An experimental study of the repeated blasting effect on surrounding rock weakness incorporating ultrasonic wave velocity measurement

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Abstract

Repeated blasting leads to progressive and cumulative effects on blast-induced damage zones in which the extension zone and the intensity of weakness are dynamic. This paper presents the results of an experimental study intended to examine cumulative weakness intensity due to repeated blasting to simulate a bench blasting situation in open pit mining. For this purpose, four concrete blocks were made which were subjected to two different blasting patterns. A grid was designed to measure ultrasonic wave velocity in the blocks. The blocks were blasted by a detonating cord and their weakness intensity index was defined by calculating the difference between wave velocity before and after blasting rounds. The results show that weakness intensity due to the second blasting round was increased when compared to the results of the first blasting round. In addition, dispersion of weakness produced by the second blasting round was more uniform. Moreover, explosive energy distribution in terms of the initiation and propagation of fractures caused by the second blasting round affected the performance of the second blasting round energy. This study increased the current understanding of the repeated blasting cumulative effect on a surrounding rock mass in terms of weakness which affects the mechanical properties of a rock mass.

1. Introduction

In a blasting operation, only part of the explosive energy is used to crush and displace rocks to achieve the goal of rock mass blasting, while most of the energy is transferred into the surrounding rock mass which causes damage to it. Damage to the remaining rock mass due to blasting refers to a noticeable decrease in the mechanical properties of a rock mass due to the creation of new discontinuities or the enlargement of existing discontinuities on scales ranging from meters to micrometers (**Persson et al., 1993**). In other words, damage to a rock mass makes it weaker. Blast-induced damage (BID) and the excavation damaged zone (EDZ) have been extensively investigated in various rock engineering projects, ranging from dams and tunnels to waste repository facilities. Up to the present time, many studies have been carried out to evaluate the degree of BID in remaining rock mass, developing predictive models to estimate the extent of the EDZ and illustrating how the geomechanical parameters of a damaged rock mass are affected. A detailed review on these topics are given by **Raina et al. (2000)** and **Bastante et al. (2012)**.

A critical review of literature in this context reveals that most researchers focused on underground blasting operations and the propagation mechanism of fractures due to blasting in open pit mining (**Chuanbo et al., 2012; Aliabadian et al., 2013; Onederra et al., 2013; Hu et al., 2014; Lai et al., 2015; Hall, 2015; Paswan et al., 2017; Wang et al., 2018; Lak et al., 2019**). However, the accumulative effect of repeated bench blasting in open pit mining has been less studied. In open pit mining, a blasting operation repeats in several sequences for each working bench that leads to progressive and cumulative effects on in-situ rock mass properties. Weakening of the remaining rock mass in a working bench due to cyclic blasting is the most damaging cumulative effect. In this regard, the extension and intensity of surrounding rock mass weakness will be dynamic and blasting round-dependent.

In this work, a systematic experimental study was performed to investigate a repeated blasting effect on the cumulative weakness of a surrounding rock mass which is a simulated bench blasting situation in open pit mining. The weakness zone was defined as the scope where micro-fracturing initiation and propagation due to blasting alters the physical and mechanical properties of a rock mass from its in-situ condition. In this regard, weakness intensity was represented by variations of rock mass altering in a weakness zone. In this order, four concrete blocks were blasted by a detonating cord. The ultrasonic wave velocity before and after repeated blasting

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Table 1: Properties of produced blocks

Density (kg/m³)	Tensile strength (MPa)	Uniaxial compressive strength (MPa)	Ultrasonic wave velocity (m/s)
2150	2.8	26	4600

Table 2: Designed blasting patterns

Block	Burden (cm)	Spacing (cm)	Blast hole diameter (cm)	Blast hole length (cm)	Number of blast holes	Number of rows
A1	3	4.5	0.6	7	6	2
A2	3	4.5	0.6	7	12	4
B1	4	5.5	0.6	7	6	2
B2	4	5.5	0.6	7	12	4
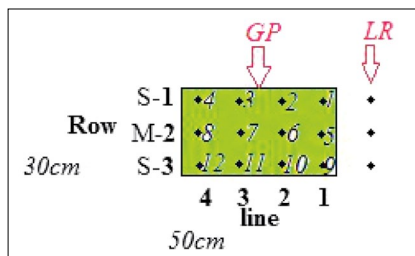
Figure 1: Measurement grid

was measured. The weakness index was defined and the results of two different blasting patterns were discussed.

