockbursts for which local Mercalli intensities were estimated. In addition to PGA of about 0.1–0.15 g, the earthquake records were selected to represent various types of spectral and duration properties so that they could stand for typical earthquakes, which shape the seismic code philosophy. For the purpose of this study, the earthquake records were named from the name of the recording station rather than from the main events. Detailed data on the six earthquakes is displayed in Table 1. Two of these records had particularly long (‘Campano’, $t_d = 55$ s) and particularly short (‘Lazzio’, $t_d = 4$ s) strong motion durations.

In Fig. 5, the logarithm of Arias intensities (Eqs. (4)) for the analyzed rockbursts are displayed vs. PGA together with the averaged estimations of MM intensities V–VIII [9] as well as of the six selected earthquakes. It can be seen that the surface measurements of the rockbursts produce

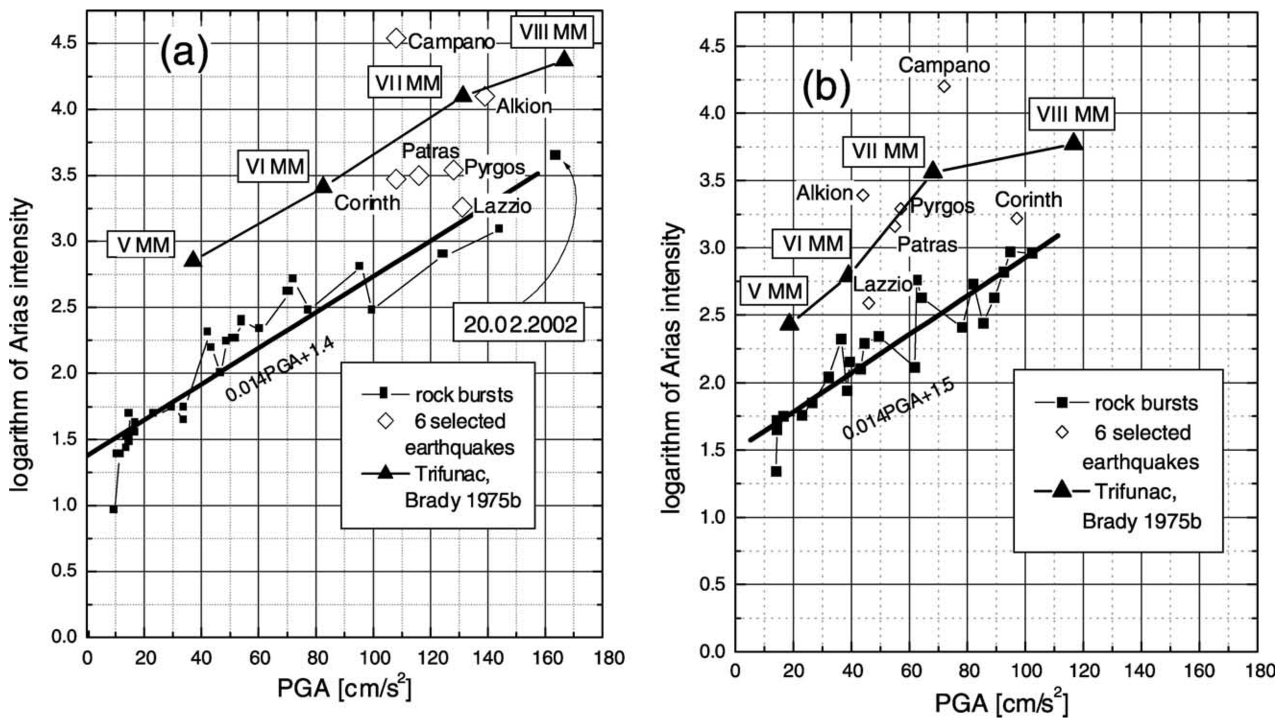

Fig. 5. Arias intensity vs. peak ground acceleration for the analyzed rockbursts, six selected earthquakes and averaged Trifunac and Brady [9] results. (a) Horizontal components and (b) vertical components.

substantially smaller (~10 times less) seismic energy as indicated by Arias intensity although their dependence with PGA exhibit similar pattern.

In Fig. 6, the strong motion duration of the rockbursts as defined by Trifunac and Brady [9] is plotted vs. PGA together with respective averaged estimations for MM intensities V–VIII and durations of the six selected European records. In this case, it can be seen that typical earthquakes exhibit substantially longer durations than rockbursts, which usually last no longer than 2–3 s. Except for one record, all the seismic records had durations longer

