Control measurements of seismic effects of blasting with AN-FO explosive

Siniša Stanković, Ana Pintera, Vječislav Bohanek, Vinko Škrlec

Abstract— **Blasting is a set of complex actions for which, in addition to proper calculations and methodology, safety is most important factor. Safety and accuracy increase can be determined from previous blasts in similar environments, but if even one parameter changes, it is very important to achieve the optimal conditions thru control measurements. The seismic impact of blasting is a very important part when designing a blasting works. The basic parameter on which further activity is based during the calculation is the oscillation velocity. With the increasing expansion of cities and settlements, there is a need for increasingly demanding blasting that takes place near inhabited facilities. To accurately determine the impact and permissible charge weight per delay that will not damage surrounding structures, various control and testing methods are used. To achieve accurate results, we need as many control measurements as possible and thus show that blasting and all accompanying activities can be performed in the vicinity of the settlement with additional aggravating circumstances such as unreinforced concrete underground water tanks, transmission lines and/or telephone lines.**

Keywords— **blast-induced vibrations, charge weight per delay, control measurements, AN-FO explosive**

I. Introduction

The application of blasting is very wide and versatile, both on the surface and underground, i.e., where there is a need to change the natural configuration of the terrain or the need for free space in the rock mass. As technology has advanced, blasting is increasingly used in populated areas. Still, some environmental impacts as a side effect of blasting are present, out of which ground vibration is most important [1].

When blasting is performed, part of the energy released is not spent on the crushing of rock, but the kinetic energy of elastic waves appears, which differ in intensity, shape of deformation and speed of propagation [2]. With the passage of such waves, oscillations of rock particles occur, which are an undesirable phenomenon during blasting in populated areas.

During the blasting, with the accurate calculations and supervision of blasting operations, we strive for the safest possible conditions for the environment. So far, certain approaches are known for determining the criteria for the possibility of damage to surrounding structures at a certain distance from the blasting source: empirical equations, descriptive tables and scales of seismic intensity caused by blasting and databases of allowable values of ground oscillation velocity.

When using any approach, it is necessary to know the dependence of the ground oscillation velocities at a certain

Siniša Stanković, Ana Pintera, Vječislav Bohanek, Vinko Škrlec
Faculty of Mining, Geology and Petroleum Engineering
Croatia

distance from the blast for the rock mass in which the blasting is performed. The better the knowledge and data processing, the safer the use of explosives and the possibility of control and verification of blasting operations. There are many predictors used to foresee the rate of ground oscillation during blasting [3], as well as Artificial Neutral Network (ANN) method [4], [5].

At the very beginning of the understanding of the problem, the categorization of the degree of seismic effect according to the damages caused, by the later addition of the value of oscillation velocities as an additional parameter (SV Medvedev's scale and modified Mercalli's scale). The next approach was with the application of empirical equations worked on by a large number of authors [6]–[10] but such approaches often followed specific situations and environments in which blasting was performed, and were not uniform. The third way that defines damages and the possibility of their occurrence is made with the help of various standards at the national and international level. By following standards, all parameters necessary for blasting are controlled and monitored during test blast at a safe distance, and the final results are corrected to obtain acceptable oscillations or other parameters that are below the allowable limit prescribed by the standard or legal regulation.

Assessing the impact of seismic action during blasting on structures consists of three parts, the first part refers to the assessment of ground oscillations that occur as a result of blasting in a certain vicinity of the structure, followed by data analysis that will provide appropriate data to assess the structure's response to oscillations, and the final part involves determining the limit values of the oscillation velocities not to cause damage to the structure [11].

II. Ground oscillation velocity predictors and Standards

Expected ground oscillation velocities can be calculated if a known mass of explosive charge (which may refer to multiple blastholes or to single one) is used at known distance of the observation point from the blast. According to US Bureau of Mines Bulletin 656 [12] the ground oscillation velocity is calculated:

$$v = 714 \left(\frac{D}{W^a} \right)^b \tag{1}$$

Where:
v - ground oscillation velocity (mm/s)
D - distance between the blast and the observation point (m)
W - charge weight per delay (kg)
a - exponent of the charge weight per delay (0,5)
b - exponent of the rock factor (-1,6)

