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Dynamic Fracture Process Analysis of Controlled Blasts to Minimize the Excavation Damage Zone in Underground Excavations

Min, G. J., Park, S. W., Oh, S. W., and Cho, S. H.*
Chonbuk National University, Jeonju, Republic of Korea
Kim, B. H.
Spokane Mining Research Division, CDC/NIOSH, 315 E Montgomery Avenue, Spokane WA 99207 USA
Fukuda, D.
Hokkaido University, Sapporo, N13W8, Japan

ABSTRACT: Smooth surfaces with minimum damage in underground excavations have been demanded by the civil and mining industry such as the walls of tunnels and production drifts in underground mines. However, the consequences of aggressive blasting due to the lack of controlled blast design and precision drilling can lead to unexpected damage on the perimeter of the opening. The damages result in overbreak, loose rock to be scaled, and permanent damage to the remaining perimeters with the exposure of ground-fall hazards. To reduce injuries from ground falls, improved blast designs based on practical blast damage in perimeter blasting have been recommended by the National Institute for Occupational Safety and Health (NIOSH) through the DRIFT blast design software. This software models blast design using existing methods for perimeter blasting adding a new concept taken from the buffer row method with the perimeter row to reduce perimeter damage. In this study, to investigate the fracture process and pattern on the perimeter with a different application of the blast design method, the perimeter blasting was numerically analyzed using the two-dimensional dynamic fracture process analysis (2D-DFPA) with different perimeter drill-hole patterns. The influence of the blast design method and initiation error of the detonation on the fracture patterns are also discussed.

1. INTRODUCTION

Ground fall has been considered as a major safety issue in underground excavations in the mining industry. In particular, poor blast design and drilling and the presence of unknown geologic structures can lead to unexpected overbreak or underbreak and damage to the adjacent ground. Rock-blasting techniques in underground metal/nonmetal mines need to be optimized to minimize the extent of the loose and damaged rock mass. Meanwhile, in order to apply optimized blasting techniques for minimizing the perimeter damage in controlled blasting, a tunnel/drift blast design software called DRIFT[1] (Iverson et al., 2013) has been developed by the National Institute for Occupational Safety and Health (NIOSH). This blast design software operates with the application of several optimized blast design methods, based on the practical perimeter damage, including the concept of buffer -holes to reduce perimeter damage.

In this study, the fracture processes of controlled blasting are analyzed using a numerical approach, which is based on two-dimensional dynamic fracture process analysis (2D-DFPA) with various perimeter drill-hole patterns to investigate blast-induced damage near underground mine openings. This perimeter blast design utilizes the calculated spacing between the buffer and perimeter blast-holes using blast design methods, such as Holmberg's (1982) method or the buffer-row method. The influence of the blast design method and initiation error of detonation on the fracture plane formation and the blast-induced damage are discussed in the sections that follow.

2. BLAST DAMAGE MODEL BASED ON PERIMETER DRILLHOLE DESIGN METHOD

NIOSH developed the blast design software DRIFT as a solution to control the perimeter and reduce scaling requirements for underground metal/nonmetal mine drifting applications. This software incorporates a new concept, which focuses on the importance of buffer-holes in blast design. In this study, the blast drill patterns were designed using the DRIFT software, based on the

[1] Only a beta version is available for now. An official version of the software will be released by NIOSH later in 2019.

traditional Holmberg method with the addition of using buffer holes.

2.1. *Holmberg method*

As the traditional approach for perimeter control, the Holmberg method (Holmberg, 1982) has been widely applied. This method introduces the design sectors as the cut, the stopping, the contour, and the lifter sectors. The holes/explosives included in the different sectors are responsible for fracturing the related rock mass. For perimeter blasting control, the Holmberg method simply determines the perimeter burden based on the spacing of the contour holes using:

$$B = 1.25E \qquad (1)$$

where B is the perimeter burden, and E is the spacing of the contour hole.

The control of the charge concentrations in the holes close to the contour is also implemented by analysis of perimeter damage with the expected crack limit using the critical particle velocity (PPV).

Fig. 1 represents the blast drill-hole pattern designed by the Holmberg method as incorporated in the DRIFT software. Also, the red circles and green circles, which are represented in Fig.1, are the practical damage radii of the contour holes and the full charge holes, respectively. Description of practical damage radius will be presented in the next paragraph. This blast design consists of 26 full charge holes and 24 contour holes. Note that the buffer-hole is excluded in this blast design.

