Journal of Sustainable Mining 16 (2017) 14–23

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Journal of Sustainable Mining

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Seismometric monitoring in the area of the Piekary Śląskie junction of the A1 motorway in terms of recording the vibrations resulting from mining tremors

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A R T I C L E I N F O

Article history:
Received 1 February 2017
Received in revised form
12 June 2017
Accepted 16 June 2017
Available online 21 June 2017

Keywords:
Mining tremors
Ground vibrations
Seismometric monitoring

A B S T R A C T

This article summarizes two years of observations of ground vibrations induced by mining tremors generated by hard coal mining within the Upper Silesian Coal Basin. Seismograms recorded in seismometric monitoring carried out in the area of the Piekary Śląskie junction of the A1 motorway were analysed. The purpose of the analysis was an attempt to explore a set of records in terms of the so-called attenuation relation. As a result, regression relations of the velocity of ground vibrations were obtained together with their statistical evaluation, in the function of tremor energy and their epicentric distances, divided by the duration of seismograms. The strongest regression dependencies with a determination coefficient of 91% were obtained for the tremors registered from a distance of up to approximately 5.5 km with a wide energy range from 5E4J to 3E8J for recording times longer than 3s. Moreover, the spectrum analysis of recorded seismograms showed that the scope of the maximum frequencies is between 5 Hz and ca. 15 Hz and it was confirmed that high frequency components are attenuated with the distance from the source.

1. Introduction

During the construction of the A1 motorway within the cities of Bytom and Piekary Śląskie as well as the Bobrowniki municipality, the area of the motorway was subjected to geodetic monitoring, i.e. devices for measuring rock mass deformation as well identification of rapid surface deformations were installed in the road structure. The monitoring prepared in this way resulted from the fear of the effects of mining activities, on the surface, from both the “deep” operation of collieries currently being carried out within that area and the “shallow” historical excavation of zinc, lead and brown iron ore deposits (Pilecki & Kotyrba, 2007). Additionally, a zone which contains the active Radzionków fault has been found within the area of the Piekary Śląskie junction. Therefore, the conducted geodetic monitoring of the A1 motorway, after the completion of the Sośnica-Pyrzowice section, was expanded and complemented with meteo-hydrogeological monitoring and seismometric monitoring.

The purpose of the seismometric monitoring is to monitor the maximum ground vibration caused by seismic and paraseismic factors that could have a negative impact primarily on the structure of the motorway, as well as to monitor the emission of vibrations occurring during the potential development of the subsidence process.

The analysis of ground vibrations that has been carried out from the beginning of the recordings, i.e. from August 2014, shows that there are multiple origins of vibrations. A large group of phenomena has been identified (ca. 260), including mining tremors associated with the operation of collieries located in relatively close proximity to the Piekary Śląskie junction of the A1 motorway and also high-energy tremors from the collieries located far away from this point.

Generally, the recording of the parameters of vibrations induced by mining tremors can serve two purposes:

- a deterministic purpose – consisting of the determination of whether a particular tremor causes damage to an object, generating a parameter exceeding the critical value known, for example, from standards,

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http://dx.doi.org/10.1016/j.jsm.2017.06.002

- a stochastic purpose - a “tremor” means a set of recordings defined at any time by a probability distribution around the mean value and this is the typical purpose in the case of forecasting (Kornowski, Markowski, & Zuberek, 2002). In this case, the equation known as the attenuation relation is the predictor.

The purpose of this article was to use the records of tremors at station no. 1 of the seismometric network to determine the functional dependencies of the velocity parameter of ground vibrations in the area of the Piekary Śląskie junction of the A1 motorway on the energy of tremors and their epicentre distance to the station, this being the so-called attenuation relation. Moreover, the conducted spectral analysis of velocity seismograms allowed the frequency range of recorded signals to be determined.

2. Materials and methods

2.1. Seismometric system

The seismometric system is a computerized, automated system for ground vibration measurement (velocity and acceleration), together with data lines, transmission equipment and computing devices with software for the interpretation of measurement data and reporting of the results (Lurka & Logiewa, 2007). The measurement system is used for the direct measurement of vibrations in the field and for the analysis of recorded seismic signals and it consists of apparatus and parts for observation. The apparatus parts include ACTS-3100 measurement probes cooperating with a SAV 310 signal conditioner and 64-channel recording server equipped with an A/D converter. Three accelerometers constitute the measuring sensors in the probes (directed in the positions N-S, W-E and Z), manufactured by “IMI SENSORS”, series 660, type TO-8, mounted in a special housing fastened to the bottom of the probe. The measurement probes have been installed at the bottom of holes drilled in the measurement wells, at a depth providing contact with the solid.

The observation part of the system includes a server for the processing and analysis of seismic data (working alongside a digital recorder). Both the apparatus and observation part have the possibility of remote GPRS transmission.

Technical parameters of the system:

- measured parameter: velocity and acceleration of ground vibrations;
- type of transmission: current;
- measuring range: 1 Hz–100 Hz (−3 dB);
- signal attenuation 50 Hz: −40 dB (filter turned on);
- output voltage of the conditioner: ±10 V;
- current consumption of the probe: 6 mA ±0.5 mA;
- power circuit: Un = 230 V, Um = 253 V, consumption ca. 100 VA;
- DC voltage supplying the transmission line: 3 × 15 V ± 1 V;
- number of input channels of the converter's card: 64;
- input voltage range of the recorder: programmable, max ±10 V;
- A/D converter: 16 bits;
- A/D converting dynamics: 96 dB;
- nonlinear distortion: < 3%;
- measurement accuracy: < 5%;
- sampling frequency: 500 Hz.

The seismometric system has been installed in the area of the Piekary Śląskie junction of the A1 motorway within the Radzionków fault zone. The system consists of 5 three-component stations recording ground vibrations and at every station (1, 2, 3, 4 and 5) the amplitudes of the velocity of vibrations are monitored, and at two (4a, 5a) the amplitudes of the acceleration of vibrations are recorded. The location of measurement stations is shown in Fig. 1.