According to Sadovski equation the expected oscillation velocity is calculated [2]:

$$v = k \left(\frac{\sqrt[3]{Q}}{R} \right)^n \qquad (2)$$

Where:

v - ground oscillation velocity (cm/s)

Q - charge weight per delay (kg)

R - distance between the blast and the observation point (m)

k - coefficient of blasting method

n - coefficient of seismic waves attenuation on the propagation path

According to ISEE, Blasters Handbook [13], the calculation is as follows:

$$v = 1725 \left(\frac{D}{\sqrt{W}} \right)^{-1,6} \qquad (3)$$

Where:

v - ground oscillation velocity (mm/s)

D - distance between the blast and the observation point (m)

W - charge weight per delay (kg)

Every deliberately provoked human action that has a specific goal must adhere to certain standards and regulations. Standards differ according to limits, with the help of which the values of permissible oscillation velocity for different types of buildings are determined. Some of the most common standards are USBM RI8507; ISO 4866: 1990; DIN 4150; British Standard 7385.

USBM RI8507 standard is the American standard, i.e., its largest application is within the USA, and it determines the criterion of seismic impact of blasting with the help of particle velocity and frequency of oscillations. The display of the maximum permissible oscillation velocity in relation to the oscillation frequency is shown in Figure 1.

Figure 1.   Ground oscillation velocity limit for various types of structures
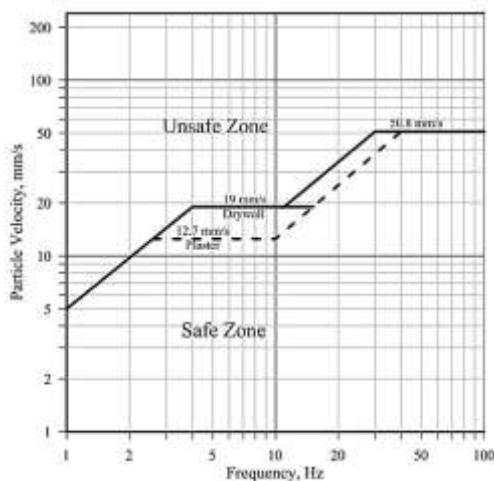
according to USBM RI8507 [14]

ISO 4866: 1990 is an international standard that defines the principles of performance for measuring vibration and the data processing, which takes into account the assessment of the effect of vibration on the object itself. This estimate was obtained on the basis of oscillations from the object, which were then processed with the help of analytics on the frequency, amplitude of vibrations and the duration of the vibrations. Measurements of air shock wave and other effects of dynamic pressures are not included within this standard. The standard is applicable to both underground and aboveground structures, but not to special facilities such as nuclear power plants. The amplitude, frequency and duration of vibrations can be controlled using this standard, but it does not limit the ground oscillation velocity.

The DIN 4150 standard, which has been adopted for the Croatian standard HRN DIN 4150: 2011 [15], is the most strictly defined standard of all the above and has the widest application. Values within the standard vary with respect to the structure being observed as well as measurement position, Table 1.

TABLE I.   GUIDELINE VALUES FOR VIBRATION VELOCITY TO BE USED WHEN EVALUATING THE EFFECTS OF SHORT-TERM VIBRATION ON STRUCTURES AS PER HR DIN 4150:2011

Line	Type of structure	Vibration at the foundation at a frequency of			Vibration at horizontal plane of highest floor at all frequencies
		1 Hz to 10 Hz	10 Hz to 50 Hz	50 Hz to 100 Hz*)	
1	Buildings used for commercial purposes, industrial buildings, and buildings of similar design	20 mm/s	20 – 40 mm/s	40 – 50 mm/s	40 mm/s
2	Dwellings and buildings of similar design and/or occupancy	5 mm/s	5 – 15 mm/s	15 – 20 mm/s	15 mm/s
3	Structures that, because of their particular sensitivity to vibration, cannot be classified under lines 1 and 2 and are of great intrinsic value (e.g. listed buildings under preservation order)	3 mm/s	3 – 8 mm/s	8 – 10 mm/s	8 mm/s
*) At frequencies above 100 Hz, the values given in this column may be used as minimum values.					

