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Significance of blasting induced vibration frequencies in assessing their impact on a building
Znaczenie częstotliwości drgań wzbudzanych robotami strzałowymi w ocenie ich oddziaływania na budynek

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Abstract: *The use of explosives to excavate rock in open-cast mining induces vibrations in the surrounding area, which may impact nearby structures. As early as the 1960s, time-delayed firing of successive EM charges was introduced, which dramatically improved both the quality of excavation (fragmentation and shape of the dump) and reduced the intensity of vibrations propagated to the environment. Through the use of increasingly new developments in millisecond firing (non-electrical and electronic systems), a wide range of possibilities for controlling the seismic effect has been achieved. A very important parameter of the induced vibrations is the structure of their frequency, achange of which can decisively influence the mechanism of vibration transmission from the ground to the structures and the impact assessment. As the seismic effect depends significantly on the geological conditions of both the deposit and the surrounding area, the analysis of vibrations induced from the detonation of single EM charges (signature hole (SH) method) best characterises these conditions. This paper presents the results of a study on the control of the structure of vibrations induced by the firing of EM charges using an electronic initiation system and the influence of the structure of these vibrations on the interaction of the building-ground system. The application of millisecond delay selection procedures to the design of blasting operations for the firing of EM charges, allows inducing vibrations with a favourable structure, resulting in strong attenuation during the transition from the ground to the objects.*

Streszczenie: *Użycie materiałów wybuchowych do urabiania skał w górnictwie odkrywkowym wzbudza w otoczeniu drgania, które mogą oddziaływać na zlokalizowane w pobliżu obiekty budowlane. Już w latach 60. ubiegłego stulecia wprowadzono odpalanie kolejnych ładunków MW z opóźnieniem czasowym, co w zdecydowany sposób poprawiło zarówno, jakość urabiania (rozdrobnienie i kształt usypu) jak i obniżyło intensywność drgań propagowanych do otoczenia. Przez zastosowanie coraz nowszych rozwiązań w zakresie milisekundowego odpalania (systemy nieelektryczne i elektroniczne) uzyskano szerokie możliwości sterowania efektem sejsmicznym. Bardzo ważnym parametrem wzbudzanych drgań jest ich struktura częstotliwościowa, której zmiana może w zdecydowany sposób wpływać na mechanizm przenoszenia drgań z podłoża do obiektów budowlanych i ocenę oddziaływania. Ponieważ efekt sejsmiczny w istotny sposób zależy od* *warunków geologicznych zarówno złoża jak i otoczenia, analiza drgań wzbudzanych od detonacji pojedynczych ładunków MW (metoda signature hole (SH)) najlepiej charakteryzuje te warunki. W artykule przedstawiono wyniki badań nad sterowaniem strukturą drgań wzbudzanych w czasie odpalania ładunków MW z zastosowaniem elektronicznego systemu inicjowania oraz wpływem struktury drgań na interakcję układu budynek-podłoże. Zastosowanie do projektowania robót strzałowych procedur związanych z doborem opóźnienia milisekundowego do odpalania ładunków MW, pozwala na wzbudzanie drgań o korzystnej strukturze, dzięki czemu uzyskuje się silne tłumienie przy przejściu z podłoża do obiektów.*

Keywords: *blasting works, millisecond blasting technique, assessment of vibration impact, frequency structure of vibrations*
Słowa kluczowe*: technika strzelnicza, strzelanie milisekundowe, ocena oddziaływania drgań, struktura częstotliwościowa drgań*

1. Introduction

Vibrations induced by work employing EMs have an important feature, namely the ability to predict the timing of events as well as their intensity. In the case of an earthquake or a shock induced by underground mining, it is difficult to determine the time of its occurrence, let alone its intensity (energy), as it is an event related to natural forces. The vibrations induced by the detonation of an explosive are largely predictable, as humans decide the timing of their occurrence and the energy released during the event can be determined with greater or lesser accuracy, and is even controllable.

Therefore, measures to minimise the impact of vibrations on the surroundings, in the case of blasting operations in open-cast mining, are aimed at controlling the source on the one hand, and reducing the vibration energy transmitted from the ground to the objects to be protected, on the other [1].

Minimisation of impact is already achieved at the design stage, which is based primarily on knowledge of the blasting technology, as well as increasingly accurate recognition of the nature of the vibrations propagated into the environment, while assessing their impact on objects in the vicinity. The successive steps of the work are identified here [2]:

– identification of the nature of the building development in the vicinity of the worksite,
– identification of the source of vibrations, taking into account the conditions under which the works are carried out and the path of propagation of the vibrations from the source to the protected objects,
– identification of the mechanism of transmission of vibrations from the ground to the foundations of the object,
– assessment of the impact of blasting work on structures,
– determination of the conditions for safe blasting operations,
– documentation of the impact through control measurements and/or vibration monitoring.

An analysis of the scope of work provided for in the above-mentioned points allows the following division to be made: points 1 to 4 are the preparation of the base for the implementation of point 5, whereas point 6 is the control of the implementation of point 5. At the same time, it is important to realise that all points are active and inter-connected. Their dynamic interrelationships make it impossible to confirm that everything has already been done and this will continue to be so for years to come.

The dynamic variability of the parameters determined in the individual stages is generated primarily in the source of the vibrations, their propagation and the mechanism of transmission from the ground to the objects, i.e. in terms of points 2 and 3. The reason for these changes is the technical advances in blasting – the advent of new EMs and new increasingly precise systems for firing EM charges. Additionally, thanks to the use of modern analytical instruments, which allow the study of the structure of vibrations, the knowledge of both the propagation of vibrations and the interaction of the building-ground system is deeper today and allows for more accurate conclusions to be drawn.

It is well known that the millisecond delays between the detonation of successive EM charges is important for the intensity of the induced paraseismic vibrations, and is therefore an important parameter of blasting work and must not be neglected, because by not selecting the delay correctly, especially when using new, very high-precision firing systems, the opposite effect can be achieved – where impact is expected to be minimised, significant amplification can be achieved.

As already mentioned, one of the points carried out in preventive activities is the identification of the source of vibrations. Today, it is possible to go further – to recognise the controllability of a vibration source, i.e. how to design the source to achieve the best possible mining effect while minimising the impact of vibrations on surrounding buildings. In blasting work, designing the source means selecting the geometrical parameters of the grid and blast holes, selecting the masses and number of EM charges fired with a deliberate and purposeful millisecond delays.

