

Anna Soltys (soltys@agh.edu.pl)

Józef Pyra

Michał Twardosz

Faculty of Mining and Geoengineering, AGH University of Science and Technology

CONTROL OF THE VIBRATION STRUCTURE INDUCED DURING WORKS WITH THE USE OF EXPLOSIVES

STEROWANIE STRUKTURĄ DRGAŃ WZBUDZANYCH W CZASIE ROBÓT Z UŻYCIEM MW

Abstract

This article presents the results of research on controlling the structure of vibrations induced during the firing of explosives with the use of non-electrical and electronic systems and the influence of the vibration structure during a transition from the ground to the building. The use of procedures associated with the selection of millisecond delay for firing explosive charges during blasting allows to get the excitation of favourable structure vibrations, thanks to a strong damping which is obtained at the transition from the ground to the structure. This means that optimally designed blasting works do not have to limit the mass of the explosives in the borehole as well as their number.

Keywords: Open-pit mining, blasting technique, millisecond blasting, vibration structure, impact of vibrations on buildings

Streszczenie

W artykule przedstawiono wyniki badań nad sterowaniem strukturą drgań wzbudzanych w czasie odpalania ładunków MW z zastosowaniem systemów nieelektrycznych i elektronicznych oraz wpływem struktury drgań na interakcję układu budynek-podłoże. Zastosowanie do projektowania robót strzałowych procedur związanych z doбором opóźnienia milisekundowego do odpalania ładunków MW pozwala na wzbudzenie drgań o korzystnej strukturze, dzięki czemu uzyskuje się silne tłumienie przy przejściu z podłoża do obiektów. Oznacza to, że optymalnie zaprojektowane roboty strzałowe nie muszą ograniczać masy ładunków MW w otworze oraz ich liczby.

Słowa kluczowe: górnictwo odkrywkowe, technika strzelnicza, strzelanie milisekundowe, struktura drgań, oddziaływanie drgań na zabudowania

1. Introduction

The use of explosives in the process of mining rock deposits is a source of vibrations, especially when using explosive charges in long holes; this may have an effect on the buildings in the vicinity of an open-pit mining excavation. The aim of each mining plant is, on the one hand, to minimise this impact and, on the other hand, to use large masses of explosives for blasting as this ensures a reduction in the costs of blasting. The introduction of modern explosives, the mechanical loading of explosives for use in blast holes, and both non-electrical and electronic firing systems creates the possibility to carry out blasting works in a manner which is both appropriate and safe for the environment.

Blast-induced vibrations have an important feature, which is the ability to precisely determine the timing of events (the timing of the firing of charges is human determined) as well as their intensity (changes in mass of the applied charges) and structure (e.g. the use of various delays between successive charges). In the case of an earthquake or a shock induced by underground exploitation, it is difficult to predict the time of occurrence, and even more so its intensity and structure as it is an incident associated with the forces of nature.

The nature of research into the vibrations is related to activities aimed at minimising their impact on the environment. These actions, in the case of blasting works in open-pit mining, are aimed at controlling the source on the one hand and reducing the energy of vibrations transmitted from the ground to protected objects on the other [1, 3, 4, 9, 10, 16, 17, 20].

The minimisation of the vibration impact on the environment is achieved by activities at the stage of design. These are primarily based on knowledge of the technologies of the performed blasting works and the increasingly accurate identification of the nature of the propagated vibrations with simultaneous assessment of their impact on objects in the vicinity.

Specifically, the following points are important in the context of minimising the impact of vibrations on the environment:

- ▶ recognition of the nature of the construction in the vicinity of the work site;
- ▶ recognition of the vibration source, taking into account the condition of works and the path of vibration propagation from source to objects;
- ▶ recognition of the mechanism of vibration transmission from the ground to the foundations of the object;
- ▶ assessment of the impact of blasting works on the objects;
- ▶ determination of conditions for the safe execution of the blasting works;
- ▶ documentation of the impact by control measurements or vibration monitoring.

Analysis of the scope of work envisaged in the abovementioned points allows for the following division: points 1 to 4 prepare the basis for the implementation of point 5; point 6 is the control of the implementation of point 5. At the same time, it is important to be aware that all points are active and influence each other. Their dynamic relationship do not make it possible to say that everything has already been performed and will be continued in future years.

The dynamic variability of parameters determined in particular stages abovementioned is mainly generated in the source of vibrations, their propagation and their transfer mechanism from ground to objects, i.e. in the context of points 2 and 3. The reason for these dynamic

changes is, on the one hand, a change in the geological conditions at the location of the blasting works (shifting of exploitation fronts) and, on the other, technical progress in the execution of blasting works, i.e. the development of new explosives and new precision systems for initiating charges. In addition, thanks to the use of modern analytical apparatus which enables the study of the structure of vibrations, knowledge of both the propagation of vibrations and the interaction of the building-ground transition mechanism is better today and allows for more accurate conclusions.