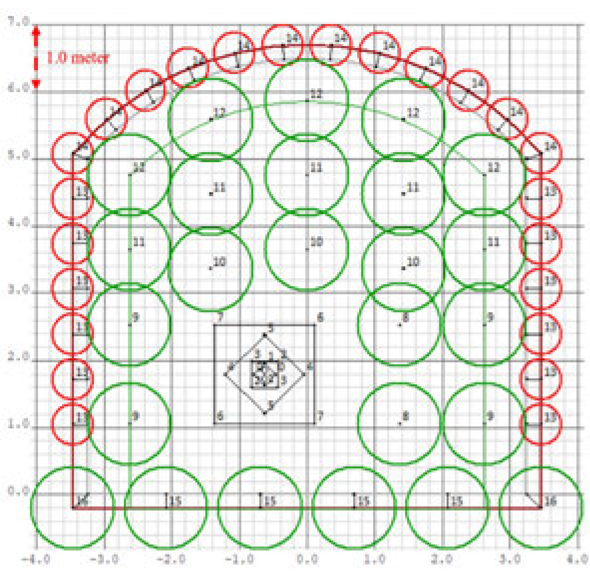

Fig. 1. Blast design using the Holmberg method.

2.2. *Buffer-row method*

The purpose of a a buffer hole is to improve fracturing of the rock just inside the perimeter holes so that extent of damage at the perimeter can be more closely controlled. The buffer-row design method applies amount of charge and hole spacing of buffer holes to optimize fracturing and reduce overbreak beyond the perimeter. The radial damage is defined by a practical damage limit applied to the rock lying between the buffer-holes and the contour hole. The practical damage limit is quantitatively represented as a practical damage radius (R_d), which is calculated from the buffer-holes, and would determine the contour burden. The practical damage zone consists of both crushing and cracking components. The concept of the buffer row method corresponds to the practical damage radius with the designed drift contour as:

$$R_d = B \qquad (2)$$

where R_d is practical damage radius and B is perimeter row burden.

The contour blast design using the buffer-row method as shown in Fig. 2 was also designed using the DRIFT software. Also, the red circles, blue circles and green circles, which are represented in Fig.2, are practical damage radii of the contour holes, the buffer holes, and the full-charge holes, respectively. They include 33 full-charge holes, 23 buffer-holes, and 24 contour holes.

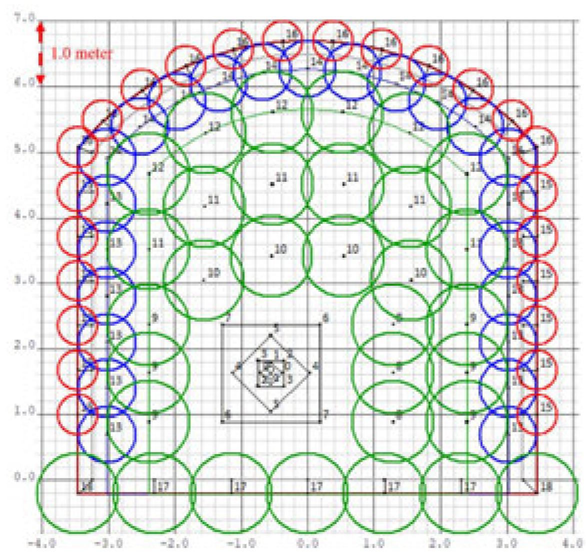

Fig. 2. Blast design using the buffer-row method.

3. DYNAMIC FRACTURE PROCESS ANALYSIS OF PERIMETER BLASTS

3.1. *Model description*

The numerical analysis of the perimeter blasting was performed by applying 2D-DFPA, which is capable of simulating multiple crack initiations, propagations, and coalescences mainly in rocks and rock-like materials, such as concrete while considering the makeup of the material (Cho and Kaneko, 2004). For these analyses, finite element models were created based on the perimeter blast designs, which are already presented in Fig. 1 and Fig. 2. In this study, the influence of the blast pattern on the fragmentations is analyzed.

A rock with the inhomogeneous material properties is also statically considered using Weibull's distribution (Weibull, 1951), which designates the microscopic strength of rocks. The microscopic strength x_t, is represented using the coefficient of uniformity *m,* the mean strength in volume V_{ele}, and Γ as the Gamma function. The cumulative probability distribution $G(V_{ele}, x_t)$ can be rewritten as:

$$G(V_{ele}, x_t) = 1 - \exp\left[-\frac{V_{ele}}{V_{ele\_0}} \left(\frac{x_t}{\bar{x}_t(V_{ele\_0})} \right)^m \Gamma(1 + \frac{1}{m}) \right] \quad (3)$$

Where the size effect is considered, using the mean strength $\bar{x}_t(V_{ele\_0})$ in a reference volume V_{ele_0}. Random numbers satisfying Weibull's distribution were generated to provide the spatial distribution of the microscopic strengths in the analysis model.

