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Reducing the adverse effects of blasting on the cave ecosystem near the future exploitation field Gradusa

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Original scientific paper

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Abstract
The future exploitation field of crushed stone Gradusa is located in the area of the Sunja municipality in the Sisak-Moslavina County. Near Gradusa, there is a cave that is part of the ecological network as a conservation area important for several species and habitat types of bats. The significance of the cave is also its location in the continental part of Croatia where it is among a small number of objects that bats can use in all periods of their annual cycle. Due to the location and importance of habitats, there was a need to define the primary environmental impact assessment for the ecological network. This assessment is the most important document for the possible acquiring of a location permit for exploitation of the future quarry of Gradusa. This paper presents the results of trial blasting and guidelines for reducing the adverse blasting effects on the cave ecosystem near the future exploitation field Gradusa. These are vibrations and noises, which may have an adverse impact on the habitats of bats. Cavers and experts on bats have also been included in the process of selecting the micro-location.

Keywords:
Exploitation field, cave, habitats of bats, trial blasting, adverse blasting effects

1. Introduction

The vibration generated by construction or quarry blasting may have an adverse impact on the environment. The vibration effects vary from annoying human disturbances to structural damage. Scientists and experts in this area agree that the level of excited ground and structure vibrations depends on blasting technology, explosive type and mass, delay-timing variations, site geology, scaled distance, parameters of waves propagating at a location, susceptibility ratings of adjacent and remote structures, and other factors (**Mesec et al., 2010; Mesec et al., 2016**). However, the prediction of particle velocity has great importance in the minimisation of the environmental complaints. Estimating the particle velocity and other components of ground vibration are very useful in blast design (**Kahriman, 2004**).

The noise is caused by a blast of air pressure radiating out from the blast and is commonly referred to as air blast or air blast overpressure. It is measured in decibels using the linear weighting scale dB (**URL 1**). The following factors have the most effect on the level of noise: the mass and type of explosive, the distance from the blast field, bench blasting design, configuration of the surrounding terrain and weather conditions at the time of the explosion. Reducing the noise reduces uncontrolled mechanical work and damage caused by the air shock when detonating an explosive charge. This means that in practice, attempts should be made to determine the optimal parameters for quarry blasting. Also in the immediate and inhabited environment, the following practices should be applied: low benches, a smaller hole diameter, postponement of blasting initiation in misty and cloudy weather with strong wind or during heavy winters, and so forth (**Department of Environment and Heritage Protection (QLD), 2013**). Measurements have shown that at high wind, the noise levels can rise by as much as 10 to 15 dB. The level of noise from blasting is primarily the result of a sudden increase in pressure of gases in the detonation of the explosive charge. There at the blasthole, gases transfer pressure to the air through gaps and voids in the rock mass.

In practice, the peak particle velocity of vibrations compares with the safe limits (safe vibrations level), which defines the specific standard. Commonly accepted standards in the world like the British standard (BS) (**British Standards (BS), 1993**), USBM (**US Office of Surface Mining (OSM), 1983**), etc. are based on the hypothesis that the first assessment of vibration effects should be made before the beginning of construction activities (**Svinkin, 1999**). The German standard DIN 4150 (**German Standard, DIN 4150 - 3, 1999**), based on measured ground oscillations, is mostly applied for assessment of damage caused by blasting near structures that are under

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Table 1: Boundary limit of ground oscillations according to DIN 4150 standard

	Vibration at the foundation at a frequency of			Vibration at horizontal plane of highest floor at all frequencies
	<10 (Hz)	10-50 (Hz)	50-100 (Hz) *	
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
Dwellings and buildings of similar design and/or occupancy	5 mm/s	5 – 15 mm/s	15 – 20 mm/s	15 mm/s
Structures that, because of their particular sensitivity to vibration, cannot be classified underlines 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

special protection (see **Table 1**). This standard has also been accepted in the Republic of Croatia.

All blasting must be carried out properly by a competent person following best practice environmental management, to minimise the likelihood of adverse effects being caused by air blast overpressure and ground-borne vibration at noise-sensitive places and on people in the surrounding area (**Department of Environment and Heritage Protection, Queensland, 2016**). Additionally, by increasing the blast field, the air impact pressure drops exponentially. **Figure 1** shows a comparison of sound pressure and sound pressure level in dB.

To determine permitted noise levels, in many countries the criteria for allowed noise limit by blasting have been developed (**URL 1**). These criteria define limits for air blast, measured in dB. A summary is presented in **Table 2**.

During trial blasting on the future exploitation field Gradusa, the Instantel Minimate Plus seismographs are used to measure ground vibration and air blast. Ground vibrations are measured with a seismic geophone sensor, and air blast is measured with a microphone designed to measure and record airblast pressure changes over time. Airblast pressure is reported in the linear field in decibels (dB).

