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REDUCTION OF VIBRATIONS CAUSED BY BLASTING WORKS IN MITIGATING THE NEGATIVE EFFECTS ON THE ENVIRONMENT

REDUKCIA VIBRÁCIÍ VYVOLANÝCH TRHACÍMI PRÁCAMI PRI ZMIERŇOVANÍ NEGATÍVNYCH ÚČINKOV NA ENVIRONMENT

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Abstract

Vibration caused by blasting works is one of the basic problems in quarries, and intense vibrations can cause critical environmental damage near the quarries. Disintegrating the rock mass by blasting works generates seismic waves with different maximum particle velocities and a wide range of frequencies. This process depends mainly on the structural properties of the rocks, charge properties and the blasting technology. It is very important to investigate how to regulate the vibrations caused by blasting works in mitigating the negative effects of the blasting works in quarries. The maximum values of environmental particle vibration velocity depend on a large number of different factors. Using the velocities and frequencies of seismic waves, the optimal millisecond interval was sought to reduce the intensity of the vibrations caused by blasting works on the environment. The experiments confirmed the theoretical assumptions that the greatest decrease in vibration intensity occurs when the seismic waves are in the opposite phase. The results of the experiments were confirmed in practice during the research of blasting works in the quarry Mníchová Lehota.

Abstrakt

Vibrácie spôsobené trhacími prácami sú jedným zo základných problémov lomov a intenzívne vibrácie môžu spôsobiť kritické poškodenie životného prostredia v blízkosti lomov. Rozpojovanie horninového masívu trhacími prácami generuje seizmické vlny s rôznymi maximálnymi rýchlosťami kmitania a širokým rozsahom frekvencií. Tento proces závisí hlavne od štrukturálnych vlastností hornín, vlastností použitej trhaviny a technológie trhacích prác. Je veľmi dôležité preskúmať, ako regulovať vibrácie spôsobené trhacími prácami pri zmierňovaní negatívnych účinkov trhacích prác v kameňolomoch. Maximálne hodnoty rýchlosti kmitania v prostredí závisia od veľkého množstva rôznych faktorov. Pomocou rýchlostí a frekvencií seizmických vĺn sa hľadal optimálny milisekundový interval na zníženie intenzity vibrácií spôsobených trhacími prácami na životné prostredie. Pokusy potvrdili teoretické predpoklady, že najväčší pokles intenzity vibrácií nastáva, keď sú seizmické vlny v opačnej fáze. Výsledky experimentov sa v praxi potvrdili pri výskume trhacích prác v lome Mníchová Lehota.

Keywords

blasting works in quarries, seismic waves, particle velocity, seismic safety, optimal millisecond delay interval

Kľúčové slová:

trhacie práce v lomoch, seizmické vlny, rýchlosť kmitania, seizmická bezpečnosť, optimálny milisekundový interval oneskorenia

1. Introduction

The blasting technology has undergone a great development since the invention of dynamite by Alfred Nobel in 1867, and the blasting work is still the most efficient and economical method for disintegrating the rock environment. On the other hand, disintegrating also gives rise to many problems caused by noise and vibration. In particular, vibrations generated by blasting can cause damage to surrounding buildings and discomfort to residents. Reducing or regulating the effects of vibration is a problem for most quarry operations.

Bench blasting is known to be an effective way to reduce vibration. This method involves detonating the individual charges in the blastholes one after the other with a certain time delay. Seismic waves generated during the blasting works interfere with each other, and the vibration velocity, Peak Particle Velocity (PPV), can be reduced using the appropriate time intervals. Despite the theoretical simplicity, it is usually difficult to predict the PPV with a sufficient accuracy due to the error in the timing of the delay between the individual charges and the inhomogeneity of the rock environment.

Several studies on vibration control have been performed and practical methods have been known (Langefors and Kihlström, 1978; Persson et al., 1994; Dojčár et al., 1996; Dojčár and Pandula, 1998; Müncner, 2000; Pandula and Kondela, 2010; Baulovič, 2019), which have recommended:

1) the use of a delay time between blastholes;
2) reducing the number of the blastholes at the same delay time;
3) the use of the multi-row blasts and appropriate delay times between the rows;
4) the use of a split charge and appropriate timing between charges;
5) dividing the quarry wall into more benches, and thus reducing the amount of charge per blasthole.

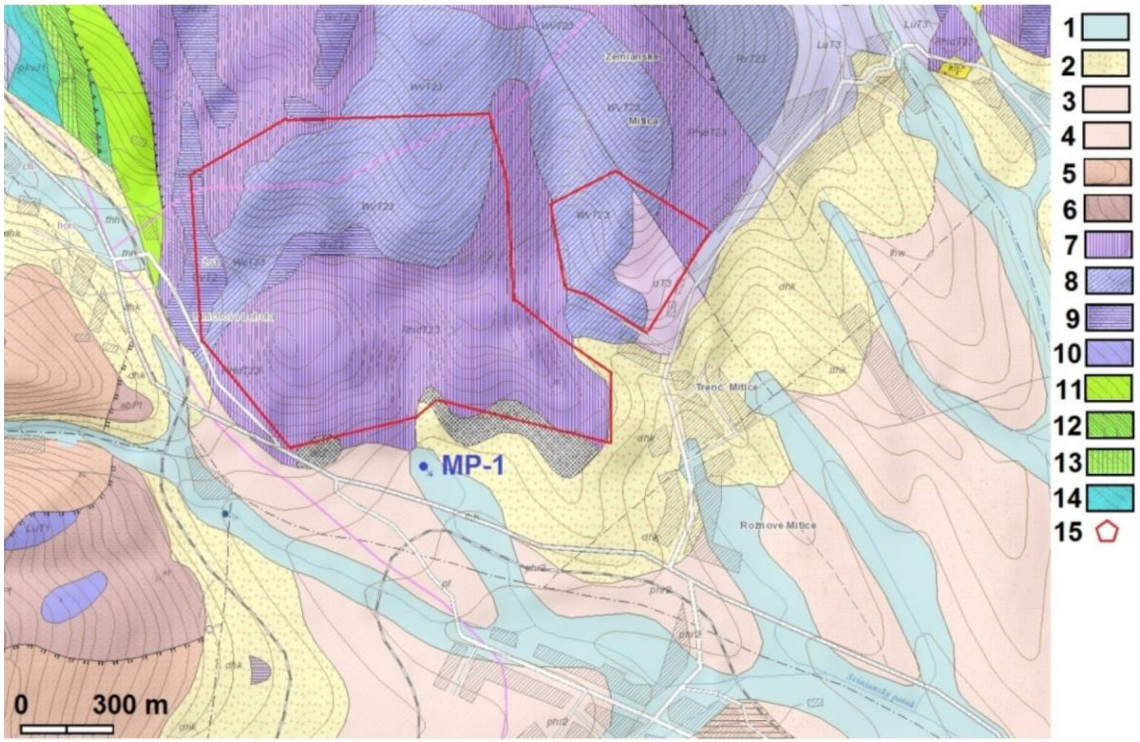
From the above methods, it is assumed that the use of a delay time is advantageous for local vibration reductions, since a tested blasting timing scheme is used. Although this idea was proposed by Langefors (Langefors and Kihlström, 1978), we found out that the accuracy of this method is not always sufficient. The accuracy of the detonation timing using conventional pyrotechnic detonators had always been a problem, which was solved by the introduction of electronic detonators. The arrival of the electronic detonators has increased the possibilities of vibration reduction (Baulovič, 2019).

