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SIGNAL PROCESSING APPLICATION FOR VIBRATION GENERATED BY BLASTING IN TUNNELS

Purpose. To study the vibrations waves generated by blasting in a tunnel using the signal processing tools.

Methodology. Field tests are carried out to measure vibration wave during blasting operations at different locations in the tunnel and its immediate environment. Results of the measurements are processed by the autocorrelation method, which consists of filtering based on signal shape recognition. A comparison is accomplished between the peak particle velocities (*PPV*) measured and those obtained after filtering.

Findings. The results obtained after filtering gave a significant reduction in *PPV* of the measured vibration amplitudes in comparison to those obtained after treatment for the three components: longitudinal, transversal and vertical ones. Good knowledge of vibration source is important for amplitude attenuation regarding the observed difference between the recorded seismogram during explosion of a single unit charge and other standard explosions.

Originality. The work introduces signal processing methods for filtering vibration signals related to blasting, which is insufficiently studied.

Practical value. This study shows that the treatment of blasting vibrations by a filtering method should reduce the peak velocity of the particles by separating the signals and eliminating the interference in the initial signal.

Keywords: *blasting, vibration amplitude, signal processing, autocorrelation methods, filtered signal, signal degradation*

Introduction. The most popular method for removing hard rock is blasting with explosive. In practice, a set of blast holes is formed in the rock in a well-designed manner and the loading is carried out in accordance with the pre-established firing plan. The explosion takes place in a predetermined order, at intervals of several milliseconds, breaking the rock into blocks of suitable size. The main disadvantage of this method is that a significant part of energy is not spent on fracturing the rock but released in various forms such as heat, sound and vibration. The method called "graduated distance" is based on the principle that "the vibration level at a point is inversely proportional to the explosion distance, on the other hand, it is directly proportional to the explosion charge" [1]. Many empirical relationships have been introduced to express the charge weight, the distance from the source and the peak particle velocity [2, 3]. The linear superposition method has been used and validated by Anderson, et al. and Hinzen, et al. [4]. The last mentioned author proposed a wave trains simulation generated by the blasting which seems to give good results. However, studies presented by Blair and Boinier [5] show that vibrations are very much influenced by parameters which cannot be reduced in general terms because they are very specific to the considered site and the particular conditions of a given shot. Moreover, Blair also performed numerical simulations using Kjartasson's Q-constant theory to represent the wave attenuation in spectral domain. The obtained results indicate that the particle velocity does not vary linearly with distance, which contradicts empirical laws. Furthermore, Boinier's studies highlighted the insufficiency of the relationships used today to fully shed light on the various phenomena associated to vibrations [6].

In this context, all the well known methods (empirical, linear superposition, artificial and numerical intelligence) can predict ground vibrations caused by mine blasting operations. Nevertheless, the geological and geotechnical conditions, the explosive characterization and geometry have not yet been integrated into this type of relationship [7]. As the number of influencing parameters is high, artificial neural networks (ANN) and several artificial intelligence methods (AIM) have been developed to predict the vibrations related to rock explosions [8]. Many researchers have used ANN and supporting vector machines to estimate the peak particle velocities PPV and airbrush. The empirical and AIM methods only provide a maximum amplitude estimation of particle speed, and give no information about the complete seismic waveform [9, 10].

Any measurement of a physical phenomenon necessarily involves signal processing. The obtained experimental data are analyzed and processed in order to extract only the useful values and those reflecting the phenomena reality.

A frequency signal processing was introduced in the vibration monitoring studies, using a filter which consists in reducing certain harmonics amplitudes on the amplitude spectrum of the Fourier transform, meanwhile the inverse transform is accomplished to reconstruct the signal in function of time. This analysis makes it possible to improve a behavioral study, or identification of likely frequencies to trigger a particular vibration mode; note that, the Fourier spectrum only provides relative amplitude levels as a function of frequency.

