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OPTIMIZATION OF SEISMIC EFFECTS OF BLASTING WORKS IN LIETAVSKÁ LÚČKA QUARRY

OPTIMALIZÁCIA SEIZMICKÝCH ÚČINKOV TRHACÍCH PRÁC V LOME LIETAVSKÁ LÚČKA

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Abstract

Increasing demand for construction raw materials is putting pressure on increased exploration in mining operations. This causes an increase of blasting work and the associated increase in technical seismicity in the surrounding area of mining operations. Vibrations generated during blasting are one of the main problems in mining in open pit. Controlling their impact on the surrounding infrastructure and the environment is one of the conditions that are defined in the mining law. Therefore, it is important to study and reduce the negative effects of this work on the environment. The choice of technological process and basic parameters of the blasting has a fundamental impact on the economic costs, duration and impact of the shot on the environment. Experimental measurements of the technical seismicity of blasting were performed in the vicinity of the quarry Lietavská Lúčka in the Lietava village. The results of the measurements were used to evaluate the impact of technical seismicity from blasting on family houses in the Lietava village. The results were also used to adjust the timing of individual blasts and the charge weight per borehole. The article presents the results of experimental measurements and the method of the timing of blasting in a quarry so that the negative effects of vibration from blasting are reduced. Charge weight per borehole was not reduced in order to avoid economic losses or a reduction in the volume of mining in the quarry Lietavská Lúčka.

Abstrakt

Zvýšený dopyt po stavebných surovinách spôsobuje tlak na zvýšenie ťažby v banských prevádzkach. To spôsobuje nárast trhacích prác a s tým spojený nárast technickej seizmicity v blízkom okolí banských prevádzok. Vibrácie generované pri odstreloch sú jedným z hlavných problémov pri ťažbe v povrchových baniach. Kontrolovať ich dopad na okolitú infraštruktúru a životné prostredie je jednou z podmienok, ktoré sú definované v banskom zákone. Preto je dôležité študovať a znižovať negatívne účinky týchto prác na životné prostredie. Výber technologického postupu a základných parametrov odstrelu má zásadný vplyv na ekonomické náklady, trvanie a vplyv odstrelu na životné prostredie. V okolí kameňolomu Lietavská Lúčka v obci Lietava boli vykonané experimentálne merania technickej seizmicity clonových odstrelov. Výsledky meraní boli použité na hodnotenie vplyvu technickej seizmicity z clonových odstrelov na rodinné domy v obci Lietava. Súčasne boli výsledky využité na úpravu časovania jednotlivých clonových odstrelov a nálože na časový stupeň. V článku sú prezentované výsledky experimentálných merani a spôsob úpravy časovania odstrelov v lome tak, aby negatívne účinky vibrácií od odstrelov boli znížené. Zároveň neboli znížené nálože na časový stupeň, aby nedochádzalo k ekonomickým stratám alebo zníženiu objemu ťažby v lome Lietavská Lúčka.

Keywords

blasting work in quarries, seismic effects of blasting work, millisecond timing, law of attenuation of seismic waves

Klúčová slová

trhacie práce v lomoch, seizmické účinky trhacích prác, milisekundové časovanie, zákon útlmu seizmických vĺn

1 INTRODUCTION

One of the basic problems in blasting work is the solution of the seismic effects of vibrations arising during blasting in mining operations. The basic problems of solving the seismic effects of blasting works are clearly formulated, and yet it has not yet been possible to completely solve the problems that cause blasting work. Compared to underground mining works, blasting works in quarries is a bit easier. With new advances in blasting technologies, many undesirable factors can now be avoided. Optimal explosion results are thus achieved much easier and faster. This study points to an experimental methodology for determining delay time by monitoring blasting (Abbaspour and all, 2018; Zhang and Goh, 2016).

The basic idea of optimizing the seismic effects of blasting work is explained simply by the assumption of superposition of sinus seismic waves. When two identical seismic waves are superimposed with a certain delay, the amplitude of the superimposed wave may vary according to the phase delay. If the delay is half the period of the sine wave, the two waves interact with each other most effectively, and as a result, the amplitude of the superimposed wave is minimized. However, because the actual vibrations of the blasting during blasting work have complex properties, it is not so easy to define optimal delay times. The most suitable delay time was first proposed in the literature in 1963. The method of calculating the delay time in quarries was used mainly to achieve a suitable rock dissociation effect by providing a new free surface or collisions between the dissociated rock (Soltys and all, 2017; Langefors and Kihlström, 1978; Coltrinari, 2016).

The vibrations could be further reduced by using a method in which the waves are superimposed on each other in phase or in antiphase. In blasting work, it is assumed that the method of calculating the delay time is determined according to the structural properties of the rock environment. The properties of the rock mass in which the blasting works are carried out are obtained by measuring the propagation speed of seismic waves in situ (Sambuelli, 2009).

During the millisecond duration of the blasting during blasting work, waves from several sources propagate simultaneously. With the same period but with a different phase, each point of the environment in which the blasting works take place oscillates. At time 1 T (T period), the wave propagates from the source to a distance called the wavelength l. It is expressed by the relation l = v. T = v / f, where f is the wave frequency. The distance between the two nearest points oscillating with the same phase is the wavelength. The velocity v at which the ripple propagates through the elastic medium is called the phase velocity of the ripple. This is the speed at which the same phase of oscillation of certain points moves. The phase wave speed is different for bodies of the same substance in transverse and longitudinal waves. In certain places, where the waves pass through each other, a problem arises as to the deflection of a given point in the environment (Feher and all, 2020; Afeni, 2009; Konček and all, 2020).

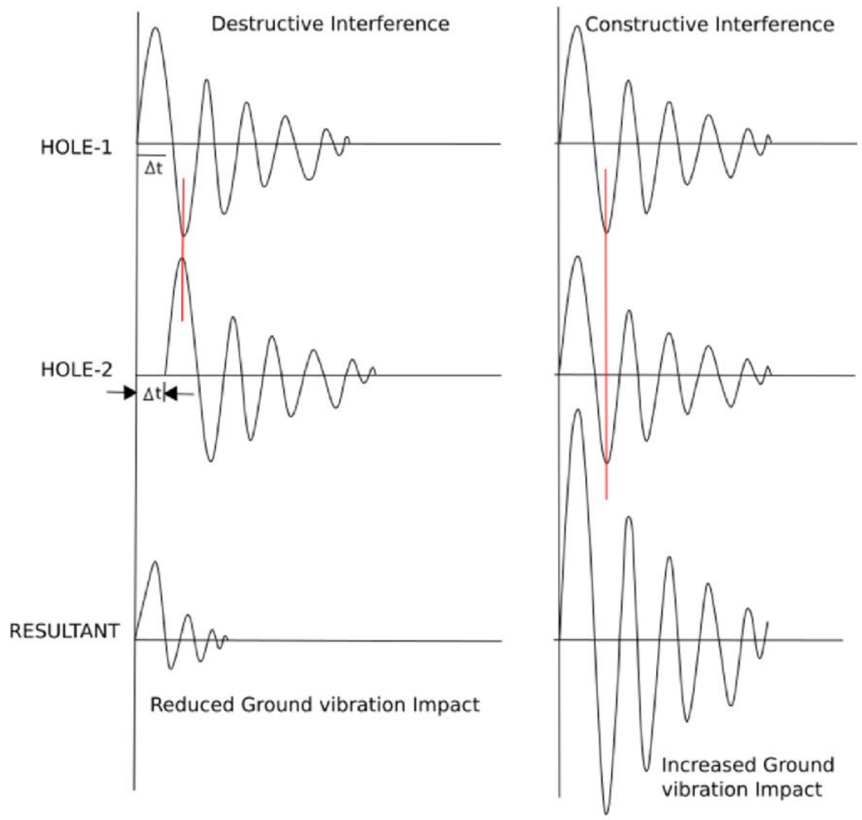

Fig. 1 Destructive and constructive interference of waves during the firing of two boreholes (Lalwani and Menon, 2016)

