Study on Control of Crack-Propagation in Blasting

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Abstract

One way of achieving controlled crack growth is to introduce notches into the surface of the guide-hole wall. This results in high stress concentration at the notch tips when the stress wave reaches a guided hole. The model experiments using PMMA specimens, which have a notched guide hole between the charge holes, were simulated by a dynamic fracture process analysis (DFPA) software to examine the effect of the notched guide hole on crack-propagation control. The influence of the shape of the guide hole and the initiation time lag on the crack-propagation control is discussed.

1. INTRODUCTION

Several mechanical excavation techniques employing tunnel boring machines (TBM) and rock splitters have been proposed to minimize rock damage. These then can serve as underground repository sites for nuclear waste disposal with the rock forming a natural barrier against possible seepage or leak. Such mechanical excavations, however, are extremely expensive and very time consuming. One way of achieving controlled crack growth along specific directions and inhibit growth along other directions is to generate stress concentrations along those preferred directions. The most direct way of achieving this is to introduce notches along the prescribed directions on the surface of the bore-hole wall. This results in a very high stress concentration at the notch tips when the gas pressure acts on the drill hole wall or a stress wave reaches a guided hole.

Several researchers have suggested a number of methods for achieving fracture plane control. Fourney et al. (1978) suggested a blasting method which utilizes a ligamented split-tube charge holder. Nakagawa et al. (1982) examined the effectiveness of the guide-hole technique by model experiments. Katsuyama et al. (1983) suggested a controlled blasting method using a sleeve with slits in a borehole. Mohanty (1990a,b) suggested a fracture plane control technique using satellite holes on either side of the central pressurized hole, and demonstrated its use through laboratory experiments and field trials. Nakamura et al. (1992) suggested a new blasting method for achieving crack control by utilizing the charge holder with two-wedge-shaped air cavities. Mukugi et al. (1992) developed a drilling system with gloving tools for making the notched hole in a single pass, which is applicable to hard rocks. Nakamura (1999) performed model experiments to examine the effectiveness of the guide hole with notches. Cho et al. (2002, 2004) performed experiments using a notched charge hole to visualize the fracturing and gas flow due to detonation of explosives. Recently model experiments using PMMA plates and electric detonators were carried out to observe the propagation of cracks between two charge holes in blasting by Nakamura et al. (2004). The applicability of the guide-hole method using a circular hole having two notches between the charge holes was examined.

In this study, the model experiments performed by Nakamura et al. (2004), which have a notched guide hole between the charge holes, are analyzed by the numerical method (DFPA) to examine the effect of the notched guide hole on crack-propagation control. The influence of the shape of the guide hole and the initiation time lag on the crack-propagation control is discussed.

Figure 1: Fracture patterns in the PMMA specimens (after Nakamura et al., 2004).
hole on crack-propagation control in blasting. The effect of the shape of the guide hole, distance between the charge holes and the initiation time error on the crack-propagation in blasting is investigated. The purpose of this study is the development of a high-precision fracture control technique for rock excavation with greatly reduced damage in the remaining rock.

2. MODEL EXPERIMENTS

PMMA has been shown by earlier workers to be a suitable material for laboratory experiments on rock blasting process because PMMA being a transparent material, makes crack patterns easily visible. Nakamura and Cho et al. (2004) carried out model experiments using PMMA plates and electric detonators to observe the dynamic fracture process by means of high-speed videography. A high accuracy firing circuit is used to control firing time of two charges. The dimension of PMMA specimens (length×width×thickness) are 400×300×20mm\(^2\) for Type I and 300×300×20mm\(^2\) for Type II experiments. Figure 1 shows examples of fracture patterns produced by blasting in PMMA specimens. These studies revealed that in the case of simultaneous firing of two charges with very small inter-hole delay, the resulting fracture was co-linear along the line connecting the charge holes. The circular guide hole between two charge holes was found to be not effective in fracture plane control. The circular guide hole with two notches is effective in driving the cracks along the line connecting two charge holes.

3. DYNAMIC FRACTURE PROCESS ANALYSES

3.1. Description of dynamic fracture process analysis (DFPA) code

The dynamic fracture process analysis (DFPA) code (Cho et al., 2002, 2003 and 2004) was used to simulate the model experiments. In the DFPA code incremental displacement form of a dynamic finite element method is used to describe large-scale displacement behavior. A re-meshing algorithm is used to model crack propagation, assuming that tensile fractures, i.e., crack initiation, propagation, and coalescence, occur at element boundaries. Therefore, cracks are modeled as separations of randomly distributed flaws and the evolution of the fracture process zone. Therefore, it is reasonable to apply the DFPA, which incorporates microscopic strength distribution and the fracture process zone (FPZ) model (Cho, Ogata and Kaneko, 2005), to simulate dynamic crack-propagation in PMMA. Von-Mises criterion is used to judge yield due to applied stress in PMMA.

