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OPTIMIZATION OF SEISMIC EFFECT DURING BLASTING OPERATIONS BY VELOCITIES OF SEISMIC WAVE'S PROPAGATION IN QUARRIES

OPTIMALIZÁCIA SEIZMICKÝCH ÚČINKOV TRHACÍCH PRÁC V LOMOCH POMOCOU RÝCHLOSTI ŠÍRENIA SEIZMICKÝCH VĹN

Blažej Pandula [1], Julián Kondela [2], Vladimír Budinský [3], Marta Prekopová [4], Ján Baulovič [5], Ján Feher [6], Jozef Čambal [7]

Abstract

Harmful seismic impact of the blasting operations is an important issue limiting the extent of blasting operations representing significant part within industrial chain. The unreasonably high technical seismic safety results in decrease of the explosive charges and blasting and as a consequence it causes lower economic efficiency of both the shooting and blasting and quarrying. On the contrary, the underestimation of the seismic impacts could cause large scale material damages. In this paper we describe methodology for assessment of seismic wave's propagation velocity, which enables the optimization of the seismic effect of blasting operations in the quarry Včeláre.

Abstrakt

Škodlivý seizmický dopad trhacích prác je dôležitým problémom, ktorý obmedzuje rozsah trhacích prác predstavujúcich dôležitú súčasť priemyselného reťazca. Neodôvodnený vysoký dôraz na seizmickú bezpečnosť spôsobuje zníženie hmotnosti náloží odstrelov, čoho následkom dochádza k zníženiu ekonomickej efektivity trhacích prác. Naopak, podhodnotenie seizmických účinkov trhacích prác môže viesť k obrovským materiálnym škodám. V tomto článku opisujeme metodiku určovania rýchlosti šírenia seizmických vĺn, ktorá umožňuje optimalizovať seizmické účinky trhacích prác v lome Včeláre.

Keywords

blasting operations, velocity of seismic waves propagation, millisecond timing, seismic safety, seismic waves attenuation

Kľúčové slová

trhacie práce, rýchlosť šírenia seizmických vĺn, milisekundové časovanie, seizmická bezpečnosť, útlm seizmických vĺn

1 Introduction

Seismic has an important and well-known role during blasting operations. Despite of the clearly stated seismic methodology, the engineering seismic did not reveal the empirical approach and often relies more on the head of blasting instead of scientifically verified knowledge. The nature of the rock environment where the blasting is realized is very complicated and usually the physical and mechanical features of the rocks cannot be well defined. (Pendula and Kindelay, 2010)

The effect of the pressure originated in the blast centre is creation of stress waves propagating through the surrounding environment and spreading the part of the explosive energy to greater distance. The resulting vibrations are non-periodical and propagate through the rock environment as seismic waves. Their propagation is influenced mainly by the features of the rock massif; (Don Let (1960), Dogcart at al. (1996), Barton (2007), Clemente and al. (2002), Pendula and Kindelay (2010) and Banerjee and Kumar (2016)).

In this sense we should focus on the statement of (Mosinec, 1976): "The history of the rocks, their mineralogical composition, and alternation after secondary processes as serpentinization. Dolomitization and crystallisation, increase/decrease of porosity, moisture and pressure – these all parameters are reflected in the velocity propagation of the elastic waves, and thus make the velocity a gauge of data about the rocks properties.

The velocity propagation of seismic waves depends on the velocity propagation in the solid part (skeleton) of the rock, on the porosity (percentage of volume of the pores/volume of the rock), on the velocity propagation through the filled pores and on the parameters of blasting. In general, there is a rule, that the seismic velocity in highly porous rocks is lower comparing with the rocks characterized with low content of pores. Also, the velocity is significantly greater in saturated environment than in non-saturated rocks with the same content of pores (Lama and Vutukuri (1978), Kalab (2004) and Barton (2007)). The velocity of spreading through the skeleton is influenced by its mineralogy; the velocity of the filled pores depends on the nature of the infill (air, water) and is usually lower than the velocity of propagation through the skeleton. The porosity is influenced by pressure generated during the blasting; increasing pressure decreases the porosity and increases the Young module *E* and the velocity of the waves as well. Contrary, the blasting lead to rock massif destruction and thus result in decreasing of the velocity propagation of seismic waves; (Mareš et al. (1990), Dojčár at al. (1996), Barton (2007), Pandula and Kondela (2010), Kalab at al. (2015) and Banerjee and Kumar (2016)).

