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# A numerical study of the impact of short delays on rock fragmentation

Changping Yi[a,*], Jonny Sjöberg[b], Daniel Johansson[a], Nikolaos Petropoulos[a]

[a] Division of Mining and Geotechnical Engineering, Luleå University of Technology, Sweden
[b] Itasca Consultants AB, Sweden

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## 1. Introduction

Blasting techniques are widely employed in mining in order to fragment rock mass into smaller pieces to facilitate subsequent handling (mucking, haulage, crushing, etc.). Short delay blasting techniques can improve fragmentation compared to simultaneous initiation, but the optimum delay time for blasting is still under discussion. The optimum delay time to improve fragmentation has been studied by e.g. Tatsuya et al.,[1] Aldas et al.,[2] Shi and Chen[3] and Petropoulos et al.,[4] but different conclusions were obtained.

With the application of electronic detonators and with short delay times, a hypothesis of achieving improved fragmentation through stress wave interaction has been proposed by Rossmanith et al.[5,6] In these papers, a model was proposed to describe the stress wave interaction between adjacent boreholes with Lagrange diagrams, which reveals how a positive effect of the interaction of the stress waves could be achieved with the assumption of an infinitely long charge length. With the inspiration of Rossmanith and co-workers, Vanbrabant and Espinosa[7] stated that the delay times to match an overlap of the negative tail of the particle velocity can improve fragmentation. They conducted a series of field tests and claimed that the average fragmentation improved by nearly 50%. Chiappetta[8] also claimed that the very short delays between holes, such as 2 ms, help to improve blast performances. However, there are different opinions. Blair[9] stated that the delay time and initiation accuracy are not typical governing factors for blast performances. Johansson and Ouchterlony[10] investigated the influence of delay time on the fragmentation with a series of small-scale tests. Their results showed no distinct differences in fragmentation when there were shockwave interactions compared to no shockwave interaction. The investigation of Katsabanis et al.[11] indicated that selecting a very short delay time for fragmentation optimization is questionable. Schill and Sjöberg[12] studied the influence of delay times on the blasting effect in a two-hole model with the LS-DYNA[13] code and concluded that there was an effect of interacting stress waves. However, this effect was local around the interaction plane, implying that very short delay will not generate a dramatic increase in fragmentation contrary to what was proposed by Rossmanith et al.[5,6] The results of Schill and Sjöberg[12] also indicated that longer delay times (in which the stress wave would have passed the neighboring boreholes) also resulted in improved fragmentation. The quantitative results of stress wave interaction between two adjacent boreholes were analytically and numerically investigated by Yi et al.[14] The analytical model based on the assumptions used by Rossmanith et al.[5,6] was compared with a numerical model in LS-DYNA and the results were not consistent.

In the present paper, a four-hole model was built to study the possible effect of overlapping negative tails by using the 3D finite element method. A method was presented to form fragments based on finite element modeling results and damage concepts. An approach was proposed to evaluate blast-induced fragmentation based on numerical results.

## 2. Model and materials

A four-borehole model was constructed to model the field tests. The model geometry and the sizes are shown in Fig. 1. The borehole diameter is 310 mm. The depth of the borehole is 16 m, the length of subdrilling is 1 m and the length of stemming is 5 m. The green part in the model geometry was selected to be evaluated after blasting. The model is discretized with hexahedral elements. The element size of the green part is 6 × 6 × 6 cm while the element size of the yellow part is 12 × 12 × 12 cm. The green part and the yellow part are connected with transition elements. The total number of elements is approximately 23 million.

* Corresponding author.
*E-mail address:* changping.yi@ltu.se (C. Yi).

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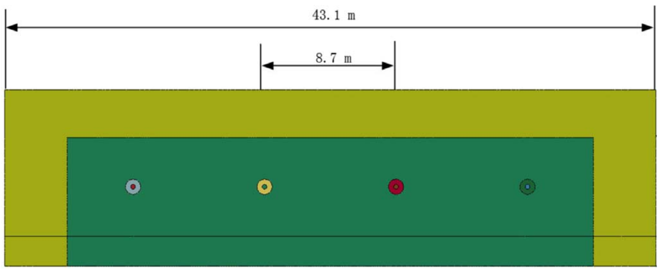


**Fig. 1.** Geometry of the four-borehole model. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article).

The explosives and the stemming material are modeled with Eulerian elements. The rock surrounding the borehole is also modeled with Eulerian elements to accommodate for the large deformation in that region. The other rock parts are modeled with Lagrangian elements. The Eulerian elements are merged to the Lagrangian mesh. The radius of the interface between the Eulerian elements and the Lagrangian elements is 0.5 m. The initiation point is 1 m above the bottom of the blast holes. In order to model an infinite domain, non-reflecting boundaries are used on surfaces which are connected to continuing rock material. The top and front surfaces are modeled as free faces (Fig. 2).

The Riedel-Hiermaier-Thoma (RHT) material model[15] which is an advanced plasticity model for brittle materials such as concrete and rock was employed to describe the dynamic response of rock mass in Lagrangian elements. This material model involves three limit surfaces which describe the strength of the material, see Fig. 3. The first surface is the yield surface which is limited by a cap surface. Beyond this surface the material starts to deform plastically with a linear hardening description. When the material reaches the failure surface, the damage of the material starts to evolve until the damage is equal to one. The damage level in this model is defined as $D = \sum \frac{\Delta\varepsilon^p}{\varepsilon^f}$,where $\Delta\varepsilon^p$ is the accumulated plastic strain and $\varepsilon^f$ is the failure strain. The parameters of RHT material used in this paper are from Schill[16] in which these parameters were calibrated based on the material tests presented by Haimson and Chang.[17] The RHT material parameters are shown in Table 1.