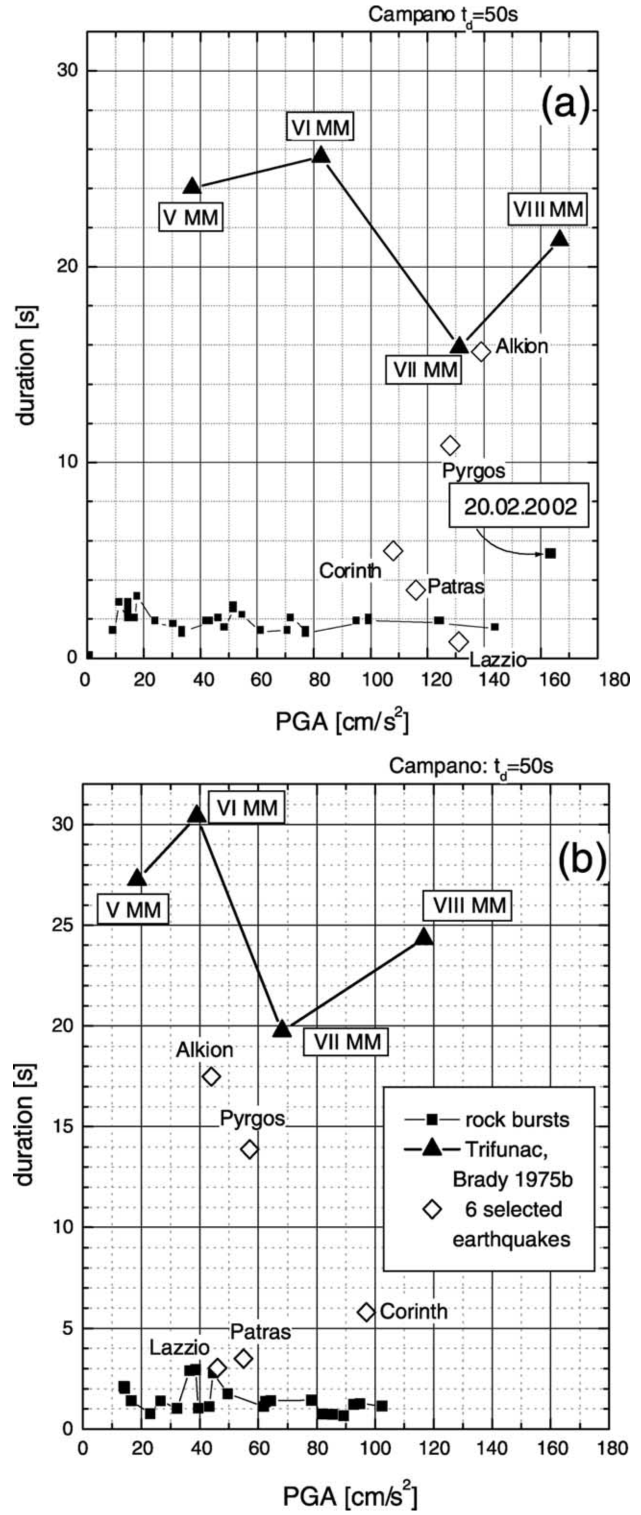

Fig. 6. Strong motion duration vs. peak ground acceleration for the analyzed rockbursts, six selected earthquakes and averaged Trifunac and Brady [9] results. (a) Horizontal components and (b) vertical components.

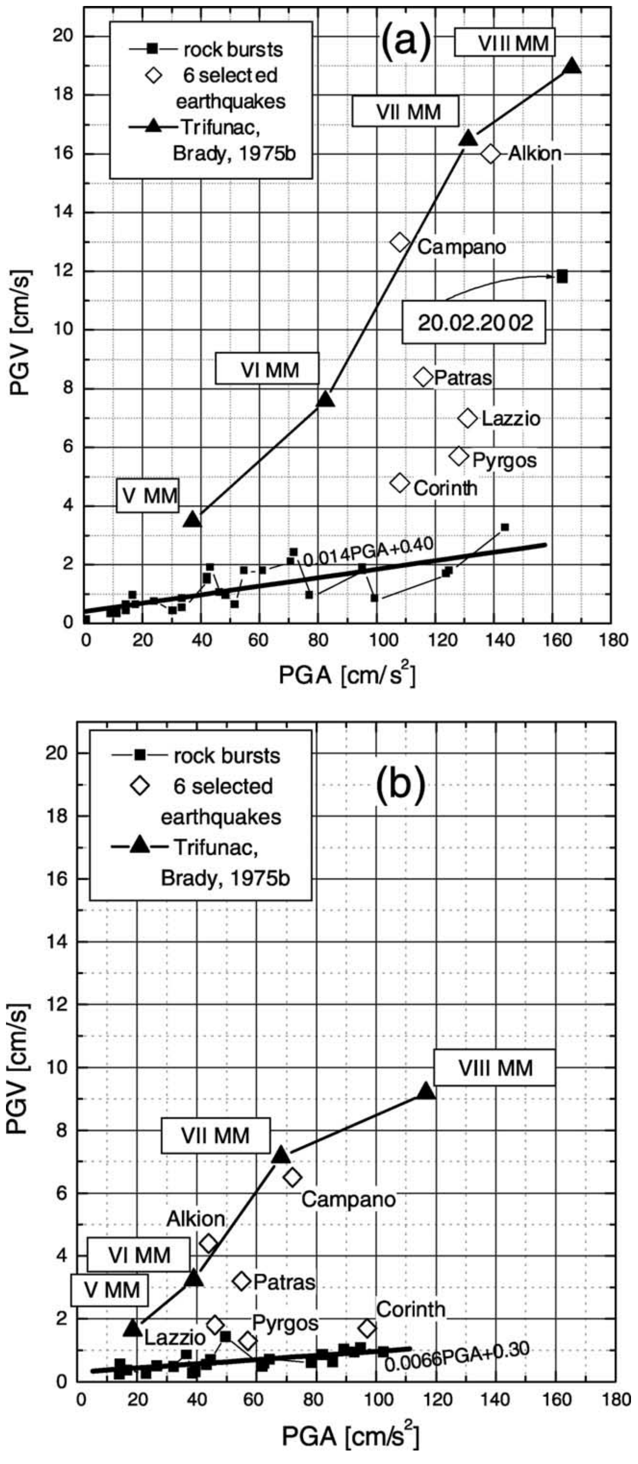

Fig. 7. Peak ground velocity vs. peak ground acceleration for the analyzed rockbursts, six selected earthquakes and averaged Trifunac and Brady [9] results. (a) Horizontal components and (b) vertical components.

