Finite Element simulations of blasting and fragmentation with precise initiation

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Abstract

By using blasting caps with electronic delay units, it is possible to control the time of ignition between the boreholes of a mine. This has opened up new possibilities to optimize the blasting in order to achieve a better fragmentation which would significantly reduce the costs for the mining industry. The potential benefits of being able to control the ignition times has been described by Rossmanith [1], where stress wave interaction should according to theory and experience result in higher fragmentation, throw, swelling and digability. This theory has in this work been tested through Finite Element simulations using the LS-DYNA software. The rock material used is Westerly granite, which has been modeled with the RHT material model and it uses damage mechanics to describe the fracture of the rock. Also, a 2D-fragmentation evaluation routine has been proposed that makes it possible to study the level of fragmentation in section cuts of the Finite Element model.
A 3D FE-model of two boreholes was used to evaluate the influence from ignition times, borehole distance and the amount of explosives. The results show that there indeed is a stress wave interaction effect and in this region there is an increase in fragmentation. However, the zone with increased fragmentation is considered to be small. The main effect on the fragmentation comes from the distance to the explosive charge and the amount of explosives.

Introduction

In an open pit mine, the rock is separated from the rock face by blasting. The blasting is done by drilling several boreholes with certain spacing and filling these with explosive emulsion. The explosives are then ignited by blasting caps. The blasted rock is fragmented and depending on the size of the boulders, the rock has to be further processed by crushing and grinding. Thus, if the fragmentation is improved this would yield easier handling, lower energy cost, faster material flow and improved metal recovery. Until recently, it has not been possible to precisely control the ignition times of the blasting caps. However, by using blasting caps with electronic delay units it is possible to control the delay times down to 1 ms. By this a new spectra of possibilities is emerging where it is possible to optimize e.g. the positioning of the boreholes and amount of explosives. This was identified by Rossmanith [1] who presented a hypothesis that states that the rock fragmentation would be improved in areas between the boreholes where tensile stress waves meet, overlap and interact. The theory was confirmed in full scale tests by Vanbrant and Espinosa [2] who claims that an improvement of average fragmentation by 50 % was possible by using overlapping tensile waves. Chiapinetta [3] also states that an improved fragmentation is possible and the ignition delay should be set before the stress wave of the preceding borehole reaches the next borehole. However, when extending the theory to 3D, Blair [4] showed that the stress wave interaction would be limited and localized since the stress waves are never similar in shape.

The relevance of the Rossmanith theory is studied in this work by the use of 3D Finite Element simulations. The work is performed as a parametric study where effect from ignition delay time, distance between the boreholes and amount of explosives on the level of fragmentation is studied. Due to the size and necessary level of discretizations, the model is limited to two boreholes. The RHT model, Riedel et al. [5], is used to describe the rock material behavior and failure. In order to evaluate fragmentation, a 2D fragmentation identification algorithm is proposed.

The work is performed within the Vinnova research project “Improved blasting results with precise Initiation”.

Model

The model is built to resemble the Aitik open pit mine in Sweden in terms of borehole spacing and depth, see Figure 1. A one borehole model was used to determine a suitable size and modeling technique.