2.2. Recordings of mining tremors in the area of the Piekary Śląskie junction

Over the period of two years, when the ground vibrations were continuously monitored using a seismometric system in the area of the Piekary Śląskie junction of the A1 motorway, several groups of characteristic events were specified among the registered phenomena identified. In particular, vibrations associated with the movement of motor vehicles, electrical interference from external electric fields, such as atmospheric discharges, electrical interference of apparatus and, most spectacularly, vibrations induced by mining tremors. Throughout the whole period of monitoring, no event could be unambiguously linked to the subsidence processes in the area of the motorway, that is with a geotechnical hazard was registered.

Due to the course of the southern part of the A1 motorway through the Upper Silesian Coal Basin and, thus, in the area of active collieries, the seismic activity recorded by mining seismological systems and the Regional Upper Silesian Seismological Network of the Central Mining Institute (*Górnośląska Regionalna Sieć Sejsmologiczna GIG*) distinguished itself from other recordings on the seismograms of the seismometric monitoring.

Between August 20, 2014 and August 31, 2016, 255 events were recorded which were correlated with mining tremors originating from several collieries located very close to the Piekary Śląskie junction (i.e. Bobrek, Centrum, Piekary and EKO-PLUS) and also coal mines located at a greater distance away (Śląsk, Halemba, Bielszowice, Pokój, Staszic, Janina, Szczygłowice, Budryk and Sośnica). The recordings at station no. 1 of the seismometric system were selected for analysis (Fig. 1).

Each of the identified tremors was attributed with its own energy E [J] and epicentre distance D [m] to the station. Then, the maximum velocity amplitude $Vxmax$ [m/s] and the duration of the phenomenon T [s] were determined based on the seismograms. The frequency f [Hz] was determined based on the amplitude spectrum of the velocity seismogram which was established using the FFT method. The assumed criterion for the selection of its value was the frequency for which the amplitude was decreasing to ca. 5% of its maximum value, i.e. when almost flat noise spectrum was actually observed. The strongest tremor recorded by the seismometric system, with energy of 4E9 J, came from the Śląsk colliery. This tremor's seismogram is shown in Fig. 2. It was recorded at station no. 1 from a distance of ca. 16 km, with a maximum value of vibration velocity of 0.0006 m/s.

The values of the analysed parameters (log$E$, D, $Vxmax$) obtained for the tremors’ seismograms subject to study and recorded within the Piekary Śląskie junction are presented in the form of histograms in Fig. 3.

The set of tremors registered at station no. 1 in the area of the Piekary Śląskie junction is characterized by the following parameters:

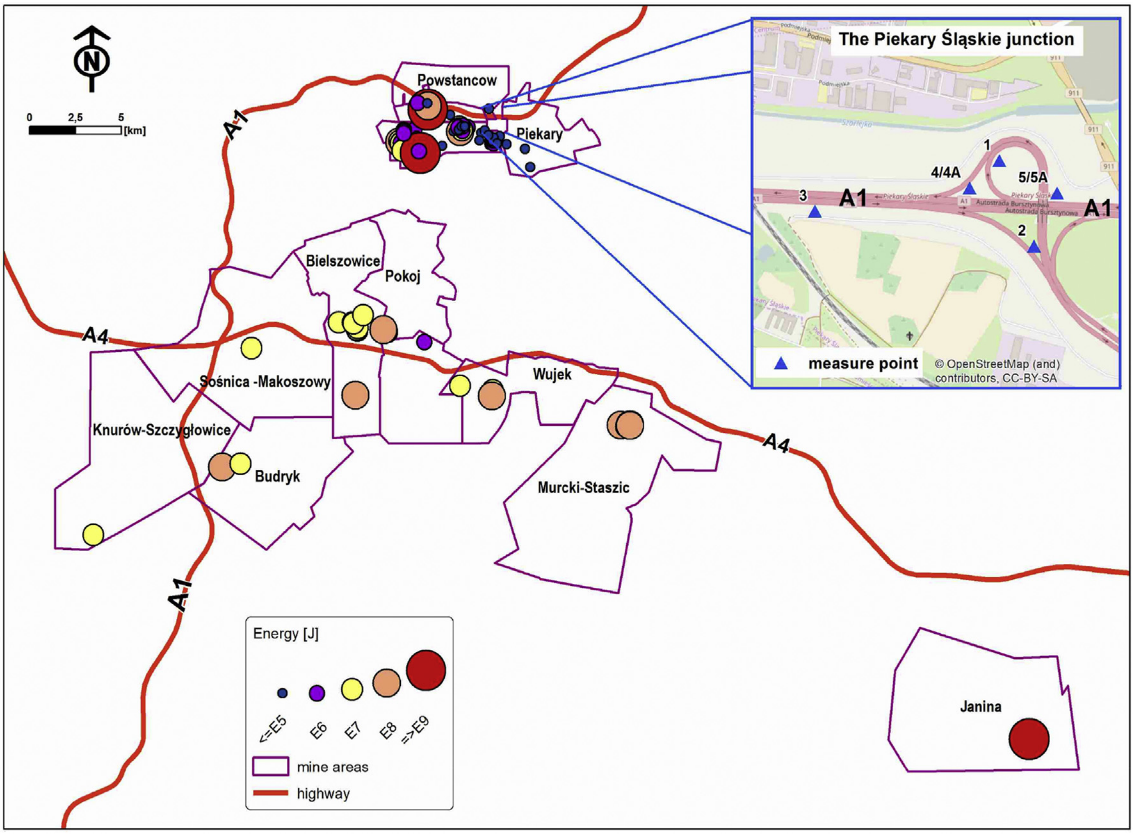

Fig. 1. Location of collieries together with the tremor centers and location of measurement stations of the seismometric system at the Piekary Śląskie junction of the A1 motorway.