The velocity of the seismic waves is measured by seismographs – devices for seismic signal recording and modification. Their main aim is to register the mechanical vibrations of the ground particles induced by seismic wave transfer from the source to individual geophones and to record the arrival time and the course of the wave.

To measure the particle velocity of the seismic wave during blasting operations, vibration monitors are used. We consider as vibration monitors a complex of devices for registration of the seismic signal created by blasts. The main goal of the vibration monitor is to record the mechanical vibration of the ground particles induced by seismic wave arrival from the source to the geophones and to record the peak particle velocity and course of the seismic wave on the monitored standpoint. See in (Pandula and Kondela, 2010) and too (Knejzlik at al., 2012).

Seismic devices are not so frequently used during blasting operations. Therefore, it was necessary to suggest a methodology for measuring the velocity propagation of seismic waves by devices determining usually only the blasting effect during blasting operations. Vibration monitors are more channelled; therefore at least one of the channels can measure the velocity of the seismic wave propagation. This measurement is not as precise as the measurement of the seismic velocity by seismographs, but it is sufficient to determine the millisecond timing of the blasting.

The seismic effects of blasting works can be significantly reduced by dividing the whole explosive into several partial charges. Very effective is the millisecond timing of the blasting, after which the time delay of each charge result in the interference of seismic waves and the negative effects are cancelled; (Don Leet (1960), Mosinec (1976), Dojčár at al. (1996), Barton (2007), Clemente and al. (2002), Holub (2006), Pandula and Kondela (2012), Kalab at al. (2013), Banerjee and Kumar (2016) and Triparthy at al. (2016)).

Maximal decreasing of the vibration velocity during blasting operations can be achieved by timing interval for charges (Mosinec, 1976):

$$\tau = \frac{10^5}{c_p} \text{ in } [\text{ms}], \qquad (1)$$

where c_p is propagation velocity of the longitudinal seismic waves through the rock environment between blasts and protected object; is expressed in [m×s^{-1}].

In accordance with selected value of characteristicτ, the total weight of the explosive can be:

$$Q_c = Q_č \times N^t \text{ or too } Q_c = Q_p \times N^t \text{ in } [\text{kg}], \qquad (2)$$

where $Q_č$ is the permitted weight of the timing blast i.e. weight on the millisecond timing level in [kg], N is number of charges, or rather group of charges with weight Q_p blasted with interval τ and t is an exponent dependent on the massive features according tab.1.

Based on tab.1, the higher are the propagation velocities of seismic waves, the lower are the millisecond timing intervals during blasting operations. Therefore, for the correct determination of the timing interval it is important to know the propagation velocities of the seismic waves through the rock environment, where the blasting operations are planned.

Tab. 1 Values of exponents dependent on the rock massif features (Műncner, 2000)

c_p [m×s^{-1}]	τ [ms]	t
≤1000	100	0.3
1000 ÷ 1500	70	0.45
1500 ÷ 2000	60	0.6
2000 ÷ 2500	50 ÷ 40	0.7
2500 ÷ 3000	40 ÷ 35	0.8
3000 ÷ 3500	35	0.9
3500 ÷ 4000	35	1.0
≥4000	20 ÷ 10	1.0

2 Methodology of the measurement and devices used during the blasting operations

Experimental measurements were carried out in a Včeláre limestone quarry. Based on the experiments realized in the quarry by seismograph Terraloc Mk8 and vibration monitor UVS 1504 we have measured velocities of propagating seismic waves generated during the blasting works. Their interpretation can help to assess the millisecond timing interval leading to the decreasing seismic effects of the blasting works to the surrounding environment.