3.2. Analysis of the Model Experiments

A no free-surface model was used, consisting of two charge holes and a guide hole between two charge holes, as shown in Figure 1. The outer boundary is considered as a continuous boundary. The finite element layout around the notched guide hole is illustrated in Figure 2. The parameters for the analysis model are listed in Table 1. Here the mean yield strength, mean tensile strength and fracture energy are taken from a previous study (Cho et al., 2004).

![Figure 2: Schematic geometry for the analysis model.](image)

The DFPA code (Cho et al., 2002, 2003 and 2004) was used to simulate a stress-wave-induced fracture of rock. However, this study applied the DFPA to dynamic fracture process analysis of PMMA. In connection with the dynamic crack propagation in PMMA, Ravi-Chandar and Yang (1997) examined a method of simulating dynamic crack growth in PMMA. The method incorporated the nucleation of randomly distributed flaws and the evolution of the fracture process zone. Therefore, it is reasonable to apply the DFPA, which incorporates microscopic strength distribution and the fracture process zone (FPZ) model (Cho, Ogata and Kaneko, 2005), to simulate dynamic crack-propagation in PMMA. Von-Mises criterion is used to judge yield due to applied stress in PMMA.

### Table 1: Parameters for the analysis model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-wave velocity (m/s)</td>
<td>2620</td>
</tr>
<tr>
<td>S-wave velocity (m/s)</td>
<td>1514</td>
</tr>
<tr>
<td>Density (kg/m(^3))</td>
<td>1188</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>5.97</td>
</tr>
<tr>
<td>Poisson's rate</td>
<td>0.28</td>
</tr>
<tr>
<td>Mean microscopic yield strength (MPa)</td>
<td>70</td>
</tr>
<tr>
<td>Mean microscopic tensile strength (MPa)</td>
<td>20</td>
</tr>
<tr>
<td>Fracture energy (Pa-m)</td>
<td>200</td>
</tr>
</tbody>
</table>

### Table 2: Blast patterns for the analysis model

<table>
<thead>
<tr>
<th>Type of the guide hole</th>
<th>Type I-1</th>
<th>Type I-2</th>
<th>Type II-1</th>
<th>Type I-3</th>
<th>Type I-4</th>
<th>Type II-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacing S (cm)</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Type</td>
<td>Notched</td>
<td>Regular</td>
<td>None</td>
<td>Notched</td>
<td>Regular</td>
<td>None</td>
</tr>
</tbody>
</table>

Six blast geometries were selected for the experiments, as shown in Table 2. To apply a blast pressure to the hole boundary, the following pressure function \(P(t)\) with respect to time \(t\) was used:

\[
P(t) = P_\text{JWL}(V(t))P_s(t)
\]

where, \(P_\text{JWL}(V(t))\) is the JWL pressure, which has been extensively used to describe the isentropic expansion of detonation products, and is called the JWL equation of state, and \(P_s(t)\) denotes a pressure-time function with 10\(\mu\)s rise time. \(V(t)\) is the relative volume, \(V_p(t)/V_0\). Here, \(V_p(t)\) is...
the volume of gas produced and $V_0$ is the volume of the explosive. In this study $V_e(t)$ is calculated from the expanded volume of charge hole.

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

$$P_{jwl}(V(t)) = A \exp(-R_1 V(t)) + B \exp(-R_2 V(t)) + C V(t)^{\omega + 1}$$

where, $A = 1032.15$ (GPa), $B = 90.57$ (GPa), $C = 3.72735$ (GPa), $R_1 = 6.0$, $R_2 = 2.6$, and $\omega = 0.57$. The parameters were for PETN explosive (Hornberg and Volk, 1989). Only the lower 10mm of the electric detonator contained the main PETN charge (0.4 g). The decoupling ratio (i.e. ratio of hole diameter to charge diameter) in these experiments was kept fixed at 2.2.

3.3. Fracture Process Analysis and Results

Figures 4 show the maximum principal stress distributions and crack propagation in the blast models with simultaneous initiation condition. High compressive stresses due to applied blast pressure cause compressive yield around the charge-hole wall. Here, the non-cracking zones around the charge holes correspond to the compressive yield zone. In figure 4(a), the computed stress fields, which correspond to the tangential tensile stress, extend from the charge holes and radial cracks are generated from near compressive yield zone at 40\(\mu s\). At 80\(\mu s\) the stress waves propagating from charge holes superpose in the middle of the charge holes and the cracks starts to propagate from the tips of the notch of the guide hole. After 40\(\mu s\), the propagating cracks from the right side of the guide hole meet the radial crack from the charge hole. At 240\(\mu s\), cracks completely connect between the charge holes.