2. Experiments

Sample preparation, laboratory tests, ultrasonic wave measurement, blasting method and plans for the study of a repeated blasting cumulative effect on surrounding rock mass weakness are described in the following sections.

2.1. Sample preparation

Four concrete blocks (A1, A2, B1, and B2) were prepared manually with sizes of 50 cm in length, 30 cm in width and 14 cm in height. It should be noted that the concrete mixture, production process and storing conditions for all four blocks were the same. Physical and mechanical properties as well as ultrasonic wave velocity of blocks were determined in the laboratory as shown in **Table 1**. Block A1 and B1 were intended for blasting in one round while, A2 and B2 were appointed for two blasting rounds. Two different patterns were designed for block groups A and B as shown in **Table 2**.

2.2. Pre-blasting experiments

In order to measure ultrasonic wave velocity, a measurement grid was designed beyond the last row of blast holes. It should be noted that the grid was the same for all four blocks. The measurement grid included 12 points which were placed in 4 lines and 3 rows. Measurement

lines and rows were parallel and perpendicular to the fire line, respectively. Grid line numbers show the distance from the fire line where No.1 and 4 represent the nearest and farthest distance to the fire line, respectively. Grid rows No. 1 and 3 are in the direction of the lateral blast holes while, No. 2 is aligned with the middle blast holes. **Figure 1** illustrates the measurement grid. After designing the measurement grid, ultrasonic wave velocity was measured and recorded for all the points in each block before the blasting operation.

2.3. Post-blasting experiments

In order to blast the blocks, the full length of the blast holes was charged by a detonating cord of 12 g/m and a diameter of 5.8 mm. Each blasting round included two rows of blast holes. In each block, the blast holes located in a row were blasted simultaneously. In addition, the delay time interval between two blasting rounds was 175 ms. In fact, all blast holes in blocks A1 and B1 were blasted in a round simultaneously while the delay time between two blasting rounds in blocks A2 and B2 was 175 ms. **Figure 2** shows charged and blasted blocks. After the blasting operation, the ultrasonic wave velocity was measured and recorded for all points in each block again.

3. Results and discussion

Weakness index was defined according to the **Equation 1**:

$$W = \left(\frac{t_{post} - t_{pre}}{t_{post}} \right) \times 100 \qquad (1)$$

Where:

W - is surrounding rock weakness (%),

t_{pre} - is the ultrasonic wave passing time through an intact specimen (μsec),

t_{post} - is the ultrasonic wave passing time through a blasted specimen (μs).

In this regard, the weakness index for all points in the studied blocks were calculated and given in **Table 3**.