The resulting oscillation is the sum of the vectors of the given partial oscillations. The principle of superposition also applies to the folding of waves. Waves from one source pass through a certain space as if another wave, propagating in the same space, did not exist at all. In the area where the waves overlap, according to the principle of superposition, the resulting wave will be the vector sum of the individual waves. Thus, the deflection of a particular environmental element will be the vector sum of the deflections that that element should have from each of the waves. Enlargement, reduction or even cancellation of the deviation at a given location may occur (Fig. 1). If the phase difference of the two waves is at a certain point 2 or another even multiple, interference amplification occurs. If the phase difference is an odd multiple, interference attenuation occurs (Lalwani and Menon, 2016; Kudelas and all, 2019; Remli, 2019).

Different cases of interference are very complex, because interfering waves can vary in wavelength, amplitude, phase and direction of propagation. The simplest case of interference is the interference of two waves of the same wavelength, traveling through the medium at the same phase speed and in the same direction. Such a case of interference occurs during blasting work. The resulting amplitude at the interference of two identical waves is the largest at the points of collision of waves with the same phase, the smallest at the points of

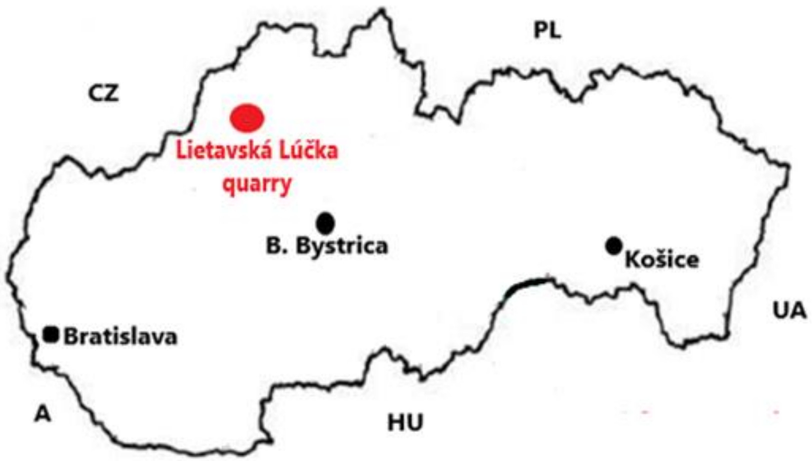

Fig. 2 Location of the mining operation - Lietavská Lúčka quarry

collision of waves with opposite phase. Therefore, it is necessary to design the millisecond timing of blasting work depending on the structural properties of the rock environment, which are expressed by the speed and frequency of seismic waves (Viskup and all, 2012; Knejzlík and all, 2012).

Experimental measurements were performed in the vicinity of the quarry Lietavská Lúčka in the Lietava village. From the measured values, we evaluated the effects of artificially excited seismicity due to bench blasting in the quarry Lietavská Lúčka on family houses in the Lietava village. The blastings were fired on the same quarry wall with the progress of blasting work towards the Lietava village. Charge weight per borehole was not reduced in order to avoid economic losses or a reduction in the volume of mining in the quarry Lietavská Lúčka. The reduction of the seismic effects of blasting on the environment was achieved using millisecond timing. The volume of mining was maintained and no additional economic costs were required.

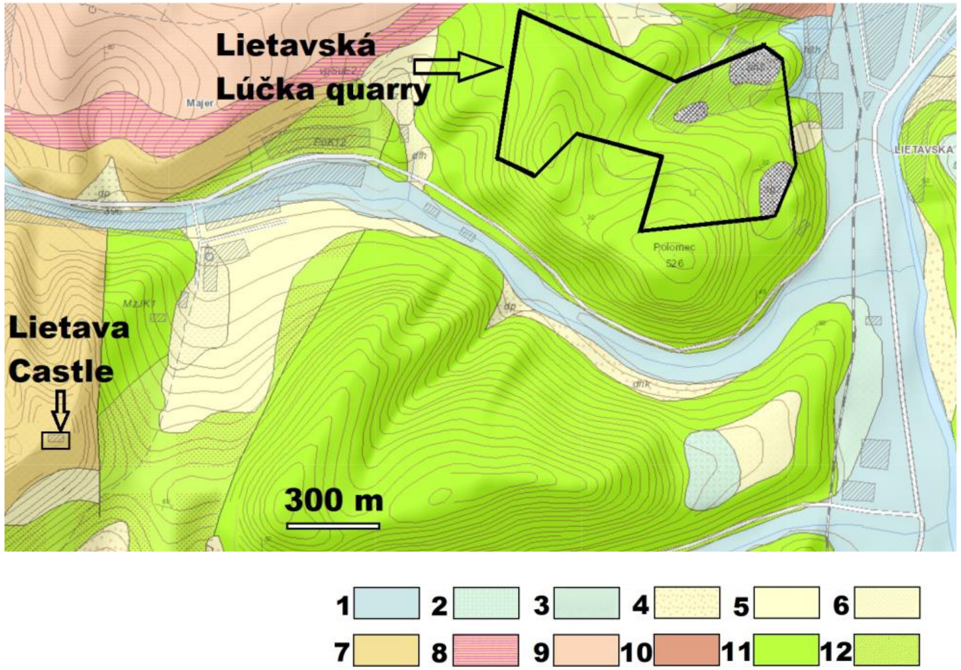

Fig. 3 Geological map of the surroundings area of the Lietavská Lúčka quarry

Quaternary fluvial sediments:
1-lithofacial unstructured alluvial clays, or sandy to gravelly clays,
2-gravels and residual gravels of undifferentiated accumulations of the 3rd and 2nd river terraces,
3- gravels, sandy gravels and sands of bottom accumulation, deluvial sediments:
4-mostly aluminous-stony,
5-deluvial sediments as a whole, 6-landslides,
Tertiary Paleogene of the klippen belt zone and Myjava Paleogene of the Súľov conglomerate:
7-carbonate conglomerates, sandstones, - claystones (predominant) and sandstones,
8-Súľov Formation organodetritical limestones, sandstones,
9–Domaniža Formation, claystones (predominant) and sandstones
10-Borovské Formations - carbonate breccias, conglomerates and sandstones,
Mesozoik:
11-Mráznické Formation, gray and dark gray limestones with siltstones, silty slates,
12 –Porubské Formation clayey-sandy shales, sandstones, sandy limestones, orthoconglomerates.

2 BRIEF DESCRIPTION GEOLOGICAL STRUCTURES AROUND THE QUARRY LIETAVSKA LÚČKA (TRANSMISSION ENVIROMENT)

The quarry Lietavská Lúčka is located in the Slovak Republic (Žilina Region, Žilina District), about 4 km north of the Lietava village (Fig. 2).