With the development of high-precision digital electronic detonators, very accurate timing of blasting operations has been made possible. Vibrations can be reduced using a method in which the waves are superimposed on each other in phase or in antiphase (Mogi and Kou, 1999). The solution to reducing vibration is to set the delay time correctly. In blasting works, it is assumed that the method of calculating the delay time is based on the propagation velocity of seismic waves and their frequency. Furthermore, the effect of interference by superposition of the seismic waves is taken into account when calculating the delay time. Two seismic waves can achieve the maximum vibration interference when the delay time is half the time of the wave period. In the literature, the delay time is given according to the experience gained from many projects. Langefors (Langefors and Kihlström, 1978) proposed a millisecond delay interval $\Delta t = T/2$ (T is the period of vibration waves), which allows most vibrations to interfere with each other within a constant vibration cycle and the same vibration shapes. The delay times are determined on the basis of the effect of the rock environment disintegration and the effect of the wave superposition. The structural properties of the rock environment, in which the blasting works are performed, are obtained by measuring the velocity of seismic waves in situ (Leššo, 2018). During the millisecond timing of blasting, waves from multiple sources propagate simultaneously. If the phase difference of the two waves is 2π or another even multiple at a certain point, interference amplification occurs. If the phase difference is an odd multiple, interference attenuation occurs. The different cases of interference are very complex, since interfering waves can vary in wavelength, amplitude, phase and direction of the propagation. The simplest case of interference is the interference of two waves of the same wavelength passing through the environment at the same phase velocity and in the same direction. Such a case of interference occurs during the blasting work. The resulting amplitude during the interference of two identical waves is the largest at the collision points of the waves with the same phase, and the smallest at the collision points of the waves with the opposite phase. Therefore, the millisecond timing of blasting works needs to be designed depending on the structural properties of the rock environment, which are expressed by the velocity and frequency of seismic waves (Kou and Rustan, 1992; Wada et al., 1994; Tatsua et al., 2000; Lalwani and Menon, 2016; Leššo, 2018). Therefore, it is necessary to design the millisecond timing of blasting works depending on the structural

Fig. 1 View of the highest part of the quarry Mníchová Lehota

properties of the rock environment, which are expressed by the velocity and frequency of seismic waves (Lalwani and Menon, 2016; Leššo, 2018).

The research was carried out in cooperation with Austin Detonator Slovakia and Klub ZPS in Vibroakustika, Ltd. Žilina in the quarry Mníchová Lehota. The measurements of the velocity of the seismic wave propagation and the technical seismicity of the bench blasting 561 (hereinafter referred to as BB 561) were performed in the quarry Mníchová Lehota. The aim of the research was to determine the millisecond timing of individual blastholes during the mining blast by means of the propagation velocity and the frequency of seismic waves measured in the rock mass, to control the blasting delay of individual blastholes in a way that the maximum damping effect of the seismic waves generated by blasting is achieved. The aim was to achieve, by regulating the delay, that no damage is caused to the water resources in the zone of hygienic protection of the 1st degree located near the quarry Mníchová Lehota and the residential buildings in the village Trenčianske Mitice, as well as persons who are located in the residential buildings. To accurately determine the millisecond blasting timing of individual blastholes, electronic detonators with a delay setting accuracy of 0.1 millisecond were used.



Post Tertiary:

1- clays, sandy clays, loams, clayey sand and gravels of river and stream bottom lands,

2- aluminium-stony (sporadically stony-sandy)down-slopes and debris,

3- loess loams with loess locality,

4- mainly clayey and sandy gravels, sands and sand clays with rock fragments in the lower intemediate alluvial cones with a loess loam cover and flushes;

Crystallinity of Považský Ínovec:

5- muscovite strips up to grained pararula with amphibolite of staurolite and /or garnet often diaftorized and chloritized,

6- krivosúdsky complex of strata – vulcanoclastic sedimentary rock, smallgrained conglomerates largely light green fine-grained sandstones, locally violet siltstones;

Mesozoic of chočský overthrust:

7- dolomites, 8- wettersteinské limestones,

9- dark grey limestones,

10- lúžňanské complex of strata – pink, off white and white fine - up to course grained quartzites (silicious sandstones), in a few isolated cases conglomerates;

Mesozoic of krížňanský overthrust:

11- solid limestones and solid clays,

12- grey organodetritic limestones,

13- grey solid limestones,

14- sandy crinoid limestones,

15- border of the minig area

Fig. 2 Geological structure around the quarry Mníchová Lehota (Mahel', 1982)

2. Geological structure around the quarry Mníchová Lehota (transmission environment)

The Mníchová Lehota quarry (Fig. 1) is situated in the triassic carbonate sediments of the Choč overthrust nappe, mainly dolomites and Wetterstein limestones. At the western edge of the quarry, the crystalline of Považský Ínovec and the Mesozoic of the Krížňa overthrust nappe in the Zliechov sequence stand out. There can be observed the Dolomites and Wetterstein limestones of the Křížna nappe on it, in which the Mníchová Lehota quarry is founded. In the south, the quarry is bordered by the Neogene sediments of the Banov Hills. On the Post-Tertiary sediments near the former natural springs of mineral waters, there is a protected natural formation - the Mitická Slatina peat bog. There are several water sources in the vicinity of the Mníchová Lehota quarry. The MP-1 water source, captured by a well in 1992, has been protected and used by law since 2002.

