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Methodology of designing blasting works in open pit mining in terms of their impact on construction objects

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Abstract
The firing of explosive charges with (millisecond) time delay gives a wide range of possibilities in designing multi-row blasting patterns and, at the same time, contributes positively to the minimization of the impact of blasting works on building infrastructure in the vicinity of mines. Selection of the appropriate millisecond delay should be based primarily on seismograms of vibrations induced during the firing of single explosive charges and analysis of the frequency structure of these vibrations. Using this type of data, the article presents a procedure for optimizing millisecond delays with the use of a computer programme dedicated to modern, electronic initiating systems that are currently applied towards obtaining a favourable vibration structure in terms of the assessment of the impact on buildings in accordance with the standard regulations applicable in Poland.

Keywords
blasting design, millisecond blasting technique, vibration structure, impact of vibrations on buildings

Introduction

Exploiting rock materials in the vast majority of cases involves using explosives in the fragmentation process. Detonating explosive charges during blasting works induces vibrations which can harm building structures in the surroundings. Therefore, mines carry out activities aimed, on the one hand, at establishing conditions assuring the safe performance of blasting works for the surrounding area and, on the other hand, at documenting the level of this impact (Dowding et al., 2018; Fehér et al., 2019; Kudelas et al., 2019; Winzer et al., 2016).

The problem of the impact of vibrations induced by blasting works has been known in the mining industry practically since large explosive charges have begun to be used in rock fragmentation. The introduction of the method of firing explosive charges in long blast holes, especially in mines surrounded by housing units, made it necessary to search for new solutions for detonation thereof. Therefore, in the 1940s, a millisecond firing of explosive charges was introduced in the United States, which made it possible to reduce the intensity of the impact of blasting works on the surroundings, as well as to improve the efficiency of the explosive through cooperation between charges detonated at intervals.

Outline of the issues related to designing firing explosive charges with millisecond delay

In recent years, blasting works have undergone significant technological and organizational changes. Mechanical loading of modern explosives has been put into operation (Ammonium Nitrate Fuel Oil - ANFO, emulsion and slurry explosives). Also, non-electric and electronic initiating systems are becoming increasingly popular, and the performance of blasting works is largely entrusted to specialized service providers. With regard to the development of initiating systems, it should be stated that at present, detonating explosive charges is carried out with a millisecond delay in open pit mining (Sołtys, 2018).

The problems related to the impact on the surroundings or search for solutions aimed at obtaining the optimum granulation of the output laid at the basis of the aforementioned initiating systems development aimed at extending the possibility of firing as many charges in series as possible. Switching from a fuse system from electric or non-electric to electronic ones is an expression of the implementation of the aforementioned assumptions. State-of-the-art electronic systems are not only characterized by very high initiation precision but also offer a wide range of possibilities for designing the firing of multi-row blasting patterns in terms of both the quality of the output and minimizing the impact of the works with the use of explosives on surroundings. The PN-B-02170:2016-12 standard is currently used in Poland to evaluate vibrations transmitted by the ground to buildings.

Approximate characteristics of the harmfulness of vibrations according to the standard can be presented using the scale of dynamic influences SWD I and SWD II. The SWD scales are presented in the frequency-velocity and frequency-acceleration coordinate system. The values of the centre frequencies of 1/3 octave bands are given on the horizontal axes and on the vertical axes - the maximum values of acceleration or vibration velocity in the 1/3 octave bands. They have five zones separated by boundaries determining the degree of harmfulness of vibrations for the building (Figs. 1 and 2).

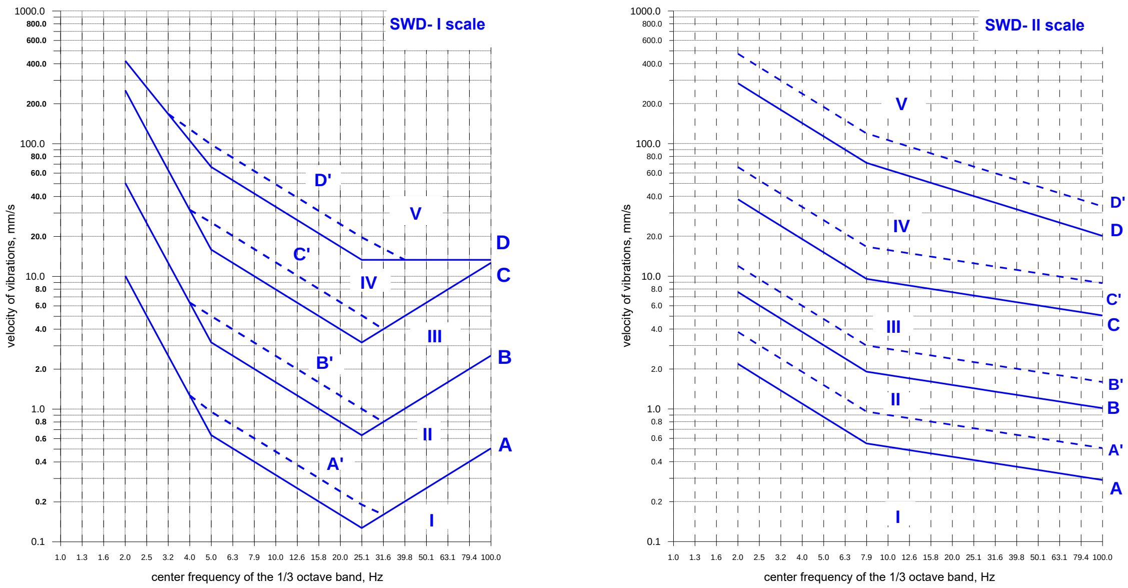

Fig. 1 SWD-I and SWD-II scales in the coordinate system: centre frequency of the 1/3 octave band - maximum vibration velocity in the band