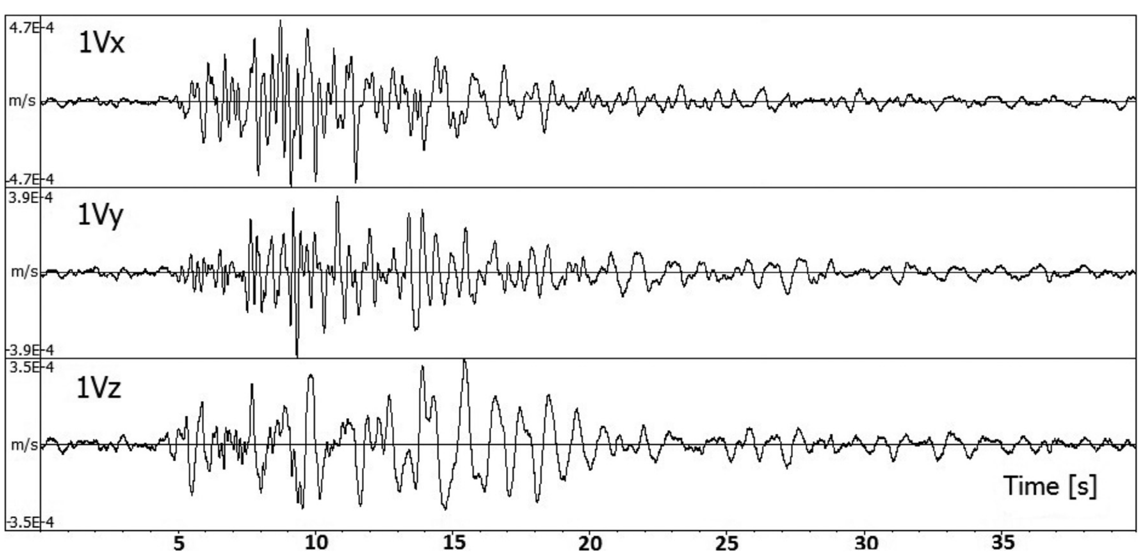

Fig. 2. The tremor from the Śląsk colliery dated April 18, 2015 with an energy of 4E9 J (local magnitude 4.1) recorded at stations no 1 of the seismometric network.

- energy range: from 4E2 J (Centrum colliery) to 4E9 J (Śląsk colliery). The most recorded phenomena had energy of ca. E4 J (Fig. 3a);
- epicentre distances: from 467 m (KWK Powstańców Śląskich colliery) to ca. 44 km (KWK Janina colliery) (Fig. 3b);
- maximum vibration velocity amplitudes: from 0.04 mm/s to 2 mm/s (Fig. 3c).

3. Results and discussion

3.1. Dependencies of the maximum velocity on the energy and distance

The method of regression analysis was used for the development of the functional dependencies between the velocities of

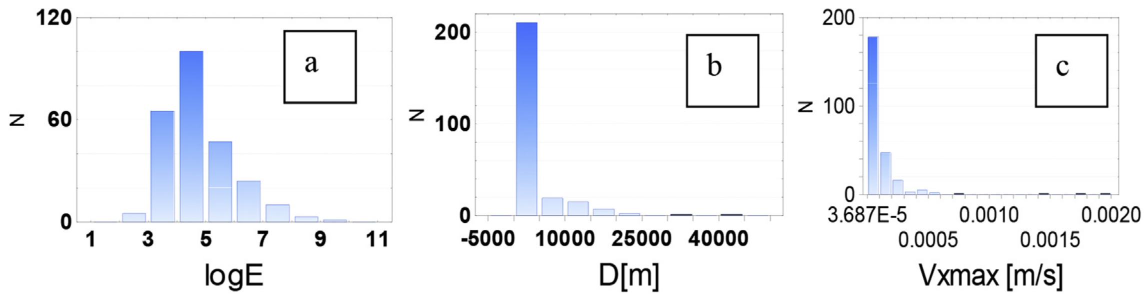

Fig. 3. Histograms of the distribution of studied parameters of tremors recorded at station no. 1 of the seismometric network, observed between August 2014 and August 2016. From left: tremors energy, log*E;* epicentre distances to the station no 1, *D* [m]; maximum velocity of the horizontal component at station no. 1 *Vxmax* [m/s].

vibrations and the values of the energy of tremors, and also the epicentre distances, according to the adopted Joyner-Boore model (Joyner & Boore, 1981). The dependency describing this relationship, also known as attenuation relation, for the conditions within the Upper Silesian Coal Basin (Stec & Mutke, 2010) is presented as an equation (1)

$$\log Vxmax = a \cdot \log E + b \cdot \log D + c \quad (1)$$

where: *Vxmax* – maximum value of vibrations velocity [m/s], *E* – seismic energy of tremors [J], *D* – epicentre distance [m], *a, b, c* – coefficients estimated from the recording.

The quality assessment of the regressive dependencies was carried out by the comparison of calculated parameters, such as the regression coefficient *R* and determination coefficient R^2 as well as the assessment of the significance of variables based on the Student's t-test. The determination coefficient indicates the percentage of the observed variation of the variable (in this case, the velocity of ground vibrations) explains the model assumed. The model was verified based on the analysis of residues that being the differences between the values measured and the values resulting from the model analysed.

In the first approach, a regression analysis was carried out for all tremors recorded at the stations of the seismometric network (for the energy range of $4E2 \le E \le 4E9$ J and epicentre distance of 470 m to 44 km) and the following equation (2) was obtained

$$\log Vxmax = 0.34\log E - 1.02\log D - 2.17 \quad (2)$$

with the following parameters of the statistical dependency assessment:
$R = 87\%$, $R^2 = 76\%$ and the relevance of all tested components resulting from the Student's t-test for the assumed level of relevance–0.05.