Fig. 3 A view of the individual floors of the quarry Mníchová Lehota with a visible high rate of rock mass disturbance and the site of blasting works

3. Measurement methodology and used equipment

Digital four-channel seismographs were used to measure the seismic effects of the blasting:

- ABEM Vibraloc and seismic sensors of the Swedish company ABEM (Fig. 4, 5),
- Svan 958 A vibrometer and SV 84 mechanical vibration sensor (Fig. 6).

***Fig. 4** The monitoring station in the quarry Mníchová Lehota quarry at a distance of 18.5 m from the initial blasthole including the three-component Vibraloc sensor on a special base*

***Fig. 5** The monitoring station MS2, water source MP-1 and Vibraloc measuring equipment including the three-component Vibraloc sensor on a special base on a concrete step in the entrance to the water source building*

***Fig. 6** The monitoring station MS3 Trenčianske Mitice, part Rožňové, no. 371, 2nd floor, children's room, including the three-component Svantek sensor on a special base in the middle of the room (Sobota and Šimo, 2019)*

The monitoring station MS1 was located in the quarry Mníchová Lehota at a distance of 18.5 m from the initiation blasthole. At the monitoring station, a three-component Vibraloc seismic sensor was placed on a special pad, which ensured contact with the rock (Fig. 4).

The monitoring station MS2 was situated in the water source building MP-1. The distance of the monitoring station from the blasting point was 900 m. At the monitoring station, a three-component Vibraloc seismic sensor was placed on a concrete base at the entrance to the water source building (Fig. 5).

The monitoring station MS3 was situated in a residential building in the village of Trenčianske Mitice, part Rožňové no. 371. The distance of the monitoring station from the place of blasting was 900 m. A three-component Svan 958 A vibrometer was placed in the monitoring station in order to objectify the impact on people in the indoor environment of the residential building (Fig. 6).

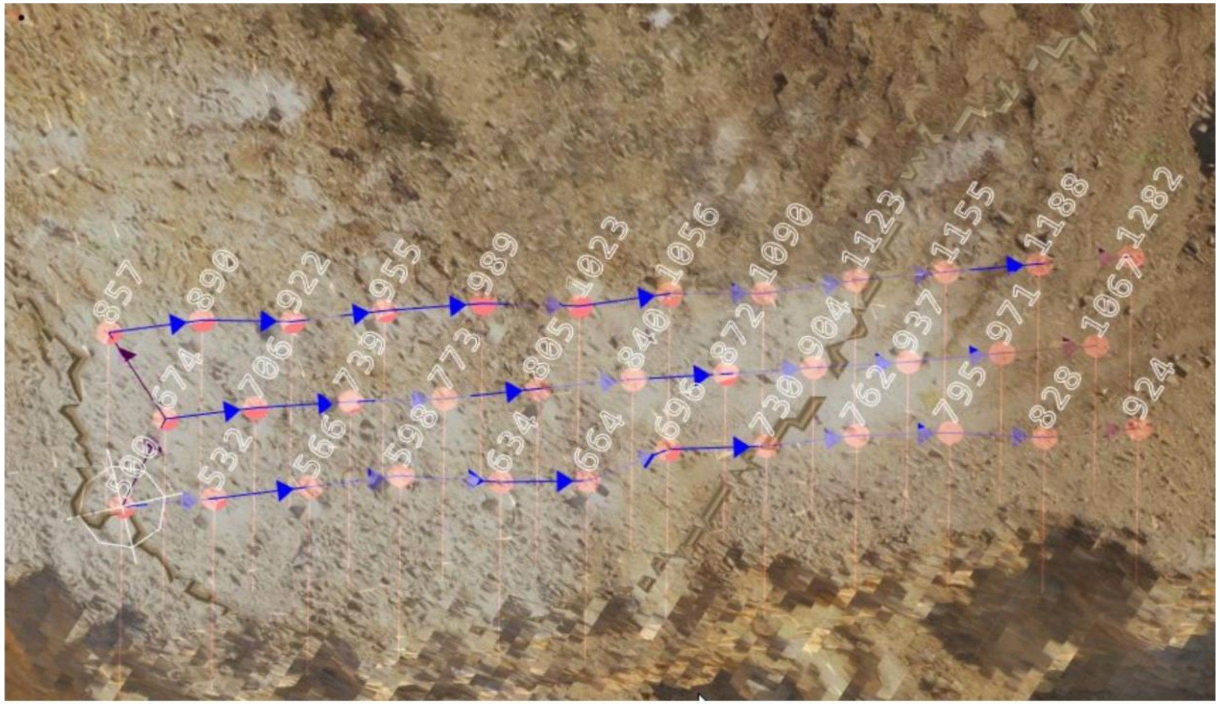


Fig. 7 Diagram of the blasthole layout and timing of the bench blasting 561 in milliseconds

4. Vibration source

The source of seismic effects was the bench blasting no. 561 in the quarry Mníchová Lehota.

Parameters of BB 561

Blast number: bench blasting 561, total charge 3275.0 kg, charge per one-time stage 100 kg, bench blasting duration 500 ms, 35 blastholes with a blasthole depth of 20 m, distance between blastholes 3.2 m, scope 3.5–4.2 m, the delay interval between the detonations of individual blastholes is shown in Fig. 7.

Tab. 1 Data on the position and distance of geophones from BB 561

Station number	**Station description**	**Geophone coordinates**			**Distance from the blast to the station**		**note**
		x	**y**	**z**	**slope**	**horizontal**	
1	3rd floor BB	-	-	-	27.5 m	18.5 m	blast
2	Water source MP-1	-	-	-		900 m	
3	Rožňové no. 371	-	-	-		900 m	

Fig. 8 Seismic profile on the quarry wall before blasting. 24 geophones were deployed in a range of 2 m to the distance of 48 m

5. Measured values

Prior to blasting, the velocity of seismic waves at the blasting site was measured using a Terraloc Mk8 seismic equipment. The seismic profile was placed parallel to the quarry wall approximately 10 m from the edge of the quarry wall in the length of 48 m (Fig. 8). The resulting measurement record is shown in Fig. 9.

