Firing Explosive Charges with Millisecond Delay in Surface Mining – Historical Outline

Anna SOŁTYS[1)]

[1)] dr inż.; AGH University of Science and Technology, Faculty of Mining and Geoengineering, Cracow, Poland dr inż.; AGH University of Science and Technology, Faculty of Mining and Geoengineering, Cracow, Poland

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Abstract

Blasting works conducted in surface mines with large explosive charges are associated with the problem of unfavourable influence of vibrations, induced by detonating the charges, on structures in the vicinity of the mines. Applying explosives to mine deposits also influences effectiveness of blasting works, associated with fragmentation of rocks. Since the beginning of the 1950s, explosive charges are most often fired with millisecond delays. The article pre-sents the historical outline of research into millisecond firing with electric, non-electric and electronic systems, conducted in surface mines in Poland and around the world. As a result of the works, it was concluded that the interval and precision of set millisecond delays signifi-cantly influence intensity of vibrations induced by detonating explosive charges, and fragmen-tation of rocks. In electrical systems the actual firing times of detonators may significantly differ from their nominal times, hence there is a risk of overlapping delay times and, as a re-sult, a risk of increasing intensity of vibrations. Researchers indicate that maintaining specified time interval between detonations of consecutive explosive charges may successfully limit the seismic effect. It was the reason behind introducing "8 millisecond criterion" into the practice of blasting works in 1960s, as the minimal delay time between consecutively fired charges. With technical progress in initiation systems, precision of set delays significantly improved, as electronic initiation systems show it. The research conducted with the system clearly shows that the commonly assumed minimal 8 ms time does not have to be a binding rule any more. Precision of state-of-art electronic detonators successfully enables designing multiple row fir-ing patterns, with minimal delay time shorter than 8 ms between consecutively fired charges.

Keywords: blasting works, millisecond blasting technique, ground-borne vibration

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Introduction

Blasting works in surface mining are associated with detonating large explosive charges. Series consist of a few through several to even a few hundred charges placed in long blastholes. The works are often conducted in the vicinity of residential buildings and other structures, hence the issue of limiting the influence of vibrations induced by blasting works, is crucial for surface mines.

Conducting blasting works in multiple hole firing patterns lead to searching for solutions which, on one hand, may enable producing a large amount of rock of desired fragmentation and, on the other hand, limit the influence of blasting on the surrounding. Hence, in vast ma-jority of cases, in surface mining, explosive charges are detonated with millisecond delays, with electric, non-electric or electronic systems.

Effective use of the firing method requires selecting optimal delays for given geological and mining conditions. It is a very difficult process which requires applying specialised soft-ware, often a large number of in situ measurements which provide relevant base information and verify the assumed simulation models.

Experiences from firing charges of explosives, with a millisecond delay

Basing on the Bureau of Mines' reports, in late 1940s and early 1950s, millisecond delay firing was adopted as a method which both enables limiting intensity of tremors induced by blasting works and has a significant influence on improving fragmentation of rocks. The main characteristic variables associated with millisecond delay firing in given geological and mining conditions were: delay interval, number of applied delay intervals and the number of explosive charges per delay number. However, despite the fact the research showed that while applying the same total weight of explosives, vibrations induced by millisecond delay blasting are less intensive than the ones generated by instantaneous firing, the influence of the aforementioned variables on the intensity of vibrations induced by millisecond delay firing was not fully un-derstood (Nicholson, Johnson, Duvall, 1971).

One of the first research works concerning millisecond firing of explosive charges in sur-face mines, was conducted in 1960s by the Bureau of Mines (Duvall, Johnson, Mayer, Devine, 1963; Kopp, Siskind, 1986). The aim of the experiments, considering specified assumptions, was to compare intensity of vibrations induced by firing explosive charges instantaneously and with time delay. Blasting works were conducted in a limestone mine.

The first stage of the research program covered the following issues:

– determining propagation of vibrations induced by both instantaneous and millisecond delay blasting,

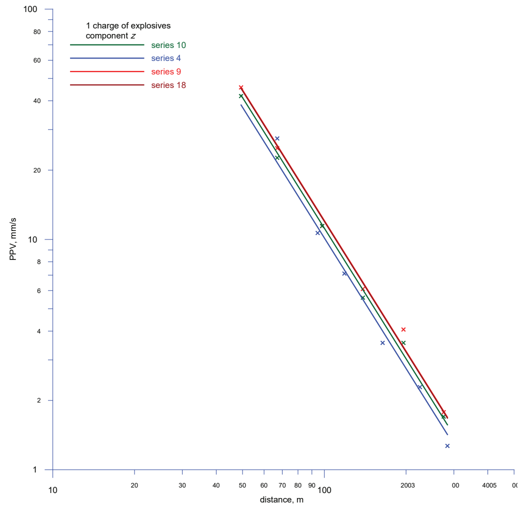

Fig. 1. Seismic effect of firing single explosive charge (based upon RI 6151)
Rys. 1. Efekt sejsmiczny odpalania pojedyn-czego ładunku MW (opra-cowano na podsta-wie Raportu RI 6151)

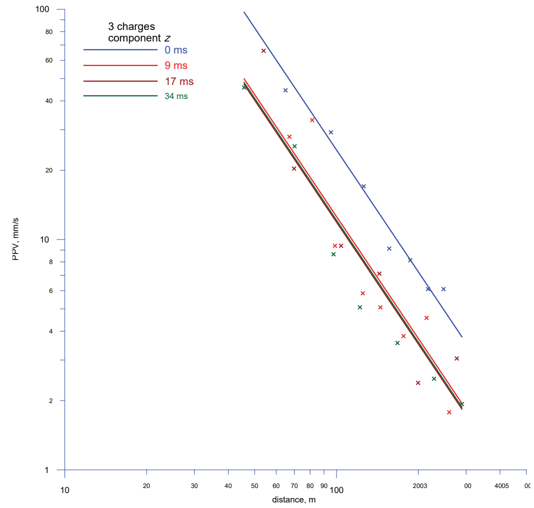

Fig. 2. Seismic effect of firing 3 explosive charges instantaneously and with 9 ms, 17 ms and 34 ms delay (based upon RI 6151)
Rys. 2. Efekt sejsmiczny odpalania 3 ładunków MW natychmiastowo i z opóźnieniem 9 ms, 17 ms i 34 ms (opracowano na podstawie Raportu RI 6151)

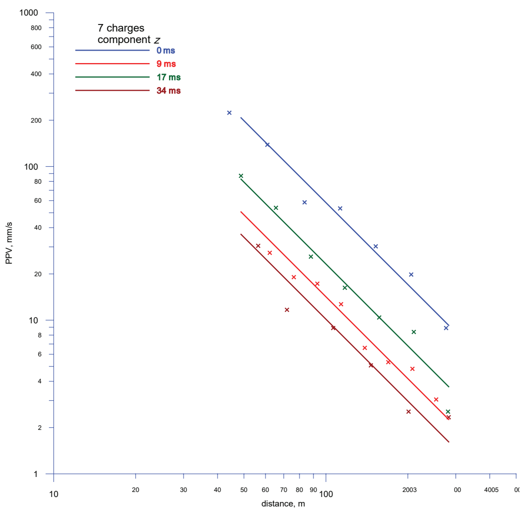

Fig. 3. Seismic effect of firing 7 explosive charges instantaneously and with 9 ms, 17 ms and 34 ms delay (based upon RI 6151)
Rys. 3. Efekt sejsmiczny odpalania 7 ładun-ków MW natychmiastowo i z opóźnieniem 9 ms, 17 ms i 34 ms (opracowano na podstawie Raportu RI 6151)

