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 (PGVH) and peak ground horizontal acceleration (PGAH) at any point of earth’s surface depend on seismic energy, epicentral distance and site effect. Distribution maps of PGVH and of PGAH 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 PGVH 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 PGVH 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 PGAH is less useful for the evaluation of the intensity of mining induced vibrations is explained. The PGAH 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/s² 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

© 2020. The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution-NonCommercial License (CC BY-NC 4.0, https://creativecommons.org/licenses/by-nc/4.0/deed.en) which permits the use, redistribution of the material in any medium or format, transforming and building upon the material, provided that the article is properly cited, the use is noncommercial, and no modifications or adaptations are made.
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>
<thead>
<tr>
<th>Year</th>
<th>( 10^5 \leq E &lt; 10^6 ) [J]</th>
<th>( 10^6 \leq E &lt; 10^7 ) [J]</th>
<th>( 10^7 \leq E &lt; 10^8 ) [J]</th>
<th>( 10^8 \leq E &lt; 10^9 ) [J]</th>
<th>( E \geq 10^9 ) [J]</th>
<th>Total, N</th>
<th>Coal extraction mln. tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>1 035</td>
<td>157</td>
<td>12</td>
<td>1</td>
<td>1</td>
<td>1 206</td>
<td>76,1</td>
</tr>
<tr>
<td>2011</td>
<td>866</td>
<td>147</td>
<td>18</td>
<td>3</td>
<td>0</td>
<td>1 034</td>
<td>75,5</td>
</tr>
<tr>
<td>2012</td>
<td>795</td>
<td>210</td>
<td>15</td>
<td>2</td>
<td>0</td>
<td>1 022</td>
<td>78,6</td>
</tr>
<tr>
<td>2013</td>
<td>1 105</td>
<td>297</td>
<td>25</td>
<td>0</td>
<td>0</td>
<td>1 427</td>
<td>76,5</td>
</tr>
<tr>
<td>2014</td>
<td>1 322</td>
<td>374</td>
<td>61</td>
<td>5</td>
<td>0</td>
<td>1 765</td>
<td>72,5</td>
</tr>
<tr>
<td>2015</td>
<td>975</td>
<td>296</td>
<td>45</td>
<td>4</td>
<td>4</td>
<td>1 322</td>
<td>72,2</td>
</tr>
<tr>
<td>2016</td>
<td>1 210</td>
<td>411</td>
<td>15</td>
<td>4</td>
<td>0</td>
<td>1 640</td>
<td>70,4</td>
</tr>
<tr>
<td>2017</td>
<td>1 009</td>
<td>242</td>
<td>18</td>
<td>2</td>
<td>0</td>
<td>1 271</td>
<td>65,5</td>
</tr>
<tr>
<td>2018</td>
<td>1 129</td>
<td>336</td>
<td>32</td>
<td>5</td>
<td>2</td>
<td>1 504</td>
<td>63,4</td>
</tr>
<tr>
<td>2019</td>
<td>948</td>
<td>241</td>
<td>26</td>
<td>1</td>
<td>0</td>
<td>1 216</td>
<td>60,4</td>
</tr>
<tr>
<td>Total, N</td>
<td>10 394</td>
<td>2 711</td>
<td>267</td>
<td>27</td>
<td>7</td>
<td>13 407</td>
<td>711.1</td>
</tr>
</tbody>
</table>

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/s² to 2.8 m/s². 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).
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](image)

![Fig. 4. Janina $M_L = 3.8$ mining tremor – FFT frequency of velocity vibrations](image)
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).

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
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 $PGV_{H,rock}$ 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 amplifica-
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 profiting 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](image-url)
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, $W_f(1-5)$. 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:

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

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, Ormontowice 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/s² (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):

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

where:

- $PGA_{H10rock}$ — peak vibration acceleration for bedrock within a band of up to 10 Hz (mm/s²),
- $E$ — 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.
5. Discussion of results

The recorded vibrations of the strong seismic events induced by mining activity indicate that in many cases relatively high $PGA_H$ 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
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
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

<table>
<thead>
<tr>
<th>I$_{MSHS}$</th>
<th>Perceived shaking</th>
<th>Potential damage</th>
<th>$PGA_H$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Not felt or weakly felt</td>
<td>None</td>
<td>0÷0.005</td>
</tr>
<tr>
<td>II</td>
<td>Felt indoors by many people, outdoors by few. Dishes rattle, hanging objects begin to sway.</td>
<td>$Buildings$ in good technical condition: None. $Buildings$ in poor technical condition ($BPTC$): first slight extension of existing cracks.</td>
<td>0.005÷0.010</td>
</tr>
<tr>
<td>III</td>
<td>Strongly felt indoors by many people. Weak shaking of the whole building. Open windows and doors may close.</td>
<td>Intensification of existing damage $BPTC$: first new damage to non-structural decorative elements.</td>
<td>0.01÷0.025</td>
</tr>
<tr>
<td>IV</td>
<td>Strongly felt by most people. Many people are frightened and run outside. Furniture may be shifted. Rocking of the whole building.</td>
<td>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.</td>
<td>0.025÷0.040</td>
</tr>
<tr>
<td>V</td>
<td>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.</td>
<td>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.</td>
<td>0.040÷0.060</td>
</tr>
<tr>
<td>VI</td>
<td>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.</td>
<td>$Buildings$: 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.</td>
<td>0.060÷0.100</td>
</tr>
</tbody>
</table>
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/s² (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


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