Within the standard, we also look at the frequency generated from the vibration source in combination with the ground oscillation velocity. It follows from all this that the permissible limit of the ground oscillation velocity increases with increasing frequency. When blasting, the oscillation frequency ranges from 20 to 100 Hz and therefore does not fall into the most dangerous range below 10 Hz. The diagram that determines the particle velocity limit for different constructions as a function of frequency is shown in Figure 2.

The British Standard 7385 is the standard used in the UK and is also determined using the ratio of oscillation frequency and oscillation velocity, the display of maximum values of oscillation velocity for individual buildings in relation to the oscillation frequency is given in Table 2 and Figure 3.

One of the most commonly used models for calculating the allowable charge weight per delay is the M. A. Sadovski equation (2).
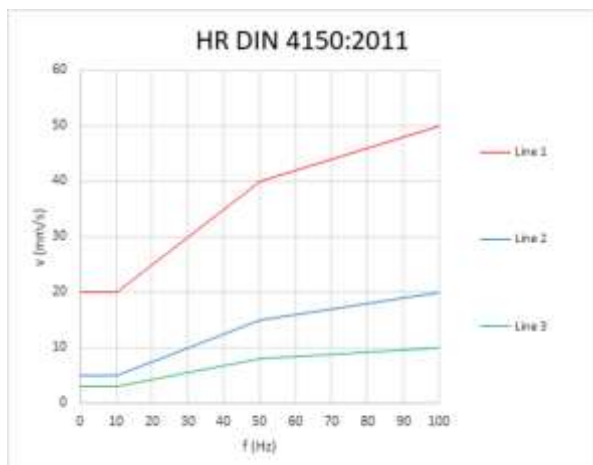
15

Figure 2. Curves for guideline values specified in table 1 for velocities measured at foundation as per HR DIN 4150:2011

TABLE II. TRANSIENT VIBRATION GUIDE VALUES FOR COSMETIC DAMAGE BY THE BRITISH STANDARD 7385

| Line	Type of building	Peak component particle velocity in frequency range of predominant pulse	
		4 Hz to 15 Hz	15 Hz and above
1	Reinforced or framed structures Industrial and heavy commercial buildings	50 mm/s at 4 Hz and above	
2	Unreinforced or light framed structures Residential or light commercial type buildings	15 mm/s at 4 Hz increasing to 20 mm/s at 15 Hz	20 mm/s at 15 Hz increasing to 50 mm/s at 40 Hz and above
NOTE 1 Values referred to are at the base of the building.			
NOTE 2 For line 2, at frequencies below 4 Hz, a maximum displacement of 0,6 mm (zero to peak) should not be exceeded.			
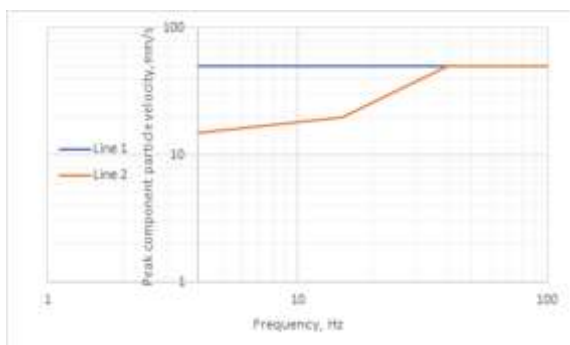
Figure 3. Transient vibration guide values for cosmetic damage by the British Standard 7385

During the test blasting, two seismographs are installed that measure the oscillation velocity traveling in the direction of the structure of interest. Seismographs must be placed at precisely defined distances from the blast in order to usable results and be able to solve a system of equations. The main equation for the blasting mode coefficient (k) and the attenuation coefficient on the propagation path (n) is:

$$v_{1,2} = k \cdot \rho_{1,2}{}^{n} \tag{4}$$

Where:

v_1 - ground oscillation velocity on the first instrument (mm/s)
v_2 - ground oscillation velocity on the second instrument (mm/s)
Q - maximum charge weight per delay (kg)
R_1 - distance between the blast and the first observation point (m)
R_2 - distance between the blast and the second observation point (m)
k - coefficient of blasting method
n - attenuation coefficient of seismic waves on the propagation path.
ρ - scaling of explosive

Scaling of explosive ρ is necessary to predict ground oscillation velocity when both Q and R differ:

$$\rho = \frac{\sqrt[3]{Q}}{R} \tag{5}$$

The coefficients k and n are calculated from following equations:

$$n = \frac{log \frac{v_1}{v_2}}{log \frac{\rho_1}{\rho_2}} = \frac{log \frac{v_1}{v_2}}{log \frac{R_1}{R_2}} \tag{6}$$

$$k = \frac{v_1}{\rho_1^n} = \frac{v_2}{\rho_2^n} \tag{7}$$

After the coefficients k and n are included in the initial formula, the dependence of the oscillation velocity on the charge weight per delay at a certain distance from the blasting site is obtained [2].