The impact of blasting work on buildings is assessed by the intensity of the induced vibrations and their frequency – both of which can be adjusted by changing the parameters of the source. In terms of assessing the impact on a building, it should additionally be borne in mind that the final effect is vibration of the building's foundations and not of the ground on which it sits.

The simplest way to assess the harmfulness of vibrations transmitted from the ground to buildings may be to use appropriately constructed scales. On the basis of selected relevant parameters characterising the forcing and the object receiving the vibration, the expected effects of the vibration can be assessed using a scale [2-11]. Globally, a range of scales and standards are used to assess harmfulness. This large number is due to the difficulty in capturing normatively all the factors which can affect vibration harmfulness. Thus, by necessity, the standards apply to specific types of building and take into account only part of the factors which would need to be considered in a particular case.

In most global standards, the parameters assessed are vibration velocity and frequency [2]. The limits of these parameters are determined tabularly or on scales which allow the impact of vibrations on surrounding buildings to be assessed. How much variation there is in the limit values between countries is illustrated by the example of the American USBM and Polish SWD scales (Figures 1 and 2).

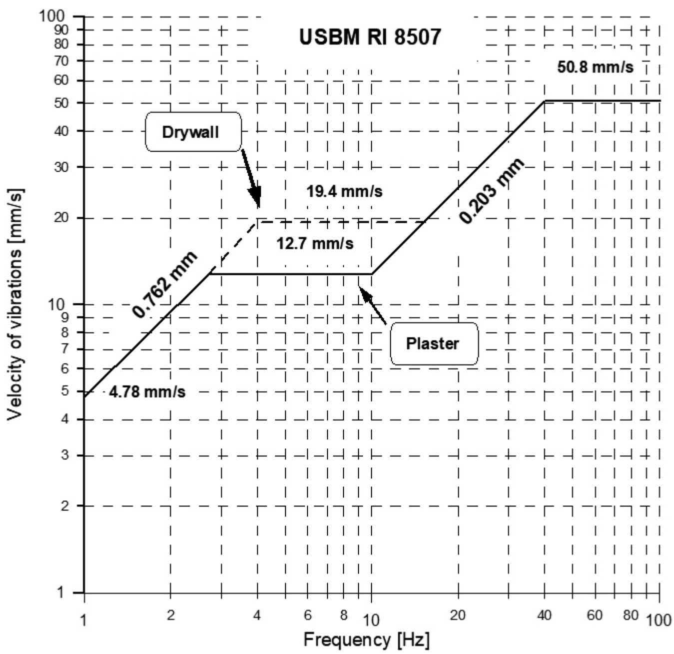


Figure 1. Harmfulness scale according to the Bureau of Mines [7]

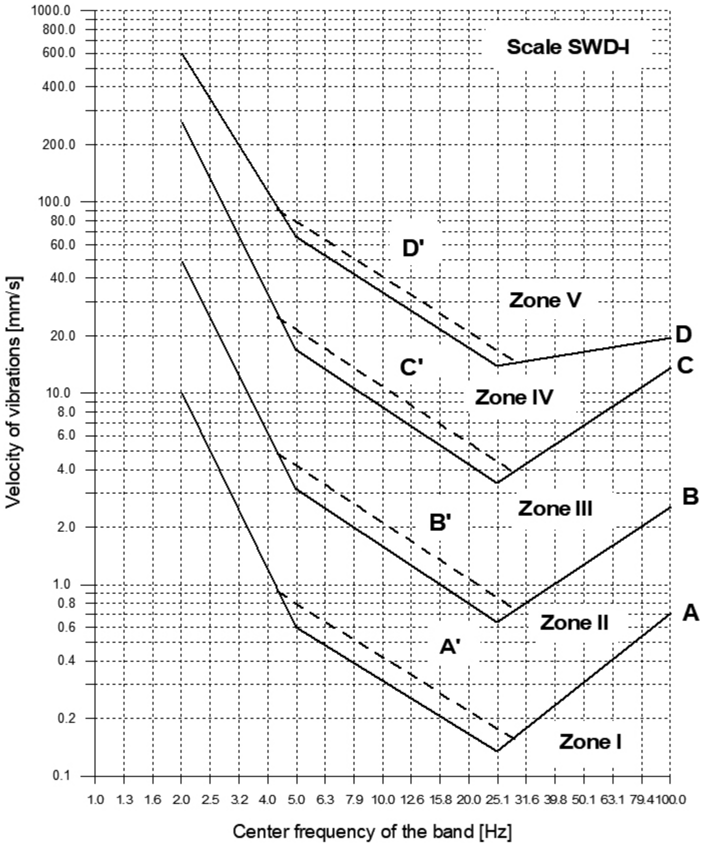


Figure 2. SWD scale according to PN-B-02170:2016-12 (velocity version) [11]

When comparing the scales presented, it should be taken into account that the SWD scale concerns long-term vibrations and the USBM scale is dedicated to the assessment of vibrations induced by blasting work, i.e. short-term (impulsive) vibrations. The vibrations assessed are ground vibrations in the case of the US standard, and vibrations measured on the building foundation in the case of the Polish standard. One is undoubtedly puzzled by the fundamental difference in the assessment of the impact of low-frequency vibration on buildings. What these scales have in common, and it is a common feature of most of the scales used worldwide, is that two vibration parameters: velocity and frequency are used for evaluation, although here too there is a difference in the methodology for obtaining the aforementioned parameters.

2. Analysis of measurement results and impact assessment using SWD scales

In the evaluation using SWD scales, seismograms (full time vibration waveforms) of the horizontal components of the vibrations, i.e. in *x* and *y* directions recorded at the measurement point on the side of the vibration source, should be used. The version of the standard prior to 2016 (PN-B-02170:1985) allowed the impact to be assessed by plotting the peak acceleration (or displacement) values on the SWD scale along with the correlated instantaneous frequency over time. The authors of the previous version of the standard have repeatedly pointed out in publications that a good solution (although not included in the standard) is to filter the time curve by thirds and carry out an impact assessment by plotting the maximum values of the measured parameter on the SWD scale histogram for the frequencies of the middle 1/3 octave bands. This procedure for carrying out the analysis has been included, as a requirement, in the revised standard PN-B-02170;2016-12 (Figure 3).