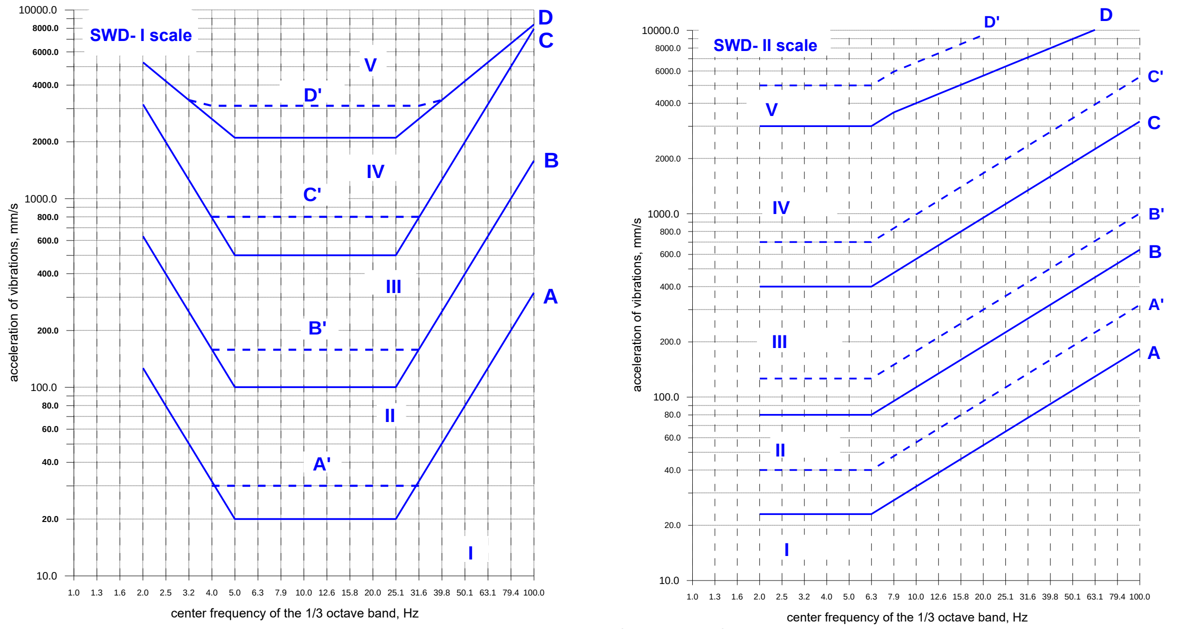

Fig. 2 SWD-I and SWD-II scales in the coordinate system: centre frequency of the 1/3 octave band - maximum vibration acceleration in the band

<u>The dynamic influence SWD-I scale</u> applies to buildings with a compact shape, small external dimensions of the horizontal projection (not exceeding 15 m), one or two-storey buildings and with a height not exceeding any of the dimensions of the horizontal projection.

<u>The dynamic influence SWD-II</u> scale applies to buildings not higher than five above-ground storeys, the height of which is less than twice the smallest width of the building (h / b <2; h - building height, b - the smallest building width) and low-rise buildings (up to 2 storeys), but not meeting the conditions specified for the SWD-I scale.

The zones of influence have the following interpretation (PN-B-02170: 2016-12):

zone I - vibrations negligible in the evaluation of the impact of vibrations on the building,

line A - a lower limit for taking into account dynamic influences on the building; for vibrations below this limit, dynamic influences may not be taken into account,

zone II - vibrations harmless to the structure; However, accelerated wear of the building and the first scratches in plaster, wall corners and facets, etc., can be expected,

line B - limit of building stiffness, a lower limit of the formation of scratches and cracks in structural elements,

zone III - vibrations harmful to the building, causing local scratches and cracks, thus weakening the building structure and reducing its load-bearing capacity and resistance to further dynamic influences; plaster may fall off, scratches may appear on the joints of structural elements, etc.,

line C - strength limit of individual building elements, a lower limit of heavy construction damage,

zone IV - vibrations which are highly harmful to the building, pose a threat to people's safety; numerous cracks appear, as well as local damage to walls and other individual structural elements of the building; there is a possibility of suspended objects falling, ceilings sheets falling off, cornices falling off, roof tiles falling, roof beams slipping out of bearings, etc.; required to remove the source of vibrations as quickly as possible or reduce its influence,

line D - structure stability limit, a lower limit of failure of the entire building; vibrations above this limit may cause a building failure and endanger the safety of human life,

zone V - vibrations cause the building to fail due to collapsing walls, falling ceilings etc., a full threat to the safety of human life; if there is a risk of vibrations, this type of building must not be used.

The determination of zone I and line A determines the practical issue of the possibility of ignoring dynamic influences - it has been precisely indicated that vibrations classified to zone I may be negligible in evaluating the impact of vibrations on buildings.

Assessment of the impact using SWD scales should be performed on the basis of measurements made by sensors attached directly to the building structure.

At present, in the assessment using SWD scales, it is required to record the full waveforms of horizontal vibrations components (x, y), the analysis of which is carried out by filtering the signal with a third-octave filter.

The results obtained, as a histogram of the maximum velocity values in a given frequency band, are plotted on the SWD scale with an ascription of effects corresponding to a given zone. This means that the frequency structure of induced vibrations plays a significant role in the impact assessment using the SWD standard and scales.

