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Advanced blasting in jointed and faulted rock

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With 6 Figures

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Summary: Employing the method of Lagrange diagrams in conjunction with fracture mechanics and elastic wave propagation the author will show how to calculate the delay time for precise initiation blasting in jointed and faulted rock. Open pit mine blast design will be considered in detail. In addition, the effect of short delay time initiation on fragmentation enhancement as well as vibration control will be discussed. A very convenient and illustrative method to present the dynamic behaviour associated with wave and crack propagation is to use the so-called **Lagrange diagram**. It is a very simple but extremely powerful method.

1. Characterization of stress waves and cracks

In a solid various types of waves can propagate: body waves and surface waves (P-wave: longitudinal or primary wave/pulse, S-wave: shear or secondary wave/pulse). These two waves/pulses are of importance in blasting and a full understanding is required for short time delay calculations as well as optimization of fragmentation. A stress wave is the propagation of a disturbance in space and travels in time. Hence, one can describe the stress wave in two ways, either in space or in time. Figure 1 shows the propagation of a P-wave, a S-wave and a crack (C). An arbitrary stress wave of pulse type with finite pulse length and finite duration is shown in Figure 2. One of the important parameters in the new Advanced Blasting Technology is the pulse length or pulse duration.

Consider two adjacent blast holes, shown in Figure 3, which are separated by the spacing s. In the following the wave/pulse interaction between the blastholes will be studied in the light of fragmentation improvement.

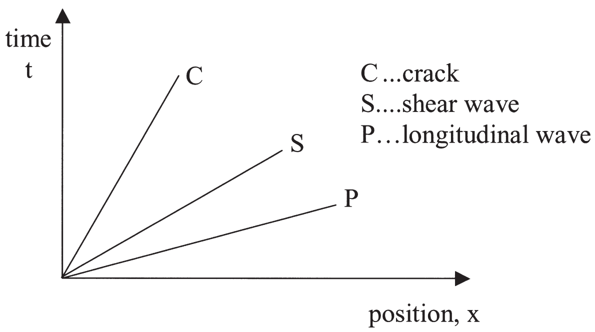

Fig. 1: Lagrange diagram representing the one-dimensional propagation of longitudinal (P) wave, shear (S)-wave and a crack (C)

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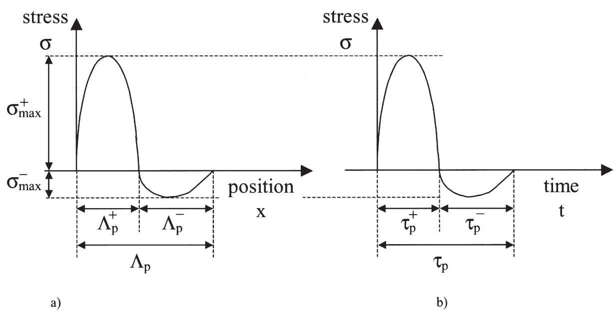

Fig. 2: Representation of a one-dimensional stress wave/pulse in the space domain and b) time domain.

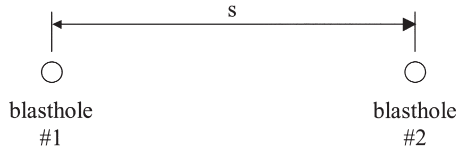

Fig. 3: Geometrical configuration of two adjacent blastholes The various regions of overlap of stress waves are given in Figure 4. The superposition of various waves causes the crushing of the material.

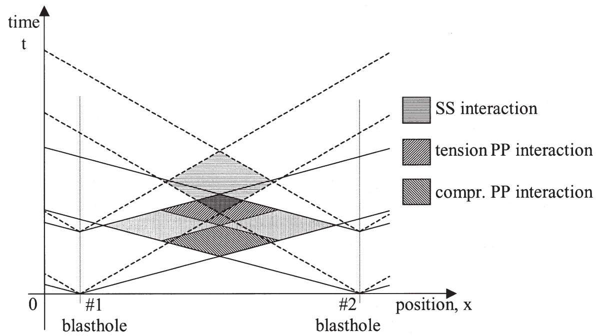

Fig. 4: Identification of overlapping interaction regimes for medium length P-wave and S-wave pulses.

The preceding equations can also be used to investigate the interaction between any type of stress wave that radiates from a blast-hole and a crack which emerges from an adjacent blast-hole. Denote the crack speed with cc and the crack extension with r_c. In the Lagrange diagram a crack shows up with one line only. However, it will normally take some small but finite time interval to incubate and initiate the crack. In the Lagrange diagram in Figure 5 this is expressed by a small delay Dc. The ensuing crack movement can be rather complex and is best discussed on the basis of the rack path drawn in Figure 5.

When the blast-hole #1 detonates P- and S-waves propagate into the material and a set of borehole cracks emerge from the blasthole. These cracks are initiated due to excessive tangential strain along the borehole wall and once the cracks are born, they draw energy from the stress waves and from the gas pressurisation of the blasthole. The cracks propagate at a speed lower than 1/6 of the P-wave speed. Hence, the stress waves quickly outdistance the cracks and the cracks draw their energy from the gas energy.