than any rockbursts. In earthquake engineering, the duration effect is an important parameter of seismic load [14,15] whereas here it is suffice to note its very short value. A slight reduction of duration with increasing PGA can be observed for the records of rockbursts. Similar effect for earthquakes is explained by the fact that usually less intense earthquakes are recorded at longer epicentral distances for which durations are usually longer which is probably also the case for the recorded mine tremors.

In Fig. 7, the dependence of PGV vs. PGA is shown. For typical 'El Centro' type earthquakes with long durations, the ratio PGA/PGV ≈ 10. Similar results are displayed from Trifunac and Brady [9] paper for MM = V–VIII. The six selected European records show somewhat less values. In

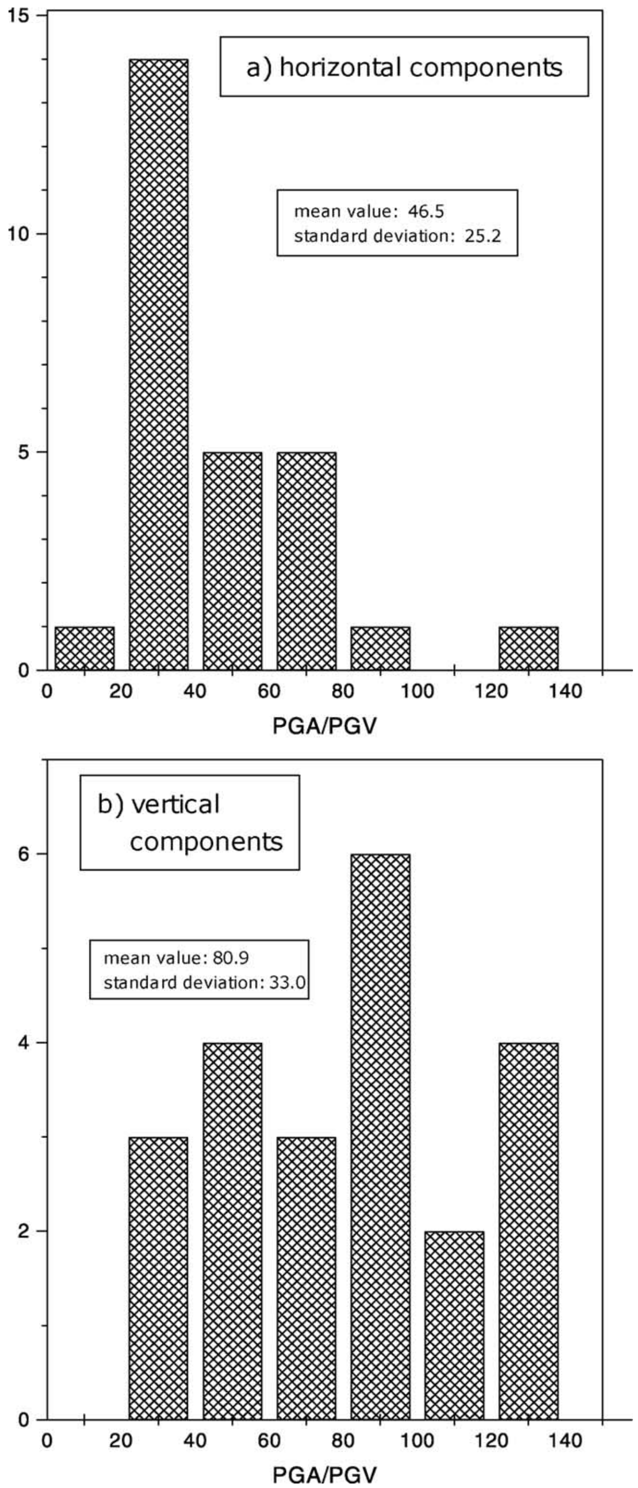

Fig. 8. Histogram of PGA/PGV ratio for the analyzed rockbursts.