The Včeláre quarry is located in Wetterstein limestones of a Silica nappe. The Silica nappe is extensive horizontal and subhorizontal body dominated by middle- and lower-Triassic carbonate sediments. Wetterstein limestones are mined raw materials used mainly in metallurgical and cement industry. The village Včeláre lies on the Quaternary deluvial-eolic loess and loamy loess covering the underlying limestones. Contrary to the limestones, the loess is typical by higher attenuation of the seismic waves. (Kaličiak, 1991)

For measurements and graphical records of the propagating seismic wave's velocities and of the seismic effects resulting from the blasting the following digital seismic devices were used:

- seismic device Terraloc Mk8 from Swedish company ABEM and geophones from ABEM, as well; in fig.2.
- vibration monitor UVS 1504 and geophones of the velocity UVS; in fig.3.
- vibration monitor ABEM Vibraloc and geophones of the particle velocity ABEM; in fig. 4.

Graphical record of the seismic wave was recorded near bench blasting, No.4430 and No.4431, on the profile P1 at the standpoints S1, S2, S3 and X in figs. 1, 2 and 3. At the standpoints S1 and X in the Včeláre quarry, geophones of both devices Terralock Mk8 and vibration monitor UVS 1504 were located close to each other in order to determine the propagating seismic waves velocities; in fig.3. Vibration monitors ABEM Vibraloc were located at the measured standpoint S2 – church and standpoint S3 – house to record the effect of seismic waves on the objects; in fig.5. Distances between the blasts and standpoints are shown in tab.2 and fig.1. The measured values at the individual standpoints can be seen in tab.3.

Tab.2. Basic data regarding the blasts positions and standpoint distances from the blasts (fig.2)

Standpoint	Blast	Geophones and blasts coordinates			Distance between the blast and standpoint		Note
		x	y	z	Oblique[m]	Horizontal[m]	
S1-Včeláre quarry	4430				166	165	blast
S1-Včeláre quarry	4431				172	213	
S2- church	4430 4031					1020	
S3- house	4430 4031					1013	

Fig. 1 Location and distance of the bench blasting in Včeláre quarry to the standpoints in Včeláre quarry - S1 and in Včeláre village, church – S2 and house - S3.

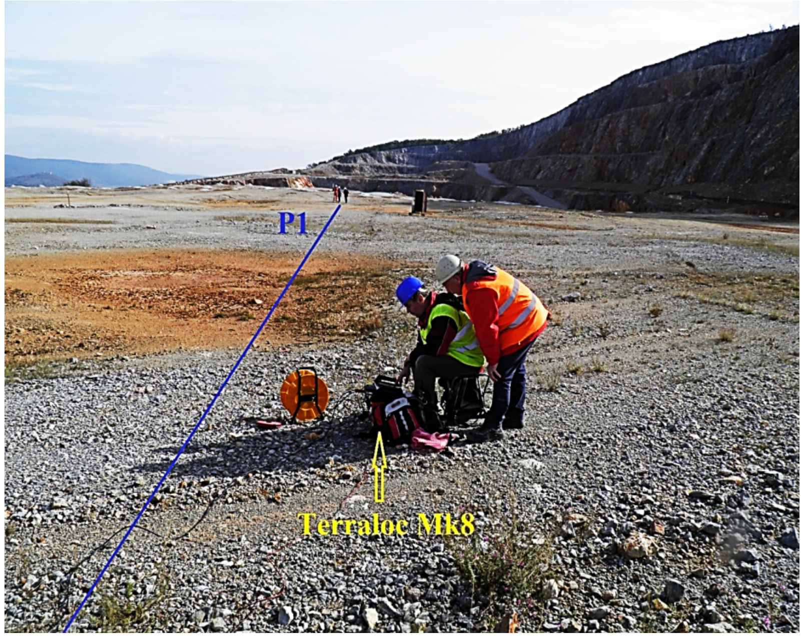

Fig. 2 Seismic device Terraloc Mk8 during the measurement of propagating seismic waves velocities from the blasting, P1 – 184 m long seismic profile located in the Včeláre quarry.

