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Research paper

Control and documentation studies of the impact of blasting on buildings in the surroundings of open pit mines

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ABSTRACT

Environmental Protection Law together with Geological and Mining Law impose on a mining plant a duty to protect its surroundings against the effects of mining operations. It also refers to the impact of vibrations on people and buildings induced by blasting works. Effective protection is possible only if the actual level of the impact is known, hence it has to be recorded. It was and still is the keynote idea of the research conducted at the AGH Laboratory of Blasting and Environmental Protection. The effect of many years of research is the development of an original and, in particular, an effective procedure to record the impact of blasting works with periodical measurements of vibration intensity or monitoring the vibrations' impact on buildings in the surrounding area. These assumptions form part of preventive actions taken by open pit mines, which are aimed at minimizing the impact of blast workings on the surroundings and are often recommended by experts. This article presents the course of action concerning control tests of vibration intensity in the surroundings of a mine. It also shows it is necessary to monitor vibrations in buildings as it is a source of knowledge for the mining plant management personnel and engineers who conduct blasting works, thus contributing to an increase in awareness of the responsible management of a mining plant. The Vibration Monitoring Station (KSMD) developed by a research group, after several upgrades, has become a fully automated system for monitoring and recording the impact of blast workings on the surroundings. Moreover, it should be emphasised that without the mine management personnel's cooperation, it would be impossible to work and achieve the common goal, i.e. conducting blasting works in a way that is safe for the surroundings.

1. Introduction

Detonating explosives in long boreholes is a commonly applied technique for quarrying rocks, hence the problems associated with the method are such an important issue for the surface mining industry. Only 20–30% of the energy of detonated explosives actually quarries rocks. The rest is lost, and as a result, may cause fly-rock debris, airblast and seismic waves. The latter are a source of many problems, because ground vibrations can affect different buildings located in the vicinity of mines. In this case, determining a permissible explosive limit which takes into consideration the protection of such structures is crucial. From the point of view of operation effectiveness and economic reasons, as many charges as possible should be detonated in one series (bench blasting), which may contribute to enhancing the impact.

Thanks to many years of research (financed also by the mines) conducted at the AGH Department of Surface Mining and actions aimed at disseminating the idea of such preventive actions in mining companies, specific research procedures were developed and the mining plant management personnel reached a certain level of awareness of the problem. The effects of this are consultations, control measurements and even the full monitoring of the impact of blasting works on the surroundings. It has significantly improved the psychological comfort of both the mining plant management personnel and those involved in research and analyses. Such actions are also well-received by the local communities and the general public.

A determination of a permissible explosive limit for blasting works is the first step in the preventive actions of open pit mines. More and more mines initiate extensive actions aimed at safe blasting works with simultaneous, periodic or constant documentation of the impact on the buildings in the surrounding area. Such

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actions are slowly becoming routine and young engineers treat them as obvious, associated with the responsible management of a mining plant.

Knowledge of the applied blasting technology, together with an analysis of the intensity of vibrations propagating around a mine, considering the structures in the surrounding area, is an important element of preventive actions. The buildings within the range of vibrations, which propagate as a result of detonating explosive charges, are treated as protected structures. The use of proper, i.e. effective, preventive measures has to result from identifying the issue as cause and effect. It is necessary to explain whether there is cause and effect between damage to a given building (or several buildings) and mining the deposit with explosives, and whether, sometimes, the building vibrations are annoying for people.

It presents the general course of action in a dynamic diagnosis (Winzer, Sołtys, & Pyra, 2016) where the following stages are necessary:

– recognition of building types in the surroundings of a mine,
– recognition of vibration sources, considering mining conditions and the route of vibration propagation from the sources to the buildings,
– assessment of the impact of blasting works on buildings (and assessment of their level of nuisance for people),
– correct diagnosis stating whether there is a cause and effect connection between the actual technical condition of given buildings and vibrations induced in a mine.

The choice of preventive actions in a mine, aimed at minimizing the impact of blasting works, mostly depends on (Winzer et al., 2016):

– the threat level for structures located in the surroundings, their number and purpose (industrial building, residential and utility buildings, protected buildings),
– the frequency of blasting works,
– the technique of blasting works.

Generally, preventive actions are divided into two groups of issues: basic research and documenting the impact of vibrations on the surroundings (Fig. 1).

The aim of basic research is to determine conditions for conducting safe blasting works, considering local geological and mining conditions, and the type, quality and technical condition of buildings in the surrounding area. The final effect of basic research is the determination of the dependences which enable calculations of a permissible explosive limit for the forecast production in a specified time period, together with the description of the technique and

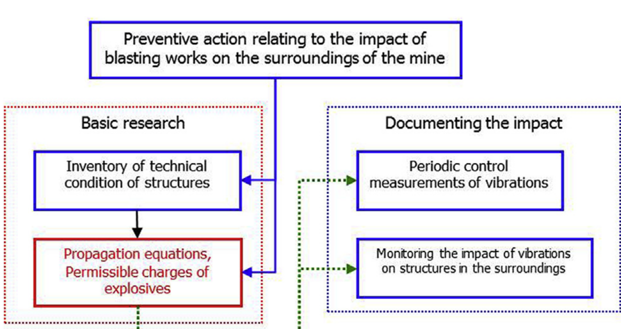

Fig. 1. Preventive actions in open pit mines concerning the impact of blasting works on the surroundings.

technology of conducting the blasting works.

By documenting the impact of blasting works whether the dependences determined in basic research are up-to-date is verified, in other words, if the level of the intensity of vibrations induced in the surroundings complies with the predicted values together with the assessment of the impact of recorded vibrations on buildings. The actions can be realised as periodic control measurements or, in a wider scope, as monitoring vibrations in selected buildings in the surroundings of an excavation.

