Computer simulations of blasting with precise initiation

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Abstract: Using blasting caps with electronic delay units, it has become possible to employ wave superposition in rock blasting. This paper presents computer simulations to investigate the hypothesis that fragmentation is improved in areas between blast holes where the tensile waves meet, overlap and interact. In this study, a numerical methodology using the code *LS-DYNA* was developed. *LS-DYNA* is a commercially available multi-purpose finite-element code, which is well suited to various types of dynamic modeling. Two different element formulations were used — Euler formulation in, and close to, the blast hole, and Lagrange formulation in the rock volume farther from the blast hole. The models used have a resolution (element size) of 50 mm and comprise approximately 20 million elements. Single and dual blast hole configurations have been studied, and a methodology to calculate possible fragmentation based on model interpretation was developed. The results showed that the amount of explosives and the blast hole spacing had the largest effect on fragmentation. The effect of varying delay times was small and local, implying that a significant increase in fragmentation should not be expected through wave superposition.

Theme: Excavation

Keywords: Blasting, wave superposition, electronic detonators, *LS-DYNA*, *RHT* material model

1 INTRODUCTION

The primary purpose of all blasting is to fragment the rock into pieces of suitable dimensions for further handling. An improved fragmentation can result in reduced costs for both blasting and transportation of the blasted rock, improved environmental aspects, and reductions in energy consumption during crushing and grinding of the blasted rock, as well as improved metal recovery.

Using blasting caps with electronic delay units, with delay times down to 1 ms, it has become possible to employ wave superposition in rock blasting. A hypothesis proposed by Rossmanith (2002) states that fragmentation is improved in areas between blast holes where the tensile waves meet, overlap and interact. There are practical experiences showing that improved fragmentation, throw, swelling, and diggability, can be achieved through this, see e.g., Vanbrabant & Escobar (2006). However, quantitative computational models that describe this phenomenon are lacking.

To address this issue, a research project has been initiated, as a joint effort between the industrial partners LKAB and Boliden Mineral AB, and Luleå University of Technology (through Swebrec — The Swedish Blasting Research Centre) and with primary funding from Vinnova (the Swedish Governmental Agency for Innovation Systems). The project was initiated to further investigate the hypothesis by Rossmanith (2002) and to develop better computational tools for simulation of blasting with electronic programmable delay (EPD) caps. The objective of this project is to: (i) achieve a better fragmentation, throw and other results from blast in quarries and mines, and (ii) study the extension of Rossmanith's concept to a three-dimensional geometry by identifying the rock volumes within a blast where the wave interaction from neighboring blast holes may create additional damage (and thus enhanced fragmentation) for varying detonation delay times. The first objective is industrial-oriented, whereas the second objective is more of scientific nature.

The project comprises nine (9) different tasks involving computer simulations of blast performance, coupled with full-scale field tests, and model scale tests. This paper presents some results from initial conceptual computer simulations of blasting with short delay times. Moreover, plans for validating field tests are discussed.

2 COMPUTER MODELING OF BLASTING

2.1 Modeling approach

Computer modeling of blast fragmentation is challenging. Firstly, it requires a representative material model, which is difficult to develop for a heterogeneous and sometimes discontinuous material such as rock. In addition, the material model should be able to replicate the rock response to large pressures (of the order of GPa) and subsequent damage to the rock including crushing and fracturing. Moreover, computer simulation requires a material model for the explosive agent. The numerical models must have a high resolution (discretization) to obtain an acceptable representation of the wave interaction and formation of fragments. These requirements are at front of (or even beyond) the current state-of-the-art in three-dimensional dynamic modeling.

The initial task of the research project was focused on investigating different approaches to model the blasting process. It was found that a suitable way forward was to apply the 3D finite-element code *LS-DYNA* (Hallquist, 2007) to this problem. *LS-DYNA* is a commercially available multi-purpose finite-element code, which is well suited to various types of dynamic modeling.

A methodology was developed to model blasting with short delay times, and to evaluate the possible effects on fragmentation. In the model, two different element formulations were being used — Euler formulation in, and close to, the blast hole, and Lagrange formulation in the rock volume farther from the blast. It should be noted, however, that only the first few milliseconds of the blast can be modeled using this approach, as large deformations will cause grid distortion after this. Thus, this approach only considers the fragmentation caused by stress waves and their possible interaction (and not the subsequent heave and throw of the blasted rock).