2.1. Source of the shocks

The source of the seismic effects was bench blasts No. 4430 and 4431 within the limestone quarry lying 1 km on the south from the Včeláre village. The blasting was located at the middle part of the II-level of the north margin of the quarry; see fig.5.

Tab.3 Measured particle velocities and frequencies for CO No. 4430 and 4431

Standpoint	**x** v[mm×s^{-1}]	**y** v[mm×s^{-1}]	**z** v[mm×s^{-1}]	**x** f [Hz]	**y** f [Hz]	**z** f [Hz]
S1 = quarry	36	26,5	49.9	13	5,5	25
S2 – church	1.06	1.05	1.3	4.2	4.1	4.5
S3 – house	1.188	2.084	0.83	6.71	3.47	4.6

- Bench blast No. 4430: 11 boreholes with 105 diameter and 16 to 19.4 m length, with shot 4.2 to 4.7 m and 5.3 m distance were drilled. The overall charge was 1064 kg explosive with maximal charge 99 kg for one timing step. The details about explosives are in tab.2; non-electric discharge. The scheme timing of the blasting is on fig. 6.
- Bench blast No. 4431: 13 boreholes with 105 diameter and 16 to 19.4 length, with shot 4.2 to 4.7 m and 5.3 m distance were drilled. The overall charge was 1167.5 kg explosive with maximal charge 94.5 kg for one timing step. The details about explosives are in tab. 2; non-electric discharge. The scheme timing of the blasting is on fig. 6.

3 Measured propagating velocities of seismic waves, seismic effects of bench blasting and their analysis

Record of the wave field from the seismograph Terraloc Mk8 at bench blasts No.4430 and No.4431 at 184 m long profile P1 in the quarry Včeláre is displayed in fig.7. Geophone´s offset was 8 m and the profile was located 165 m from initiation borehole of the bench blast No.4430; see fig.6. The measured velocity of propagating seismic waves from the blast between the first geophone at the profile P – standpoint S1 and sixth geophone – standpoint X at 48 m was 4112 $m \times s^{-1}$; see fig.7.

According the Terralock Mk8 seismograph, the propagating velocity was determined as 4112 $m \times s^{-1}$. Comparing the velocities from both devices we found out that the final velocity computed based on data from vibration monitor UVS 1504 is lower than the velocity measured by Terralock Mk8 device. This difference may result from various time interval reading, which was 0.1 milliseconds for Terraloc Mk8 and 4 milliseconds for vibration monitor UVS 1504. Such accuracy of determination of seismic wave's propagation velocity is sufficient to optimize the timing interval of blasting operations in particular rock environment

According to tab.1, the maximal decrease of the particle velocities for blasting operations in Včeláre quarry is reached for timing interval of charges 10÷20 milliseconds; the measured velocity of propagating seismic waves is higher than 4000 $m \times s^{-1}$. For non-electric discharging during blasting operations also 9, 17, 25, 42 or 64 milliseconds of timing interval can be used. The timing interval of during monitoring blasts in Včeláre quarry was 17 and 25 milliseconds; see fig.6. This corresponds with measured particle velocities in monitored objects in Včeláre village; in tab.3.

Fig.3 The standpoints S1 – Včeláre quarry. The geophones belonging to the seismic device Terraloc Mk8 - R1 are located near the geophones R2 - of the vibration monitor UVS 1504. The standpoint X – position of the geophones of the both devices (Terraloc Mk8 and vibration monitor UVS 1504) on the profile P1, 48 m from the standpoint.

Fig. 4 Standpoints S2 and S3. The vibration monitor ABEM Vibraloc located at the standpoint S2 – church and at the standpoint S3 – house No. 17 in the village Včeláre.