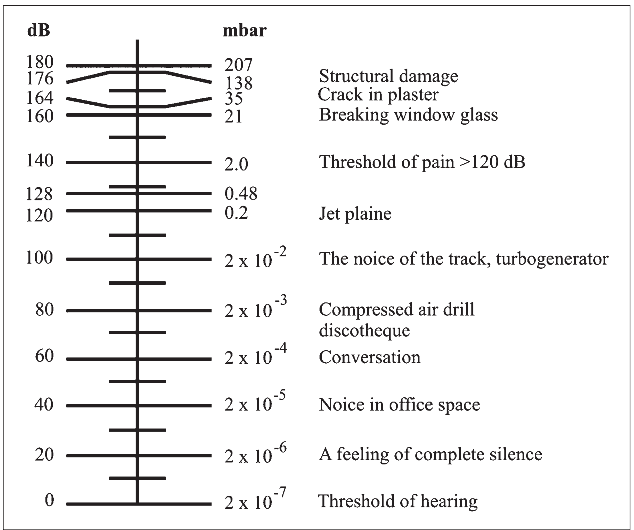


Figure 1: Diagram of typical noise levels in decibels [dB] and millibars [mbar]

2. Case study

The future quarry will have a form of an irregular pentagon, with a total area of 9.16 ha (see **Figure 2**). It is planned to excavate up to 100 000 m^3 of crushed stone annually. Table 3 shows the characteristic distances related to cave and exploitation field.

The Cave of Gradusa is located on Pupić hill, with its entrance on its northeast slopes, at an altitude of 173 m (see **Figure 3**). The entrance to the cave was most likely discovered during the former exploitation of mineral raw materials for the ironworks in Sisak, and it is believed that today's entrance is open during the mining process for these purposes. The cave stretches in a length of 455 m with a clearly expressed main channel, submerged in one part. Difficult narrow passages, partially flooded canals and mud sliding skylight caves, rank in a very demanding category of speleological objects (**Pišl Z. et al., 2014**).

Underground spaces of the cave are not negligible in size since the main channel in some places reaches a height of over 10 meters. In addition to the main chan-

Table 2: Common noise emissions criteria

Emission type	Receptor	Regional criteria			
		Ontario	USA	Australia	UK
Noise [dB]	Residential		129 (< 6 Hz)		120
		128	133 (< 2 Hz)	115 (95 %)	120 (95 %)
			134 (< 0.1 Hz)	120 (max)	125 (max)

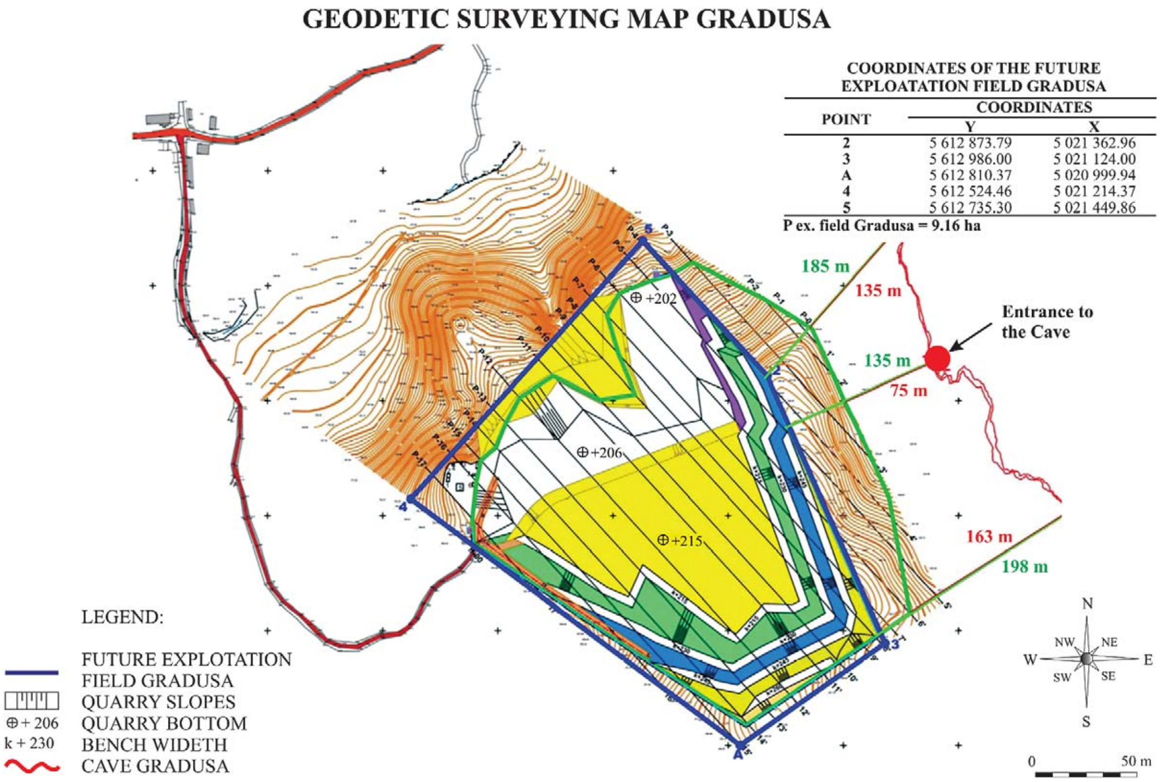


Figure 2: The future exploitation, bench width (**Jovičić and Jurenić, 2013**)