There are numerous tools, software and hardware that allow real-time or delayed signal processing. Our research work focuses on the vibrations measurement during explosive digging of motorway tunnels followed by signal processing standing on the autocorrelation method which allows filtering based on pattern recognition. It makes it possible to recognize along the seismic trace and the arrival of various events and compare them to the measured results.

Autocorrelation method. Autocorrelation method as a mathematical tool is often used in cross-correlating a signal by itself. It makes it possible to detect regularities, repeated profiles in a signal such as a periodic signal disturbed by a lot of noise [11].

A signal x is transmitted and then measured by an acquisition system, as in our case the vibrations measuring generated by explosives. These different operations generally lead to the initial signal degradation. The measured signal x_m can be represented by the following form

$$\forall \in \mathbb{R}, \quad x_m(t) = x(t) + b(t), \qquad (1)$$

where signal b represents the signal degradation effect. The first idea would be to apply frequency filtering methods; though, they can only be applied if the spectra of signals x and b are separated, which is a hypothesis which is unlikely to be verified. A more realistic hypothesis is to suppose that the signals x and b are independent because they result from different physical systems. At that point, we can exploit the autocorrelation properties. Suppose that the measured signal is written by the following formula

$$\forall \in \mathbb{R}, \quad x_m(t) = A \sin(2\pi v_0 t + \phi) + b(t), \qquad (2)$$

where b is an independent signal. If the signal indeed has this structure, then its autocorrelation is expressed by the following formula

$$\forall \tau \in \mathbb{R}, \quad R_{xm}(\tau) = \frac{A^2}{2}\cos(2\pi v_0 \tau) + R_b(\tau). \qquad (3)$$

Now, if we have only the noisy signal, then to calculate the periodicity, "Autocorrelation" will help us. Autocorrelation of the noisy signal is = autocorrelation of the original periodic signal apart from 0 lag.

Why & How

1. Let us consider, our original signal is $x(n)$.

2. The noise which is added in the original signal is = $v(n)$.

3. So the noisy signal = $y(n) = x(n) + v(n)$.

Let us try to calculate the autocorrelation of $y(n)$ in a theoretical way

$$R_{yy}(k) = \sum_N (x(n) + v(n))(x(n-k) + v(n-k)); \qquad (4)$$

$$R_{yy}(k) = \sum_N (x(n)x(n-k) + x(n)v(n-k) + \\ + v(n)x(n-k) + v(n)v(n-k));$$

$$R_{yy}(k) = \sum_N x(n)x(n-k) + \sum_N x(n)v(n-k) + \\ + \sum_N v(n)x(n-k) + \sum_N v(n)v(n-k);$$

$$R_{yy}(k) = R_{xx}(k) + R_{xv}(k)^0 + R_{vx}(k)^0 + R_{vv}(k)^0. \qquad (5)$$

Where:

1. $R_{vv}(k)^0$ = autocorrelation of awgn, which is = 0 for all k except $k = 0$ (we have canceled it because we will not take $k = 0$ case in our calculation).

2. As $x(n)$ is a periodic sequence & $v(n)$ is random noise, so there is no similarity in between these two signals. So that $R_{xv}(k)$ & $R_{vx}(k) = 0$.

So that it is clear that Autocorrelation of the noisy signal is = Autocorrelation of the original periodic signal apart from 0 lag (because at 0 lag, the $R_{vv}(k)! = 0$) [12].

Geology and site description. The tests are carried out at the Ait *Yahia Moussa* tunnels. The tunneling is being carried out as part of the penetrating motorway linking the Wilaya of Tizi Ouzou to the East-West motorway in Algeria. The tunnels are located in *Kabylie* in the Tell Atlas region as shown in Fig. 1.

With a 760 m right tube and a 750 m left tube, the Aït Yahia Moussa tunnels extend towards N60E. The maximum thickness of the cover tunnel is 103 and 110 m for the left and the right tube respectively.

The tunnel area and its immediate environment are formed by the metamorphic base formations, consisting of quartzite, schist and gneiss.