The rock material was simulated using the RHT (Riedel-Hiermaier-Thoma) material model. This model is used in applications where an accurate description of the dynamic strength is required for high strain rates and pressures, see also Riedel et al., 1999. The RHT model is particularly well suited for brittle materials subjected to dynamic loading, and has been implemented in *LS-DYNA*. The RHT model comprise a yield limit, a failure surface, and a residual failure surface, and with post-failure strain-hardening response. The possible effects from pre-existing discontinuities in the rock mass, as well as spatial variability of rock properties, were not considered in this study.

An algorithm to calculate possible fragmentation based on model interpretation was also developed. This algorithm was based on "tying together" areas with calculated damage (yielding) in the model, thus assuming that such volumes of damaged rock constitute a rock fragment.

Initially, a single blast hole model was developed as a test case in which modeling technique, boundary conditions and required model size was determined. This pilot study was followed by a conceptual model of two blast holes representing a typical bench blast. The borehole diameter, burden and spacing were equivalent to that used at the Aitik open pit mine in northern Sweden. The finite element model geometry is shown in Figure 1. In the portions of the model where a high level of fragmentation is expected, an element size of 50 x 50 x 50 mm was used. Farther away from the borehole, an element size of 100 x 100 x 100 mm was employed. All elements are of linear displacement 1-point interpolation (constant strain) type. The total number of elements for the model is around 20 million. The height of the explosive column is 11 m with a borehole diameter of 311 mm, and the point of ignition is 1 m above the bottom of the blast hole (note that holes are sub-drilled 1 m below the planned bench surface). Non-reflecting boundaries were used on all boundaries that border surrounding rock. The top and front boundary of the model was modeled as free surfaces, see Figure 2. The calculation time using a 8-core CPU was about 23 hours.

2.2 Input data and analyzed cases

Input data to the RHT material model was obtained through parameter identification using Westerly granite as the reference material (this is a rock material for which extensive test data exists that permit determining input data to the RHT model). Data from Haimson & Chang (2000) were used together with an optimization routine developed for *LS-DYNA* (Stander, et al., 2011). The full set of resulting model parameters are described in Schill (2011). For the gravel representing the stemming of the blast hole, a perfectly plastic, presssure-dependent material model was used, with parameter values described in Schill (2011).

For the explosives, a reference blasting agent (emulsion E682-b) was used for which the JWL equation of state parameters had been determined previously, see Hansson (2009). JWL refers to the Jones-Wilkins-Lee equation of state, which is perhaps the most common equation of state for hydrodynamic calculations of detonation product expansions (see e.g., Baudin & Serradeill, 2010).

The analyses were conducted as a parametric study in which ignition delay times, amount of explosive, and distance between the blast holes, were varied. The analyzed cases are described in Table 1. For the case with increased distance between the blast holes, the model size was increased to 29.2 (from 25.7) m.

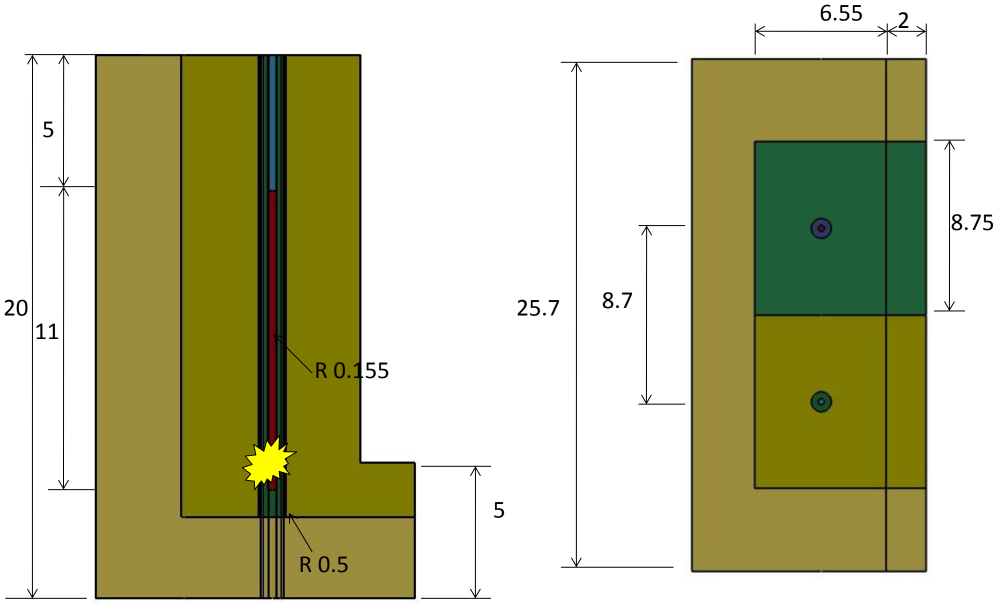

Figure 1. Geometry of the finite element model of two blast holes: vertical cross-section(left) and horizontal plan view (right).

