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Research of the Technical Seismicity Due to Blasting Works in Quarries and Their Impact on the Environment and Population

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Abstract: Vibrations caused by blasting works have an impact not only on buildings but also the internal environment of the buildings. If these buildings are situated in the surroundings of quarries, the citizens can perceive these vibrations negatively. By applying an appropriate millisecond timing interval, it is possible to lower the intensity of vibrations to the levels that the citizens will not perceive as negative effects inside the buildings. The limit values for this vibration intensity have not been defined to date. For the protection of the building from the vibrations, normative values of the particle velocity and frequency were determined. Hygienic standards for the inhabitants of the housing were applied, which assessed the impact of the vibration on humans through the measurement of the vibration acceleration in the housing. In this article, the results of the research carried out in Trebejov Quarry are presented. The experimental blasts carried out in Trebejov Quarry proved that the reduction in the vibration intensity under the value 2 mm.s^{-1} led to the satisfaction of the inhabitants.

Keywords: blasting works; seismic effects; milliseconds timing interval; the internal environment of buildings; ground vibration; environment; mining; blasting work in quarries

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1. Introduction

Nowadays, the application of explosives to break rocks is a very common way of extracting rocks [1,2]. The blasting technique has to have a minimal impact on civil properties in the surrounding area. This is a crucial requirement to reduce the damage to the buildings and citizens' health [3].

Blasting in quarries is a commonly applied technique for quarrying rocks; hence, the problems associated with this method are a very important issue for the surface mining industry. Explosive energy is used to break rock. However, the use of this energy is not 100% efficient.

Some of the energy escapes into the atmosphere to generate air blast or air vibrations. Some of the energy also leaves the blast site through the surface soil and bedrock in the form of ground vibrations [4]. Waves of air vibrations and soil vibrations disturb the material and massif, causing their movement when they encounter buildings or structures and shaking. Vibrations of soil enter the house through the basement or foundations, and air waves affect the house over the walls and roof.

The shaking of the surface of the Earth wave causes the structure to shake and rattles objects hanging on walls or sitting on shelves inside the building. This "interior noise" will alarm and startle people living in the house.

It is necessary to analyze these vibration impacts on facilities/buildings and the residential buildings around the mines [4]. In this case, determining a permissible explosive limit that takes into consideration the protection of such structures is crucial. The determination of a permissible explosive limit for blasting works is the first step in the precautionary safety measures of quarries. Increasing numbers of mines initiate extensive precautionary measures aimed at safe blasting works with simultaneous, periodic, or constant documentation of the impact on the buildings in the surrounding area [5]. It presents the general course of action in a dynamic diagnosis [5] where the following stages are necessary: recognition of the building types in the surroundings of a mine, recognition of the vibration sources, considering of mining conditions and the course of the vibration propagation from the sources to the buildings, assessment of the impact of the blasting works on buildings (and assessment of their level causing a nuisance for citizens), and a correct diagnosis (stating whether there is a cause and effect connection between the actual technical condition of the given buildings and the vibrations induced in a mine). Precautionary measures in surface quarries, aimed at minimizing the impact of blasting works, mostly depend on the followings [5]: the threat level for structures located in the surroundings, their number and purpose (industrial buildings, residential and utility buildings, and protected buildings), frequency of the blasting works and technique of the blasting works. Drilling and blasting are widely used methods for rock fragmentation in open-pit mines, tunneling and civil projects. Flyrock, as one of the most dangerous effects induced by blasting, can cause substantial damage to structures and injury to humans [6]. Due to the development of new explosive systems and initiation devices, blast design and execution software tools, the blasting process has now become more efficient and safer than before. Moreover, the hazards from blasting can instead be predicted before the actual blasting; thus, the adverse impacts of blasting can be controlled and reduced [6].

Several authors deal with the use of mathematical modeling to predict vibration from blasting while also using elements of artificial intelligence. Such a modeling system has been developed for decades [7,8]. Various tools are used to solve vibration prediction. Toraño et al. [9] created a finite element method (FEM) model that predicts ground vibrations due to blasting. Dehghani [10] used artificial neural networks (ANNs) and dimensional analysis techniques to evaluate and calculate the blast-induced ground vibration. Fişne et al. [11] tried to predict the peak particle velocity (PPV) with the help of the fuzzy logic approach using parameters of distance from blast face to vibration monitoring point and charge weight per delay. Mohammadnejad et al. [12] applied a novel artificial method, called a Support Vector Machine (SVM), which has been proposed for the prediction of blast-induced ground vibration by taking into consideration the maximum charge per delay and the distance between the blast face and monitoring point. Armaghani et al. [13] used two artificial intelligence techniques, namely, the adaptive neuro-fuzzy inference system (ANFIS) and artificial neural network, for the prediction of ground vibration in quarry blasting sites. Keshtegar et al. [14] created a set of nonlinear mathematical models to solve the problem. Azimia et al. [15] proposed a new hybrid evolutionary artificial neural network (ANN) optimized by a genetic algorithm (GA) to predict peak particle velocity (PPV). Hosseini et al. [16] explored the possibility of using three methods of soft computing, namely, genetic programming (GP), response surface methodology (RSM) and multivariate adaptive regression splines (MARS), to predict the peak particle velocity (PPV) values. Zhang et al. [17] used a particle swarm optimization (PSO) and extreme gradient boosting machine (XG Boost) to create the PSO-XG Boost mode. Koteleva et al. [18] described an approach of mathematical processing of signals using spectral analysis, wavelet analysis and fractal analysis. Zhou et al. [19] applied a new intelligent model (regression tree-based), known as gene expression programming (GEP).

The effect of the prospective research is the development of an original and, in particular, effective procedure to record the impact of blasting works with periodical measurements of vibration intensity or monitoring the vibrations' impact on the buildings in the surrounding area [20]. Due to the complex way in which seismic waves propagate near the quarries, the assessment process may show differences between the expected values and those measured during the blasting work. The identified differences emphasize the importance of seismic measurements in situ as an appropriate method to determine the level of safety of the blasting work in quarries with respect to the seismic effect [21–24]. The systematic repetition of measurements helps to improve the efficiency of blasting works [25–27]. The planning of blasting works in quarries depends on measurements carried out during the blasting works. Based on the pre-measured parameters, the parameters of the next blast, such as burden borehole spacing and drilling angle, are adjusted, and the firing pattern, in addition to charge weight per delay and distance, is the most important parameter to reduce the influence of blasting vibration. The objects located in the vicinity of the blasting can be protected from seismic effects by proper timing charges in boreholes during the blasting works. The development of electronic detonators has greatly increased the safety and accuracy of blasting works and their timing [28–30]. Suppose the intensity of the vibration is large enough. In this case, a violation of the environment or even its destruction may occur, so it is necessary to find a suitable evaluation method, which on the one hand, ensures the security of the non-infringement and, on the other hand, would determine the most effective blasting technology [31–34]. The impact assessment of the seismic effects caused by the blasting works depends on the distance of the blasting from the objects and the charge weight per delay used in blasting. To determine the limit of charge weight per delay, the minimum distance is needed to determine the attenuation of the seismic waves in the monitored area [34–37].

Hundreds of studies have been completed that focused on the regulation of the vibrations, and the most relevant practical methods are as follows [38], which recommended:

(1) Application of time-delay between individual boreholes;
(2) Reduction in the borehole number at the same time of the time-delay;
(3) Application of the periodic blasts and the appropriate time between sequencies of the blasts;
(4) Application of the graduated charge and appropriate timing between the charges;
(5) Distribution of the quarry wall in more benches and, as a consequence, reduction in the charge capacity for one borehole.

Based on these recommendations, it can be assumed that the use of the time delay method is suitable for the local reduction in vibrations during blasting work. However, this idea was proposed by Langefors many years ago [38], and we found out that the accuracy of this method was not at the required level. Moreover, the timing accuracy of the detonation using conventional pyrotechnical detonators always caused a problem, which was finally solved by the introduction of the electronic detonators. The initiation of the electronic detonators enabled a wider application of the appropriate reduction in the vibrations. The occasion has arisen to develop a new theory on the reduction in vibrations by applying electronic detonators.