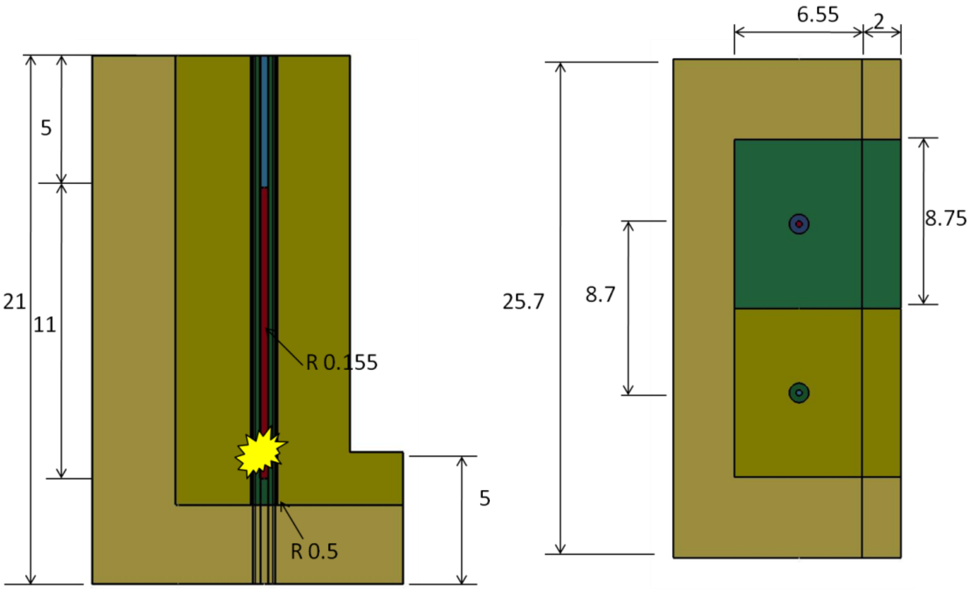

Figure 1: Geometry of the two borehole model: vertical cross section (left) and horizontal plan view (right).

In Figure 1, the explosives (red) and is 11 m high and the upper part of the borehole is filled with gravel (blue). The explosives, the gravel and elements surrounding the blasthole have been modeled with Eulerian elements to accommodate for the large displacements in that region. In order to simulate an infinite domain, non reflecting boundaries have been used, see Figure 2. Still it is only possible to simulate the first 15-20 ms of the blast with this approach due to distorted elements. However, the stress waves have passed through the model and the only kinematics left is the particle movement.

The FE dicretization is performed using hexahedron elements only. In the parts where a high level of fragmentation is expected, an element size of 50x50x50 mm is used. Farther from the boreholes, the element size is increased using transition elements to 100x 100x100 mm. The total model size is 20 million hexahedron elements. In the case of increased borehole distance, the number of elements is 24.5 million.