Environmentally safe blasting works are primarily associated with the determination of permissible explosive charges and their possible use. Determination of the permissible charges is a basic activity, but must be performed with consideration to the manner in which the works are to be executed and certainly, by the determination of the implementing conditions for which the restrictions have been introduced.

As mentioned above, one of the points implemented in the preventative strategy is to identify the source of vibration. Today, we are able to go further than that – to recognise the possibility of controlling the source of vibration, i.e. how to design the presented source in order to achieve the best possible mining effect and at the same time minimise the impact of vibrations on the surrounding buildings. In blasting works, designing a source means selecting the geometric parameters of the blasting pattern and individual blast holes, and the selection of the mass and number of charges fired with a deliberately selected millisecond delay.

The impact of blasting work on buildings depends on the intensity of the induced vibrations and their frequency; both parameters can be adjusted by changing the parameters of the source. In terms of the assessment of the impact on the structure, it should also be remembered that the final effect taken into account is the vibration of the foundation, not the ground.

The aim of this article is to demonstrate the possibility of using modern blast control apparatus to control the structure of the induced vibrations and to indicate new possibilities for reducing the seismic effect of blasting.

2. Evaluation of the impact of vibrations on buildings in the vicinity of the excavation site

In order to assess the impact of vibrations induced by blasting works, the guidelines of PN-B-02170:2016-12 standard [8] are used. The approximate characteristics of the harmfulness of vibrations according to this standard can be presented using the dynamic SWD scale.

The frequency of vibrations plays an important role in assessing the impact using SWD scales. To illustrate this problem, Fig. 1 shows the SWD I scale, on which the limit values are applied, taking the B limit as the acceptable vibration velocity level. For example, the frequencies selected are 25 Hz, 10 Hz, 5 Hz and 2 Hz [19] and the allowable vibration velocity values are 0.62 mm/s, 1.6 mm/s, 3.0 mm/s and 50.0 mm/s, respectively. As can be observed, the difference in vibration velocity is very high; for extreme frequency values, this amounts to an 80-fold difference.

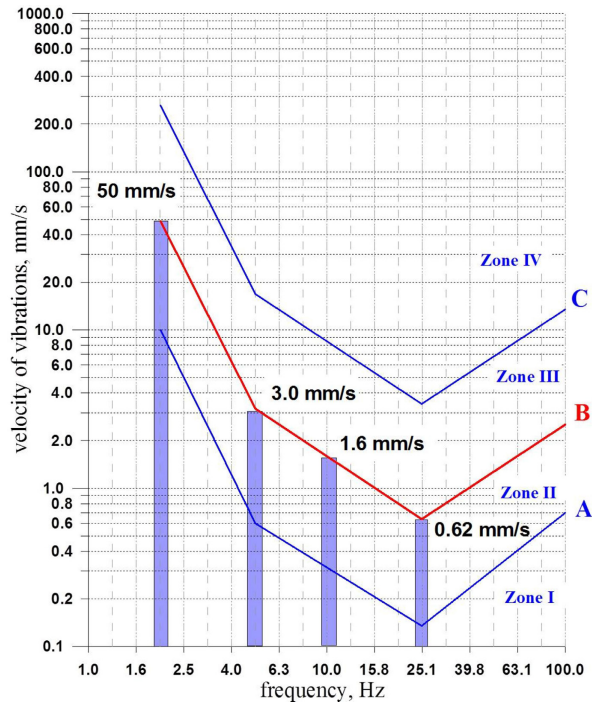


Fig. 1. SWD I scale – specific values of permissible vibration velocities for the frequencies of 25, 10, 5 and 2 Hz [19]

In many pieces of research [5, 6, 9, 17, 18], it has been proven that the applied millisecond delay has a significant influence on the structure of vibrations induced during the firing of charges. This means that by choosing a millisecond delay, it is possible to change the frequencies of propagated vibrations in the substrate and thus influence the degree of vibration transmission to the building structure.

When determining the conditions of the environmentally safe execution of blasting works, it should not be ignored that in most cases, propagation equations are determined for the ground, i.e. for vibration propagation through the ground. However, buildings on this ground are protected. This means that an important element of the procedure is to identify the interaction between the building and the groundborne vibrations. Thus, the problem of vibration frequency, i.e. the structure of vibrations induced in the substrate, again applies. It can be assumed that the vibration during the transition from the ground to the foundation of the building is more or less dampened. The frequency of vibrations is also modified and in most cases, the higher frequencies do not transfer to the foundations of the building. Frequency modification and attenuation in the lower frequency range is negligible [5, 6, 9, 17].