Fig. 3 shows a schematic view of large-scale perimeter blasting. The analysis model includes the opening, continuous boundary, and charge holes. The model was discretized into triangular elements. The stopping and the buffer row were considered to be free faces. The applied parameters to the numerical simulation are listed in Table 1.

Table 1. Parameters of the analysis model

Parameter	Value
Compressive strength (*MPa*)	140
Tensile strength (*MPa*)	7.5
P-wave velocity (*m/s*)	4,750
Elastic modulus (*GPa*)	41
Density (kg/m^3)	2,600
Fracture energy, Mode I ($Pa{\cdot}m$)	200

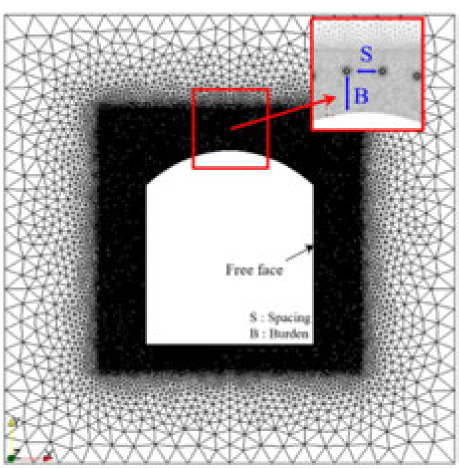

Fig. 3. Finite element layouts of the perimeter blasting for the analysis model.

Applying a blast pressure on the blast-hole wall and cracks, the Jones-Wilkins-Lee (JWL) equation of state (Lee et al., 1973), which is widely applied for describing the expansion of explosives, was utilized. The applied pressure *P(t)*, represented as a function of time *t*, was used as:

$$P(t) = P_{JWL}(V(t))F_s(t) \quad (4)$$

where $P_{JWL}(V(t))$ is the JWL pressure, and $F_s(t)$ represents a pressure-time function (Cho et al., 2004), as shown in Fig. 4. In the figure, t_1 is the rising-time [$10\mu s$], t_3 is decay-time [$10\mu s$] and t_2 is a time [$1ms$], where F_s remains constant. The t_1 corresponds to the shockwave occurrence on the blast-hole wall, and the t_2 is the duration of explosion gas pressurization on the blast-hole wall.

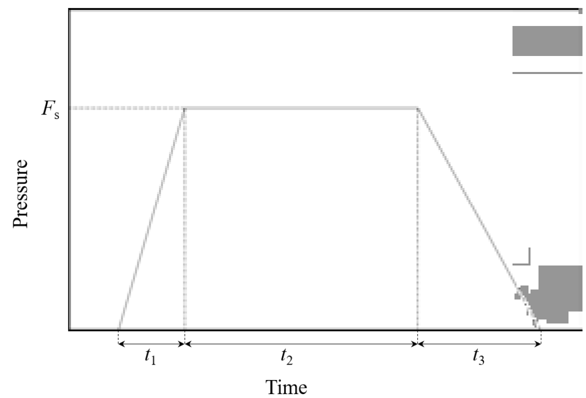

Fig. 4. Pressure-time history for gas pressure in the boreholes.

The pressure $P_{JWL}(V(t))$ as a function of *V(t)* constant entropy can be written as:

$$P_{JWL}(V(t)) = A\exp(-R_1V(t)) + B\exp(-R_2V(t)) + CV(t)^{-(\omega+1)} \quad (5)$$

where A = 365.29 [GPa], B = 2.703 [GPa], C = 0.227 [GPa], R_1 = 4.999, R_2 = 0.892, and ω = 0.23. The parameters were for emulsion explosives (Sanchidrian et al., 2015). *V(t)* is the relative volume, $V_e(t)/V_o$. Here, $V_e(t)$ is the volume of the gas produced, and V_o is the volume of the explosives. The pressure, varied due to a volume change resulting from decoupling of the charge hole, was expressed according to the ratio of the relative volume.

The nonlinear behaviors due to the fractures failed in a brittle manner also were considered using fracture process zone (FPZ) theory (Hillerborg, 1983; Labuz et al., 1985; Whittaker et al., 1992). Describing FPZ, tensile softening curves are applied as shown in Fig. 5 (Cho et al., 2003). In Fig. 5, S_t is tensile strength of materials, W_1 and W_2 correspond to W as the $\sigma = S_t/4$ and $\sigma = 0$, respectively. The cracks were characterized by micro-crack ($0 < W \le W_1$), bridging crack ($W_1 < W \le W_2$), opening crack ($W > W_2$).