In most open pit rock material mines, blasting works are performed by professional companies, which offer a wide range of explosives, modern systems for firing explosive charges, and an increasing number of IT systems for designing blasting works. Among the tools used in Poland for designing the millisecond firing of multi-row blasting patterns, there are the following programmes: Blasting Solutions, Paradigm, Shot Plus or I-Blast, which use the Signature Hole method to build base information (Bernard T., 2012; Burke B., 2008; Sołtys et al., 2017b; Sołtys et al., 2021; Šrek J. and Mikoláš M., 2021). The method consists in simulating the seismic effect based on a seismogram of vibrations obtained during the firing of single explosive charges (Anderson et al., 1983, 1985; Andrews, 1981; Crenwelge, 1988; Hinzen et al., 1987). The studies have shown that the characteristics of the seismic signal are determined not only by the weight of the detonated explosive charge and the distance but also by the geological structure of the deposit at the site where the blasting works are performed and the properties of the rock mass on the path of the waves and at the reception point (e.g. the properties of the ground under the building). Relying on Bernard's considerations (2012), the signal induced by blasting series may be presented as the sum of single signals induced by subsequent explosive charges fired with time delay, according to relation (1):

$$SG(t) = \sum_{i=1}^{N} s_i(t) \tag{1}$$

where:

- $SG(t)$ – seismic signal of fired series (expressed in the time domain),
- $s_i(t)$ – elementary seismic signal induced by the detonation of a subsequent explosive charge (expressed in the time domain),
- N – the number of explosive charges in a single series

Assuming, however, that each explosive charge induces an almost identical signal as a result of detonation (except for an amplitude), the relation (1) takes the form of the following expression (2):

$$SG(t) = \sum_{i=1}^{N} a_i S(t - \Delta t_i) \tag{2}$$

where:

- $S(t)$ – seismic signal of fired series (expressed in the time domain),
- Δt_i – charge delay time in a sequence,
- a_i – single seismic amplitude coefficient

As a result of carrying out a number of simulations of the seismic effect for a specific location of the designed series of explosive charges, the IT tool offers a wide range of solutions that require thorough analysis and optimal selection made by the designer, which constitutes the most important element of the design process of blasting works. The selection of a proper solution out of several thousand possibilities should, on the one hand, be backed up by broader analyses and, on the other hand, it requires verification by measuring vibrations at a selected point in the vicinity of the mine and comparing the predicted (simulated) effect with the real outcome. In most cases, global standards use the peak particle velocity (PPV) in order to evaluate the impact of vibrations. Frequency is also used in the analysis (usually momentary frequency, correlated in time with PPV); therefore, the aforementioned computer programmes analyze and propose solutions considering mainly the minimization of PPV values. However, this does not limit the individual parameterization of the outcomes by the designer, which makes it possible to search for optimal solutions that bring the expected results.

The specificity of the Polish standard for evaluation of vibration impact on buildings (PN-B-02170:2016-12) required the development of a procedure for selecting the optimal solution while taking into account the fact that the assessment using SWD scales is made by examining the vibration structure (third-octave band filtration) within the range of frequencies of 2 to 100Hz. Therefore, it is necessary to analyze the structure of vibrations induced in the ground, as well as vibrations transmitted to buildings, in order to study the impact of blasting works on building structures. Identification of the interaction between the building and the ground is often a key to finding optimal solutions. The millisecond delay has a significant influence on the structure (amplitude and frequency) of vibrations, i.e. by means of the time delay between detonations of subsequent explosive charges. It is possible to change the structure of vibrations registered in the ground and thus to search for solutions which allow obtaining the appropriate effects, for example, strong damping of vibrations when transferred to the ground of the building or a vibration structure which is more favourable in terms of the assessment of impact using SWD scales.

The main objective of this article is to indicate the possibilities of using modern systems of firing explosive charges to minimize the impact on building structures located in the surrounding area while taking into account the specificity of the Polish standard.

The vibration measurements of the ground and the foundation of the building, both during the firing of single holes and the verification measurements, were made using the Vibraloc by ABEM AB.

Materials and methods

Firing of single explosive charges

In most cases, programmes for designing blasting works require the development of a database of local conditions of the excavation and its surroundings. The seismograms of vibrations induced by a single explosive charge (Signature Hole method) were adopted as the basic information. Seismograms are used for computer simulations of vibrations that can be induced by firing a series of charges characterized by a specific number and mass and are detonated in a definite location under appropriate geological and mining conditions.

The Signature Hole method implies that the seismogram of vibrations induced by a single explosive charge is characteristic and repeatable of the path travelled by the seismic wave from the excitation point to the reception point and differs in various geological conditions of the deposit and surroundings. It should be added that the seismogram may also differ for several excitation points (the area where blasting works are performed) and for several reception points, which means that in order to correctly characterize the local conditions, single charges should be fired in several (a dozen or so) places in the excavation (different l, faults, changes in the properties of fragmented rock) and vibrations should be recorded simultaneously in several points in the vicinity of the mine. Considering requirements concerning the evaluation of vibrations with the application of the Polish standard, they should be measured both on the ground and on the foundations of buildings in the vicinity of the mine excavation. Figures 3 and 4 illustrate examples of seismograms and the structure of vibrations induced by single explosive charges fired in one of the rock material mines (phyllite mine) at different exploitation levels (I and III).