Therefore, preventive actions ought to involve (Fig. 1):

– an inventory of the technical condition of structures in the surrounding area,
– recognizing directions of vibration propagation and the level of the intensity in the surroundings of a mine working. On this basis, the range of the adverse influence of vibrations and permissible explosive limit are determined,
– conducting periodic control measurements,
– in special cases, monitoring vibration levels in protected structures.

The last two points are often recommended by appraisers. Recently these points have also been required by the licence-granting authorities. These are regulations imposed by Environmental Protection Law and Geological and Mining Law, applied to enterprises which may significantly impact the environment. Most mines which use explosives fall into this category.

2. Material and methods

An important element in preventive actions conducted by surface mines is documenting the level of impact which vibrations induced by blasting works have on structures in their surroundings. It can be realised through periodic control measurements or continuous monitoring of the impact (Fig. 1).

2.1. Research procedure

The aim of periodic tests is to monitor the level of vibration intensity and its compatibility with the previously obtained dependences (vibration propagation equation), i.e. indicate if:

- blasting works are conducted following the assumed limitations (permissible explosive limit),
- the intensity of vibrations does not exceed the predicted level, resulting from applied parameters of blasting works and the distance from protected structures (ground vibration measurements),
- induced vibrations do not have an adverse influence on structures in the surroundings (measurement of vibrations in the foundation of a structure or structures).

Such analysis can be conducted with the following parameters ρ (Fish, 1951; Lopez Jimeno, Lopez Jimeno, & Ayala Carcedo, 1995), which are calculated with the general propagation equation (1):

$$u = k \cdot \rho^{\beta} \tag{1}$$

where:

u – velocity of vibrations, mm/s,
k – coefficient characterising geological and mining conditions, experimentally determined,
ρ – relative explosive charge expressed with equation: (2)

$$\rho = \frac{Q^n}{r} \tag{2}$$

where:

β – experimentally determined exponent.
Q – weight of explosive charge.
r – distance between the measuring point and the blasting works.
n – exponent assumed in the range of 1/3, ½ or 2/3.

The procedure of determining permissible explosives charges for the conditions in a given mine includes measurements of vibration intensity (u) at different distances (r) from blasting works conducted with different (if possible) explosive charges (Q). Derivation of the propagation equation (1) and considering the critical value of ground vibration velocity (u_{cr}), which protects the buildings in the surroundings, enables the determination of the allowable value of parameter (ρ_{mpv}) in the form (3):

$$\rho_{mpv} = \left(\frac{u_{cr}}{k}\right)^{\frac{1}{\beta}} \tag{3}$$

where:

ρ_{mpv} – maximum permissible value of parameter (relative charge).
u_{cr} – critical value of velocity of ground vibrations, mm/s.
k, β – experimentally determined parameters of equation (1).

Fig. 2 presents the procedure of determining parameter ρ_{mpv} in a graphic form.

The method of blasting works, following the determined limitations, is associated with selecting the weight of an explosive charge (Q) depending on the distance from the protected structures (r). The choice does not always refer to allowable values (they can be lower), but by applying a specific explosive charge and making measurements at certain distance, it enables calculation of the value of another parameter (ρ_p) for the given blasting in the form (4), based on the dependence (2):

$$\rho_p = \frac{Q^n}{r} \tag{4}$$

A properly selected explosive charge means that an inequality binds parameters (ρ_{mpv}) and (ρ_p) (5):

$$\rho_p \leq \rho_{mpv} \tag{5}$$

At the same time, parameter (ρ_p) is the predicted value of vibration intensity, which can be induced at a certain distance from the blasting works.

If measurements are made during blasting works, the results, in the form of the measured velocity of vibrations (u_{zxy}), enables, based on the dependence (3), the determination of the third parameter – (ρ_{PVL}), in the form (6):

$$\rho_{PVL} = \left(\frac{u_{zxy}}{k}\right)^{\frac{1}{\beta}} \tag{6}$$

whose value ought to be compared with the predicted value (ρ_p) for blasting works. The inequality ought to look as follows (7):

$$\rho_{PVL} \leq \rho_p \tag{7}$$

The procedure of determining parameters ρ is presented in graphic form in Fig. 2.

As a result, the interdependence of parameters ρ can be presented in the form of inequality (8) and (9), and as a graph, as in Fig. 3:

$$\rho_{mpv} \geq \rho_p \geq \rho_{PVL} \tag{8}$$

thus:

$$\left(\frac{u_{cr}}{K}\right)^{\frac{1}{\beta}} \geq \frac{Q^n}{r} \geq \left(\frac{u_{zxy}}{K}\right)^{\frac{1}{\beta}} \tag{9}$$

The procedure developed in the 1990s at the AGH Laboratory of Blasting and Environmental Protection (Winzer et al., 2016) enables, on one hand, monitoring if blasting works are conducted following the assumed limitations (permissible explosive charges; blue bar), and, on the other hand, verification of the predicted (brown bar) intensity of vibrations at the points where the measurements are made (green bar) (Fig. 3).

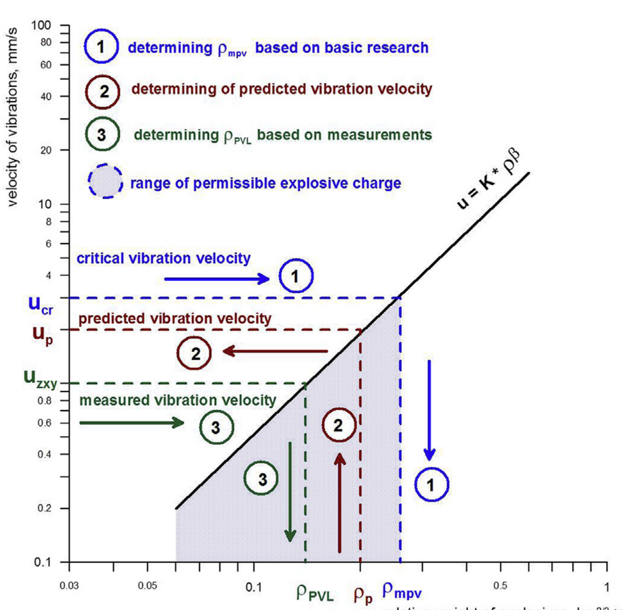

Fig. 2. Determining values of parameters ρ.