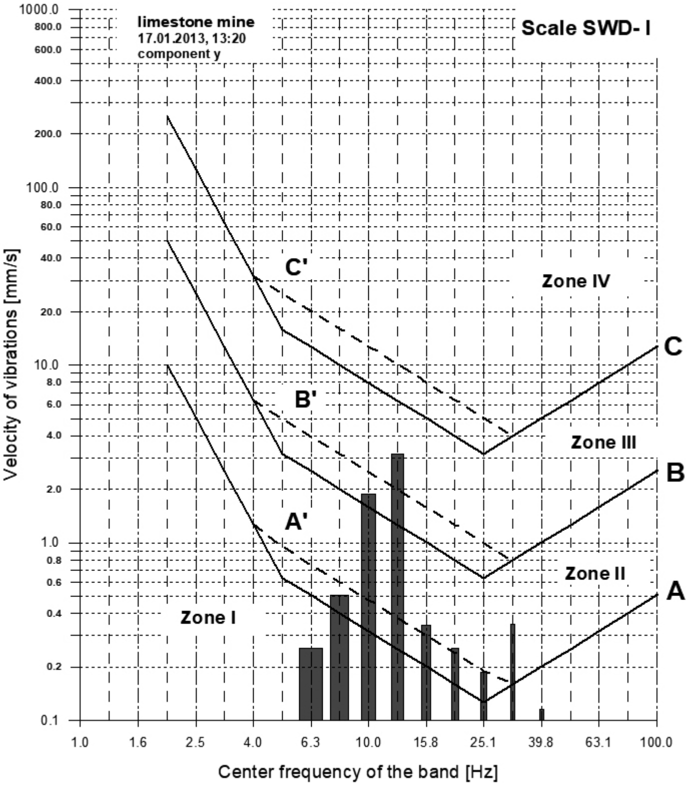


Figure 3. Assessment of vibration impact using a histogram of maximum velocity values for the frequencies of the middle 1/3 octave bands

As can be seen, vibration frequency plays an important role in impact assessment. To illustrate this problem, Figure 4 shows the SWD I scale, onto which, taking the B limit as an acceptable level of vibration intensity, the velocity limits are plotted. As an example, frequencies of 2, 5, 10 and 25 Hz were selected. The permissible vibration velocity values are respectively: 50.0, 3.0, 1.6 and 0.62 mm/s. As can be seen, the difference in vibration velocity is very large – 80 times for the extreme frequency values. This means that, under the requirements of the Polish standard, the frequency of vibrations recorded on the foundations is a very important evaluation parameter.

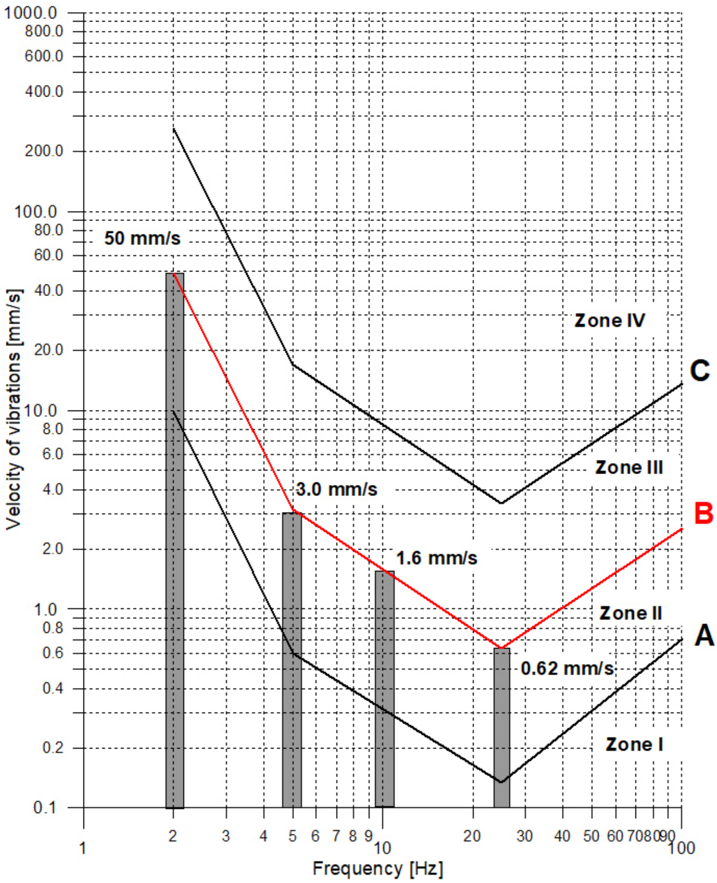


Figure 4. SWD I scale – characteristic values of permissible vibration velocities for frequencies of 2, 5, 10 and 25 Hz [12]

It has been demonstrated in a number of papers [13-21] that applied millisecond delays significantly affect the structure of the vibrations induced during the firing of EM charges, meaning that by selecting the millisecond delay, the dominant frequencies can be changed. It should be added that a shift in the dominant foundation vibration frequencies from 10 Hz to the region of 25 Hz results in a change of vibration qualification from zone II to zone III. The difference with the 25 Hz frequency is clear. The change in vibration frequency caused by the applied delay is an element which is very rarely considered by blasting designers.

3. Building-ground interaction

As already mentioned, in Poland, the assessment of the impact of vibrations on structures concerns vibrations measured on the foundation of the building. However, field measurements of vibration intensity, the purpose of which is to determine the propagation equations, are carried out by mounting meters in the ground (subsoil), and in order to determine the conditions for safe blasting, it is necessary to indicate the threshold values for these vibrations, i.e. the values of the permissible ground vibration velocities which will not have a harmful effect on the building. To carry out this procedure correctly requires the recognition of the vibration transmission mechanism from the ground to the building, i.e. the interaction of the building-ground system.