The E682-b emulsion explosive was used and it was modeled with an explosive material model in LS-DYNA and with the Jones-Wilkins-Lee (JWL) equation of state.[18]

$$p = A\left(1 - \frac{w}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{w}{R_2 V}\right)e^{-R_2 V} + \frac{wE}{V} \tag{1}$$

where $p$ is the pressure, $A$, $B$, $R_1$, $R_2$ and $w$ are constants; $V$ and $E$ are the specific volume and the internal energy respectively. The density of E682-b emulsion explosive is 1180 kg/m$^3$. The velocity of detonation is 5866 m/s. The Chapman-Jouguet pressure ($P_{CJ}$) of E682-b emulsion explosive is 10.06 GPa. For E682-b emulsion explosive, $A$ = 285.73 GPa, $B$ = 6.715 GPa, $R_1$ = 4.933, $R_2$ = 1.962, $w$ = 0.52, The detonation energy per unit volume $E_0$ = 3.176 kJ/cc. These parameters

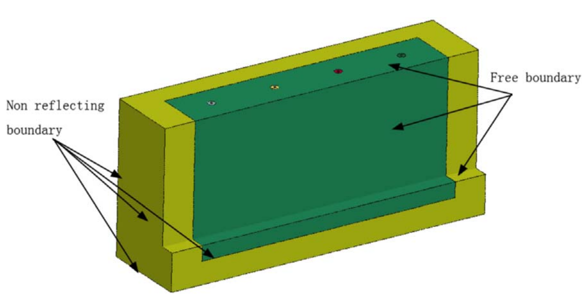


**Fig. 2.** The boundary conditions.

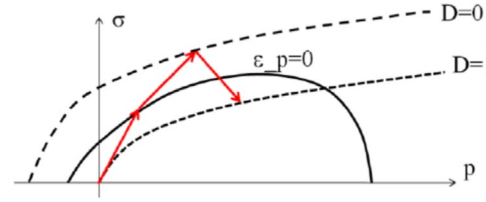


**Fig. 3.** Stress limit surfaces of the RHT model, after Schill.[16]

**Table 1**
RHT model parameters for rock mass in Lagrangian elements.

| | | | |
|---|---|---|---|
| Density | 2627 kg/m$^3$ | Ref. compressive stain rate | 3.0e8 |
| Shear Modulus | 18.6 GPa | Ref. tensile strain rate | 3.0e9 |
| Pore crush B0 | 1.22 | Failure tensile strain rate | 3.0e22 |
| Pore crush B1 | 1.22 | Failure compressive strain rate | 3.0e22 |
| Bulk Modulus T1 | 40 GPa | Compressive strain rate dependence exponent | 0.032 |
| Bulk Modulus T2 | 0 | Tensile strain rate dependence exponent | 0.036 |
| Bulk Modulus A1 | 40 GPa | Volumetric plastic strain fraction in tension | 0.001 |
| Bulk Modulus A2 | 0 | Compressive yield strength | 200 MPa |
| Bulk Modulus A3 | 0 | Tensile yield strength | 7 MPa |
| Failure surface A | 2.618 | Damage parameter D1 | 0.04 |
| Failure surface N | 0.7985 | Damage parameter D2 | 1.0 |
| Shear strength | 36 MPa | Minimum damaged residual strain | 0.01 |
| Uniaxial tensile strength | 10 MPa | Residual surface parameter AF | 0.873 |
| Lode Angle Q0 | 0.567 | Residual surface parameter AN | 0.559 |
| Lode Angle B | 0.0105 | Grunnisen Gamma | 0 |
| Compaction pressure | 6 GPa | Crush pressure | 133 MPa |
| Initial porosity | 1.0 | Porosity exponent | 3 |

were calibrated by Hansson based on the cylinder test.[19]

The stemming material and the rock mass in Eulerian elements are modeled by a soil material model (*MAT_SOIL_CONCRETE) since the RHT material model does not support the Eulerian solution technique. This model is a perfectly plastic, pressure dependent yield function.[13] It also includes fracture and a residual strength surface where the material loses its ability to carry tension. The soil material parameters for rocks and stemming calibrated by Schill[16] are given in Table 2.

## 3. Fragmentation evaluation

Fragmentation is one of the important indicators to evaluate blast performance. It is complicated to directly evaluate fragmentation based on finite element method. In this paper, after the calculation, the elements with damage level above 0.6 were blanked out to form cracks in the rock mass. An instance for the case of 3 ms delay time is shown in Fig. 4. Fig. 4(a) shows the damage distribution in the rock mass after blasting. Fig. 4(b) shows the overall crack pattern after the elements with damage level above 0.6 are blanked out. Hence, the rock mass is separated into smaller fragments by these cracks.

If the dimensions of these fragments can be determined, the fragment size distribution can be evaluated. It is not an easy task in 3D, but it is straightforward in 2D and a routine was implemented in LS-PREPOST[20] code which is an advanced interactive program for

**Table 2**
Parameters for rock mass and stemming in Eulerian elements.

| Parameters | Rock mass | Stemming material |
|---|---|---|
| Density (kg/m$^3$) | 2770 | 1650 |
| Shear Modulus (GPa) | 26.1 | 10 |
| Bulk Modulus (GPa) | 37.6 | 3.6 |
| Pressure Cutoff (MPa) | 2.67 | 0.01 |