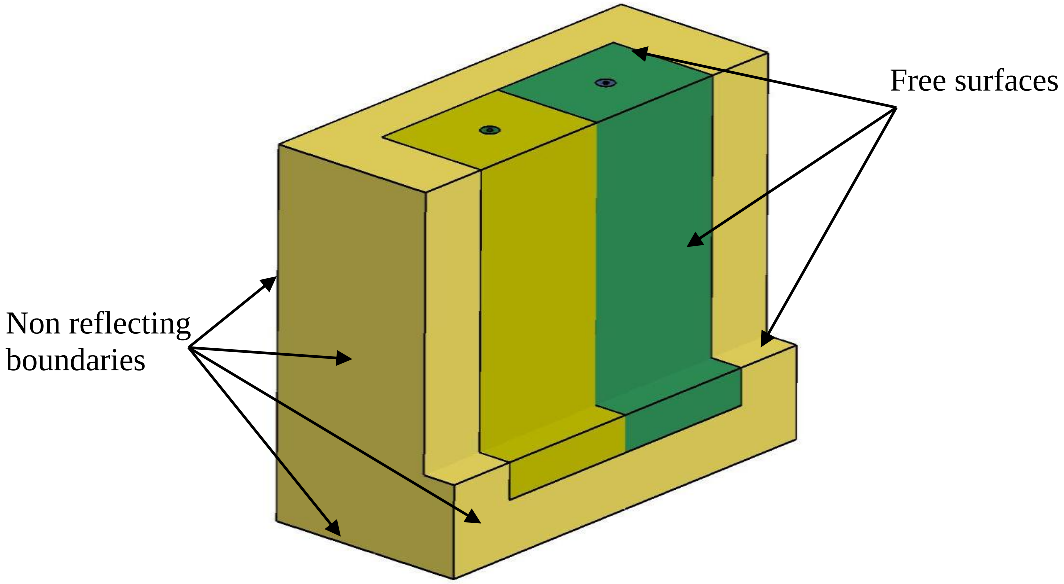

Figure 2: Non-reflecting and free surfaces

Material

The rock material chosen is Westerly granite which is a well documented type of rock. It is modeled using the RHT material model, see Riedel et al. [5]. For further reference on the implementation in LS-DYNA, see Borrvall et al. [6]. The material was calibrated using triaxial compressive tests in 3 principal directions from Haimson et al. [7] using an optimization routine in LS-OPT, see Stander et al. [8]. The uniaxial compression strength, shear strength and uniaxial tensile strength were set to 200 MPa, 36 MPa and 10 MPa respectively. Further, no pore crush or strain rate dependency were used. The result from the parameter identification is presented in Figure 3. The explosives (Emulsion E682-b) are modeled using a JWL equation of state with parameters from Hansson [9]. The gravel was modeled using *MAT_SOIL_CONCRETE which also was used for the granite part with Eulerian spatial description.

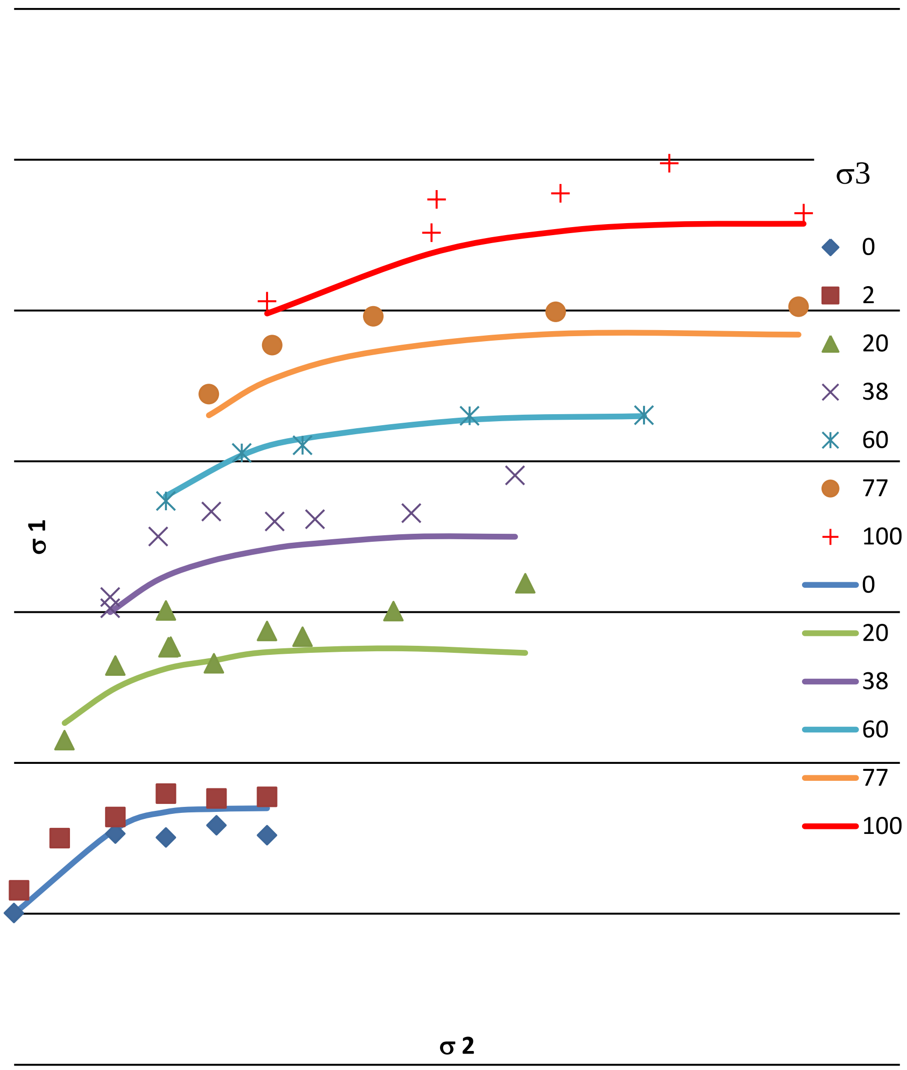

Figure 3: Experimental (points) and simulated (solid) compression strength for Westerly granite.