The vibration velocity measuring instruments stored at the monitoring stations 1, 2 and 3 were calibrated and their sensitivity was checked before the measurement. The measured values during the blasting at the monitoring stations are provided in Table 2. A graphical course of individual components of seismic waves was also recorded at each monitoring station (10, 11, 12). The measured values are provided in Table 2.

Based on the measured values of velocities and frequencies of individual components of waves during bench blasting in the quarry Mníchová Lehota, we were able to assess the effects of the individual blasts and evaluate their impact on water sources in the zone of hygienic protection of the 1st degree, located near the quarry Mníchová Lehota, according to STN EN 1998-1/NA/Z1.

6. Permissible particle velocity for slopes, mining and engineering works

We do not come with any recommendations for the assessment of surface and underground mining and engineering works built directly in the rock mass. These works are usually considered as buildings on the surface, which is far from capturing the real conditions, because the rock mass can withstand much higher vibration velocities compared to buildings.

Ensuring the seismic safety of these works during blasting works consists in preventing the formation of residual deformations in the mass of rocks on which these works are built. Only such strain that does not cause permanent deformations is permissible in the rock mass.

Tab. 2 Measured data of frequencies and maximum vibration velocities during the BB 561

Station/detonation	**x [Hz]**	**y [Hz]**	**z [Hz]**	**x [mm. s^{-1}]**	**y [mm. s^{-1}]**	**z [mm. s^{-1}]**
1 - quarry	5.3	4.5	68	101	119	325
2 - water source MP–1	5.6	4.25	9.94	0.7	0.84	0.4
3 - Rožňové no. 371	7.3	6.2	23	0.52	0.74	0.32

The evaluation of the rock stability of pits, adits, underground chambers, protective pillars, hydrotechnical tunnels, slopes, notches, quarry floors, heaps, etc., is therefore based on the deformation properties of rocks.

The criterion is the relative deformation and the benchmark is again the particle velocity v_p. Some authors rely on the general deformation model of rocks as a continuous elastic-plastic environment. Under a certain amount of pressure, both the loading and the relief of the rock take place flexibly, while upon exceeding a certain limit, permanent residual deformations occur. Their accumulation due to periodic blasting can lead to loss of stability and rock collapse. Then, the relative deformations $\varepsilon_0 \leq 0.0002 \div 0.0003$ are still within the elasticity limits (Pandula and Kondela, 2010).

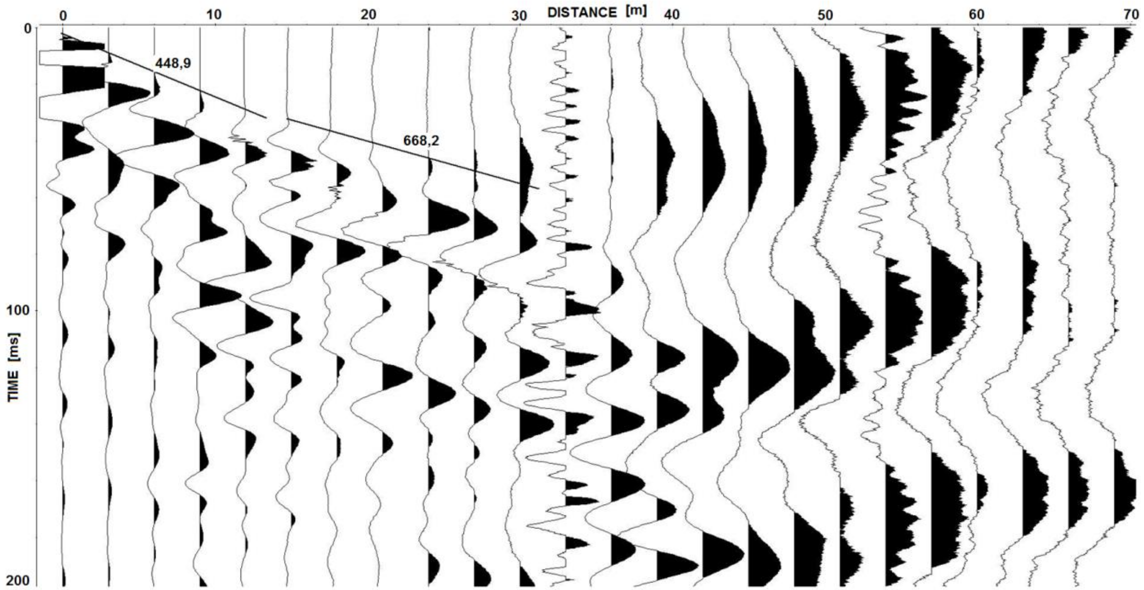


Fig. 9 Seismic record from the Terraloc Mk 8 measuring equipment from a 48 m profile with the identified speed and frequency of seismic P - wave propagation. The record shows that up to a depth of 3 m, the velocity of seismic waves was 400 m.s^{-1} with a frequency of 5.8 Hz. At a depth of 3 m there was a change in the speed of propagation of seismic waves to a speed of 600 - 700 m.s^{-1} with a frequency of 16.4 Hz