To the southwest of the city of Žilina, the Lower Cretaceous limestones of the Křížna nappe form significant morphological elevations. In one of the elevations is the quarry Lietavská Lúčka. Calmstones and nodular limestones are pelagic sediments assigned to the Mráznické Formation and are of Upper Hoterive age. Baremian limestones are also found in their overburden (Fig. 3). In the north-western wall, the apt marls of the Párnica Formation form. From the point of view of the disturbance of individual rocks, we can consider the massif of calmstones and siltstones to be moderately disturbed. Negative impacts of seismic effects of blasting works in the quarry Lietavská Lúčka may be reflected in individual construction objects in the Lietava village. The distance between Lietavská Lúčka quarry and the castle Lietavský is less than 1.5 km, therefore seismic effects on this object must be considered as well (Kačer and all, 2013).

3 METODOLOGY OF MEASUREMENT AND APPARATUS USED FOR MEASURING TECHNICAL SEISMICITY

The measuring positions were situated in such a way that it was possible to determine the law of attenuation of seismic waves. One measuring position was near the blasting and two measuring positions were in the residential buildings of the Lietava village, which were closest to the quarry Lietavská Lúčka. (Pandula and Kondela, 2010). The following digital seismic devices were used at the following measuring positions to measure and record the seismic effects of blasting works (bench blasts CO 138, CO 139, CO 140, CO 141, CO 142 and CO 143):

- vibrograph ABEM Vibraloc a sensors from a swedish company ABEM (Fig. 4C),
- vibrograph Minimate Pro 6 a sensors from a canadian company Instantel (Fig. 4A),
- vibrograph Svantek a sensors from a polish company Svantek (Fig. 4B).

Vibrographs provide digital and graphical recording of all three components of the peak particle velocity, horizontal longitudinal - vx, horizontal transverse, vertical - vz. Minimate Pro 6 - Instantel and ABEM Vibraloc vibrographs work autonomously, automatically

Fig. 4 Used vibrographs for measuring technical seismicity in Lietavská Lúčka quarry

performing channel tests without the intervention and influence of the operator on the measured and registered vibration characteristics. Vibrographs Minimate Pro 6 - Instantel and ABEM Vibraloc and Svantek 958 A - Class 1 have an AD converter with an automatic 14-bit dynamic range, which corresponds to 0.05 ÷ 250 mm.s^{-1}.

ABEM electrodynamic geophones with a frequency range of 2 ÷ 1000 Hz and a sensitivity of 20 mV/mm.s^{-1} were used for these measurements. Furthermore, a three-component geophone from Instantel with a frequency range of 2 ÷ 1000 Hz and a sensitivity of 10 mV/mm.s^{-1}. The geophones were placed on a special pad with steel sharp points, which ensured continuous contact with the ground (Pandula and Kondela, 2021).

The measuring positions were situated so that it was possible to assess the impact of artificially induced seismicity by bench blastings (CO 138, CO 139, CO 140, CO 141, CO 142 and CO 143) on residential buildings no. 2 and no. 3 in the Lietava village. The distances between the sensors and the blasts and the position of the measuring position relative to the blast are shown in Figure 5.

Measuring positions were located in quarry and on the nearest surrounding buildings (Baulovič and all, 2016):

- position situated directly in the quarry (S1),
- residential house in the Lietava village (house number 2) (S2),
- residential house in the Lietava village (house number 3) (S3).

	S1	S2	S3
CO 138	14 m	315 m	312 m
CO 139	14 m	303.5 m	300.5 m
CO 140	14 m	292 m	289 m
CO 141	14 m	280.5 m	278.5 m
CO 142	14 m	253 m	250 m
CO 143	14 m	269 m	266 m

***Fig. 5** Position of opinions from bench blasting CO 138, CO 139, CO 140, CO 141, CO 142 and CO 143 in Lietavska lúčka quarry in relation to measuring position (S1, S2 and S3) and distance of individual opinions*

All these positions (S1, S2, S3) can be seen in (Fig. 5). From the measured values peak particle velocities, we evaluated the effects of artificially excited seismicity due to bench blastings in the vicinity of the quarry Lietavská Lúčka on the family houses no. 2 and 3 in the Lietava village. The blasts were fired in the same quarry wall with the progress of blasting work towards the village, so the distance was reduced by a blast. The size of the charge in blasthole did not change. CO 142 blasting was carried out on a new quarry wall at a distance of 250 m from the assessed objects.

To determine the law of attenuation in the transmission environment between sources (Bench blasts CO 138, CO 139, CO 140, CO 141, CO 142 and CO 143) and receptors (residential buildings in the Lietava village), the measuring position S1 was located 14 m from the initiation borehole in the quarry Lietavská Lúčka. An ABEM Vibraloc digital four-channel vibrograph was used to measure seismic effects at measuring position S1 (Fig. 6).

To assess the seismic effects on residential buildings in the Lietava village, the measuring position S2 was located on an apartment building (house no. 2) in the Lietava village. Two Minimate Pro 6 vibrographs - Instantel and ABEM Vibraloc - were placed on measuring position S2. Vibrograph ABEM Vibraloc was located at the entrance to the living area on a concrete base (Fig. 7A). The vibrographs Minimate Pro 6 - Instantel were located indoors on paving stones (Fig. 7B).

Also for the assessment of seismic effects on residential buildings, the measuring position S3 was situated on an apartment house (house no. 3) in the Lietava village. A Svantek 958 vibrograph was placed at measuring position S3. The vibrograph Svantek 958 was located outdoors on a concrete base (Fig. 8).

4 SOURCES OF VIBRATION

The source of seismic effects were bench blasts CO 138 CO 139, CO 140, CO 141, CO 142 and CO 143. The positions and distances of blasts in relation to the measuring positions (S1, S2 and S3) can be seen in Fig. 5.

Parameters of bench blasts CO 138, CO 139, CO 140, CO 141, CO 142 and CO 143 in Lietavská Lúčka quarry (see Tab. 1). The timing and arrangement scheme of the boreholes at blasts are shown in Fig. 9, 10, 11, 12, 13 and 14.

***Fig.6** Measuring position S1 (14 m from the initial borehole) and the used measuring vibrograph ABEM Vibraloc placed on the rock*

***Fig. 7** Measuring position S2 - used measuring vibrograph ABEM Vibraloc (A) and Minimate Pro 6 (B)*

***Fig. 8** Measuring position S3 - used measuring vibrograph Svantek 958*

Tab. 1 Parameters of blastings in Lietavská Lúčka quarry

Date of blast	Blast No.	Weight of explosives / Charge weight per borehole [kg]	Explosives	Description of drilled boreholes	Timing of blast delay [ms]
20.02.2021	138	2967/65	Blendex 80 (2852 kg), Poladyn Eco (115 kg)	46 boreholes with a diameter of 95 mm, with an inclination of 80° and an average depth of 10 m in three rows were drilled. The spacing between the boreholes was 3.5 m and the engagement of the first row was 5 m.	17, 25, 42, 67 (Nitronel non-electric ignition)
30.03.2021	139	3229/ 65	Blendex 80 (3092 kg), Poladyn Eco (137 kg)	50 boreholes, otherwise the description is the same as for CO 138	17, 25, 42, 67 (Nitronel non-electric ignition)
12.04.2021	140	1614/ 65	Poladyn 31 Eco (90 kg), Emulinite (624 kg), Blendex (800 kg)	36 boreholes, otherwise the description is the same as for CO 138 and 139	42 (Nitronel non-electric ignitron)
23.04.2021	141	1631/ 65	Poladyn 31 Eco (85 kg), Emulinit (696 kg), Blendex (850 kg)	34 boreholes, otherwise the description is the same as for CO 138, 139 and 140	17 (Nitronel non-electric ignition)
23.04.2021	142	402.5/ 65	Poladyn 31 Eco (22.5 kg), Blendex (380 kg)	9 boreholes, experimental blast - the nearest to the monitoring objects	17 (Nitronel non-electric ignition)
27.04.2021	143	1716/65	Poladyn 31 Eco (90 kg), Emulinite (726 kg), Blendex (900 kg)	36 boreholes, otherwise the description is the same as for CO 138, 139, 140 and 141	17 (Nitronel non-electric ignition)