A1-CH.
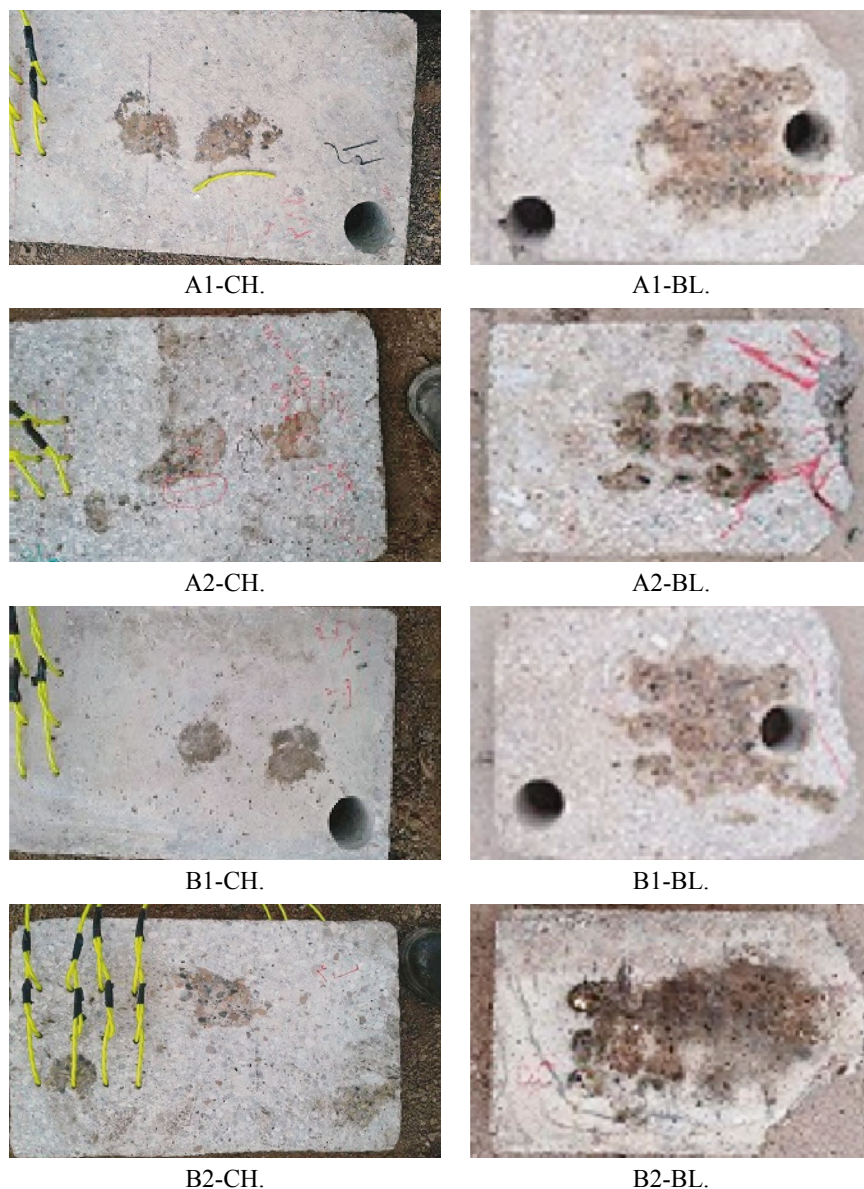

A1-BL.

A2-CH.

A2-BL.

B1-CH.

B1-BL.

B2-CH.

B2-BL.

Figure 2: Charged and blasted blocks

Table 3: Calculated weakness index in the measurement points

Blocks	Measurement points											
	1	2	3	4	5	6	7	8	9	10	11	12
A1	41	40	39	39	39	36	36	36	36	20	15	8
A2	46	43	42	40	45	40	39	38	42	40	37	35
B1	38	37	36	17	36	36	24	12	37	15	12	10
B2	42	40	38	37	39	38	37	37	40	39	37	34

3.1. Weakness in blocks A1 and A2

Figure 3 and **Table 4** show a frequency histogram and statistical data of W in blocks of group A, respectively. **Figure 3** shows that the distribution of W due to a second blasting round is similar to the normal distribution. **Table 4** shows that the average of W increased by

26.5% due to the second round of blasting while its standard deviation was decreased by 71.3%.

Figure 4 shows plot values of W in blocks A1 and A2 in each measurement point. As seen in the figure, the variations of W at points which were placed in grid row No.1 and 2 (No. 1 to 8) in block A1 are low while, points of row No. 3 show high variations in W values. According to **Figure 4**, W in block A2 indicates that a large part of cumulative weakness in the points of row No. 1 and 2 is due to the first blasting round. Moreover, it is shown that points which have less W due to the first blasting round (No. 9 to 12), represent more variations with respect to the second blasting round. Contingent upon **Table 4** and **Figure 4**, it can be concluded that W due to the second blasting round has less dispersion and its distribution is more uniform when compared to the results of the first round of blasting.
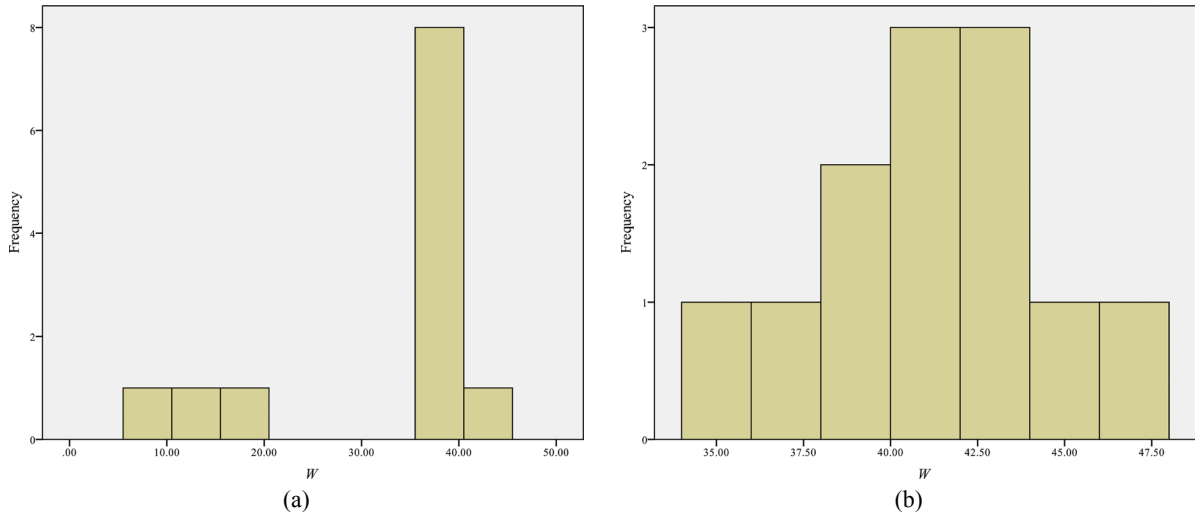
(a)