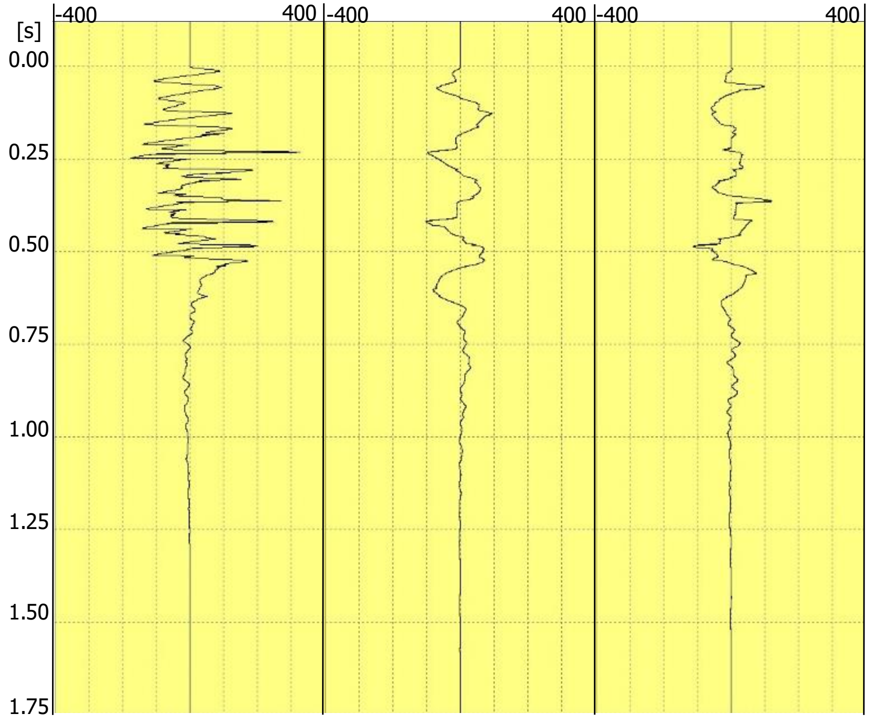


Fig. 10 Graphic four-second record of the course of individual components of bench blasting seismic waves in the Mníchová Lehota quarry. The record comes from the ABEM Vibraloc measuring equipment at the monitoring station MS1, 18.5 m from the initiation borehole

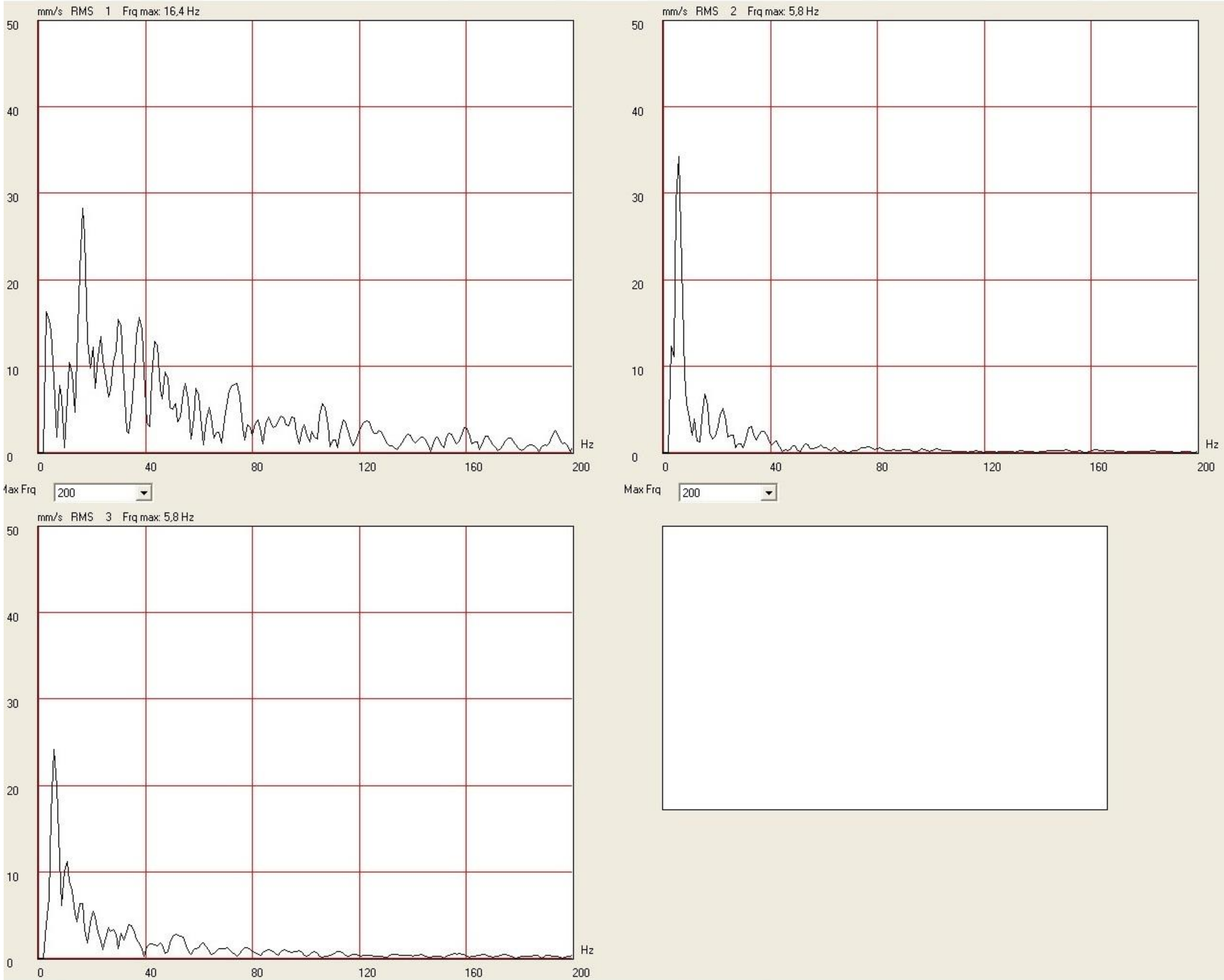


Fig. 11 Frequency FFT analysis of individual wave components from the measurement at the monitoring station MS1 – the quarry Mníchová Lehota

Device type	SVAN 958A	**Standard** DIN 4150-3		
Serial No.	36632			
File name	Buffer_2			
Measurement time	11:29:32			
Measurement date	18. 10. 2019			
Logger step	1 s			
FFT band	175.000 Hz			
Measure Trigger mode	Off			
Recorded at	18. 10. 2019 11:38:42			

		X	**Y**	**Z**
Peak	mm/s	0.519	0.741	0.320
Dominant frequency	Hz	7.324	6.226	23.071
Peak Acceleration	mm/s^2	23.878	29.007	46.398
Peak Displacement	mm	0.011	0.019	0.002

