Arch. Min. Sci. **65** (2020), 3, 419-432

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.24425/ams.2020.133200

JÓZEF DUBIŃSKI[1], GRZEGORZ MUTKE[1*], JACEK CHODACKI[1]

DISTRIBUTION OF PEAK GROUND VIBRATION CAUSED BY MINING INDUCED SEISMIC EVENTS IN THE UPPER SILESIAN COAL BASIN IN POLAND

The solutions presented permit the practical determination of the physical parameters of peak ground vibration, caused by strong mining tremors induced by mining, in the Polish part of the Upper Silesian Coal Basin (USCB). The parameters of peak ground horizontal velocity (PGV_H) and peak ground horizontal acceleration (PGA_{H10}) at any point of earth's surface depend on seismic energy, epicentral distance and site effect. Distribution maps of PGV_H and of PGA_{H10} parameters were charted for the period 2010-2019. Analysis of the results obtained indicates the occurrence of zones with increased values of these parameters. Based on the Mining Seismic Instrumental Intensity Scale (MSIIS-15), which is used to assess the degree of vibration intensity caused by seismic events induced by mining, and using the PGV_H parameter, it was noted that the distribution map of this parameter includes zones where there vibration velocities of both 0.04 m/s and 0.06 m/s were exceeded. Vibrations with this level of PGV_H correspond to intensities in the V and VI degree according to the MSIIS-2015 scale, which means that they can already cause slight structural damage to building objects and cause equipment to fall over. Moreover, the reason why the second parameter PGA_{H10} is less useful for the evaluation of the intensity of mining induced vibrations is explained. The PGA_{H10} vibration acceleration parameter, in turn, can be used to design construction of the objects in the seismic area of the Upper Silesian Coal Basin, where the highest acceleration reached a value of 2.8 m/s^2 in the period from 2010 to 2019.

Keywords: induced seismicity, Upper Silesian Coal Basin, peak ground velocity, mining seismic intensity scale

1. Introduction

In numerous coal basins all over the world, e.g. Upper Silesia Coal Basin (in Czech Republic and in Poland), Jiangsu Province, Henan Province, Liaoning Province and Shandong Province (in China), Kuzbass and Vorkuta Coal Basin (in Russia), Austar mine (in Australia), mining activity

[1] CENTRAL MINING INSTITUTE, 1 GWARKÓW SQ., 40-166 KATOWICE, POLAND

[*] Corresponding author: gmutke@gig.eu

induces seismic events (Cesca et al., 2013; Dou et al., 2014; Mutke & Dubiński, 2016; Foulger et al., 2018; Feng, 2018; Orlecka et al., 2020). The seismic energy and magnitude of these dynamic phenomena vary over a very broad range. The strongest seismic events, induced by mining in the Upper Silesia Coal Basin (both in Polish and Czech part of the basin), exhibit seismic energies exceeding 10^9 J and local magnitudes of $M_L \geq 4$ (Kaláb & Knejzlik, 2012; Marcak & Mutke 2013; Holub et al., 2013; Kozłowska et al., 2016). They constitute a hazard to the stability of underground mine workings and they manifest themselves in the form of rock-bursts, which lead to excavation damage and loss of their functionality as well as accidents affecting miners (Ptacek, 2020; Mutke et al., 2015). A no less significant effect of mining tremors is their influence on the surface in the form of ground vibrations. These may result in damage to buildings and technical infrastructure as well as in the discomfort of local residents (Mutke & Dubiński, 2016). This problem becomes more significant in situations where mining activities are conducted under built-up areas or in their immediate vicinity.

The Upper Silesian Coal Basin (USCB) is one such region, where seismicity induced by hard coal mining activities is present in numerous highly urbanized areas, as well as built up yet rural areas. To minimize potential damage to the structure as a result of the ground vibrations generated by mining tremors, it is necessary to properly design new structures and protect existing ones.

Research conducted in the Polish part of the USCB area, based on the measurements of a surface seismic network that registers ground vibration parameters, has made it possible to identify the relationship between peak ground motion (PGM) parameters (PGV_H – Peak Ground Horizontal Velocity and PGA_{H10} – Peak Ground Horizontal Acceleration), and the seismic energy of the mining tremors (or local magnitude) and epicentral distance (Chodacki, 2016; Dubiński et al., 2017). The seismic energy is determined based on seismograms registered by seismological stations of the Upper Silesian Regional Seismological Network (USRSN). This relationship has made it possible to prepare isoline distributions of the aforementioned PGM parameters (PGV_H and PGA_{H10}) in the form of maps matched to the USCB area. Thanks to this, it is possible to identify zones where the PGV_H and PGA_{H10} parameters reach maximum values, and also to determine zones for planned mining activities where the forecast seismicity will lead to PGV_H and PGA_{H10} values that constitute too great a risk of causing damage to buildings (Mutke et al., 2015; Mutke, 2019).

2. Seismic activity characteristics in the USCB area

Permanent seismological observations have been conducted in the USCB area for nearly 50 years and these monitor the seismicity induced by ongoing hard coal mining plant activities. The USRSN provide comprehensive data on mining tremors with seismic energy values of $E \geq 10^5$J and local magnitude of $M \geq 1.7$. It should be noted that this network is much larger than individual mine micro-seismological networks that are currently operating in nearly all mines in the USCB area. Therefore, the USRSN regional network allows the registration of vibrations also in the far wave field, in which seismic energy is calculated. The USRSN monitoring system registers tremors by means of 26 seismometric and accelerometric stations. It uses thirteen medium period (eight second) triaxial VE-53-BB seismometers manufactured by GeoSIG Ltd. and thirteen triaxial GeoSig AC-73 accelerometers (including four underground AC-73 DH accelerometers placed in 30m-deep boreholes) to register ground vibration velocities and accelerations. The USRSN was expanded in EPOS PL project by seven seismic stations. Additionally, short period recordings are performed by means of thirteen short (one second) period Willmore MK III and

SS-1 Ranger seismometers. The seismic data is transmitted continuously to the Local Geophysical Data Centre at GIG, developed under EPOS PL project (Mutke et al., 2019). Software such as GeoDAS – Data Acquisition System software (GeoSIG Ltd), SEISAN – The Earthquake Analysis Software (University of Bergen & British Geological Survey) and Multilok (Central Mining Institute - Poland) is used to interpret the mining-induced seismic tremors.