(b)

Figure 3: Frequency histogram of weakness index in blocks of group A; (a) block A1; (b) block A2

Table 4: Statistical data of calculated weakness in blocks A1 and A2

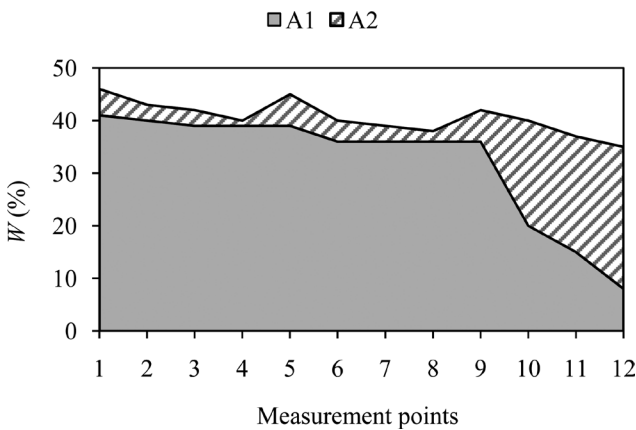|	Min.	Max.	Avg.	SD
Block A1	8	41	32.08	11.14
Block A2	35	46	40.58	3.2

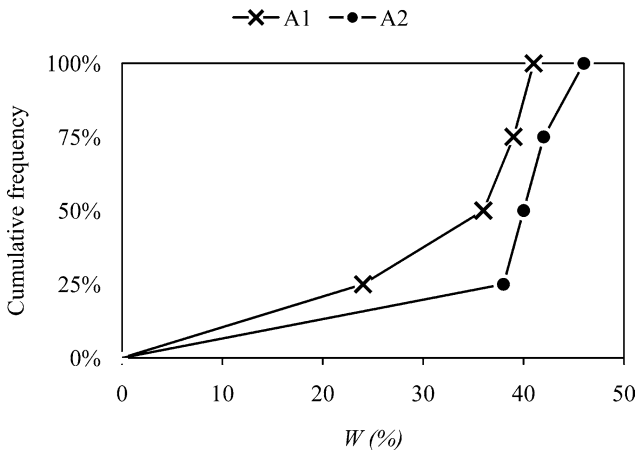**Figure 4:** Weakness diagram in blocks A1 and A2

Figure 5: Cumulative frequency of weakness in blocks A1 and A2

In **Figure 5**, cumulative frequency charts of W in blocks A1 and A2 are illustrated. Contingent upon **Figure 5**, it is noted that the difference between the cumulative weaknesses in blocks A1 and A2 corresponds to the lower, middle and upper quartiles, which are 14%, 4% and 3%, respectively. It indicates that the largest difference between the resulted W of A1 and A2 is produced by the 25% measurement points.

3.2. Weakness in blocks B1 and B2

A frequency histogram and statistical data of W in blocks group B are shown in **Figure 6** and **Table 5**, respectively. **Figure 6** shows that the distribution of W due to the second blasting round is similar to the normal distribution. As can be seen in **Table 5**, the average of W was increased 47.77% due to the second round of blasting, while its standard deviation was decreased 64.92%.

The calculated W in blocks B1 and B2 is presented in **Figure 7**. As can be seen from the figure, there is clear fluctuation in W at points of row No.1 and 3 due to one round of blasting (block B1). In these rows, points which are placed on the grid line No. 4 (the furthest points to the last blasting row) show sharp variations. From the figure, it can be concluded that the largest portion of overall weakness at points of grid lines No.1 to No.3 is produced by the first blasting round. Similar to blocks of group A, points placed on line No.4 show the highest increase of W due to the repeated blasting when compared to the other points. Furthermore, it can be concluded from **Table 5** and **Figure 7** that W due to the second blasting round has less dispersion and its distribution is more uniform when compared to the first round of blasting results.