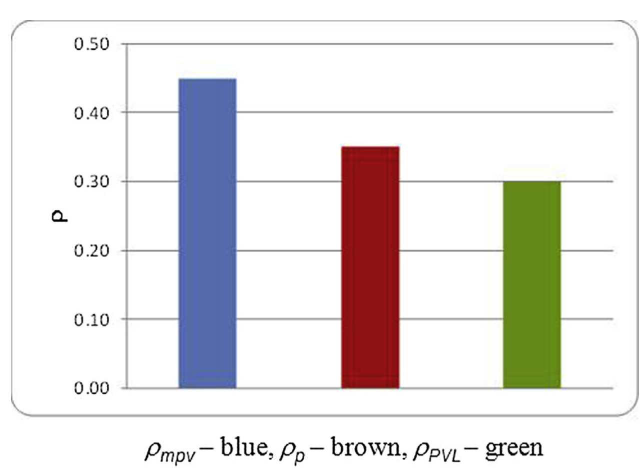

Fig. 3. Graphic analysis of the results of control tests.

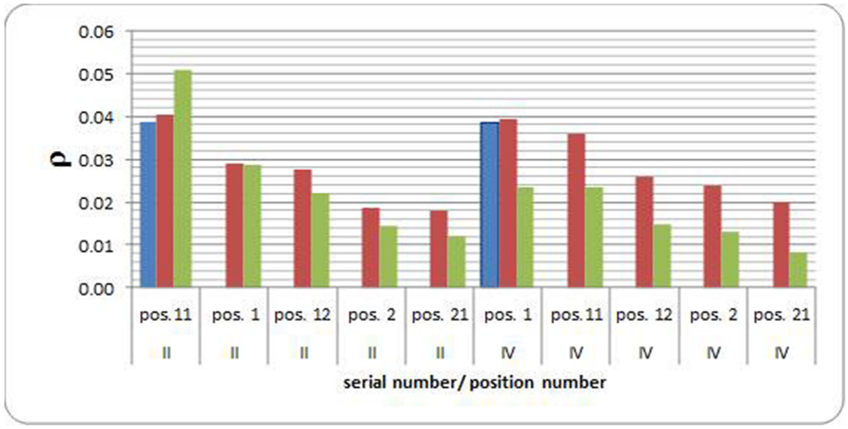

Fig. 4. Example of the assessment of the intensity of vibrations.

The comparison of the values of parameters ρ, can be interpreted as follows:

$$\rho_{mpv} \geq \rho_p \tag{10}$$

– permissible explosive charges were not exceeded, blasting works were conducted following the limitations,

$$\rho_{mpv} < \rho_p \tag{11}$$

– permissible explosive charges were exceeded, or
– the monitoring station was located within the zone of the impact of vibrations and that is why permissible charges were seemingly exceeded.

Often, both during basic and control measurements, monitoring stations are located within the zone of impact to obtain additional information about the propagation of vibrations in the approaching mining fronts. It is done on purpose, hence it cannot be stated that the value of parameter ρ is exceeded. In such a situation it cannot be concluded that permissible charges are exceeded.