Fragmentation evaluation

The main result when evaluating fragmentation is the rock size distribution. Thus, only looking at the damage level in the material is not enough since a connection between the boulder volume and the damage has to be done which is not an easy task. Also, since the main failure mode is tensile, the damage will typically localize to one element. Instead a fragment identification procedure was developed where material with excessive damage is removed and considered to be gravel. The remaining elements are subjected to the identification procedure that searches the model and looks for elements which are still connected and identifying these as boulders. This is not an easy task in 3D, but it is fairly straightforward in 2D and a routine was implemented in LS-PREPOST. To accommodate for not being able to evaluate the complete volume, a number of 2D cuts are made both horizontal and vertical. One issue needed to be addressed was the presence of “brigde” elements that occurred when the damaged rock had been removed, see Figure 4.

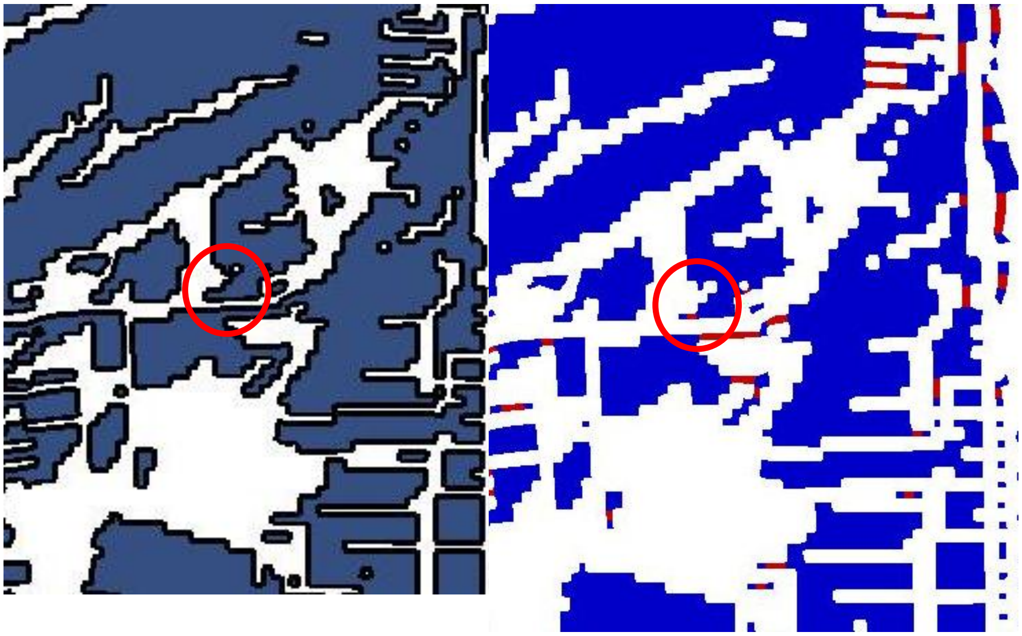

Figure 4: Bridge elements (left) are cancelled out in the fragment identification procedure (right)

The “bridge” elements are a single row of elements that connect two boulders and yields one very large boulder. If an element has two opposing sides which are free, these are identified as a bridge element and cancelled out. The routine output is a number of identified boulders and the corresponding areas. Due to the discretization, boulders with area less than 0.0025 m^2 (50x50 mm) cannot be identified and are considered to be gravel. The relative area of each boulder is added to get an accumulated area plot, see Figure 5. The accumulated area plot is constructed to resemble a mass passing (or “sieve curves”) which are commonly used in the blasting community to evaluate fragmentation. In the accumulated area plot, every curve represents a section cut. If the curve is higher and to the left (green curve in Figure 5), a higher level of fragmentation is identified in that cut.