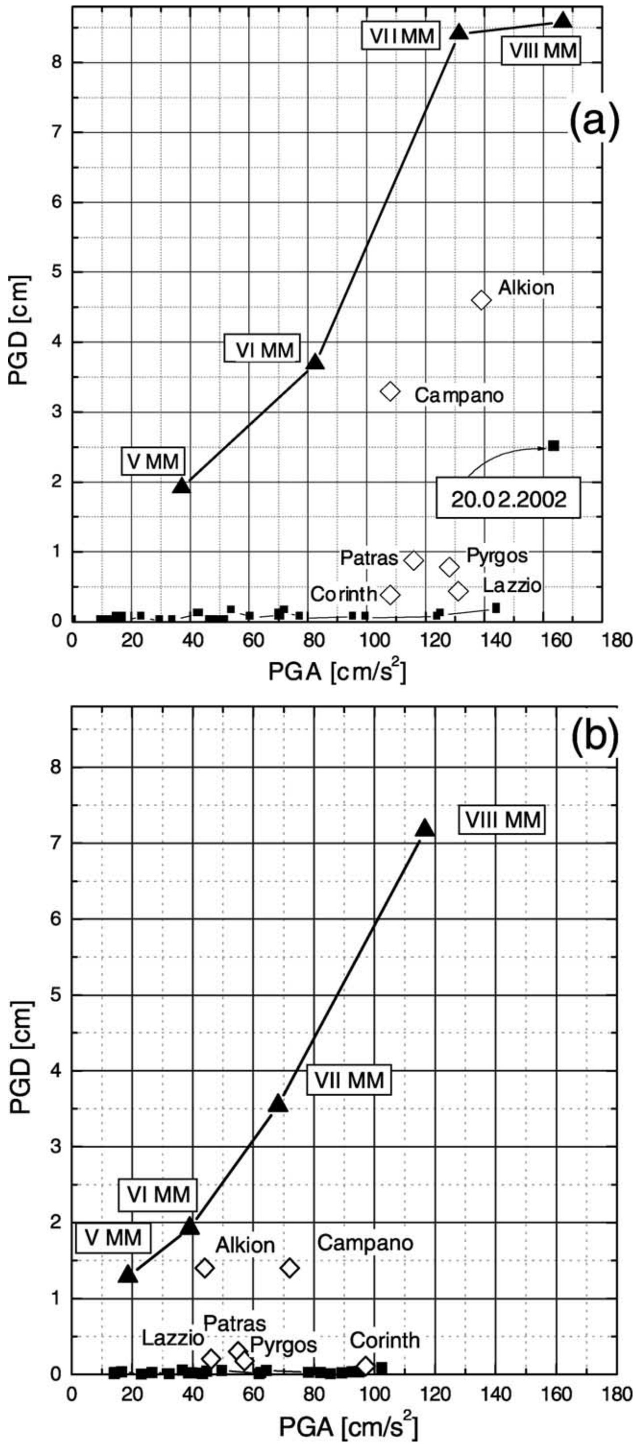

Fig. 9. Peak ground displacements vs. peak ground acceleration for the analyzed rockbursts, six selected earthquakes and averaged Trifunac and Brady [9] results. (a) Horizontal component and (b) vertical component.

Table 2
Surface characteristics of some strongest 'Polkowice' rock bursts from January to December 2000

Date	Name and number of measuring station, g: ground; f: foundation		Horizontal, vertical									
			Acceleration						Velocity PGV (cm/s)		Displacement PGD (cm)	
			PGA (cm/s^2)		$\log_{10} I_A$ (cm^2/s^3)		t_d (s)					
January 13 2000 Energy: 1.6×10^6 J	'Akacjowa',	g01	9.59,	23.0	0.95,	1.76	1.43,	0.77	0.249,	0.258	0.0165,	0.0045
	'3 Maja',	g03	46.7,	overflow	2.00,	–	1.94,	–	0.995,	–	0.0452,	–
	'3 Maja',	f03	34.3,	61.9	1.64,	2.11	1.21,	1.13	0.833,	0.496	0.0437,	0.0081
	'Miedziana',	g04	34.4,	85.5	1.75,	2.44	1.42,	0.73	0.541,	0.640	0.0184,	0.0102
March 15 2000 Energy: 7.1×10^6 J	'Akacjowa',	g01	23.9,	43.2	1.69,	2.10	1.78,	1.13	0.771,	0.548	0.0495,	0.0150
	'3 Maja',	g03	Overflow,	overflow								
	'3 Maja',	f03	61.0,	$p-z$	2.32,	–	1.36,	–	1.795/1.78[a],	–	0.0643,	–
	'Miedziana',	g04	70.7,	92.6	2.61,	2.82	1.43,	1.23	2.088,	0.944	0.0881,	0.0336
	'Sosnowa',	f02	30.3,	32.2	1.74,	2.04	1.64,	1.03	0.429,	0.486	0.0157,	0.0100
September 14 2000 Energy: 2.0×10^7 J	'Akacjowa',	g01	4.89,	89.2	2.24,	2.63	1.55,	0.66	0.947,	1.030	0.0459,	0.0186
	'3 Maja',	g03	124.2,	overflow	2.89,	–	1.81,	–	1.646,	–	0.0805,	–
	'3 Maja',	f03	99.5,	49.5	2.48,	2.34	1.92,	1.76	0.776/1.29[a],	1.431	0.0520,	0.0535
	'Miedziana',	g04	Overflow,	overflow								
	'Sosnowa',	f02	77.8,	82.1	2.48,	2.73	1.29,	0.75	0.890,	0.863	0.0481,	0.0223
November 15 2000 Energy: 3.3×10^7 J	'Akacjowa',	g01	16.9,	39.5	1.55,	2.15	2.00,	1.04	0.923,	0.320	0.0769,	0.0166
	'3 Maja',	g03	Overflow,	overflow								
	'3 Maja',	f03	Overflow,	36.5	–,	2.32	–,	2.90	–,	0.894	–,	0.0576
	'Miedziana',	g04	42.8,	62.4	2.30,	2.76	1.77,	1.36	1.498,	0.592	0.1249,	0.0227

Overflow—some records have crossed the 1 m/s^2 limit per channel.
[a] Comparative value from direct measurement of velocity (f03v—'3 Maja').

a paper by Heidebrecht et al. [16], 75 seismic records from a Canadian data base were divided into five categories