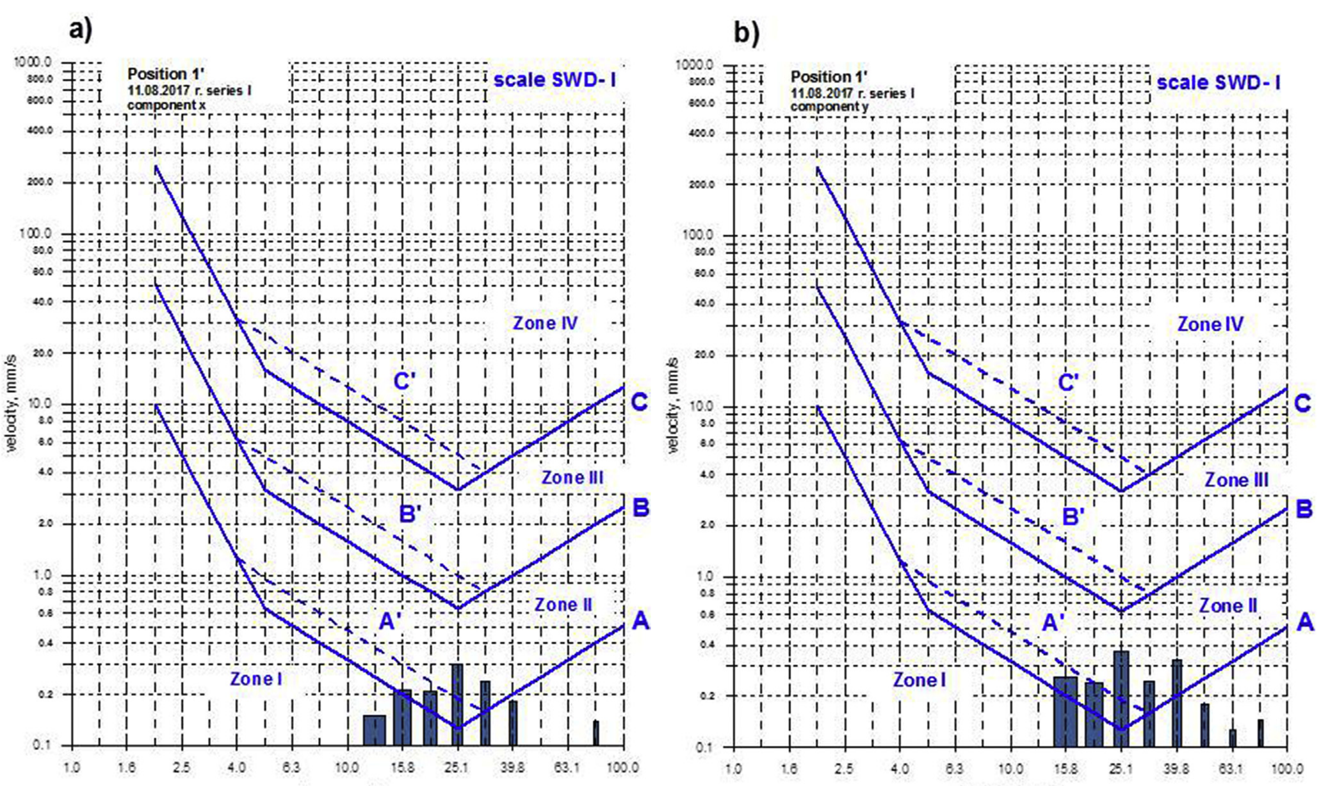

Fig. 5. Assessment of the impact of vibrations on a protected structure: a) component x, b) component y.

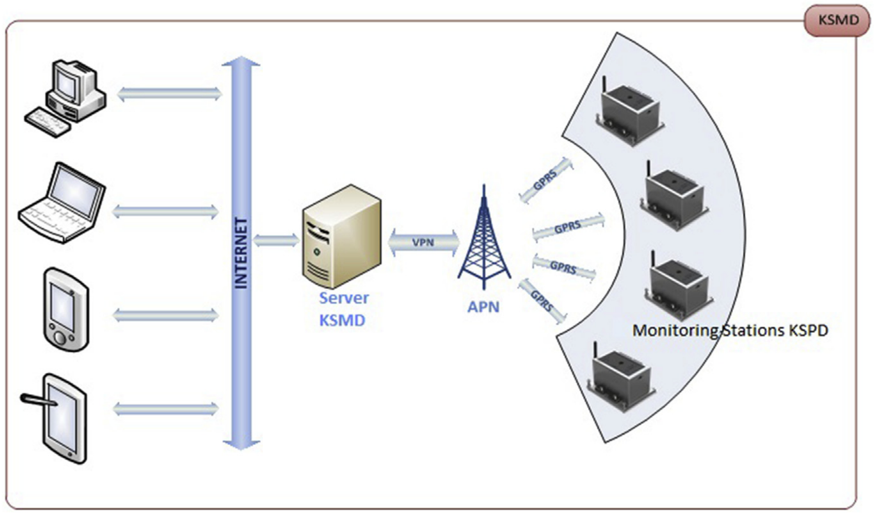

Fig. 6. Vibration Monitoring Station APN – model 2012, block diagram.

$$\rho_p \geq \rho_{PVL} \tag{12}$$

– measured intensity of vibrations does not exceed the predicted level,

$$\rho_p < \rho_{PVL} \tag{13}$$

– intensity of vibrations is higher than the prediction.

Fig. 4 presents a graphical analysis of the results of control tests, following the procedure described above, (markings as in Fig. 3), where volumes of parameters ρ for given measuring points are collected. Control measurements were made in one of the dolomite mines when two series of explosive charges in long boreholes were detonated. The graphical analyses presented in Fig. 4, in spite of the fact they represent actual control measurements, present all the interpretations described above.

As previously mentioned, during control measurements, vibrations in the foundations of buildings in the area surrounding the mine working are also measured. Results of the measurements enable the assessment of the induced vibration impact of, following standard PN-B-02170:2016–12 (Polish Committee for Standardization, 2016), applying SWD scales. Fig. 5 presents such an assessment for recordings made during the same cycle of control tests, for a series of the highest intensity.

As Fig. 5 shows it, vibrations induced during the detonation of a series of explosive charges ought to be qualified for Zone II of SWD-I scale – vibrations harmless to the structure; yet accelerated deterioration of the building may be expected together with the first scratches on the plaster surface, corners and covings (Polish Committee for Standardization, 2016).

The advantages of control measurements, following the described procedure, are:

- measurements of vibrations both in the ground and the protected structures,
- ability to compare the measured intensity of vibrations with the predicted value, resulting from the propagation equation considering the applied parameters of works,

Fig. 7. Vibration Monitoring Station – model 2012, general view.

- measurements, analyses and assessments, conducted by a specialist company with additional measurement equipment and specialist software, enable monitoring of more structures and making independent assessments of the impact,
- periodic documentation of the impact of vibrations on buildings and, if needed, adjusting conditions to conduct blasting works in a way which is safe for the surroundings.

The essential disadvantage of the solution is the fact that, first of all, the controls are periodic and sometimes only occasional.

2.2. Monitoring the impact of vibrations on the surroundings

Monitoring vibrations induced during blasting works is the subject of research and projects which, since 1996, have been conducted at the AGH Department of Surface Mining (Winzer et al., 2016) and have been carried out in cooperation with the industry. The effect of the works was the implementation of equipment with measuring, analytical and archiving functions. While designing the first measurement system, it was assumed that, following Polish standards, the measurement of vibrations has to be supplemented with the assessment of the impact. Hence, the system was equipped with software which enabled application of correction filters

Table 1
The number of measurements of vibrations made in given mines – stations belonging to mines.