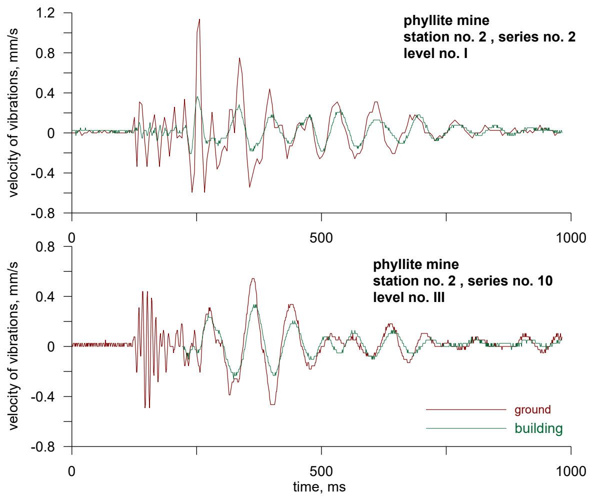

Fig. 3. Seismograms of vibrations (horizontal x- component) induced during firing of single explosive charges - the place of detonation: level I and III

Although measurements were taken on the same site in the ground and on the building foundation, the recorded vibration structure differs significantly (Figure 4). The result shows that in the higher frequency range, the building strongly dampens vibrations, while with regard to lower frequencies, the damping is weaker. It should be emphasized that the phase of intense vibrations is very short and does not exceed 400 ms (Figure 3).

The firing of single explosive charges in another rock material mine (marl mine) made it possible to determine the structure of vibrations induced in the environment (Figures 5 and 6). According to the presented relations, the intense phase of vibrations lasts approximately 1,500 ms in this case (Figure 5), and the structure of the vibration is predominated by frequencies lower than 6.31Hz to 12.59Hz (Figure 6). It should also be stressed that the vibration damping during the transition from the ground to the foundation is low (for the predominant frequencies), and its absence should be taken into account when firing a greater number of explosive charges. An even clearer presentation of vibrations structure was obtained by carrying out a time-frequency analysis, i.e. Matching Pursuit (MP) (Sołtys, 2015; Pyra and Sołtys, 2016, Sołtys et al., 2017a; Sołtys et al., 2017b). The results thereof are illustrated in Table 1 and Figure 7.

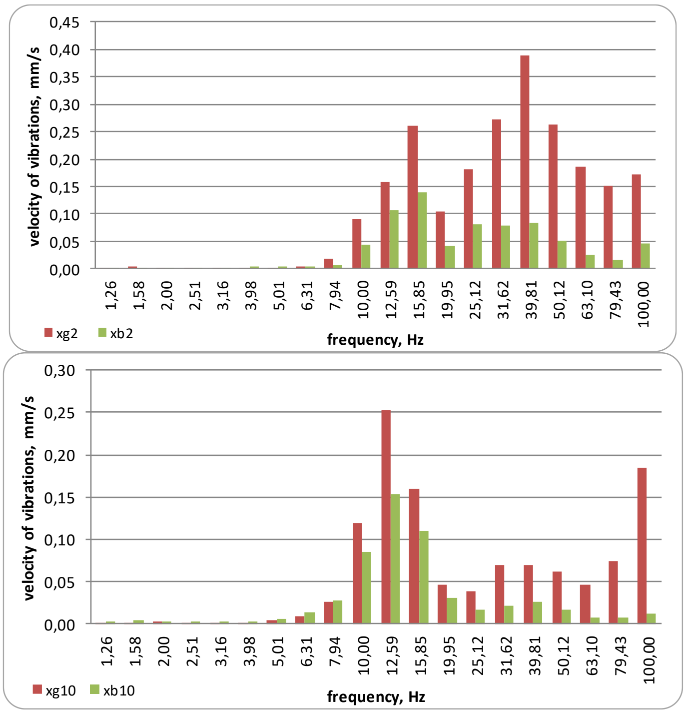

Fig. 4. Vibration structure of the ground and building induced during firing of single explosive charges - the place of detonation: level I and III

The MP algorithm assumes the decomposition of the signal with the use of functions called time-frequency atoms, selected from the dictionary $G = \{g_1(t), g_2(t),\ldots, g_n(t)\}$. The concept of an atom should be defined as an elementary part of a signal intended to reflect the characteristics thereof best. The atom can be represented as a single window function $g(t)$ by scale a, translation b and frequency modulation ξ (Durka, 2003; Mallat and Zhang, 1993; Wawrzyniak, 2007).

$$g_I(t) = \frac{1}{\sqrt{|a|}} \cdot g\left(\frac{t-b}{a}\right) \cdot e^{i\xi t} \tag{3}$$

where:

I - the index determining the set of parameters for a particular atom, $I = (a, b, \xi)$
a - scale coefficient
b - translation coefficient,
ξ - frequency modulation,
$e^{i\xi t}$ - complex exponential function

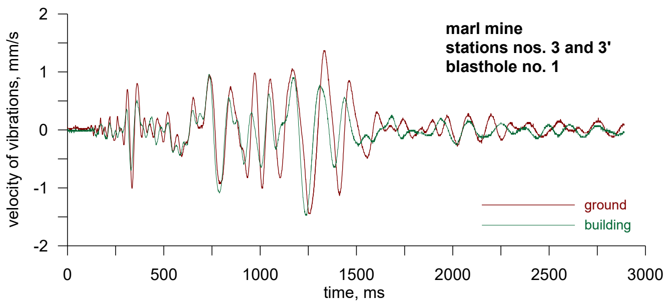

Fig. 5. Seismograms of vibrations (horizontal x- component) induced during firing of a single explosive charge in a rock material mine