Currently, in blasting operations to regulate vibrations by millisecond timing, electronic detonators are mostly applied; nevertheless, these detonators have many limitations [39]. As the non-electric detonators are exploded at a millisecond timing simultaneously with more boreholes, the vibrations of the blasting operations could be reduced by a reduction in the shot, distribution of the charge capacity in the borehole and by the division into more time sequences. If the technology of blasting operations with a millisecond time delay is used, the accuracy of the delay of the non-electronic detonators is relatively low, with a deflection delay of ca $\pm$ 3 σ, where σ is the relevant deflection. The non-electric detonators prove the following time delay: 9, 17, 25, 33, 42 and 67 milliseconds, regulating the velocity of the chemical combustion [40]. Therefore, the disintegration of the rocks by applying the non-electronic detonators causes uncertainty and non-stability in the regulation of the vibration reduction [41].

The development of highly precise digital electronic detonators enabled a very accurate timing of the blasting operations. The digital electronic detonators provide an accurate delay by applying the chip of the integrated circuit. The delay extent is approximately 1 ms up to 16 s, and the delay deflection is only approximately 0.1 ms. The digital electronic detonators are able to provide an accurate time delay of the combustion according to the requirements in situ. Applying the digital electronic detonators enables us to achieve the required effect of rock disintegration, and, moreover, they provide an adequate protection of the nearby environment from the blasting operations.

When the blasting operations are carried out by applying electronic detonators, the vibrations evoked by the blasting operations can be effectively reduced by the adjustment of the convenient sequence of delay. The vibration can be further reduced by applying the method enabling the superimposing of waves in the phase or in the antiphase [42]. Fu and Sun [43] found that if the model of linear superposition is applied for the vibration regulation, the best results can be achieved only if the delay deflection is lower than 1–3 milliseconds. Mogi and Kou [42] proposed the method of the combined delay based on the electronic initiation scheme. The optimum delay time could be achieved by simulating the interference of superimposed vibration waves from the individual boreholes. Wang et al. [44] pointed out the abilities of the Hilbert–Huang Transform (HHT) in identifying important features related to millisecond blasting, particularly detonation times. The real delay time can be identified by analyzing the peak distribution of the instantaneous energy. They found that the instantaneous energy of the vibration signal is an accurate indicator of the initiation sequence.

Yi et al. [45] developed a monitoring and regulating system of the interference of the wave shape in order to reduce vibrations according to the millisecond delay timing. The optimum time of delay could be deduced from different times of delay and the propagation of surface waves to simulate times with different boreholes taking into consideration various conditions of timing; by applying this method, the interference of the wave shape can be achieved, leading to a reduction in the vibration. Shi and Chen [46] investigated the influence of the maximum explosion capacity on the delay and the choice of the optimum interval for the reduction in the vibration intensity by the interference of the wave shape. According to the terrain experiments, the maximum charge capacity for the delay was 15 ms, which enabled the vibration to be reduced by 24.5%.

The paper describes the results of research that was realized in Trebejov Quarry and its surroundings. The aim of our research was to identify the values at which the seismic impact of the blasting operations does not damage the buildings in the environment of the quarries and the inhabitants of the buildings are not subjected to vibrations by the blasting operations, which could be dangerous for them. Through the Slovak Hygienic Standards, the impacts of the vibrations on inhabitants are determined by the measurement acceleration of the vibration in the buildings and other places where the inhabitants are living. However, the most accurate standard cannot prevent inhabitants living in the housing nearby the quarries from complaining about the impact of the blasting operations, as they perceive them negatively; nevertheless, they do not measure them accurately. The problem with the inhabitants of the housing is that they accentuate only the negative impact of the blasting operations/complaints of the inhabitants, causing the quarries and mining facilities existing near to the expanding housing agglomerates higher financial and time costs. By applying the modified millisecond timing and monitoring the blasting operations in the quarries, we tried to experimentally record the optimum interval of particle velocity values and their frequency which would not affect the inhabitants in a negative way. Within this research, a series of six research blasts was performed in Trebejov Quarry, whereas the seismic impact of these blasts on the housing was measured in the village of Trebejov. There were two measuring points at our disposal for measuring the impact of the blasting works. The purpose of these blasts was to carry out research, and they were designed in order not to exceed the limits in accordance with legal provisions. During the first research blast No. 693, the charge was blasted only in one borehole without any propagation delay. In the case of further research blasts, two boreholes were blasted with an increased propagation delay of 1, 5, 10, 15 and 20 ms. In all cases of these research blasts, the seismic impacts of the blasts on the given measuring points were measured and evaluated. The results of this research were also compared with those of the vibrographs of the common surface mining blasts.

2. Materials and Methods

2.1. Blasting Works and Seismic Effects in Quarries

Seismic wave propagation is affected by the properties of the surrounding environment, which cannot be defined exactly in many cases. In rocks, a seismic wave running through tectonic faults with great attenuation spreads relatively easily and over long distances along these faults (Figure 1). Common frequencies which arise during blast are stored; they range between 5 and 50 Hz. Frequencies $f < 10$ Hz correspond to charges with an equivalent mass $m_{ev} > 2000$ kg; frequencies $f > 50$ Hz correspond to charges with an equivalent mass $m_{ev} < 5$ kg [47].

Figure 1. Bench blasting in quarry (source: author).

2.2. Geological Construction of the Rock Environment in the Surroundings of Trebejov

The area of interest is incorporated into the Black Mountain hills range, which is characterized by a diverse geological structure. Crystalline rocks predominate in the central part of the mountain range, where flat relief also dominates. For example, the rest of the rock cover, quartzite or limestone is found in the northern and southern parts of the mountain range. Medium-cut relief is usually found in the suburbs and uplands. Deep-cut reliefs are also present, with a very deep-cut relief in the highest parts of the mountain range and other parts of the territory. At the highest altitudes, slopes are above 20°, but in most areas, the slopes are around 6–20° [48].

In Trebejov Quarry, which is east of the village of Trebejov, the Ramsau dolomites can be found. The dolomites are from light grey to grey; only rarely they are dark grey. The thickness of the dolomite rock beds in Trebejov Quarry varies from 10 to 100 cm. Sometimes they appear in massifs. As they are rheologically very hard rocks, they create morphologically dominant shapes in the terrain. Mainly microcrystallic, but sometimes thicker, crystallic dolomites can be found with a low content of fossils, namely, lamellibranchia and dasycladacean—presumably diplopora. Residuals of crinoids can be observed only rarely in the dolomites. In many places of the quarry, the dolomites are karsificated along the tectonical structures or they create breccia. From the microstructural point of view, dolomicrites are present, but sometimes sparite can be found in the ortochemical component (Figure 2) [48].

Quaternary: 1—clay, gravel and sand (Holocene); 2—sandy gravel and gravel (Pleistocene); 3—deluvium (unstructured), mainly loam stony. Neogene: 4—klcovske formation varhanovske gravel: polymict, weathered, without pebbles of carbonates (upper Baden-lower Sarmatian). Mesozoic: 5—variegated clayey shales and clay sandy shales, with interbeds of quartzite (lower Trias); 6—luznanske formation: quartzite and quartzite sandstone, locally with the interbed shales (lower Trias); 7—Ramsau dolomites (ladin) [48].

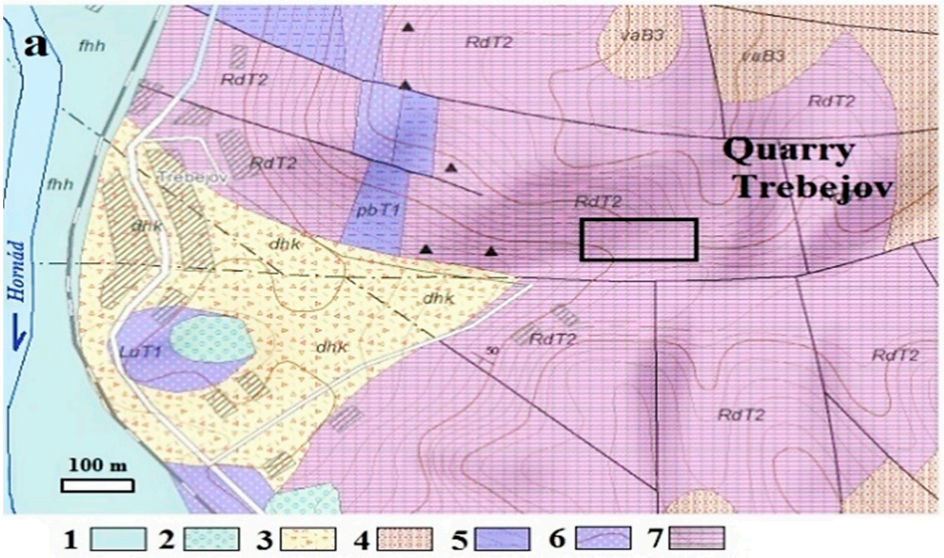


Figure 2. Geological map of the surroundings of Trebejov Quarry [48].