As a result of the factors presented above, research of the interaction between the building and the foundations should be conducted which takes into account the structure of vibrations of both the ground and the foundations of the building. Figure 2 shows the structure of the ground and foundation vibrations, recorded during the firing of a blasting pattern with a delay of 20 ms in the limestone mine. In this case, by introducing a 20 ms delay (electronic firing),

very strong vibration damping was achieved. While controlling the source, vibrations were induced in the substrate, the intensive high-frequency phase of which was dampened during the transition to the foundation and thus, without reducing the mass of charges, the impact on the buildings was minimised. The applied delay (electronic firing) induced vibrations in the ground, where the frequency of 50.12 Hz was predominant and had a value close to the frequency of the millisecond delay.

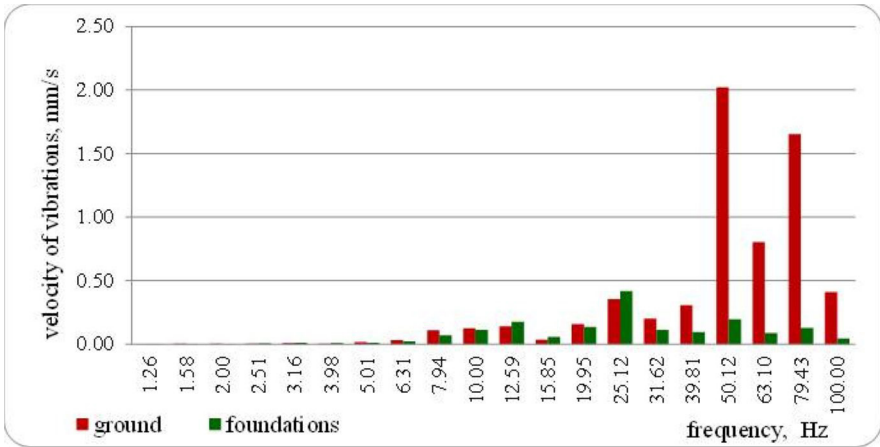


Fig. 2. Interaction of ground to foundation vibration transition system – limestone mine – delay 20 ms

Figure 3 shows the structure of ground and building vibrations recorded when firing the blasting pattern inside a dolomite mine with a delay of 67 ms (non-electric firing). As with the 20 ms delay, the applied delay induced vibrations in the ground, where the frequency of 15.85 Hz is predominant and it has a value close to the frequency of the millisecond delay (at 67 ms delay, MW charges were fired at 14.92 Hz).

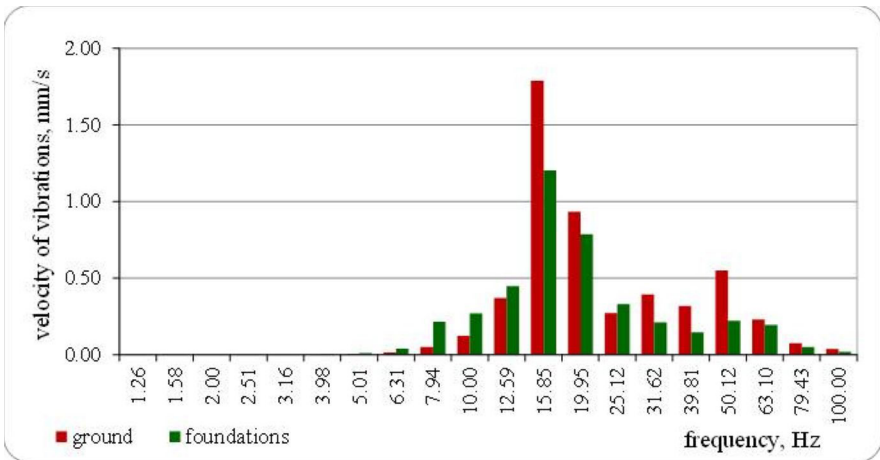


Fig. 3. Interaction of ground to foundation vibration transition system – dolomite mine – delay 67 ms

As Fig. 3 shows, during the transition to the foundation, the dominant frequency vibrations were suppressed by a small percentage, and the modification of the vibration structure was negligible. Comparing Figs. 2 and 3, it can be observed that there is a strong dependence of damping on the vibration structure propagated by the substrate. Higher frequencies, in the case of the 20 ms delay, were completely suppressed, while in the case of the 67 ms delay, the frequencies were unchanged, although the vibration intensity on the foundation was lower.

Modification of the vibration structure during the transition from the ground to the foundation must be taken into account as Polish standard [8] allows for evaluation based on the vibration recorded on the foundation. In other countries, the assessment is based on substrate vibrations and therefore, when making comparisons, conditions of the applicability of individual standards must be clearly identified.