Table 1 presents the number of mining induced seismic events by energy class that occurred over the period of 2010-2019 in the USCB. Table 1 shows that over a period of 10 years, the USCB experienced 7 mining tremors with seismic energy of $E > 10^9$J (local magnitude $M > 3.8$). The histogram of seismic energy and cumulated seismic energy of tremors induced by mining in the Polish part of Upper Silesia, during the period between 2010-2019 is shown in Fig. 1. Every few years there is a rapid increase in accumulated energy, although the amount of extracted coal in the USCB decreases every year. Meanwhile Fig. 2 depicts the epicenter distribution of these tremors on the map of the USCB. It shows the epicenter concentration zones, which often occur under urban areas.

TABLE 1

The number of mining induced seismic events in energy classes that occurred over the period of 2010-2019 in the USCB

Year	Number of tremors, N					Total, N	Coal extraction mln. tons
	$10^5 \le E < 10^6$ [J]	$10^6 \le E < 10^7$ [J]	$10^7 \le E < 10^8$ [J]	$10^8 \le E < 10^9$ [J]	$E \ge 10^9$ [J]		
2010	1 035	157	12	1	1	1 206	76,1
2011	866	147	18	3	0	1 034	75,5
2012	795	210	15	2	0	1 022	78,6
2013	1 105	297	25	0	0	1 427	76,5
2014	1 322	374	61	5	0	1 765	72,5
2015	975	296	45	4	4	1 322	72,2
2016	1 210	411	15	4	0	1 640	70,4
2017	1 009	242	18	2	0	1 271	65,5
2018	1 129	336	32	5	2	1 504	63,4
2019	948	241	26	1	0	1 216	60,4
Total, N	10 394	2 711	267	27	7	13 407	711.1

It should be stressed that the location of seismic zones change due to changes of mining activities conducted in the USCB area. Once extraction is finished, local seismicity decreases and epicenter concentration areas begin to fade, while on the other hand they start appearing in other locations where extraction has commenced.

In the period from 2010 to 2019, in the USCB several very strong seismic events induced by mining occurred with a local magnitude exceeding $M_L = 3.5$. In the epicentral zone they caused peak ground velocity PGV_H between 0,05 and 0,1 m/s and peak ground acceleration PGA_{H10} between 1.5 m/s^2 to 2.8 m/s^2. The highest amplitudes were observed in the epicentral zone and these were in the form of direct horizontal transverse waves with a short duration of time, even less than 3s, and dominant frequencies in the range from 1Hz to 10 Hz. The *PGA/PGV* coefficient of these tremors varied from 15 to 80, whereas for earthquakes the *PGA/PGV* coefficient is lower and varies between 5 and 15 (Mutke & Dubiński, 2016; Mutke 2019).

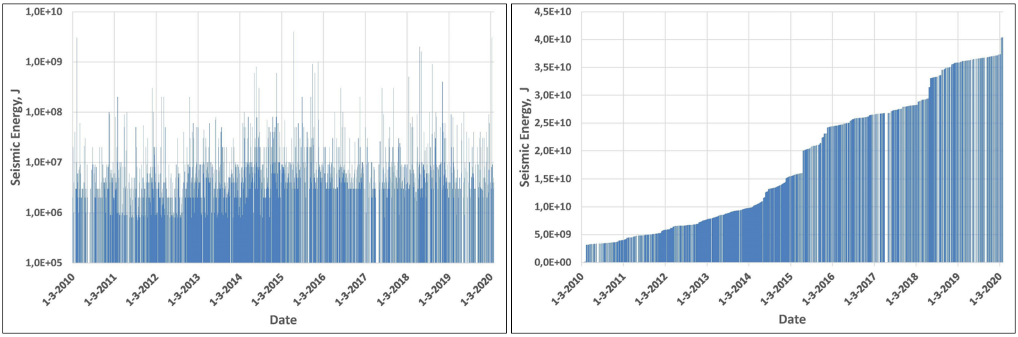

Fig. 1. Histogram of seismic energy (left) and the cumulated seismic energy (right) of tremors induced by mining in the Polish part of Upper Silesia, occurring between 2010-2019

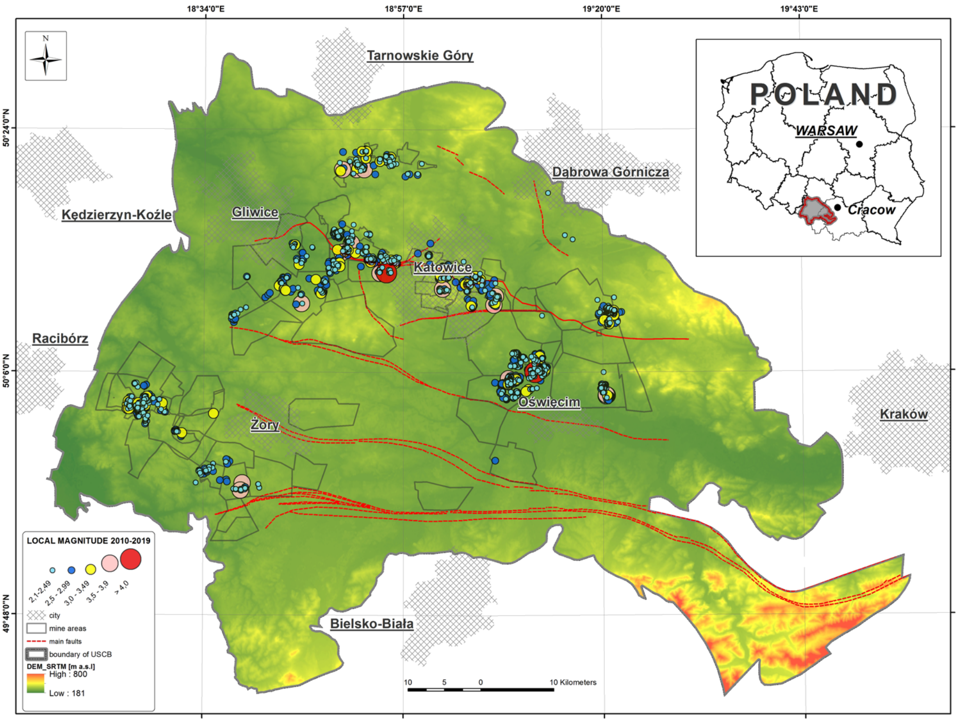

Fig. 2. Epicenters distribution map for mining tremors with magnitudes $M \geq 2$ in the USCB over the period of 2000-2019