Dolomite is mined in this quarry, which was formed as a result of conversion from various types of limestone. The boundary of the mining area is given by the size and form of the deposit. Trebejov Quarry is located approximately 800 m east of the residential part of the village of Trebejov (Figure 3) [48].

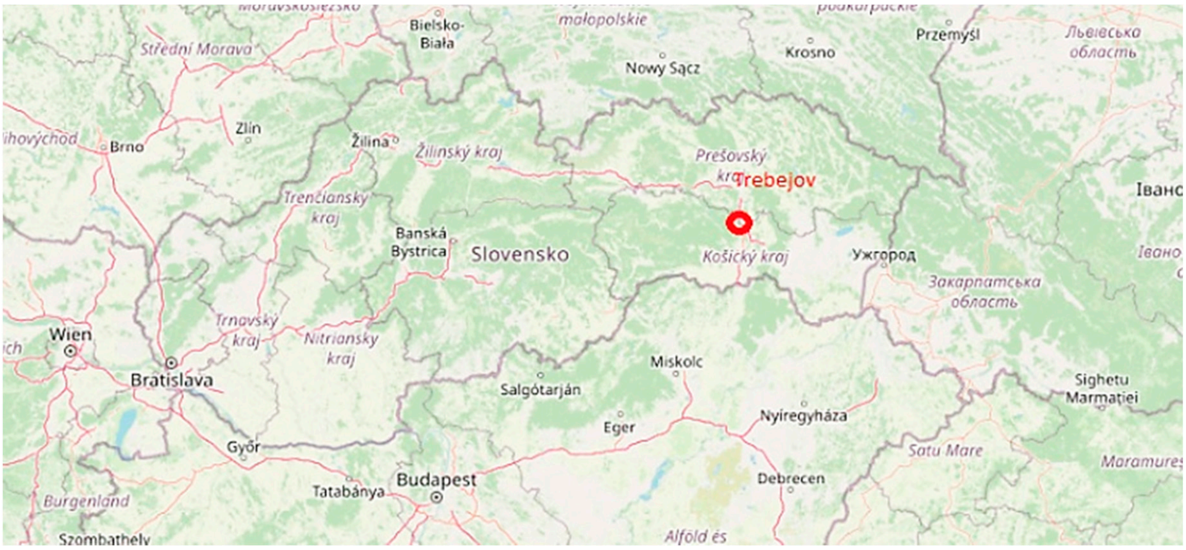


Figure 3. Demonstration of a quarry on the map of the Slovak Republic [49].

2.3. Positions of Measurement and Apparatus Used for Measuring Technical Seismisity

The source of technical seismicity, i.e., seismic shock or vibrations caused by an artificial source, can vary, such as, machinery, heavy transport, road or rail transport, mining shocks and shocks caused by blasting in quarries.

The following digital seismic instruments were used to measure and graphically record the seismic effects of the blasting operations at the indicated measuring stations:

2.3.1. Minimate Pro 6—Instantel

A special instrument by INSTANTEL-MINIMATE PRO 6 was used for seismic measurement. The MINIMATE PRO 6 provides 64 MB of memory, improved durability, metal housing, connectors and water resistance (Figure 4). It is possible to connect two standard ISEE or DIN triaxial geophones to monitor the vibration sources from two different locations. Another option is to connect one ISEE or DIN triaxial geophone and one ISEE linear microphone, as well as the possibility to connect an audio microphone if air overpressure measurement is required. The main parameters of the device are as follow: frequency range: 2 to 250 Hz; accuracy: from 2 to 4 Hz and 125 to 250 Hz: +5% to −3 dB of an ideal flat response, from 4 to 125 Hz: ±5% or ±0.5 mm/s (0.02 in/s).

Figure 4. Placement of the vibrographs Minimate Pro 6-Position S1 (source: author).

The MINIMATE PRO 6 situated in the measured position was calibrated before the measurement, and its sensitivity was also checked. The graphs of the individual components of the seismic wave were recorded in the positions of the measurement. The vibrographs were placed on the measuring positions enabling us to assess the impact of the technical seismicity on the monitored objects. Based on the measured values of particle velocities and frequencies of the individual components of the wave at the shot, the seismic load of the building constructions and effects on a housing construction were evaluated according to STN EN 1998-1/NA/Z1. [50,51].

2.3.2. Svantek 958 A—Class 1

The monitoring point was placed about 630 m from the blasting works, which were carried out in the quarry. A special instrument by SVANTEK-SVAN 958A was used to measure noise and vibration. SVAN 958A Class 1 Four-Channel Sound and Vibration Analyzer are designed for all applications requiring simultaneous Class 1 audio and vibration assessment. Each of the four input channels can be independently configured to detect sound or vibration with different filters and RMS detector time constants that provide a great flexibility in measurement. The main parameters of the device are as follows: SV 84 triaxial high sensitivity accelerometer for ground or building vibration measurements; (1 V/g) SV 38 triaxial accelerometers for whole-body measurements (1 V/g MEMS type); 2 vibration profiles for simultaneous measurement of PPV and VDV; simultaneous FFT analysis; simultaneous WAVE recording, according to DIN 4150-3 standard; frequency range: 0.5 Hz ÷ 20 kHz. The real advantage of the SVAN 958A is its ability to perform advanced analysis simultaneously with a level meter. In practice, this allows us to obtain broadband results [51,52].

The measurement positions S1 and S2 were located inside the residential building No. 91 and at the entrance to the cellars of the object under assessment. At the S1 position, a (Minimate Pro 6) vibrograph was placed at the entrance to the residential building on the foundations. Vibrograph Svantek 958 (position S2) was placed in the corridor of the entrance to the kitchen inside the residential building (Figure 5). The vibrographs provide a digital record of all three components of the particle velocity, dominant frequency, peak acceleration and peak displacement of the environment in the horizontal longitudinal-v_x, horizontal transverse-v_y and vertical-v_z directions, respectively. The vibrographs operate autonomously, automatically performing a channel test without any intervention, and the operators influence the measured and registered vibration characteristics.

Figure 5. Placement of the vibrograph Svantek 958 A-Position S2 (source: author).

2.4. Parameters of Research Blasts in Trebejov Quarry

The source of the seismic effects was the monitored blasts No. 693–698 on the dolomite deposit of the quarry located about 0.6 km east of the village. The borehole diameter was 105 mm, 65° inclination, 30.7 m depth, 4.0 m burden and 4.2 m spacing (Figure 6).