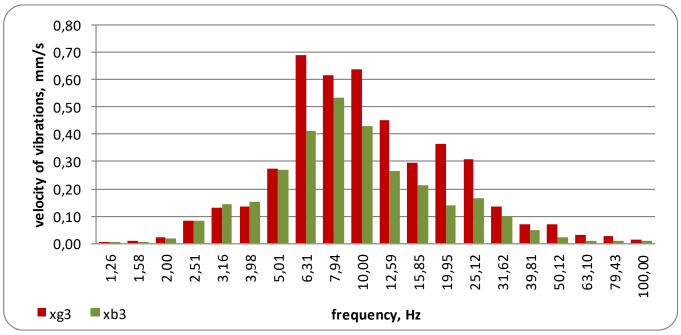

Fig. 6. Vibration structure of the ground and building induced during firing of a single explosive charge in a rock material mine

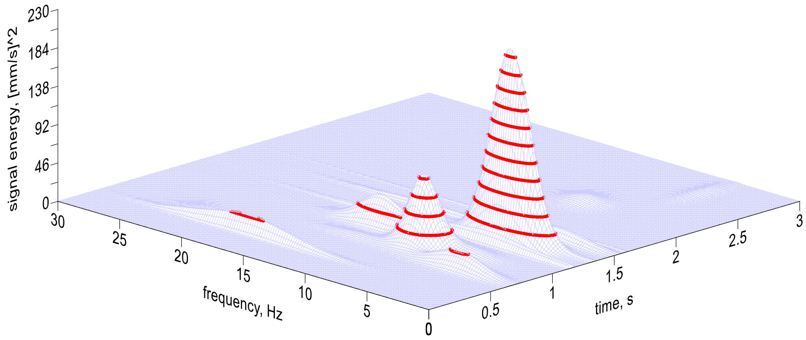

Fig. 7. Spatial image of ground vibrations (x-component) for the case presented in Figure 5

The presentation of the vibration structure in the form of a spatial image (Figure 7) allows for identifying the frequencies during vibrations, as well as determining the share of individual frequencies in signal energy. Resulting of the MP analysis (Table 1), almost half of the energy of vibrations is connected with the Gabor atom, which has a frequency of 6.44Hz. Thus, the dominance of this frequency is very clear - the atom has both the highest amplitude and is associated with the largest part of the energy of vibrations (Figure 8); this fact is supported by the result of the third-octave band analysis (Figure 6).

Tab. 1. Results of MP analysis of ground vibrations for the waveform presented in Figure 3

Atom no.	Amplitude, mm/s	Frequency, Hz	Signal energy, $(mm/s)^2$	Signal energy share %
0	1.577	6.44	230.83	47.4%
1	0.779	9.33	84.24	17.3%
2	0.695	13.50	38.06	7.8%
3	0.764	18.08	23.64	4.9%
4	0.541	4.49	22.04	4.5%
5	0.509	4.75	14.27	2.9%
6	0.716	8.10	14.19	2.9%
7	0.273	6.21	8.05	1.7%
8	0.237	8.91	7.84	1.6%
9	0.417	13.95	6.26	1.3%
percentage of signal energy explained				94.6
total signal energy			486.8	

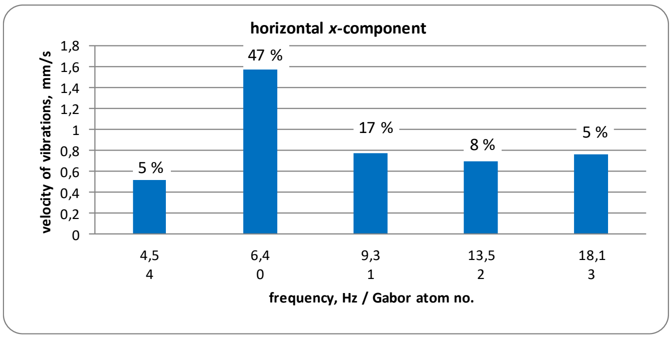

Fig. 8. Histogram of Gabor atoms - with regard to the case presented in Figure 6

The waveform of vibrations, information from seismogram analyses and the structure of vibrations induced during the firing of single explosive charges are significant not only in the design procedure but also at the stage of selecting optimal solutions resulting from vibration simulation with the use of computer tools (programmes).

Design procedure using a computer programme

Optimal use of the possibilities of electronic igniters for firing a series of explosive charges requires the use of IT tools in the design process. As previously mentioned, for most computer programmes, the criterion for selecting the optimal solution is minimizing PPV, i.e., achieving the lowest possible particle velocity. However, when taking into account the conditions resulting from the impact assessment using the SWD scales, that is not always an appropriate solution. In order to adapt the procedure for selecting the optimal solution to the specific national conditions, it was necessary to carry out a number of analyses taking into account the impact of millisecond delay on the vibration structure and the mechanism of transmission of vibrations from the ground to the foundations of the building. As a result of the design and research work carried out, an original selection procedure was proposed, comprising:

- analysis of existing studies conducted with regard to the intensity and structure of vibrations of the ground/foundation of the building,
- analysis of the interaction between the building and the ground,
- indication of the desired intensity and structure of ground vibrations,
- determination of indicators for selecting a group of solutions satisfying expectations,
- detailed analysis of various combinations of delays,
- selection of the optimal solution,
- performance of blasting with the use of the selected solution,
- verification of vibration simulation through control measurements.

The result of the aforementioned procedure has been presented based on the example of the blasting design performed for a selected rock mine.

Design of firing a multi-row blasting pattern - case study

On the floor of the safety level "Ia" in the (selected) rock mine in question, a series of 41 blast holes were prepared in 5 rows to be fired (Figure 9).