III. Excavation of the open cut by blasting on the Zagreb-Split-Dubrovnik Motorway, section Bisko-Šestanovac

The part of the Adriatic Motorway covered in this paper refers to the Bisko-Šestanovac section, which is part of the Zagreb-Split-Dubrovnik Motorway, and passes through the town of Trnbusi, Figures 4 and 5. Within the territory of the Republic of Croatia, the motorway enables the connection of the coastal area and Adriatic ports, and also connects the western European parts with Southeast Europe and the Middle East.

The main problem when performing blasting at the location shown is precisely the distance at which the inhabited facilities, transmission lines and telephone line are located. The town of Trnbusi is supplied with drinking water with the help of trucks, and then stored in unreinforced

concrete underground tanks, which are also one of the problems for blasting.

Figure 4.   Trnbusi - excavation works close to populated area

Figure 5.   Trnbusi - after the construction of the Motorway

IV.   Calculation of blasting parameters

In Trnbusi, drilling and blasting have been performed alternately from the east and the west, Figure 6. The blasting is divided into two basic parts, contour, and productive blasting. Due to the area itself inhabited and limited charge weight per delay, contour blasting was performed before the drilling of productive boreholes.

To execute blasting works, it is necessary to first make a calculation of blasting parameters. The maximum burden is calculated according to Langefors and Kihlström:

$$V = \frac{d_b}{33} * \sqrt{\frac{P*s}{\bar{c}*f*(E/V)}} \tag{8}$$

Where:

V - burden (m)
d_b- diameter of drill-bit (mm)
P - degree of packing (kg/dm^3)
s - weight strength of explosives
c - approximation of rock factor (kg/m^3)
f - degree of fixation
E/V - spacing/burden ratio

It should be mentioned that weight strength of explosive compares products on an equal-weight basis, and it is expressed in percent, using straight nitro-glycerine dynamite or ANFO as a standard. In practice, things are complicated by the fact that properties of ingredients of explosive used as standard can vary and strength of standard explosive can vary with explosive charge diameter (as a consequence of non-ideal behaviour). In addition, not only amount of energy of explosive release but also the rate of energy release plays a role. Weight strength of explosive can be determined from experiments or predicted theoretically. Theoretical prediction can be done applying appropriate non-ideal detonation model (e.g. Wood-Kirkwood detonation model) which takes into account dependence of detonation parameters on charge diameter [16].

Figure 6.   Design drawing

The values obtained by this calculation were corrected according to the data obtained from the test blast and are 1.0 m x 1.0 m for the shallowest parts, while for the deepest part of the open cut they are 2.0 m x 2.0 m, to ensure a sufficient quantity of explosive per m^3 of intact rock.

V.   Setting up instruments

Seismographs from the leading manufacturer Instantel inc. types Minimate and Blast Mate were used for test blast (Figure 7). Control measurements were done with only 1 instrument at the nearest facility.

The instruments are located in a line passing through the middle of the blasthole or closest part of blasting area for which the measurements are made. The measuring system

consists of a monitoring unit and a geophone. Within the system, oscillation velocity is measured at the location of the geophone, and the measurement records give the attenuation

17

curve. The geophone must be securely attached to the

ground and connected to the instrument.

Figure 7.   Instantel Minimate ground oscillation velocity measuring instrument

With the help of a geophone, it is possible to simultaneously measure the oscillation velocity in three mutually perpendicular directions. Each direction of oscillation is measured using a separate component, thus distinguishing the longitudinal, transverse, and vertical direction.