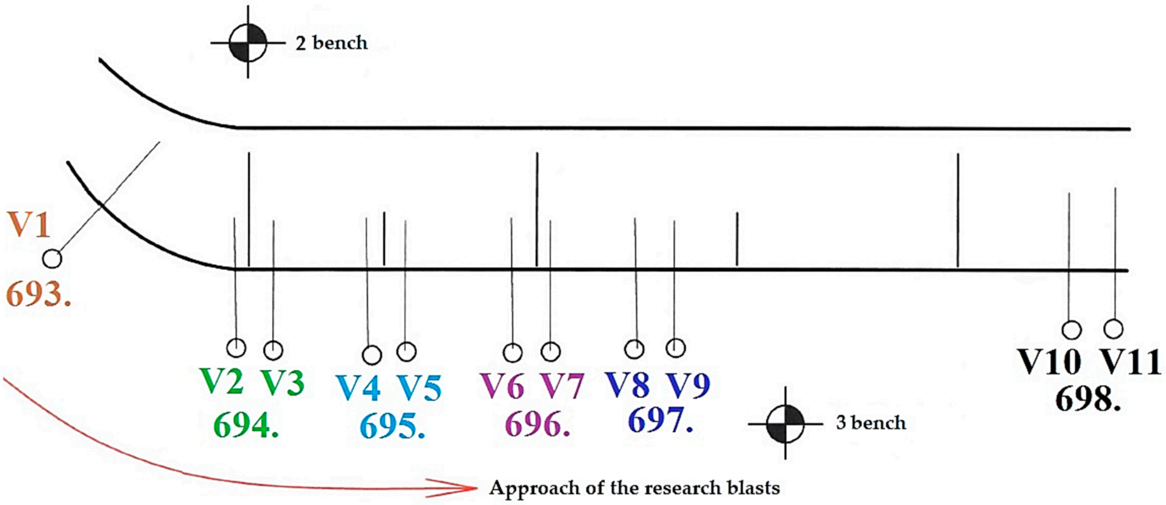


Figure 6. Position of the boreholes on the 3 bench-No. V1—blast 693; V2, V3—blast 694; V4, V5—blast 695; V6, V7—blast 696; V8, V9—blast 697; and V10, V11—blast 698 in Trebejov Quarry [48].

The weight of the charge in one borehole was 175 to 180 kg of explosive Andex M and 5 to 10 kg of explosive Poladyn 31 Eco (see Table 1). The total load of the explosives was 2042 kg. The blasts were carried out using UNITRONIC 600 electronic timed detonators. In total, 693 were realized at time 0 in one borehole V1. Blast No. 694 was performed in two boreholes, V2 and V3, with millisecond timings of 0 and 1 ms. Blast No. 695 was realized in V4 and V5 boreholes with millisecond timing delays of 0 and 5 ms. Blast No. 696 was performed in two boreholes, V6 and V7, with millisecond timing delays of 0 and 10 ms. Blast No. 697 was performed in two boreholes, V8 and V9, with millisecond timing delays of 0 and 15 ms. Blast No. 698 was performed in V10 and V11 boreholes with millisecond timing delays of 0 and 20 ms. Before charging, the inclinometric alignment of boreholes V1 to V11 was performed (see Table 2).

Table 1. Parameters of the Poladyn 31 Eco and Andex M explosive [53].

Parameters	**Poladyn 31 Eco**
Oxygen balance [%]	4.8
Heat of explosion [kJ/kg]	3973
Concentration of energy [kJ/dm^3]	5364
Volume of gaseous products of explosion [dm^3/kg]	883
Specific energy [kJ/kg]	1001
Consistency	plastic
Density [g/cm^3]	1.40 ± 0.14
Trauzl test [cm^3], average	380
RWS [%Hx], minimum	80
VOD [m/s], minimum (in cartridges)	>2000 m/s (ø 25 ÷ 32 mm) >4500 m/s (>ø 32 mm)
VOD [m/s] (plastic pipe ø 32 mm)	5000
VOD [m/s] (steel pipe ø 34 mm)	6000
Parameters	**ANDEX M**
Density (g/cm^3)	0.78–0.88
Minimum borehole diameter (mm)	34
Borehole type	dry
Typical detonation velocity (m/s)	2500–3500
Relative gravimetric energy density (%)	100
Relative bulk energy density (%)	104
CO_2 (kg/t)	178
Consistency	anfo

Table 2. Parameters of the blasts in quarry [48].

Blasts	Borehole	ANDEX M (kg)	Poladyn (kg)	Total Charge in Borehole (kg)	Total Charge for Blast (kg)	Lower Timing (millisec.)	Upper Timing (millisec.)	Time of Blast (hh, mm)
693	V1	180	5	185	185	0	50	11.09
694	V2	180	5	185	370	0	50	11.18
	V3	180	5	185		1	51	
695	V4	180	5	185	370	0	50	12.07
	V5	180	5	185		5	55	
696	V6	175	10	185	370	0	50	12.25
	V7	180	5	185		10	60	
697	V8	180	10	190	377.5	0	50	13.03
	V9	180	7.5	187.5		15	65	
698	V10	180	5	185	370	0	50	13.47
	V11	180	5	185		20	70	

2.5. Methods for Evaluation of Seismic Effects of Blasting Works in Quarries

The explosion of the charge performs an air pressure wave, which acts on the environment by the magnitude of the overpressure P at a certain distance from the place of the explosion. It consists of a thin layer of compressed air, which has the characteristics of a shock wave near the source (exploding charge) and passes to a sound wave at a greater distance. With a well-sealed charge, a health hazard due to its action is much less likely than a hazard due to the material being scattered. Under certain conditions, the pressure wave can damage the semi-enclosed or attached charge [48]. In such cases, even a relatively small charge can cause more extensive damage. The intensity of the pressure wave is measured by the pressure sensors or sonometers with a very short time base. The following equation is used for approximate calculation of overpressure [34,51]:

$$P = k.\sqrt{\frac{Q}{L^3}} \tag{1}$$

where P is the overpressure in [Pa], k is a constant depending on the influence of the environment around the charge and on the specific energy of the explosive (for industrial explosives with stabilized detonation velocity k = 13 to 15, for others it is smaller), Q is the mass of the charge [kg] and L is the distance of the assessed point from the center of the explosion. A relatively low pressure is harmful to the human body. Severe to fatal injuries occur even at overpressure above 0.1 MPa. Overpressures above 0.005 MPa are very intense and painful [34,51].

According to the Regulation of the Government of the Slovak Republic No. 549/2007 Coll. on the protection of health against noise and vibration for the assessment of noise, harmfulness depends not only on the intensity and frequency spectrum but also on the time of the exposure to noise. In the case of a short-time exposure to noise (1 to 200 ms), during which the maximum emission of sound energy occurs, an impulse sound can be identified. The stable sources of impulse noise are mainly firearms used and explosives (e.g., shots in quarries), but also other technologies giving rise to a sudden release of energy. The maximum permissible noise level L_{Amax} for impulse noise with a number of pulses of less than 20 pulses per second and a duration of less than 1 s, in terms of exposure to the human body, is 130 dB. Acoustic wave pressure, in terms of exposure to residential buildings, can cause damage at values above 100 Pa. Because the effect of sound pressure is expressed in terms of levels expressed in decibels, to assess the effect on the human body, the sound pressure can be converted to levels according to the correlation relationship between a decibel (dB) and pascal (Pa).

$$\mathrm{dB} = 20 \times 10\, log(0.05\ \mathrm{Pa}\ \times 106) \tag{2}$$

The harmful effects of air pressure waves are as follows: 198 dB, severe and fatal injuries; 180 dB, severe damage on common buildings; 174 dB, most window panes broken; 154 dB, some window panes broken; 148 dB, very intense human sensation; 143 dB, harmless to buildings; 140 dB, some very large window panes broken; 138 dB, maximum permissible value, no damage will occur; 134 dB, maximum acceptable value when no damage occurs [34,51].

The method used to measure ground vibration is dependent on the blasting application and the type of data that need to be collected. Velocity is the most common method used to measure ground vibration. This is because it is relatively easy to measure, and it is referenced in most relevant legislation and standards. Velocity is measured with an instrument called a geophone.

Acceleration is a less common way of measuring ground vibration. This is because it is not referred to in many blasting standards. However, manufacturers of sensitive equipment, such as computer hard drives, sometimes provide maximum vibration limits in terms of acceleration, measured in "g". Acceleration is also preferred to velocity when measuring vibration for research and scientific purposes, as the equipment used can detect vibrations over a wider range of frequencies than geophones [54].

The relation between the particle velocity and acceleration was proved, but the calculations could not include the versatility of the impact interaction during the transmission of the energy of the seismic waves, which extended through the rock environment to the construction of the housing. Therefore, we decided on the experimental method of measurement. The application of the electronic timing enabled us to assess the vibration source in an accurate way, which was the blast.

Within our research, the parameters of the particle velocity and acceleration of the vibration were assessed in order to determine the seismic impact of the blasting operations on both the buildings and the inhabitants.