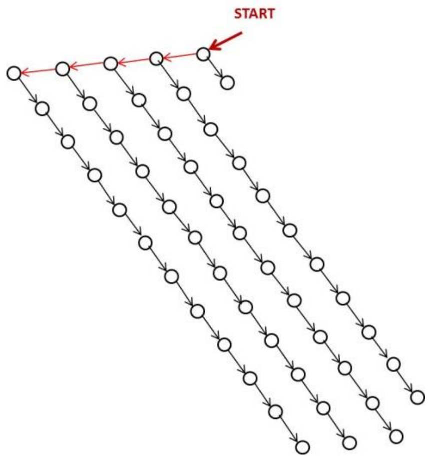

Fig. 9. Designed blast holes pattern

For the execution of the firing design with the use of a computer programme, a vibration seismogram was selected for a single explosive charge with a location close to the designed series. As a result of the calculations made, the following 3 combinations of millisecond delays (boreholes/rows) were selected for further analyses:

a) delay between blast holes on the same row was 28 ms, and 121ms between rows (variant #1),
b) delay between blast holes in 14ms row, between 162ms rows (variant #2),
c) delay between blast holes in 43ms row, between 54ms rows (variant #3),

The results of the calculations of simulated vibration parameters are presented in the form of PPV for particular components, correlated frequencies therewith and the maximum value of the spatial vector (Table 2).

Tab. 2. Parameters of selected vibration simulation variants

Variant no.	Delay, ms		PPV, mm/s			Frequency, Hz			Vector, mm/s	Minimum delay, ms
	between blast holes	between rows	u_z	u_x	u_y	f_z	f_x	f_y	u_{zxy}	
#1	28	121	1.829	2.050	1.296	37	32	31	2.599	9
#2	14	162	2.390	2.403	1.272	45	50	31	3.104	8
#3	43	54	1.776	1.636	1.086	34	42	30	2.190	10
	verification (measurement) – variant no. #3		0.866	1.941	1.438	52	62	39	2.402	

In the case of designing multi-row blasting patterns, real-time millisecond delay constitutes important information when selecting variants. The percentage share of particular millisecond delays for subsequent variants is illustrated in Figures 10, 11 and 12, while Table 2 presents the minimum values of this delay.

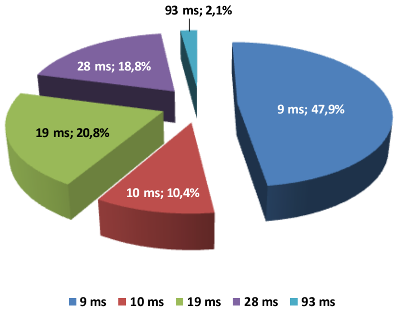

Fig. 10. Histogram of real-time millisecond delays for variant #1

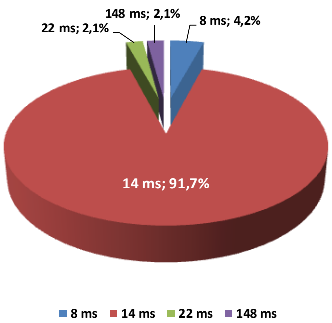

Fig. 11. Histogram of real-time millisecond delays for variant #2

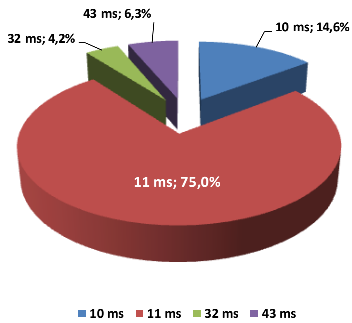

Fig. 12. Histogram of real-time millisecond delays for variant #3

As it results from the presented histograms (Figure 10 ÷ 12), the analysis of the real-time millisecond delay is significant, as in many cases, the distribution of delays does not show many relations to the values assumed between blast holes in a row and between the rows themselves. As an example, for variant #1, the use of delay of 28ms and 121ms gives almost 50% delay share of 9ms, 50%, while for variant #3, the use of 43ms and 54ms delays gives a 75% delay share of 11ms. It should be added that the actual millisecond delay significantly depends also on the geometric arrangement of blast holes in the pattern. Thus, such analyses should be conducted for each pattern individually.

The filtering (3^{rd}-octave band) analysis of the full waveforms of vibrations resulting from the simulation allows us to examine and compare the vibration structure for individual variants. The effect of such analysis is presented in Figure 10 (horizontal x-component). It is noticeable that 3 phases may be distinguished in the vibration structure: i.e. the phase of lower frequencies (from 12 to 16Hz), the phase of medium frequencies (from 40 to 50Hz) and the phase of higher frequencies (within 80Hz). As has been shown above, as a result of the analysis of the structure of vibrations induced by the firing of single explosive charges, during the transition from the ground to the foundation of the building, higher frequencies are strongly damped, while vibrations damping at lower frequencies is absent or minor. Therefore, the selection of the variant should be primarily determined by the low vibration intensity in this frequency range. Ultimately, variant #3 (Figure 13, blue curve) was selected as the most favourable option for firing the series, and the final version of the design of firing the pattern of explosive charges (according to variant #3) is presented in Figure 14.