Therefore, during field surveys, where possible, vibration measurements should also be taken simultaneously in the ground and on the building's foundations. Many years of research confirm [1, 2, 12, 18, 22] that the mechanism of vibration transmission from the ground to the building is influenced by geological, mining and structural factors. These factors include:
– the type of rock being worked and the medium in which the vibrations are propagated,
– the characteristics of the ground on which the buildings stand,
– the blasting technique, the method of firing and, above all, the method of firing the EM charges,
– the foundation type, weight and construction of the building.

The above-mentioned factors not only determine the intensity of the vibrations induced during blasting, but can also change the frequency structure of these vibrations [1, 2, 12, 18, 22], and this has a significant impact on the attenuation of vibrations during the transition from the ground to the foundations. How different a building's response to ground-propagated vibrations can be is shown graphically in the form of seismograms (Figures 5 and 7) and vibration structures (Figures 6 and 8), using the example of a marl mine and a slate mine. Complementarily, Figures 6 and 8 also show the variation of the attenuation coefficient in the transition of vibrations from the ground to foundations.

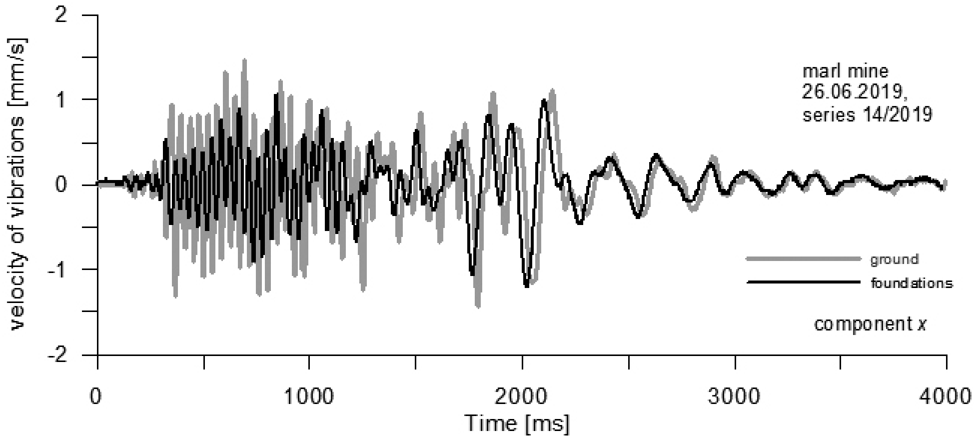


Figure 5. Seismogram of ground and building foundation vibrations recorded during the firing of a series of EM charges in a marl mine (horizontal component x)

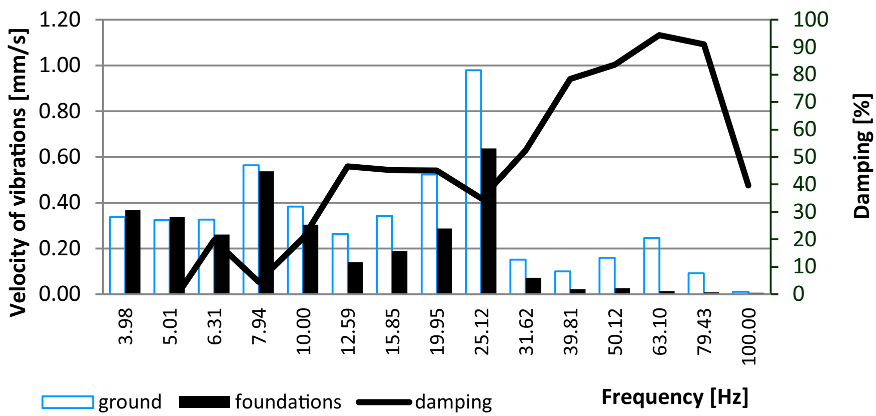


Figure 6. Vibration structure of the ground and foundation of the building shown in Figure 5

In the case of the marl mine, the ground vibrations are characterised by frequencies lower than 4 to 25 Hz and in the range of these frequencies the attenuation does not exceed 50%. In contrast, the ground in the vicinity of the slate mine is characterised by higher frequencies (80-100 Hz), which are strongly attenuated in the transition to the foundations. In the dominant frequency range, attenuation exceeds 90%. Evaluating the vibrations on the basis of their frequency structure, it can be seen that in a shale mine compared to a marl mine, ground vibrations of 30% higher intensity induce half the vibrations on the foundations.

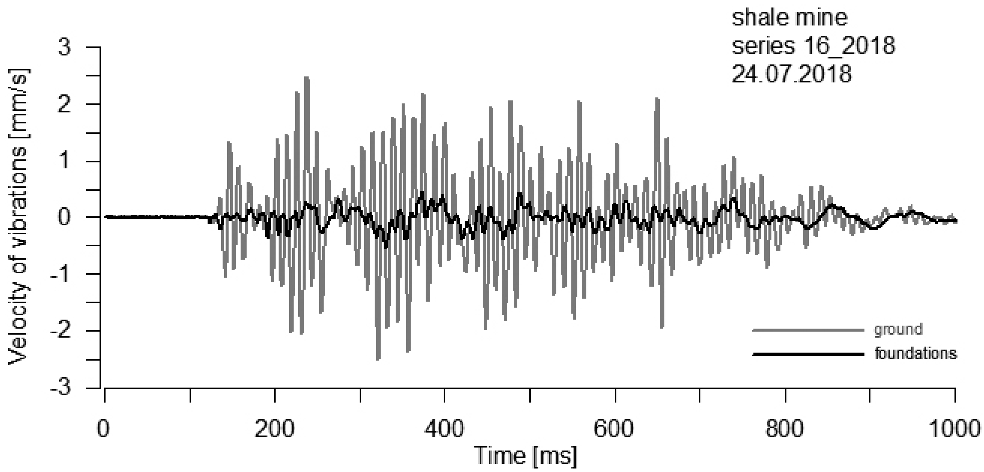


Figure 7. Seismogram of ground and building foundation vibrations recorded during the firing of a series of EM charges in a shale mine (horizontal component x)