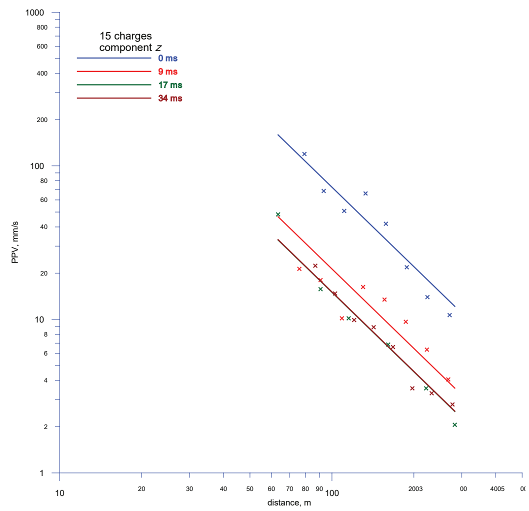

Fig. 4. Seismic effect of firing 15 explosive charges instantaneously and with 9 ms, 17 ms and 34 ms delay (based upon RI 6151)
Rys. 4. Efekt sejsmiczny odpalania 15 ładun-ków MW natychmiast-owo i z opóźnieniem 9 ms, 17 ms i 34 ms (opracowano na podstawie Raportu RI 6151)

– determining if intensity of vibrations at different distances is influenced by the length and number of delay intervals in millisecond delay blasting,

– comparing intensity of vibrations induced by instantaneous and millisecond delay firing.

Within the framework of the experiment there were conducted 12 test blastings, applying a single row firing pattern. There were 3, 7 and 15 explosive charges detonated – including 3 detonated instantaneously and 9 detonated with millisecond delay.

The vibrations were measured at the distance of between 45 m and 900 m. The firing order and orientation of the series along the sidewall were selected at random, to avoid the influence of location of fired series on results of measurements in the context of assumed variable blasting parameters. A detonation cord was used to initiate charges in blastholes. It linked explosive charges in the blastholes into instantaneously fired series. The delay for millisecond delay firing, was achieved by using 9 ms, 17 ms and 34 ms delay connectors (two 17-millisecond connectors), which were linked into series with a detonation cord between adjacent blastholes of a given series. Only one explosive charge per delay number was detonated.

It was also planned to detonate 5 single explosive charges and multiple row 2 millisecond firing delay. During multiple row firing, maximum 4 charges per de-

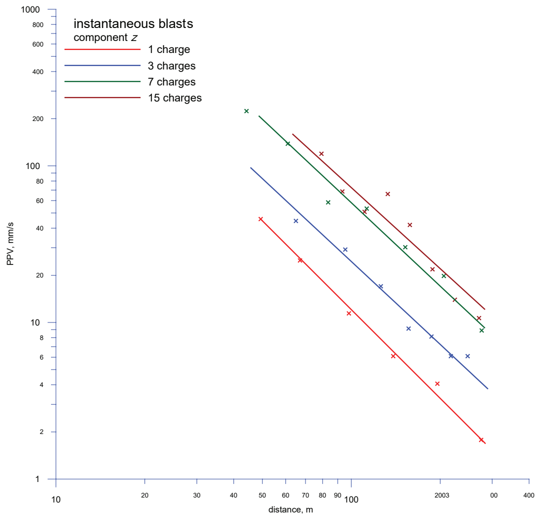

Fig. 5. Seismic effect of instantaneous blasts for different number of explosive charges (based upon RI 6151)
Rys. 5. Efekt sejsmiczny dla odpalania na-tychmiastowego przy różnej liczbie ładunków MW (opracowano na podstawie Raportu RI 6151)

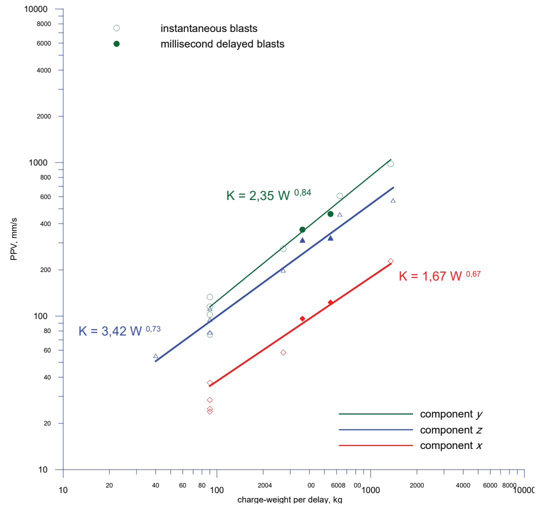

Fig. 6. Dependence of vibration velocity on explosive charge weight (based upon RI 6151)
Rys. 6. Zależność prędkości drgań od masy ładunku MW (opracowano na podstawie Ra-portu RI 6151)

lay number were fired in the first series and 6 charges per delay number in the second one. While firing, vibrations were measured with seismographs at different distances from the location where blasting works were conducted.

As a result, it was concluded that with an increase in the distance, the intensity of vibra-tions decreases. Fig-ures 1, 2, 3 and 4, in graphic form, present the dependence of intensity of vibrations on the distance (vertical compo-nent z), for the conducted test blastings. The figures were based upon data from Report of Investigations (RI) 6151.

Comparison of intensity for instantaneous firing, but with a different number of explosive charges (1, 3, 7 and 15 explosive charges), indicates a significant in-fluence of total charge weight (Fig. 5). Thus, for series fired instantaneously in more than one blasthole and for milli-second delay series, where respectively 4 and 6 blastholes were fired per one delay, it was attempted to determine the influence of explosive charge weight on the intensity of vibrations (Fig. 6).

As a result of the conducted research it was con-cluded that:

– intensity of vibrations induced by millisecond delay blasts is, in general, lower than the intensity of vibrations induced by instantaneous firing of the same number of blastholes (Fig. 2, 3 and 4),

– an analysis of results for instantaneous firing indicates a dependence of intensity of vibrations on the number of charges in a series, i.e. the total weight of explosives (Fig. 5),

– for millisecond delay blasts, and one charge per delay number, there was no significant influence of the number of delay intervals and delay time on the intensity of vibrations, which indicates that explosive charge weight per delay or the number of charges fired per delay may matter,

– intensity of vibrations induced by millisecond delay firing, and one blasthole per delay number is, on average, by 42% higher than when a single explosive charge is fired,

– intensity of vibrations for millisecond delay firing, and more than one charge per delay number, is roughly the same as for instantaneous blasts, in which the total weight of the charge equals the weight of a charge per delay in millisecond delay firing (Fig. 6).