The following figures present the results of verification of the model assumed by examining the residuals (i.e. the differences between the observations of the log *Vxmax,* a dependent variable, and the values resulting from the assumed model). Therefore, a test for the normality of the distribution (Fig. 4) as well as homoscedacity (Fig. 5) was carried out, verifying whether the variance of the random component (residual) is the same for all observations.

Based on the plots received (Figs. 4 and 5), it has been found that the residues of the model have normal distribution and the homoscedastic condition was kept.

It is necessary, in the assessment of the statistical reliability of the results obtained in the regression analysis, to determine the confidence intervals (Kornowski & Kurzeja, 2008). A confidence limit determines the likely range of deviation of calculation results from the actual value (Stanisz, 2007). For the assessment of the safety of buildings, confidence limits of 95% are assumed (Kwiatek, 2010) and such confidence limits have been assumed for the regression described with equation (2). The exemplary confidence limits (Lower Control Limit – LCL and Upper Control Limit – UCL) for regression 2, for the assumed values of energy *E* and distances *D*, are presented in Table 1.

Results from the analysis of the values specified in Table 1 show that the greatest dispersion determined by the quotient of the value of the upper confidence level (*UCL*) to the average value *Vxmax* does not exceed 1.5 and it is present for those tremors with the greatest energies.

The obtained parameters of the statistical assessment of the analysed model are high and it would seem that this model is well described by equation (2). While the dispersion of the variable log*E* in relation to *D* clearly suggests that the analysed set is non-homogenous due to the variable epicentre distance which is shown in the histogram of the variable *D* (Fig. 3b). On this basis, a subset of tremors (over 200) originating from the collieries that are closest to the seismometric network (i.e. Bobrek, Centrum, EKO-PLUS and Piekary) has been distinguished for further analysis. These tremors are characterized with epicentre distances of 500 m to ca. 5500 m. Then, this group of tremors was divided in terms of the duration of the main phase of the recorded phenomena into short duration (up to 1.5 s), medium duration (between 1.5 and 3 s) and long duration (more than 3 s). The obtained results (coefficients) of the studied attenuation relations and values of the parameters for the statistical assessment are summarized in Table 2; and Figs. 6–9 present the planes that constitute a geometrical representation of the estimated models together with the dispersion of the values from the observations.

Analysis of Table 2 shows that the best regression fitting, $R^2 = 91\%$, was obtained for the set of tremors determined during long periods of time, i.e. longer than 3 s. These tremors are characterized by energies of 5E4 J to 3E8 J and epicentre distance of 2 km–5.5 km. The weakest fitting $R^2 = 32\%$ belonged to the model obtained for the set of tremors with short durations, i.e. up to 1.5 s, energies of 4E2 J to 9E4 J with epicentre distances of ca. 0.5 km to ca. 4.7 km.

3.2. Spectrum of the selected class of tremors

Among the tremors recorded by the seismometric network's sensor, two groups have been selected that include tremors with the same energies within the group, recorded at the same station, no. 1, (horizontal component) and distinguishable due to their great dispersion of locations. The first group includes four tremors with energies of 2E7 J localized in four collieries from different distances *D*, i.e.:

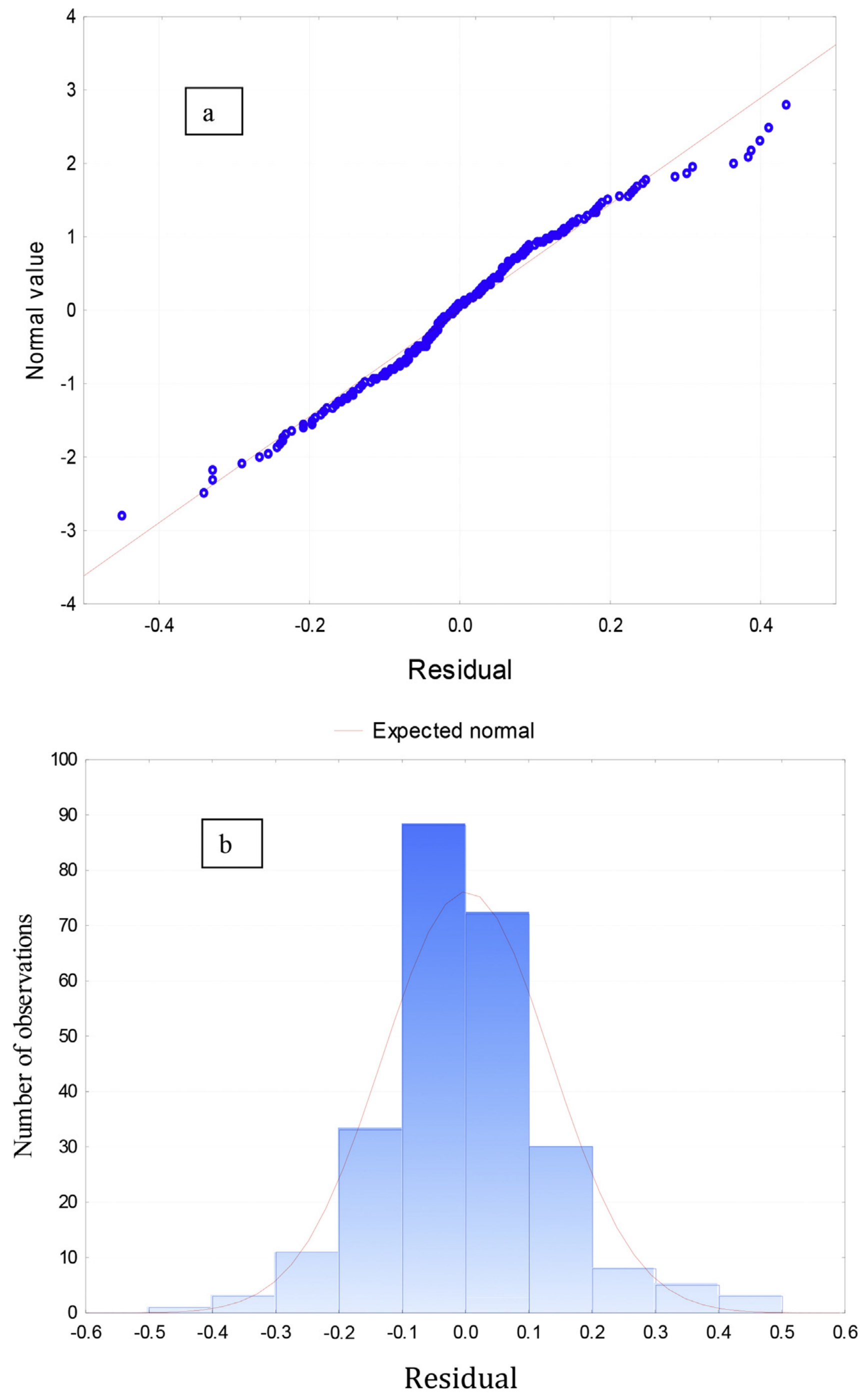

Fig. 4. Residual normality plot (a). Residual probability plot (b). The set of tremors assumed for interpretation.

- EKO-PLUS, $D = 3.7$ km;
- Bobrek, $D = 5.4$ km;
- Pokój, $D = 12.9$ km;
- Staszic, $D = 17.8$ km;

and their amplitude spectra of velocity seismograms are presented in Fig. 10.

The second group consisted of 4 tremors with energies of 3E6 J and originating from the collieries:

- Centrum, $D = 1.97$ km;
- Bobrek, $D = 4.64$ km;
- Bielszowice, $D = 13.47$ km;
- Sośnica, $D = 18.16$ km;

and their amplitude spectra of velocity seismograms are presented in Fig. 11.

To allow the comparison of the amplitude spectra of seismograms presented in Figs. 10 and 11, these figures have been scaled in the same manner horizontally and vertically.

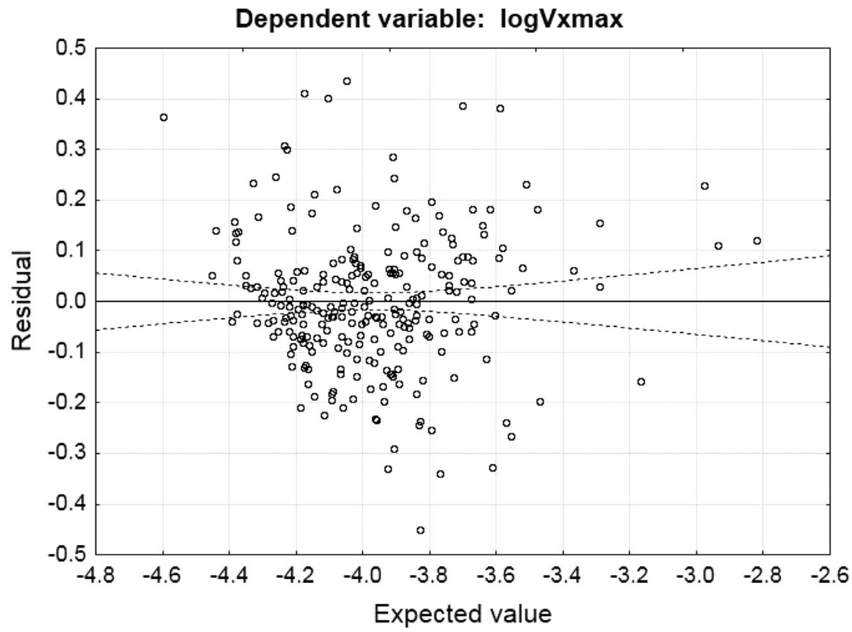

Fig. 5. Residual scatter plot in relation to the values predicted for log*Vxmax* defined with equation (2) (points) with a matching regression line (continuous line) and 95% confidence intervals for regression (dotted line).

Table 1
The forecasted values of ground vibrations velocity *Vxmax* for the tremors recorded at station no 1 within the confidence interval of −95% (Lower Control Limit − LCL) and +95% (Upper Control Limit − UCL).

D, m	Energy, J														
	1.0 E+05 J			1.0 E+06 J			1.0 E+07 J			1.0 E+08 J			1.0 E+09 J		
	Vxmax	*LCL*	*UCL*	*Vxmax*	*LCL*	*UCL*	*Vxmax*	*LCL*	*UCL*	*Vxmax*	*LCL*	*UCL*	*Vxmax*	*LCL*	*UCL*
	$\times 10^{-6}$ m/s	$\times 10^{-6}$ m/s	$\times 10^{-6}$ m/s	$\times 10^{-6}$ m/s	$\times 10^{-6}$ m/s	$\times 10^{-6}$ m/s	$\times 10^{-6}$ m/s	$\times 10^{-6}$ m/s	$\times 10^{-6}$ m/s	$\times 10^{-6}$ m/s	$\times 10^{-6}$ m/s	$\times 10^{-6}$ m/s	$\times 10^{-6}$ m/s	$\times 10^{-6}$ m/s	$\times 10^{-6}$ m/s
500	615	531	712	1360	1120	1640	2990	2340	3810	6580	4890	8850	14,500	10,200	20,600
1000	304	277	333	669	582	769	1470	1220	1780	3250	2540	4150	7160	5310	9650
3000	98.1	94.1	102	216	202	231	476	424	535	1050	886	1240	2310	1850	2890
5000	58.5	54.8	62.4	129	122	136	284	259	311	625	543	721	1380	1130	1670
10,000	28.9	25.7	32.4	63.6	58.4	69.2	140	129	153	309	274	347	680	577	801
20,000	14.2	12	16.9	31.4	27.5	35.9	69.2	61.7	77.5	152	135	172	336	289	390
30,000	9.33	7.61	11.4	20.6	17.4	24.2	45.3	39.4	52	99.8	87.3	114	220	189	255

Table 2
Results of the regression analysis log*Vxmax* = $a \cdot \log E + b \cdot \log D + c$ for the tremors with $D \leq 5.5$ km recorded at station no 1 of the seismometric network.