Mine/mineral	Start date (dd.mm.yyyy)	No. of monitoring stations	No. of measurement points (buildings)	No. of measurements
Gypsum mine 1	05.07.2012	4	8	1353
Limestone mine 1	04.07.2012	3	3	1285
Limestone mine 2	29.10.2012	4	5	1053
Limestone mine 3	25.05.2013	4	5	403
Gypsum mine 2	09.04.2013	4	5	1268
Dolomite mine 1	15.04.2013	2	5	1339
Limestone mine 4	14.03.2014	2	3	525
Limestone mine 5	19.07.2016	1	1	102
Dolomite mine 2	23.11.2016	2	2	439
Slate mine	24.05.2015	2	2	62
Total				7829

Table 2
Number of vibration measurements made in given mines – measurements made by an outside company.

Mine/mineral	in service (dd.mm.yyyy)	No. of monitoring stations	No. of measurement points (buildings)	No. of measurements
Dolomite mine	since 04.08.2015 -	1	7	126
Limestone mine 6	since 23.08.2016	4	4	904
Granite mine	15.05.2015–31.07.2015	1	1	24
Dolomite mine 3	02.09.2015–10.02.2016	1	1	42
Basalt mine	25.05.2016–26.06.2017	1	1	44
Amphibolite mine	16.08.2016–23.03.2017	2	2	30
Limestone mine 7	03.11.2016–22.02.2017	1	1	86
Dolomite mine 4	09.06.2017–30.06.2017	1	1	14
Total				1270

Table 3
Recorded vibrations in the 1st quarter 2013, lime stone mine, station no. 1.

Date (dd.mm.yyyy)	Time	Velocity of vibrations, mm/s			Frequency, Hz		
		u_z	u_x	u_y	f_z	f_x	f_y
09.01.2013	13:25:22	0.71	1.15	0.98	11.0	9.6	11.6
17.01.2013	**13:20:37**	**1.52**	**2.64**	**5.20**	**12.6**	**11.4**	**11.0**
17.01.2013	13:23:05	1.24	2.64	2.20	13.0	12.0	11.6
14.02.2013	13:21:44	2.08	3.43	2.44	17.0	16.7	11.3
19.02.2013	13:28:19	0.57	1.19	0.80	9.7	8.2	10.6
25.02.2013	13:22:17	1.34	2.34	1.75	20.4	9.6	9.3
26.02.2013	13:21:47	1.56	2.20	2.53	17.7	11.1	11.0
07.03.2013	13:12:10	0.88	1.09	1.01	13.2	10.2	12.8
22.03.2013	13:28:05	1.35	2.37	3.06	14.3	14.0	11.7
27.03.2013	13:19:50	0.82	2.11	1.43	21.7	17.6	10.8

following standard PN-85/B-02170 (Polish Committee for Standardization, 1985). The standard was, back then, in force thus it was possible to assess the impact immediately after the measurement. The procedure remained virtually the same, yet with new analytical and graphical capabilities. Cooperation between the Department and Exploconsult Sp. z o.o., and then also with A-STER s.c. enabled the quick development of the system, up to the current fully automated one.

To monitor vibrations induced by blasting works, the following measurement systems have been used in surface mining industry (Winzer et al., 2016):

– Small Vibration Monitoring Station – Explo 504,
– 3 versions of Vibration Monitoring Stations:
– KSMD with radio communications,
– KSMD GSM with mobile phone communications,
– KSMD APN with Internet communications.

At present, in 12 open pit mines there are 39 measurement points:

- KSMD APN model – 10 mines and 28 Vibration Monitoring Stations (KSPD),
- KSMD GSM model – 2 mines and 11 measurement points.

Moreover, the AGH Laboratory of Blasting and Environmental Protection has two KSPD stations and Exploconsult has five stations. The stations are periodically rented to monitor open pit mines, as well as to measure the impact of works conducted with explosives (e.g. macrolevelling for building roads and tunnels, demolition works).

The oldest systems, Explo 504 and KSMD with radio communications, were decommissioned.

In 2011, a new version of KSMD, cooperating with a server and employing packet data transmission – APN (Fig. 6), was developed.

The motives for the implemented changes were: to streamline performance of the system through establishing a direct connection between a monitoring station and the central server, to limit the role of the operator, to use wireless Internet communication with the server to store data which can be instantly accessed without communicating with the monitoring stations. Introducing new electronic systems also enabled remote servicing and updating the software of the monitoring stations.

The Vibration Monitoring Station KSPD is a basic element of the system (Fig. 7). It is equipped with a 3-axial velocity sensor and a number of systems to process and store measurement data. The GSM/GPRS modem which automatically sends the collected measurements to the KSMD server located at AGH, Cracow, is an integral part of the station.

The function of the Internet service is to manage the stations and measurements they make. It can be used to check the measurements, generate reports, manage the equipment, description of buildings and the system users (Winzer et al., 2016).

The most important advantage of the new system is the ability to collect measurement data on the server. KSPD monitoring stations, after recording an event in their memory, automatically contact the server and transfer the data there. If there are problems with the connection, data transmission is renewed until it is