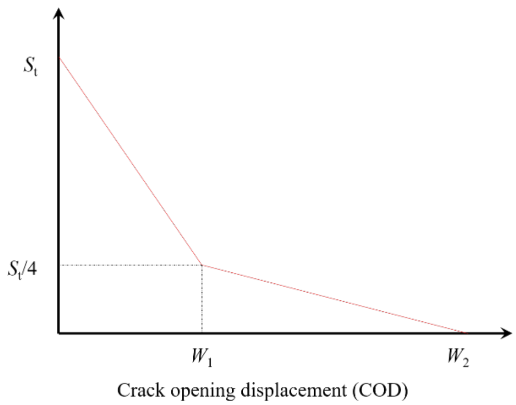

Fig. 5. Tensile softening curve for FPZ.

3.2. *Rock fracture process in the perimeter blast simulation*

Fig. 6 shows the distribution of maximum principal stresses and crack propagations for the perimeter hole blasts designed with the Holmberg and buffer-row blast design methods.

At the elapsed time of 50μs, the result shows that the radial stress wave propagates around the charge-hole. (see direction of stress propagation at 50μs in Fig. 6 (a))

At the elapsed time of 100μs, a concentration of the compressive stress appears in the left and right part along the contour row of the middle of each hole. (see stress concentration at 100μs in Fig. 6 (a)) The concentration of the compressive stress prevent the growth of the cracks generated in the backside of each loading space and cause the tensile stress in a direction orthogonal to the line to be excavated. Also, in the case of the buffer-row method, the concentration of the compressive stress wave is not presented in the vicinity of free surfaces due to the short perimeter burden. The second detonations on the roof were initiated at 150μs with crack generation. The cracks were also propagated at 200μs along the contour line. The compressive stress concentrations were also observed along the contour row at the top and bottom part of the middle of each hole. The fracture processes were finished at the elapsed time of 550μs. A fracture was formed along the contour row, while the crack growth to the adjacent ground was suppressed

Fig. 7 presents the crack propagation of the perimeter blasting corresponding to Fig. 6 analysis models. The micro-crack (black line in Fig. 7), which is statistically distributed in the volume of rock, becomes an opening crack (red line in Fig. 7) as the failure criteria are satisfied. It is noted that the final crack at the elapsed time of 550μs in Fig. 7 presents smooth rock surfaces including opening cracks to intersect the row of holes.