- PGA/PGV = 3–6 (approximate value 5)
- PGA/PGV = 6–8 (approximate value 7)
- PGA/PGV = 8–12 (approximate value 10)
- PGA/PGV = 12–24 (approximate value 20)
- PGA/PGV = 24–35 (approximate value 30)

Such diversification is motivated by the application for modeling seismic effects on civil engineering structures to construct appropriate base shear format for Canadian

Table 3
Surface characteristics of some strongest 'Polkowice' rock bursts from January to May 2001

Date	Name and number of measuring station g: ground f: foundation		Horizontal, vertical									
			Acceleration						Velocity PGV (cm/s)		Displacement PGD (cm)	
			PGA (cm/s^2)		$\log_{10} I_A$ (cm^2/s^3)		t_d (s)					
February 2 2001 Energy: 3.4×10^7 J	'Akacjowa',	g01	125.2,	overflow	2.89,	–	1.78,	–	1.774,	–	0.0937,	–
	'3 Maja',	g03	51.6,	78.2	2.27,	2.41	2.56,	1.44	0.649,	0.606	0.0442,	v0.0091
	'3 Maja',	f03	17.7,	38.5	1.62,	1.94	3.18,	2.95	0.582/0.62[a],	0.280	0.0442,	0.0169
	'Miedziana',	g04	95.8,	94.8	2.81,	2.97	1.81,	1.27	1.810,	1.069	0.0700,	0.0387
	'Sosnowa',	f02	144.0,	overflow	3.09,	–	1.52,	–	3.254,	–	0.1774,	–
	'Guzice',	g06	14.4,	14.1	1.43,	1.34	1.95,	2.11	0.464,	0.250	0.0389,	0.0129
May 1 2001 Energy: 4.4×10^7 J	'Akacjowa',	g01	14.8,	26.5	1.47,	1.85	2.85,	1.39	0.641,	0.499	0.0707,	0.0238
	'3 Maja',	g03	72.3,	102.4	2.70,	2.96	2.06,	1.14	2.396,	0.956	0.1503,	0.0899
	'3 Maja',	f03	43.5,	44.6	2.20,	2.29	1.91,	2.79	1.904,	0.689	0.1161,	0.0424
	'Miedziana',	g04	54.7,	64.3	2.39,	2.63	2.22,	1.42	1.733,	0.715	0.1435,	0.0534
	'Sosnowa',	g02	15.0,	14.3	1.70,	1.72	2.51,	2.02	0.454,	0.561	0.0259,	0.0230
	'Sosnowa',	f02	14.5,	14.3	1.52,	1.65	2.17,	2.09	0.610,	0.426	0.0426,	0.0227
	'Guzice',	g06	11.4,	16.6	1.38,	1.75	2.81,	1.42	0.355,	0.368	0.0201,	0.0349

Overflow—some records have crossed the 1 m/s^2 limit per channel.
[a] Comparative value from direct measurement of velocity (f03v—'3 Maja').

seismic code. The records with higher PGA/PGV ratio are usually acquired at shorter epicentral distances and are called 'acceleration dominated' whereas the records with low PGA/PGV values are usually acquired at large distances and are called velocity dominated. The ground vibrations induced by rockbursts are recorded at very short, few kilometers distances and their PGA/PGV ratio equals about 40–80 with higher values for vertical component (Figs. 7 and 8). From this perspective they show an extreme near field pattern. This is reflected by particularly steep shape of acceleration response spectrum (e.g. Fig. 4)—strong near field type shape of the plot. This means that in spite of their relatively high PGA values (0.1–0.2 g), the rockburst records should not be classified as the earthquakes with similar PGA values. In fact they should be better classified by their PGV values as already has been done for blasts [17]. In their analyses, they indicate that blasts with PGV <5 cm/s do not cause any damage to typical buildings, blasts with PGV 5–14 cm/s may cause some minor damage and blasts with PGV >19 cm/s cause substantial damages. These conclusions were later corrected by more detailed study of Siskind et al. [2], which indicated a need to further reduce 5 cm/s threshold to avoid small cracks and to enhance living standards of the local residents. The observations of the effects of rockbursts on buildings in the Polkowice area show that minor damage of non-structural character can be observed for similar values of PGV = 3–5 cm/s.

In Fig. 9, PGD vs. PGA are shown, again for the analyzed rockbursts, for the averaged values of MM = V–VIII [7], as well as for the six selected earthquakes. This time, difference between earthquakes and mine tremors is even more evident. The PGD of rockbursts at their greatest values reach about 0.1–0.2 cm (Tables 2 and 3) whereas earthquake records with respective 0.1–0.15 g PGA reach about 5–8 cm or more.

The differences between earthquakes and rockbursts with respect to PGV and PGD as shown in Figs. 7 and 8 manifest in spectral contents of respective earthquakes. In Fig. 10, the central frequencies f_{centr} for the recorded rockbursts and the six selected earthquakes as defined by Eqs. (6) are shown. Although dependence of this parameter with PGA is not particularly evident, a shift of rockbursts to higher frequencies is evident. Observing the Fourier spectrum of typical rockburst as shown in Fig. 3, substantial contribution of components in the frequency band of 20–40 Hz can easily be noted. Such high frequency components are usually not present in the earthquake records. What's more, contribution of components with frequencies less than 5 Hz which usually dominate seismic records can hardly be seen for rockbursts (e.g. Fig. 3).