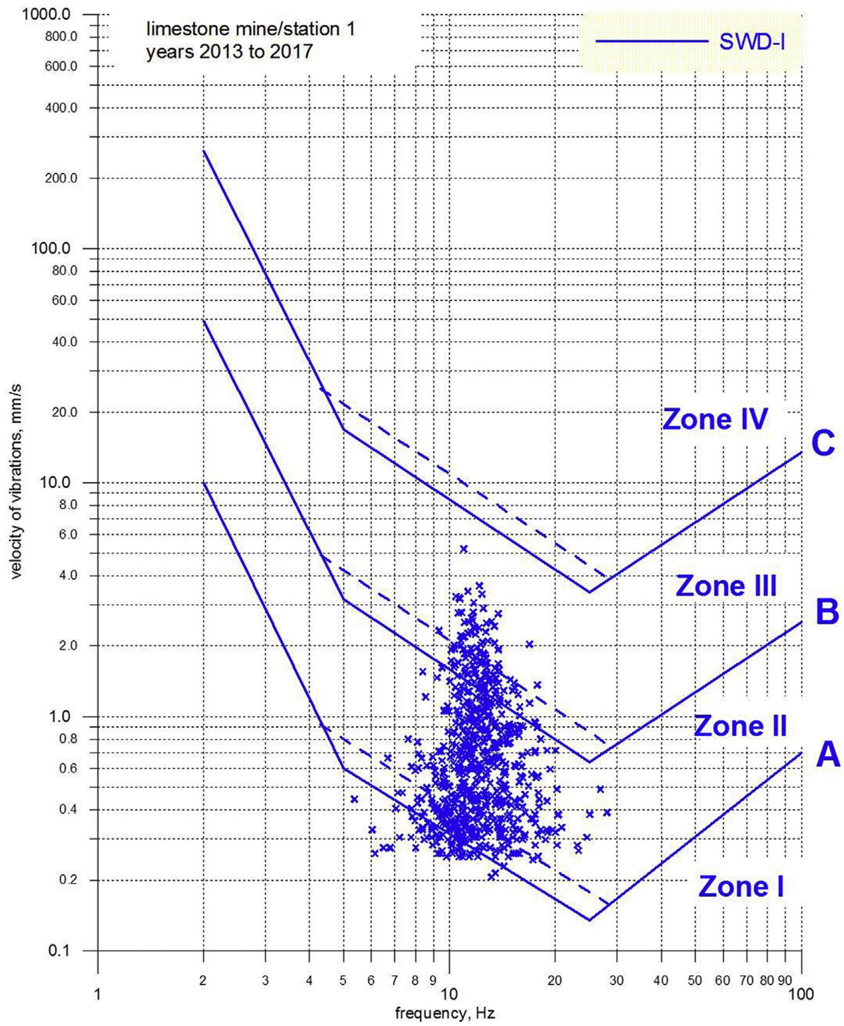

Fig. 8. Results of recorded vibrations, 2013–2017, limestone mine/station 1.

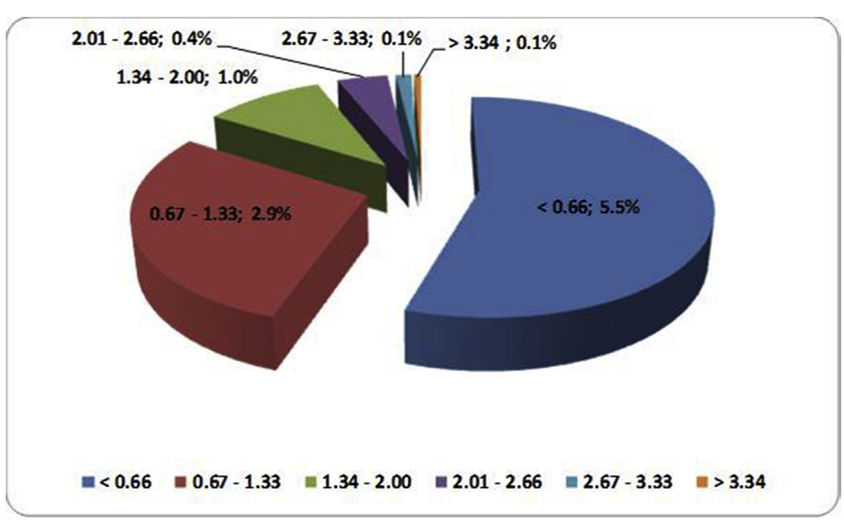

Fig. 9. PPV percentage distribution in the assumed value ranges, 2013–2017, limestone mine/station 1.

successful. It is crucial as, unlike the KSMD server, KSPDs do not store data. Consequently, a system operator, to conduct analyses on the basis of measurement data base, only uses the server.

Advantages of the new KSMD APN system:

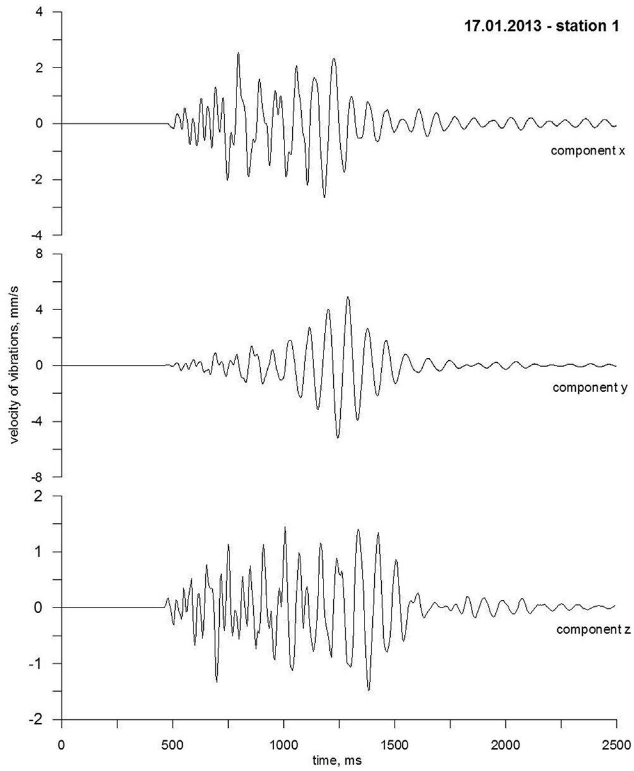

Fig. 10. Seismogram of vibrations recorded on 17 January 2013, limestone mine 2/station 1.

– continuous measurement of vibrations in a building,
– unlimited memory,
– automatic transmission of data to the server,
– automation of station steering and maintenance processes.

The modernized KSMD system went into service in 2012, hence it is possible to summarize its five years of operation.