PPV 0,741 mm/s

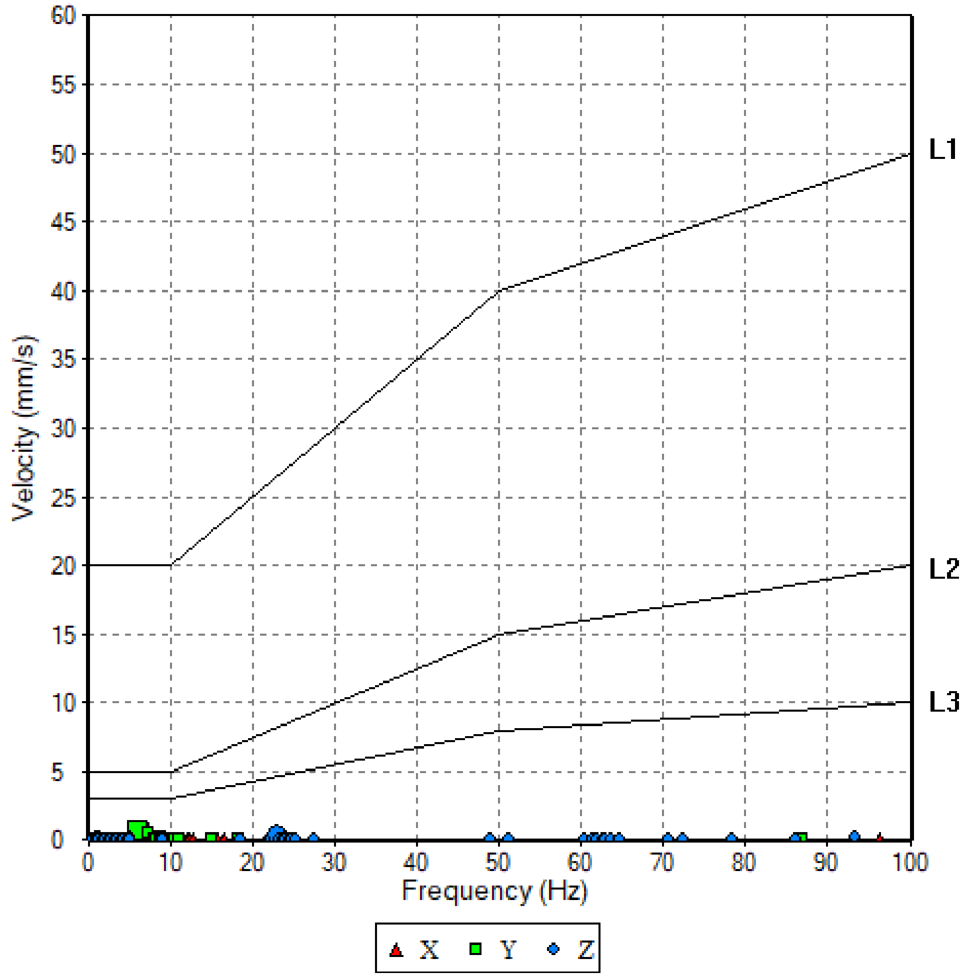


Fig. 12 Measured peak values of the vibration velocity, frequencies, accelerations and blast deflection in the residential object in the village Trenčianske Mitice, part Rožňové, measuring standpoint MS3 (Sobota and Šimo, 2019)

For works that must have a long lifespan (notches, etc.), the condition of seismic safety can be expressed depending on the velocity of longitudinal waves in the mass c_p:

$$v_p = \mathbf{0.0001c_p}\ [m.s^{-1}]$$

For underground and other mining works, due to their different required lifespan, the boundary conditions of vibration may be different. It is recommended to classify works into four classes, in the vicinity of which, depending on the lifespan, relative deformations of $10^{-4} \div 5.10^{-4}$ are permissible.

Depending on the function of the elastic-plastic properties of the rocks and the permissible relative deformation, the following relation is recommended for the calculation of the permissible particle velocity (Dojčár et al., 1996):

$$v_p = \frac{375 \cdot \left(c_p^2 - \frac{4}{3} \cdot c_s^2 \right) \cdot \left\{ \left[1 + (1 - 2 \cdot \mu) \cdot \varepsilon_0 \right]^{\frac{8}{3}} - 1 \right\}}{c_p \cdot \left[1 + (1 - 2 \cdot \mu) \cdot \varepsilon_0 \right]^4}$$

where:

1) v_p is the permissible particle velocity [mm.s^{-1}],
2) c_p, c_s are the velocities of longitudinal and transverse waves in the mass [m.s^{-1}],
3) μ is the Poisson's ratio,
4) ε_0 is the permissible relative deformation.

The values of v_p calculated from the formula for individual classes of mining works are provided in Table 4. These correspond very well with the values of c_p measured and determined for solid rocks in various underground mines (300 ÷ 500 m.s^{-1}). For periodic blasts, it is recommended to reduce the permissible particle velocities in Tables 4 and 5 by the safety coefficient c_s, (v_p/c_s), depending on the object class T:

Tab. 3 Safety coefficient for individual object classes

Object class T	**1**	**2**	**3**	**4**
Safety coefficient c_s	1.52	1.44	1.36	1.3

The quality of buildings (q) is provided in Table 5. The overall quality consists of four sub-values:

$q = q_1 + q_2 + q_3 + q_4$.

The quality q is put into relation for the calculation of the permissible particle velocity. The recommended permissible particle values are given in Table 5. Table 4 shows the permissible particle velocities in rock environments with different degrees of disturbance, expressed by the strength coefficient c_f and the velocity of propagation of longitudinal waves c_p.

Sources of drinking water are situated in the rock mass and their lifespan is expected to be several decades. We consider the blasts carried out in the quarry Mníchová Lehota to be periodic, given that this is a permanent mining operation in the quarry. We place the class of the assessed object, sources of drinking water, among the particularly important works with a lifespan of more than 10 years T-1. The assessment of the quality of an object depends on several factors. It is based on the method of its foundation, construction, used material and physical condition of the object at the time of measurement. In the case of assessing the seismic effects of blasting works on drinking water sources, it is not only an assessment of the physical condition of the water management work, but mainly an assessment of the rock environment, which is the collector. For the above reasons, we set a value of 6 for the quality parameter *q* of the object, where the permissible vibration velocity of the individual components is 2.2 mm.s^{-1} (Table 5). At values of vibration velocities less than 2.2 mm.s^{-1}, no further disturbances occur even in the disturbed rock environment.