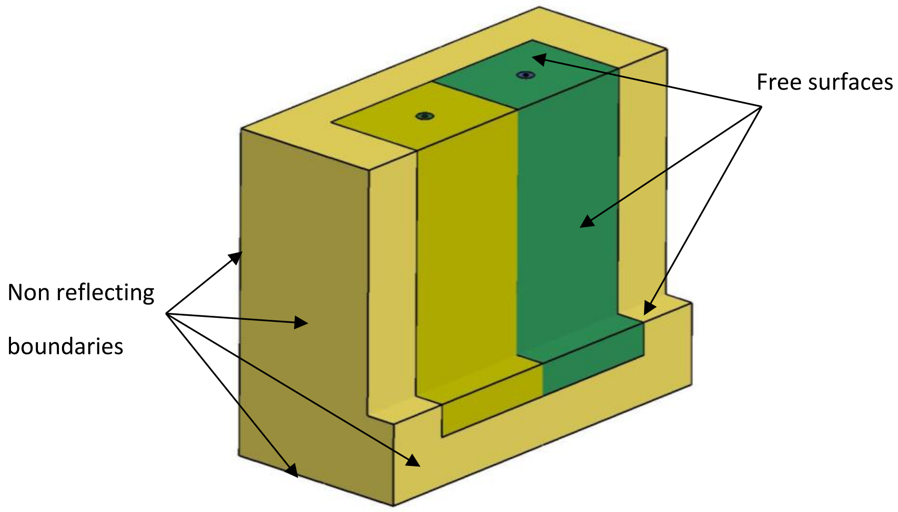

Figure 2. Boundary conditions for the finite element model using *LS-DYNA*.

Table 1. Analyzed cases.

Case no.	*Ignition time*		*Amount of explosive*		*Distance between blast holes*
	Hole 1	Hole 2	Hole 1	Hole 2	
1	0 ms	0 ms	11 m	11 m	8.7 m
2	0 ms	1.5 ms	11 m	11 m	8.7 m
3	0 ms	5 ms	11 m	11 m	8.7 m
4	0 ms	0 ms	11 m	11 m	12.3 m
5	0 ms	0 ms	8 m	8 m	8.7 m
6	0 ms	0 ms	8 m	11 m	8.7 m

2.3 Interpretation criterion

In order to evaluate the fragmentation it is necessary to be able to distinguish between cracked rock and undamaged rock. In this work, this was obtained by "canceling out" elements that are considered to be fully cracked and study the remaining rock material. This method provides a measure of the fragment size but it requires an identification routine where connected elements are identified and the corresponding volume (or area) is calculated. The drawback of the method is that it is mesh size dependent and due to the limited level of discretization, it is not possible to determine fragments less than 50x50x50 mm. Thus, fragments below this size are considered to be fully crushed material. In this project, a damage level of 60 % was chosen as the limit where the material is considered to be fully cracked/crushed. Since the main failure mode is tension damage, the damage will typically localize to one element. Thus, the chosen damage level does not have a significant influence on the fragmentation results.

The fragment identification procedure was only applied to two-dimensional interpretation sections through the model. By measuring the fragments in a number of vertical and horizontal cuts through the model, it was possible to evaluate the fragment size. The output from the fragment size identification routine is the number of identified fragments and the size of each fragment. By comparing the initial (undamaged) area with the total area of the fragments it is possible to get a measure of the total rock area that is identified as fully crushed i.e., fragments with a cross section area less than 0.0025 m^2. The relative area of each fragment is added to the accumulated area in order to get an accumulated area plot.

Using this method it is then possible to study the accumulated area for different fragment sizes and compare the fragmentation between different cuts and simulations. The accumulated area plot should resemble the mass passing plot ("sieve curve") which is commonly used in fragmentation analysis. The procedure is summarized in Figure 3.

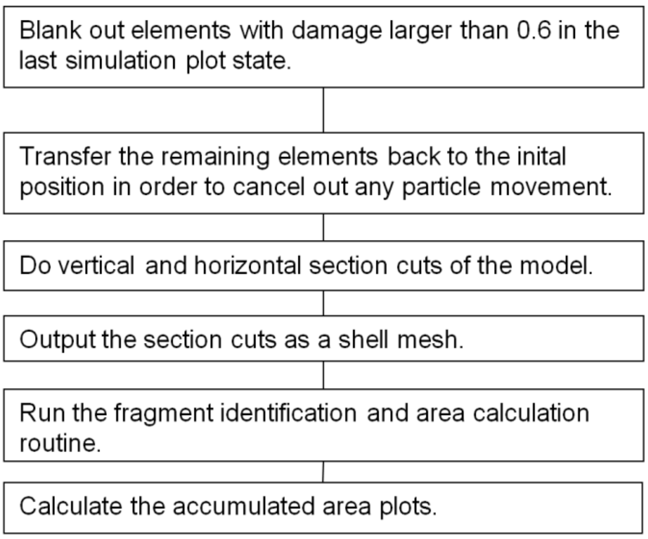

Figure 3. Procedure for fragment size calculation.