3. Millisecond firing of charges

Since there was a possibility of changing the delay between the charges being fired in individual blast holes, the influence of the time delay between detonations of charges on the effect of blasting works was investigated. As early as 1940-1950, as a result of research conducted in the United States, millisecond firing was recognised as a technique for blasting works which reduced vibrations and allowed the obtaining of a mining product with the desired fragmentation [2, 7].

Siskind [8] writes about the criterion of 8 ms as the minimum time between charges which allows us to speak of millisecond firing. He also mentions that the genesis of this criterion is not fully known and cites the results of studies [7] for which the following delays were used: 0, 9, 17 and 34 ms.

In papers [11–13], the authors prove that the criterion of 8 ms is not always justified in all cases. In a substrate with low frequencies of approximately 10 Hz, a delay close to 8 ms increases the intensity of the recorded vibrations and the actual delay should be around 60 ms.

In [11], the authors state that the time delay should be within half of the interval of the dominant frequency, whereas Siskind in [14], who is also a co-author of the work [11], suggests that the delay should not be less than one quarter of the dominant frequency of vibrations.

Currently, three systems are used in open-pit mining for initiating charges: electric, non-electrical and electronic. The development of initiation systems is moving in the direction of increasing safety, increasing the accuracy of set delays and offering more and more options for selecting delays. It can be said that the Polish market is dominated by non-electrical systems (Euronel, Exel, Indetshock, Nitronnel, Rionel) and electronic (Ergonic, E*star, Hot Shot, i-con, Riotronic, UniTronic 600) systems offered by several foreign and domestic manufacturers.

In the case of non-electrical systems, when designing the blasting pattern and selecting millisecond delays for individual charges, it should be remembered that the delay between charges is equivalent to a connector delay only in case of charges arranged in one row series and fired with a breaking in the hole/snubber. In any other case, the actual initiation time of

individual charges must be calculated and on this basis, it is possible to determine the actual millisecond delay.

For example, Fig. 4 shows a schematic connection diagram of 30 charges in three rows with 25 ms and 42 ms connectors. The actual millisecond delays achieved are significantly different from the nominal times of the applied connectors; in 80% of cases, the delay between MW charges was 8 and 9 ms (Fig. 5).

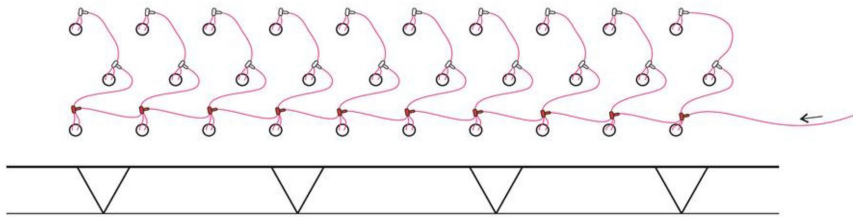


Fig. 4. Connection of the 30 MW charges arranged in three rows (25 and 42 ms connectors)

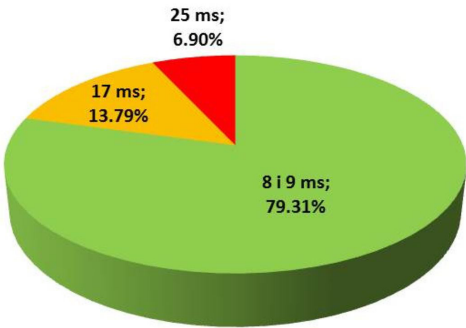


Fig. 5. Actual time of millisecond delays for the connections shown in Fig. 4

In the case of the initiation of charges with an electronic system, there are no problems with the selection of delays in multi-row blasting patterns. Each detonator can be given any delay in the range from, for example, 1–15,000 ms (each manufacturer offers a slightly different range), i.e. only the blasting engineer's knowledge and connection influence the selection (Fig. 6).

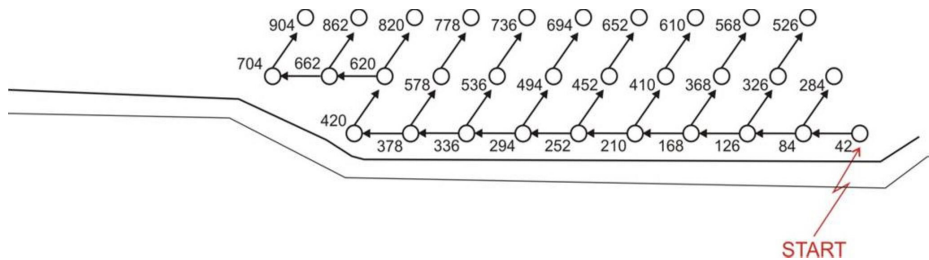


Fig. 6. Connection of the openings net using the electronic system

4. Effect of milliseconds delay time on vibration structure

As has already been mentioned, modern initiation systems, characterised by the high precision of pre-set millisecond delays, give a wide range of possibilities for selecting the duration of these delays, taking into account local geological and mining conditions. The use of an electronic system for firing the multi-row blasting patterns requires optimal design with regard to millisecond delays, which on the one hand will allow the obtaining of an appropriate granulation of the blasting product, and on the other, will ensure minimisation of the impact of the detonation of charges on the environment [15].