Overview of the performance of the measuring and analytical system is associated with realizing aims which the system has to fulfil. If we assume that the aim of monitoring is verification of the blasting works' impact on buildings in the surroundings and documenting the impact for given buildings, then the summary ought to include information on the number of measurements, intensity of recorded vibrations and assessment of the impact of vibrations on buildings where KSPD stations were installed.

3. Results

In the 5 year period (2013–2017), the KSMD APN monitoring stations made 9099 vibration measurements induced by blasting works conducted in open pit mines.

Tables 1 and 2 present the number of measurements made at monitoring stations in given mines until 30 June 2017.

In all the cases, KSPD monitoring stations are attached to the foundations of buildings at the ground level, i.e. vibrations of a building, not of the ground in its surrounding, are measured. It is important information, as in other countries standards specify different requirements (Dowding, 1985; Persson, Holmberg, & Lee, 1994). For example, in Poland, Mining Intensity Scales (Barański, Kloc, Kowal, & Mutke, 2014) require measuring ground vibrations.

Results of measurements made by limestone mine 2/station 1 were analysed in detail. Table 3 shows a fragment of results recorded in the 1st quarter of 2013. The fragment was selected as the event recorded on 17 January had the highest intensity from the whole five years of operation of the station.

Fig. 8 presents results visualized in SWD-I scale (horizontal components x and y). Fig. 9 presents percentage distribution of maximum velocity in assumed ranges of values.

Visualized results of measurements are presented in two graphs because, due to the shape of the boundaries of SWD scales, the maximum value of vibration velocity (without frequency) does not provide full information about the impact. We also have to be aware of the fact that the measurements results in the form of maximum velocity values of vibrations correlated with frequency, applied to SWD scale, do not provide assessment of the impact. They merely present the scale of the problem and enable initial conclusions concerning the level of recorded vibrations in the long run.

4. Discussion

From analysing data presented in Figs. 8 and 9, it ought to be concluded that almost 85% of vibrations induced by blasting works did not exceed the maximum value of 1.33 mm/s, i.e. they were assigned to Zone I of the SWD-I scale. This means that they can be classified as negligible while assessing the impact on a protected structure (Polish Committee for Standardization, 2016).

As previously mentioned, on 17 January 2013, the event with the highest intensity in the whole five-year-long period was recorded. The seismogram and the structure of the vibrations are presented in Figs. 10 and 11. As Fig. 11 shows it, frequency of 12.59 Hz

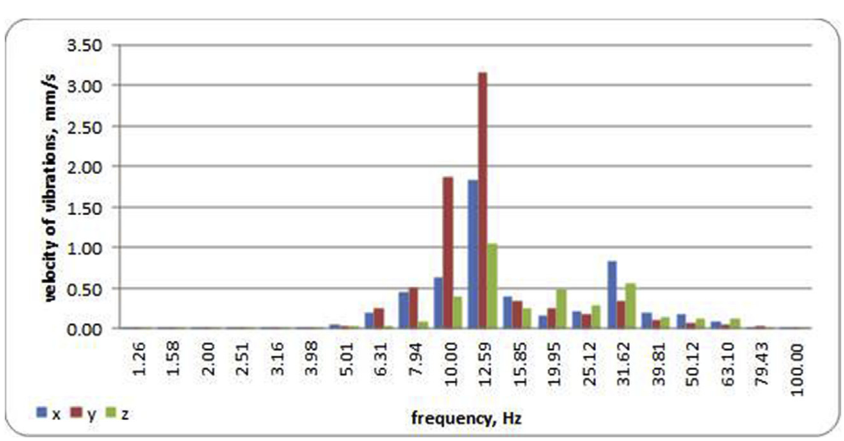

Fig. 11. Structure of vibrations recorded on 17 January 2013, limestone mine 2/station 1.