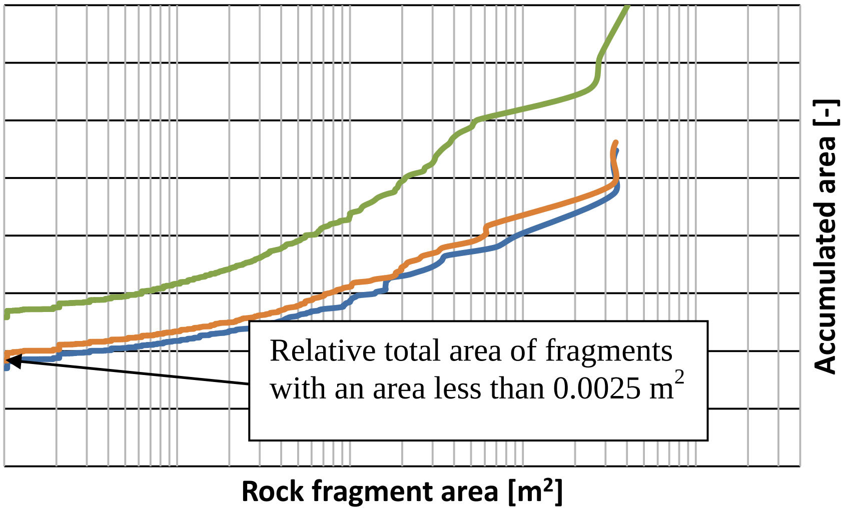

Figure 5: Accumulated area plot

Results

The work is done as a parametric study where the effect of the ignition delay, the borehole distance and the amount of explosives are studied, see Table 1. A simulation with simultaneous ignition, and borehole distance and amount of explosives which resembles the Aitik mine is used as reference case (simulation 1 in Table 1). The results will be presented using the nomenclature found in Figure 6. The vertical cuts V1, V2 and V6, V7 are symmetrically positioned around the respective boreholes while V3 and V5 are symmetric around cut V4 which is always on the symmetry line. All results and area plots are evaluated at 15 ms. By then, the tension waves has left the model and the elements are getting distorted due to particle movement.

#	Ignition time		Amount of explosives		Distance between boreholes
	BH1	BH2	BH1	BH2	
1	0 ms	0 ms	11 m	11m	8.7 m
2	0 ms	1.5 ms	11 m	11m	8.7 m
3	0 ms	5 ms	11 m	11m	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

Table 1: Description of simulations.