Report of Investigations 6151 proposed an equation (1) to determine propagation of vibrations v depending on weight of charge W and distance D from the blast to the measuring point, which, is still commonly applied in research works and reports for the industry.

$$v = K \cdot W^{b} \cdot D^{-n} \qquad (1)$$

where:
v – velocity of vibrations, mm/s
D – distance from blast to measuring point, m
K, b, n – empirically determined coefficients character-ising geological and mining conditions

The second very important element of RI 6151 was determining an 8 ms criterion, which became a well-known and commonly-applied rule defining "separation" between explosive charges. Separation means here, that the seismic effect induced by detonations of consecutive explosive charges, with at least 8 ms delay interval, is not enhanced. Nevertheless, as Reisz and Siskind stated, the origin of the criterion is not fully understood (Reisz, MacClure, Bartley, 2006; Siskind, 2005).

The research works searched for a dependence be-tween a delay interval, burden, distance between blastholes and rock fragmentation (Kopp, Siskind, 1986). The research also showed that designing blasting works to improve rock fragmentation, has positive influence on reduc-ing intensity of vibrations and air blast pressure (AB).

Bergman (Bergmann, Wu, Edl, 1974), investigating the influence of parameters of millisecond delay firing on the rock fragmentation, conducted test blastings in a granite mine, applying square and rectangular firing patterns. As a result of the tests, he concluded that rectangular firing patterns, where the distance between blastholes equals two-fold burden, have a good influence on rock fragmentation. Additionally, he stated that to improve rock fragmentation, the delay between adjacent blastholes ought to be 3.3 ms/m of burden.

Andrews (1975) basing on research conducted in a limestone mine prepared guidelines to reduce AB pressure. He concluded that, firstly, AB pressure is influenced by the average velocity of a blast propagating along the surface and, secondly, applying delay interval higher than 3.3 ms/m of burden, between blastholes gives positive effects in reducing AB pressure.

In his further research Andrews (1981), updated his previous findings and the ones pro-posed by Bergmann. He concluded that worse rock fragmentation occurs when the delay in-terval between blastholes in a row is greater than 16.6 ms/m of burden. It is caused by displac-ing of burden, before a stress wave of the next charge enhances further rock fragmentation. The best results are obtained when the delay interval between blastholes in a row falls in the range of 3.3÷16.6 ms/m of burden. The delay between rows ought to be two- to three-fold delay between blastholes in a row. It gives sufficiently long time to displace the burden to-wards the sidewall, enabling easier movement of burden between consecutive rows.

Winzer (Winzer, 1978; Winzer, Anderson, Ritter, 1981; Winzer, Furth, Ritter, 1979) of Martin-Marietta Laboratories investigated the influence of parameters of blasting works on rock fragmentation. He based his research mainly on analyses of blastings filmed with high speed cameras. On the basis of obtained results, he concluded that the times of firing series of millisecond detonators significantly differ from the ones provided by manufacturers, as a re-sult, some of blastholes "fall out" of the firing sequence. Analyses of actual firing times of 55 blastholes, enabled calculating burden and time intervals of given detonations for various fir-ing patterns. Taking it into consideration, Winzer, to minimise ejection of stemming and scat-tering rock debris, recommended applying delay of 11.3 ms/m of burden for the burden be-tween blastholes in a row and 25.6 ms/m of burden between rows. Investigating influence of blastings conducted with multiple row firing patterns with millisecond delay on rock fragmen-tation, he observed that arranging times of detonating explosive charges in a V-shape gives a positive effect and coined a term of apparent burden. The term is associated with movement of rocks between the planes of cut and it means that apparent burden is the distance between planes of simultaneous cut of burden from solid rock, resulting from simultaneous detonation of explosive charges. The plane of cutting the burden is referred to as "echelon".

Basing on the assumptions, Winzer (Winzer et al., 1981) conducted test blastings in a few surface mines. The applied delays fell within the range of 12.6 ms ÷ 14 ms/m of burden between blastholes in one row and 32.8 ms/m of burden between planes of cut (echelons). It was possible through using sequential multi-circuit millisecond delays. Results of the conducted blastings showed that the obtained rock fragmentation was better than for blastings with shorter delay times. Moreover, he concluded that for blastings with more than five planes of cut, it is necessary to lengthen delays between given planes, increasingly in deeper (further) sections of a detonated firing pattern, to obtain sufficiently loosened rock.

Winzer (Winzer et al., 1979; Anderson, 1993) also conducted research concerning the dependence btween firing times of detonators and effectiveness of blasting. The works concerned millisecond detonators, which, according to the author, as it has been already mentioned, enabled controlling rock fragmentation and a proper muck pile shape, as well as, more and more often, controlling intensity of vibrations and the AB. He also stated that many re-searchers tried to select the sequence of millisecond delays to get the optimal rock fragmentation, yet, in most cases those were empirical attempts, and the proposed solutions concerned only local conditions of given mines.

In those years, designing initiation of blasting works was associated with its influence on so-called active burden or formation of a new, internal free faces It was mainly based on the assumption that millisecond delays in detonators which were available then, were relatively close to their nominal firing times. What is important, which Winzer paid attention to, in reality, most of the dependences for the optimal millisecond delay, proposed by researchers, were based on nominal firing times of detonators.

In his research and publications, he showed, as it has been already mentioned, that there are differences, sometimes significant ones, between nominal and actual firing times of detonators and they do influence the effect of blasting.

Awareness of the fact how significant is firing explosive charges with time delay for rock fragmentation, muck pile shape, flyrock production, backbreak, as well as the level of vibrations and AB, led to a re-

Fig. 7. Sequential blasting machine REO BM 125-10b (https://www.worthpoint.com/worthopedia/sequential-blasting-machine-bm125-10b)
Rys. 7 Zapalarka sekwencyjna REO BM 125-10b (https://www.worthpoint.com/worthopedia/sequential-blasting-machine-bm125-10b)

search program concerning use of delay times in blasting works.

The research works were conducted in situ in surface mines. They applied high speed cameras to record firing series of explosive charges. Then the recorded films were analyzed frame by frame. Proper arrangement of the cameras, their frame rate and synchronization in all the cameras the moment when recording a detonated series starts, played a really significant role.

During initiation of explosive charges, there were tested all the delay numbers in the range of 0–19 for detonators fired in series with an electric system, and all the delay numbers in the range of 1–14, for series fired with a non-electric system. To obtain a reliable database, electric detonators of three manufacturers, who back then supplied the south-eastern region of the USA's market with such products (Atlas, DuPont, Hercules), and Ensign/Bickford Primadet's non-electric system, were applied.

Electric detonators were connected in one or two rows and initiated with sequential blasting machine REO BM 125. The look of the blasting machine is presented in Figure 7.

Sequential blasting machine REO BM 125, was a 10-circuit unit with 12 selectable preset inter-circuit delays (10, 17, 25, 30, 50, 60, 75, 100, 125, 150, 175 and 200 millisecond).