Fig. 5 Boreholes charging and connecting, bench blast No. 4430 and 4431 (left) and the wall after the blasting operations (right)

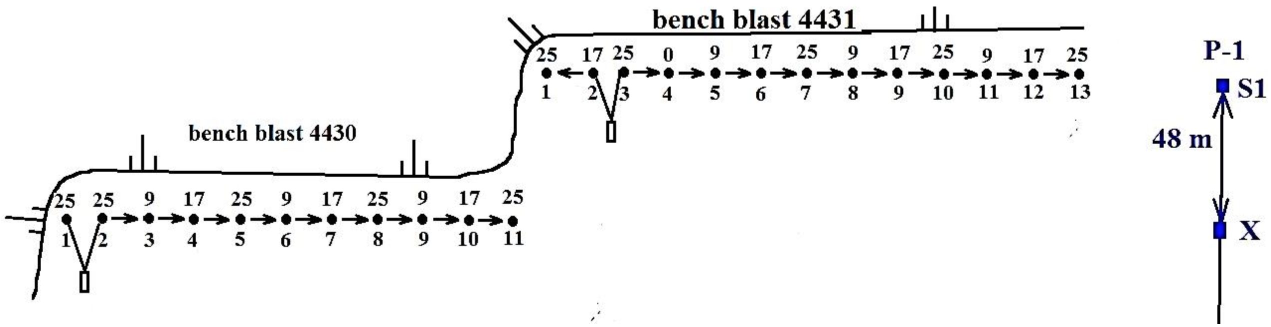

Fig. 6 Timing scheme of the bench blasts No. 4430 and No. 4431

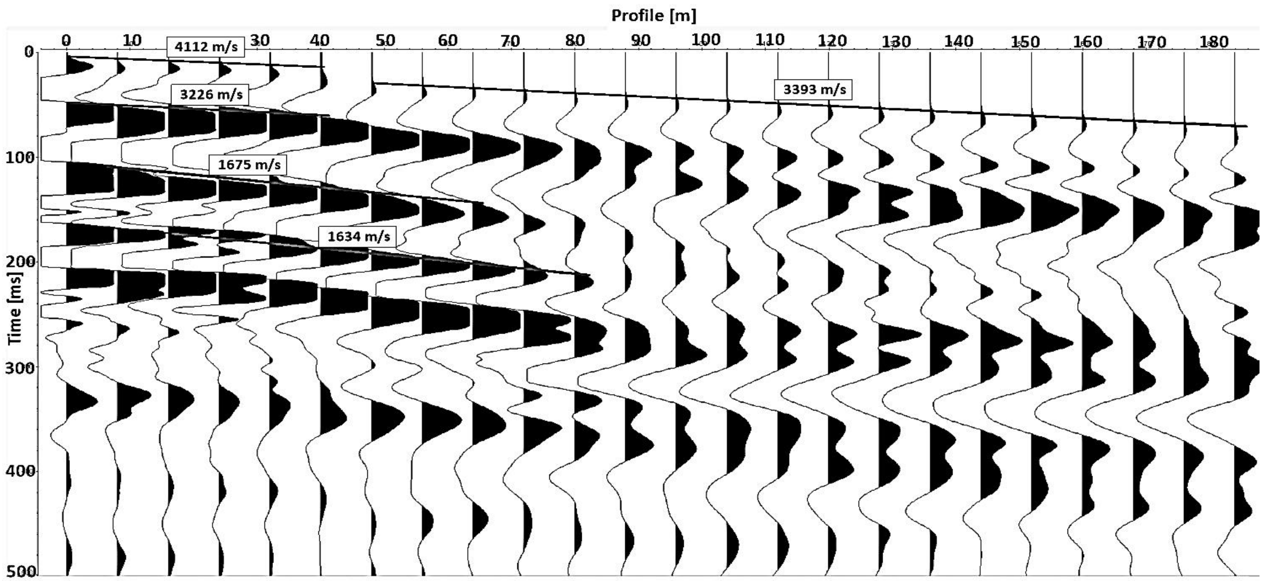

Fig. 7 Record of the wave field from Terraloc Mk8 seismograph for bench blasts No. 4430 and No. 4431 in the Včeláre quarry between first six geophones at the profile P1. The geophone offset is 8 m.