The ultrametamorphic complex is made of granites and granito-gneiss leucocrates (reomorphiques) fine to coarse, with biotite, rarely with muscovite, one also finds there pegmatoïdes granites infrequently fine or aplitoides.

Rock mass characterization. The geotechnical identification study on the rock mass surrounding the tunnels shows that the rock has low compressive strength and is moderately

Fig. 1. Location map of the study area

elastic, almost ductile. The GSI (Geological Resistance Index) of the rock mass, also taking into account the discontinuity factor, characterizes the rock as medium to good and which constitutes a determining element in the description of the environment continuity.

The rock quality is very poor with an RQD (Rock Quality Designation) of 20 % and with a very narrow gap spacing of 200 to 600 mm. The massif geotechnical parameters are summarized in Table 1.

In addition, observations and measurements carried out on discontinuities conditions characterize the tunnels rock mass, overall of very low persistence (continuity < 1) and with narrow to partially openings.

According to the geotechnical description, the tunnels' rock mass could be considered as a medium rock mass of low continuity.

Blasting geometry and instrument specification. The blasting activities were carried out on the site by blasting holes with a diameter of 64 mm and a depth of 3.5 and 4.4 m respectively for the stross and the calotte, with a 50 mm diameter explosive cartridge with a charge weight of 1 kg. In the stross firing round two cartridges are used, which gives a load of 2 kg per hole, while we used 2, 3 and 4 kg per hole in the cap volley. Each hole is detonated with micro-delay electric constant detonators in surface by 20 microseconds. The used explosive is Temex, these characteristics are presented in Table 2.

The blast vibrations are measured using the SUMMIT M Vipa seismograph, designed by the German design office DMT, as presented in Fig. 2. The instruments were pre-calibrated in the laboratory before being used on site for recording purposes.

Table 1

Geotechnical parameters of rock mass

Geotechnical parameters	Values
UCS, Uniaxial compressing strength (MPa)	15.0
GSI, Geological Resistance Index	45
mi, Material constant	32
D, Disturbance factor	0−0.8
Ei, Elasticity module (GPa)	8.250
γn, Unit weight (kN/m³)	26
c, Cohesion (kPa)	537−345
Rock quality designation (RQD %)	20
Spacing of discontinuities (mm)	200−600
Continuity of discontinuities	< 1
Opening of discontinuities (mm)	0.1−1.0

Characteristics of the explosive

Characteristics	
Nature	Gelatinous
Filling cartridge density (grs/cm^3)	≈1.22
Water resistance	Very good
Velocity of detonation (steel confined in $\varnothing = 40$ mm) (m/s)	4 500 ~ 5500
Self excitation factor (mm)	50 ~ 80
Scattering (mm)	15 ~ 20
Test to lead block (trauzl) (cm^3/10g)	≥320

Fig. 2. Seismograph picture

These instruments are self-triggering digital engineering seismographs with the ability to record all three components of soil vibration and acoustic waves; it provides ultra-sensitive vibration monitoring for continuous and event-based recording.

The master station is equipped with a receiver and a data recorder. Measurement files, waveforms and seismic events are recorded and located, easy to use, small, robust, 24-bit technology, 4GB internal memory, virtually unlimited external storage via the USB port make it easy to obtain data. The seismograph parameters are given in the following Table 3.

Experimental procedure. Considering that the main objectives of this research are to measure and study the blasting vibration waves at different locations in the immediate environ-

The seismograph characteristics

Main performance parameters of SUMMIT M Vipa	
Frequency Range	DC − 5 kHz
Sample Interval	1, 2, 5, 10 kHz
Recording Mode	Continuous or event based
Trigger Mode	Amplitude threshold for each channel, trigger also on KB and vector sum
Signal Input Range	±5 V differential input
Measurement range	175 mm/s with standard sensor DMT-3D/DIN, larger ranges on request
Time synchronization	Internal GPS module (ext. Antenna), absolute time accuracy: < 1 sample
Operation Temperature	− 20 to + 70 °C
Humidity Range	0 − 95 %

ment of the tunnels as well as the structure of the tunnels themselves, and to analyze vibration waves using signal processing methods, various measurements are taken. To accomplish the abovementioned research, the vibration measurements were carried out during the blasting of two blast holes at the stross level, complete stross, of the cap and half part of the stross.