Series initiated with a non-electric system were connected differently, in a way which was most applicable in a mine working. Three 10-feet-long bundles of detonation cord (approx. 3 m) were used to initiate non-electric detonators. All the three lines were initiated instantaneously with a common detonation cord to obtain zero delay time.

The conducted tests show that after applying electric detonators provided by different manufacturers, in all the analysed detonators there were deviations in the average firing time from their nominal times for a given delay number. Additionally, as a delay increased, there was observed a dramatic increase in 10 standard deviations. It may increase a risk of overlap-ping delays between adjacent detonators and lead to spontaneous "crowding" of delays or to a sequential error, where detonators of lower and higher delay number will be fired in the opposite order.

The obtained results lead to a conclusion that the firing times of detonators can be treated as a random (stochastic) variable, hence the occurrence of a sequential error or the problem of crowding delays ought to be considered in the context of probability not certainty that such a phenomenon will occur. To determine probability of success i.e. that there will not be an error in the sequence of firing detonators, the criteria of success ought to be clearly specified. E.g. a statement, that all the detonators of the first delay have to detonate before the detonators of the second delay, and they, in turn, have to detonate prior to the detonators of the third delay etc. could be such a criterion.

To calculate probability of success, two approaches can be applied:

– computer simulation for all the detonators, randomly selecting the times of firing them (Monte Carlo method). Then, for each determined set of firing times, applying a proper criterion, check if success was achieved,

– analytical determination of probability of success. In spite of the fact that result formulas can be hard to assess, it is possible to try to do it with numerical methods.

Winzer, in his research followed the second approach, believing it to be better. Basing on sta-tistical considerations, he proposed a dependence, so-called Winzer index, whose value below 3 indicates significant probability of overlapping adjacent delay number of detonators (Winzer et al., 1979; Bajpayee, Mainiero, Hay, 1985; Pal Roy, 2005).

Winzer index (S) is expressed with the following equation (2):

$$S = \frac{T_{(n+1)} - T_n - \tau}{\left[\sigma_{(n)}{}^2 + \sigma_{(n+1)}{}^2\right]^{1/2}} \gtrsim 3 \qquad (2)$$

where:
$T_{(n+1)}$ – average delay time for number (n+1) of detonators, s
T_n – average delay time for number n of detonators, s
τ – required time interval between detonations in adjacent blastholes, s
$\sigma_{(n+1)}$ –standard deviation for number (n+1) of detonators, s
σ_n – standard deviation for number n of detonators, s

Within the framework of the conducted research project, Winzer attempted to verify the dependence in the in situ conditions in a surface granite mine. The calculated probability of success fluctuated between 5% and 70% for no sequential error, and between 0.2% and 19% for detonations in adjacent blastholes separated by at least 8 ms. The conclusions confirm the 8 ms criterion presented in RI 6151.

Persson et al. (Persson, Holmberg, Lee, 1994) also referred to the low precision of delay of electric detonators, concluding that scattering in firing times is inevitable for detonators of the same nominal firing time. It may be caused by a slight difference in the length of the delaying element, content of components they are made of or a change in the burning rate resulting from "aging" (expiring), when it was stored.

Loss of precise delay negatively influences rock fragmentation, scattering rock debris and causes an increase in the intensity of ground vibrations. Overlapping delays may lead to a situation when blastholes are fired with excessive burden, if explosive charge in the front blasthole does not detonate properly. Figure 8 presents schematically distribution of firing times for detonators with precise and imprecise delays.

Authors (Persson et al., 1994) referred to the results of Winzer's research, who showed probability of potential overlapping of delay times, especially for higher delay numbers of detonators. Yet they observe that over the years precision of delay detonators significantly improved and scattering in firing times is much smaller. They also indicate that scattering in firing times, in a sense, may be beneficial, by giving an opportunity to apply a greater total weight of an explosive charge (as a greater number of charges) per nominal time interval, as probability that all the charges of the same delay will be detonated at the same time is very low.

In 1973, NITRO Nobel company launched the first non-electric detonator called NONEL (Biessikirski, Sieradzki, Winzer, 2001; Olofsson, 1990). An important novelty in the system was developing in-hole pyrotechnic detonators of fixed time delays (e.g. 450 ms, 475 ms and 500 ms), which on the surface are linked with so-called connectors), built of non-electric detonators, built in plastic tubes. The connectors transmit the signal to the in-hole detonators and have a different range of delay (e.g. 17 ms, 25 ms, 42 ms). The idea of a non-electric system is that the delay of firing times for given explosive charges are controlled from the surface, through selection of proper connectors and their arrangement. It is particularly important in multiple row firing patterns, as it is possible to avoid overlapping delays and instantaneous detonation of explosive charge weight greater than it is acceptable. The applied delay times are much more precise than in electric detonators. As standard maximal 1% deviation of milli-second delay in reference to the nominal time is assumed (Prędki, 2011). Nevertheless, in the in situ conditions, even such a slight deviation of

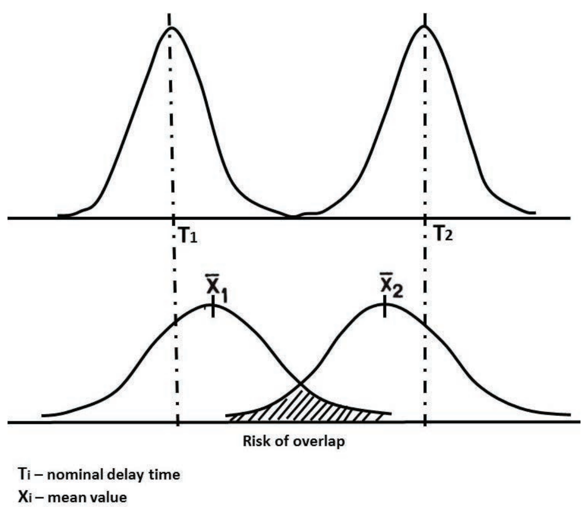

Fig. 8. Distribution of firing times for precise and imprecise detonators (Persson et al., 1994)
Rys. 8. Rozkład czasów odpalania w przypadku dobrej i złej precyzji zapalników (Persson et al., 1994)

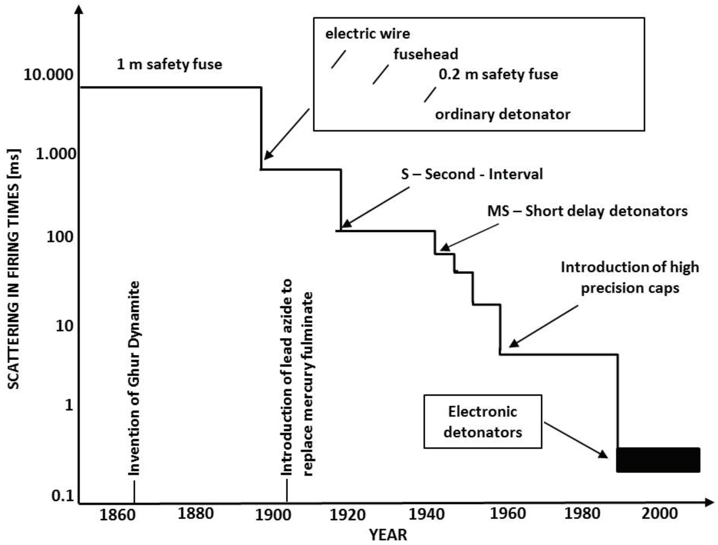

Fig. 9. Development of initiation systems, precision of setting delays over the last 100 years (Persson et al., 1994; Landman, 2010)
Rys. 9. Rozwój systemów inicjowania pod kątem precyzji zadawania opóźnień, w ciągu ostatnich 100 lat (Persson et al., 1994; Landman, 2010)

delay times also may influence actual delay sequence.