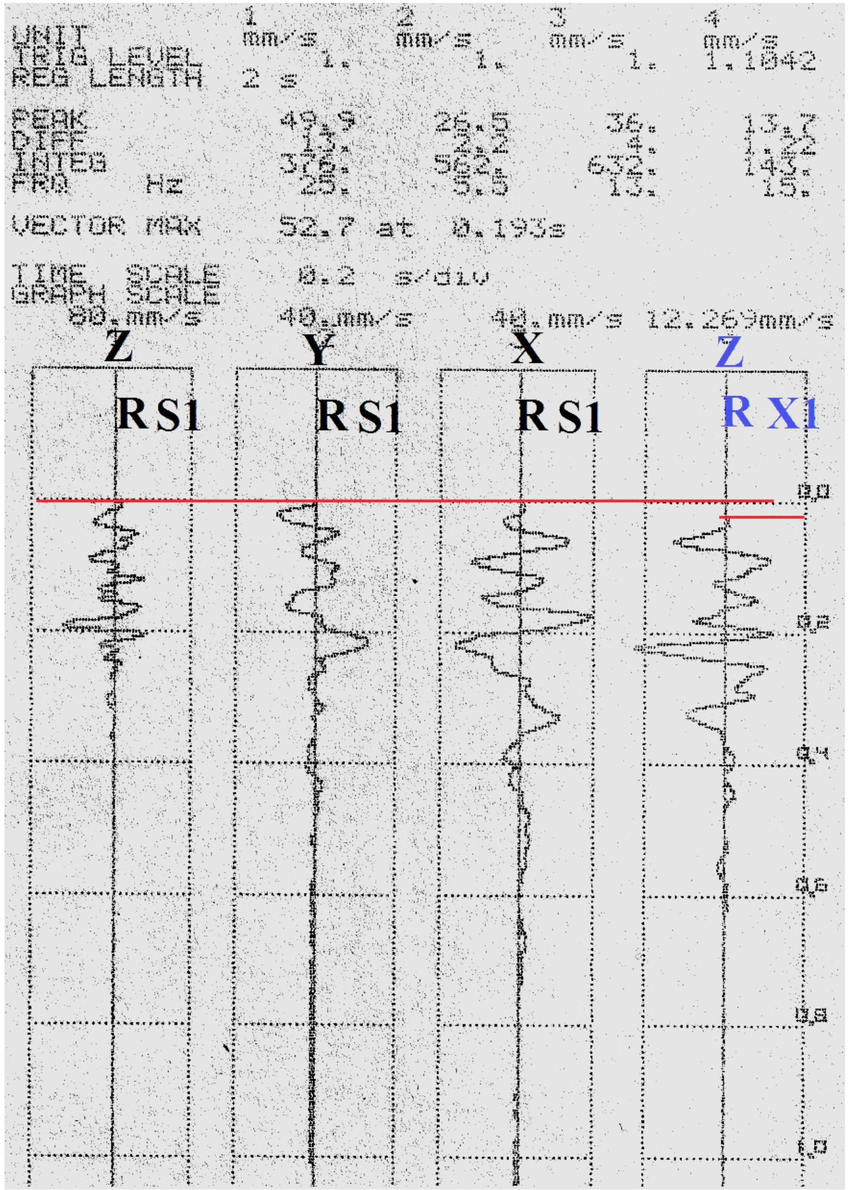

***Fig. 8** Graphical record of individual wave components – vertical - Z, transversal – Y and longitudinal –X at standpoint S1 at 165 m distance from the initiation borehole of bench blast No. 4430, from vibration monitor UVS 1504 in the Včeláre quarry; fig.5. The fourth channel recorded the particle velocity of the vertical wave component – Z at standpoint X at 48 m distance from the standpoint S1; fig.3.*

Measurements from Terraloc Mk8 seismograph and vibration monitor UVS 1504 shows that timing interval 17 milliseconds resulted in higher attenuation of seismic waves generated during blasting in Včeláre quarry than timing interval 25 milliseconds; see figs. 9 and 10. Timing interval 9 milliseconds for non-electric discharging is used in praxis very rarely. Seismic effects on the quarry Včeláre surroundings would be for 9 milliseconds´s interval of timing lower.