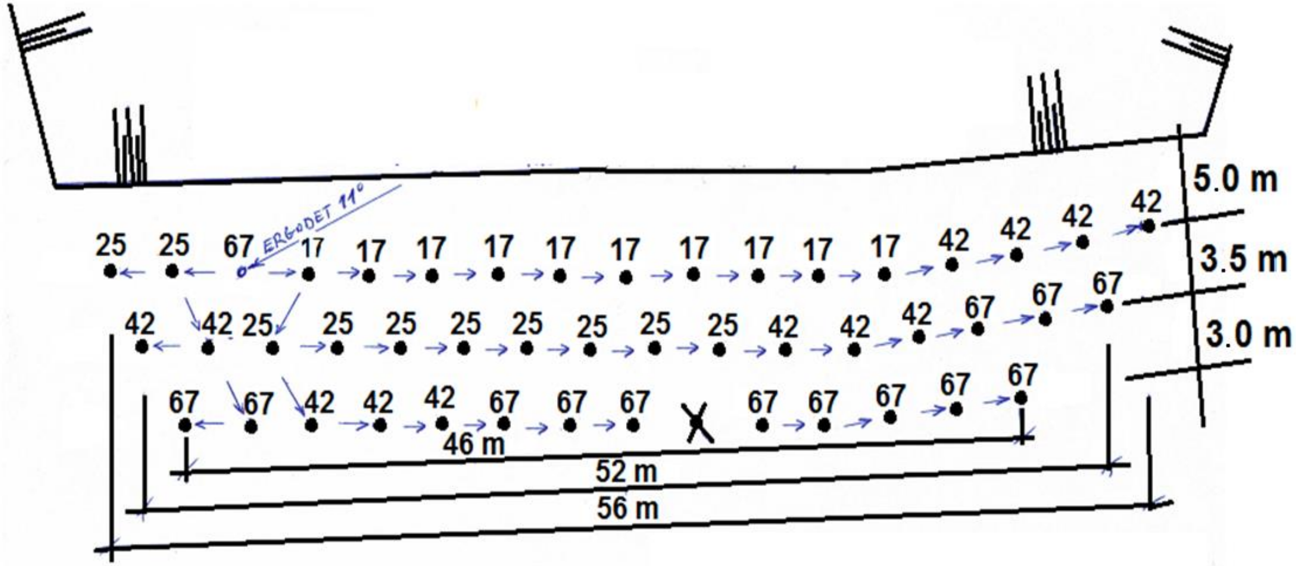

Fig. 9 Scheme of millisecond timing and distribution of boreholes during three-row bench blast CO 138 in Lietavská Lúčka quarry

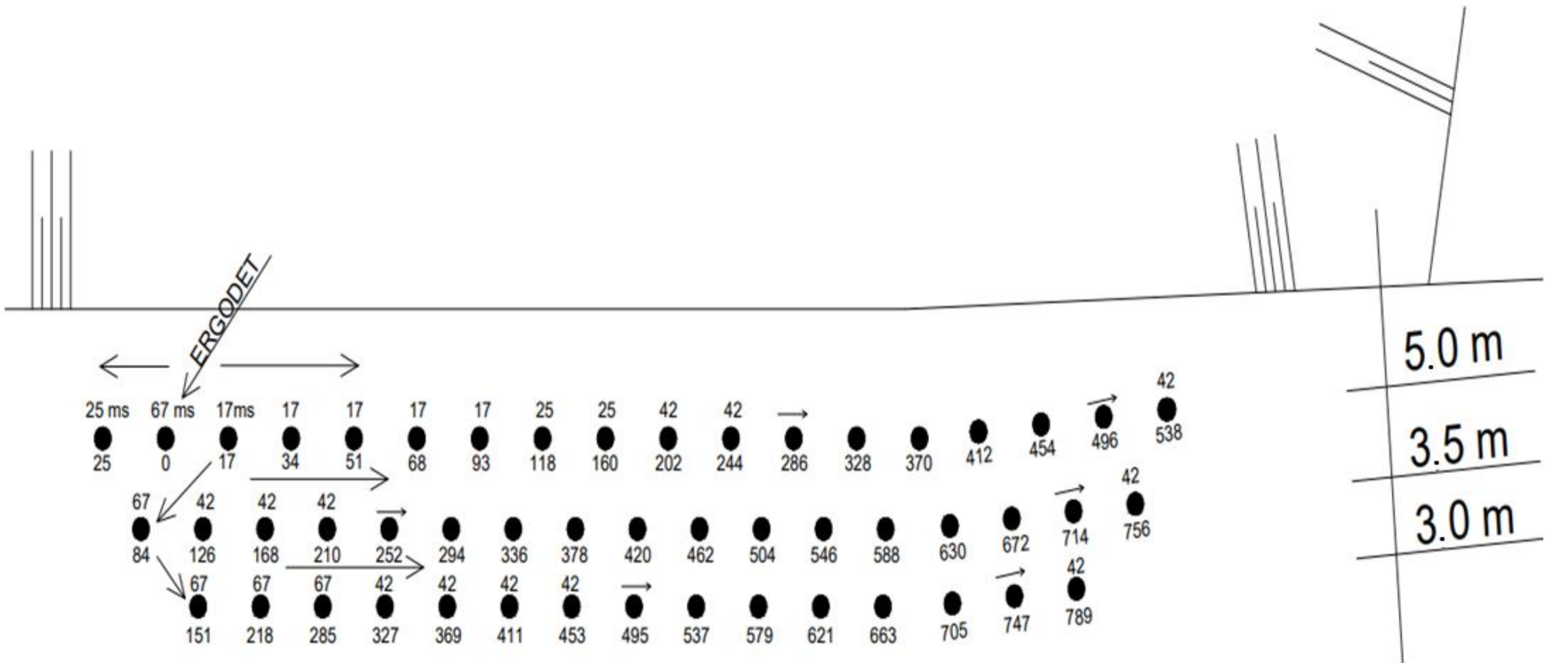

Fig. 10 Scheme of millisecond timing and placement of boreholes during three-row bench blast CO 139 in Lietavská Lúčka quarry