Type of set – duration	*a*	*B*	*c*	*R*, %	R^2, %	Distance range *D*, m	Energy range *E*, J	Set size, *N*
Short	0.18	−0.35	−3.73	56	32	467–4670	4E2–9E4	60
Medium	0.38	−1.07	−2.18	85	73	1003–5204	2E3–9E5	119
Long	0.36	−1.22	−1.54	95	91	1966–5465	5E4–3E8	50
All set	0.35	−0.97	−2.40	88	77	467–5465	4E2–3E8	229

The quality analysis of the spectra presented in the figures leads to the following conclusions:

- for the group of strong tremors being the subject of the study (with energies of 2E7 J and 3E6 J) from distances between ca. 18 km and 2 km, the significant value of the amplitude spectrum does not exceed the value of 20 Hz;
- the differences between the spectra of the same set are visible in the value of the maximum amplitude as well as in the range of the usable frequency of the spectrum and both values decrease

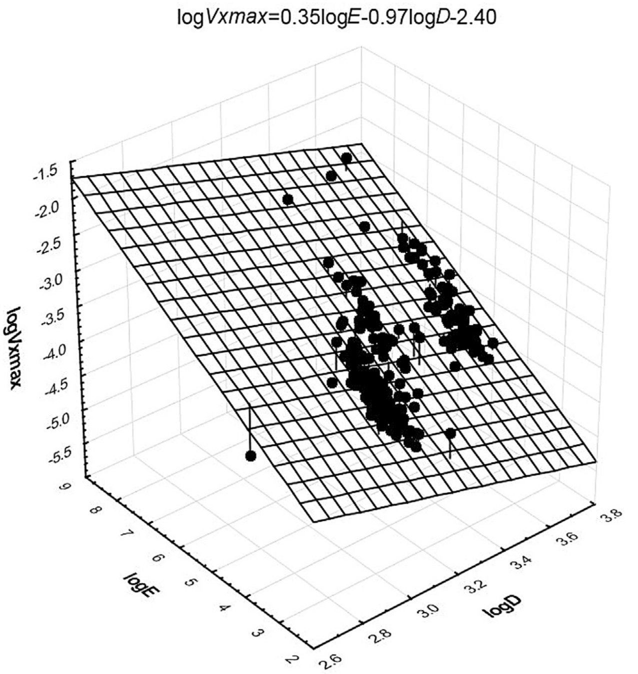

Fig. 6. Surface plot 3D log*Vxmax* in relation to log*E* and log*D* with data scattering for tremors from collieries located close to the Piekary Śląskie junction.

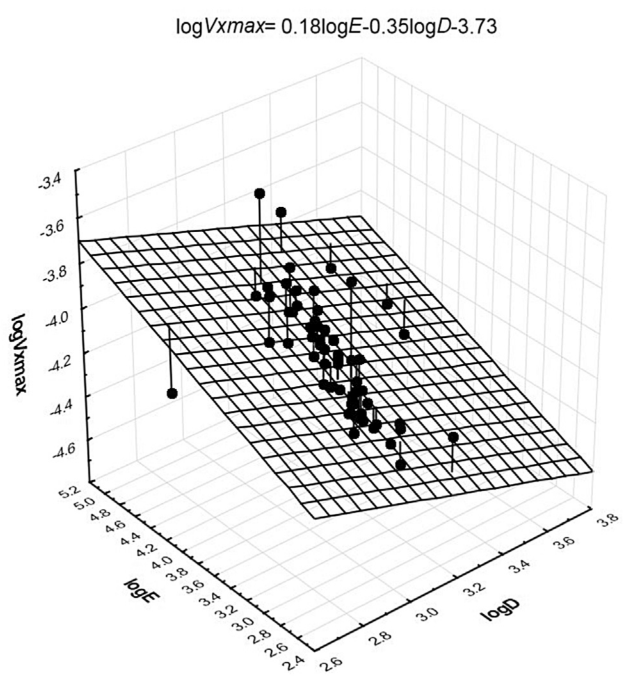

Fig. 7. Surface plot 3D log*Vxmax* in relation to log*E* and log*D* with data scattering for tremors from collieries located close to the Piekary Śląskie junction, for $t \leq 1.5$ s.

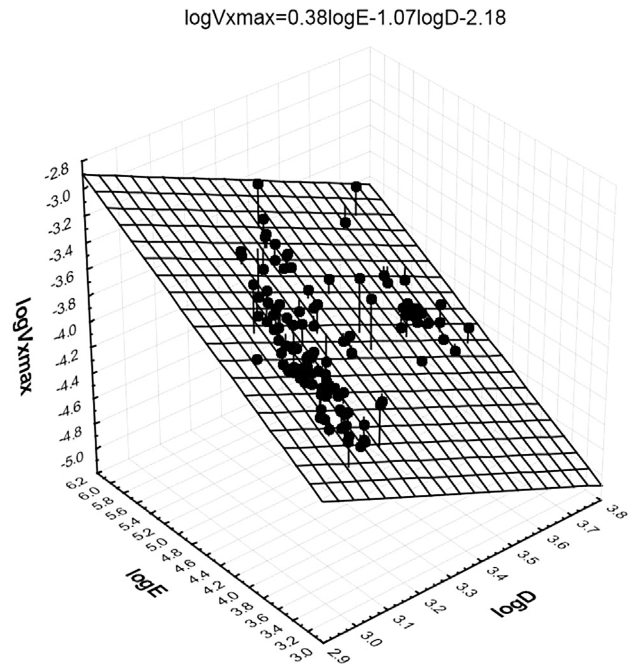

Fig. 8. Surface plot 3D log*Vxmax* in relation to log*E* and log*D* with data scattering for tremors from collieries located close to the Piekary Śląskie junction, for $1.5 \text{ s} \leq t < 3$ s.