A cumulative frequency chart of resulted W in blocks B1 and B2 is shown in **Figure 8**. From the figure, it is calculated that the difference between W in blocks B1 and B2 corresponds to the lower, middle and upper quartiles, which are 24.25%, 8% and 3%, respectively. It
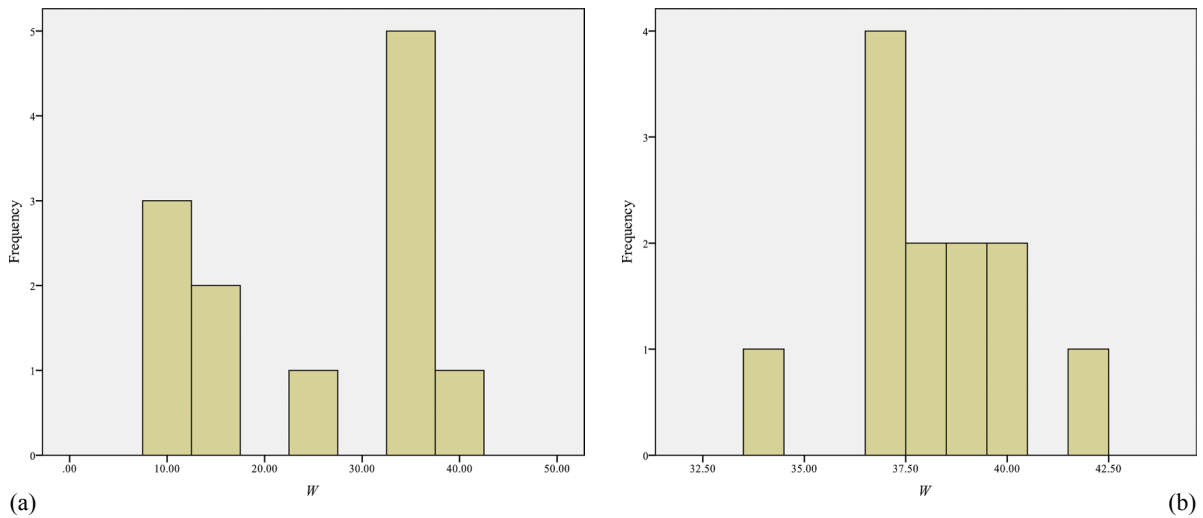
(a)   (b)

Figure 6: Frequency histogram of weakness index in blocks of group B; (a) block B1; (b) block B2

Table 5: Statistical data of calculated weakness in blocks A1 and A2

	Min.	Max.	Avg.	SD
Block A1	10	38	25.83	11.83
Block A2	34	42	38.17	4.15

Figure 7: Weakness diagram in blocks B1 and B2

shows that the largest difference between the obtained W of B1 and B2 is formed by the 25% measurement points.

3.3. Discussion

The prime motivation for this study was to experimentally investigate the effect of a repeated blasting round on the produced weakness in a remaining rock mass. For this purpose, four concrete blocks were blasted by a detonating cord and ultrasonic wave velocity was measured in pre and post blasting rounds. A comparison of blocks blasted in two rounds (A2 and B2) with blocks which were blasted in a single round (A1, B1) based on **Tables 4** and **5** shows that there is an increasing trend with respect to the number of blasting rounds. Investigation of this increasing trend in lower, middle and upper quartiles as well as average values indicates that the amount of increase in weakness due to repeated blasting is nonlinear.