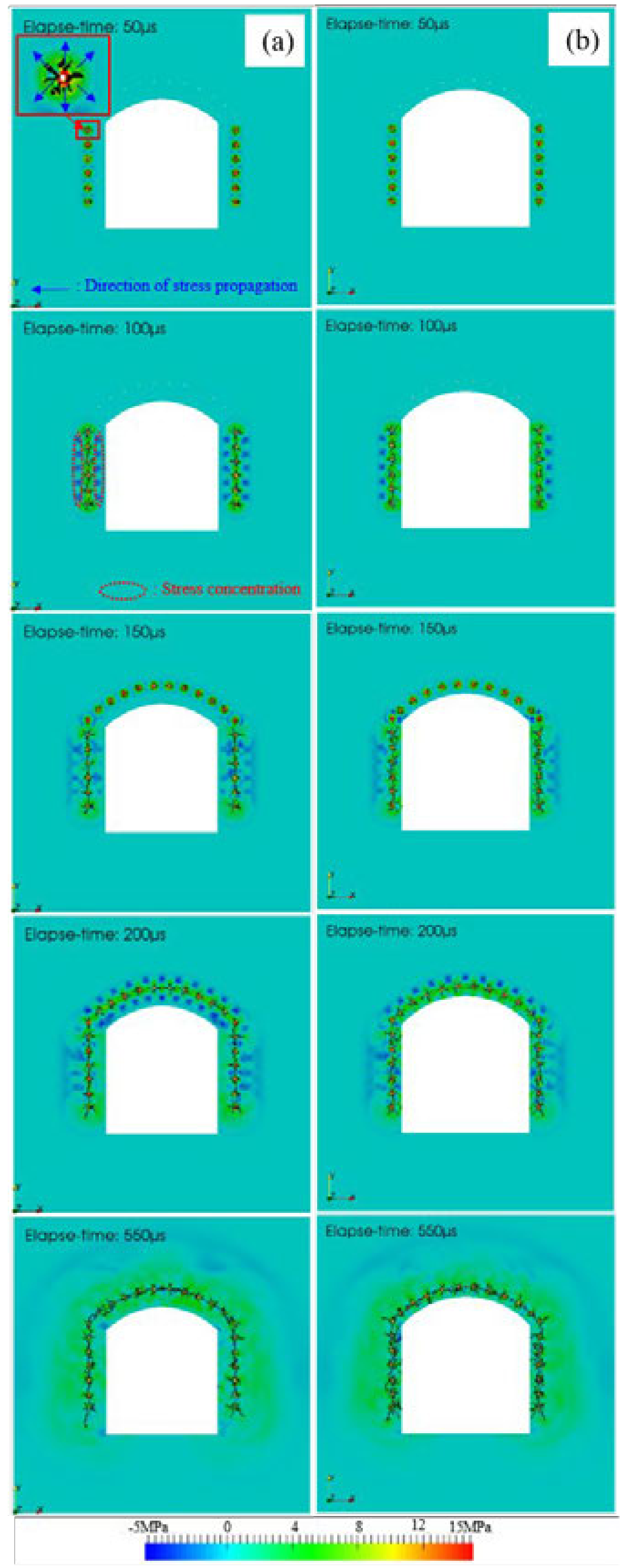

Fig. 6. Maximum principal stress distribution with the application of the (a) Holmberg and (b) buffer-row blast design methods.

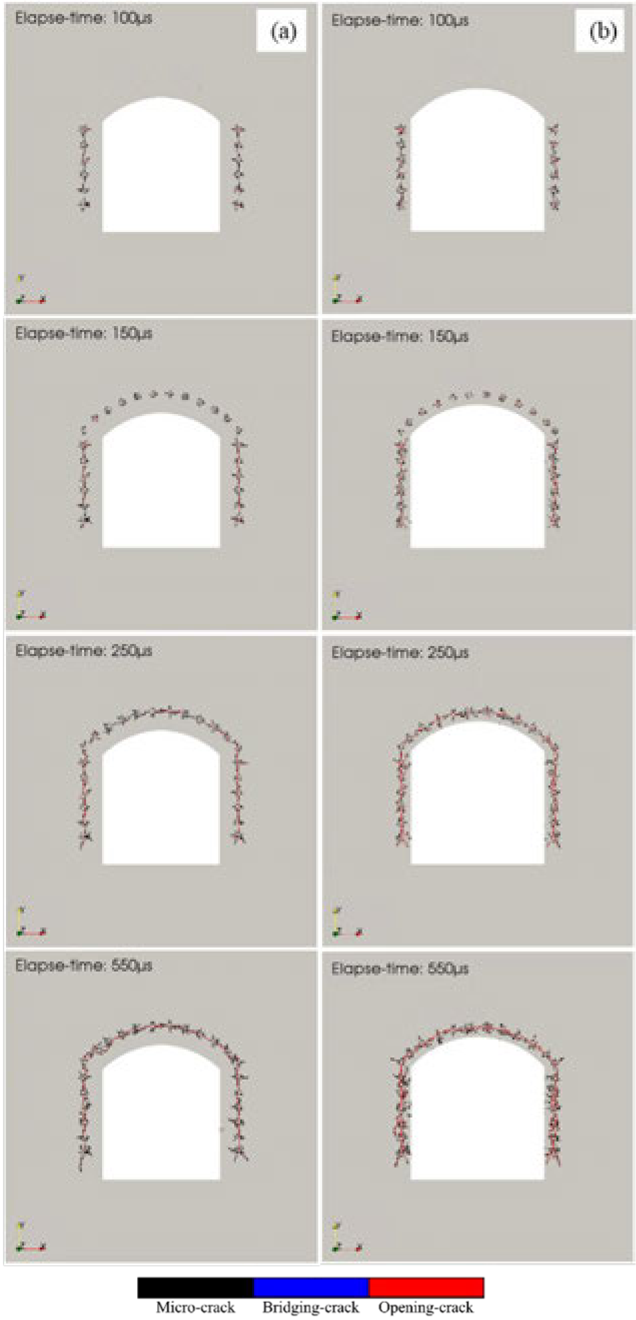

Fig. 7. Crack propagation with the application of the (a) Holmberg and (b) buffer-row blast design methods.

4. DISCUSSIONS ON THE FRACTURE PROCESS AROUND THE CONTOUR HOLES

4.1. Influence of blast design method on the fracture plane formation

Even though the contour blasting forms the smooth fracture, cracks also occur on the backside of the as-designed fracture. The area, which is called blast damage, may increase the risk of rock fall due to excessive fracturing. Since the smooth fracture caused by the perimeter blasting is influenced by various factors (spacing, burden, initiation error, etc.) with complexity, it is necessary to consider these factors with a simple analysis model.

In this study, based on the numerical analysis, the fracture plane formation and the depth of the damage were analyzed with different blasting design methods. The initiation error between blast holes was neglected.

