Modelling explosive/rock interaction during presplitting using ALE computational methods*

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This is a sampling of the papers presented at the conference, the proceedings can be bought from the SAIMM

Synopsis

Arbitrary Lagrangian Eulerian (ALE) computational techniques allow treatment of gases, liquids and solids in the same simulation. ALE methods include the ability to treat shock waves in gases, liquids and solids and the interaction of shock waves with each other and with media from one of the other categories. ALE codes can also treat explosive detonation and the expansion of the explosive gases and their interaction with air and solids. ALEGRA is a 3-D ALE code that has been developed at Sandia National Laboratories over the past few years. ALEGRA has been applied to a 2-D simulation of presplitting using decoupled explosives in rock blasting with very interesting results. The detonation of the explosive at the bottom of the hole sends a shock wave up the borehole driven by the explosive gas expanding into air. The explosive gas compresses the air against the stemming column where it rebounds and recompresses at the bottom of the borehole. This type of ringing takes several cycles to damp out. The explosively induced expansion of the borehole is also treated by ALEGRA as well as the shock wave imparted to the rock. The presentation of this paper will include several computer animations to aid in understanding this complex phenomenon.

Introduction

The concept of air-decking is a relatively old technique, dating to 1880s. However, it has only been since the 1980s that it has gained widespread acceptance for use in presplitting (Hopler[1998]). While air-decking seems to show promise for improving the efficiency of explosives, the mechanism by which this is accomplished is not well understood. There has been some research conducted that investigates the use of air-decking, but it has been somewhat limited in scope and has tended to be more empirical and production-oriented. High-speed photography was used by Chiappetta and Mammele[1987] to study the effects of air decks on surface blasts. Liu and Katsabanis[1996] used finite element modelling (FEM) to investigate the effect air-decking has on damage to the rock-mass.

This paper investigates the interaction of the explosive and the air in the borehole using numerical methods. It also investigates the interaction of the explosive gas and the rock mass. The numerical methods used are finite difference and finite element modelling (FEM). In particular, Arbitrary Lagrangian Eulerian (ALE) computational techniques are used. Due to the nature of the problem, some information about how air-decking can be beneficial cannot be gleaned from experimental observation. For this reason, numerical techniques are an invaluable tool for obtaining this difficult- and sometimes impossible-to-get information that can lead to an understanding of a physical phenomenon such as decoupled explosives in rock blasting.

ALE methods allow for the treatment of gas, liquids and solids in the same simulation. The ALE code used, ALEGRA, has been developed by Sandia National Laboratories over the past few years (Summers *et al.*[1997]). ALEGRA is an explicit 3-D finite element code that emphasizes strong shock physics and large deformations. It has the ability to treat shock waves in gases, liquids, and solids. It also has the ability to treat the interaction of shock waves with each other and with media from one of the other categories. This allows us to treat explosive detonation and the expansion of the explosive gases and their interaction with air and solids.

Finite element model

For this study, a borehole with air-decking was modelled with an axisymmetric 2-D model. The centreline of the borehole was the axis of symmetry for the model. Figure 1 is a

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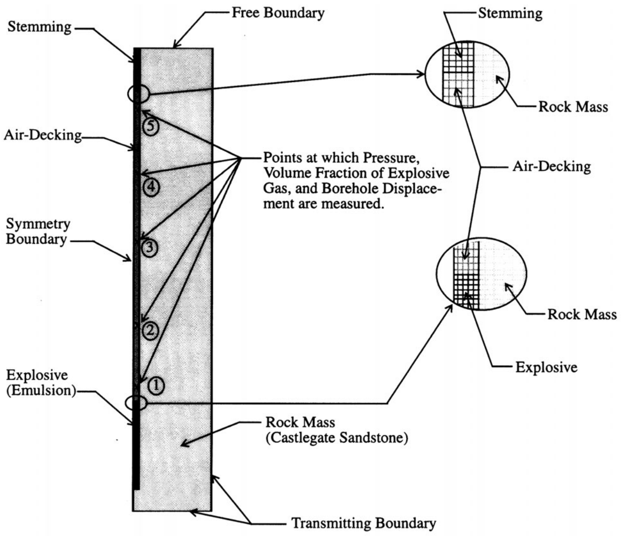

Figure 1—Solid model of finite element mesh. Figure shows boundary conditions and material types

detail of the finite element model. The borehole had a depth of 30.0 m and a radius of 0.15 m. The explosive was a bottom charge that filled 20% of the depth of the borehole. The stemming was modelled to 10% of the borehole depth. This left the air-deck to be 70% of the borehole depth. The explosive and air deck were modelled with an Eulerian mesh while the stemming and rock mass were modelled with a Lagrangian mesh.

For simplicity's sake, the stemming was modelled with the same material properties as the rock mass, thereby having a much stiffer response to the shock wave than usual. This resulted in higher pressures than would actually be generated with a more compressible stemming material such as drill cuttings or gravel. However, it would not qualitatively change the behaviour of the shock wave or the explosive gas in the borehole.