The selection of the optimum millisecond delay for a given set of conditions, especially in the case of multi-row patterns, requires IT support, i.e. the application of IT software for the purpose of designing. The basic information required for these programmes is:

- ▶ the location of a blast hole series and the location of protected objects;
- ▶ the parameters of the planned blasting with regard to length of the holes, their number and location, burden, distance between holes and rows, weight of explosive charge in the hole, length of stemming and rebore;
- ▶ a recording of the vibrations induced by firing a single charge at a location close to the area of the planned blasting pattern (using the Signature Hole method);
- ▶ an indication of the seismic effect of the given series at a similar location.

Based on this data, the program calculates a prediction of the seismic effect and proposes a number of solutions, from which the system operator can choose the optimal solution.

In one of the quarries (Mine A), an experimental blasting using an electronic initiation system was performed in order to minimise the impact of blasting works on the surrounding buildings.

The first blasting was prepared using experience from blasting with the use of a non-electrical system, without software support. The distribution of the achieved millisecond delays is shown in Fig. 7 – almost 80% of the charges were detonated with a delay of 10 ms.

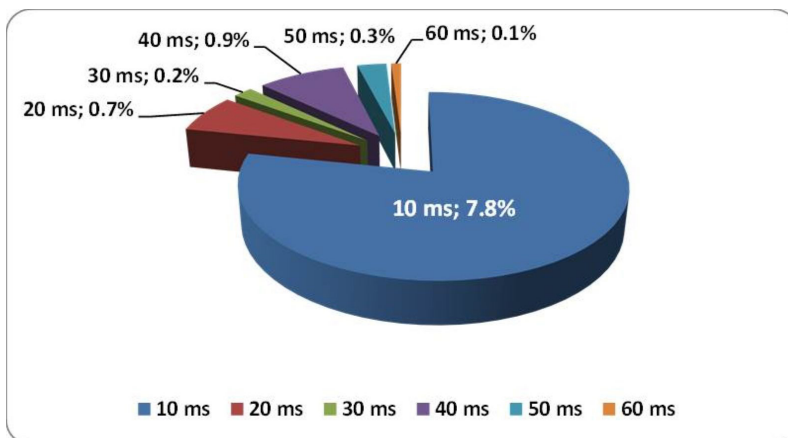


Fig. 7. Distribution of millisecond delays – testing series

Figures 8 and 9 show the seismogram and structure of vibrations recorded on the ground and on the building foundation (position 2 and 2'). Figures 8 and 9 show that 12.59 Hz and 15.85 Hz are the predominant frequencies in the ground and on the foundation of the building. Vibration damping is also observed when vibrations pass from the ground to the foundation at a level of 20% to 50% (within the dominant frequencies).

In the next stage of research, blasting design was introduced with the use of software in which the algorithm provides the formation of a database based on the Signature Hole method. The analysis of seismograms of vibrations obtained during the firing of individual charges indicated the possibility of shifting the frequency of vibrations propagated by the ground to the range of higher values (50 Hz to 100 Hz). The performed seismic simulations confirmed this observation; this allowed the design and execution of dozens of experimental and production blasts within a period of three years.

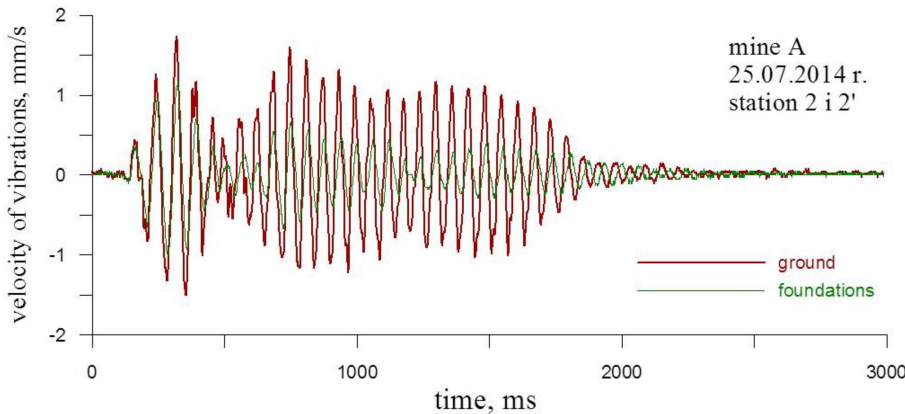


Fig. 8. Seismogram of ground and foundation vibration – component x – testing series