Constant progress in production of detonators brought introduction of an electronic initia-tion system, whose very precise delays, set with 1 ms intervals, and deviation of ± 0.01%, enables designing very complex multiple row firing patterns. It has a significant influence on much better effects of blasting, especially considering the control over the intensity of in-duced vibrations, scattering rock debris, as well as rock fragmentation (Prędki, 2011; Persson et al., 1994).

Figure 9 presents development of initiation systems through lowering scattering of firing times, from 10 seconds to approximately 1 millisecond.

As it can be seen in all pyrotechnic initiation systems firing times are scattered. Improve-ment in the precision of set delay was gradual, as the length of the delaying element, its com-position, density, burning rate of the pyrotechnic mixture changed, until digital technology was introduced in form of an electronic system, where microchips were used in detonators (Landman, 2010).

Yet it ought to be remembered that the selection of millisecond delays, especially in an electronic system has to be a process which is tightly controlled and which considers a number of factors influencing the effect blasting works have on the surrounding area. Designing an optimal millisecond delay enables influencing the seismic effect through controlling frequency structure of vibrations. An advantage of millisecond firing is also the fact that it creates addi-tional free faces, to quarry the rock mass better; and as it has been already mentioned, high precision of set delays has a beneficial influence on possibility to produce a large amount of well-fragmented rocks (Sołtys, 2017a). Figure 10 presents how firing time of explosive charg-es influences the formation of free faces and rock fragmentation.

In instantaneous firing (Fig. 10b), detonation in the first blasthole is not able to facilitate the work, through forming an additional free faces, for an explosive charge in the next blasthole, which may result in formation of oversized rock fragments. Hence, the more free faces there are, the more effectively an explosive charge work in each consecutive blasthole i.e. the rock is better fragmented. That is why it is important to apply a proper millisecond de-lay.

A huge advantage of an electronic initiation system, unlike in a non-electric system, is the certainty that the programmed detonators will be fired in a given moment. Moreover, a person conducting blasting works has full control over proper functioning of all the elements of the system, and each anomaly can be instantly eliminated. In non-electric detonators, pyrotechnic ones, firing times differ greatly within the nominal values, and to some extent also within mean values (as it has been already explained). Landman (2010), compared the distribution of firing times in both electronic and non-electric detonators, to observe the risk of overlapping delays, assuming nominal delay of 17 ms (Fig. 11).

The essential problem in proper use of modern initiation systems is the selection of millisec-ond delays. In Poland, the research into the influence of millisecond delays on the intensity and structure of vibrations, in changeable characteristics of the ground in the surrounding of a mine working, was conducted in late 1980s and early 1990s, at the Central Mining Institute's Barbara Experimental Mine and at the AGH's Laboratory of Blasting Techniques (Sołtys, 2017b).

Basing on available electric detonators of 25 ms delay, it was demonstrated that the delay cannot be assumed as the main one and recommended for use in

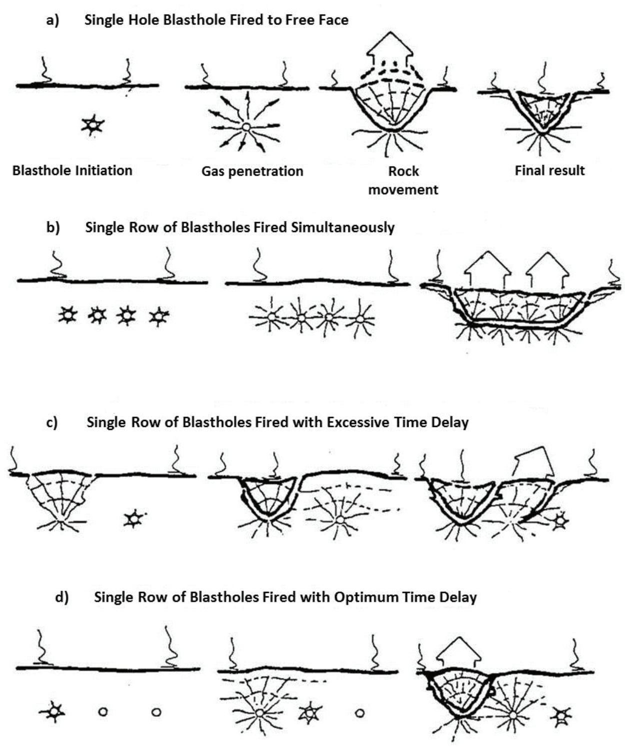

Fig. 10. Influence of firing time of explosive charges on formation of additional free faces and rock fragmentation (Ireland, 2000; Landman, 2010)
Rys. 10. Wpływ czasu odpalania ładunków MW na tworzenie dodatkowych powierzchni odsłonięcia i fragmentację urobku (Ireland, 2000; Landman, 2010)

mining all rock minerals, due to possibility of overlapping detonation times of explosive charges, which does not help opti-mise the effects of blastings. In many countries it was attempted to avoid the inconveniences through using electronic detonators or multi-circuit blasting machines (Winzer et al., 1979; Dworok, 1993; Winzer, Biessikirski, Sieradzki, 1997).

Research into millisecond delay conducted in Poland

Before non-electric and electronic detonators appeared on Polish market, the AGH's La-boratory of Blasting Techniques had taken actions to design a millisecond-delay blasting ma-chine, with which it would be possible to fire blastholes with precisely determined delay of 0 ÷ 150 ms. The developed blasting machine ZT 480t, which was approved by the President of the State Mining Authority for test blastings in appointed mining enterprises (Biessikirski, 1991). Applying the blasting machine was a valuable experience both for the AGH's research team and for the blasting personnel in mines. Tests conducted with the blasting machine for comparative analyses, to identify changeability of signal characteristics, used a seismic signal induced by detonation of a single explosive charge. It is a method used in geophysical re-search, to identify the structure of geological layers. It was decided to follow such an ap-proach for the vibrations induced by firing a series of explosive charges, and the seismic effect of a single explosive charge was assumed as the base information on possible changeability of the ground in the surrounding of a mine working (Winzer, Biessikirski, 1996; Sołtys, 2017b).

Simultaneously, in Barbara Experimental Mine a blasting machine Barbara-30 with elec-tronically adjusted delays between firings. The basis for developing the blasting machine was an analysis of blasting works conducted in 65 surface mines, with an electric initiation system. The system of three blasting machines enabled firing 120 blastholes (40 blastholes per one machine). In the blastholes there could be two parallel instantaneous electric detonators of class 0.2. In each blasting machine, for each of 10 outputs, 4 blastholes in series can be con-nected. Delays were set within the range of 8 ÷ 108 ms (Dworok, 1993).