Table 3: The characteristic distances on the future exploitation field Gradusa

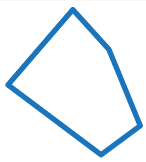
	**The shortest distance of the overall slope from the entrance to the cave [m]**	**The average distance from the future quarry Gradusa to the cave [m]**	**The maximum distance from the overall slope to the cave [m]**
	135	**270**	**420**

Figure 3: Entrance to the cave of Gradusa

nel, separated from the input capacity is a side passage extending to the water (see **Figure 4**). Water flows that are found in the cave were not clearly associated with surface waters. However, the existence of some source zones at the foot of cave, suggest that connection (**Pišl Z. et al., 2014**). The cave Gradusa is part of the ecological network as a conservation area important for species and habitat types. The main objectives of preservation of this area are the species of Mediterranean horseshoe bat (Rhinolophus euryale) and Common bent-wing bat, and habitat type 8310 caves and a cave closed to the public (**NN (124/13), 2013**).

Figure 4: The interior of the cave (photo D. Basara)

2.1. Defining the parameters of the trial blasting

The following data from the Preliminary mining project (**Jovičić and Jurenić, 2013**) and Mineral reserve elaborate (**Jovičić and Jurenić, 2012**) is used to determine the parameters of the trial blasting:

- Mineral raw material: crushed stone of carbonate type - lithotamnical limestone, from engineering geological sampling the rock mass according to the generally recognised classification the rocks are very rough (**Novosel et al., 1980**),
- The appearance of very small blocks, the surface of cracks is very small, cracks filled with clay and rock fragments occur, cohesion (c = 0.15 - 0.20 MPa), specific weight (γ = 25.1 kN/m^3), uniaxial compressive strength (σ = 15 - 28 MPa), resistance to the Boeme abrasion test = 31 cm^3/cm^2, estimate GSI value = 30 - 35,
- Geometric parameters of the future quarry: number of benches 5, the height of each bench (H = 15 m maximum), overall slope height (H_o = 68 m),
- The shortest distance from the overall slope of the future exploitation field Gradusa to the cave (L_o = 135 m).

2.2. Technical features of trial blasting

To determine the trial blast regime considering the specificity of the local factors, respectively for the determination of the maximum allowed quantity of explosive per delay, the length of the shortest distance L_o = 135 m of the overall slope from the cave was taken.

According to the engineering geological features of the rock mass type (very rough and crushed stone of carbonate type), the experience and a request for reducing the adverse blasting effects on the cave ecosystem, the following parameters were taken:

- oscillation frequency estimationf = 10 to 50 Hz,
- maximum allowed oscillation velocity according to DIN 4150PPV = 8 mm/s.

Considering that so far in Croatia there was no research like this, there is no standard methodology to collect the data needed to evaluate the blast impact on the bats' habitats inside a speleological facility. However, in spite of this, adequate research has been carried out following international standards (**Turbridy et al., 2005; URS, 2012; West Virginia Department of Environmental Explosives and blasting, 2006**).

For example, the US Office of Surface Mining (OSM) recommends an oscillation limit of 0.30 inches per sec-

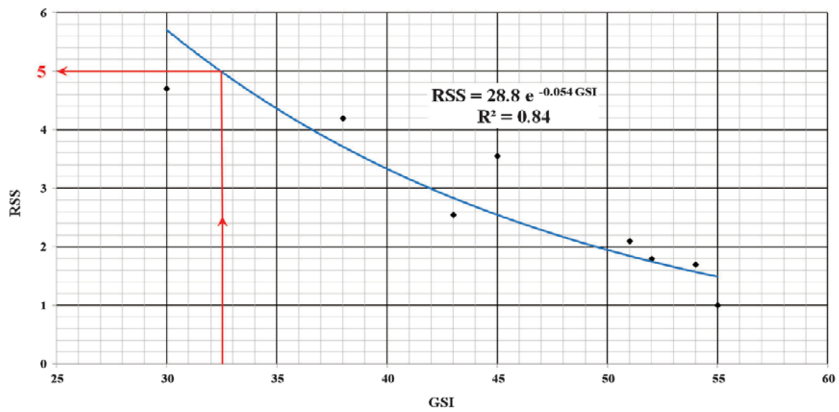


Figure 5: Relative seismic sensibility (RSS) depending on the geological strength index (GSI)