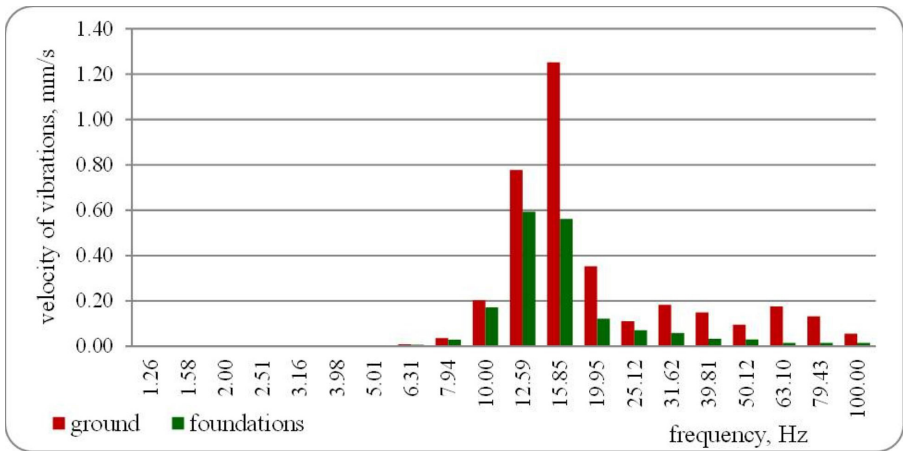


Fig. 9. The structure of ground and foundation vibration – component x – testing series

Figures 10, 11 and 12 show the results of a seismic analysis for a production series located close to the first testing series. The measurements were taken on the ground and on the foundations of the building and the result of the analysis was presented in the same way as in the figures above. As a result of software simulation, a delay pattern was used. This resulted in more than 70% of the actual delay time of 22 ms, which is more than double that of the experimental series.

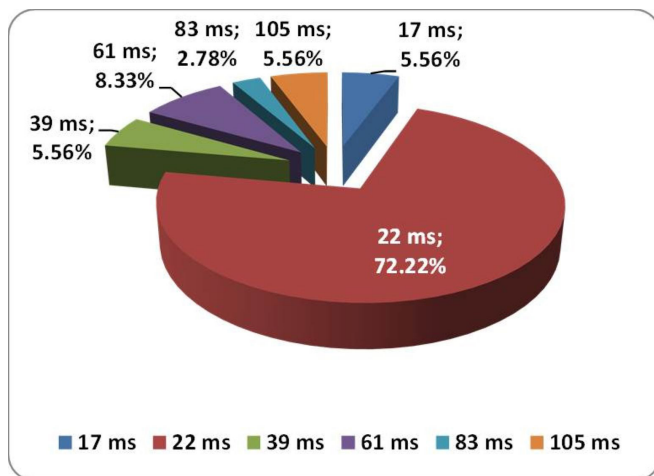


Fig. 10. Distribution of millisecond delays – production series

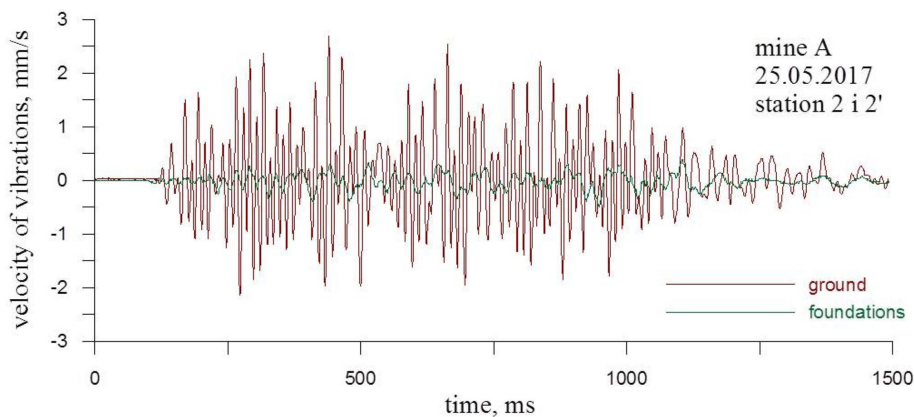


Fig. 11. Seismogram of ground and foundation vibration - component x – production series

It should be added that in the production blasts, the charge weight per millisecond was increased by 30% and the analysed design was characterised by the highest intensity of blasting in 2017 on the first level 'Ia' in mine A.