The first in situ research, applying blasting machine Barbara-30, were conducted in two mines producing porphyry and chalk marlstone, basing on 17 series of explosive charges, both continuous and separated, detonated in long blastholes. In the porphyry mine, 15 ms delay was applied and much lower intensity of vibrations was recorded in monitored buildings, than with 25 ms delay detonators. In turn, in the chalk marlstone mine, with blasting machine Barbara-30, 30 ms and 35 ms delay was applied. Comparison of the seismic effect created as a result of the blastings with the level of vibrations recorded after applying 25 ms delay detonators, did not show any significant decrease in the intensity of vibrations. However, effectiveness of blasting with 30 ms and 35 ms delay, improved the muck pile shape and its fragmentation (Dworok, 1993).

The observations and the experience gathered

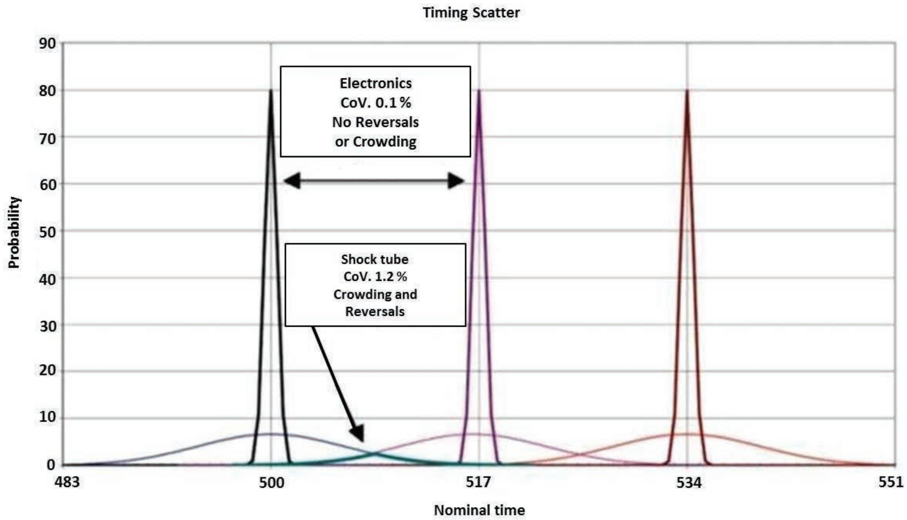

Fig. 11. Distribution of actual firing time of pyrotechnic detonators, illustrating risk of over-lapping times compared with electronic detonators, where there is no such risk (Landman, 2010)
Rys. 11 .Rozkład rzeczywistego czasu odpalania zapalników pirotechnicznych, ilustrujący ryzyko nakładania się czasów w porównaniu do zapalników elektronicznych, gdzie nie ma ry-zyka nakładania się czasów odpalania (Landman, 2010)

Fig. 12. Mining millisecond blasting machine Explo 201 (Biessikirski, 1996)
Rys. 12. Górnicza Zapalarka Milisekundowa Explo 201 (Biessikirski, 1996)

during the research, contributed to developing and in-troducing into service millisecond blasting machine Explo 201 (Fig. 12) (Biessikirski, 1996). In 1995, the exploder, by the decision of the President of the State Mining Authority, was approved for use in surface min-ing. It enabled popularisation of delay time other than 25 ms and start larger scale research works.

Blasting machine Explo-201 (Biessikirski, 1996) was a 20-circuit capacitor blasting machine with ad-justable current to charge batteries of blasting capaci-tors. It is dedicated for firing in-stantaneous and milli-second delay detonators of safe electric current of 0.2 A and 0.45 A. The delays were selected from the range of 0 ÷ 99 ms, and a time step of 1 ms. The exploder was relatively easy to use, but there were difficulties to make blasting circuits for large firing pat-terns. Blast works conducted with different millisecond delay times in gypsum and limestone mine clearly showed that op-timal millisecond delay times have a huge potential both to control rock fragmentation and limit the impact on the environment.

Sample results of tests carried out with the blasting machine Explo 201

Approving blasting machine Explo 201 for use in surface mining, in 1996, enabled con-ducting test blastings with various millisecond delays in a lime-stone mine. The commercial scale blasting was con-ducted.

Within the framework of the in situ research, 9 se-ries of explosive charges were fired in long blastholes, maintaining possibly stable test conditions, which can be obtained in industrial conditions, for both blasting works and measurements:

– explosive charges in a blasthole were initiat-ed with instantaneous electric detonators with blasting machine Explo 201,
– during the tests the following delay times were applied: 5 ms, 15 ms, 20 ms, 25 ms, 30 ms, 40 ms, 50 ms and 60 ms.

Measurements of intensity of vibrations were con-ducted in constant points in the profile in changeable ground conditions, which enabled also checking the influence of a millisecond delay on the structure of re-

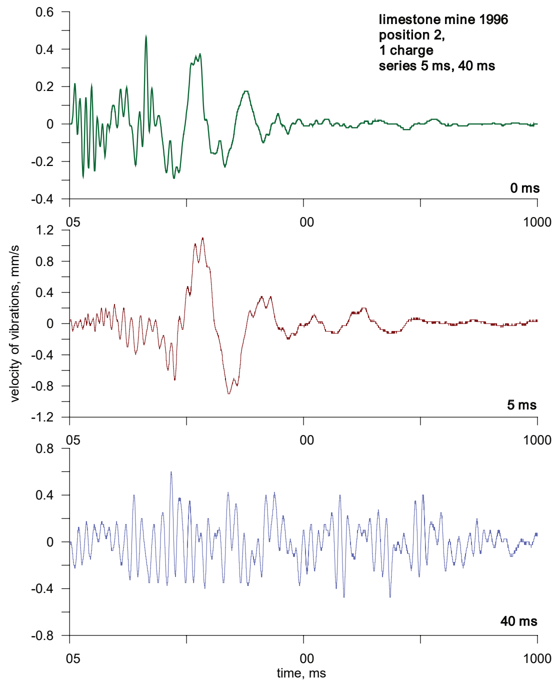

Fig. 13. Seismograms of vibrations – position 2; 0 ms, 5 ms and 40 ms delay
Rys. 13. sejsmogramy drgań – stanowisko 2 – opóźnienia 0 ms, 5 ms i 40 ms