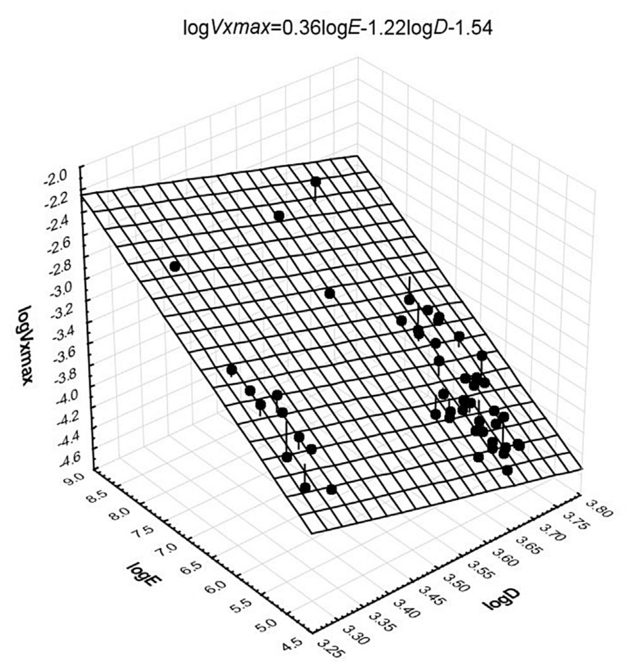

Fig. 9. Surface plot 3D log*Vxmax* in relation to log*E* and log*D* with data scattering for tremors from collieries located close to the Piekary Śląskie junction, for $t > 3$ s.

with the epicentre distance. This phenomenon is explained in the literature (e.g. Kornowski & Kurzeja, 1999; Kornowski et al., 2002) as follows: a rock mass acts as a low pass filter and the role of high frequency values decreases with the increase of the epicentre distance, and the differences between the amplitude spectra of seismograms probably reflect the differences in the directional properties of the source and course as well as the distance that the waves travelled.

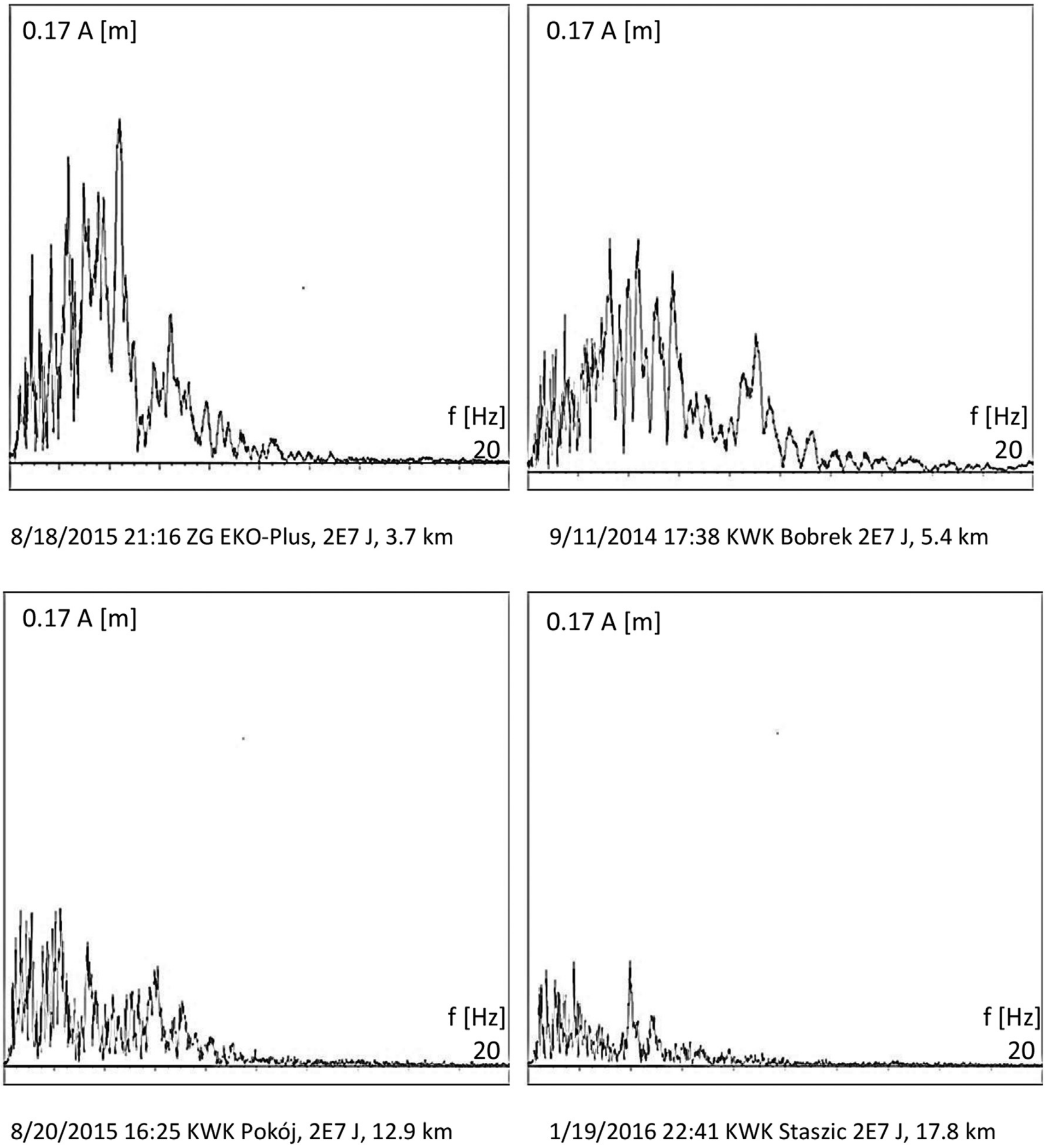

Fig. 10. The amplitude spectra of velocity for the tremors with an energy of 2E7J (local magnitude 2.9).