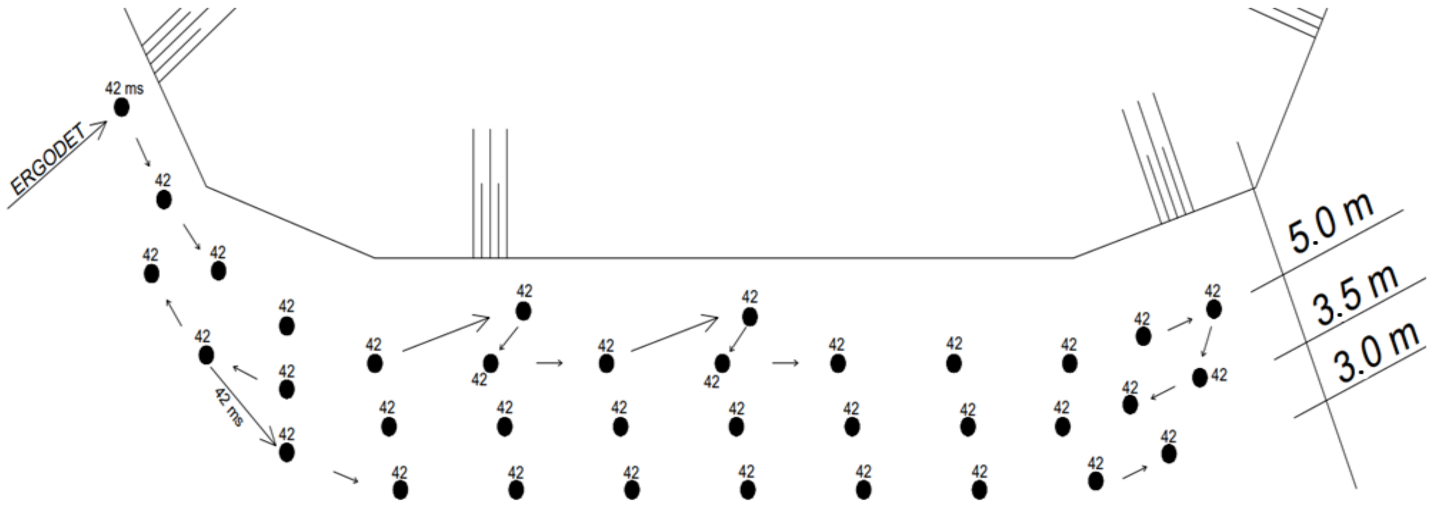

Fig. 11 Scheme of millisecond timing and distribution of boreholes during three-row bench blast CO 140 in Lietavská Lúčka quarry

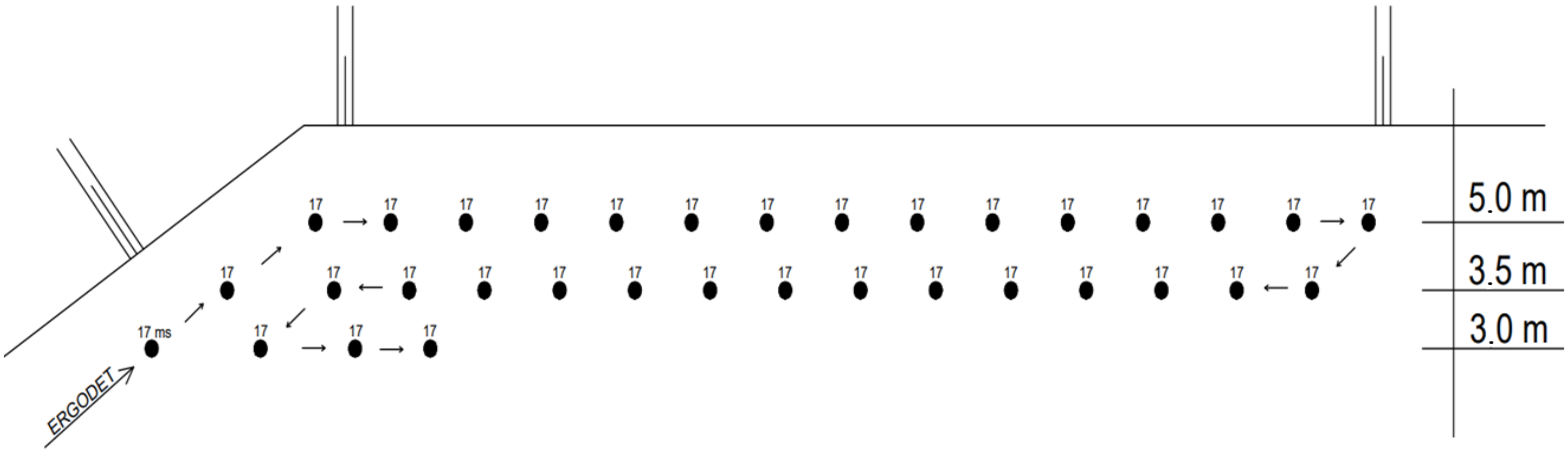

Fig. 12 Scheme of millisecond timing and placement of boreholes during three-row bench blast CO 141 in Lietavská Lúčka quarry

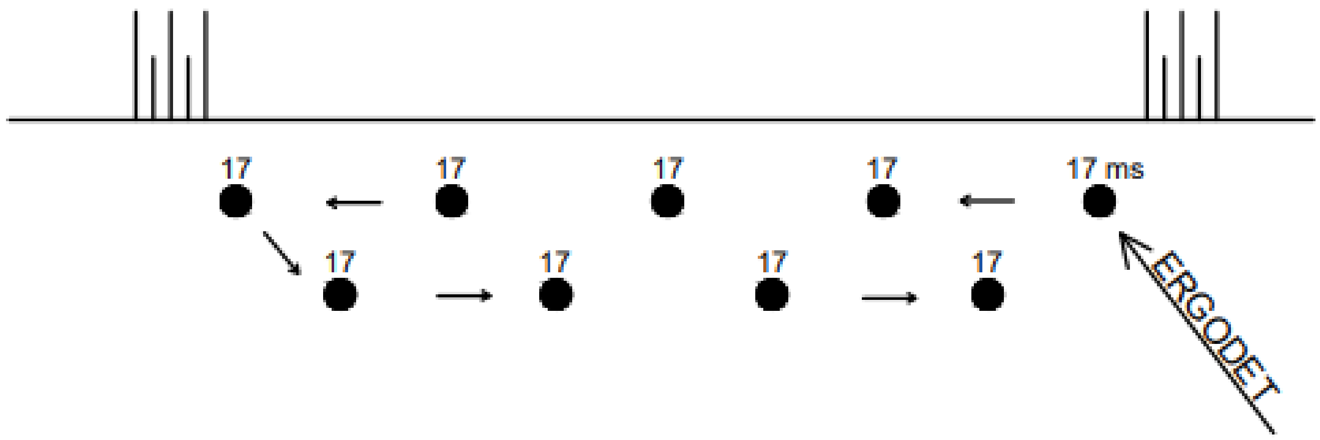

Fig. 13 Scheme of millisecond timing and distribution of boreholes during three-row bench blast CO 142 in Lietavská Lúčka quarry