3 MODELING RESULTS

3.1 Model evaluation

The modeling results from the model with two blast holes were interpreted with respect to possible fragmentation. The results were evaluated for a set of evaluation cuts in horizontal and vertical direction, as shown in Figure 4. The vertical cuts are clustered symmetrically around borehole 1 (V1 and V2), the symmetry line (V3, V4, and V5), and borehole 2 (V6 and V7). Horizontal cuts are presented for qualitative purpose only, thus these are not used for the accumulated area plots since they for certain cuts contains too few rock fragments (a smaller element size may be needed to remedy this). Also, only the parts with high density mesh (50 mm element size) are used for the accumulated area plots. All simulations are run to 15 ms. By that time the first pressure wave has by far passed the model and the rock has started to expand. Typically, after 15 ms, the tension wave cracking is finished and elements start to get very distorted due to particle movement.

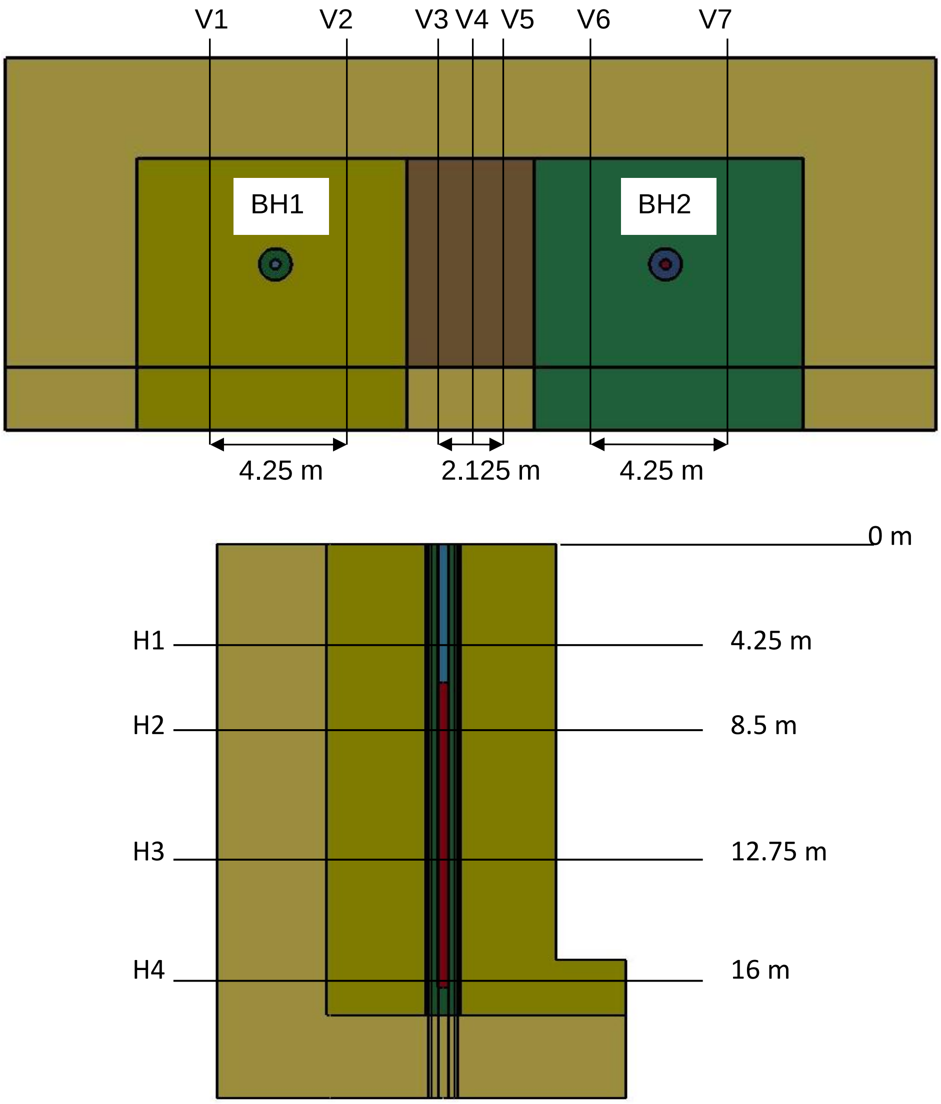

Figure 4. Vertical (top) and horizontal (bottom) evaluation cuts used for results presentation.