The failure analysis of the simple model (see Fig. 8) was performed based on the blast design methods of the Holmberg method and the buffer-row method to examine the fracture plane formation and the depth of the damage. The burden of the contour hole was assumed as a distance from contour hole to free-surfaces where the buffer-holes and stopping hole were located. Table 2 shows the burden and spacing, which was applied to the perimeter blasting model. Fig. 9 shows crack patterns with consideration of the various spatial microscopic strength distributions in the Holmberg and buffer-row design methods.

The analysis of fracture plane formation was performed with specific criteria due to the complicated shape of the fracture plane and quantification of the fracture profile.

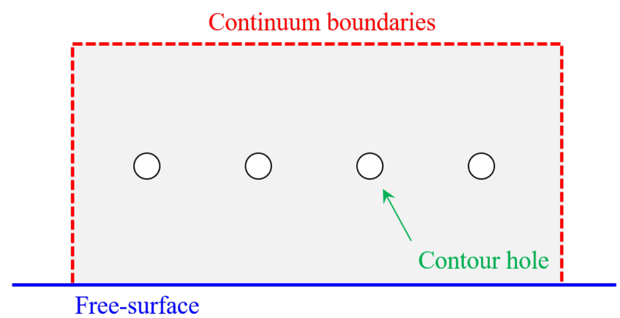

Fig. 8. Geometry for 4-hole contour blasting simulation.

Table 2. Blast patterns for the contour blasting simulation

Model No.	Blast pattern	Burden (*m*)	Spacing (*m*)
1	Holmberg Method	0.9	0.78
2	Buffer-row Method	0.4403	0.7044

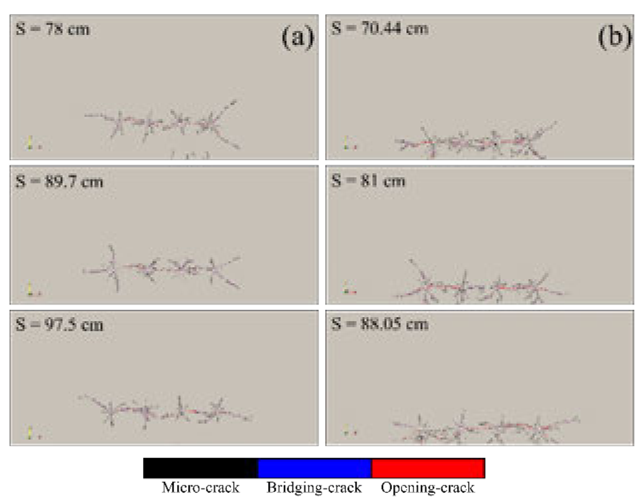

Fig. 9. Crack patterns with various spatial microscopic strength distributions in the (a) Holmberg and (b) buffer-row design methods

The criteria of the fracture roughness were determined with a definition as shown in Fig. 10. The fracture roughness was quantified using the maximum distance (Dmax) from the design fracture plane to the fractured plane in a vertical direction. The spatial microscopic strength distributions were also considered by using Weibull's distribution, which is already mentioned in the large-model description. Fig. 11 shows the fracture roughness with different spacing and different blast design methods. It is noted that the fracture roughness generally was greater in the Holmberg method compared to the buffer-row method.

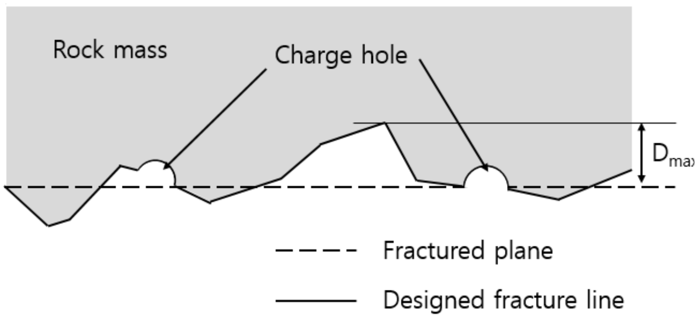

Fig. 10. Definition of the fracture smoothness.