The seismic events were felt in an area with a radius of 30-40 km, but directly behind the epicentral zone, the amplitudes of PGV_H and of PGA_{H10} were quickly attenuated. In the aforementioned epicentral zones, the high energy or high magnitude ($M > 3$) mining seismic events were intensely felt by people, causing fear and panic.

An example of the registration of one of the strongest mining tremors in the USCB area is presented in Fig. 3. The seismogram of the Janina M_L = 3.8 mining tremor occurred on September 30, 2015 near the city of Libiąż. The following vibration parameters were monitored in the epicentral zone: PGV_H = 0.066 m/s; PGA_{H10} = 1.7 m/s^2; the frequency of the main phase's vibration was below 5 Hz for the horizontal component NS on which the highest amplitudes of vibration velocity were recorded (Fig. 4); a very short duration time of velocity ground vibrations, 1.2 s (Fig. 5). Duration time in Fig. 5 mean the amount of the time in which the central 90% of the integral of the squared velocity takes place, and is called t_{90} and was introduced by Trifunac and Brady (Trifunac & Brady, 1975). The chart was calculated as the cumulative integral normalized to the value of 1.

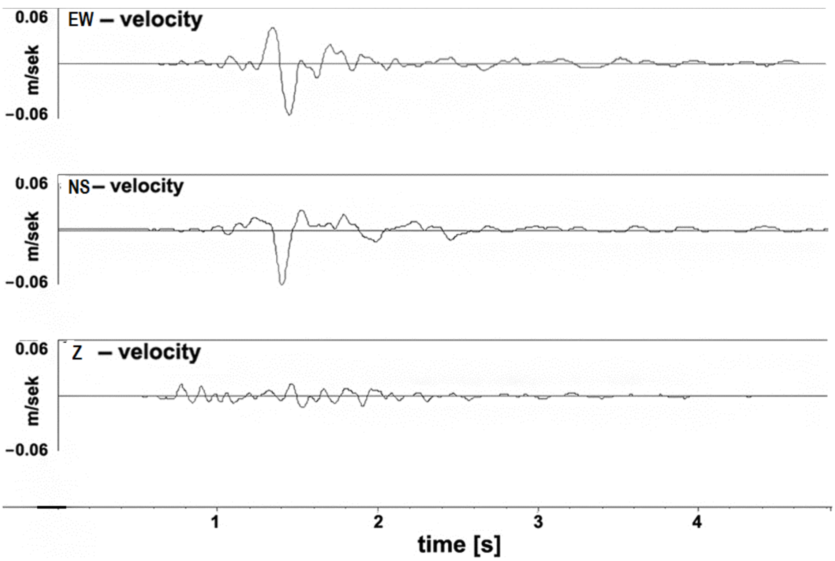

Fig. 3. Janina M_L = 3.8 mining tremor velocity seismogram, recorded in the epicentral zone

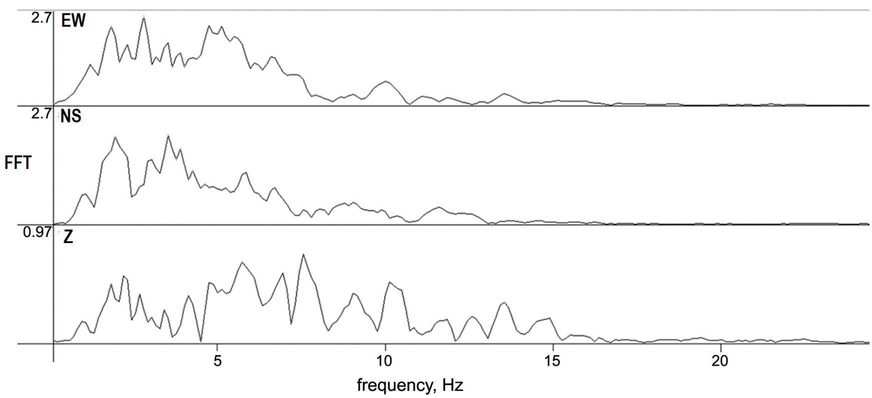

Fig. 4. Janina M_L = 3.8 mining tremor – FFT frequency of velocity vibrations

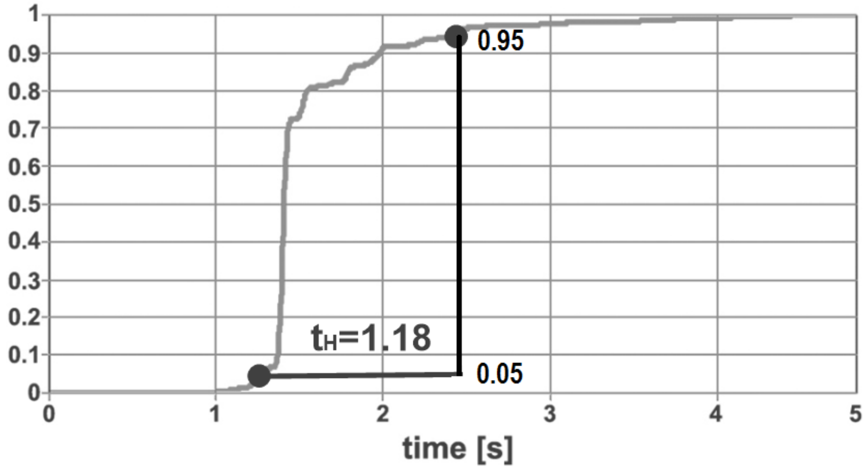

Fig. 5. Janina $M_L = 3.8$ mining tremor – time duration (1.2 s) of velocity vibrations (EW direction) recorded in the epicentral zone

The falling of chimneys was observed after this seismic event in more than 50 buildings in poor technical conditions (Fig. 6). In hundreds of buildings damages to decorative elements (cracks in the plaster, sliding off of roof tiles) were observed. In many residential buildings severe cracks in walls were observed (Fig. 7).