3.2 Case no. 1: 0 ms delay time, 11 m explosive, 8.7 m spacing

The first analyzed case served as a benchmark for the evaluation of the parametric study. With 0 ms delay time (same ignition time for both blast holes), the stress waves will meet at the symmetry line (cut V4 in Figure 4) between the holes. The model also produced symmetrical results with respect to crack pattern and pressure distribution, see Figure 5. The resulting fragmentation pattern is shown in Figure 6 for two selected evaluation cuts, and the accumulated area plot for the vertical cuts is presented in Figure 7.

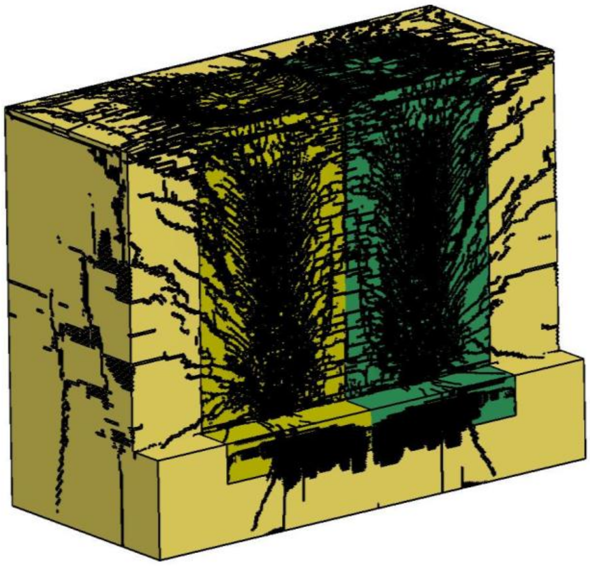

Figure 5. Crack pattern for Case no. 1.

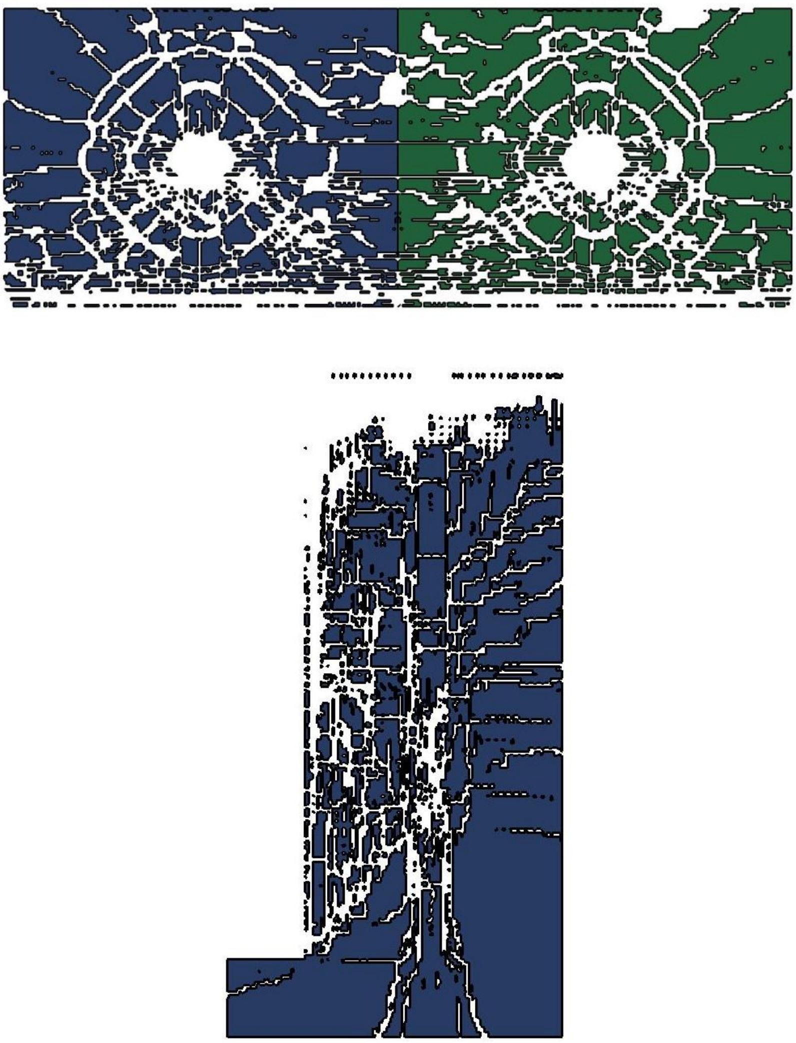

Figure 6. Fragmentation pattern for horizontal cut H1 (top) and vertical cut V4 (bottom); see Figure 4 for location of evaluation cuts. White areas re considered to be fully crushed (damage level > 60 % and thus a fragment size less than 50 x 50 mm).