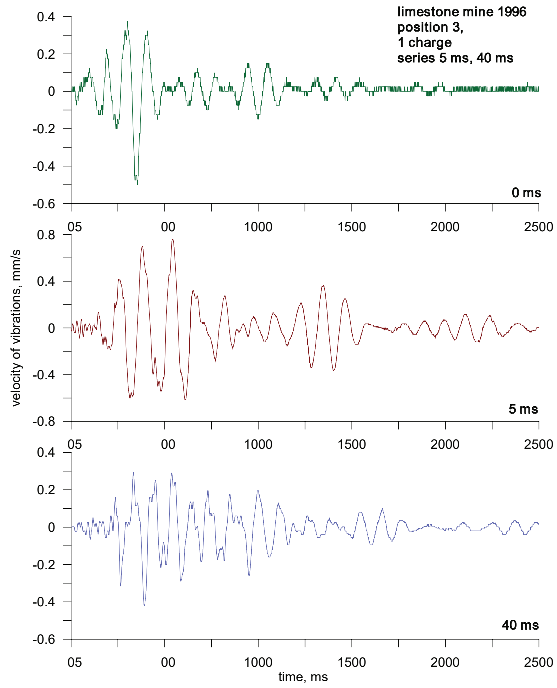

Fig. 14. Seismograms of vibrations – position 3; 0 ms, 5 ms and 40 ms delay
Rys. 14. sejsmogramy drgań – stanowisko 3 – opóźnienia 0 ms, 5 ms i 40 ms

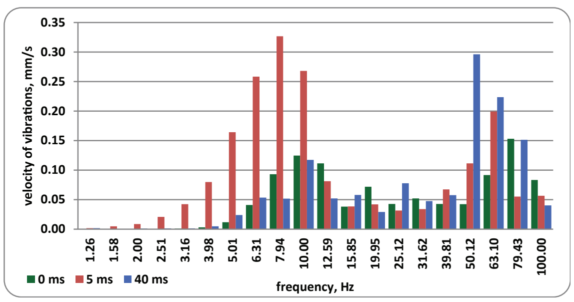

Fig. 15. Frequency structure of vibrations – position 2; 0 ms, 5 ms and 40 ms delay
Rys. 15. Struktura częstotliwościowa drgań – stanowisko 2 – opóźnienia 0 ms, 5 ms i 40 ms

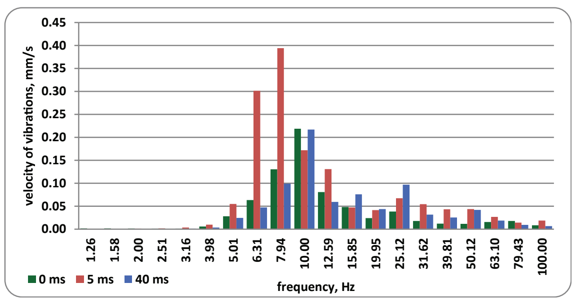

Fig. 16. Frequency structure of vibrations – position 3; 0 ms, 5 ms and 40 ms delay
Rys. 16. Struktura częstotliwościowa drgań – stanowisko 3 – opóźnienia 0 ms, 5 ms i 40 ms

corded vibrations. Figures 13, 14, 15 and 16 present seismograms and the structure of vibrations recorded in two measuring position during millisecond delay firing series of 15 explosive charges with 5 ms and 40 ms delay and their comparison with vibrations induced by a single explosive charge.

Figures 13 to 16 show that:

– the structure of vibrations induced by a single explosive charge enables determination of changeability of ground characteristics – in position 2 dominate the frequency val-ues of 10 Hz and 79.43 Hz, and in position 3 only frequency of 10 Hz,

– 5 ms delay in both positions moved the structure of vibrations towards lower frequency of 7.94 Hz,

– 40 ms delay in position 2 induced vibrations of higher dominant frequency of 50.12 Hz and 63.10 Hz, and in position 3 the structure vibrations is very similar to the vibrations induced by firing a single explosive charge.

The observations enable concluding that by selecting a millisecond delay, it is possible to control the structure of vibrations induced in the ground, and the seismic effect of blasting depends on both peak velocity of vibrations and their frequency.

The conducted test blastings confirmed rationality of firing single explosive charges to obtain basic data on the range of changeability of the ground in the surrounding of a mine.

Conclusions

Firing explosive charges with a millisecond delay became a basic method of quarrying large rock masses in surface mining. The research initiated in 1950s into possibility of distributing energy of explosives over time, enabled recognising possibilities of using interaction of consecutively detonated explosive charges to get the most favourable fragmentation of rocks while minimising the influence of blasting works on the buildings in the surrounding area. Report of Investigations 6151 indicates the first technical conditions (8 ms criterion) of conducting millisecond delay blasting, and the conclusions drawn there, in many aspects are either still valid, or lead to further research. Yet it has to be remembered what actually the technical capabilities to conduct in situ research (millisecond firing of explosive charges, recording and analysing seismic effects) were in those years.

Conclusions of RI 6151 and research conducted over the span of years by many authors, involved in developing a technique to conduct blasting works, became the stimulus to search for advanced technologies applied in millisecond delay systems for firing explosive charges, as it is proved by introducing better and better solutions in electric systems, a non-electric system in 1970s, and an electronic system in 1990s.

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Literatura – References

1. Anderson, D.A. (1993): Blast Monitoring: Regulations, Methods and Control Techniques. Ed.-in-Chief John A. Hudson, Comprehensive Rock Engineering: principles, practice & pro-jects. Vol. 4, Excavation, support and monitoring (p. 95–110). Oxford: Pergamon Press Ltd.
2. Andrews, A.B. (1975): Airblast and Ground Vibration in Open Pit Mining. Mining Congress Journal, 61(5), p. 20–25.
3. Andrews, A.B. (1981): Design Criteria for Sequential Blasting. Paper in Proceedings of the Seventh Conference on Explosives and Blasting Technique (Phoenix, AZ, Jan. 12–23, 1981). Society of Explosives Engineers, p. 173–192.
4. Bajpayee, T.S., Mainiero, R.J., & Hay, J.E. (1985): Overlap Probability for Short-Period-Delay Detonators Used in Underground Coal Mining. United States Bureau of Mines RI 8888.
5. Bergmann, O.R, Wu, F.C., & Edl, J.W. (1974): Model Rock Blasting Measures Effect of Delays and Hole Patterns on Rock Fragmentation. Engineering and Mining Journal, 175(6), p. 124–127.
6. Biessikirski, R. (1991): Wybrane informacje na temat konstrukcji i testowania zapalarki milisekundowej [Selected information about the construction and testing of the millisecond blasting machine]. Konferencja: Problemy techniki strzelniczej w górnictwie – perspektywy rozwoju (p. 61–64). Kraków: Wydawnictwo ZG AGH, 347/91.
7. Biessikirski, R. (1996): Zapalarka milisekundowa Explo-201 [Explo-201 millisecond blasting machine]. Konferencja: Technika strzelnicza w górnictwie, Jaszowiec (47-67). Kraków: Wy-dawnictwo IGSMiE PAN.
8. Biessikirski, R., Sieradzki, J., Winzer, J. (2001): Uwagi praktyczne do nieelektrycznego odpa-lania długich otworów na przykładzie systemu Nonel Unidet [Practical remarks to non-electric blasting long boreholes considering the Nonel Unidet system as an example]. Konferencja Technika Strzelnicza w Górnictwie, Jaszowiec (p. 241–251). Kraków: Agencja Wydawniczo-Poligraficzna ART-TEKST.
9. Duvall, W.I., Johnson, C.F., Mayer, A.V.C., Devine, J.E. (1963): Vibrations from Instantane-ous and Millisecond-Delayed Quarry Blast, United States Bureau of Mines RI 6151, Pitts-burgh.
10. Dworok, R. (1993): System zapalarki typu “BARBARA-30” z regulowanymi elektronicznie opóźnieniami międzystrzałowymi. Materiały Wybuchowe i Technika Strzelnicza: Aktualny Stan i Perspektywy Rozwoju, 1, p. 222–236. Kraków: AGAT-PRINT.
11. Ireland, K. (2000): Initiation and timing of blasts. Surface Mining Explosives Engineering Training Course. Modderfontein, Johannesburg: AEL Pty Ltd, (Chapter 4).
12. Kopp, J.W., Siskind, D.E. (1986): Effects of Millisecond-Delay Intervals on Vibration and Airblast From Surface Coal Mine Blasting. United States Bureau of Mines RI 9026.
13. Landman, G.V.R. (2010): How electronics can release the imagination. The Journal of The Southern African Institute of Mining and Metallurgy, 109, p. 491–499.
14. Nicholson, H.R., Johnson, C.F., Duvall, W.I. (1971): Blasting Vibration and Their Effects on Structures. United States Bureau of Mines Bulletin, 656.
15. Olofsson, S.O. (1990): Applied Explosives Technology for Construction and Mining. Sweden: Applex, Ärla.
16. Pal Roy, P. (2005): Rock Blasting Effects and Operations. Leiden: A.A. Balkema Publishers.
17. Persson, P., Holmberg, R., & Lee, J. (1994). Rock Blasting and Explosives Engineering. Boca Raton: CRC Press.