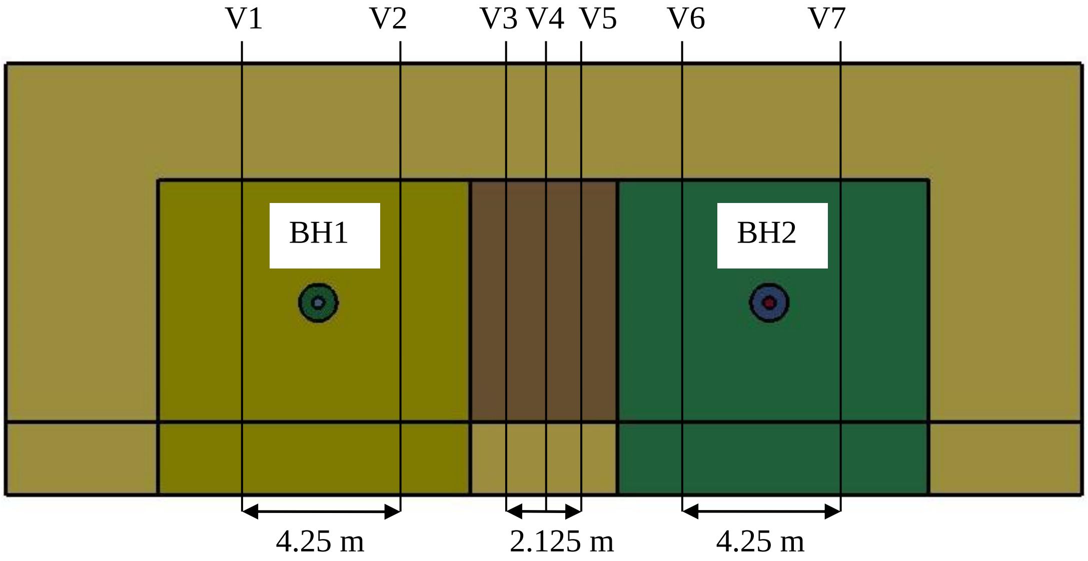

Figure 6: Vertical cuts used in the results presentation, borehole 1 (BH1) is located to the left and borehole 2 (BH2) to the right.

Figure 7 presents the overall crack pattern for the reference model and Figure 8 presents a horizontal cut just above the explosives. It appears that the results are symmetric. Also, the fragmentation is high around the boreholes. At the symmetry line, see Figure 9, there is an effect of an interacting stress wave at the top of the model. This is also confirmed by the accumulated area plot, see Figure 10. However, the fragmentation is considerably lower in the cuts surrounding the symmetry line indicating that the effect is fairly local.