VI.   Calculation of the permitted charge weight per delay

The maximum permitted charge weight per delay was determined by test blast for different distances of oscillation source from monitoring points. The calculation was made according to M. A. Sadovski (2). Based on the results obtained from the test blast (MP1) in the direction MP1/MO1/MO2 (Figure 8), a calculation of the permissible charge weight per delay was obtained.
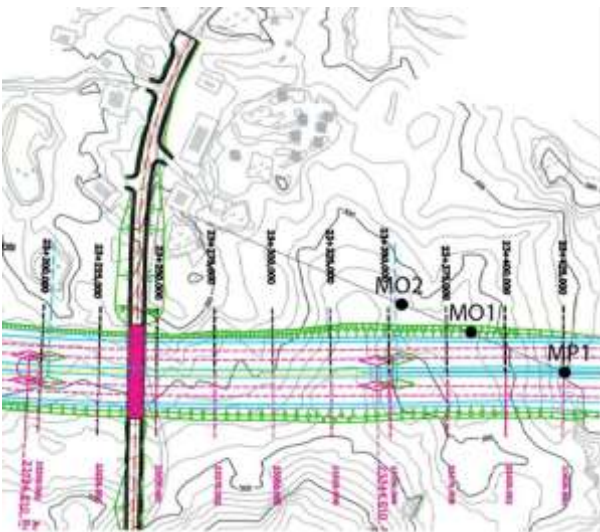

Figure 8.   View of the blasting area (MP1), the first and second observation points (MO1, MO2) during test blast

For the maximum amount of explosive charge of 20 kg, and the distance of the first observation point from the blasting area of 40 m and the second observation point of 76 m, the oscillation velocities were 58.9 mm/s and 6.7 mm/s respectfully.

VII.   Blasting works

Blasting works were carried out in two phases. Contour blasting was performed first. Contour holes were loaded from the bottom with half a cartridge of Perunit Φ 50 mm and a detonating cord with 80 g/m' (C-80) to the stemming zone. A detonating cord with 12 g/m' (C-12) was used through the plug and for the connection with other contour holes. Retarders are placed between the holes, depending on the proximity of inhabited objects. After contour holes were blasted, drilling of productive holes started.

Within productive blastholes, the explosive loading depends on the depth of the open cut and the distance from the inhabited objects. On more distant and shallower parts, one Perunit Φ 50 mm cartridge was placed in the blasthole, and ANFO explosive was placed up to the stemming zone. Within the parts closer to populated objects and within the deeper parts of the open cut, the loading was executed in decks using up to five detonators per blasthole, where each detonator must detonate separately, and there must be no time overlapping. The flyrock was reduced with the help of the use of non-electric detonators and by increasing the stemming by 10-15%. The increase of the stemming served as an additional safety against the flyrock, because due to the size of the blasting area and the limited time for the execution of works, the protection by covering the blasting area with blasting mats or similar was not feasible.

VIII.   Control measurements - data processing and analysis

Control measurements were performed during ten production blasts. The blasts were executed from the shallow outer part towards deepest (central) part of the open cut, thus the most distant blasting area was located at 94,05 m on one side, and 74,54 m on the other side of the observation point. As the terrain rose more and more towards the central part, forming the shape of a hill, the deeper holes were not filled along the entire length, but separately up to a maximum of 5 decks per hole. Thus, the first and farthest blastholes were filled in 1 section while the number of decks increased with each successive pair. The separator is a one-meter-long stemming made of inert material such as crushed stone. Complete data on the mass of explosives obtained by calculation according to the test blast, the actual charge weight per delay used and the distance of the blasting area from the observation point are given in Table 3.

During the construction, the initial chainage for blasting was 23+345-23+360. The calculation of test blast determined the charge weight per delay of 77.40 kg, but the depth of the open cut in this position according to the Design was such that borehole could be loaded with no more than 32,5 kg in total. The following blast at chainage