Fig. 8 displays the wave course recorded by vibration monitor UVS 1504 at standpoint S1 (first three channels) and at standpoint X, which was located at profile P1 48 m from standpoint S1 (channel 4). The wave generated by the blast induced record, registered at the 0 time on channel 1, 2 and 3. The 4-th channel record the wave arrival to geophone located 48 m with 12 milliseconds shift, thus corresponding with seismic velocity of 4 000 m×s^{-1}.

Fig.8 presents graphical record of individual wave components: vertical - Z, transversal – Y and longitudinal – X. It is the standpoint S1 at 165 m distance from the initiation borehole of bench blast No.4430, from vibration monitor UVS 1504 in the Včeláre quarry; see fig.5. The fourth channel recorded the particle velocity of the vertical wave component denoted as Z at standpoint X at 48 m distance from the standpoint S1; fig.3.

The plots 9 and 10 demonstrate the dependence of maximum particle velocity components on reduced distance during bench blasts No.4430 and 4431 in Včeláre quarry – seismic wave attenuation law. The point highlights the measured values of particle velocity at the individual measuring standpoints of bench blasting in the quarry Včeláre near houses in Včeláre village for timing interval 25ms and 17 ms; (Pandula and Kondela, 2017). We can notice on the plots displaying the dependence between peak particle velocity and distance of bench blasts i.e. figs.9 and 10 that the line inclination differs significantly. For timing interval 17 milliseconds the line is steeper, and thus reflects higher attenuation of seismic waves, see fig.9, than for timing interval 25 milliseconds in fig.10. In this way optimal seismic effect during blasting operations can be attained in particular rock environment; (Viskup at al. (2005), Kondela and Pandula (2012), and too Pandula and Kondela (2017)). Bench blasts No.4187 and 4188 were carried out in the quarry Včeláre in the previous period.

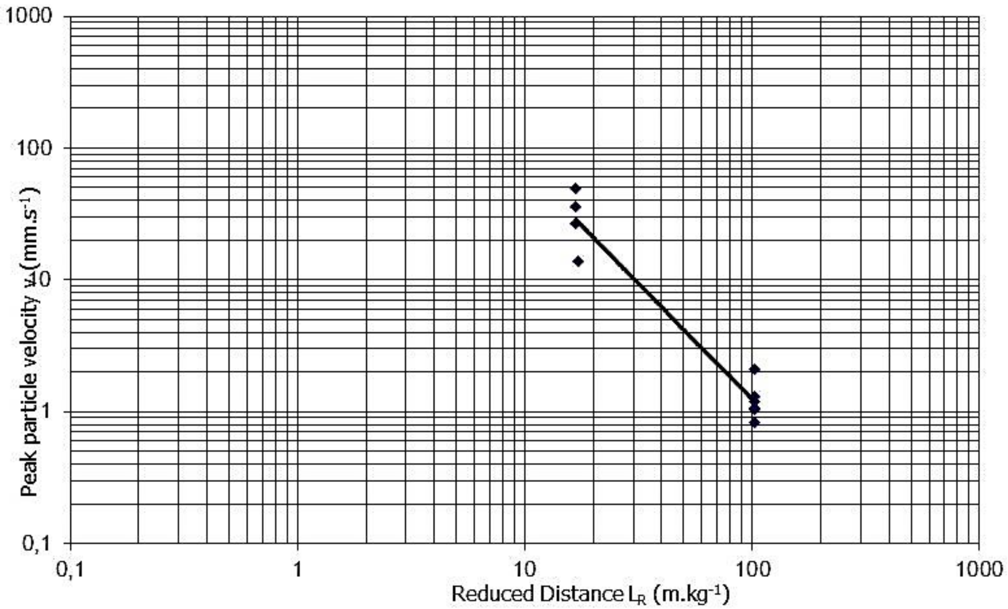

***Fig. 9** Graphical dependence of maximum particle velocity components at reduced distance at bench blasts No. 4430 and 4431 in Včeláre quarry – seismic wave attenuation law. The points display the measured values of particle velocities at individual measured standpoints of bench blasts in Včeláre quarry for 17 millisecond timing interval.*