2.6. Permissible Vibration Limit Values

In technical practice, the assessment of the impact of the blasting operations is focused on different technical buildings and constructions depending on their importance for the society, the characteristics of the construction, their methods of utilization or their age, etc. (e.g., nuclear power plants, water dams, transport tunnels, engineering networks, tower buildings and historical ones and housing). In many countries, accurate normative values are defined for their protection from the damage caused by the particle velocity and frequency. Different countries apply different standards, and others modify or adopt them. The Slovak, Czech and German praxes prescribe low values, i.e., 5–10 mm.s^{-1}, but, for example, in Russia, the admissible values are up to 30 mm.s^{-1}, and in the USA, they are up to 50 mm.s^{-1} [34,55,56]. The problem lies in the precise assessment of the stated and secure standards for housing, as the inhabitants of them have different experiences with the impact of the blasting operations. There are hygienic standards for the inhabitants of the housing, which evaluate the impacts of blasting operations on humans through the measurement of the vibration acceleration in the housing [51].

In the village of Trebejov, it is possible to classify buildings into resistance class B based on the recommendations of the STN EN 1998-1/NA/Z1 [51] seismic loading of building structures concerning charges used for aperture blasting, which are in the order of tens of kilograms, where oscillation frequencies are usually f > 10 Hz and based on the resistance of buildings to technical seismicity. As for the type and category of foundation soil of the protected objects, due to the absence of more specific characteristics and data, we can classify them into category b, which is the closest to reality (groundwater level is more than 3 m below the surface level). Based on measured data during blasting in Trebejov Quarry, where the oscillation frequencies were f <10 Hz, and due to the long-term nature of blasting at the limestone deposit in Trebejov Quarry, a predominantly higher age of buildings cracks was identified. Concerning Trebejov Quarry and the buildings in the municipality of Trebejov, the maximum permissible particle velocity (velocity component) was determined as $v_d \leq 3$ mm.s^{-1} (Table 3) [34,51].

Table 3. Table Dependence of the damage level on maximum particle velocity, type of the structure and foundation soil according to STN EN 1998-1/NA/Z1 [51].

Maximum Particle Velocities for the Frequency Area			Level of Damage	Class of Resistance of an Object	Type of Foundation
f_k < 10 Hz	10 Hz < 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

From the viewpoint of the impact of the blasting on the inhabitants of the buildings, it is also necessary to introduce the admissible parameters of the vibrations in the indoor environment of the buildings. According to Law No. 355/277 regarding the protection, support and development of public health, Decree MZ SR No. 549/2007 and No. 237/2009

(Table 4) concern residential buildings, dormitories and retirement homes, for the reference time interval [57–59]:

day: $a_{wmax,p}$ = 0.11 m.s^{-2},

measured max. values: a_{wmax} = 0.078 m.s^{-2}.

Table 4. Allowed values of vibration quantities in the indoor environment of buildings [58,59].

Description of the Protected Room in Buildings	**Reference Time Interval**	**Continuous or Intermittent, Periodic or Steady-State Random Vibration**	**Shocks and Vibrations with Large Dynamics Occurring Several Times a Day**
		a_{weq} [$m*s^{-2}$]	a_{weq} [$m*s^{-2}$]
Enhanced areas (such as hospital rooms, spa patients)	Time of occurrence for day, evening and night	0.004	0.008
Residential rooms, dormitories, retirement homes	Time of occurrence for day evening night	0.008 0.008 0.005	0.11 0.11 0.05
Nurseries, schools and libraries	Time of occurrence while using the room	0.008	0.11

3. Results

3.1. Methodology of Measurement and Evaluation of Measured Data

The measurements were carried out in the receptor/family house situated in the nearby environment of Trebejov Quarry and simultaneously in the indoor environment of the housing according to the standards. The transmitting rock environment was carbonate rocks—dolomites. Vibrographs placed on the sites were calibrated before the measurement, and their sensitivity was checked. The graphical course of the individual seismic wave components at the measured firing No. 693–698 is demonstrated. The individual graphical records are four seconds long. The vibrographs were placed on the measuring points (see Figure 7) in order to assess the impact of the technical seismicity on the assessed objects (Table 5).

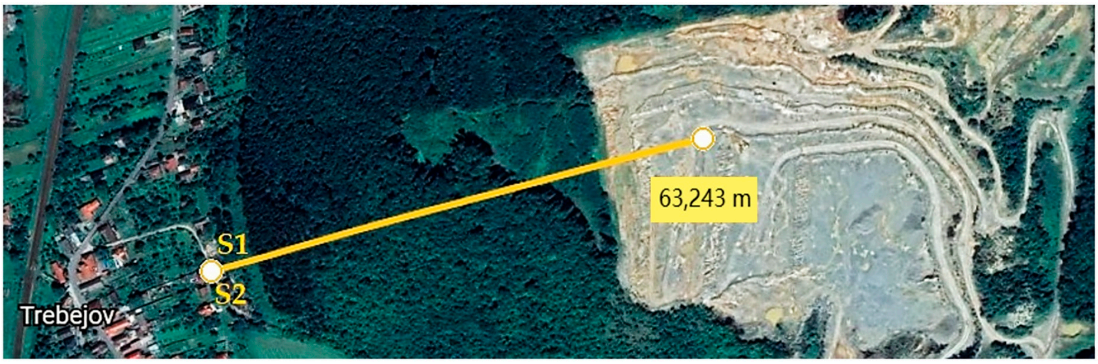


Figure 7. Measuring points S1 and S2 ([60], (source: author)).

Table 5. Measured values of peak particle velocity in blasts (source: author).

Blast No.	**Profile**	**Position of the Measurement**	**v_x [mm.s^{-1}]**	**v_y [mm.s^{-1}]**	**v_z [mm.s^{-1}]**
693.	-	S1/Minimate	0.81	1.15	0.81
694.	-	S1/Minimate	1.46	1.55	1.26
695.	-	S1/Minimate	1.59	1.13	0.87
696.	-	S1/Minimate	1.23	1.63	0.81
697.	-	S1/Minimate	1.2	1.62	0.82
698.	-	S1/Minimate	0.98	1.58	0.58

3.2. Analysis and Evaluation of Measured Data

While monitoring the blasts, the vibrations were measured during the daytime when the operational blasts were carried out in Trebejov Quarry. The vibrations lasted 200–250 ms with shock impulses. Since there was no repeated long-lasting (more than 500 ms) seismic loading of the monitored object, the wave energy was absorbed by the object in a way so as not to disturb its equilibrium state. The influence of 250 ms vibrations with repeated shock impulses did not result in steady periodic loading of the monitored object, which did not exceed the limit values (STN EN 1998-1/NA/Z1) [51]; the particle velocity v_d = 3.0 mm.s^{-1} could not have damaged the monitored object. An example of the measured values for the individual experimental blasts is shown in the records of the Svantek 985 A device (Table 6). Figures 8 and 9 display the maximum values of the particle velocity and acceleration on standpoints S1 and S2 (building No. 91 in the village of Trebejov) during blasts No. 693, 694, 695, 696, 697 and 698.

Table 6. Measured values of peak acceleration in blasts (source: author).