Three (03) seismographic stations are mounted at different distances from the explosion sources to measure the vibrations speed in the three orthogonal directions, longitudinal, transversal and vertical ones.

Table 4 summarizes the accomplished measurements (firing points, measurement points, measurement distances, total quantities of explosive).

Fig. 3 shows the seismographs arrangement. They were placed on the ground when recording outside as presented in Fig. 3, *a* and on the ground near the walls in the case of recording inside the tunnel as presented in Fig. 3, *b*.

Vibration data recorded by the seismograph. The measurement results are given in the form of an amplitude-time curve related to vibration level signal of each measurement station according to the longitudinal, transversal and vertical components. Two measurement cases of the vertical component were neglected because they are considered as isolated cases.

Ground movement is defined by the amplitude, frequency content and the strongest movement duration for all physical quantities: displacement, particle velocity and acceleration. It is therefore these maximum values which are generally used to characterize a vibration. These quantities are good indicators for the potential impact of an underground vibration. In our case we will study the peak particle velocity (*PPV*) which is expressed in mm/s and the seismic signature.

In Fig. 4, the obtained results of *PPV* are plotted as a function of the measurement distance between the seismographs and the explosions, the measurements are classified into five blasting patterns according to the used explosive quantities in the various rounds of fire.

The first apparent tendency shows that on average, large explosions with higher explosive charges, lead to higher vibration levels, and this is most evident in the measurement locations which are "inside the tunnel": P2, P4, P5 and P8. This relationship between the explosive amount and the vibrations' intensity is not entirely true.

The *PPVs* of the measurement point P1 are 51 % higher than those of P8 at the same distance; however, the explosive

Firing points and measurement points description

Blast	Part to be blasted	Measuring point	Distance (m)	Seismograph location	Q_{exp} (Kg)
T1	Stross	P1	50	Inside the tunnel	04
T2	Clotte + stross	P2	235	Inside the tunnel	415
	Clotte + stross	P3	355	outsider the tunnel	415
T3	half-stross	P4	200	Inside the parallel tunnel	48
T4	Stross	P5	50	Inside the tunnel	96
	Stross	P6	120	Inside the tunnel	96
	Stross	P7	355	outsider the tunnel	96
T5	Clotte	P8	50	Inside the tunnel	367
	Clotte	P9	120	Inside the tunnel	367
	Clotte	P10	355	Inside the tunnel	367

a

b

Fig. 3. Seismographs arrangement:

a − outside the tunnel; b − inside the tunnel

quantity of T1 blast of 4 kg is smaller than the quantity of blast 8 at the calotte level (367 kg), which confirms that the measured vibration amplitudes do not depend on the total load of a volley but on the instantaneous load.

The results of point P4 give a 55 % higher *PPV* than that of point P3 with a higher explosive charge 11 % more and at an interval distance of 155 m, which is why the *PPVs* are higher inside the tunnels, either inside the tunnel where was the blast or inside the parallel tunnel. It is difficult to say what is driving this behavior, electrical ignition, delay time, less efficient loading, the rock mass geotechnical characteristic enveloping the tunnels?

It is known that seismic vibrations are generally more noticeable on the surface than underground, though; this observation is far from being generalizable. At the measurement points carried out as shown in Fig. 5, the measured amplitudes inside the tunnel are greater than those measured outside (on the surface) which mainly depends on the geological environment and the site effects which can locally amplify ground movements.

Another apparent tendency is that the *PPVs* of the vertical component are much higher than the *PPVs* of the longitudinal and transversal components over all the measured points. This amplification of vertical *PPV* is explained by the importance of the height and the pressure of the encasing rocks. The vertical wave appears in the signal when the distance to the source is important enough; this distance depends on the source depth

Results of discussion of processing signal. After the acquisition and before interpretation, an essential step in data processing chain consists in filtering and separating the obtained waves from the seismic noise and especially the waves between them, it is then necessary to use signal processing methods.