23+330-23+345 by the calculation which included both trial and first productive blast, the maximum charge weight per delay of 26,14 kg was obtained. Since this amount would fill about 65% of the blasthole, it was decided to load the

blasthole in two decks of 15,5 kg per delay, while the calculation according to the test blast should have been 51,62 kg. Blastholes at chainage 23+138-23+165 were loaded with 17,7 kg of explosives per delay, while blastholes at chainage 23+320-23+330 were loaded with 8,7 kg of explosives per delay. Furthermore, at chainage 23+165-23+195, 10,3 kg of explosives were placed in the blasthole per delay, blastholes at chainage 23+305-23+320 were loaded with 7,5 kg, while blastholes at chainage 23+195-23+305 loaded with 11 kg of explosives per delay. Charge weight per delay of 7,9 kg were loaded in the blastholes located at chainage 23+195-23+215, while the blastholes at chainage 23+260-23+290 required 12,26 kg according to the calculation based on the test blast, i.e., with corrections taken, this quantity was 7,2 kg per delay. The blastholes of the last blast were located at chainage 23+215-23+260 and the charge weight per delay calculated according to the test blast was 13,47 kg, while the actual charge weight per delay was 8,8 kg.

TABLE III.   CALCULATED AND LOADED QUANTITIES OF EXPLOSIVE, DISTANCE, AND CHAINAGES

Chainage	Distance (m)	Test blast calculation of charge weight per delay (kg)	Loaded charge weight per delay (kg)	PVS measured at closest structure (mm/s)
23+138-23+165	74,54	38,53	17,7	12,0
23+165-23+195	60,38	20,48	10,3	22,2
23+195-23+215	53,81	14,50	7,9	13,7
23+215-23+260	52,51	13,47	8,8	13,8
23+260-23+290	50,89	12,26	7,2	15,9
23+290-23+305	57,76	17,93	11,0	23,0
23+305-23+320	65,63	26,30	7,5	0,8
23+320-23+330	74,34	38,22	8,7	2,3
23+330-23+345	82,17	51,62	15,5	20,1
23+345-23+360	94,05	77,40	32,5	27,2

As explained earlier, the basic calculation is created according to test blast results. The calculation was performed using formulas 4 to 7. As per HRN DIN 4150:2011 for dwellings, the maximum PVS limit of 20 mm/s has been chosen. Following calculations gave the attenuation coefficient (n) of 3,3866, the scaling of

explosive $\rho 1 = 0,0678$ and $\rho 2 = 0,0357$, and the coefficient of blasting method (k) equal to 533358. The attenuation curve of the test blast as well as the required parameters are shown in the graph in Table 4, and Figure 9.

The curve obtained by observation for the first blast, i.e., for two points of the test blast and one control observation point during productive blast, is shown in Figure 10, and the subsequently calculated data in Table 5.

TABLE IV.   PARAMETERS FOR OBTAINING A TEST BLAST ATTENUATION CURVE

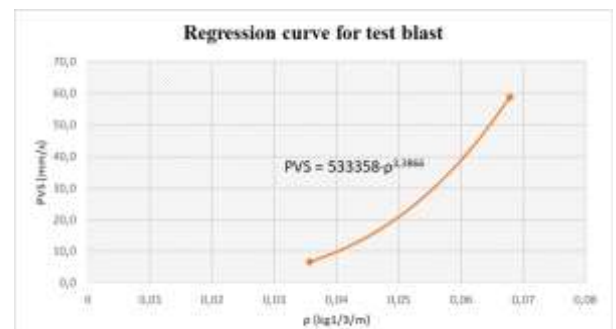| ρ	PVS
0,06786	58,9
0,03572	6,7

Figure 9.   Graphical representation of the regression curve for the test blast
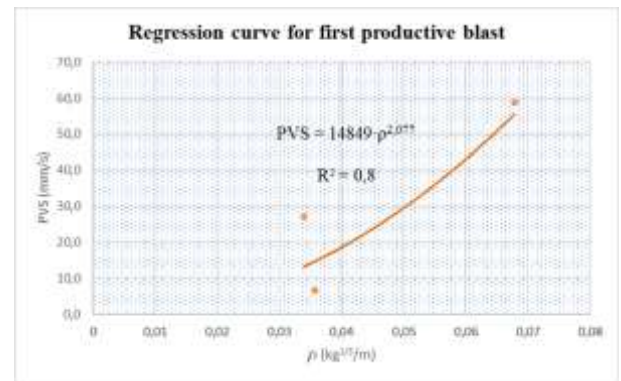

Figure 10. Graphical representation of the regression curve for the first productive blast

TABLE V.   PARAMETERS OBTAINED FROM THE REGRESSION CURVE EQUATION OF THE FIRST PRODUCTIVE BLAST

R (m)	20	40	60	80	100
Q (kg)	0,38	3,02	10,18	24,12	47,12

The equation of the regression curve including the first productive blast is $PVS = 14849 \cdot \rho^{2,077}$, and the correlation index R^2 is 0,8.