18. Prędki, S. (2011): Krótkie porównanie wiodących w górnictwie odkrywkowym systemów in-icjowania materiałów wybuchowych [The short comparison of the most popular explosive's initiation systems]. Instytut Przemysłu Organicznego, Materiały Wysokoenergetyczne, 3, p. 25–31.
19. Reisz, W., McClure, R., Bartley, D. (2006): Why the 8ms Rule Doesn't work. Proceedings of the 32 MacClure R.nd Annual Conference on Explosives and Blasting Technique, Journal of Explosives Engineering, 2, p. 14–22.
20. Sołtys, A. (2017)a: Dobór opóźnienia milisekundowego z zastosowaniem symulacji kom-put-erowej - weryfikacja efektu sejsmicznego w oparciu o pomiary terenowe [Delay time optimiza-tion based on computer simulation – verification of ground borne vibration effect according to field measurements]. Przegląd Górniczy, 3, p. 98–106.
21. Sołtys, A. (2017)b: Odpalanie pojedynczych ładunków MW jako baza do wyznaczania op-ty-malnego opóźnienia milisekundowego [Firing of singular explosive charges as the basis for determining the optimal millisecond delay]. Przegląd Górniczy, 7, p. 52–62.
22. Winzer, S.R. (1978): The Firing Times of Millisecond Delay Blasting Caps and Their Effect on Blasting Performance. National Science Foundation, contract DAR-77-05171, Martin-Marietta Laboratories (pp. 36).
23. Winzer, S.R., Anderson, D.A., & Ritter, A.D. (1981): Application of Fragmentation Research to Blast Design for Optimum Frgamentation and Frequency of Resultant Ground Vibration. Symposium on Rock Mechanics, MIT Press, p. 237–242.
24. Winzer, S.R., Furth, W., & Ritter, A.P. (1979): Initiator Firing Times and Their Relationship to Blasting Performance. Paper in 20th U.S. Symposium on Rock Mechanics, University of Texas at Austin, p. 461–470.
25. Winzer, J., Biessikirski, R. (1996): Uwagi o doborze opóźnienia milisekundowego ze względu na ograniczenie wielkości drgań parasejsmicznych [Remarks on the choice of millisecond de-lay due to limiting the size of paraseismic vibrations]. Konferencja: Technika strzelnicza w górnictwie, Jaszowiec (297-308). Kraków: Wydawnictwo IGSMiE PAN.
26. Winzer, J., Biessikirski, R., Sieradzki, J. (1997): Minimalizacja szkodliwego oddziaływania robót strzałowych na otoczenie, jako kierunek prac badawczych prowadzonych w Katedrze Górnictwa Odkrywkowego AGH [Minimizing the harmful impact of blasting on the envi-ron-ment as the direction of research work conducted at the Department of Surface Mining AGH]. Górnictwo Odkrywkowe a Ochrona Środowiska – Fakty i mity, p. 367–378.
27. https://www.worthpoint.com/worthopedia/sequential-blasting-machine-bm125-10b

Abstrakt

Wykonywanie w kopalniach odkrywkowych robót strzałowych z zastosowaniem dużych mas materiałów wybuchowych wiąże się z problemem niekorzystnego oddziaływania drgań, wzbudzanych detonacją ładunków, na zabudowania w otoczeniu kopalń. Stosowanie materia-łów wybuchowych w procesie urabiania złóż wpływa również na efektywność robót strzało-wych, związaną z granulacją urobku. Od początku lat 50., ładunki materiałów wybuchowych odpalane są najczęściej milisekundowo. W artykule przedstawiono rys historyczny badań w zakresie odpalania milisekundowego z zastosowaniem systemów elektrycznych, nieelektrycz-nych i elektronicznych, prowadzonych w kopalniach odkrywkowych zarówno w Polsce jak i na świecie. W efekcie tych prac stwierdzono, że interwał i precyzja zadawanych opóźnień milisekundowych mają istotny wpływ na intensywność drgań indukowanych detonacją ła-dunków MW, jak i na stopień rozdrobnienia urobku. W przypadku elektrycznego systemu inicjowania rzeczywiste czasy detonacji zapalników mogą się znacznie różnić o czasów nomi-nalnych, stąd istnieje ryzyko nakładania się czasów opóźnień a tym samym może nastąpić wzmocnienie intensywności drgań. Autorzy badań wskazują, że zachowanie określonego od-stępu czasowego między detonacją kolejnych ładunków materiałów wybuchowych może sku-tecznie ograniczać efekt sejsmiczny. To było przyczyną wprowadzenia w latach 60. ubiegłego wieku do praktyki wykonywania robót strzałowych „kryterium 8 milisekund", jako minimal-nego czasu opóźnienia pomiędzy kolejno odpalanymi ładunkami. W miarę postępu technicz-nego systemów inicjowania, precyzja zadawanych opóźnień uległa znacznej poprawie, czego dowodem jest elektroniczny system inicjowania. Jednocześnie badania z zastosowaniem tego systemu wyraźnie wskazują, że powszechnie przyjęty w praktyce minimalny czas 8 ms nie musi już być obowiązującą regułą. Precyzja nowoczesnych zapalników elektronicznych z po-wodzeniem umożliwia projektowanie wieloszeregowych siatek strzałowych, z minimalnym czasem opóźnienia mniejszym niż 8 ms pomiędzy kolejno odpalanymi ładunkami.

Słowa kluczowe: roboty strzałowe, odpalanie milisekundowe, oddziaływanie drgań, systemy inicjowania w robotach strzałowych