Tab. 4 Vibration velocities during periodic blasts

Rock properties	**Strength coefficient** c_f	c_p **[km.s^{-1}]**	**Permissible particle velocities** v_p **[mm.s^{-1}]**			
			1*	**2***	**3***	**4***
Strongly cracked and porous	0.5 ÷ 1	1 ÷ 2	41	82	122	204
Strongly cracked and porous	1 ÷ 3	2 ÷ 3	68	136	203	340
Rocky, strongly cracked	3 ÷ 5	3 ÷ 4	95	190	284	475
Relatively solid, cracked	5 ÷ 9	4 ÷ 5	122	244	367	600
Solid, slightly cracked	9 ÷ 14	5 ÷ 6	149	298	445	745
Very strong, solid	14 ÷ 20	6 ÷ 7	178	356	533	890

* **Classes of engineering works:**

1. Particularly important works with a lifespan of over 10 years, ε_0 = 0.0001 (hydrotechnical tunnels, pits, main mining works, drainage and other water management works).
2. Important works with a lifespan from 5 to 10 years, ε_0 = 0.0002 (shaft bottoms, headings, ceiling pillars, stable slopes of floors and heaps, etc.).
3. Works with a short lifespan from 1 to 5 years, ε_0 = 0.0003, (corridors, chambers, etc.).
4. Works with a lifespan of up to one year, ε_0 = 0.0004, (stopes, slopes of working floors, etc.).

Tab. 5 Vibration velocities during periodic blasts

Object class T	**Permissible particle** v_p **[mm.s^{-1}] for the quality q of the object**								
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	46	27.6	16.5	10	6	3.7	**2.2**	1.3	-
2	75	46	27.6	16.5	10	6	3.7	2.2	1.3
3	120	75.6	46	27.6	16.5	10	6	3.7	2.2
4	198	120	75	46	27.6	16.5	10	6	3.7

7. Permitted vibration velocity for protected water management works

Based on Eurocode 8 STN EN 1998-1 /NA/Z1 Seismic loading of building structures, with regard to the charges used for bench blasting in the Mníchová Lehota quarry, which represent hundreds of kilograms, where the vibration frequencies are usually f < 10 Hz, and on the basis of the resistance of water management works to technical seismicity, the water source in the vicinity of the quarry Mníchová Lehota can be included among the particularly important works with a lifespan of more than 10 years T-1.

As for the quality of the object, due to the absence of more specific characteristics and data, we can classify it as the quality of the object q-6.

Based on the above and due to the longer-term nature of blasting at the Mníchová Lehota limestone deposit and with regard to the nature of the transmission environment, for disconnection by bench blasting at the Mníchová Lehota deposit and for water management works near the quarry, the maximum permissible particle velocity (velocity component) can be set to

$v_d \leq 2$ mm.s^{-1}.

8. Measured seismic effects of bench blasting works and their analysis

For living spaces, hostels, retirement homes, for the reference time interval, permissible vibration acceleration values (Sobota and Šimo, 2019) are:

evening: $a_{weq,p} = 0.008$ m.s^{-2}, $a_{wmax,p} = 0.11$ m.s^{-2},
night: $a_{weq,p} = 0.005$ m.s^{-2}, $a_{wmax,p} = 0.05$ m.s^{-2},
day: $a_{weq,p} = 0.008$ m.s^{-2}, $a_{wmax,p} = 0.11$ m.s^{-2},

where a_{weq} [m.s^{-2}] is the equivalent weighted vibration acceleration obtained by applying the frequency weighting function to the time function of the vibration acceleration.

a_{wmax} [m.s^{-2}] is the maximum weighted vibration acceleration - the highest value of the weighted vibration acceleration in the monitored time interval and at a given location using the time weighting function Slow.

Tab. 6 The peak value of the vibration velocity and maximum weighted values of vibration acceleration in reference stations MS3 and MS2 on water source MP–1

		MS3 v_{peak}/v_{ef} **[mm.s^{-1}]**	**MS3** $a_{w,max}$ **[m.s^{-2}]**	**MS2** v_{peak} **[mm.s^{-1}] / f [Hz]**
Bench blasting 561	direction "x"	0.519/0.197	0.002	0.696/5.60
	direction "y"	0.741/0.272	0.003	0.839/4.25
	direction "z"	0.320/0.133	0.006	0.405/6.94

According to Eurocode 8 design of structures for seismic resistance STN EN 1998-1/NA /Z1 seismic load and rules for buildings, the value of vibration velocity is assessed: Effective value of vibration velocity $v_{ef,z,T}$ [mm.s^{-1}] is equivalent to vibration velocity for the time interval T = 1s at a given location using the time weighting function Slow.

The peak value of the vibration velocity $v_{peak,z,T}$ [mm.s^{-1}] is the peak value of the vibration velocity when using the Peak function.

Assessed effective and peak values of vibration velocity and maximum weighted values of vibration acceleration in reference stations MS3 Trenčianske Mitice, residential building no. 371 and MS2 on water source MP–1 (Table 6).

The assessed values of the equivalent $a_{Rweq,z}$ and the maximum $a_{Rwmax,z}$ vibration acceleration at the monitoring point MS3 from the bench blasting 561 in the indoor environment of buildings do not exceed the permissible values of the determining values of the vibration acceleration.

The analysis of the measured velocities of seismic waves and frequencies on the quarry wall showed that the quarry wall is significantly disturbed in the upper part to a depth of 3 m. Measured seismic wave propagation velocities were 300 $m.s^{-1}$ and the wave frequency was 5.8 Hz. At a depth of 3–12 m, measured propagation velocities were 600–700 ms^{-1} and the wave frequency was 16.4 Hz. Then, according to the millisecond delay theory $\Delta t = T/2$ (T is the seismic wave period), the optimal timing for the screen blast was $\Delta t = T/2 = 1/2f = 1/16.4 = 30.5$ ms. The millisecond timing delay used in the blasting was 32–34 milliseconds (Fig. 7) depending on the different structural properties of the quarry wall rock environment. The exact delay in individual parts of the quarry wall was possible using electronic detonators. By controlling the millisecond delay timing between individual blastholes, the desired fragmentation could be achieved (Fig. 13).

The measurement of seismic effects of bench blasting in the quarry Mníchová Lehota and in its vicinity was performed in the conditions of a slightly flooded transmission rock environment after the previous period of prolonged drought. Assessed effective and peak values of vibration velocity at reference stations Trenčianske Mitice, residential building no. 371 and on the water source MP-1 were not exceeded. The measured maximum values of the vibration velocity components of the bench blasting in the quarry Mníchová Lehota are provided in Table 2.