Comparing the structure of the recorded vibrations (Figs. 9 & 12) it can be noted that due to the use of a proper millisecond delay time, a complete change in the structure of vibrations in the substrate was achieved. A shift of frequencies dominating in the range of higher values occurred and this contributed to a significant increase in vibration level damping during the

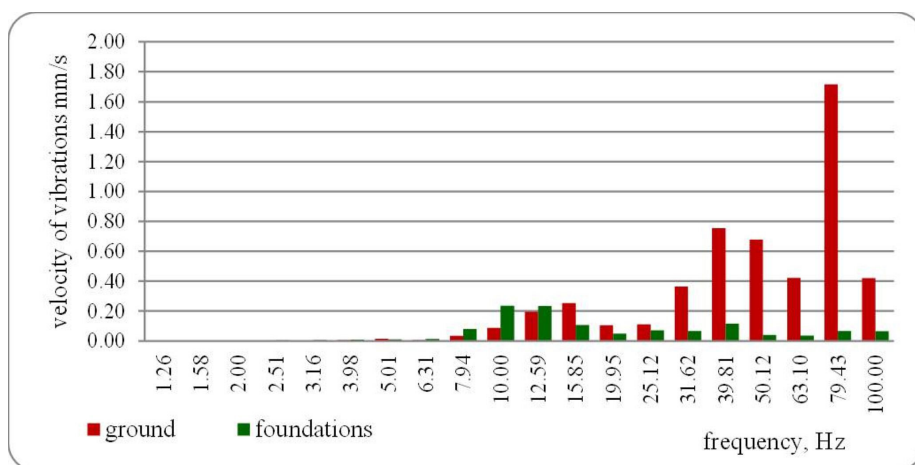


Fig. 12. Structure of ground and foundation vibration – component x – production series

7transition to the foundations of the building. In the range of frequencies dominating in the structure of foundation vibrations, the intensity has been reduced threefold.

The assumed effect of the studies was to minimise the impact of blasting works on the environment; therefore, Fig. 13 presents a comparison of the vibration impact assessment for the analysed series with the application of the SWD-I scale from Polish standard [8].

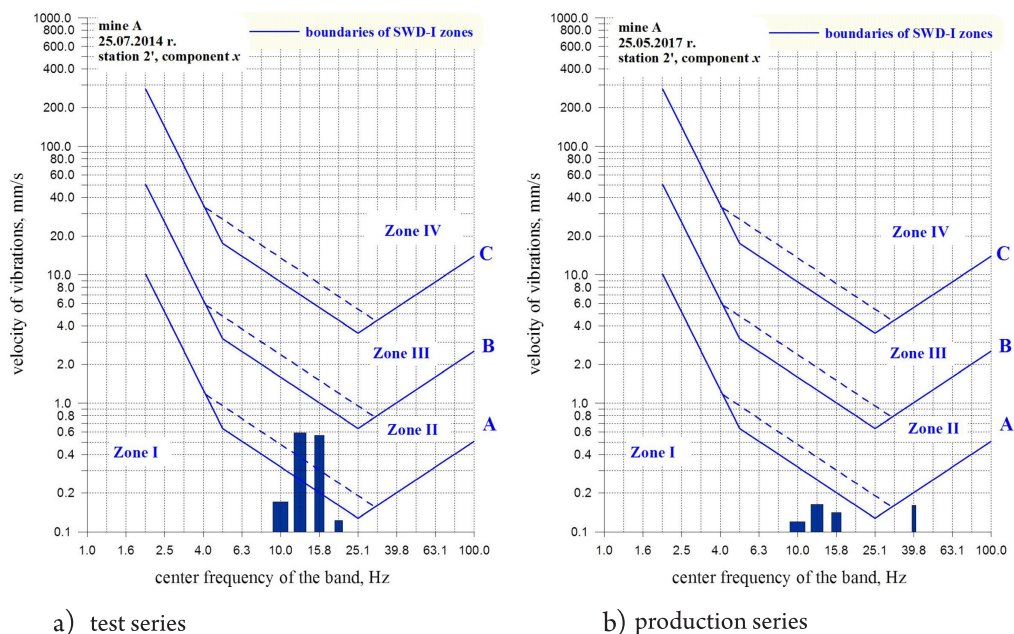


Fig. 13. Comparison of the assessment of blasting works influence on the environment – component x – testing series and production series

5. Summary

The impact of vibration induced by blasting works on buildings continues to be a problem that requires a prudent approach and a compromise between protecting the interests of mines and those of local communities.

The implementation of modern firing systems to blasting works in open-pit mining increases the possibility to control the undesirable seismic effects. Minimisation of the impact of blasting works on structures in the environment can be achieved not only by limiting the mass of explosives, but also by the skilful selection of millisecond delays. This allows for the modification of the frequency structure of the vibrations in the direction of increasing the attenuation when vibrations transfer from the ground to building foundations.