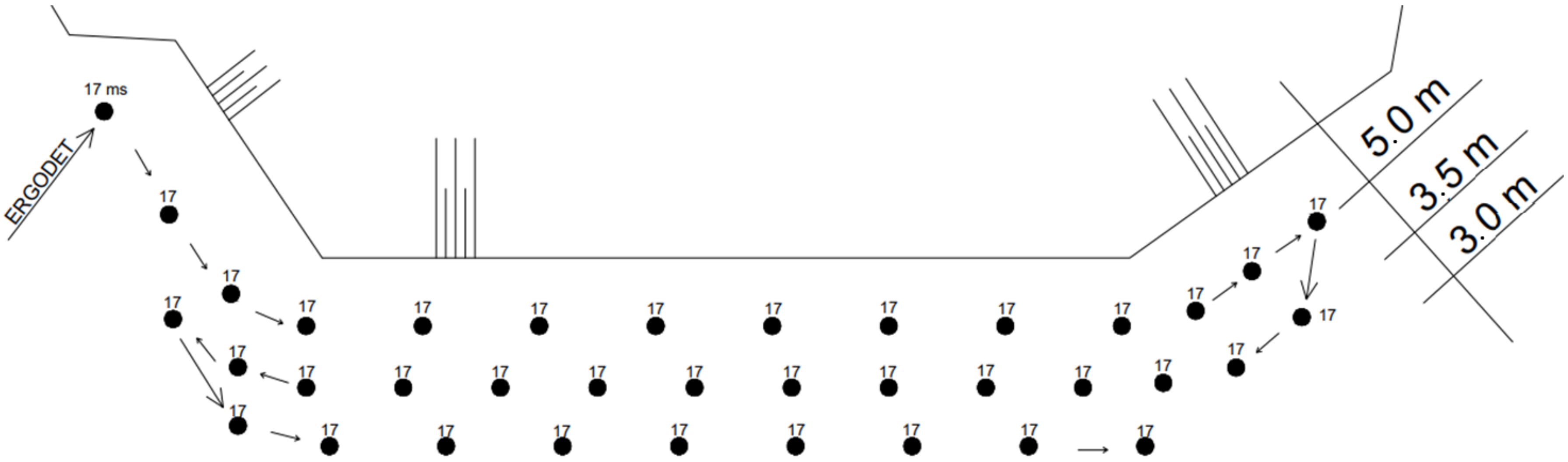

Fig. 14 Scheme of millisecond timing and distribution of boreholes during three-row bench blast CO 143 in Lietavská Lúčka quarry

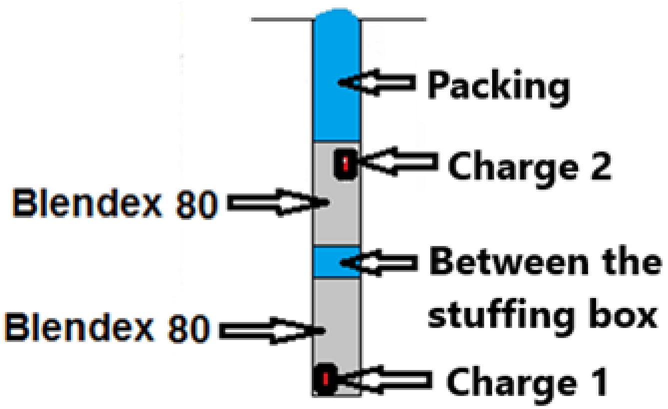

Fig. 15 Borehole charge design and explosives used in bench blastings

On Fig. 15 you can see the construction of the charge in the boreholes in the bench blasts CO 138, CO 139, CO 140, CO 141, CO 142 and CO 143. The maximum charge in one borehole was divided into a charge of 2 x 31 kg of Blendex 80 explosive and a charge of 2 x 1.5 kg Poladyn 31 Eco, 0.5 m intermediate packing.

The parameters of the blasts, the range burden and spacing between the boreholes in the row and between the rows, were still the same during the blasts.

5 MEASURED VALUES AND RESULTS

The vibrographs stored on the measurent position were calibrated before measurement and their sensitivity was checked. Graphical waveforms of individual components of seismic waves at bench blasts CO 138, CO 139, CO 140, CO 141, CO 142, CO 143 were recorded at the measuring positions S1, S2 and S3. The individual graphical recordings were four seconds (See Fig. 16). The vibrographs were placed on the measuring positions so that it was possible to assess the influence of the excited technical seismicity on the assessed objects. The measured values peak particle velocity at the individual measuring positions are given in Table 2 (Pandula and Kondela, 2021).

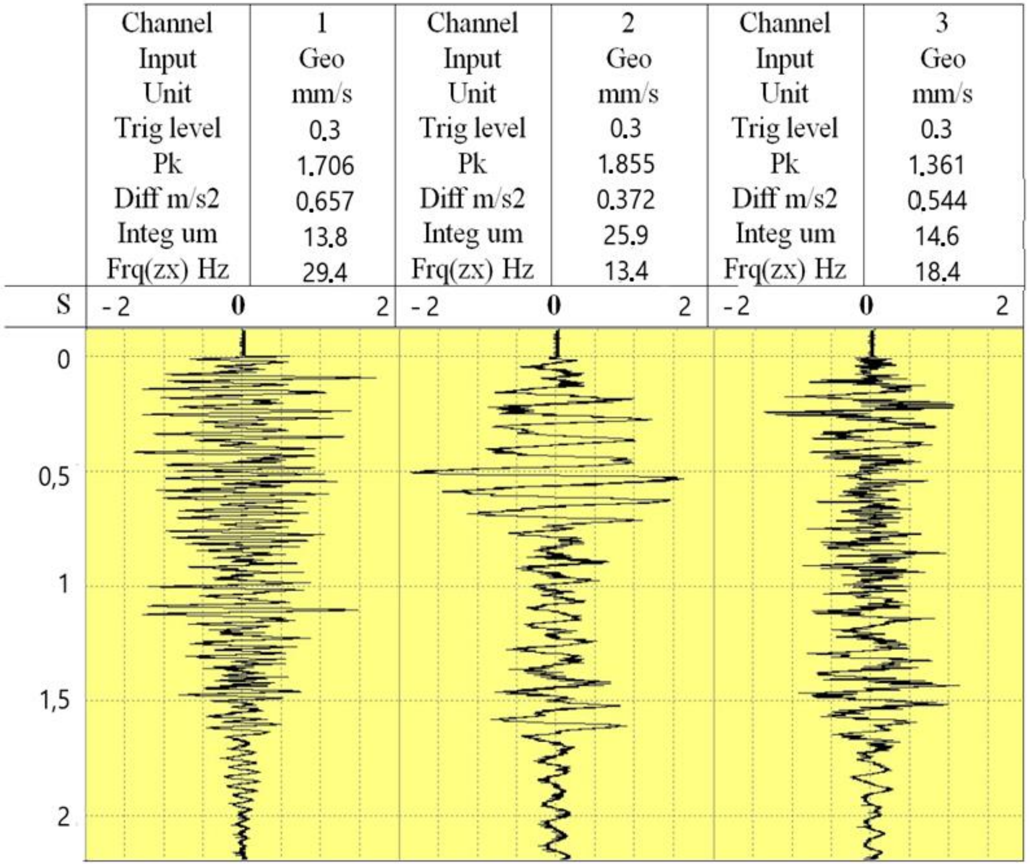

Fig. 16 Graphical recording of individual components vx, vy, vz of seismic wave at bench blast CO 140 - measuring position S2 (entrance to a residential building no. 2 - vibrograph ABEM Vibraloc)

Tab. 2 Measured maximum values of peak particle velocities and frequencies of individual positions S1, S2 and S3 at bench blasts CO 138, CO 139, CO 140, CO 141, CO 142 and CO 143

Position	**Distance [m]**	**Timing delay [ms]**	**Total charge weight per borehole [kg]**	**v_x [mm. s^{-1}]**	**v_y [mm. s^{-1}]**	**v_z [mm. s^{-1}]**	**f_x [Hz]**	**f_y [Hz]**	**f_z [Hz]**
CO 138									
Lietavská Lúčka quarry (S1)	**14**	17, 25, 42, 64	65	64.9	50.0	112	19	12	40
(S2)	315			1.68	1.39	2.89	14	12	31
	315			1.31	1.18	2.78	12	17	28
	315			1.38	1.34	3.08	13	13	28
(S3)	312			4.7	3.8	3.0	32	32	17
CO 139									
(S2)	303.5	17, 25, 42, 64	65	3.36	8.45	1.42	11.4	15.6	30.2
CO 140									
(S2)	292	42	65	1.86	1.38	1.71	13.4	18.4	29.4
CO 141									
(S2)	280.5	17	65	1.58	1.55	1.93	19	18	26
CO 142									
(S2)	253	17	65	0.79	1.24	0.94	53	11	33
CO 143									
(S2)	269	17	65	2.17	2.32	1.55	10	14	29.5

Description of the legend of Table 1: v_x – peak particle velocities in the environment (horizontal/longitudinal), v_y - peak particle velocities in the environment (horizontal/transverse), v_z - peak particle velocities in the environment (vertical), f_x - maximum frequency (horizontal/longitudinal), f_y - maximum frequency (horizontal/transverse), f_z - maximum frequency (vertical).