The same process has been done for all ten productive blasts. By summarizing all the displayed data, we can see that for an increasing number of control points we come to

19

more and more precise data. Thus, for ten control measurement points regression curve equation is $PVS=999579 \cdot \rho^{3,4264}$. The curve obtained from the test blast and all ten productive blasts are shown in parallel in Figure 11. A view of all the regression curve equations is given in Table 6.

The Q/R ratio is presented in Figure 12. It is visible that the obtained ratio is the steepest in the sixth blast, i.e., it represents the largest range of the amount of explosive, while the smallest range was achieved for the second blast.
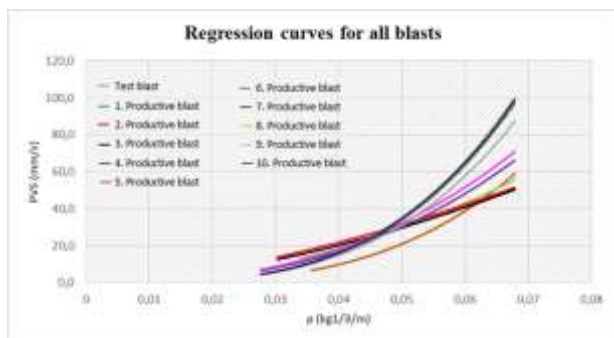

Figure 11. Graphical representation of all regression curves for all blasts

TABLE VI.   COMMON REPRESENTATION OF ALL
REGRESSION CURVE EQUATIONS

Type of blast	Regression curve equation
Test blast	$PVS=533358 \cdot \rho^{3,3866}$
First productive blast	$PVS=14849 \cdot \rho^{2,077}$
Second productive blast	$PVS=4140,7 \cdot \rho^{1,6303}$
Third productive blast	$PVS=5221,7 \cdot \rho^{1,7248}$
Fourth productive blast	$PVS=69118 \cdot \rho^{2,5835}$
Fifth productive blast	$PVS=71063 \cdot \rho^{2,5685}$
Sixth productive blast	$PVS=716036 \cdot \rho^{3,3502}$
Seventh productive blast	$PVS=967892 \cdot \rho^{3,4219}$
Eighth productive blast	$PVS=997474 \cdot \rho^{3,4275}$
ninth productive blast	$PVS=1061786,2540 \cdot \rho^{3,4418}$
Tenth productive blast	$PVS=999579 \cdot \rho^{3,4264}$

Figure 12. Graphical representation of Q/R ratio for all blasts
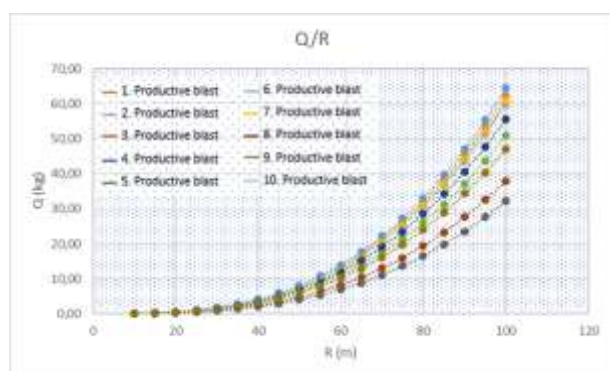
IX. Conclusion

Importance of the blast induced vibration control measurements in blasting works have been presented, i.e., their influence on the calculation of the permissible charge weight per delay in dependance to distance from blast. The main reason is that no method gives sufficiently precise data, and everything is based on measured values from different observation points during blasts.

During the execution of all operations related to blasting, within populated areas, that the correction of existing methods and calculations comes to the fore. Corrections of the results obtained by trial blasting are made according to the results of control points of observation. Within the very part of the Zagreb-Split-Dubrovnik motorway on the Bisko-Šestanovac section near the town of Trnbusi, values were measured at ten control measurement points during the execution of ten productive blasts.