Blast No.	Profile	Position of the Measurement	$a_{wmax,x}$ [mm.s^{-2}]	$a_{wmax,y}$ [mm.s^{-2}]	$a_{wmax,z}$ [mm.s^{-2}]
693.	-	S2/Svantek	28.05	42.36	49.20
694.	-	S2/Svantek	47.64	49.09	78.25
695.	-	S2/Svantek	48.19	45.49	51.70
696.	-	S2/Svantek	35.72	49.31	58.68
697.	-	S2/Svantek	27.41	52.24	58.68
698.	-	S2/Svantek	24.43	44.87	19.54

At the S1 standpoint, the Vibrograph Minimate PRO 6 was set on the reference standpoint (STN EN 1998-1/NA/Z1) [51]—foundations of the building. It monitored the effects of the vibrations on the building. At blasting No. 693, the seismic effects of one individual borehole with charge capacity, which is applied in the blasting operations in Trebejov Quarry, were measured. At blasting No. 694, the seismic effects of two boreholes with doubled charge capacity were measured. The maximum particle velocity was not doubled (Figure 8). At blasting No. 695, the seismic effects of two boreholes with doubled charge capacity and with a millisecond delay of the second blast of 5 ms were measured. The maximum particle velocity was nearly doubled, meaning that there was an accumulation of the amplitudes of the seismic wave initiated by the first and second blasts. At blasting No. 696, the seismic effects of two boreholes with doubled charge capacity and a millisecond delay of the second blast of 10 ms were measured. The maximum particle velocity was lower than that at blasting No. 695, meaning that a partial attenuation of the amplitudes of the seismic wave generated by the first and second blasts occurred. At blasting No. 697, the seismic effects of two boreholes with doubled charge capacity and a millisecond delay of the blast of the second borehole of 15 ms were measured. The maximum particle velocity was equal to that of blasting No. 696, meaning that a partial attenuation of the amplitude of the seismic wave generated by the first and second blasts occurred. At blasting No.698, the seismic effects of two boreholes with doubled charge capacity and with a millisecond delay of the blast in the second borehole of 20 ms were measured. The maximum particle velocity was lower than that at blasting No. 696 and 697, meaning that a higher attenuation of the amplitude of the seismic wave generated by the first and second blasts occurred. The value of the maximum particle velocity was equal to or lower than that at blasting No. 693; half capacity of blasting No. 698 was blasted (Table 2), (Figure 8).

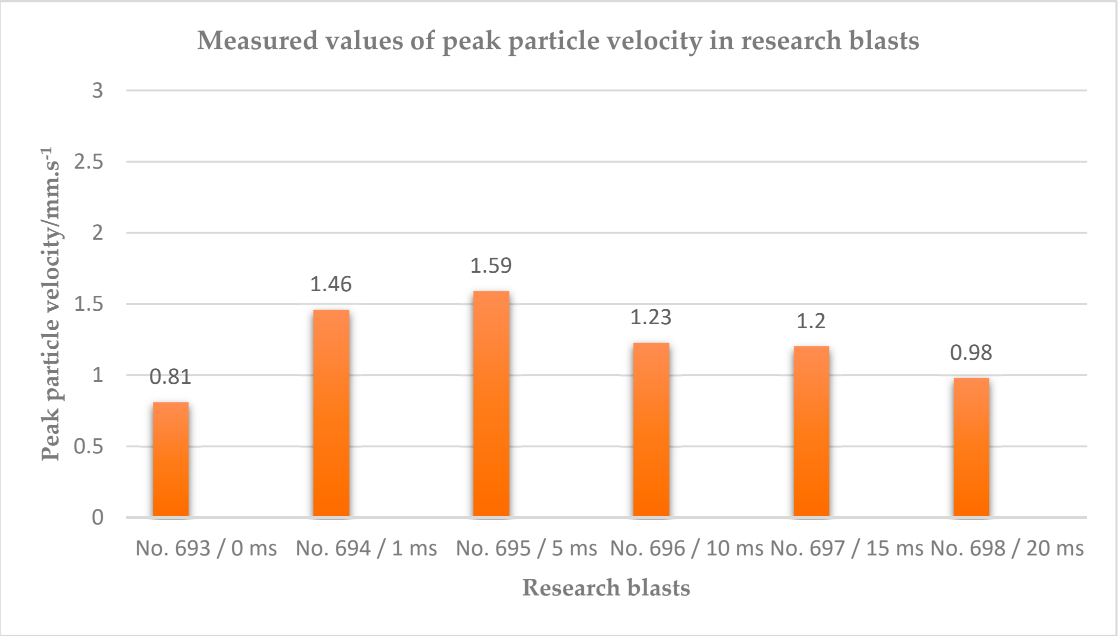


Figure 8. Dependence of measured values of peak particle velocity in research blasts (source: author).

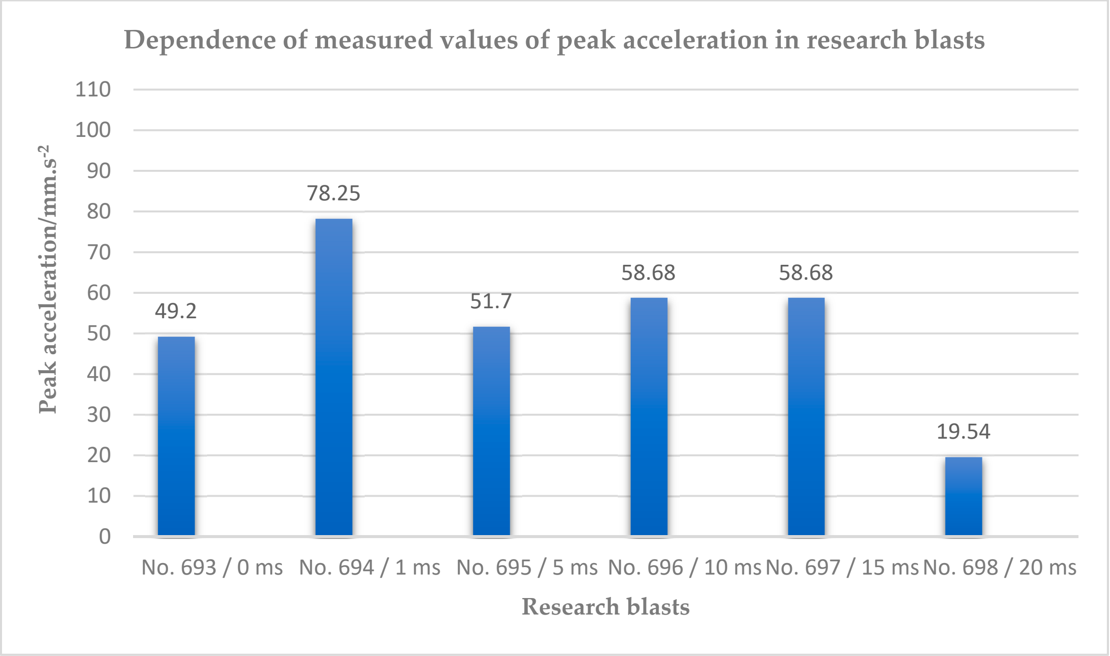


Figure 9. Dependence of measured values of peak acceleration in blasts (source: author).

From the plot (Figure 8) it is visible that the highest attenuation of the seismic wave initiated by blasting works in Trebejov Quarry and the lowest values of particle velocity on building No. 91 were achieved at millisecond timing delays of 15 and 20 ms. The highest values of the particle velocity were measured at a millisecond timing delay of 5 ms. During a timing delay of 20 ms (blast No. 698), a lower particle velocity was achieved than for blast No. 693, close to which the only borehole was detonated.

At standpoint S2, the vibrograph Svantek 958A was set at the reference point (Decree MZ SR No. 549/2007 and nr. 237/2009)—in the middle of the building. It monitored the effects of vibrations on the inhabitants of the building.