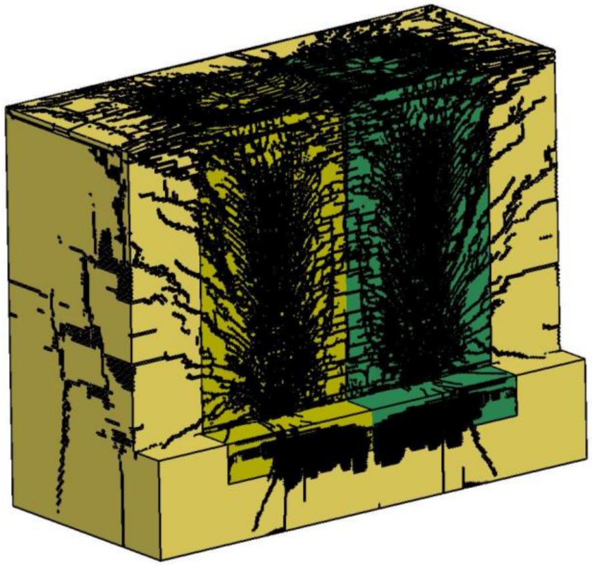

Figure 7: Overall crack pattern for reference model

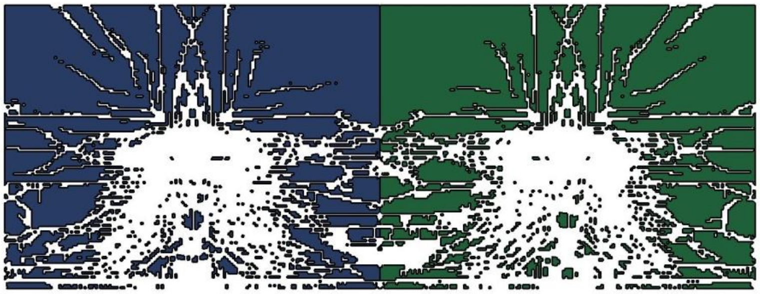

Figure 8: Horisontal cut of fragmented region

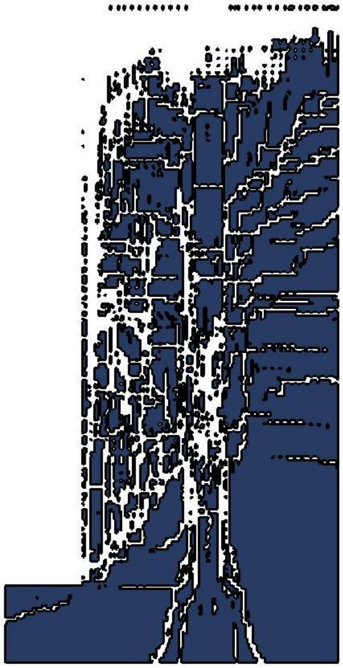

Figure 9: Vertical cut at symmetry line (V4) of reference model

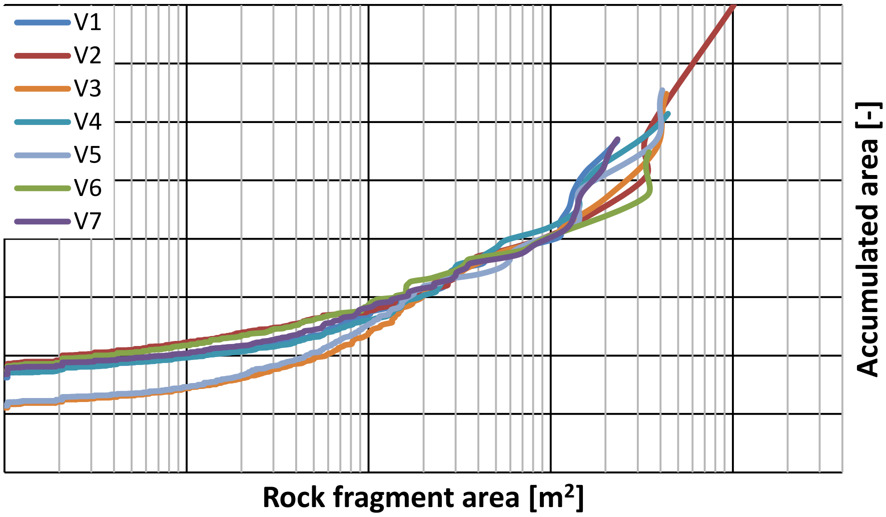

Figure 10: Accumulated area plot for reference model

The symmetry cut (V4) is the most interesting cut since it is where it is certain that the primary stress waves meet and interact in the reference case. If the accumulated area plot is studied for this cut, a number of interesting results is found, see Figure 11. Firstly, when comparing delayed ignition times it is evident that the fragmentation is not higher in the case of stress wave interaction (reference case). In fact, a delayed ignition time yields the same or a higher fragmentation. Secondly, the increased borehole distance and the decreased amount of explosives shows a much higher influence in the level of fragmentation.

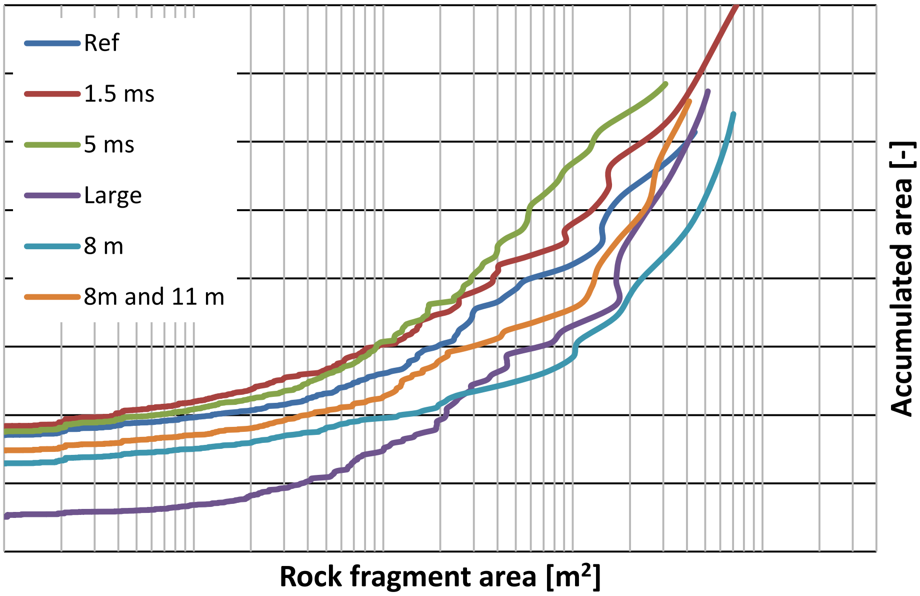

Figure 11: Accumulated area plot at symmetry cut (V4).