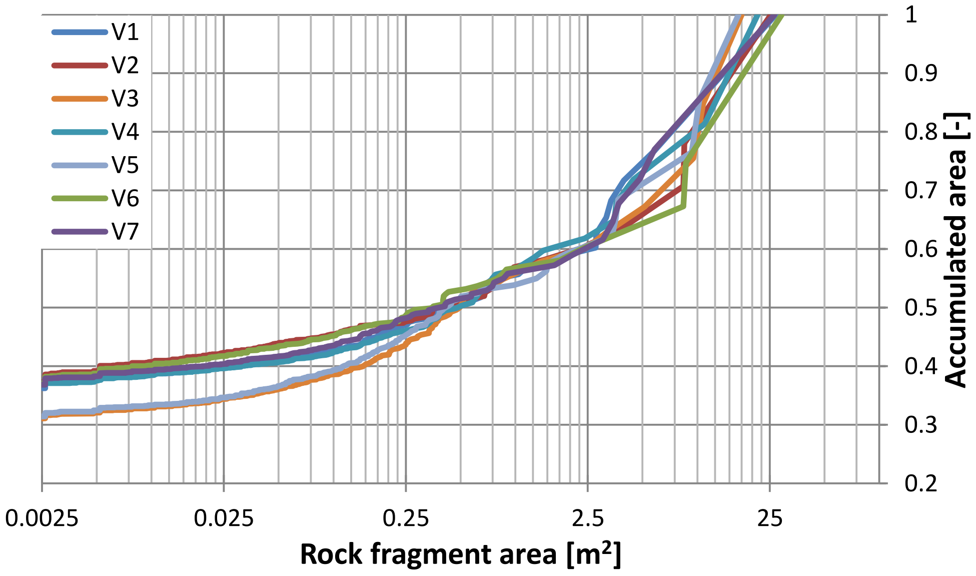

Figure 7. Accumulated area plot for Case no. 1.

The results show that fragmentation is indeed symmetric (as expected). Furthermore, the fragmentation is higher closer to the boreholes (cuts V1, V2, V6, V7) and at the symmetry line (cut V4), whereas fragmentation is lower for cuts V3 and V5. This was also as expected, since the maximum stress wave interaction should occur at the symmetry line.

3.3 Parametric study: ignition time delay, amount of explosive, and hole spacing

An increase in delay time between the blast holes was simulated in Case nos. 2 and 3 (cf. Table 1). The 1.5 ms delay (Case no. 2) corresponds to ignition in the second blast hole when the stress wave from the first blast hole have reached the second hole. For the longer delay time (5 ms), no stress wave interaction should result (in theory). In Case no. 4, a larger hole spacing was simulated and in Cases nos. 5 and 6, the amount of explosives in the blast hole was decreased (from 11 to 8 m charge length). Theoretically, it should be possible to decrease the amount of explosives and still achieve a good fragmentation, through the effect of stress wave interaction.

The parametric study showed that the results depended on all the varied parameters, but to different degrees. If the ignition times are delayed, the fragmentation became more scattered (larger difference between the different evaluation cuts). The results also indicated a strong relation to the distance from the explosive charge where the highest level of fragmentation was usually found closest to the blast hole. In many (but not all) cases, a higher level of fragmentation was found where the stress waves interact. However, the increase in fragmentation is local, i.e., localized to a thin vertical cut. Taking Case no. 4 as an example (larger hole spacing), the fragmentation decreased with increasing distance from the blast holes, with the exception of at the symmetry line (cut V4). At the symmetry line (despite being farthest away from both blast holes), a higher fragmentation was found compared to neighboring evaluation cuts — which can be interpreted as an effect of stress wave interaction.

Interestingly, the effect of delay times was for many cases found to be less than that caused by the other factors (amount of explosives and hole spacing). An example is shown in Figure 8 for the evaluation cut along the symmetry plane (V4) in the model (cf. Figure 4). If the interacting stress wave had a major influence on the results this would be indicated in this Figure, but it can instead be concluded that the other factors have a much higher influence. In fact, if the ignition times are delayed, a higher level of fragmentation is found for this evaluation cut with the highest for the 5 ms delay case. Comparing the results from the other evaluation cuts, the general trend is that an increase in delay time does not result in poorer fragmentation. Moreover, the lowest fragmentation is found for the case with increased spacing between the blast holes, see also Figure 9.