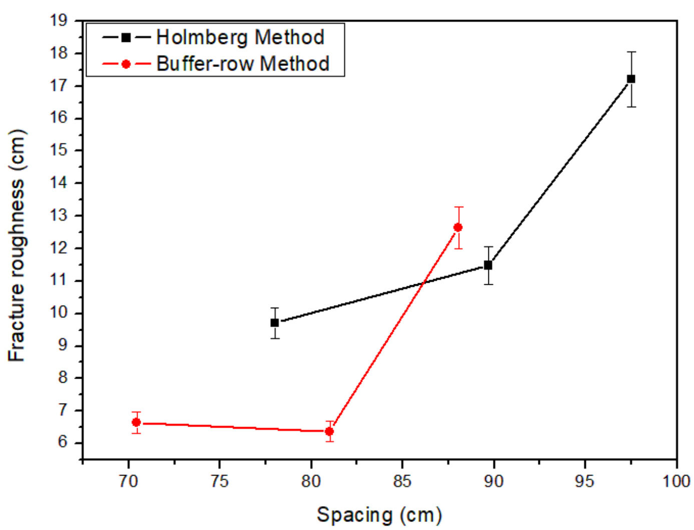

Fig. 11. Variation of the fracture roughnesses with various spacings (S, 1.15S, 1.25S) for the blast design methods (Holmberg and buffer-row).

This means that the Holmberg method might be causing rock fall due to overbreak. Also, as the spacing increases, the roughness of the fracture increases. In particular, the roughness of the fracture surface is significantly changed in 1.25*S* for both the Holmberg and buffer-row methods. This shows that wide spacing between blast holes could reduce the effect of the smooth blast.

4.2. Influence of blast design method on the damage zone

The analysis of the damage zone was also performed. To simplify the quantification, the maximum length of crack developed from the fracture surface, which is developed at the backside as shown in Fig. 12, is defined as the size of the damage region.

Fig. 13 shows the comparison of the damaged zone with the application of the Holmberg and buffer-row methods. In the Holmberg method, the distance between fractures caused by blasting ranges from 37 to 40 cm. Comparably, the buffer-row method has the distance between such fractures ranging from 28 to 44 cm. The frequency of the damage shows low values across the damaged distance in the buffer-row method compared to the traditional Holmberg method. The result indicates that proper implementation of the buffer-hole method is more successful for preventing damage to the back.

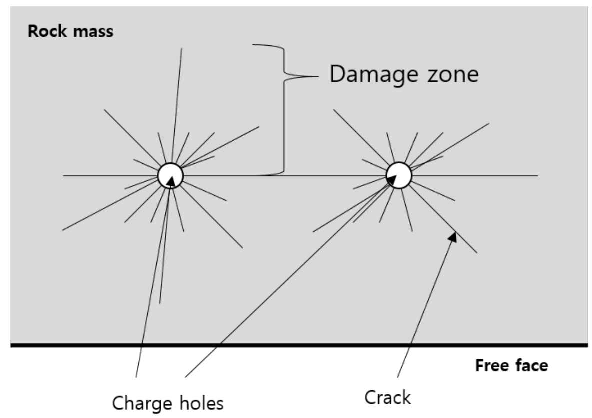

Fig. 12. Definition of the size of the damaged zone in the rock mass.

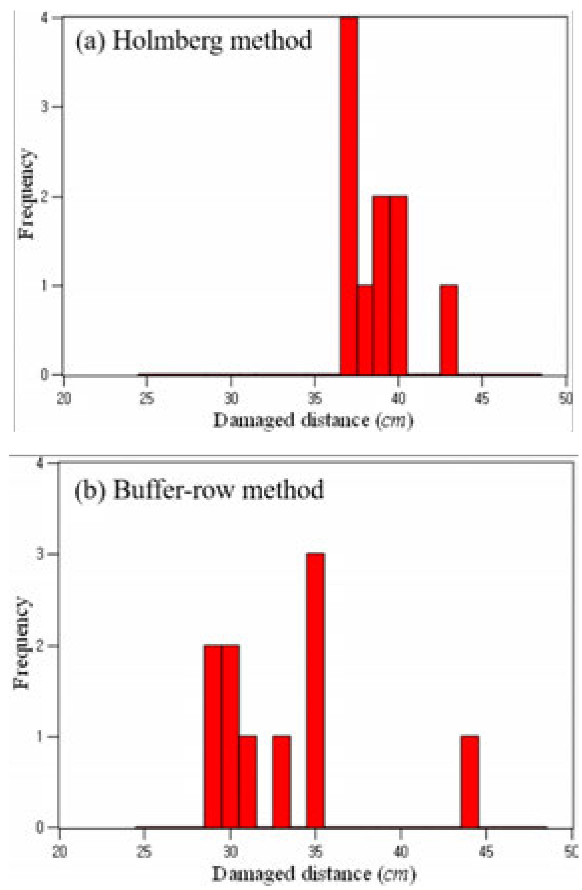

Fig. 13. Comparison of the damaged zone with the application of the (a) Holmberg method and (b) buffer-row method.