Fig. 13 Rubble after the bench blasting 561 in the quarry Mníchová Lehota

Based on the data from Table 2 and the value of the coefficient of the non-flooded transmission environment, a graphical dependence of the maximum vibration velocity components on the reduced distance during bench blasting was constructed. The graph in Fig. 14 represents the so-called law of seismic wave attenuation for the quarry Mníchová Lehota, in which the value Q was used in the form of

$$v = \left(\frac{L}{Q^{0.5}}\right) = K\left[\frac{L}{Q^{0.5}}\right]^n,$$

where "*v*" is the maximum particle velocity (maximum particle velocity component) generated by blasting, [$mm.s^{-1}$],

$L/Q^{0.5}$ is the so-called reduced distance, [$m.kg^{-0.5}$],

L is the shortest distance of the vibration source from the receptor [m],

Q is the weight of the time stage charge [kg],

K is the coefficient depending on the blasting conditions, the properties of the transmission environment, type of explosive, etc.,

n is an indicator of seismic wave attenuation (Pandula and Kondela, 2010).

From the law of seismic wave attenuation, it is possible to determine the charge size for a particular receptor at a known distance so that the maximum values of individual components of the vibration velocity do not exceed the specified maximum permitted vibration velocities.

From the law of seismic wave attenuation for the quarry Mnichová Lehota, the reduced distance for the maximum permissible vibration velocity $v_{max} = 2\ mm.s^{-1}$ is expressed by the value $L_R = 60$. Consequently, it is possible to calculate the maximum permissible charge per time stage, the so-called equivalent charge $\boldsymbol{Q_{evmax}}$ for the distance of the source - blasting works in the quarry Mníchová Lehota and the receptor - water source MP–1 as follows:

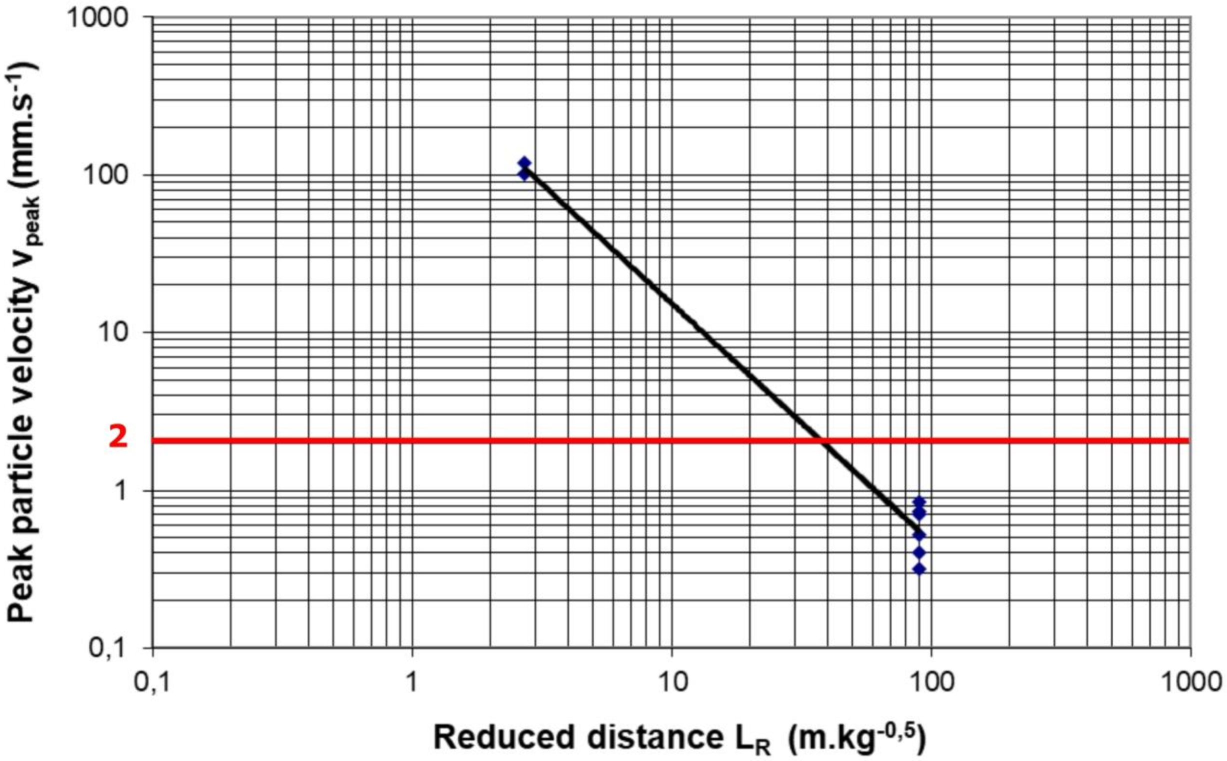


Fig. 14 The law of seismic wave attenuation for the quarry Mníchová Lehota

for a distance of 1,500 m $Q_{evmax} = (L/L_R)^2 = (1{,}500/60)^2 = 625$ kg,
for a distance of 1,000 m $Q_{evmax} = (L/L_R)^2 = (1{,}000/60)^2 = 277$ kg,
for a distance of 500 m $Q_{evmax} = (L/L_R)^2 = (500/60)^2 = 70$ kg.

In this way, for a specific distance of the source of seismic effects, i.e. blasting works in the quarry Mnichová Lehota, it is possible to calculate the maximum permissible charge per time stage, the so-called equivalent charge $\boldsymbol{Q_{evmax}}$.

9. Conclusion

Mining at the quarry Mníchová Lehota site is carried out using bench blasting. Depending on the source-receptor distance, the intensity of the seismic effects then corresponds to this fact.

The research carried out at the Institute of Geosciences, Faculty of Mining, Ecology, Process Control and Geotechnologies (FBERG) Technical University of Košice in recent years has clearly showed that in order to assess the seismic safety of large-scale blasting works, it is necessary to establish the law of seismic wave attenuation for the monitored area - studied rock environment, and determine the most accurate delay of millisecond timing depending on the structural properties of the rock environment. In practice, it is necessary to evaluate at least two measurements at two stations in order to obtain the necessary statistical set, both to determine the law of seismic wave attenuation, but also sufficient data for determining the value of millisecond timing. This information is necessary to achieve the permitted particle velocity not only for the monitored receptors, but also for persons who are in residential buildings.

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