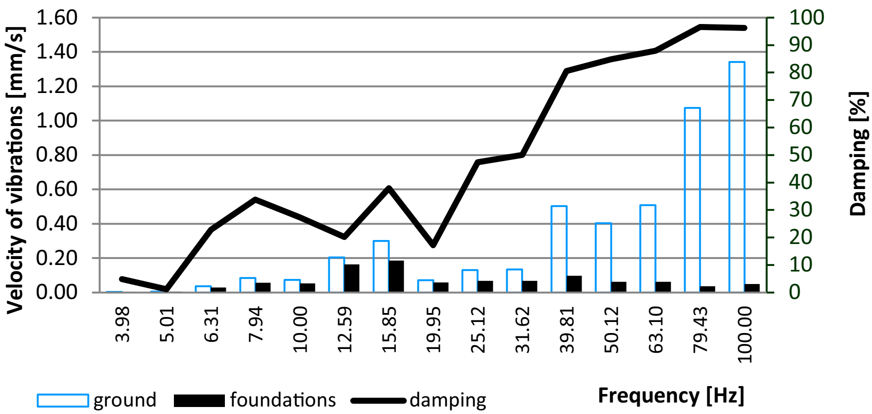
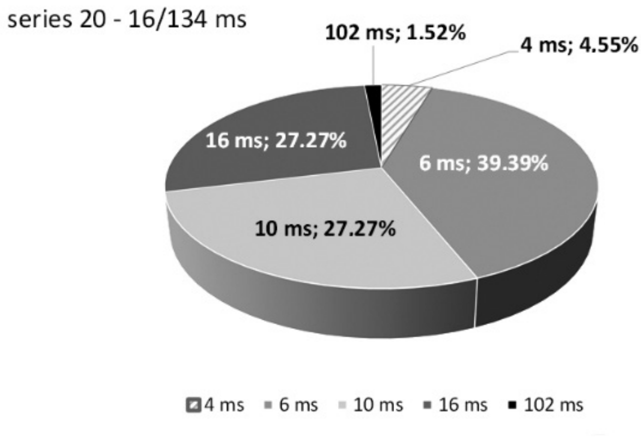
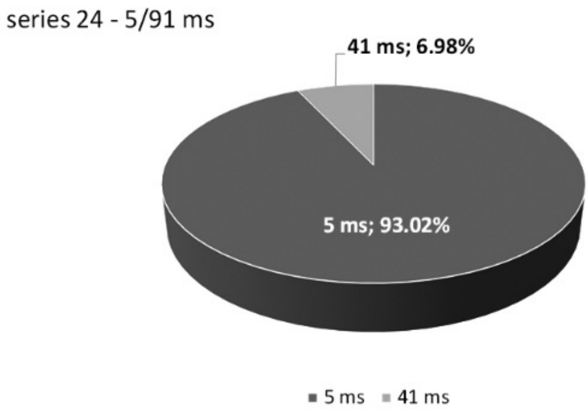


Figure 8. Vibration structure of the ground and foundation of the building shown in Figure 7

Significant differences may also occur within the same building. In one rock mine, it was observed that the vibrations induced during blasting operations, when a series of EM charges were fired with an electronic system in multi-row grids using different actual millisecond delays (Figures 9a and 9b), showed significant differences in both intensity (Figures 10 and 11) and frequency structure (Figures 12 and 13). Measurements were taken in the ground and on the foundations of the same building.



(a)



(b)

Figure 9. Structure of actual millisecond delay times – (a) series 20 and (b) series 24

In series 20, delays ranging from 4 to 102 ms were used (Figure 9a), while in series 24, a delay of 5 ms was used in the majority of charges (Figure 9b). As a result, vibrations of similar intensity but with a markedly different frequency structure were excited in the ground, which translated into an attenuation mechanism for the transition from the ground to the foundations.

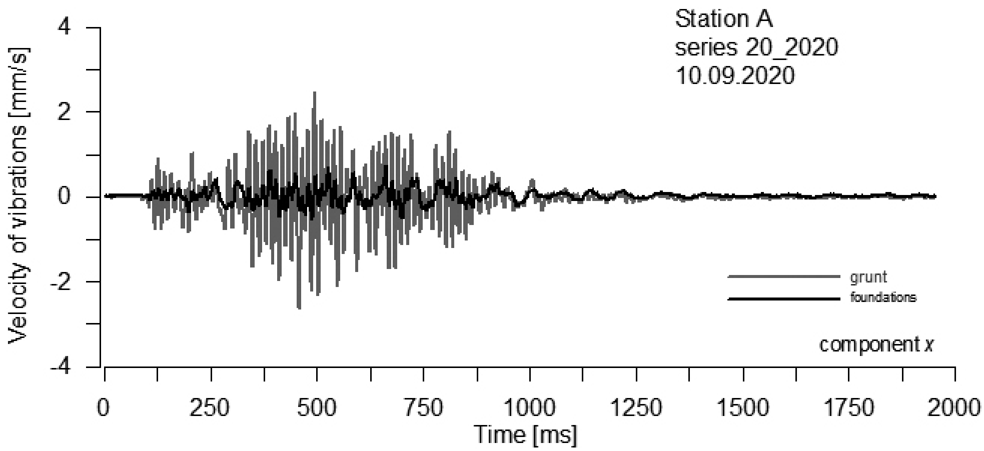


Figure 10. Seismogram of ground and building foundation vibrations – series 20, Site A

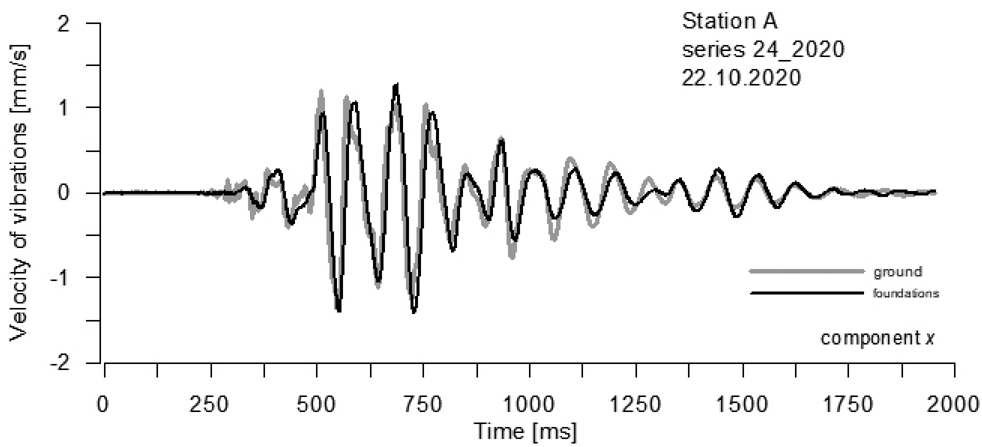


Figure 11. Seismogram of ground and building foundation vibrations – series 24, Site A