The measurement data has been converted into an MS-Excel database, the vibration signals processing is carried out on MATLAB by the *xcorr* function, in order to show the useful signal amplitudes after filtering.
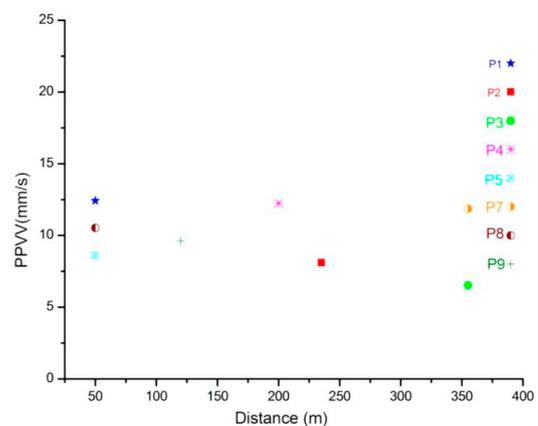
All values changing in amplitude at each period, then they are underestimated and only the periodic values are kept, whatever the period. The final signal is therefore like a "clean" waveform image from which all random interference are eliminated.
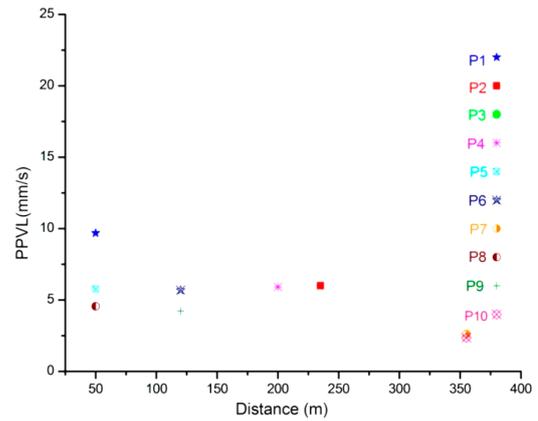
a
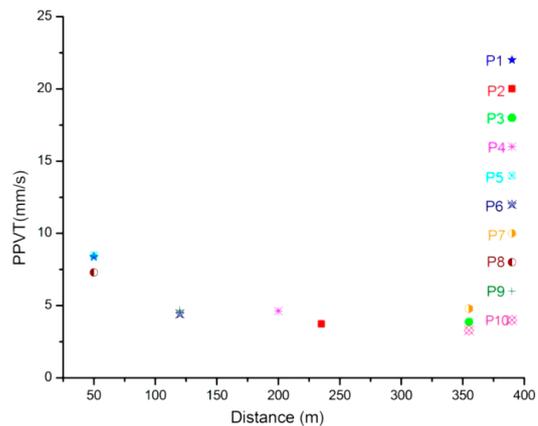
b

c

Fig. 4. PPV measured by seismograph in function of distance:

a − longitudinal component; b − transversal component; c − vertical component (*P1−P9 are measuring points, are presented and discussed in Table 4*)

The measured and filtered amplitude-time curves are shown in Fig. 5, for measuring point P1. The curves after treatment show a well accentuated central peak with the minimum of secondary peaks.

Comparisons between the measured *PPV*, and that obtained after filtering the signals of different measurement points relating to each explosion are presented in Table 5.