4.3. Initiation error influence of detonator on the fracture plane formation and damage zone

According to the results of previous studies (Yamamoto et al., 1997; Cho and Kaneko, 2004; Cho et al., 2009), the electronic detonator reduced the roughness of the fractured surface and significantly reduced the damaged area of the surrounding rock compared to the DS electric detonator.

These studies demonstrate that the precise initiation of detonation improves the potential of the smooth blast effect induced by propagated stress waves. In other words, the direction of the crack propagation can be controlled, and the damage zone can also be significantly reduced if an electronic detonator is used.

The analytical model shown in Fig. 14 simulates the dynamic fracture process described with the distribution of the maximum principal stress and crack propagation with an application of electronic detonator and DS electric detonator initiation with the Holmberg blast design method.

With the initiation of the electronic detonator shown in Fig. 14(a), the blasting load was applied to each hole with intervals of 60μs, 0μs, 90μs, and 30μs considering the initialization error of the electronic detonator. The initialization with the DS electric detonator as shown in Fig. 14(b) was also implemented with intervals of 400μs, 0μs, 800μs, and 200μs.

We determined that the rock fracturing is finished at elapsed-time of 550μs and 1,000μs with electronic and DS electric detonators, respectively. The application of the electronic detonator showed improvement in the reduction of roughness and the damaged area as compared to the DS electric detonator usages. From the analysis results, with the application of the electronic detonator, the roughness of the fractured surface and blast damage can be reduced.

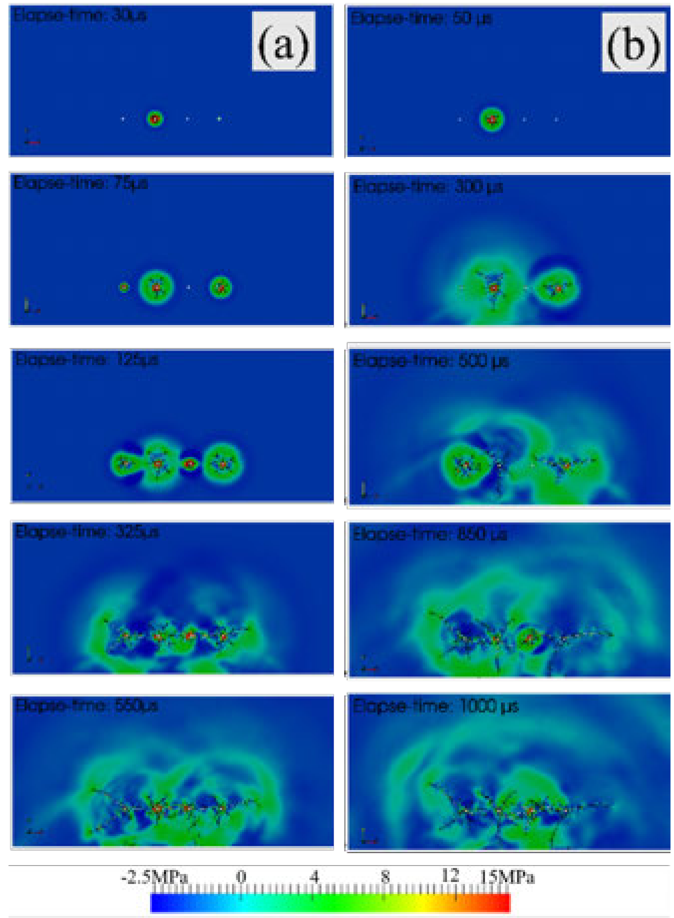

Fig. 14. Distribution of the maximum principal stress and crack propagation in considering the (a) electronic initiation and (b) electric detonating initiation for the Holmberg blast design method.

5. CONCLUSION

In order to prevent the damage due to blasting, perimeter blasting technique is very commonly used. In this study, the perimeter blast pattern was designed using the blast damage model as implemented in the DRIFT software. The Holmberg and buffer-row methods were utilized to design perimeter blast patterns. The rock fracturing process in perimeter blasting was numerically investigated using the analysis method of two-dimensional dynamic fracture process with the finite-element model, which is based on the designed perimeter blast patterns. In the numerical analysis, the inhomogeneous material properties of the rock are stochastically considered using Weibull's distribution. The stress distribution and crack propagation were compared between the Holmberg and buffer-row blast design methods. The influence of the blast design method on the roughness of the fractured surface and the blast damage was discussed using a simple 4-hole finite element perimeter blasting model. The results showed that the blast design method using a buffer-hole successfully reduces the roughness of fracture surface and blast damage in comparison to the traditional Holmberg method. This study revealed that the application of a precise detonation system, as the electronic detonator, should reduce the roughness of the fractured surface and blast damage.

DISCLAIMER

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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