6 CONCLUSION

When solving the optimization of blasting works in the quarry Lietavská Lúčka, we relied on data obtained by monitoring bench blast CO 138. These values peak particle velocity were in the safety limit according to STN EN 1998-1 / NA / Z1. The planned progress of blasting works was towards residential buildings in the Lietava village. Therefore, it was necessary to design the blasting work so that even when the blasting works approached the residential buildings in the Lietava village, the values peak particle velocity did not exceed the permitted values. The size of the charge per blasthole could no longer be reduced. Therefore, we decided to reduce the values of peak particle velocity blasting work using millisecond timing. Analysis of the millisecond timing of bench blast CO 138 revealed that some blastholes in the first and third rows were blast at the same time. In this case, up to 195 kg was blasted in one timing step. In bench blast CO 139, timing steps were omitted that caused the boreholes to be blasted at the same time in millisecond timing. The measured values of the vibration speed were at the safety limit for residential buildings, but were unacceptable for the inhabitants of these residential buildings.

Based on frequency analysis we achieved the value of the seismic wave frequency measured 14 m from the initiation borehole of the bench blast CO 138 and we determined the most suitable value of millisecond timing delay. The measured value of the frequency in Lietavská Lúčka quarry in the z-axis (the initial loading was at a depth of 10 m in the borehole and the sensor was 14 m from the borehole on the surface - therefore the z-axis) was 40 Hz. The optimal value millisecond timing delay of the blasting offset of the next borehole in the row is 1/T - period, where T = 1/f - measured frequency. Then for millisecond timing delay, 1/2f = 1/2x40 = 1/80 = 0.0125 s = 12.5 milliseconds. For non-electric ignition, the closest value is 9 and 17 ms. Since the required number of 9 millisecond connectors was not available, a timing of 17 milliseconds was proposed. At this timing, according to theoretical assumptions, the maximum damping of seismic waves should occur. At a timing of 25 milliseconds, there should be minimal attenuation of seismic waves. Timing delay of 42 milliseconds (25 + 17 ms) was used for CO 140 blasting. During this timing delay, the measured values of the peak particle velocity were safe for residential buildings in the Lietava village also for the inhabitants and did not exceed the permitted values. A timing delay of 17 milliseconds was used to bench blast CO 141. During this timing delay, the measured values of the peak particle velocity were safe for residential buildings in village Lietava also for the inhabitants and did not exceed the permitted values. The bench blast CO 142 was blasted when a new quarry wall was opened on the edge of the mining area of the quarry Lietavská Lúčka , closest to the residential buildings in village Lietava. A timing delay of 17 milliseconds was used for bench blast CO 142. The measured values of the peak particle velocity were safe for residential buildings in village Lietava also for the inhabitants and did not exceed the permitted values. To confirm the correct use of the 17 ms timing delay, a bench blast CO 143 was blasted. For bench blast CO 143, a 17 millisecond timing delay was used. The measured values of the peak particle velocity were safe for residential buildings in village Lietava also for the inhabitants and did not exceed the permitted values (23-27).

Based on the research carried out in the quarry Lietavská Lúčka, it was found that the measured peak particle velocities and seismic wave frequencies at bench blasts CO 138, 139, 140, 141, 142 and 143 in the quarry Lietavská Lúčka were safe from view of seismic safety for buildings. In compliance with the proposed maximum charge weight per borehole permissible for blasting depending on the distance from residential buildings, there will be no damage to buildings (23-27).

Based on the recommendations of STN EN 1998-1 / NA / Z1 Seismic loading of building structures, about charges used for blasting, which are tens of kilograms, where the oscillation frequencies are usually f < 10 Hz (confirmed by measurement) and based on the resistance of buildings to technical seismicity it is possible to classify residential buildings in the Lietava village into resistance class B (see Tab. 3).

Tab. 3 Resistance classes of buildings according to STN EN 1998-1 / NA / Z1

Object resistance class	Housing, civil, industrial and agricultural buildings	Engineering objects	Underground objects	Underground utilities and cables
A	dilapidated non-compliant buildings, ruins, historic buildings, monuments and fountains, buildings in personal and monument care	-	-	-
B	brick buildings, houses up to 200 m^2 – a maximum of three floors	-	-	-
C	large buildings of bricks and blocks, reinforced structures (panel, prefabricated with reinforced concrete elements)	stone bridges, statues and ornaments, retaining walls of stone and brick	ceramic and stone tiles, paving in underground buildings and underpasses	asbestos-cement and earthenware pipes, cable

As for the type and category of foundation soil of protected objects, due to the absence of more specific characteristics and data, we can classify it into category b, which is closest to reality - groundwater level is more than 3 m below the surface level (see Tab. 4).

In addition to the measured values of the oscillation frequency (f < 10 Hz), it is necessary to take into account the longer-term nature of blasting at the limestone deposit and also the higher age of residential buildings (positions of measurement) on which were found small cracks. For these reasons, the maximum permissible peak particle velocity can be determined:

$v_d \leq 3$ mm.s^{-1}.

Based on the data from Table 1, a graphical dependence of the maximum components of the peak particle velocity on the reduced distance in bench blasting was constructed. The graph in Fig. 17 represents the so-called seismic wave attenuation law for the quarry

Lietavská Lúčka, in which the value of Q in the form

$$v = (\frac{L}{Q^{0,5}}) = K\left[\frac{L}{Q^{0,5}}\right]^n,$$

where "v" is the peak particle velocity (maximum component of the vibration velocity) generated by the blast, [mm/s],

- L/Q 0.5 is called reduced distance, [m/kg$^{0.5}$],
- L is the shortest distance of the blast from receptor, [m],
- Q is the charge weight per borehole, [kg],
- K the factor depends on the blast conditions, the properties of the transmission environment, the type of explosive, etc.,
- n is an indicator of seismic wave attenuation (Dojčár and all, 1996; Pandula and Kondela, 2010; Pandula and all, 2012).

From the law of attenuation of seismic waves, it is possible to determine the size of the charge weight for a specific receptor at a known distance, so that the maximum values of individual components of the oscillation velocity do not exceed the permitted peak particle velocities. The graphical course of the law of attenuation of seismic waves for the quarry Lietavská Lúčka shows, that the permissible peak particle velocity of 3 mm.s^{-1} for frequencies less than 10 Hz will not be exceeded at a reduced distance L_R = 50. In the graph (Fig. 17) in the upper left part of the graph are measured values of vibration velocities in the quarry 14 m from the initial borehole bench blast CO 138 and in the lower right part are measured values peak particle velocities in residential buildings no. 2 and 3. (Pandula and Kondela, 2021).