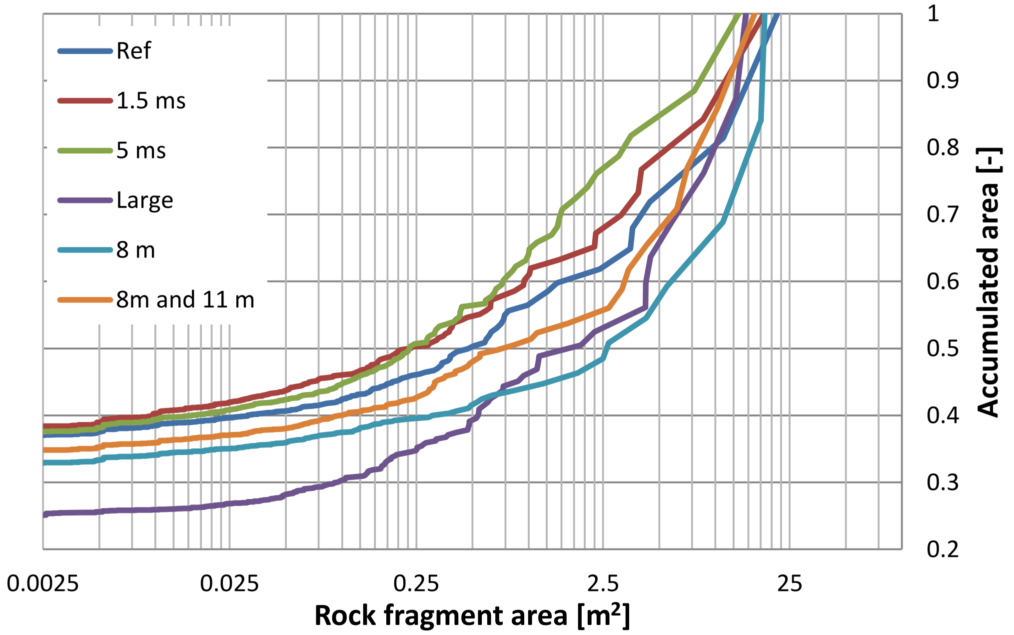

Figure 8. Accumulated area plot for vertical cut V4 (at the symmetry line) for all simulated cases.

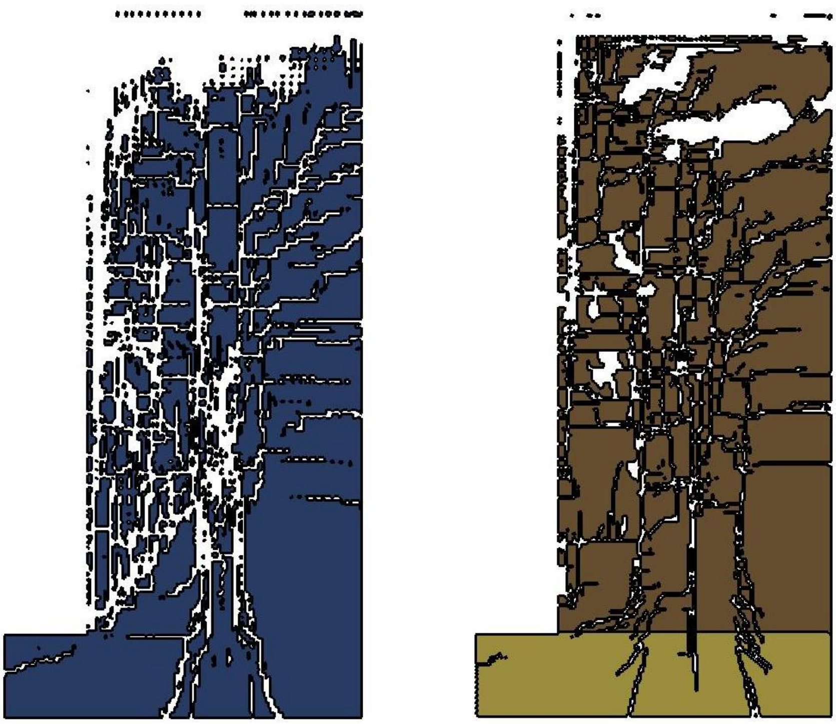

Figure 9. Fragmentation pattern for vertical cut V4 (see Figure 4 for location of evaluation cuts) and Case 1: 8.7 m hole spacing (left) and Case 4: 12.3 m hole spacing (right). White areas are considered to be fully crushed (damage level > 60 % and thus a fragment size less than 50 x 50 mm).