Fig. 6 shows the *PPV* in function of the distance from the vibration source (explosion) for practical measurements and the filtered results. All the amplitudes given after filtering are lower than the amplitudes of the measured signals, but for P7 the vertical amplitude component is higher after filtering than
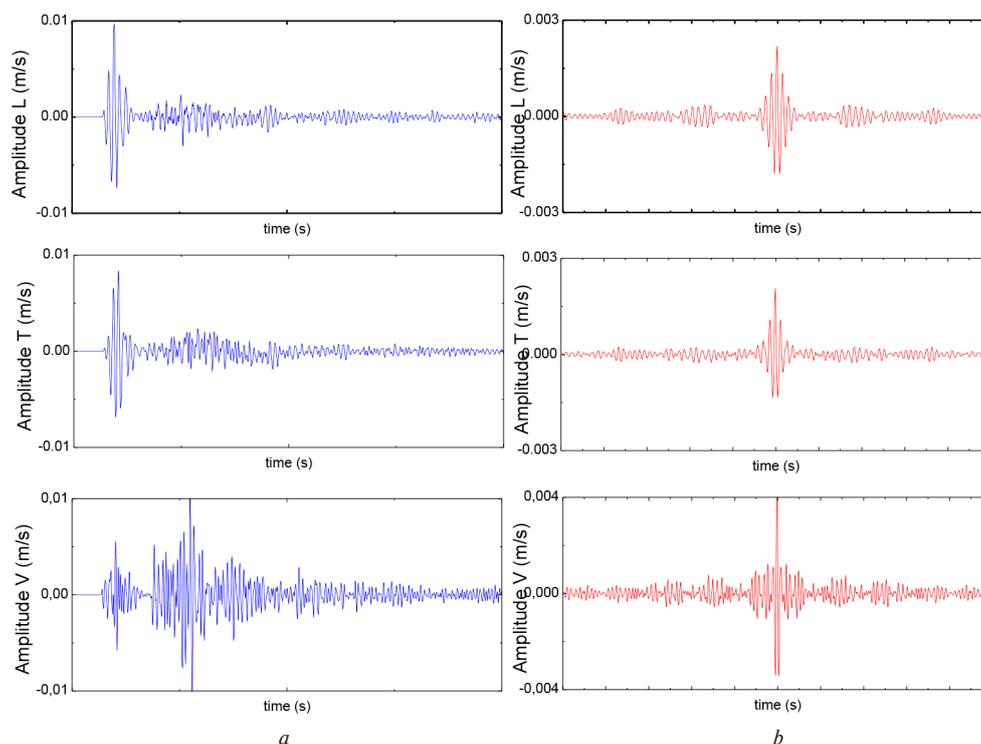
Fig. 5 . Measured and filtered Seismogram of P1:

a − measured Seismogram ; b − filtered Seismogram

Comparison between measured PPVs and PPVs treated by the autocorrelation method

Measuring points		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
PPV_L (mm/s)	Measured	9.69	6.00	2.63	5.92	5.77	5.69	2.60	4.56	4.23	2.36
	filtered	2.19	4.62	1.37	4.06	4.52	4.15	1.50	3.21	3.07	1.19
PPV_T (mm/s)	Measured	8.38	3.73	3.87	4.63	8.47	4.42	3.78	7.30	4.79	3.29
	filtered	2.06	2.45	2.31	3.61	7.13	3.61	2.42	6.51	3.43	2.09
PPV_V (mm/s)	Measured	12.42	8.10	6.52	12.24	8.61	–	11.86	10.52	9.61	–
	filtered	5.16	5.39	2.05	10.90	7.49	–	19.00	8.14	5.46	–

The subscriptions L, V and T express the longitudinal, transversal and vertical components respectively

the measured amplitude; it was considered as an erroneous point.

To make a quantitative comparison, the reduction rates between the measured *PPV* and filtered signals are calculated as a percentage as shown in Table 6.

Based on the analysis performed previously, the following points can be observed:

The difference between the measured *PPV* and the *PPV* of the signals filtered at various points varies from 21 to 77 %, from 10 to 75 % and from 13 to 68 % respectively for the longitudinal, transversal and vertical components. The most apparent percentage is linked to two measurement points, 77.39 % (*PPV_L*) and 75.41 (*PPV_T*) for P1 and 68.55 % (*PPV_V*) for P3.