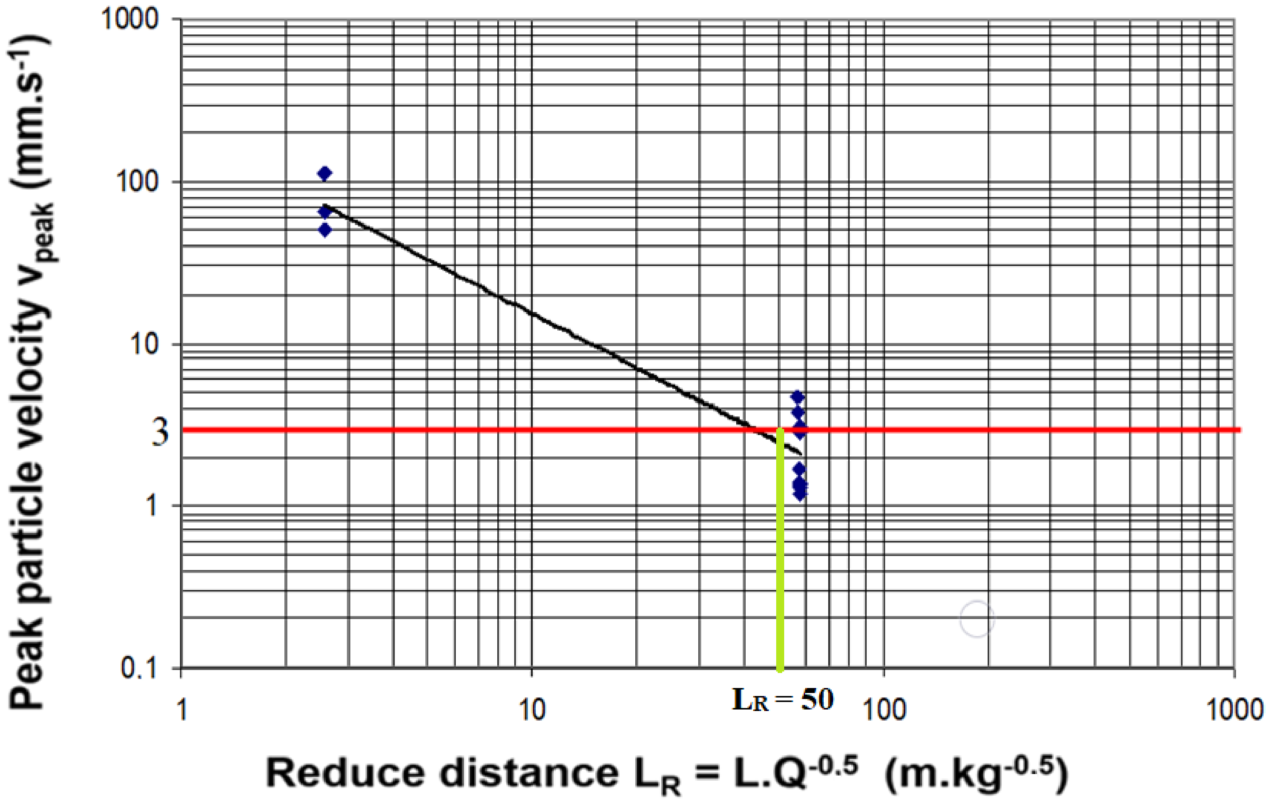

Fig. 17 Graphic dependence of the maximum components of the peak particle velocity on the reduced distance during bench blasting in the quarry Lietavská Lúčka - the law of attenuation of seismic waves. The red line indicates the maximum safe allowed peak particle velocities for buildings

Tab. 4 Dependence of the degree of damage on the peak particle velocities, type of object and foundation soils according to STN EN 1998-1 / NA / Z1

Peak particle velocities for the frequency area			**Level of damage**	**Class of resistance of an object**	**Type of foundation**
$f_k < 10$ [Hz]	**$10 < f_k < 50$ [Hz]**	**$f_k > 50$ [Hz]**			
Up to 3	3 to 6	6 to 5	0	A	a
3 to 6	6 to 12	12 to 20	0	A	b, c
				B	a
6 to 10	10 to 20	15 to 30	0	B	b, c
				C	a
			1	A	a
8 to 15	15 to 30	20 to 30	0	C	b
				B	c
			1	A	b, c
				B	a
10 to 20	20 to 30	30 to 50	0	C	c
				D	a
			1	B	b
				C	a
			2	A	a
15 to 25	25 to 40	40 to 70	0	D	b, c
				E	a
			1	C	b
				B	c
			2	A	b, c
				B	a
20 to 40	40 to 60	60 to 100	0	E	b, c

Legend class of building resistance:

A - Old buildings not conforming with regulations, ruins, historical buildings from unworked stone or bricks with arches cross-beams, girders and flat arches above the premise of the ground floor and basement : stone and brick monuments and fountains, buildings with extensive moulding decorations, buildings with special preservation and conservation status.

B - Conventional brick buildings detached or terraced houses with ground area up to 200 m three storeys at the most.

C - Big buildings from bricks and shaped bricks, well-reinforced panel buildings built from reinforced concrete components, masonry binder in cement mortar.

Legend class of soil:

Category a - Includes rocks of all classes with the design strength Rdt ≤ 0.15 Mpa, underground water level at the constant depth of 1.0 to 3.0 m below the footing bottom.

Category b - Includes rocks of all classes with design strength Rdt ≤ 0.15 Mpa, underground water level at the constant depth of more than 3.0 m. This category also includes rocks of all classes with design strength Rdt ≤ 0.15 Mpa if the underground water level is constantly at the depth of 1.0 to 3.0 m below the footing bottom,

Category c - includes rocks of all classes with the design strength Rdt ≥ 0.15 Mpa, underground water level at the constant depth of more than 3.0 m below the footing bottom. This category also includes rocks of all classes with design strength Rdt ≤ 0.6 Mpa if the underground water level is constantly at the depth of more than 1.0 m.

Mining at the quarry Lietavská Lúčka site is carried out by bench blasting. Based on the measured and calculated values during the operational blasting in the quarry Lietavská Lúčka, the law of attenuation of seismic waves was determined, on the basis of which it is possible to use the maximum permissible charge weight per borehole depending on the distance during repeated bench blasting in Lietavská Lúčka quarry. (see Tab. 5).

From the point of view of seismic safety, these values are safe for buildings and residents, and in compliance with the proposed maximum permitted blasting charges for borehole, depending on the distance from residential buildings, there will be no damage to buildings.

Tab. 5 Use of the maximum permissible charge weight per borehole depending on the distance during repeated bench blasting in Lietavská Lúčka quarry

Distance [m]	**Calculation**	**Maximum charge weight per borehole [kg]**
100	$Q_{vmax} = L^2/L_R^2 = 100^2 / 50^2 =$	4 kg
200	$Q_{vmax} = L^2/L_R^2 = 200^2 / 50^2 =$	16 kg
300	$Q_{vmax} = L^2/L_R^2 = 300^2 / 50^2 =$	36 kg
400	$Q_{vmax} = L^2/L_R^2 = 400^2 / 50^2 =$	64 kg
500	$Q_{vmax} = L^2/L_R^2 = 500^2 / 50^2 =$	100 kg

In the vicinity of the quarry Lietavská Lúčka in the Lietava village, experimental timings of individual bench blasts were performed in order to reduce the technical seismicity of the bench blasts. The evaluation of the impact of technical seismicity from bench blasting on family houses in the Lietava village showed a significant reduction in the peak particle velocity in the monitored family houses. It has been proven that even during blasting works at the boundary of the mining area, the peak particle velocity recommended by the STN EN 1998-1/NA/Z1 will not be exceeded. The parameters of blasting works was not changed, so there were no economic losses or reduction in the volume of mining in Lietavská Lúčka quarry.

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