On February 20th 2002, a rockburst with energy 1.5×10^9 J occurred below the town. This time the energy was better correlated with the effects on the surface. In Fig. 11, the strongest recorded time history signal is shown. Only the horizontal signal was recorded there with PGA 163.7 cm/s^2, PGV = 11.8 cm/s, PGD = 2.4 cm. It is

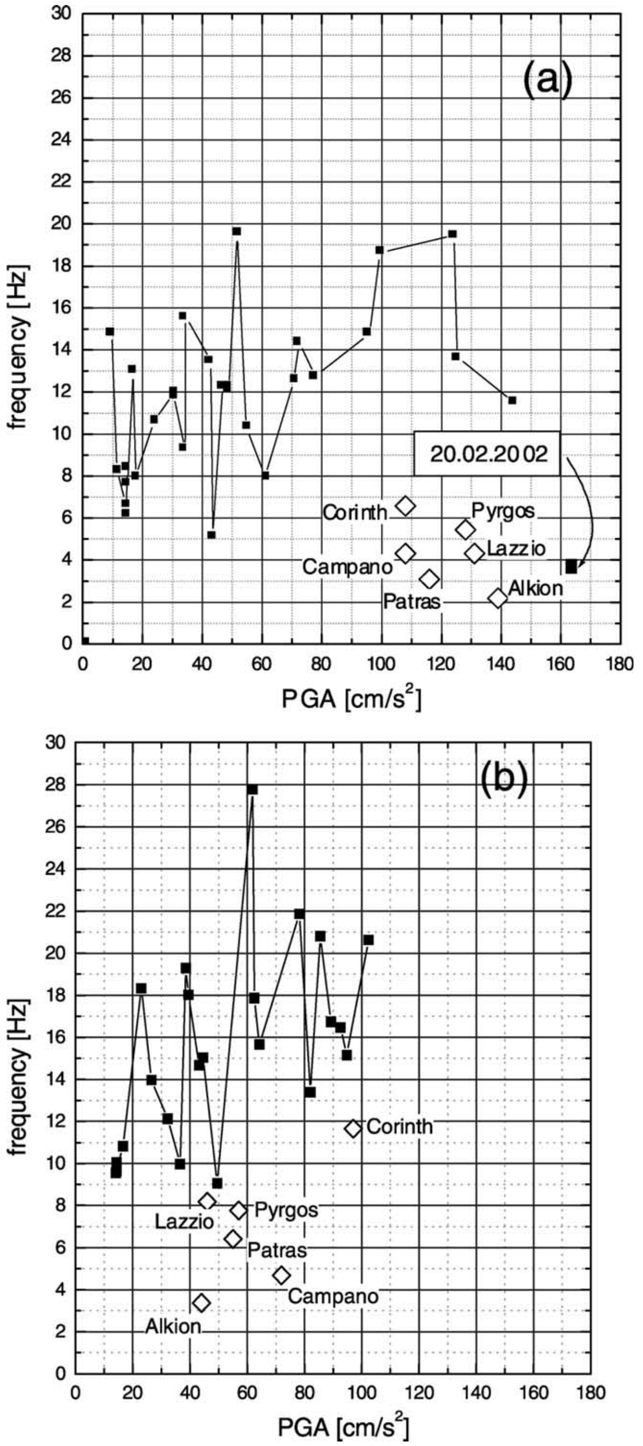

Fig. 10. Central frequency vs. peak ground acceleration for the analyzed rockbursts and six selected earthquakes. (a) Horizontal component and (b) vertical component.

interesting to note that although the peak acceleration was only about 15% higher than of the greatest previous, typical rockbursts (Table 3—Feb 2nd 2001, record f02 'Sosnowa'), the peak velocity was more than 3.5 times greater than in that case. In Fig. 12, respective Fourier spectra of the acceleration time histories from Fig. 11 are shown, displaying clear reduction of the spectral content as compared to

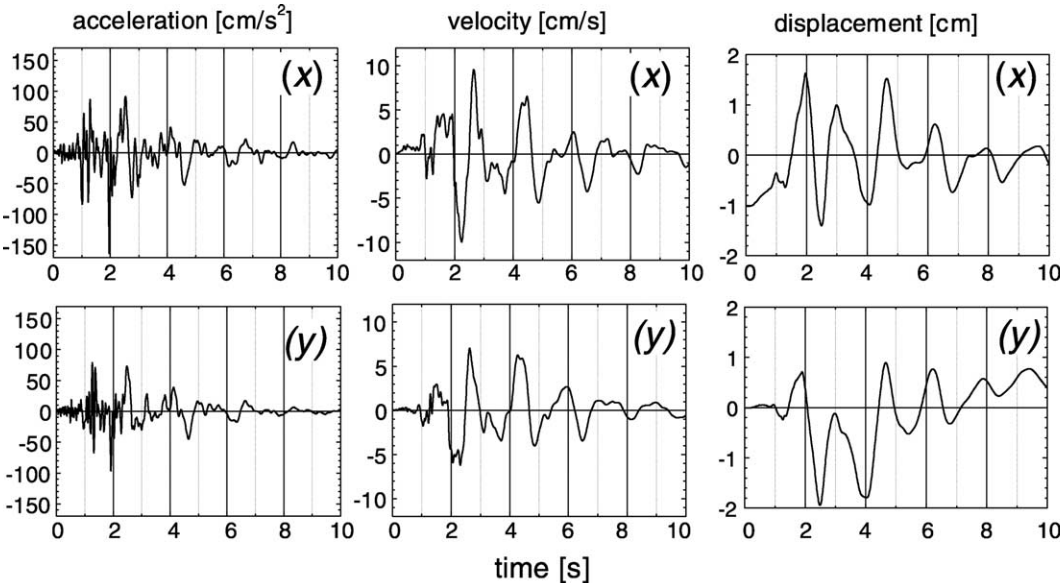

Fig. 11. Time history measurements of a rockburst from February 20th 2002 (station 'Miedziana', f04), horizontal components *x* and *y*.