It should be noted that the implementation of modern firing systems does not always have the desired effect in all conditions. It is necessary to be aware that the number of factors influencing the impact of vibrations on objects requires mindfulness and knowledge based on reliable research, which is best evidenced by the effect obtained in the analysed experimental series.

References

- [1] Baulovič J., Pandula B., Kondela J., *Research on the millisecond delay blasting impact in order to minimize seismic effects in Kučín quarry surrounding*, High-Energetic Materials 7/2015, 5–13.
- [2] Duvall W.I., Johnson C.F., Mayer A.V.C., Devine J.E., *Vibrations From Instantaneous and Millisecond – Delayed Quarry Blast*, U.S. Bureau of Mines RI 6151, 1963.
- [3] Kondela J., Pandula B., *Timing of quarry blasts and its impact on seismic effects*, Acta Geodyn. Geomater., Vol. 9, No. 2 (166)/2012, 155–163.
- [4] Kuźniar K., Chudyba Ł., *Wykorzystanie sieci neuronowych do prognozowania przekazywania drgań wzbudzanych wstrząsami górnictwymi z gruntu na budynek*. Czasopismo Techniczne, 3-B/2010, 109–117.
- [5] Maciąg E., Winzer J., Biessikirski R., *Metodyka postępowania w ochronie otoczenia w przypadku robót strzałowych*, Bezpieczeństwo Pracy i Ochrona Środowiska w Górnictwie – Miesięcznik WUG, 9/I/2007, 56–60.
- [6] Maciąg E., Winzer J., Biessikirski R., *Współdziałanie niskich budynków z podłożem w przypadku strzelań MW w kamieniołomach*, Warsztaty Górnicze – PAN – IGSMiE, No. 69/2007, 297–308.
- [7] Nicholson H.R., Johnson C.F., Duvall W.I., *Blasting Vibration and Their Effects on Structures*, U.S. Bureau of Mines Bulletin 656, 1971.
- [8] PN-B-02170, 2016-12 Ocena szkodliwości drgań przekazywanych przez podłoże na budynki.
- [9] Pyra J., *Wpływ wielkości opóźnień milisekundowych na spektrum odpowiedzi drgań wzbudzanych detonacją ładunków materiałów wybuchowych*, Wyd. AGH, Kraków 2017.

- [10] Pyra J., Soltys A., *Method for studying the structure of blast – induced vibrations in open – cast mines*, Journal of Vibroengineering, September 2016, Vol. 18, Issue 6, 3829–3840.
- [11] Siskind D.E., Crum R.E., Otterness R.E., Kopp J.W., *Comparative Study of Blasting Vibrations From Indiana Surface Coal Mines*, U.S. Bureau of Mines RI 9226, 1989.
- [12] Siskind D.E., Stachura V.J., Nutting M.J., *Low-Frequency Vibrations Produced by Surface Blasting Over Abandoned Underground Mines*, U.S. Bureau of Mines RI 9078, 1987.
- [13] Siskind D.E., Stagg M.S., Kopp J.W., Dowding C.H., *Structure Response and Damage Produced by Ground Vibration from Surface Mining Blasting*, U.S. Bureau of Mines RI 8507, 1989.
- [14] Siskind D.E., *Vibrations from blasting*, ISEE, Cleveland 2005.
- [15] Soltys A., Gołąbek B., Żołądek T., *Zastosowanie informatycznych systemów firmy Austin Powder do optymalizacji odpalania siatek wieloszeregowych z użyciem zapalników elektronicznych E*Star*, [The application of Austin Powder Company IT systems to optimize the firing of multiple-row patterns using E*Star electronic detonators], Inżynieria Mineralna, R. XVIII, No. 2/2017, 225–235.
- [16] Soltys A., Pyra J., Winzer J., *Analysis of the blast-induced vibration structure in opencast mines*, Journal of Vibroengineering, February 2017, Vol. 19, Issue 1, 409–418.
- [17] Soltys A., Winzer J., Dworzak M., *Dobór optymalnego opóźnienia milisekundowego – studium przypadku*, Konferencja „Technika Strzelnicza w Górnictwie i Budownictwie”, Ustroń 2015, 225–236.
- [18] Soltys A., Winzer J., Pyra J., *Badania efektu sejsmicznego a nowoczesne systemy odpalania ładunków MW*, Przegląd Górniczy, Vol. 71, No. 9/2015, 69–77.
- [19] Winzer J., *Przyczynek do dyskusji o sposobach minimalizacji oddziaływania robót strzałowych na zabudowania w otoczeniu*, Konferencja „Technika Strzelnicza w Górnictwie i Budownictwie”, Ustroń 2013, 347–361.
- [20] Winzer J., Soltys A., Pyra J., *Oddziaływanie na otoczenie robót z użyciem materiałów wybuchowych*, Wydawnictwa AGH, Kraków 2016.