Fig. 6. Characteristic damage of buildings located in the epicentral zone of the $M_L = 3.8$ mining tremor in Janina mine – cracks and loosening of chimney bricks (V degree of the MSIIS intensity)

3. Formulation of research problem

The essence of the research problem is to determine the relationships between the seismological data of registered mining tremors and the *PGM* parameters (PGV_H and PGA_{H10}), that characterize the ground vibrations generated by the tremors. The seismological data in this

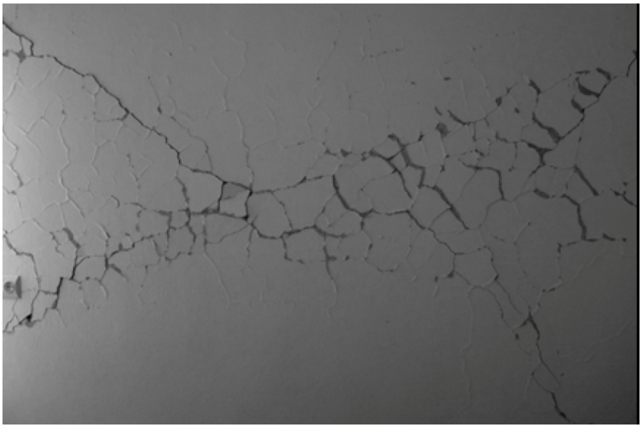

Fig. 7. Severe cracks in a wall – typical cross of Saint Andrew (V-VI degree of MSIIS intensity)

case encompasses the seismic energy value or magnitude of tremors and the location of their epicenters. The above relationships constitute a basis for elaborating maps for the distribution of PGV_H and PGA_{H10} parameters in the form of isolines representing their values, while taking into consideration local ground strata.

The significance of the defined research problem has to be stressed, particularly with regard to its practical usefulness. This is because knowing the value of PGV_H or PGA_{H10} parameters makes it possible to provide an objective intensity assessment of the vibrations generated on the surface by a high-energy tremor induced by mining (Mutke et al., 2015; COMEX 2012-2015). Furthermore, the distribution of the PGV_H and PGA_{H10} parameters serve as valuable information for the purpose of designing new, suitably reinforced buildings, located in areas influenced by seismic activity.

4. Research methodology and calculation results

A methodology involving the determination of the horizontal amplitudes PGV_{Hrock} for rock basement (ground type A according to Eurocode 8), i.e. with no vibration amplification influence caused by layers with low transverse seismic wave velocities, was used to calculate the peak ground motion amplitudes in the USCB. Afterwards, the distribution of the vibration amplification factor in the USCB was determined, depending on the thickness of the Quaternary overburden which is the main element contributing to vibration amplification in the area. Broad studies concerning the dependence of seismic side effects in the USCB on overburden properties were conducted by Mutke and Dworak (1992) and as part of the infrastructure project IS EPOS, where underground accelerometers were installed in 30m-deep boreholes as well as on the surface above them (Olszewska & Mutke, 2018; Mutke 2019).

Measurement data shows, depending on the structure of the near-surface strata, that peak ground motion values induced by mining tremors may undergo both partial amplification and damping. Quaternary overburden strata – layers with low S-wave propagation velocity and with thickness ranging from 0m to 110 m – are the main element influencing the vibration amplification phenomenon in the context of the USCB geological structure. In this perspective, the peak horizontal ground vibration velocity amplitude values are calculated using the following formula (Mutke & Dworak, 1992):

$$PGV_H = PGV_{Hrock} \cdot W_{f(1\text{-}5)} \tag{1}$$

where:

$W_{f(1\text{-}5)}$ — vibration amplification factor in the time domain,

PGV_{Hrock} — peak horizontal vibration velocity for rock basement.

Knowledge of the dominant vibration frequencies that reach the overburden strata, the transverse seismic wave propagation velocity in the overburden and the overburden thickness is key to calculating the amplification factor. Due to shallow mining tremor foci (about 1-2 km), the greatest vibration velocity and acceleration values in the USCB are related to direct S-wave. This primarily concerns horizontally polarized transverse waves, i.e. *SH* waves. Ground motion amplification for the USCB area was calculated according to the two layers viscoelastic model, using solution for body waves elaborated by Savarienskij (1959). In Upper Silesia Coal Basin (USCB), the vibrations are amplified by overburden of the Quaternary layers, located on the Carboniferous or Triassic rock basement. To calculate the amplification factor, a Quaternary thickness map and the average value of transverse wave propagation in a 30-meter near-surface layer were used, the so-called V_{S30} according to Eurocode 8. The V_{S30} was determined on the basis of seismic profiling using the MASW technique, under eighteen seismic stations of the Upper Silesian Seismological Network (GRSS). The average V_{S30} propagation velocity in the USCB area is 419 m/s. Then, knowing the Quaternary overburden thickness and average value of V_{S30} propagation velocity, the amplification of vibrations in the frequency range from 1 to 5 Hz in