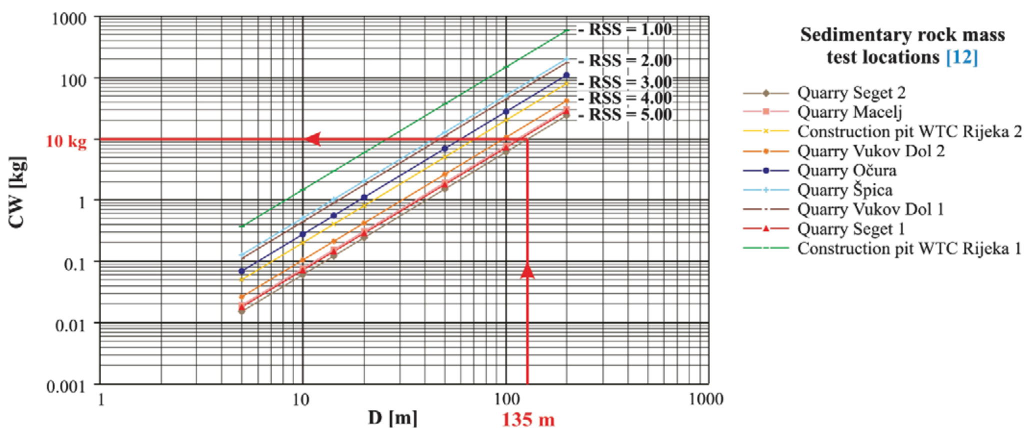


Figure 6: CW-D diagrams defining allowed charge mass of explosives per delay depending on distances and relative seismic sensibility (RSS) of the rock mass

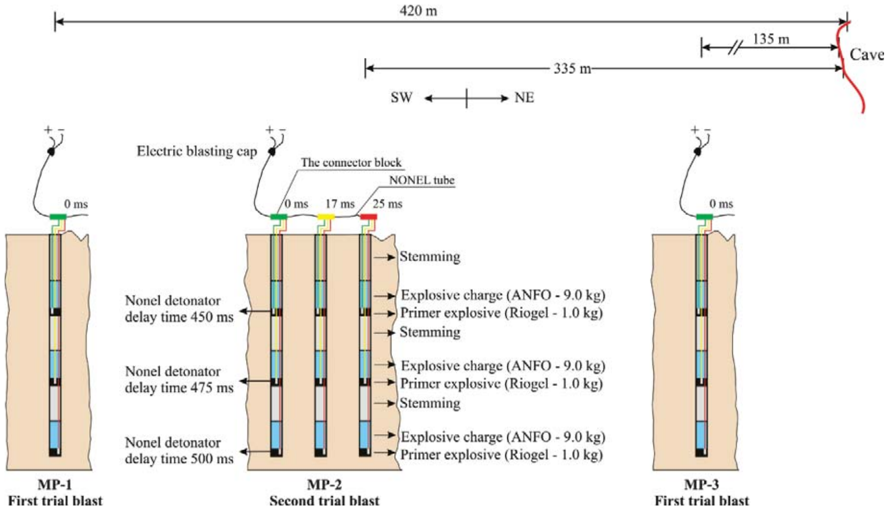


Figure 7: Trial blast field

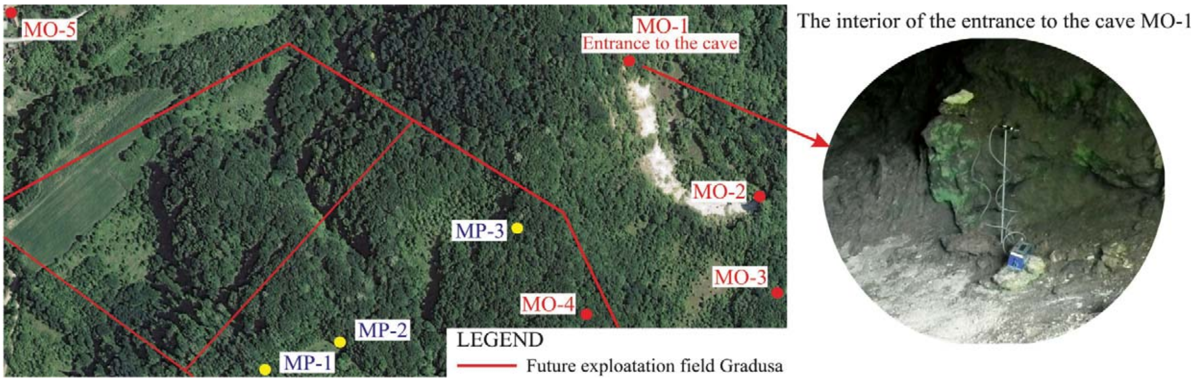


Figure 8: Field position of trial blasts (MP) and monitoring stations (MO)

Table 4: Overview of the total explosive consumption in the trial blast holes

TRIAL BLAST FIELD	Hole depth	Stemming	Explosive charge per delay ANFO bulk	Primer cartridges explosive Riogel (60.0 mm)	Total amount of explosive per blast hole	Delay time of non-electric detonators	Surface connector delay time
	[m]	[m]	[kg]	[kg]	[kg]	[ms]	[ms]
MP-1	17.0	3 × 3.0	3 × 9.0	3 × 1.0	30.0	450, 475, 500	0
MP-2	17.0	3 × 3.0	3 × 9.0	3 × 1.0	30.0	450, 475, 500	0
	17.0	3 × 3.0	3 × 9.0	3 × 1.0	30.0	450, 475, 500	17.0
	17.0	3 × 3.0	3 × 9.0	3 × 1.0	30.0	450, 475, 500	25.0
MP-3	17.0	3 × 3.0	3 × 9.0	3 × 1.0	30.0	450, 475, 500	0
Σ	**85.0**	**45.0**	**135.0**	**15.0**	**150.0**		

ond, or 7.59 mm/s. As with most other standards, the OSM explicitly recognises a frequency dependence of damage potential, with lower frequencies known to be more prone to causing damage. In accordance with the above, it can be concluded that it is justified to take it into account that the cave with bats is to be protected in the highest third category (according to the previously attached DIN 4150 standard) for which the limit of the ground oscillation (PPV) during blasting must not exceed 8 mm/s.