The reduction rate of amplitudes between the measuring point P1 at a single unit charge and the other measuring points to several loads is different from a minimum of 30 % and a maximum of 60 %.

Good knowledge of vibration sources is therefore essential for amplitude attenuation.

The closest measuring points to the vibration source (50 and 120 m) are inside the tunnel and represent more than 50 % difference in reduction between the longitudinal and transversal amplitudes of the P1 and their *PPV* for the points inside the tunnel. This is consistent with the fact that the vibration sig-nals generated by the shot represent degradation introduced by multiple sources inside the tunnel (interaction with structure, transmission systems, measurement systems and background noise).

As shown in Fig. 7, a trend can be observed between the distance to the vibration source and the difference between the *PPV* related to measured and filtered explosions for the longi-tudinal and transversal components, but a weak trend is ob-served on the vertical component (P1, P2, ... are mesuring points presented in Table 4, Fig. 7 is corrected).

Conclusions. This study allows improving the knowledge and applications of vibration waves generated by blasting in tunnels through the vibrations treatment used filtering. In the accomplished measurements, it is observed that the results de-pend mainly on the distance measurement to the vibration source and the seismographs location and the rock mass char-acteristics.

Regarding the relatively poor accuracy of ground vibration measurements, post-recording processing of vibration signals is essential for vibration amplitudes attenuation. Nevertheless, there are other factors which sometimes increase or decrease the measured vibration values. These factors may include geo-logical features, such as lower or higher rock quality in some places.
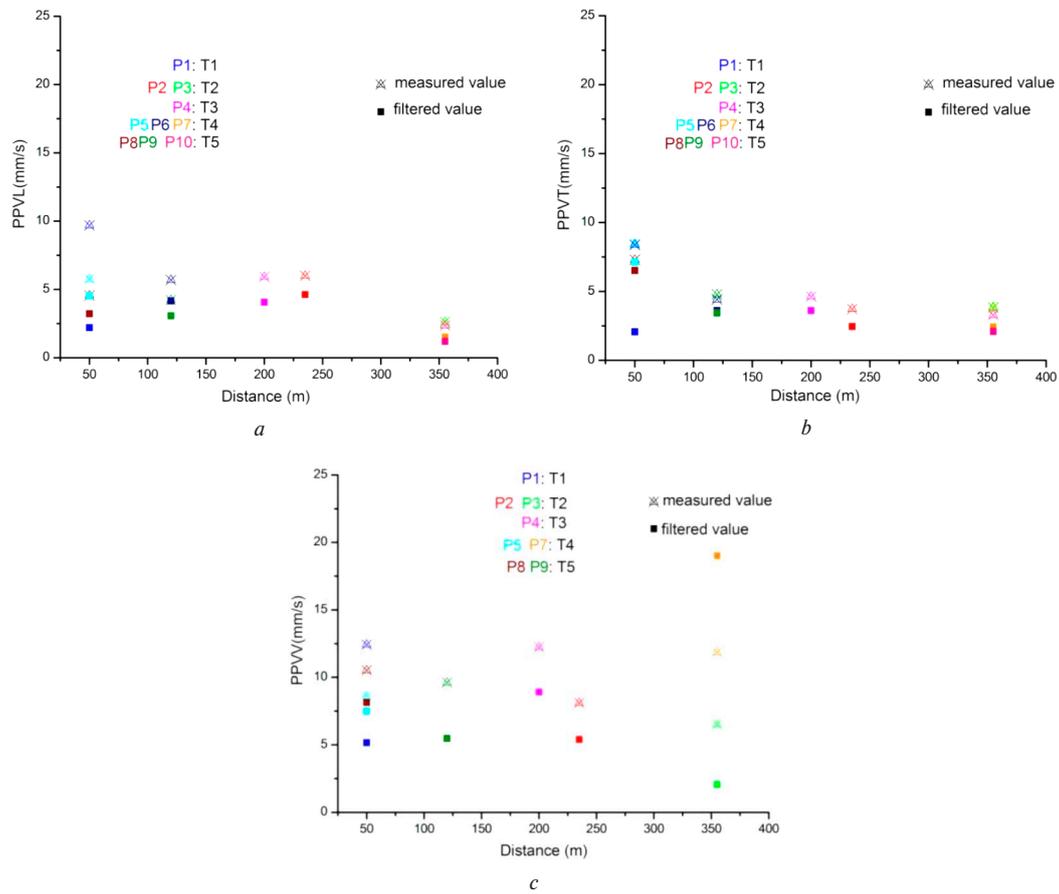
Fig. 6. Comparison between measured and filtered seismograms against explosion distance:
a — longitudinal component; b — transversal component; c — vertical component