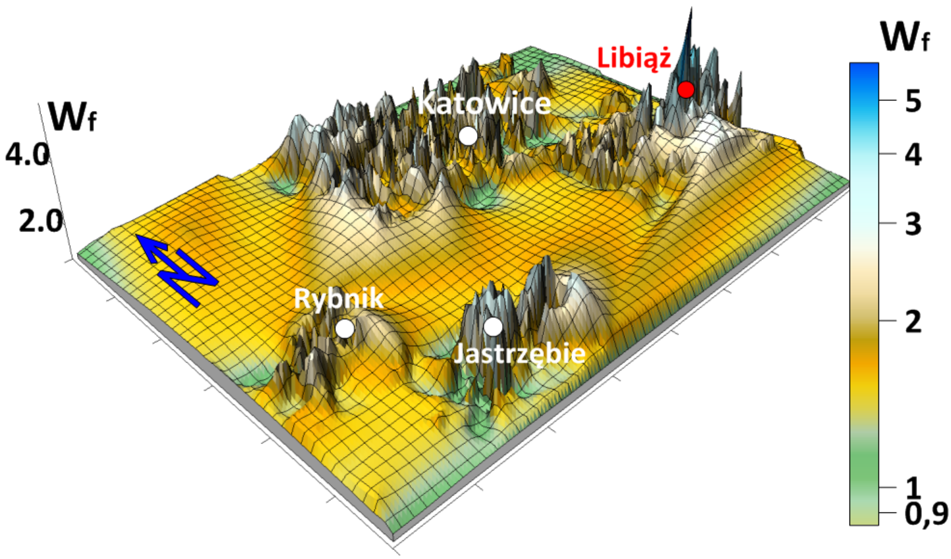

Fig. 8. Vibration amplification in time domain in the area of Upper Silesia for the strongest seismic tremors induced by mining activity

steps of 0.5 Hz at each point of the grid nodes every 2 km was determined. The main vibration phase for strong mining seismic events in USCB associated with the vibration of SH waves in the epicentral zone, has a frequency range of 1-5 Hz (Mutke & Dworak, 1992; Zembaty et al., 2015; Olszewska & Mutke, 2018; Mutke, 2019). In each computational node, the amplification was determined as the average value in the abovementioned frequency range, $W_{f\,(1\text{-}5)}$. This procedure substantially reflects the amplification of the main vibration phase from the entire seismogram in time domain. Vibration amplification in time domain for the strongest tremors in the USCB area is presented in Figure 8. Generally, the amplification in the USCB varies from 1 to 2.5. But in some areas it exceeds even 2.5 (e.g. a part of the Libiąż district, a part of the city of Katowice, Jastrzębie, Bytom etc.).

Regional empirical formulas of the peak ground motion equation (PGME) defined for the USCB (Chodacki, 2014, 2016), were used to calculate the ground vibration parameters in this area. The selected formula was defined for ground type A according to Eurocode 8, i.e. for rock basement, separately for velocity and acceleration parameters:

$$\log\left(PGV_{Hrock}\right) = 0.209 \cdot \log\left(E\right) - 0.035 \cdot R - \log\left(R\right) - 0.814 \tag{2}$$

where:

PGV_{Hrock} — peak horizontal vibration velocity for rock basement (mm/s),
E — tremor seismic energy (J),
R — epicentral distance (km).

The results of the distribution of peak horizontal vibration velocity amplitude PGV_H (calculated according to equation 1) for seismic tremors induced by mining activity in the USCB over the years 2010-2019 is presented in Fig. 9.

From the map (Fig. 9) we can find out that the largest amplitudes of vibration velocities above 0,05 m/s occurred in the area of the Żarki municipality, southern part of the city of Katowice (Panewniki district), Murcki, Ornontowice municipality, part of the city of Bytom (Miechowice district) and in the city of Jastrzębie. In the same places there were accelerations of ground vibrations in the frequency band up to 10 Hz exceeding 1.3 m/s^2 (Fig. 10). Recording of vibration of seismic tremor in the Libiąż area (Żarki municipality), for the Janina M = 3.8 seismic event positively verifies the calculations presented on the maps, Fig. 9 and Fig. 10. The values of PGV_H parameter calculated for this area (Fig. 9) correspond to the values recorded in the epicentral zone by surface seismological station (see Fig. 3).

A calculation algorithm analogous to the one used for vibration velocities was employed to calculate vibration acceleration on bedrock within a frequency band of up to 10 Hz (Chodacki, 2014):

$$\log\left(PGA_{H10rock}\right) = 0.223 \cdot \log\left(E\right) - 0.041 \cdot R - \log\left(R\right) + 0.586 \tag{3}$$

where:

$PGV_{H10rock}$ — peak vibration acceleration for bedrock within a band of up to 10 Hz (mm/s^2),
E — tremor energy (J),
R — epicentral distance (km).

Peak ground vibration acceleration amplitude values after taking into account the vibration amplification, $PGA_{H10} = PGA_{H10rock} \times W_f$, in the USCB area are presented in Fig. 10.