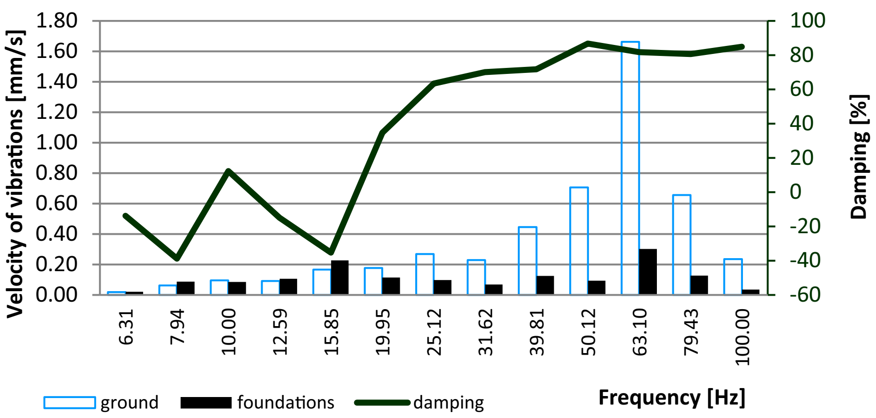


Figure 12. Vibration structure of the ground and foundation of the building shown in Figure 9

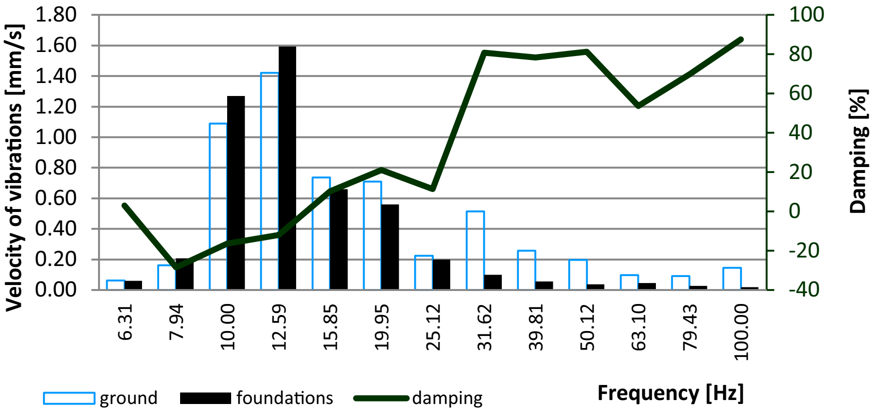
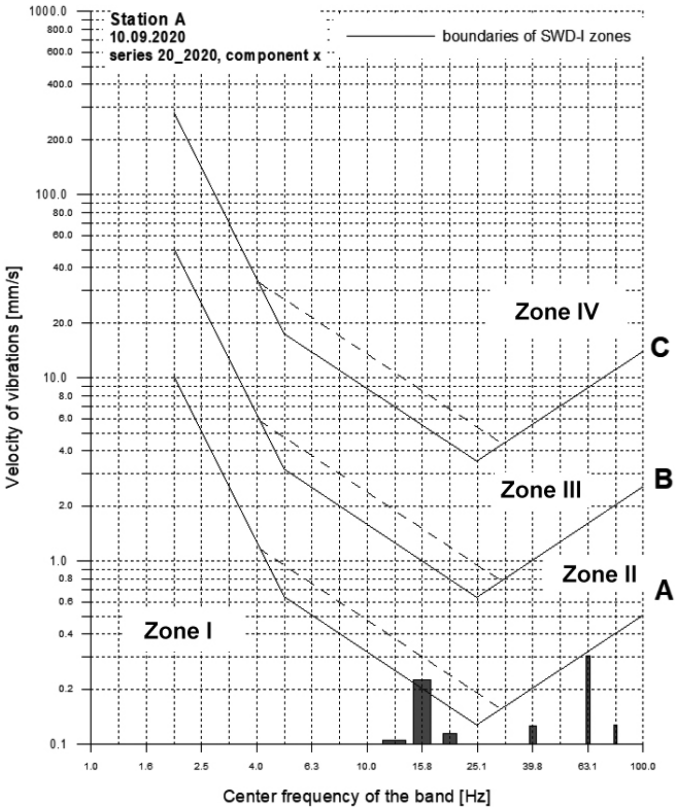
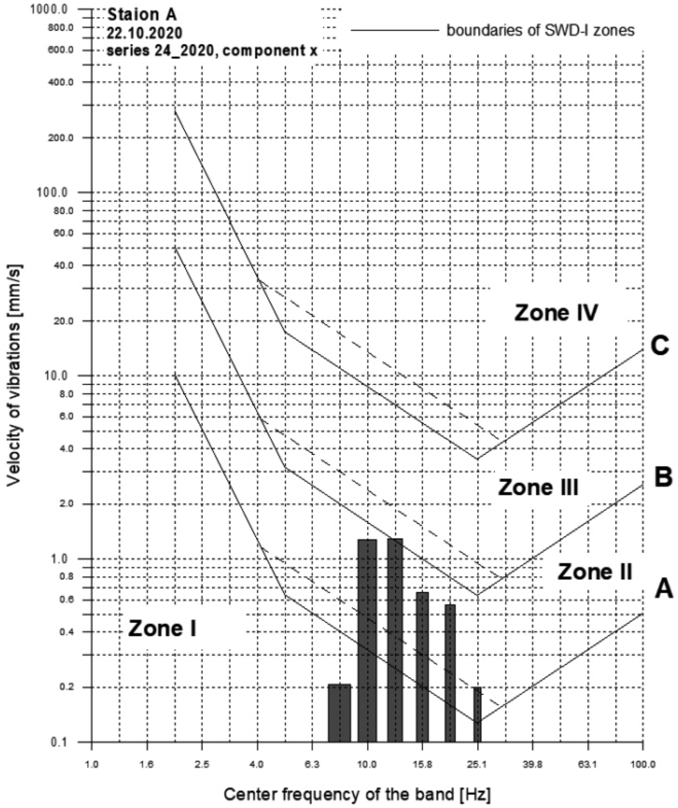


Figure 13. Vibration structure of the ground and foundation of the building shown in Figure 10

As can be seen from Figures 12 and 13, in the case of Series 20, the intense vibrations at 63.10 Hz were attenuated by 80%, and in the case of Series 24, up to 10% amplification was achieved in the low dominant frequency range. It should be noted that ground vibrations of similar intensity, but clearly different structures, induced six times higher vibrations in the building. This fact translates directly to the assessment of the vibration impact on the building, as shown in Figure 14.