Furthermore, using the DIN 4150 standard and the empirical diagram obtained on the basis of results during the constructions and bench blasting in sedimentary rock deposits GSI in the range 30 to 55 (**Mesec, 2005**), it is possible to preliminarily estimate the quantity of explosive per delay for probe blasts according to local conditions: the position of endangered objects according to blast field and engineering geological features of the rock deposit.

For this purpose, from the engineering-geological features of the rock mass represented by the geological strength index (GSI), the relative seismic sensitivity (RSS) of the relevant rock deposit should be determined (**Mesec, 2005**), (**Figure 5**).

According to data from the Preliminary mining project (**Jovičić and Jurenić, 2013**) and Mineral reserve elaborate (**Jovičić and Jurenić, 2012**) estimated GSI amounts an average of 32.5. From the accompanying diagram (see **Figure 5**) and using input data (local conditions), it emerges that RSS = 5.0 for the relevant location.

Then, for the determined value of the relative seismic sensitivity (RSS) from the CW-D diagram, see **Figure 6**, for the default distance D (m) of the endangered object from the trial blast field, the trial allowed charge mass of explosive per delay, CW is determined (**Mesec, 2005**). The obtained results may be used for some basic vibration prediction and trial blast design starting points, which should be made before quarry blasting.

According to the above CW-D diagram, for the preliminary estimated engineering geological type of rock deposit and the endangered object (cave) on the distances of L = 135 m, the maximum allowed charge mass of explosives per delay amounts to CW_{max} = 10 kg.

Above this estimated value, the maximum allowed charge mass of explosives per delay would be determined after trial blasting and seismic oscillation measurements.

As mentioned above, three test blast fields have been designed:

- **MP-1**, the first test blast (see **Figure 7**), which is the furthest from the cave - at a distance of approximately 420 m, the position shown in **Figure 8**,
- **MP-2**, the second trial blast with three blast holes, to test the proposed millisecond delay between individual blast holes (see **Figure 7**), which are approximately 335 m away from the cave, the position shown in **Figure 8**,
- **MP-3**, a third trial blast (see **Figure 7**), which is the closest to the cave - at a distance of approximately 135 m, the position shown in **Figure 8**.

It should be noted that all blast holes are fully enclosed at all depths because the quarry is not yet open or developed. However, it is a question of establishing a quarry blasting regime with associated measurements of seismic effects. Also, explosives with lower detonation velocities (about 3000 m/s) will be used for future quarry blasting.

Therefore, it is recommended to use ANFO explosives which achieve the best effects for blasting rock masses with weaker physical and mechanical properties. As well, it should be mentioned that weaker and tectonic disturbed rock masses have lower oscillation frequencies, higher amplitudes or higher oscillation velocities than solid rock masses for equal blasting conditions (**Mesec et al.,2010**).

During trial blasting on May 29, 2015, ground oscillation velocities were measured at five monitoring stations (MO). **Table** 4 gives an overview of the total explosive consumption in the trial blast holes.

3. Results of measuring the adverse blasting effects on the cave ecosystem near the future exploitation field Gradusa

Table 5 shows the results of trial blasting on which is plotted diagram of the dependence of the ground oscillation (PPV) and scaled distance (SD).

From the results shown in **Table 5**, the diagram of the dependence of the oscillation velocity (PPV) and scaled distance (SD) is drawn (see **Figure 9**).

The oscillation velocity can be calculated according to:

$$PVS = K \cdot SD^{-n} \text{ [mm/s]} \tag{1}$$

Where:

PVS – peak vector sum, [mm/s]

K – coefficient of rock characteristics and monitoring conditions,

n – coefficient of rock massif oscillations,

SD – scaled distances,

$$SD = \frac{D}{CW^{1/2}} \text{ [m/kg}^{1/2}\text{]} \tag{2}$$

Where:

CW – charge mass of explosive per delay, [kg]

D – a distance of the endangered structure from the blast, [m]

Note: For coefficients *K* and *n*, the above is valid according to the results of seismic monitoring on all sites. To note, *n* cannot be singularly called "damped oscillations of the rock massif", but should be calculated together with the coefficient *K* when calculating oscillation velocities. Measurements have proven that *K* does not depend on the type of blasting, but rather on the distance of the monitoring station (MO) from the blasting field (MP). Usually, as this distance is larger, so is the value *K*. *K* is also greater when we have rock masses of weaker quality, which are "seismically more sensitive".