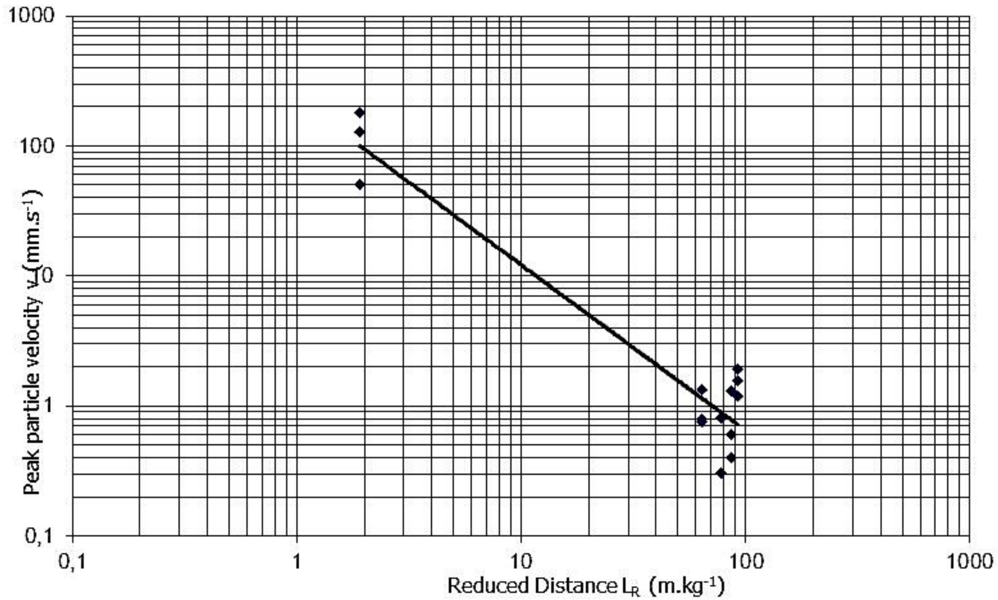

***Fig. 10** Graphical dependence of maximum particle velocity components at reduced distance at bench blasts No. 4187 and 4188 in Včeláre quarry – seismic wave attenuation law. The points display the measured values of particle velocities at individual measured standpoints of bench blasts in Včeláre quarry for 25 millisecond timing interval.*

4 Conclusion

During blasting operations in quarries usually only the experiences of chiefs are used in practise. They achieved their experiences by long term realization of blasting operations in specific conditions. Seismic effects of blasts are considered in terms of the surrounding environment damage. If the objects are intact, the seismic effects are evaluated as sufficient. In order to maximally decrease the seismic effects of blasts in particular rock environment, it is necessary to determine the velocity of propagating seismic waves. This can be assessed not only from seismic devices, but also from devices used for particle velocities measurements. This methodology was verified in several quarries.

Experimental measurements have confirmed that the accuracy of the velocity measurements of seismic wave's propagation by devices used in quarries is sufficient for determining the optimal timing interval of blasting operations. In such way it is possible to achieve higher attenuation of seismic waves and thereby reduce the seismic effects of blasting operations on the environment.

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Authors
[1] prof. RNDr. Blažej Pandula, CSc. - F BERG TU v Košiciach, blazej.pandula@tuke.sk
[2] doc. Mgr. Julián Kondela, PhD. – F BERG TU v Košiciach, julian.kondela@tuke.sk
[3] Mgr. Vladimír Budinský - F BERG TU v Košiciach, vladimir.budinsky@tuke.sk
[4] Ing. Marta Prekopová, PhD. - F BERG TU v Košiciach, marta.prekopova@tuke.sk
[5] Ing. Ján Baulovič – F BERG TU v Košiciach, j.baulovic@centrum.sk
[6] Ing. Ján Feher – F BERG TU v Košiciach, jan.feher@tuke.sk
[7] Ing. Jozef Čambal – F BERG TU v Košiciach, jozef.cambal@tuke.sk