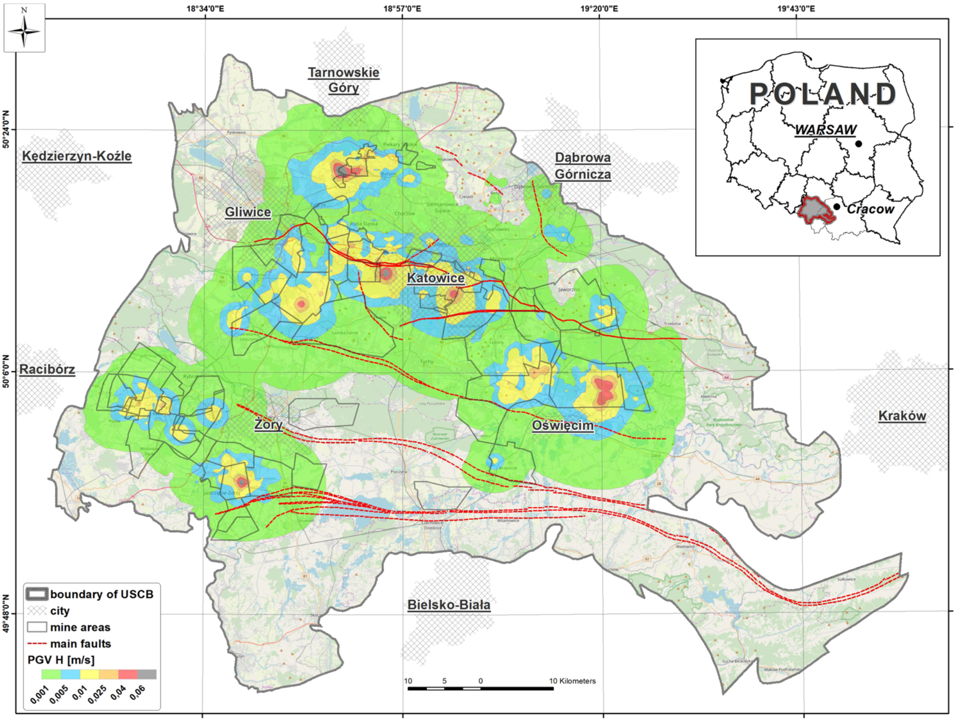

Fig. 9. Map of peak vibration horizontal velocity amplitudes PGV_H in the area of Upper Silesia, for mining-induced seismic tremors occurring in the years 2010-2019

5. Discussion of results

The recorded vibrations of the strong seismic events induced by mining activity indicate that in many cases relatively high PGA_{H10} values, and lower PGV_H values, significantly shorter time of vibrations duration, higher frequency and higher *PGA/PGV* ratios are observed when compared to recorded ground motion produced by natural earthquakes of comparable magnitude *(*Dubiński & Mutke, 2011; Mutke & Dubiński, 2016; Pachla et al., 2019). It seems that the aforementioned differences are the cause of the poor correlation of *PGA* and *PGV* vibration amplitudes recorded for strong mining tremors in the USCB area with the Instrumental Modify Mercalli Intensity scale (MMI) developed by the U.S. Geological Survey (Wald et al., 1999). For this reason, the special Mining Seismic Instrumental Intensity Scale (MSIIS-15), dedicated to mining induced seismicity, was developed under the RFCS COMEX research project (COMEX 2015). The MSIIS-15 scale is based on correlation between two measured seismic parameters, i.e. PGV_H and the duration time of vibration, with macro-seismic observation of the damages in buildings and the perceptibility of shaking by people (Dubiński & Mutke, 2011; Mutke et al., 2015). It should be emphasized that the MSIIS-15 scale is the first seismic instrumental intensity scale dedicated to seismicity induced by underground coal mining. The obtained results proved that this scale is very useful as it enables the use of a number of seismic observations in the mining area to assess the expected

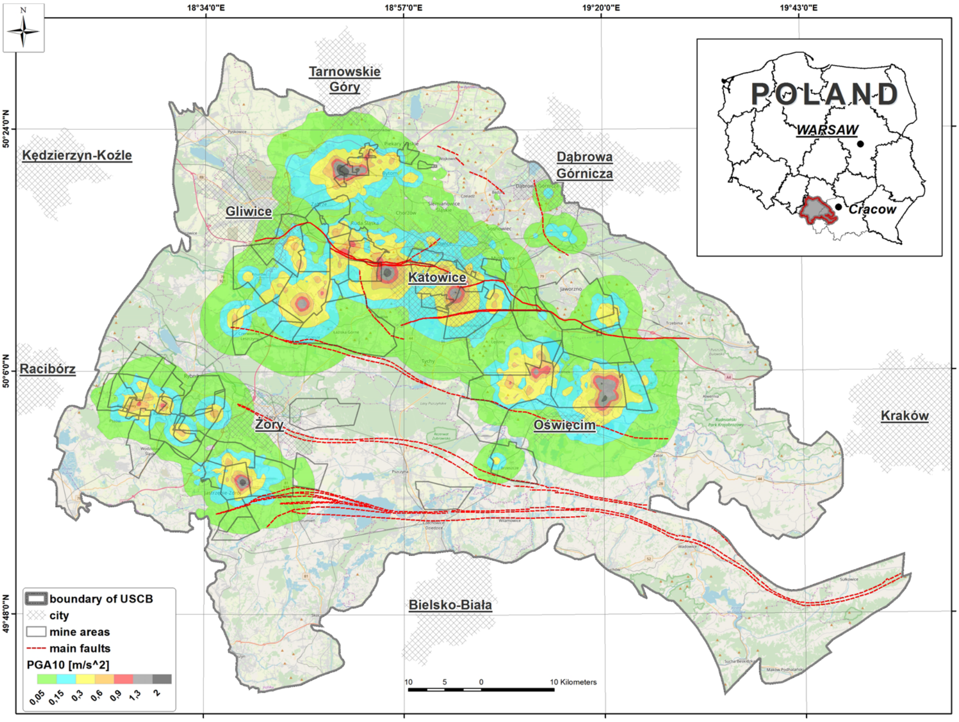

Fig. 10. Map of peak vibration acceleration amplitudes within a band of up to 10 Hz, PGA_{H10}, in the area of Upper Silesia, for mining-induced seismic tremors occurring in the years 2010-2019

damage range and the scope of liability of the mining industry. In table 2 a shortened version of the description of MSIIS-15 intensity levels for vibration velocity amplitudes PGV_H in the range of durations longer than 3 s is presented. For shorter time duration of mining tremors ($t < 3$ s), the corresponding harmful vibration thresholds are higher (Mutke et al., 2015).

Through the analysis of the maps of distribution of two basic *PGM* parameters i.e. PGV_H and PGA_{H10}, presented in Fig. 9 and Fig. 10, zones with anomalous values of seismic intensity can be determined. For example, the map of the peak horizontal ground vibration velocity amplitudes PGV_H (Fig. 9) shows that in the areas with the strongest mining tremors in the USCB values of this parameter exceeded 0,04 m/s. Using the MSIIS-15 scale this means that, within an isoline range of $PGV_H \geq 0,04$ m/s, these tremors might have caused initial light structural damage to residential buildings. Also, zones with PGV_H values exceeding 0,06 m/s can also be found, which can cause cracks to walls of buildings located in these areas, as well as fear and panic among the people. Numerous examples point to the high reliability of the relationship between the PGV_H measurement parameter and macro-seismic observations. Therefore, PGV_H is actually preferred for determining seismic intensity related to mining induced seismicity.