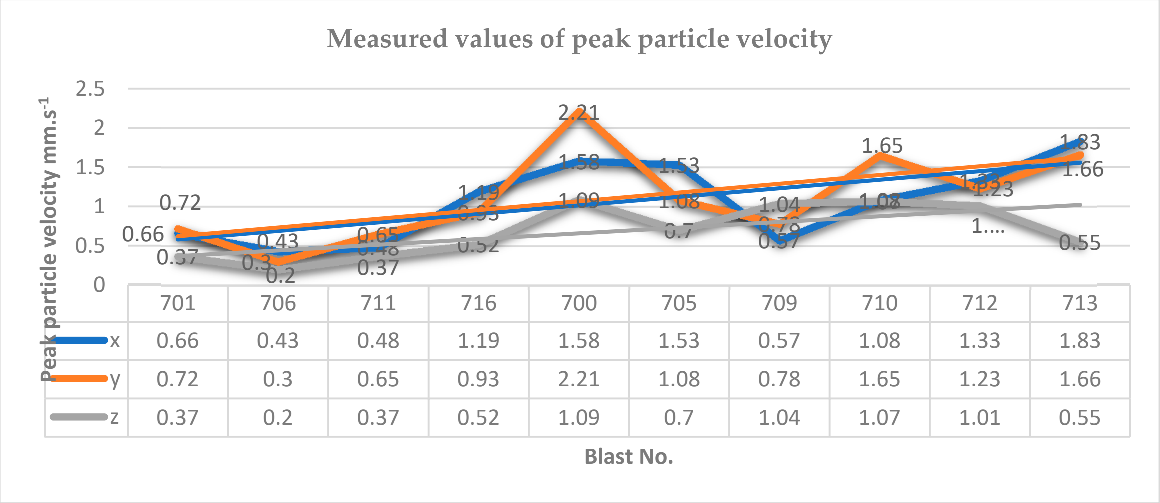
Figure 9 shows that the maximum attenuation of the seismic wave initiated by the blasts in Trebejov Quarry, and the lowest values of the acceleration at building No. 91 were achieved during a millisecond timing delay of 20 ms. The highest values of vibration acceleration, a_{wmax} = 0.078 m.s^{-2},were measured at a millisecond timing delay of 1 ms. The timing of blasts No. 694 and No. 695 with a 1 ms delay was chosen in order to obtain a double seismic effect compared to individual blast No. 693. Although the measured values were the highest, they did not reach the expected double values. The measured maximum values of the acceleration for all blasts did not exceed the limit value a_{wmax} = 0.11 m.s^{-2}, which is defined by the hygienic standard for the inhabitants of the building. The inhabitants of the building who were present at the research blasting operations did not perceive these vibrations as dangerous. At blasting No. 695, the seismic effects of two boreholes with doubled charge capacity and a millisecond delay of the blast in the second borehole of 5 ms were measured. The maximum value of vibration acceleration was approximately equal to that of blasting No. 693, meaning that a partial attenuation of the amplitude of the seismic wave generated by the first and second blasts occurred. At blasting No. 696, the seismic effects of two boreholes with doubled charge capacity and a millisecond delay of the blast in the second borehole of 10 ms were measured. The maximum value of the vibration acceleration was higher than that at blasting No. 695, meaning that a partial attenuation of the amplitude of the seismic wave generated by the first and the second blasts occurred. At blasting No. 697, the seismic effects of two boreholes with doubled charge capacity and a millisecond delay of the blast in the second borehole of 15 ms were measured. The maximum values of the vibration acceleration were equal to those of blasting No. 696, meaning that a partial attenuation of the amplitude of the seismic wave generated by the first and second blasts occurred. At blasting No. 698, the seismic effects of two boreholes with doubled charge capacity and a millisecond delay of the blast in the second borehole of 20 ms were measured. The maximum value of the vibration acceleration was lower than that at blasting No. 695, 696 and 697, meaning that the highest attenuation of the amplitude of the seismic wave generated by the first and second blasts occurred. The maximum vibration velocity was lower than that at blasting No. 693, when the charge capacity was half compared with blasting No. 698. The inhabitants of the building who were present at the research blast No. 698 also perceived these vibrations as safe. At the timing delay of 20 ms, when boreholes V10 and V11 were detonated with a delay of 20 ms (No. 698), a lower value of vibration acceleration was achieved than during No. 693, during which only one borehole V1 was detonated. In this way, it was experimentally shown that the suitable delay of the individual borehole detonation during blast works can decrease the seismic effect of the blast works and their impact not only on the buildings but also on their inhabitants. Moreover, it confirmed that if the values of the peak particle velocities measured on the building object are lower than 3 mm.s^{-1}, the inhabitants do not perceive these vibrations as dangerous. The assessed value—a measured value of the vibration acceleration quantity a_{wmax}—was determined in accordance with the metrological practice.

Based on the measured values, we can conclude that the optimum conditions in terms of the impact of seismic effects of blasting on the residents in the building in the village of Trebejov were blast No. 6 and aperture No. 698 (Figure 9).

4. Comparison of Measured Data in Research and Everyday Aperture Blasting

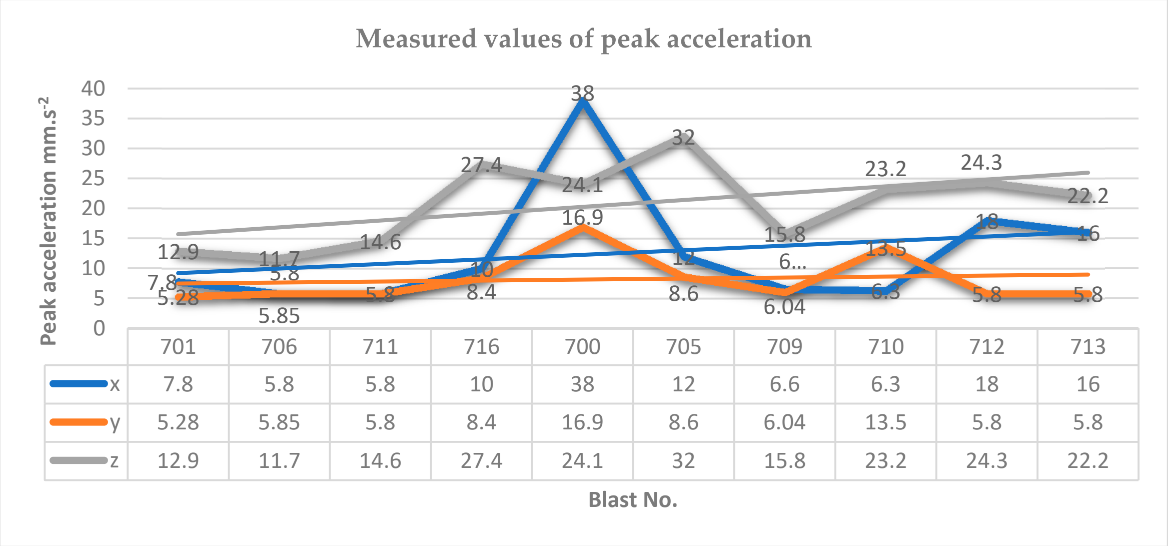
In order to assess the application of the results of research blasting (where 20 ms was determined for a suitable delay of charges) in conventional blasting, further measurement results are given in the following section. Measurements were performed for mining blasts using non-electric detonators with delays of 17 and 25 ms, which are closest to the value of 20 ms.

As we can see from the graphs Figures 10–12, reducing the weight of the charge does not mean improving the seismic effects on the environment and population. The basis for achieving the best results of technical seismicity to the surrounding environment is the correct design of the millisecond timing delay of the blasting work in the quarry. As we can see in (Table 7), it is necessary to use different timings for daily shots even within one floor, if there is a different violation in individual parts. Changes in disturbance must be determined by the propagation speed and frequency of the seismic waves. The values of the oscillation speed on the 3rd and 4th benches were optimal, and thus, the timing delay of 25 ms was determined correctly. The measured values of all blasting, which were measured on the residential building in the village of Trebejov, did not exceed the permissible values set by the relevant standard STN EN 1998-1/NA/Z1 [51] Seismic Loading of Buildings. The timing delays of 17 and 25 ms proved to be the correct solution.



Blast No.	701	706	711	716	700	705	709	710	712	713
x	0.66	0.43	0.48	1.19	1.58	1.53	0.57	1.08	1.33	1.83
y	0.72	0.3	0.65	0.93	2.21	1.08	0.78	1.65	1.23	1.66
z	0.37	0.2	0.37	0.52	1.09	0.7	1.04	1.07	1.01	0.55

Figure 10. Dependence of measured values of peak particle velocity (source: author).



Blast No.	701	706	711	716	700	705	709	710	712	713
x	7.8	5.8	5.8	10	38	12	6.6	6.3	18	16
y	5.28	5.85	5.8	8.4	16.9	8.6	6.04	13.5	5.8	5.8
z	12.9	11.7	14.6	27.4	24.1	32	15.8	23.2	24.3	22.2

Figure 11. Dependence of measured values of peak acceleration (source: author).