(a)



(b)

Figure 14. Assessment of the impact of induced vibrations during the firing of series 20 (a) and series 24 (b)

4. Intrinsic frequency of the millisecond delay

The use of high-precision explosive firing systems in open-cast mines makes it possible, on the one hand, to fire an increasing number of explosive charges in one series and, on the other, to reduce the impact of induced vibrations on surrounding buildings. However, it is also important to be aware of the risks which can occur. The millisecond delay in the firing of EM charges means that pulses are transmitted to the surrounding rock environment, each of which is another source of vibration. The frequencies of the induced vibrations are characteristic of the local conditions of the rock being excavated as well as the excavation environment. This phenomenon is used in the signature hole (SH) method to design optimum millisecond delays for firing single-row and multi-row grids. Vibration measurements carried out during blasting operations carried out using both non-electrical and electronic systems showed, in many cases, the occurrence of frequencies in the structure of the induced vibrations related to the millisecond delay used. In the case of the non-electric system, popular delays of 25, 42 or 67 ms induced vibrations of 40.0, 23.8 and 14.9 Hz respectively. The use of a high-precision electronic system has exacerbated this problem, and it is therefore necessary to monitor during blasting, whether the millisecond delay applied will result in vibrations with an unfavourable vibration frequency from an impact assessment point of view.

During experimental work with an electronic system for blasting operations carried out in a marl mine, delays were designed using the SH method. In one series, 16x EM charges of 87 kg each were fired with a delay of 42 ms. The structure of the induced vibrations of the ground and building foundation, for the horizontal component, is shown in Figure 15. As can be seen in the figure, the vibration structure, both in the ground and on the building foundation, is dominated by a frequency of 25.12 Hz, i.e. a deceleration eigenfrequency of 42 ms.

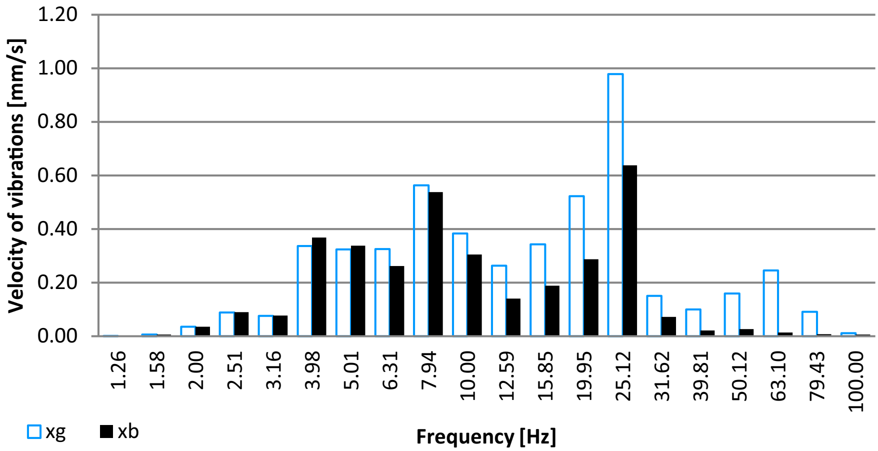


Figure 15. Structure of ground and building foundation vibrations induced during the firing of a series of EM charges with a delay of 42 ms (marl mine)

Analysis of the test results compares the vibration structure of the building foundations recorded during the firing of a series of charges and a single EM charge. The comparative analysis used the procedure for calculating the WODB index (vibration perceptibility index for buildings). This index is defined in PN-B-02170;2016-12 as the highest value of the ratio of the maximum vibration velocity values determined by seismogram analysis in the 1/3 octave bands (for the individual 1/3 octave bands) to the velocity value corresponding to the lower limit of consideration of dynamic effects on buildings covered by SWD scales in the same frequency band (line A in Figure 2). Results of the comparative analysis, WODB values, for a series fired with a millisecond delay of 42 ms and a single EM charge, are shown in Table 1 and Figure 16.

Table 1. WODB values for SH and series fired with 42 ms delay

Frequency [Hz]	WODB - line A, SWD-I scale	WODB SH	WODB 42 ms
5.01	1.00	0.43	0.53
6.31	1.00	0.82	0.52
7.94	1.00	1.33	1.34
10.00	1.00	1.35	0.96
12.59	1.00	1.05	0.56
15.85	1.00	1.06	0.94
19.95	1.00	0.88	1.80
25.12	1.00	1.32	5.03
31.62	1.00	0.63	0.45