Many years of practical experience confirm that the correlation between the PGA_{H10} parameter with the instrumental scale MSIIS-15 is visibly weaker in the case of seismicity induced by mines. Short time duration vibration accelerations (below 0.2 s) are very sensitive to

TABLE 2

A short description of MSIIS-15 intensity levels

I_{MSIIS}	Perceived shaking	Potential damage	PGV_H (m/s)
I	Not felt or weakly felt	None	0÷0.00**5**
II	Felt indoors by many people, outdoors by few. Dishes rattle, hanging objects begin to sway.	*Buildings in good technical condition:* None. *Buildings in poor technical condition (BPTC):* first slight extension of existing cracks.	0.005÷0.0**10**
III	Strongly felt indoors by many people. Weak shaking of the whole building. Open windows and doors may close.	Intensification of existing damage *BPTC:* first new damage to non-structural decorative elements.	0.01÷0.0**25**
IV	Strongly felt by most people. Many people are frightened and run outside. Furniture may be shifted. Rocking of the whole building.	Damage to decorative elements (cracks, loosening and sliding of individual roof tiles) *BPTC:* extensive damage to the decorative elements. First slight damage to structural elements – do not endanger the safety of the building.	0.025÷0,0**40**
V	Very strongly felt by most people. Most people are frightened and try to run outside. A few people lose balance. Objects fall from shelves in large number.	Slight individual structural damage – does not endanger the stability of the building *BPTC:* Many instances of slight damage to structural elements – does not endanger the stability of the building.	0.040÷0.0**60**
VI	Most people have a problem with balance. Fear and panic. In single cases, heavy objects, such as TV sets and furniture, can fall over. Objects fall from shelves in large numbers.	Cracks to many walls of buildings *BPTC:* Structural damage which does not endanger the stability of the whole load-bearing structure of the building.	0.060÷0,**100**

any heterogeneity in the near-surface layer and manifest as single peaks with high acceleration amplitudes. Short time duration single vibration peaks with high acceleration, however, do not cause a seismic response of the building (Pachla et al., 2019, Mutke, 2019). Nevertheless, the PGA_{H10} parameter provides a great deal of useful information for designing building structures planned in mining territories (Zembaty et al., 2015).

6. Conclusions

1. The development of seismometry in the Polish part of Upper Silesia Coal Basin area, which is characterized by the occurrence of seismicity induced by mining activities, enabled the obtaining of a rich database in the scope of two basic physical parameters characterizing ground motion: PGV_H – peak amplitude of the horizontal component of vibration velocity; PGA_{H10} – peak amplitude of vibration acceleration in the frequency band up to 10 Hz. The infrastructure to obtain this data has been significantly developed as part of the EPOS PL project.

2. Using the PGME equations elaborated for USCB basin and maps of vibration amplification by Quaternary loose deposits, allows each seismic event to be assigned values of ground motion parameters in the area of interest. In the Upper Silesian Coal Basin we obtained the highest PGV_H velocity vibration reached a value of 0,10 m/s (Fig. 9) and the highest acceleration PGA_{H10} reached a value of 2.8 m/s^2 (Fig. 10) in the period from 2010 to 2019.

3. The developed map of PGV_H parameter indicate the occurrence of characteristic anomaly zones with increased values of this parameter, i.e. places where vibrations caused by mining tremors are very strongly felt by most residents and can cause damage to building structures ($PGV_H > 0.04$ m/s). These ground motions correspond to the V and VI levels of intensity according to the Mining Seismic Instrumental Intensity Scale (MSIIS-15). In one such seismic zone in Żarki near Libiąż, damage to 50 roof chimneys and numerous cracks in the walls in buildings were observed. This studies show a good correlation between PGV_H parameter and the macroscopic observations in the USCB. Therefore, PGV_H parameter is used in assessing the seismic hazard in mining areas.

Acknowledgements

This work was partially financed as part of the Central Mining Institute statutory activity No. 11050617-120 (subvention of the Ministry of Science and Higher Education in Poland) as well as was partially financed by the EPOS-PL project – European Plate Observing System, funded within the Operational Programme Smart Growth 2014-2020 and co-financed by the European Union from the funds of the European Regional Development Fund (ERDF) No: POIR.04.02.00-14-A003/16-00.

References

Chodacki J., 2014. *Regional relations of damping of acceleration in the area of the Upper Silesian Coal Basin.* Wiadomości Górnicze **7-8**, 387-395 (in Polish).

Chodacki J., 2016. *New Ground Motion Prediction Equation for Peak Ground Velocity and Duration of Ground Motion for Mining Tremors in Upper Silesia*. Acta Geophysica **64** (6), 2449-2470. https://doi.org/10.1515/acgeo-2016-0109.

Cesca S., Dost B., Oth A., 2013. *Preface to the special issue "Triggered and induced seismicity: probabilities and discrimination*. Journal of Seismology **17** (1), 1-4. https://doi.org/10.1007/s10950-012-9338-z

Dou L.M., Mu Z.L., Li Z.L., Cao A.Y., Gong, S.Y., 2014. *Research progress of monitoring, forecasting, and prevention of rockburst in underground coal mining in China*. International Journal of Coal Science and Technology **1**, 278-288.

Dubiński J., Mutke G., 2009. *Experiences from using the intensity scale of mining seismic events (GSI-GZW) in Polish coal mines.* In A. Sroka (ed.), Scientific Work of Technische Universitat Bergakademie Freiberg, 10. Geokinematischer Tag, 125-135. Essen: VGE Verlag GmbH.

Dubiński J., Mutke G., 2011. *Selected relations between earthquakes and mining seismic events recorded in Polish coal mines.* In Eskikaya S. (ed.) Proceedings of 22nd World Mining Congress Istanbul-2011, vol. I, 350-357.

Dubiński J., Stec K., Mutke G., 2017. *Relationship between the focal mechanism of magnitude M_L 3.3 seismic event induced by mining and distribution of peak ground velocity.* E3S Web of Conferences.