4. Conclusions

The seismometric monitoring system used successfully supports the comprehensive assessment of security within the Piekary Śląskie junction of the A1 motorway in terms of the influence of ground vibrations originating from seismic and paraseismic phenomena. The analysis of the phenomena recorded within two years of the launch of the system showed that in addition to the phenomena associated with traffic, electrical and apparatus interference as well as other seismic phenomena, vibrations that originate from mining tremors are also recorded. Systematic observations of the state and condition of the motorway, in particular after strong mining tremors showed that there are no negative effects in the structure of this road junction.

The mining tremors seismograms archived since the beginning of the recording (255 events) allowed the parameters of the recorded vibrations to be analysed in the sense of probability. The study conducted also included the implementation of functional dependencies (regression) of ground vibration velocity on the energy of tremors and epicentre distance resulting from the so-called attenuation relations, obtaining the value of the parameters (equation (2)) and carrying out the statistical assessment of them (Table 1, Table 2). Strong regression dependencies for the tremors registered from the distances up to 5.5 km and with energies of 5E4 J to 3E8 J and a recording time longer than 3s, with a coefficient of determination of 91% were stated. The weakest regression dependence was noticed for tremors of a duration up to 1.5 s and these were tremors with energies up to 1E5 J and an epicentre distances from 500 m to 4.5 km (determination coefficient $R^2 = 32\%$). Apart from the analysis of the attenuation relation, a spectral analysis was carried out for all recordings, and the approximate band range of significant frequencies of the recorded tremors was assessed, obtaining values from ca. 5 Hz–15 Hz. Another finding resulting from the analysis of spectra of the tremors with similar energies

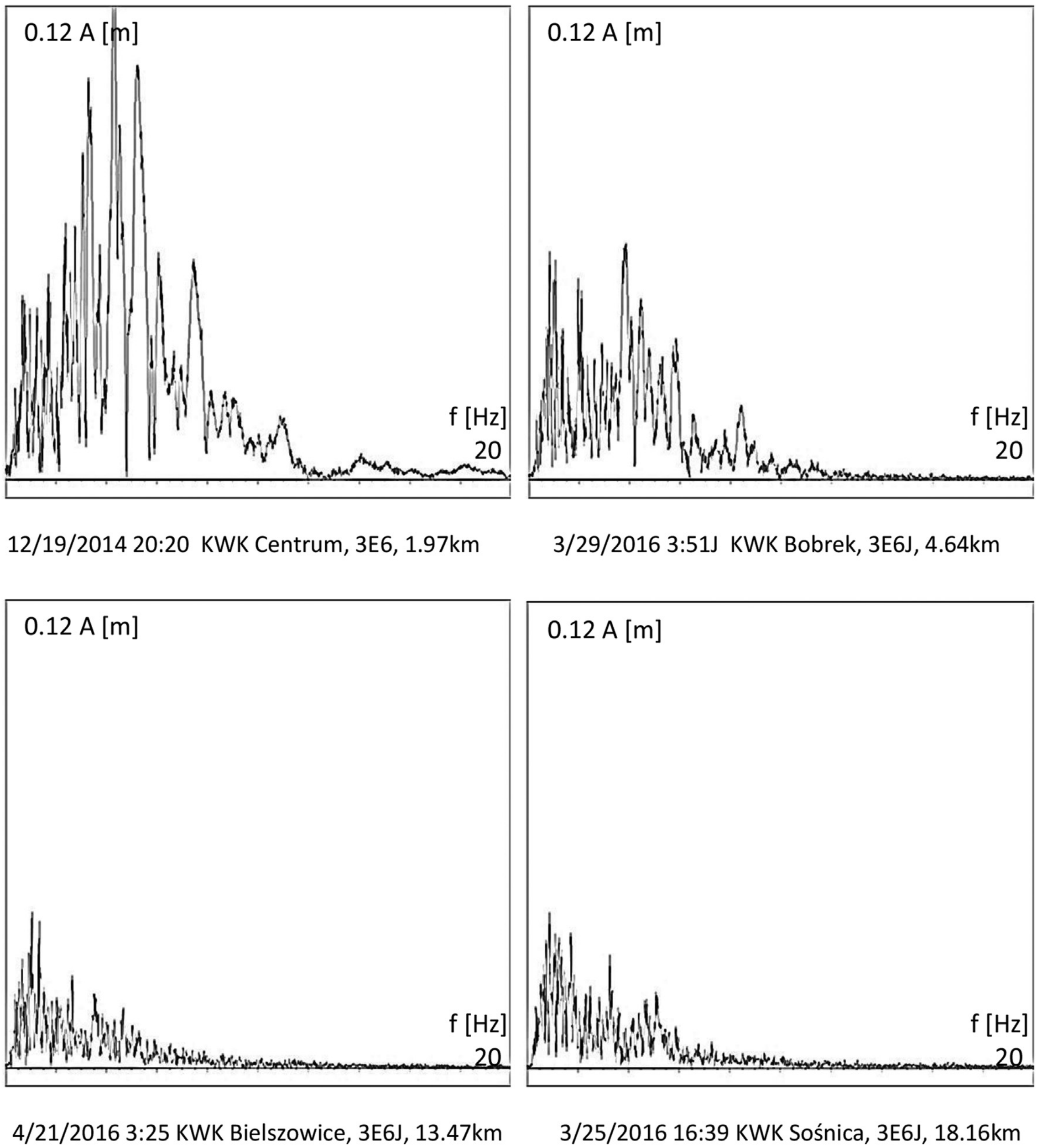

Fig. 11. The amplitude spectra of velocity for the tremors with an energy of 3E6J (local magnitude 2.5).

and large dispersion of epicentre distances (Figs. 10 and 11) was the confirmation of the fact that high-frequency components attenuate with the distance from their source.

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