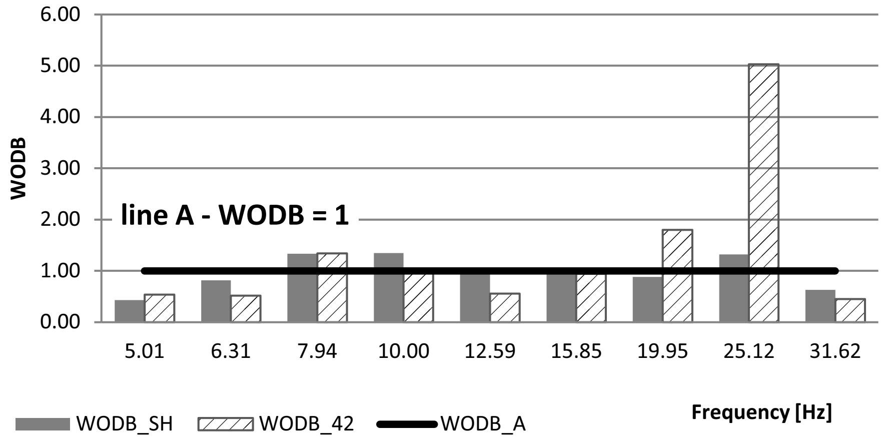
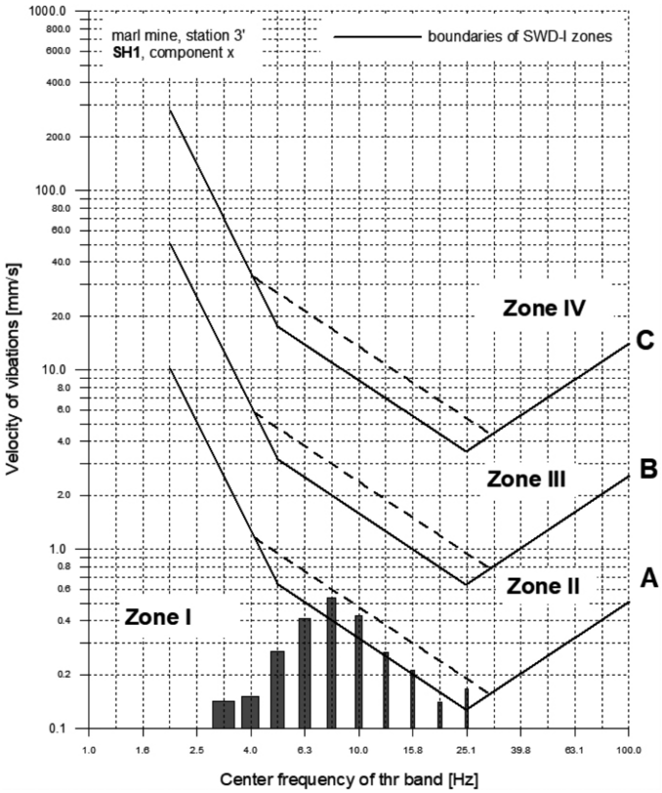
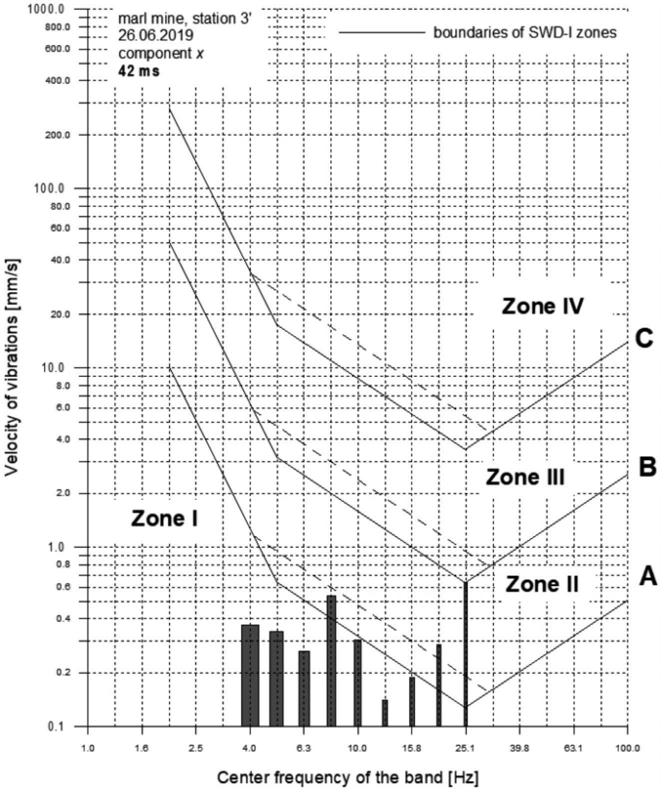


Figure 16. Comparison of WODB values for a series fired with a delay of 42 SH

As can be seen from Table 1 and Figure 16, the WODB value at 25.12 Hz increased by almost four times compared to SH. This means that firing a series of EM charges with a millisecond delay of 42 ms, under marl mine conditions, adversely affects the vibration effects on the building. How this translates to the impact assessment using the SWD-I scale is shown in Figure 17.



(a)



(b)

Figure 17. Comparison of the assessment of the impact on the building of vibrations induced with SH (a) and with a series fired with a delay of 42 ms (b)

5. Summary

- ♦ In most standards for assessing the impact of blasting-induced vibration, vibration frequency is an important parameter to be considered in the calculations and often it is not so much the peak value of the vibration velocity, but precisely the frequency associated with the velocity parameter which determines the qualification of the impact of vibration on a building.
- ♦ When analysing the scales for assessing the impact of vibrations on buildings used in different countries, it can be seen that only the Polish standard allows higher vibration velocities for lower frequencies. Based on the results of the study, it can be concluded that:
  - – an important part of the test procedure to minimise the impact of vibrations is to recognise the interaction of the building-ground system. It can be assumed that vibrations, when passing from the ground to the foundations of the building, undergo lower or higher attenuation. Also, the frequency of vibrations is modified and, in most cases, the higher frequencies do not pass to the foundations. In contrast, frequency modification and intensity attenuation in the lower frequency range is sometimes negligible.,
  - – the type of rock being worked and the medium in which the vibrations are propagated have a real impact on the frequency structure of the vibrations and the degree of attenuation. In the case of the marl mine, the ground vibrations were characterised by lower frequencies, from 4 to 25 Hz, and in the range of these frequencies the attenuation did not exceed 50%. In contrast, the ground in the

vicinity of the slate mine is characterised by higher frequencies (from 80 to 100 Hz), which are strongly attenuated in the transition to the foundations. In the dominant frequency range, attenuation exceeded 90%.,
- the applied millisecond delay significantly affects the structure of the vibrations induced during the firing of EM charges, and this means that by selecting the millisecond delay, the dominant frequencies of the vibrations propagated in the ground and thus the influence of the mechanism of vibration transmission to the foundations can be changed,
- the use of modern electronic initiation systems requires the recording of the seismic signal induced by the firing of single EM charges (SH method) at various locations in the excavation, in order to design optimum millisecond delays for the firing of single and multi-series nets,
- during blasting operations, it must be checked that the millisecond delay applied does not result in vibrations with an unfavourable vibration frequency from an impact assessment point of view.

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