FENG Xia-Ting (ed.), 2018. *Rockburst: Mechanism, Monitoring, Warning and Mitigation*. Butterworth-Heinemann; 1 edition, p. 570. ISBN-13: 978-0128050545.

Foulger G., Wilson M., Gluyas J., Julian B., Davies R., 2018. *Global review of human-induced earthquakes.* Earth-Science Reviews **178**, 438-514. http://dx.doi.org/10.1016/ j.earscirev. 2017.07.008

Holub K., Rusajova J., Holecko J., 2013. *Current induced seismicity in the Paskov mine field (Ostrava region).* Acta Geodyn. Geomater. **10** (2), (170), 181-187. DOI: 10.13168/AGG.2013.0018

Kaláb Z., Knejzlik J., 2012. *Examples of rotational component records of mining induced seismic events from Karviná region.* Acta Geodynamica et Geomaterialia **9**, (2), 173-178.

Kozłowska M., Orlecka-Sikora B., Rudziński Ł., Cielesta S., Mutke G., 2016. *Atypical evolution of seismicity patterns resulting from the coupled natural, human-induced and coseismic stresses in a longwall coal mining environment*. Int. J. Rock Mech. Mining Sci. **86**, 5-15. DOI: 10.1016/j.ijrmms.2016.03.024

Lasocki S., Idziak A., 1998. *Dominant directions of epicenter distribution of regional mining-induced seismicity series in Upper Silesian Coal Basin in Poland.* Pure Appl. Geophys. **153**, 1, 21-40. DOI: 10.1007/s000240050183

Mutke G., Dworak J., 1992. *Factors determining the effect of mining seismic events on buildings in the Upper Silesian Coal Basin.* Selected issues of the geophysical studies in the mines – Lubiatów 1991, Publs. Inst. Geophys. Pol. Acad. Sc., M-16, **245**, 115-130, (in Polish).

Mutke G., Chodacki J., Muszyński L., Kremers S., Fritschen R., 2015. *Mining Seismic Instrumental Intensity Scale MSIIS-15 – verification in coal basines*. AIMS 2015 - Fifth Int. Symp.: Mineral Resources and Mine Development. RWTH Aachen University **14**, 551-560 (ISBN 978-3-941277-22-9).

Mutke G., Dubiński J., Lurka A., 2015. *New criteria to assess seismic and rock burst hazard in coal mines.* Archive of Mining Sciences **60** (3), 743-760. DOI: 10.1515/amsc-2015-0049

Mutke G., Dubiński J., 2016. *Seismic intensity induced by mining in relations to weak earthquakes.* Proc. of the 24th World Mining Congress. Part. Underground Mining. Rio de Janeiro, 399-407.

Mutke G., **2019**. *Impact of mining seismic tremors on the surface*. GIG Publishing House. ISBN 978-83-65503-21-3 (in Polish).

Mutke G., Kotyrba A.,Lurka A., Olszewska D., Dykowski P., Borkowski A., Araszkiewicz A., Barański A., 2019. *Upper Silesian Geophysical Observation System A unit of the EPOS project*. Journal of Sustainable Mining Volume **18** (4), 198-207. doi.org/10.1016/j.jsm.2019.07.005

Olszewska D., Mutke G., 2018. *A study of site effect using surface-downhole seismic data in a mining area.* 16th European Conference on Earthquake Engineering. Thessaloniki, June 2018.

Orlecka-Sikora B., Lasocki S., Kocot J., Szepieniec T., Grasso J.R., Garcia-Aristizabal A., Schaming M., Urban P., Jones G., Stimpson I., Dineva S., Sałek P., Leptokaropoulos K., Lizurek G., Olszewska D., Schmittbuhl J., Kwiatek G., Blanke A., Saccorotti G., Chodzińska K., Rudziński Ł., Dobrzycka I., Mutke G., Barański A., Pierzyna A., Kozlovskaya E., Nevalainen J., Kinscher J., Sileny J., Sterzel M., Cielesta S., Fischer T., 2020. *An open data infrastructure for the study of anthropogenic hazards linked to georesource exploitation*. Scientific Data **7** (89), https://doi.org/10.1038/s41597-020-0429-3

Pachla F., Kowalska-Koczwara A., Tatara T., Stypuła K., 2019. *The influence of vibration duration on the structure of irregular RC building.* Bull. Earthquake Eng. 1-20. https://doi.org/10.1007/s10518-018-00546-4

Ptacek J., 2020. *Rockburst in Ostrava-Karvina Coalfield*. Symposium of the International Society for Rock Mechanics. Procedia Engineering **191** (2017), 1144-115. Elsevier.

Savarienskij E.F., 1959. *Evaluation of the impact of nearsurface layer on the amplitude of ground motion*. Izv. Akad. Nauk SSSR Geofizyka **10**, 1441-1447, (in Russian).

Trifunac M.D., Brady A.G., 1975. *A study on the duration of strong earthquake ground motion*. Bulletin of the Seismological Society of America **65** (3), 581-626.

Wald D.J., Quitoriano V., Heaton T.H., Kanamori H., 1999. *Relationship between peak ground acceleration, peak ground velocity, and Modified Mercalli Intensity in California*. Earthq. Spectra **15** (3), 557-564, DOI: 10.1193/1.1586058.

Zembaty Z., Kokot S., Bozzoni F., Scandella L., Lai C.G., Kuś J., Bobra P., 2015. *A system to mitigate deep mine tremor effects in the design of civil infrastructure.* International Journal of Rock Mechanics and Mining Sciences **74**, 81-90. https://doi.org/10.1016/j.ijrmms.2015.01.004

COMEX Project., 2015. *Complex Mining Exploitation: optimizing mine design and reducing the impact on human environment (2012-2015).* RFCS-PR-11012. Deliverable 1.4.: New European Mining Seismic Intensity Scale – MSIIS-15.

EN1998-1.Eurocode8. *Design of structures for earthquake resistance*, 2005.