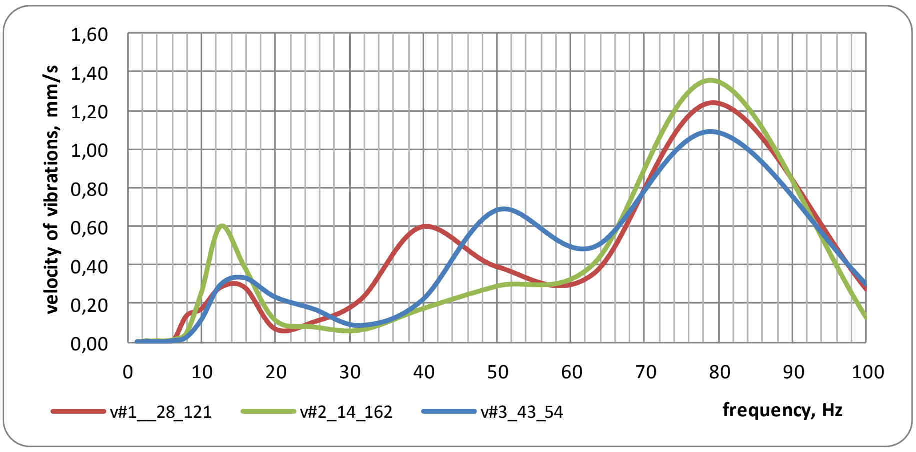

Fig. 13. Comparison of the simulated vibration structure (horizontal x-component) for variants #1, #2 and #3

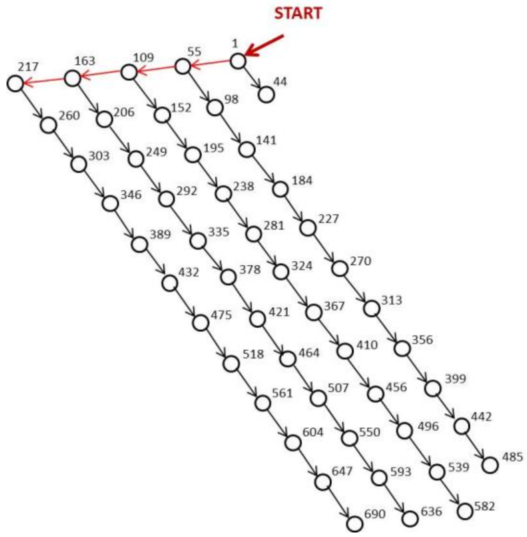

Fig. 14. Scheme of firing the pattern of (41) explosive charges according to variant #3

Verification of design of firing the pattern of explosive charges

One of the most important elements of the computer programme algorithm is the possibility of verifying the adopted model. The verification under industrial conditions is particularly difficult as the number of factors influencing the seismic effect of blasting is very high. However, the programme's structure facilitates learning by both the programme and the designer. Thanks to the experience gathered the forecasted effect is becoming more and more consistent with the real outcome. In the discussed case, the design verification was carried out by performing control measurements of vibrations induced during the firing of the designed mesh of explosive charges. The tests were carried out in the ground and on the foundation of the building, obtaining a seismogram (Figure 15), resulting in the vibration structure of Figure 16.

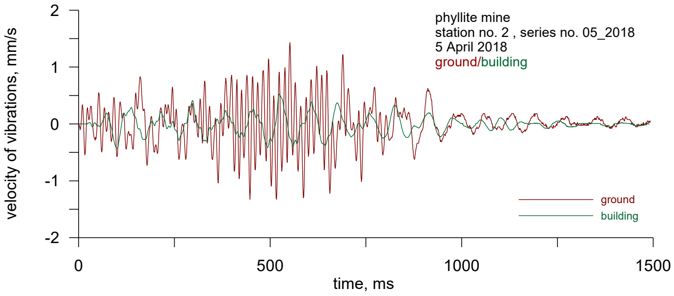

Fig. 15. Seismogram of vibrations of the ground and on the foundation of the building (horizontal x-component) recorded during the firing of a series of charges according to variant #3

The analysis of information presented in Figures 15 and 16 clearly confirms that the assumed goal has been obtained - i.e. low vibration intensity at lower frequencies and very high damping at higher frequencies.

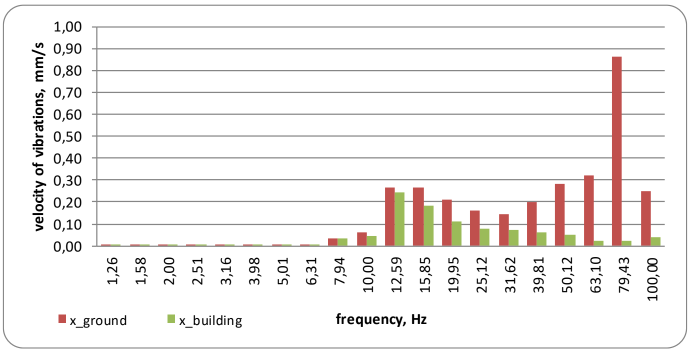

Fig. 16. Comparison of the vibrations structure of ground and building foundation for seismograms in Figure 15

It is also important for the analyses to compare the course and structure of vibrations resulting from the simulation and recorded during blasting; the effect of such an analysis is presented in Figures 17 and 18. In the discussed case, it can be stated that seismograms and the structure of vibrations simulated by a computer programme and recorded are significantly compatible. For comparison purposes, Table 2 also presents peak vibration velocity values from the analysis of the waveforms simulated and recorded during blasting (highlighted in red).