On the other hand, the results indicate that there is a noticeable decrease in the standard deviation due to an increase of a blasting round. It shows that the distribution of cumulative weakness due to a second blasting round becomes more uniform. Investigation of the difference between the weakness due to the first and second blasting rounds reveals that dispersion and intensity caused by the second blasting round depend on the quality of the first ones. In this regard, at points where weakness due to the first blasting round was lower (25% of grid points in both blocks A and B), weakness caused by the second blasting round was higher and vice versa. It shows that in the first blasting round, the largest portion
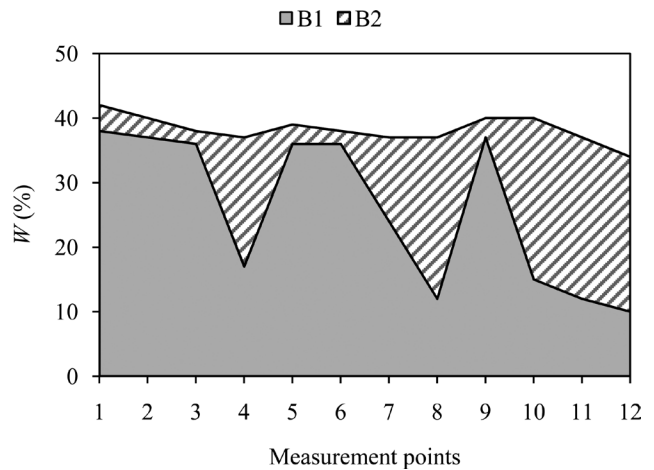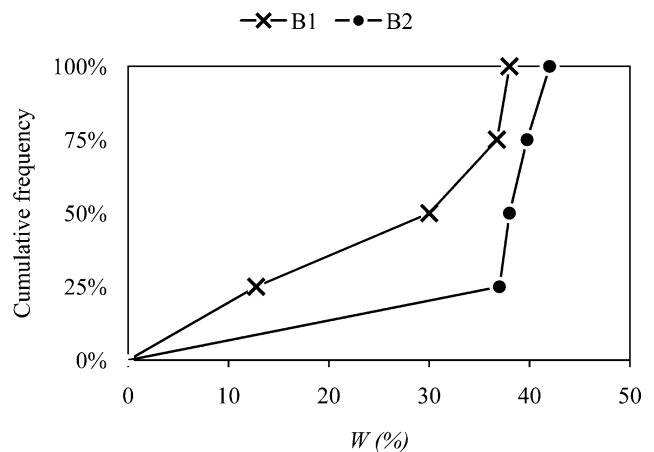

Figure 8: Cumulative frequency of weakness in blocks B1 and B2

of explosive energy initiates fractures while in the second blasting round, the largest portion of explosive energy propagates fractures produced by the first blasting round. Therefore, it can be concluded that in consecutive blasting rounds, because their sphere of influence is in a

superposition form, the results of previous blasting rounds in terms of initiation and propagation of fractures affect the performance of the blasting rounds that follow.

4. Conclusions

Results of the experimental study to investigate the cumulative effect of repeated blasting on the weakness of the surrounding rock mass are presented here. The following main conclusions are extracted from this study:

1. It was shown that the average of weakness intensity due to a second blasting round was increased 26.5% and 48% in blocks A and B, respectively when compared to results of the first blasting round. In addition, it was concluded that variations of weakness with respect to the number of blasting rounds is nonlinear.

2. It was observed that standard deviation of weakness due to the second blasting round was decreased 71% and 65% in blocks A and B, respectively. It concludes that weakness intensity due to the second blasting round has less dispersion and its distribution is more uniform when compared to the results of the first round of blasting.

3. It was inferred that the largest portion of difference between weakness produced by the first and second blasting rounds is caused by the 25% measurement points.

4. It was concluded that in consecutive blasting rounds, results of previous blasting rounds in terms of initiation and propagation of fractures affect the performance of the blasting rounds that follow.

5. References

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SAŽETAK

Eksperimentalno istraživanje utjecaja višestrukoga miniranja na slabljenje okolnih stijena na temelju mjerenja brzine nadzvučnih valova

Višestruko miniranje ima snažne i kumulativne učinke stvarajući zonu različitih stupnjeva oštećenja i oslabljenja. Prikazani su rezultati eksperimenta kojim se ispitala kumulativna oslabljenost stijene stvorena višestrukim miniranjem, a kojim su se simulirali takvi postupci kod površinskih kopova. Analiza je načinjena na četirima betonskim blokovima u kojima su ispitane dvije minske mreže. Unutar blokova izmjerena je brzina stvorenih nadzvučnih valova. Izračunan je indeks intenziteta oslabljenosti, koji je razlika brzine vala prije i nakon detonacije. Vrijednost je pokazala kako je indeks izgubio na vrijednosti tijekom drugoga kruga detoniranja. Također, raspodjela oslabljenih zona bila je puno pravilnija u drugome krugu. Razdioba energije eksplozije također je bila različita ovisno o fazi detoniranja. Rezultati su povećali znanje o utjecaju višestrukoga miniranja na okolne stijene, stvaranju oslabljenih zona te promjeni mehaničkih svojstava.

Ključne riječi:
oslabljena stijenska masa, višestruko miniranje, kumulativni učinak, brzina nadzvučnih valova

Authors contribution

Hossein Aliakbari Baydokhti (Ph.D. Candidate): initialized the idea, completed literature review and participated in all work stages such as providing samples, running experimental tests and data analysis. **Mohammad Ataei** (Full Professor): executed experimental tests, data analysis and test of its accuracy and helped with field work, managed the whole process and supervised it from the beginning to the end.