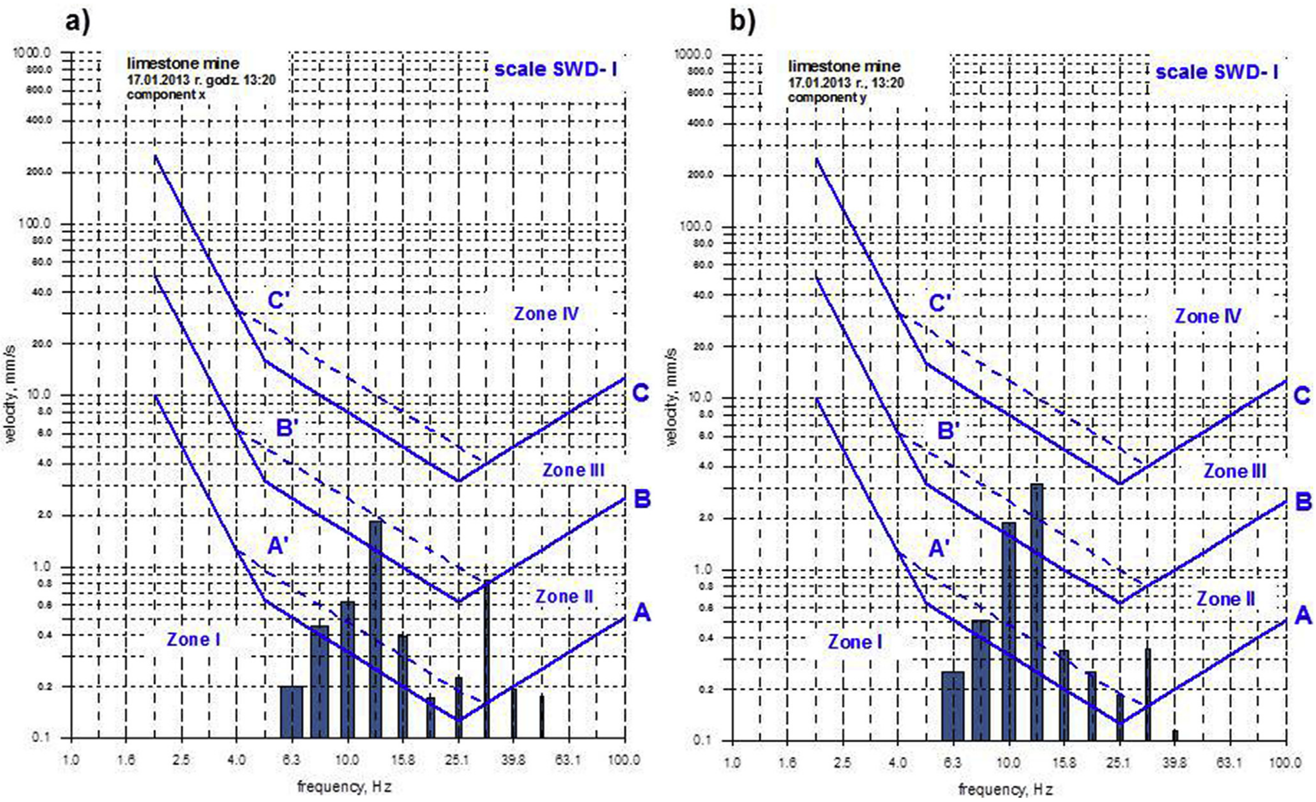

Fig. 12. Assessment of the impact of vibrations, event of 17 January 2013, limestone mine 2/station 1: a) component x, b) component y.

dominates the structure of vibrations, and horizontal component *y* is predominant in the assessment of the impact, which is confirmed in Fig. 12.

Assessment of the impact induced by vibrations, following the procedure described in the standard (Polish Committee for Standardization, 2016) (Fig. 12), showed that the vibrations ought to be classified in Zone III of the SWD-I scale. It has to be emphasised that it is the only event recorded in the period of five years, and only 4 out of 692 events (0.6% of all the records) actually exceeded the value of 3.33 mm/s.

The number of measurements and the range of measured values is crucial information in every damages claim. The fact that most of the events are documented in the form of vibration measurements, each of which can become the basis to assess the impact on a structure, together with the information that only a few were perceptible vibrations (the highest intensity) from hundreds of documented events may be important for appraisers, and, as a consequence, for the courts.

5. Conclusions

Control tests of the vibration intensity induced by blasting works, and monitoring the vibrations in structures, in the surroundings of a mine working, is an important element of preventive activities in open pit mines, aimed at minimizing the impact of mining on the surroundings. Documenting the impact means building a database, which becomes a source of knowledge for the mining plant management personnel and can also be used in damages claims. Control tests and continuous monitoring of the impact are not mutually exclusive and, in fact, they rather complement each other.

Documenting the impact of blasting works on the surroundings is a solution which enables:

- the collection of current information, for the management, about the intensity of vibrations induced by blasting works,
- the monitoring of the impact of the vibrations on buildings,
- the creation of a database which can always be accessed to present evidence in a damages claim,
- the ability to make corrections in conditions limiting the conduct of blasting works.

The KSMD system applied in mining companies, which was built with the financial contribution of open pit mines, has been gradually modernized. It is currently a state-of-the-art automatic system employing new measurement, analytical and wireless communication technologies. The system was built as a tool for the mining plant management enabling ongoing control by monitoring the current impact of blasting works on the buildings in the surroundings.

After modernisation, it is possible to use KSMD to access measurement equipment from any point in the world, to control the equipment, to view a recorded event instantly and to swiftly assess the impact.

With the monitoring, it is possible to control the intensity of induced vibrations and react quickly if they exceed safe limits.

In vibration monitoring nothing is accidental. The constant presence of the measurement equipment in a protected building enables events unrelated to blasting works to be recorded. Tremors induced by underground mining operations and vibrations induced by blasting works in adjacent open pit mines are also recorded.

After five years of the KSMD APN system there are 9099 pieces of evidence that controlled blasting works conducted in open pit mines can be harmless to buildings in their surroundings.

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References

Barański, A., Kloc, L., Kowal, T., & Mutke, G. (2014). Górnicza Skala Intensywności Drgań GSIGZWKW-2012 w odniesieniu do odporności dynamicznej budynków [Intensity scale GSIGZWKW-2012 in relation to the dynamic resistance of buildings]. *Bezpieczeństwo Pracy i Ochrona Środowiska w Górnictwie, 6*, 3–10.

Dowding, C. H. (1985). *Blast vibration monitoring and control*. Englewood Cliffs, NJ: Prentice Hall, Inc.

Fish, B. G. (1951). Seismic vibrations from blasting. *Mine & Quarry Engineering, 17*(5), 145–148.

Lopez Jimeno, C., Lopez Jimeno, E., & Ayala Carcedo, F. J. (1995). *Drilling and blasting of rocks*. Rotterdam: CRC Press.

Persson, P. A., Holmberg, R., & Lee, J. (1994). *Rock blasting and explosives engineering*. Boca Raton: CRC Press.

Polish Committee for Standardization. (1985). *Ocena szkodliwości drgań przekazywanych przez podłoże na budynki [Polish standard evaluate the harmfulness of the vibrations transmitted by the substrate to the buildings]*. PN-85/B-02170.

Polish Committee for Standardization. (2016). *Ocena szkodliwości drgań przekazywanych przez podłoże na budynki [Polish standard evaluate the harmfulness of the vibrations transmitted by the substrate to the buildings]*. PN-B-02170:2016-12.

Winzer, J., Sołtys, A., & Pyra, J. (2016). *Oddziaływanie na otoczenie robót z użyciem materiałów wybuchowych [Impact on the environment of works with explosives]*. Kraków: Wydawnictwa AGH.