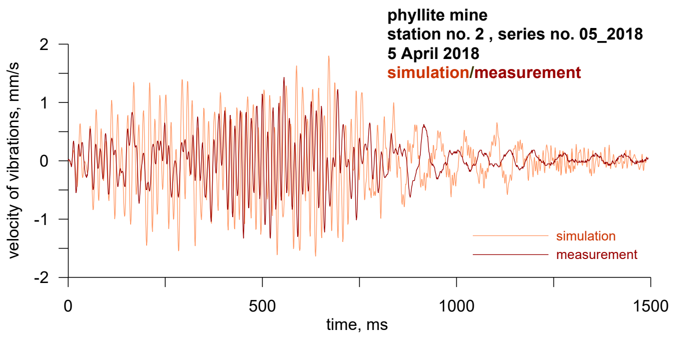

Fig. 17. Comparison of the seismogram of vibrations of the ground (horizontal x-component) resulting from the simulation and recorded during the firing of a series of explosive charges according to variant #3

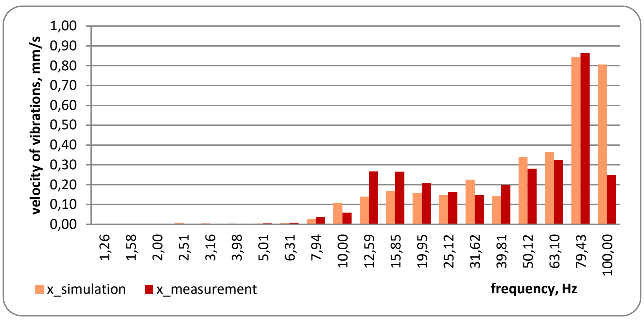

Fig. 18. Comparison of the vibrations structure of the ground (horizontal x-component) resulting from the simulation and recorded during the firing of a series of explosive charges according to variant #3

The evaluation of the impact of vibrations on the building carried out in accordance with the PN-B-02170:2016-12 standard (Figure 19) makes it possible to qualify vibrations to zone I of the SWD-I scale (negligible vibrations in terms of their impact on the object).

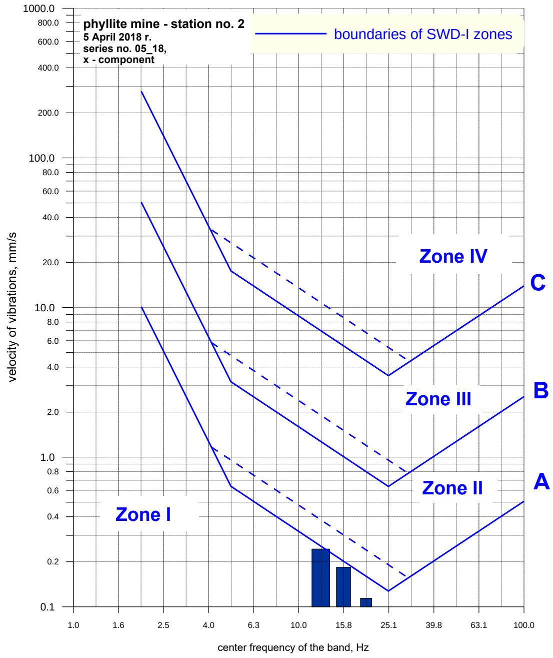

Fig. 19. Evaluation of the impact of vibrations induced during the firing of explosive charges according to variant #3 on the building

To summarise, the methodology adopted for selecting the optimal millisecond delay allows not only to determine the peak (maximum) vibration velocity values but also provides the following possibilities:

- to identify the actual distribution of delays in the designed series,
- to determine the structure of the predicted vibrations,
- to select a variant advantageous with regard to the interaction between the building and the ground,
- to evaluate the impact of vibrations on the building, taking into account the requirements of the Polish standard.

Discussion and conclusions

The use of modern initiating systems for firing explosive charges is associated with broadening the possibility of selecting millisecond delays and obtaining higher precision of firing time. This creates new perspectives for mass rock mining with the use of firing explosive charges in long blast holes. In the 1990s, the Signature Hole method started to be used for describing geological conditions and vibration propagation in programmes dedicated to designing blasting works. The method is based on the registration of seismic signals induced by the firing of single explosive charges in different excavation sites. The records obtained make it possible to conduct simulations of the seismic effect that can be induced by a series of explosive charges fired at intervals.

Based on the analyses carried out and considerations concerning vibrations induced by blasting works, it can be stated that:

- The examination of the structure of vibrations induced by the detonation of a single explosive charge is essential when determining the input data for a computer programme in order to design the delays.
- In order to design the firing of multi-row blasting patterns, it is required to analyze the real-time millisecond delay between subsequent detonations of explosive charges and to take into account the geometric arrangement of blast holes and the position of explosives in cut holes. The impact of these elements makes it impossible to indicate one (constant) delay between blast holes in a row and between rows (optimal millisecond delay), even for selected areas of the excavation or floors where blasting works are carried out. Each design concerning the firing of a multi-row blasting pattern requires an individual approach.
- When designing a multi-row blasting pattern, the actual millisecond delay constitutes important information for selecting variants. In many cases, the distribution of delays does not show many relations to the values assumed between blast holes in a row and between the rows themselves, as demonstrated in work.

- The structure of ground vibrations induced by the firing of a multi-row series in relation to a single explosive charge remained unchanged in the lower frequency range. On the other hand, higher frequency vibrations were induced, which significantly dampened the foundation of the building. The analysis of information presented in Figures 15 and 16 unequivocally confirms that the assumed objective has been achieved.

Verification of the adopted solution by measuring vibrations at a selected point is a vital element included in the procedure of designing the firing of a series of explosive charges. On the one hand, this provides the possibility to control the simulation results, while on the other hand, it allows the designer to broaden his knowledge and expertise, as well as to systematically supplement the database of computer software dedicated to designing blasting (optimizing millisecond delays). In principle, the programme offers a number of solutions, from which the designer has to choose the appropriate variant. Since this is one of the most difficult design elements, carefully preparing the selection procedure and defining certain indicators or coefficients make it easier to select a solution that will meet the assumptions made in the preliminary stages.

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