With this approach, the regression curve equations for the test blast and all ten productive blasts were obtained. As the blasts approached the residential structures, observations from more and more measurement points were utilized, the regression curve increasingly coincided, as shown in Figure 11. For the tenth blast, the regression curve equation is $PPV=999579 \cdot \rho^{3,4264}$. The relationship between the permissible charge weight per delay and the distance of measurement point from blast is given in Figure 12. Both Figures show how can the starting values change with each new control measurement data implemented.

The application of control measurements shows that their use gives more precise results, which is also proven by the fact that during the blasting works there was no any damage to the surrounding buildings or any other structure, above or below ground. This approach gives the possibility of performing blasting works safely even in circumstances that are difficult due to the presence of inhabited facilities, underground water tanks, the proximity of telephone lines and transmission lines and many other obstacles.

Acknowledgment

References

[1]   R. Resende, L. Lamas, J. Lemos, and R. Calçada, "Stress wave propagation test and numerical modelling of an underground complex," *Int. J. Rock Mech. Min. Sci.*, vol. 72, pp. 26–36, 2014.

[2]   Josip Krsnik, *Miniranje*. Zagreb: University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, 1989.

[3]   R. Kumar, D. Choudhury, and K. Bhargava, "Determination of blast-induced ground vibration equations for rocks using mechanical and geological properties," *J. Rock Mech. Geotech. Eng.*, vol. 8, no. 3, pp. 341–349, 2016.

[4]   M. Khandelwal and T. N. Singh, "Evaluation of blast-induced ground vibration predictors," *Soil Dyn. Earthq. Eng.*, vol. 27, no. 2, pp. 116–125, Feb. 2007.

[5]   M. Monjezi, M. Ahmadi, M. Sheikhan, A. Bahrami, and A. R. Salimi, "Predicting blast-induced ground vibration using various types of neural networks," *Soil Dyn. Earthq. Eng.*, vol. 30, no. 11, pp. 1233–1236, 2010.

[6]   R. F. Nicholson, "MASTER ' S THESIS Determination of Blast Vibrations Using Peak Particle Velocity at Bengal Quarry , in St Ann , Jamaica Determination of Blast Vibrations Using Peak A case study," *Dept. Civ. environemntal Eng. Lulea Univ. Technol.*,

vol. 1, pp. 51–53, 2005.

[7]   U. Ozer, "Environmental impacts of ground vibration induced by blasting at different rock units on the Kadikoy-Kartal metro tunnel," *Engineering Geology*, vol. 100, no. 1–2. pp. 82–90, 2008.

[8]   H. Ak, M. Iphar, M. Yavuz, and A. Konuk, "Evaluation of ground vibration effect of blasting operations in a magnesite mine," *Soil Dynamics and Earthquake Engineering*, vol. 29, no. 4. pp. 669–676, 2009.

[9]   Badal K. K., "Blast Vibration Studies in Surface Mines," vol. 2010, no. 10605005, p. 41, 2010.

[10]   J. Mesec, I. Kovač, and B. Soldo, "Estimation of particle velocity based on blast event measurements at different rock units," *Soil Dyn. Earthq. Eng.*, vol. 30, no. 10, pp. 1004–1009, 2010.

[11]   C. H. Dowding, *Blast vibration monitoring and control*. 1985.

[12]   NICHOLLS HR, JOHNSON CF, and DUVALL WI, "Blasting vibrations and their effects on structures," *U S Bur Mines, Bull 656*, 1971.

[13]   ISEE, *Blasters' Handbook*. 1998.

[14]   D. E. Siskind, M. S. Stagg, J. W. Kopp, and C. H. Dowding, "Structure Response and Damage Produced By Ground Vibration From Surface Mine Blasting.," *Rep. Investig. - United States, Bur. Mines*, no. 8507, 1980.

[15]   Croatian Standards Institute, *DIN 4150 Vibracije u gradevinama - - 3. dio: Djelovanje na konstrukcije*. Zagreb: Croatian Standards Institute, 2011.

[16]   M. Suceska, M. Dobrilovic, V. Bohanek, and B. Stimac, "Estimation of Explosive Energy Output by EXPLO5 Thermochemical Code," *Zeitschrift fur Anorg. und Allg. Chemie*, vol. 647, no. 4, pp. 231–238, 2021.