Fourier spectra of typical rockburst (Fig. 3). The strong motion duration of this event was equal to 5.3 s, logarithm of Arias intensity equaled 3.65 and the central frequency equaled 3.63 Hz. These results were added to Figs. 5–7, 9–10 denoted '20.02.2002'.

The rockburst caused panic among residents living on the upper floors of some higher buildings and many cases of falling furniture. Some cracks appeared on the plaster of brick buildings. On a few prefabricated 11-storey buildings, vertical cracks between elements appeared and damage of an elevator was observed. Although these damages were still of non-structural character, the impressions of people were strong, requiring even psychological help. Many of the inhabitants described the tremor as the strongest since 10–20 years. When applying descriptive scales, its intensity could be described as MM VI+. As can be seen from Figs. 5–7, 9–10, this particular rockburst differs substantially from the pattern of typical strong rockbursts occurring with return period of 3–6 months and appears more similar to low intensity earthquake. It is particularly evident when

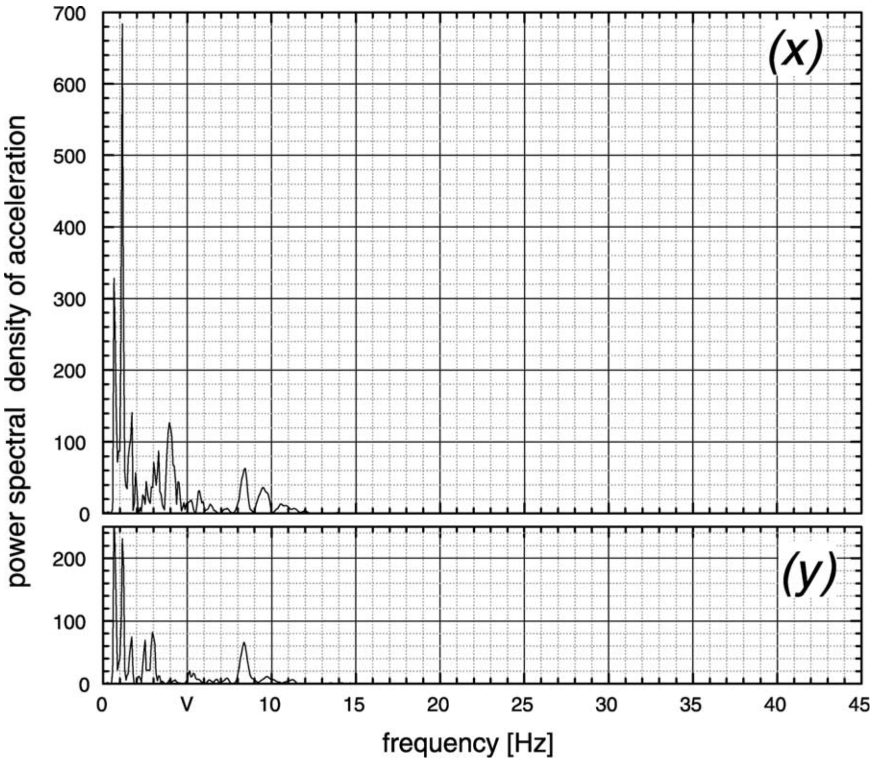

Fig. 12. Fourier spectra of a rockburst from February 20th 2002 (station 'Miedziana', f04), horizontal components *x* and *y*.

observing its rather long (as for rockbursts) duration and a shift down of frequencies dominating in the Fourier spectrum of accelerations (Fig. 12) resulting in the ratio of PGA/PGV = 14.