Looking at cut V6, which is closer to the second borehole, it is evident that simultaneous ignition does not yield a higher level of fragmentation. Again, 5 ms delay is found to yield higher fragmentation, see Figure 13 . The reference, increased borehole distance and unsymmetrical charge (8 and 11 m explosives) case more or less shows identical accumulated area curves. This is due to the fact that for this cut, the conditions regarding delay time and distance to the 11 m explosives borehole is the same for all three cases.

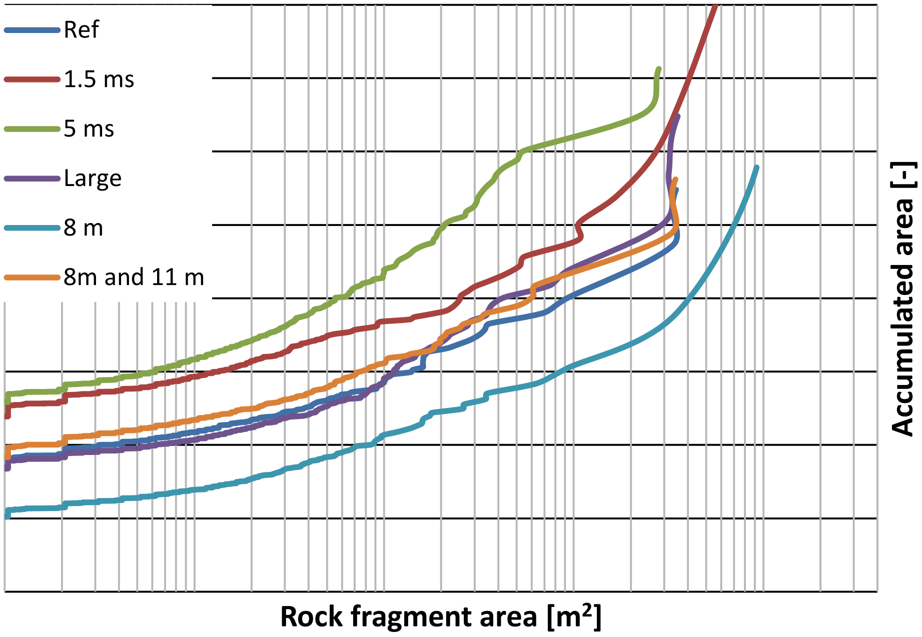

Figure 12: Accumulated area plot for cut V6.

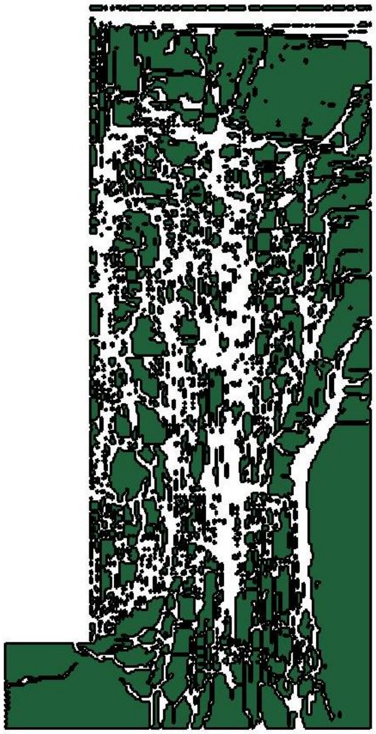

Figure 13: Verical cut V6 for the 5 ms delay time case.

Conclusion

Based on the simulations it can be concluded that:

i) There is an influence from interacting stress waves on the level of fragmentation. The interaction is found at the symmetry plane between the boreholes for a simultaneous ignition case. However, the effect is considered to be local.
ii) The studied parameters show influence on the fragmentation level. The highest influence is found from the distance between the boreholes and the amount of explosives.
iii) Looking at the ignition delay times, the highest effect was found for relatively high delay times. Thus, the primary stress wave has already passed the subsequent borehole when it is ignited.

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