From equation (1) it is possible to calculate the allowed charge mass of explosives per delay (CW) depending on the default peak particle velocities (PPV) and the distances (D) of the blast field (MP) from the monitoring station (MO):

$$CW = \left[\left(\frac{PPV}{K} \right)^{1/n} \cdot D \right]^2 \text{ [kg]} \tag{3}$$

Table 5: Results of the ground oscillation and airblast pressure level measurement

Blast Location No.	Monitoring station (Seismograph)	Maximum values of the PVS	Distance, D	Maximum charge per delay, CW	Scaled distance, SD	Principal frequency, f	Airblast pressure level
MP	**MO**	**[mm/s]**	**[m]**	**[kg]**	**[m/kg^2]**	**[Hz]**	**[dB]**
May 2015.-TRIAL BLASTING (5 blast hole, hole depth =17.0 m, hole diameter = 99 mm, spacing of the blast hole on the MP-2 = 5.0 m)							
MP-1	MO-1	-	447.45	10.00	141.50	-	-
	MO-2	-	489.87	10.00	154.91	-	-
	MO-3	0.60	482.09	10.00	152.45	8	-
	MO-4	6.61	306.75	10.00	97.00	2	59.50
	MO-5	0.60	410.41	10.00	129.78	5	-
MP-2	MO-1	0.67	382.13	10.00	120.84	9	-
	MO-2	0.61	418.62	10.00	132.38	8	-
	MO-3	0.63	411.01	10.00	129.97	7	-
	MO-4	2.15	233.13	10.00	73.72	5	55.70
	MO-5	0.73	438.67	10.00	138.72	11	-
MP-3	MO-1	1.31	201.79	10.00	63.81	10	-
	MO-2	1.71	242.28	10.00	76.62	12	57.00
	MO-3	1.60	255.82	10.00	80.90	21	57.50
	MO-4	24.94	104.40	10.00	33.01	18	84.50
	MO-5	-	517.02	10.00	163.50	-	-

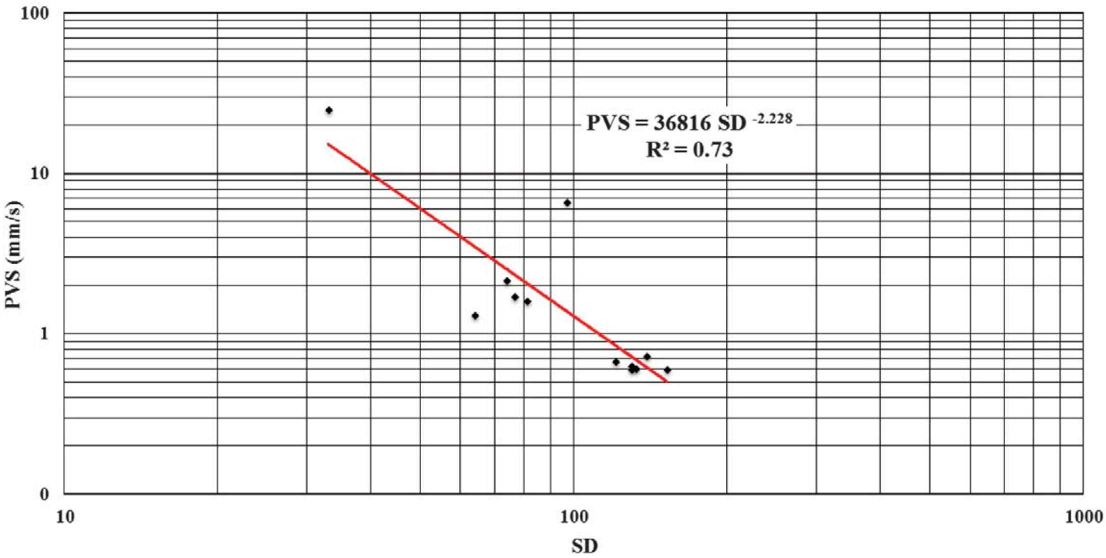


Figure 9: Dependence of ground oscillation (PPV) on scaled distance (SD)

In the specific case of the future quarry Gradusa according to the DIN standard for PPV max = 8 mm/s, with a minimum distance of the future overall slope from the blast field, D = 135 m, and:

K – coefficient of rock characteristics and monitoring conditions $K = 36\ 816$

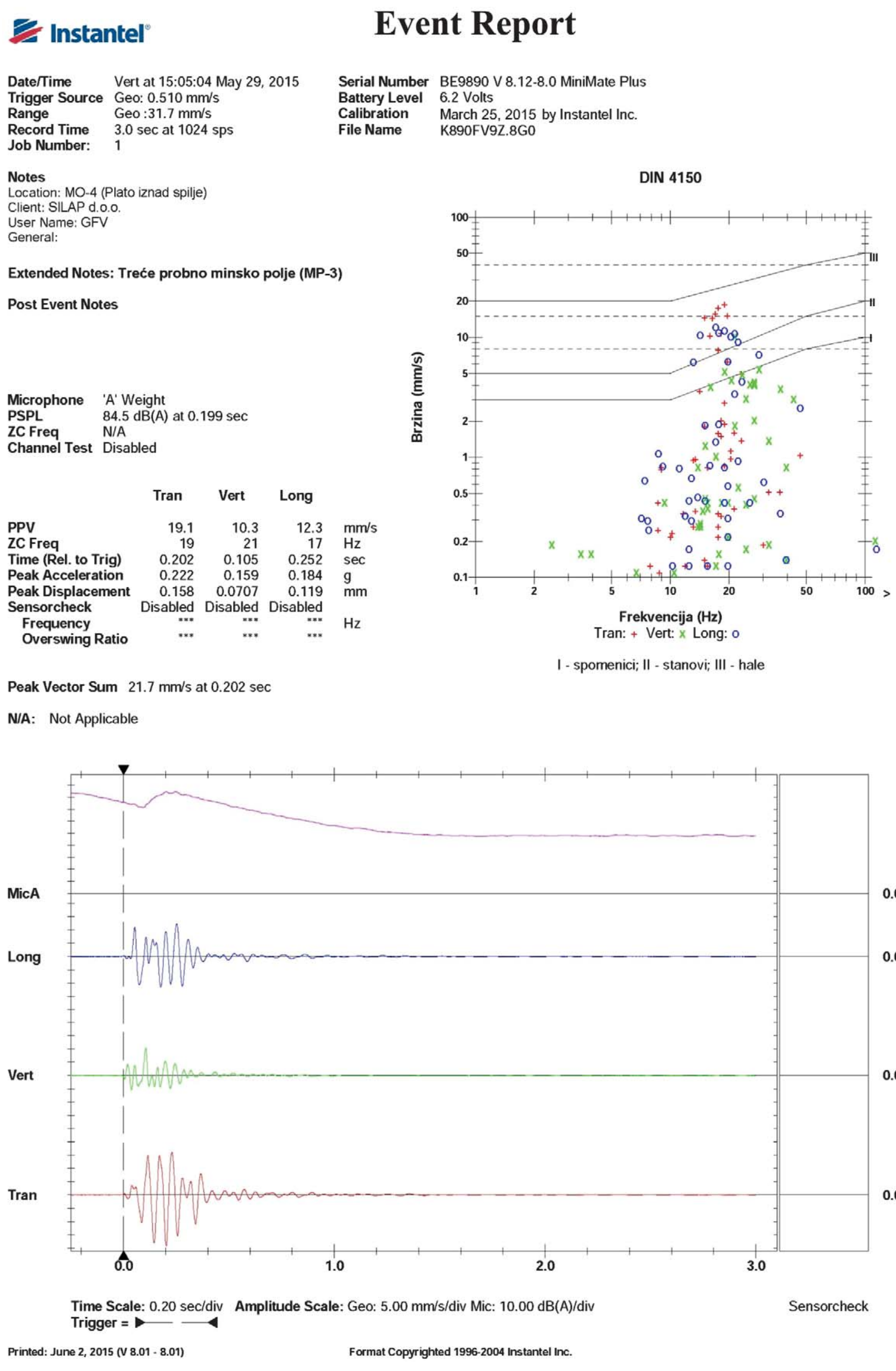
n – coefficient of rock massif oscillations $n = -2.228$ (see **Figure 9**)

for the future blasting that will be closest to the overall slope, according is:

CW = 9.39 kg, or in practice 9.4 kg.

Table 6: Allowed charge mass of explosives per delay, CW [kg] for the different distances, D [m] of the cave Gradusa from the blast field

The distance of the cave from the blast field D	Allowed charge mass of explosives per delay CW
[m]	**[kg]**
135	9.4
200	20.6
300	46.4
400	82.4



Instantel

Event Report

Date/Time Vert at 15:05:04 May 29, 2015
Trigger Source Geo: 0.510 mm/s
Range Geo :31.7 mm/s
Record Time 3.0 sec at 1024 sps
Job Number: 1

Serial Number BE9890 V 8.12-8.0 MiniMate Plus
Battery Level 6.2 Volts
Calibration March 25, 2015 by Instantel Inc.
File Name K890FV9Z.8G0

Notes
Location: MO-4 (Plato iznad spilje)
Client: SILAP d.o.o.
User Name: GFV
General:

Extended Notes: Treće probno minsko polje (MP-3)

Post Event Notes

Microphone 'A' Weight
PSPL 84.5 dB(A) at 0.199 sec
ZC Freq N/A
Channel Test Disabled

	Tran	Vert	Long	
PPV	19.1	10.3	12.3	mm/s
ZC Freq	19	21	17	Hz
Time (Rel. to Trig)	0.202	0.105	0.252	sec
Peak Acceleration	0.222	0.159	0.184	g
Peak Displacement	0.158	0.0707	0.119	mm
Sensorcheck	Disabled	Disabled	Disabled	
Frequency	***	***	***	Hz
Overswing Ratio	***	***	***	

Peak Vector Sum 21.7 mm/s at 0.202 sec

N/A: Not Applicable

Time Scale: 0.20 sec/div **Amplitude Scale:** Geo: 5.00 mm/s/div Mic: 10.00 dB(A)/div
Trigger =

Printed: June 2, 2015 (V 8.01 - 8.01)

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Figure 10: Event report at the monitoring station MO-4

Furthermore, **Table 6** gives a preliminary allowed charge mass of explosives for different distances future blast fields from the cave Gradusa according to the above mentioned DIN 4150 standard, for the third category of objects to which it applies to the oscillation velocity may not exceed 8 mm/s.