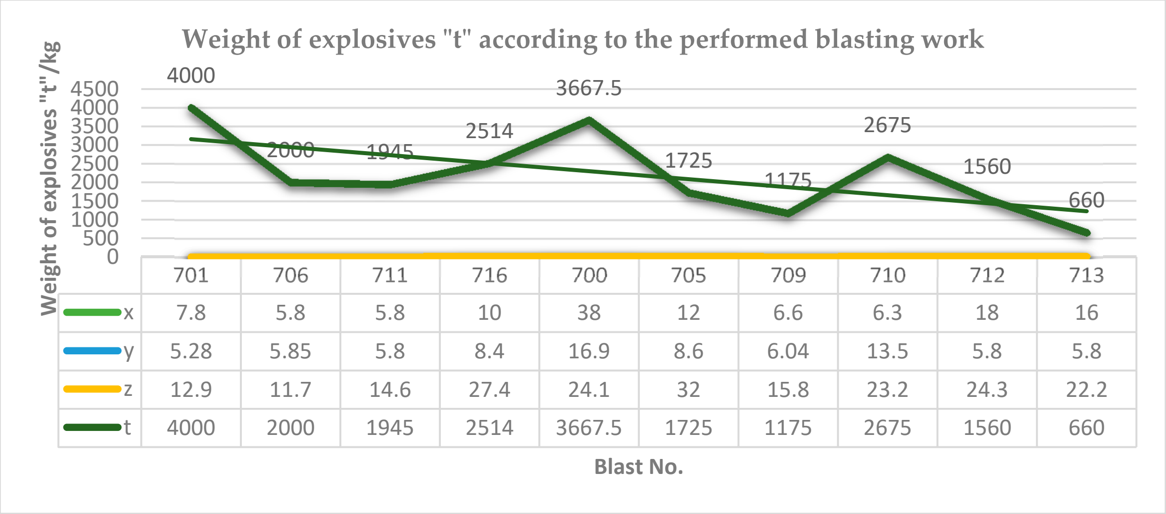


Figure 12. Graphical course of the weight of explosives according to the performed blasting work (source: author).

Table 7. Measured values of maximum particle velocities at individual delays of millisecond timing during daily aperture blasting in Trebejov Quarry [48].

Date of Blast	Blast No.	Weight of Explosives/Charge Weight per Delay [kg]	Timing of Blast Delay [ms]	Peak Particle Velocities [mm.s^{-1}]			Frequency [Hz]			Number of Bench Blast	Distance Blast-Building [m]
				x	y	z	x	y	z		
09.01. 2020	700	3667.5/187.5	25	1.58	2.21	1.09	38	16.9	24.1	2	644
31.01. 2020	701	4000/155	17	0.66	0.72	0.37	7.8	5.28	12.9	1	743
16.04. 2020	705	1725/195	25	1.53	1.08	0.70	12	8.6	32	2	636
24.04. 2020	706	2000/188	17	0.43	0.30	0.20	5.8	5.85	11.7	2	631
11.06. 2020	709	1175/125	25	0.57	0.78	1.04	6.6	6.04	15.8	4	540
25.06. 2020	710	2675/165	25	1.08	1.65	1.07	6.3	13.5	23.2	2	642
10.07. 2020	711	1945/155	17	0.48	0.65	0.37	5.8	5.8	14.6	1	743
24.07. 2020	712	1560/130	25	1.33	1.23	1.01	18	5.8	24.3	3	570
30.07. 2020	713	660/165	25	1.3	1.66	0.55	16	5.8	22.2	2	648
17.08. 2020	716	2514/165	17	1.19	0.93	0.52	10	8.4	27.4	1	744

5. Conclusions

The effects of the technical seismicity induced by blasting were measured and assessed by the velocity of the environmental particles (particle velocity (v)) according to the maximum value of one of its three components, x, y and z. The seismic protection principle of the seismic safety of the building objects against technical seismicity can be expressed by the following relationship.

$$v \leq v_d \tag{3}$$

where v is the maximum value of the particle velocity component caused by the vibration source, measured at the so-called vibration rate. For the reference position of the protected (assessed) object, the reference opinion is the ground floor of the building; the value of v depends mainly on the maximum mass of the explosive charge fired at one time point Q_{eq} [kg], further from the minimum source distance from the shock vibration receptor L [m] and the properties of the geological transfer environment between the source and the shock receptor. At the specific site, the value of v cannot be calculated in advance either analytically or empirically; the most reliable method is to determine it by a specific measurement, as in our case, i.e., v_d is the maximum allowable (limiting) particle velocity for the object (s) under consideration; there is no damage to the object at this vibration velocity—the degree of damage is 0; this value is determined independently of the blast (before blast) based on practical experience, different standards or on the basis of expert assessments by specialists. STN 73 0036: 1973-11/STN EN 1998-1: 2005/NA show the relationship between the vibration intensity expressed by the particle velocity of the individual components and the possibility of damage to the building. In accordance with the standard, the following criteria may be adopted for masonry civil buildings in an average building condition.

At peak particle velocity:

v = 0–10 $mm.s^{-1}$—there is no damage to the building;
v = 10–30 $mm.s^{-1}$—possibility of the first signs of damage;
v = 30–60 mm/s^{-1}—possibility of a minor damage.

The maximum permissible values for the size of the explosive charge determined in this way can only be used with aperture blasts with a burden of 4.0 m and a bore spacing of 4.2 m.

The analysis of the seismic effect measured in the blasts No. 693–698 in Trebejov Quarry showed that the greatest attenuation of the seismic waves induced by the technical seismicity was achieved at millisecond timing delays of 15 and 20 ms. The lowest peak particle velocity values of 0.53 $mm.s^{-1}$ in a residential building were recorded at a millisecond timing delay of 20 ms at blast No. 698. According to the valid Slovak Technical Standard STN EN 1998-1/NA/Z1, the seismic load of buildings, according to these measured values, did not cause any damage to buildings in the municipality of Trebejov. The measured values did not exceed the lowest value specified by the valid Slovak Technical Standard STN EN 1998-1/NA/Z1; the seismic load of the buildings was v = 3 $mm.s^{-1}$ for frequencies lower than 10 Hz and for the foundation soil of type b (Table 3). These values are safe from the point of view of the seismic safety of the buildings and their residents. In personal interviews, residents confirmed that they did not perceive such vibrations as dangerous.

The analysis showed that the lowest values of the acceleration at the building were achieved during a millisecond timing delay of 20 ms. The highest values of vibration acceleration, a_{wmax} = 0.078 $m.s^{-2}$,were measured at a millisecond timing delay of 1 ms. The measured maximum values of the acceleration for all blasts did not exceed the limit value, a_{wmax} = 0.11 $m.s^{-2}$, which is defined by the hygienic standard for the inhabitants of the building. The inhabitants of the building who were present at the research blasting operations did not perceive these vibrations as dangerous.

The results achieved by the research blasts were validated during the blasts in Trebejov Quarry (Table 7). These blasts were monitored at the same monitoring point as the research blasts. The millisecond delay applied at these blasts was determined by the velocity propagation and frequency of the seismic waves in the rock environment at different stages of Trebejov Quarry. The timing delays of 17 and 25 ms proved to be the correct solution for the individual parts of the quarry with different violations of the rock massif. Applying the modifications of millisecond timing and monitoring of the blasts in the quarry enabled us to identify in an experimental way the optimum interval of the values of the particle velocity and its frequency which could not harm the inhabitants.

The results achieved when monitoring the blasts in Trebejov Quarry proved that the limit value for the particle velocity is appropriate as $v_d \leq 2$ $mm.s^{-1}$, which is suitable for the inhabitants as well. The inhabitants of the monitored housing object who were present at the blasting operations did not perceive the blasts as dangerous.

Within this research, a series of six research blasts was performed in Trebejov Quarry, whereas the seismic impact of these blasts on the residential buildings and their inhabitants in the village of Trebejov was measured. The research was carried out in order to ensure that the seismic effects of blasting in Trebejov Quarry do not cause any damage to residential buildings in the village of Trebejov and especially that the inhabitants do not perceive these seismic effects as dangerous.

The research on the impact of the charge timing and parameter alteration of the blasts on the seismic effects of the blasting works will be further carried out by applying research blasts in Trebejov Quarry. Concurrently, this research will be focused on a further quarry in Vcelare, where similar research blasts will be carried out in a different environment and with other parameters.

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