Reduction rate in % between the PPVs of the measured and filtered seismograms

Point Difference* (%)	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
PPV_L	77.39	23	47.90	31.41	21.66	27.06	42.30	29.60	27.42	49.57
PPV_T	75,41	34.31	40.31	22.03	15.82	18.32	35.97	10.82	28.39	37.38
PPV_V	58.45	33.45	68.55	27.28	13.00	—	+160.20	22.62	43.18	—

* *(PPV measured − PPV filtered/PPV measured)100*

Although this article presents a new processing and filtering method for blasting vibration signals based on an experimental approach, numerous research studies should be carried out to investigate the geological conditions influence on the vibrations speed generated by explosives.
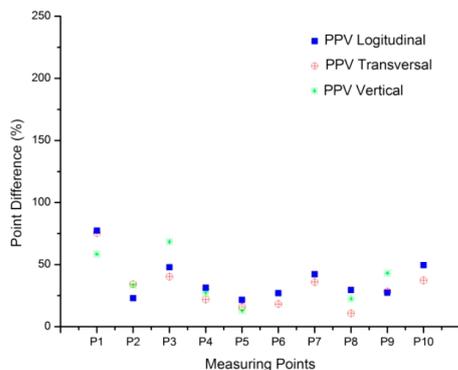

Fig. 7. Difference percentages between PPV of measured and filtered seismograms with respect to explosion distance

Recommendations. Autocorrelation does not determine the signal defect extent, but gives the possibility to know only the influence with regard to the measured raw signal. At that point, without the waveform, it is impossible to determine the exact fault magnitude. Conversely, it is necessary to carry out additional work, in particular the generated vibrations treatment in order to know the signal interference causes and origin.

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Застосування методів обробки сигналів до вібрацій при вибухових роботах у тунелях

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Мета. Вивчення вібраційних коливань, що генеруються вибуховими роботами в тунелі, з використанням інструментарію обробки сигналів.

Методика. Експлуатаційні випробування проводяться з метою вимірювання вібраційного коливання під час вибухових робіт у різних місцях тунелю та в безпосередній близькості від нього. Результати вимірювань обробляються методом автокореляції, що полягає у фільтрації на основі розпізнавання форм сигналів. Виконується порівняння пікових швидкостей частинок (ПШЧ), що були заміряні, і значень, отриманих після фільтрації

Результати. Результати, отримані після фільтрації, показали значне зниження ПШЧ виміряних амплітуд коливань у порівнянні з результатами, отриманими після обробки для трьох складових: поздовжньої, поперечної й вертикальної. Точне знання джерела вібрацій важливо для ослаблення амплітуд у зв'язку із різницею, що спостерігається між сейсмограмою, записаною під час вибуху одиничного заряду, та інших стандартних вибухів.

Наукова новизна. Полягає в застосуванні методів обробки сигналів для фільтрації вібраційних сигналів, пов'язаних із вибухом, що ще недостатньо розвинене.

Практична значимість. Дане дослідження показує, що обробка вибухових коливань методом фільтрації повинна знизити пікову швидкість частинок шляхом поділу сигналів і усунення перешкод у вихідному сигналі.

Ключові слова: *вибухові роботи, амплітуда коливань, обробка сигналів, метод автокореляції, відфільтрований сигнал, спотворення сигналу*

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