At 80\(\mu s\) no cracking around the guide hole is visible around the circular guide hole (Figure 4). A crack from the right side of the guide hole passes below the propagating radial crack from the charge hole at 120\(\mu s\), and the crack from the guide hole does not connect the charge hole to the end of the analysis.

Figure 4 (c), at 120\(\mu s\) shows superposition of the radial components of the stress waves from both the charge holes. This results in compressive stressed zones, which corresponds to a quasi-static stress field, above and below near the line joining the charge holes. Finally a radiating crack is generated between the charge holes.

Figures 5 show the resulting fracture patterns for all the models. Compressive yield zones appear around the charge holes and radial cracks (as lines) are generated from near compressive yield zone. Here, white line and black line indicates opening crack and micro-cracks respectively.

Figure 3: Finite element layout around a notched guide hole for the analysis models.

Figure 4: Calculated maximum principal stress distribution and crack propagation.

Figure 5: Fracture patterns for different specimen types (white and black line indicates opening crack and micro-cracks respectively).
black line indicates the opening crack and micro-cracks within the fracture process zone (FPZ) respectively. Note that Type I-3, Type I-4 and Type I-2 have 20 cm spacing between the charge holes. Contrary to the types that have 30 cm spacing, cracks connect between the charge holes for all cases. It is most likely that stress concentration increment caused by decreasing of the distance between the charge holes led to the generation and propagation of the cracks between the holes.

The results show that both the notched guide hole and circular guide hole are effective on control of crack propagation control in blasting. In particular, introduction of notched guide holes results in a smoother fracture plane. These results agree well with the findings from the model analysis described in Section 2.

In addition, although Nakamura et al. (2004) showed that the circular guide hole between two charge holes is not effective in fracture plane control. Theses analyses show the cracking from both the guide holes. Plane strain condition was applied in this analysis involving 20 mm thick PMMA plates, although it is realized that a more accurate analysis would require experiments with a block rather than a plate sample.

4. DISCUSSION

As mentioned above, the notched guide hole leads to earlier crack generation than the circular guide hole. Figure 6 compares the tangential stress-time histories at a right side element around both the guide holes without fracture. It is shown that the tangential tensile stress around the notched guide hole exceeds the mean microscopic tensile strength 20 MPa used for the analyses at 70 μs, while the maximum tensile stress around the circular guide is only 15 MPa. These results agree with the crack initiation timing as shown in Figs. 4 (a).

The analyses in this study considered simultaneous initiation of the charge holes. It is, however, difficult to achieve simultaneous ignition in practical blasting, especially in microsecond time scale. Figure 8 show the maximum principal stress field and cracks at 140 μs in Type I-1 with 60 μs initiation time interval between the charge holes. Here the initiation time interval refers to the initiation time error of electronic delay detonator (Yamamoto et al., 1999). Comparison with the results of Type I-1 in Figure 4, shows that the initiation time error increases the time that it takes for the cracks to generate from the notch of the guide hole.

Finally, to consider arbitrary propagation of radial cracks, this numerical model used a random number generator to give the spatial distribution of the microscopic strength. Figure 7 shows fracture patterns with different spatial microscopic strength distributions. Cracks connect between the charge holes for all the cases. It should be noted that predominant radial cracks propagate along different directions with different microscopic strength distribution and the propagation direction affects the smoothness of the fracture plane between the charge holes. It is concluded therefore, that introduction of guided charge hole increases the smoothness of the fracture plane.

5. CONCLUSIONS

Six blast geometries, which constitute the model experiments, were analyzed numerically. This study
showed that both the notched guide hole and circular guide hole are effective in controlling crack propagation in blasting. Furthermore, introduction of notched holes leads to earlier crack generation and smoother fracture plane. The influence of the arbitrary radial crack propagation and ignition time error on the fracture patterns and were also investigated. These showed that the predominant radial cracks propagate along directions with different microscopic strength distribution. It was also observed that propagation directions have significant effect on the smoothness of the fracture plane between the charge holes. Finally, it was discovered that the ignition time error increases the time the cracks generate from the notch of the guide hole.

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REFERENCES


Figure 8: Fracture patterns with various spatial microscopic strength distributions in Type I-1.