According to the conducted research and calculated maximum allowed charge mass of explosive per delay of 9.39 kg, it comes out that is well preliminary estimated GSI amounts an average of 32.5 and the maximum allowed charge mass of explosives per delay of 10 kg (see **Figure 6**).

During seismic observations measurements of blasting impacts, influences, oscillations velocities at three (MO-2, MO-3 and MO-4) out of five monitoring stations, the airblast level was recorded (see **Table 5)**. The highest level of airblast pressure amounting to 84.5 dB was measured at the monitoring station MO-4, which was closest to the blast location MP-3 (see **Figure 10**).

4. Conclusion

From the conducted measurements by the trial blasting carried out on May 29, 2015, at the location of the future exploitation field in the vicinity and the interior of the nearby cave of Gradusa, no damage was found from blasting. The speleological investigations carried out during and after the trial blasting have confirmed excellent conditions and preservation of cave habitats and the physical condition of cave channels, walls and cave speleothems.

During the trial blasting at some monitoring stations around the cave, the seismographs were not activated, indicating that the oscillation velocities were less than the sensitivity of the device, i.e., less than 0.51 mm/s. The only recorded data on the seismograph located in the cave (MO-1) during the blasting of the nearest blast field MP-3 was far below the allowed values, measured PPV = 1.31 mm/s. However, during the test blasting at the monitoring station MO-4, which was 104.40 m away from the MP-3 blast location, the oscillation velocity of 24.94 mm/s was determined.

However, according to the conducted researches and calculated maximum allowed charge mass of explosive per delay of 9.39 kg (see **Equation 3**), it comes out that is well preliminary estimated GSI amounts an average of 32.5 and the maximum allowed charge mass of explosives per delay of 10 kg (see **Figure 6**).

The highest airblast pressure level of 84.5 dB was measured at the monitoring station MO-4, which was closest to the blast location MP-3. According to **Table 3** (Common noise emissions criteria), measured values of noise during the test blasting in the open air was within acceptable limits. Inside the caves, at the monitoring station MO-1, no noise was measured during all three trial blasting. Generally, when a temperature inversion or a heavy, low cloud cover is present, values of air blast pressure will be higher than normal in surrounding areas. Accordingly, blasting should be avoided if predicted values of air blast pressure in noise-sensitive places exceed acceptable levels. Similarly, blasting should be avoided at times when strong winds are blowing from the blasting site towards noise sensitive places (**Department of Environment and Heritage Protection, Queensland, 2016**).

In conclusion, due to the specific location of the exploitation field for future quarry Gradusa blasting should take into account the results of the presented research in this paper. If necessary, the results will be partially corrected with constant monitoring and measuring of the intensity of seismic oscillation and noise. It is to be expected that all future quarry blasting will be carried out in a professionally controlled manner, which will reduce the environmental impacts of blasting to the allowed limits. This fact points to the conclusion that every subsequent blasting will increase the database of measurements that will enrich the practice of safe mining blasting.

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SAŽETAK

Mjere smanjivanja štetnih utjecaja minerskih radova na špiljski ekosustav u blizini budućega eksploatacijskog polja Gradusa

Buduće eksploatacijsko polje tehničko-građevnoga kamena Gradusa nalazi se na području općine Sunja u Sisačko-moslavačkoj županiji. U neposrednoj blizini polja Gradusa nalazi se špilja koja je dio ekološke mreže kao područje očuvanja važno za nekoliko vrsta i stanišnih tipova šišmiša. Važnost špilje proizlazi i iz njezina položaja u kontinentalnome dijelu Hrvatske u kojemu je poznat malen broj objekata kojima se šišmiši mogu koristiti u svim razdobljima svojega godišnjeg ciklusa. Zbog položaja i važnosti staništa bilo je potrebno definirati procjenu glavnih štetnih utjecaja na ekološku mrežu. Ta procjena najvažniji je dokument za dobivanje lokacijske dozvole radi moguće eksploatacije iz budućega kamenoloma Gradusa. U ovome članku prikazani su rezultati pokusnih miniranja i preporuke za smanjenje štetnih utjecaja miniranja na špiljski ekosustav u blizini budućega eksploatacijskog polja Gradusa. To su vibracije i buka koje mogu imati znatan utjecaj na stanište šišmiša. U proces odabira mikrolokacija uključeni su i stručnjaci za šišmiše te speleolozi.

Ključne riječi:
eksploatacijsko polje, špilja, stanište šišmiša, pokusno miniranje, štetni utjecaji miniranja

Authors' contribution

J. Mesec, initialising the idea and leading the research. **D. Težak**, and **J. Jug** helped with field work and conducting measurements.