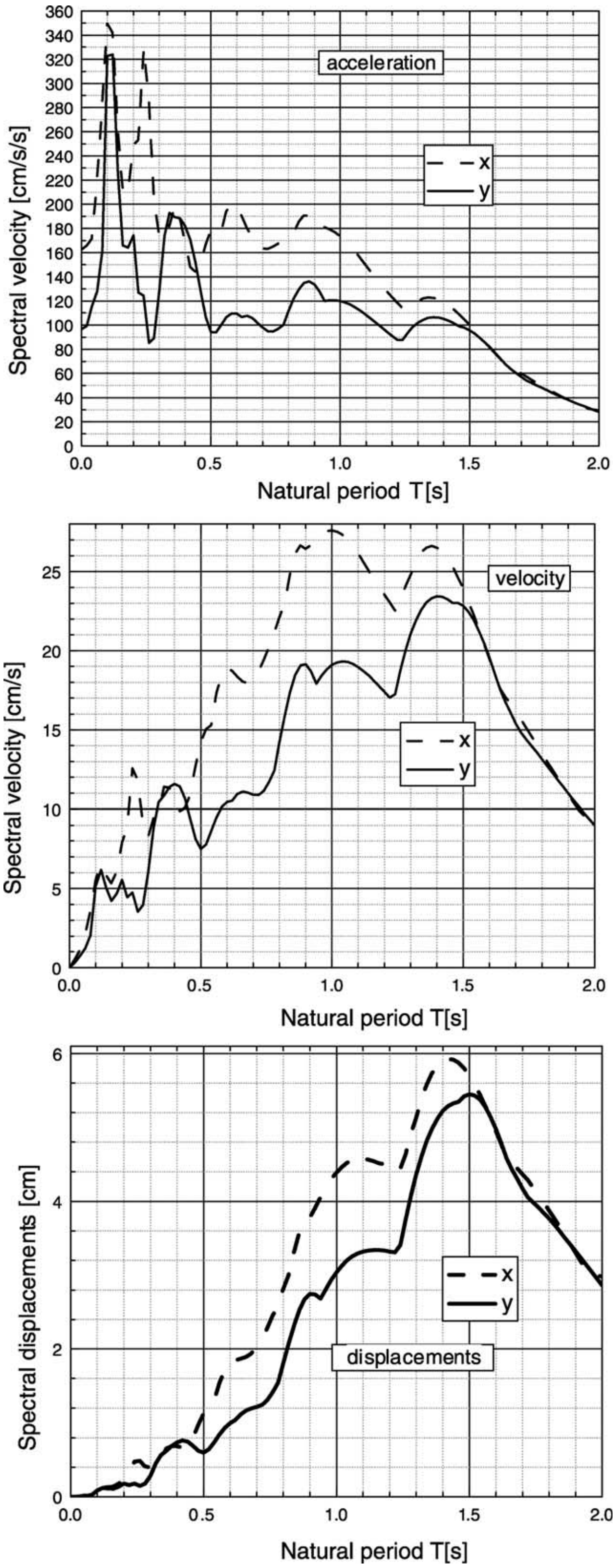

Fig. 13. Response spectra of a rockburst from February 20th 2002 (station ‘Miedziana’, f04), horizontal components x and y ($\xi = 0.05$).

In Fig. 13, respective response spectra of the accelerations from Fig. 11 are shown for 5% damping. Particularly interesting to note are structural displacements (upper plot of Fig. 13), since they are direct measures of stresses induced in the structure during the vibrations. It can be seen that as compared to a few millimeters maximum structural displacements generated by typical rockbursts, this time the displacement response reached values of a few centimeters for natural periods of 0.5–1 s which are typical for the 11-storey prefabricated buildings. This fact, together with 5.3 s strong motion duration and descriptive intensity of MM VI + described above, leads to a conclusion that the Polkowice rockburst of Feb 20, 2002 was more similar to a small earthquake than to typical rockburst. Similar strong rockbursts already occurred in the LGOM basin on March 24th, 1977 and June 20th, 1987 but did not cause that strong structural effect on the ground surface and were not properly measured then. The events of June 20th, 1987 and Feb 20th, 2002 are shown in the list of significant earthquakes provided by the USGS National Earthquake Information Center in Denver (http://neic.usgs.gov). They were registered as far as in Vienna and Strasbourg and their magnitude was estimated as $M_L = 4.9$, the same for both events. This value was settled based on teleseismic algorithms. The moment magnitudes [18] of these events calculated from local records were: $M_w = 4.5$ (1977), $M_w = 4.3$ (1987) and $M_w = 4.0$ (2002).[1]

4. Discussion and conclusions

An analysis is presented of rockburst-induced ground motion by mining in the area of town Polkowice in Western Poland. This earthquake-like phenomenon occurs in the vicinity of many mines and may cause damage to buildings and inconveniences to local communities. Typical remedy to these problems is to repair and sometimes strengthen the buildings applying general rules of seismic engineering. This requires, however, better understanding of the character of ground motion induced by rockbursts which was the aim of the research reported in this paper.

As a result of the present study, the rockburst-induced ground motion can be divided onto two types:

- Typical excitations with low intensity and return period of 3–6 months, characterized by short durations (1–2 s) and Fourier spectra shifted to higher frequencies, often above 20 Hz
- Unusual, rare events with much stronger intensity, longer duration and spectral content dominating in the lower frequency part of the spectrum

[1] Personal communication—Slawomir GIBOWICZ, Institute of Geophysics, Polish Academy of Sciences.

The structural response excited by typical rockbursts should be compared to the effects of surface mining blasts [2], where the maximum particle velocities of about 3–5 cm/s are required to cause cosmetic cracking. However, the ground motion induced by the stronger events of the second type result in much more intensive structural vibrations, similar to low intensity earthquakes. This conclusion agrees with the result of geophysical studies presented herein, which indicates some seismological similarities of strong rockbursts and small earthquakes. The differences in their records are explained by seismologists by shallow depth of rockbursts and their small magnitude [5,19,20].

One of the most difficult obstacles in the analyses of mine-induced rockbursts and their effects on buildings is a variety of parameters and methods applied in the research, depending on mine or country. This, in addition to the variety of geological conditions, makes it difficult to draw any more general conclusions from the research results [10]. The presented analysis of rockburst-induced ground motion also has limitations of this kind. It may, however, be useful for civil engineers for comparisons with the measurements acquired in the other regions subjected to rockburst influences.

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