4 CONTINUED WORK

4.1 Simulation of model scale tests

Laboratory model tests of unconfined and confined blasting have previously been carried out and reported by Johansson (2011). In these tests, the hypothesis by Rossmanith (2002) was investigated by testing different delay times and, subsequent to blasting, sieving all blasted material to determine actual fragmentation.

These tests present an excellent opportunity for model simulation and validation. Numerical simulations of the model scale tests, using the methodology developed, will thus be performed to further validate the numerical modeling methodology. To assist with this work, a "mini-cluster" for handling the calculation has been installed at Luleå University of Technology. The "mini-cluster" comprises a computational server with 24 CPU cores and 192 GB RAM, and a file server for evaluation (comprising 12 CPU cores and 96 GB RAM and a total storage capacity of around 8 TB). The cluster has been optimized for use with *LS-DYNA*.

4.2 Field tests

Some trials using EPD caps have been attempted by both Boliden Mineral AB (in open pit mining) and LKAB (in underground sublevel caving). However, a more comprehensive and controlled test has not been performed. Plans are now underway for a full-scale field test at the Aitik open pit mine (by Boliden Mineral AB). Initial blasting tests have been conducted during the fall of 2011 to determine blast wave characteristics, VOD, and other basic parameters.

A detailed test plan is being developed including a monitoring plan to follow-up fragmentation, swell, diggability, as well as energy consumption and throughput of the mill (as a secondary index of achieved fragmentation). A bench blast with electronic detonators used in half of the blast, and normal detonators for the other half is planned, to provide relevant comparisons. Fragmentation is difficult to measure in a representative and reliable way, as evidenced by previous work at Aitik (Ouchterlony et al., 2010). New systems (based on improved image processing on each bucket loaded) emerging on the market will be tested as part of this work. Comparative analyses with previously used systems (for fragmentation analysis) will also be conducted.

4.3 Full-scale simulation

Following the field tests described above, a full-scale model simulation (and possible validation) will be attempted. Using the methodology for computer simulations described previously in this appear, a sub-set of a full bench blast in the Aitik mine will be modeled. This will allow further calibration of the numerical model by comparison to field data obtained. This work will focus on optimizing delay times in open pit blasts, with particular application to the Aitik mine.

LKAB have used electronic detonators in previous field trials in underground sublevel cave mining. These results will be used for validation in the current project. Field tests aimed at identifying the impact of confined blasting conditions (through the caved waste rock) in sublevel caving are currently being performed. The final task of the project will thus involve numerical simulation of blasting in underground sublevel caving to better optimize delay times also for this application.

5 DISCUSSION AND CONCLUSIONS

The present project is still on-going and additional results are expected in the year to come. The computer simulations conducted so far have produced some intriguing results, but additional work is required to move from a conceptual stage to linking results to actual field data. Thus, the planned field tests at the Aitik open pit mine are essential to be able to improve the modeling methodology. Nevertheless, the results so far are very promising and provide a new level of quantification of the theory by Rossmanith (2002) regarding fragmentation through stress wave interaction. Judging from the results, it may be stated that the problem is more complex than described by Rossmanith. The fact that fragmentation increased for longer delay times contradict the previous theory. The cause of this is not yet known, and need further study. Based on the presented results, the following conclusions may be drawn:

- The developed methodology for computer simulation of blasting with short (or no) delay times proved to be functional, and even very large (20 million elements or more) models can be run using *LS-DYNA*.
- The algorithm for evaluation of fragmentation provides a tool for comparing modeling results with respect to expected fragmentation.
- There is a small effect of interacting stress waves, but the effect is local and a significantly improved fragmentation cannot be expected due to this phenomenon.
- The largest effect on the fragmentation was found for varying hole spacing and the amount of explosives in the blast holes.
- The highest amount of fragmentation was found for a relatively long delay time for which the primary stress wave is expected to have passed the second blast hole, which is contrary to expectations at the outset of this study.

Continued computer modeling should be undertaken and the existing conceptual model can be used for this. The following additional work is suggested:

- Simulating even longer delay times between initiation (longer simulation times may result in mesh distortion, which must be handled appropriately).
- Vary blast hole spacing and delay times (combined effect).
- Study more evaluation cuts (closer spaced) to verify how local the stress interaction effect is.
- Conduct a parametric study with respect to material properties for the RHT model.

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