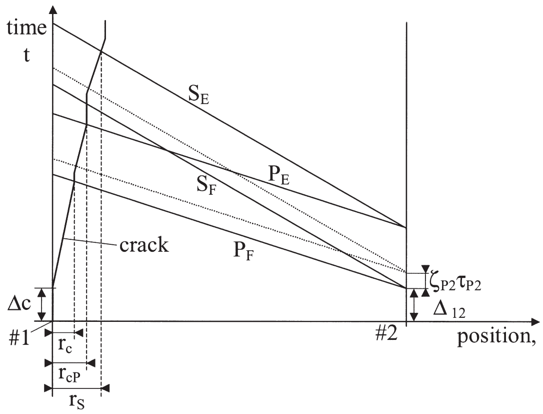

Fig. 5: Formation of blasthole cracks and their interaction with P-wave and S-wave from blasthole #2

The detonation gas pressure expands the volume of the blasthole and the formation of a large number of borehole cracks increases the volume taken by the gas considerably. Hence, the gas pressure drops and eventually the stress intensity factor at the crack tips is smaller than a critical value, and the cracks arrest. This occurs at a radius r_c.

When the P-wave interacts with the (possibly already arrested) cracks, these cracks can reinitiate and extend their lengths or at least improve the fragmentation pattern. Suppose that this fragmentation pattern is contained in a circle of radius rP. When the P-wave has passed the extended cracks have again arrested because no energy is available anymore. When the usually powerful S-wave hits the tips of these cracks they may reinitiate a second time and extend the fragmentation pattern which will finally be included in a circle of radius r_S. It should be noticed, though, that this interaction pattern is not axial-symmetric because the incident stress waves which, in a real 3D situation have a non-planar conical wave front, hit a cylindrical system of borehole cracks from one side only. Hence, the resulting fracture or fragmentation pattern is highly dependent on the direction of incidence of the stress waves.

From Figure 5 the position and time of interaction with a delayed P- or S-wave can easily be determined. However, several scenarios can be distinguished, whether or not the crack has arrested before the first wave interaction occurs or it is still propagating. Figure 5 can easily be extended to include propagating cracks.

2. Optimisation of fragmentation between two blastholes

In the following the Advanced Blasting Technology will be applied to the topic of optimal fragmentation blasting. Obviously, an optimal fragmentation pattern is achieved if the chain of ensuing operations of loading, hauling, crushing, grinding etc yield a better output.

Optimal fragmentation requires the formation of a uniform fragmentation pattern around and between the blastholes during blasting. If the delay time between the blastholes in a row and between the rows is selected appropriately, the result will be close to uniform with a narrow band distribution of fragments. Non-ideal delay timing will result in an increased number of large bolders left for secondary fragmentation.

Optimisation of fragmentation in a general blast pattern design is not a trivial matter and requires the study of the interaction of more than just two adjacent blastholes. In fact, any additional blast will spread out stress waves which are going to interact with the

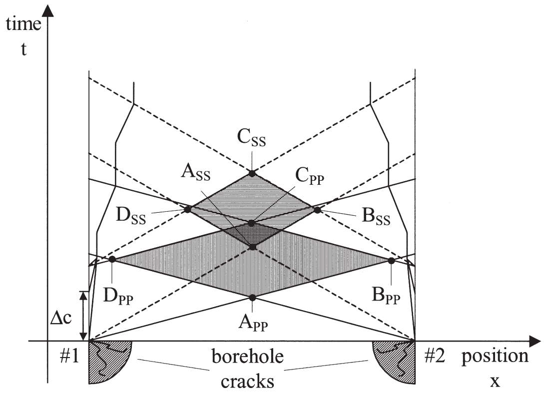

Fig. 6: Formation of fragmentation and regions of interaction of P-waves, S-waves and blasthole crack extension for simultaneous detonation of two adjacent explosive charges.

entire volume of the rock involved in the blast operation, i.e. the volume of rock already blasted and the volume of rock still to be blasted. The general problem is fairly complicated because of the non-commutativity of the creation of fragmentation in blasting. This will be detailed in a later section.

Despite of the complexity of the fragmentation problem, it can be reduced to a number of basic problems: (a) the (simultaneous or delayed) interaction of two adjacent blastholes, (b) the (simultaneous or delayed) interaction of three adjacent blastholes arranged in a triangular pattern, and (c) the (simultaneous or delayed) interaction of four or five adjacent blastholes forming a centered square (cage).

Figure 6 features the formation of fragmentation between two adjacent blastholes. Uniform fragmentation is achieved if the fragmentation pattern around the blasthole and the wave interaction pattern completely cover the entire volume between the blastholes.

Numerous experimental laboratory studies performed during the 70's and 80's at several universities, predominantly at the University of Maryland and at Vienna University of Technology, have identified tensile fracturing and crushing as the main mechanisms of blast-wave induced rock fragmentation.

In practice crushing and tensile fracturing will not occur immediately when the wave fronts intersect but delayed when appropriate sub-fronts interact. Hence, the aforementioned regimes must be redefined in terms of sub-fronts and ends. This revision of regimes may seem to be of minor importance, but becomes increasingly important with increasing wave length! For very long waves these regimes may overlap and the stress field becomes fairly involved due to multiple superposition.

If the detonation of the second blasthole is delayed, the various regimes discussed above move closer to the delayed blasthole. Hence, delayed detonation is a means to control the fragmentation pattern. On the other hand, if the stress waves become longer the regimes overlap and the potential for enhanced fragmentation increases. Long stress wave pulses are obtained by using explosives that which are characterised by a lower velocity of detonation and a larger volume of gas produced.

Further generalisations of the method of Lagrange diagrams to include the effect of jointing and faulting will be explained and demonstrated in the presentation.