The rock mass was modelled as Castlegate sandstone. The material properties used are listed in Table I. An elastic-plastic constitutive model was used. No damage model was incorporated into the simulation since looking at the rock damage was not the focus of this study. Rock damage will be included in future studies.

The air deck was modelled as an ideal gas. The parameters used are listed in Table II. A typical emulsion was modelled as the explosive. The Jones-Wilkins-Lee equation of state parameters used to model the emulsion are listed in Table III.

The axis of symmetry was located at the centreline of the borehole. The top boundary of the rock mass was modelled as a free boundary. The side boundary and the bottom boundary of the rock mass was modelled as a transmitting boundary. A transmitting boundary allows the shock wave to pass through the boundary without reflecting thereby effectively modelling an infinite boundary. This allows for much smaller, more efficient finite element meshes.

The mesh contained 10028 elements and 10488 nodes.

Table I

Parameters of Castlegate Sandstone (Zeuch *et al.*1996) for elastic-plastic constitutive model

Young's Modulus	105.5 x 10^9 dyne/cm^2
Poisson's ratio	0.23
Yield stress	165.0 x 10^6 dyne/cm^2
Hardening modulus	72.2 x 10^9 dyne/cm^2
Density	2.0 g/cm^3
β, Weight for Kinematic/ Isotropic Hardening (1=Fully Isotropic)	1.0

Table II

Ideal gas parameters for air

Density	0.001225 g/cm^3
Ratio of specific heats	1.4
Absolute temperature at reference state	288.2. K
Specific heat at constant volume	0.7178 x 10^4 dyne*cm/g*K

Table III

JWL equation-of-state parameters for emulsion

Reference density	1.25 g/cm^3
A	476 x 10^9 dyne/cm^2
B	5.24 x 10^9 dyne/cm^2
c	7.20 x 10^9 dyne/cm^2
ω	1.95
R1	3.5
R2	0.9
P_{cj}	110.0 x 10^9 dyne/cm^2
D_{cj}	6.065 x 10^5 cms
T_{cj}	4062 K
T_{ref}	298.0 K

The duration of the simulation was 100 ms. The simulation was run on an eight node parallel cluster of 400 MHz Intel Pentium II processors. The CPU time was approximately two hours.

Computational results

Figure 2 shows the detonation of the explosive and the development of the shock wave as it is imparted to the rock mass. The snapshots are taken at 0.2 ms, 0.8 ms, 1.2 ms and 1.6 ms following detonation. The snapshots in Figure 3 show the initial interaction of the shock wave and the stemming column. As the shock wave contacts the stemming, the explosive gas compresses the air and rebounds. As the shock wave and explosive gases rebound off the stemming, the pressure in the borehole increases. The snapshots also show how the shock wave is transferred to the stemming and the rock mass. The shock wave in the rock mass diminishes relatively quickly. The snapshots in Figure 3 are taken at 10.8 ms, 11.0 ms, 11.2 ms, and 11.6 ms.

The borehole pressure versus time is plotted in Figure 4. The pressure was measured at five points within the borehole. The locations of the points are all located within the air-decking and are shown on Figure 1 as circled numbers.

The first point is located immediately above the explosive. The second point is one-fourth the distance from the explosive to the stemming. The third point is the midpoint of the air-decking. The fourth point is three-fourths the distance from the explosive to the stemming. The fifth point is immediately below the stemming. As can be seen from Figure 4, the maximum pressure in the borehole occurs closest to the stemming. This occurs because of the reflection of the shock wave off the stemming. The periodicity of the peak pressures demonstrates the reflection of the shock wave off the stemming and the bottom of the borehole. Over time, the pressure in the borehole reaches equilibrium. It is the repeated expansion and contraction of the borehole walls from the rebounding pressure wave that contributes to the damage of the rock mass.

Figure 5 shows the radial displacement of the borehole wall versus time. The points of measurement are the same as those used for pressure. The peak expansion of the borehole coincides with the peak pressures. This lends support to the assertion that as the stress wave rings back and forth through the borehole, the stress at a point in the wall of the borehole increases and decreases with the approach and passing of the wave front. It is this rebounding pressure wave that contributes to the rock damage. Also, as expected, the greatest displacement occurs near the explosive and the stemming column.

The volume fraction of the explosive gas versus time is plotted in Figures 6 and 7. The volume fraction is measured at the centre of the borehole (i.e., along the axis of symmetry) and at the wall of the borehole at the same measurement points as used for pressure and radial displacement. The volume fraction at the centreline is plotted in Figure 6. As can be seen from this plot, as soon as the wave front passes a point, the explosive gas fills the entire volume. This is explained by the pressure and density of the explosive gas being magnitudes higher than that of the air. Once the air undergoes the compressive force of the high pressure and temperature of the explosive gas, the resulting volume of air is neglible. Some is pushed out of the centre of the borehole to the wall while most is pushed in front of the explosive gas. Figure 7 shows the volume fraction of the explosive gas along the wall of the borehole. As can be seen from this Figure, the volume fraction of the explosive gas fluctuates over time. This indicates that some air is pushed to the wall of the borehole and circulates along this interface.

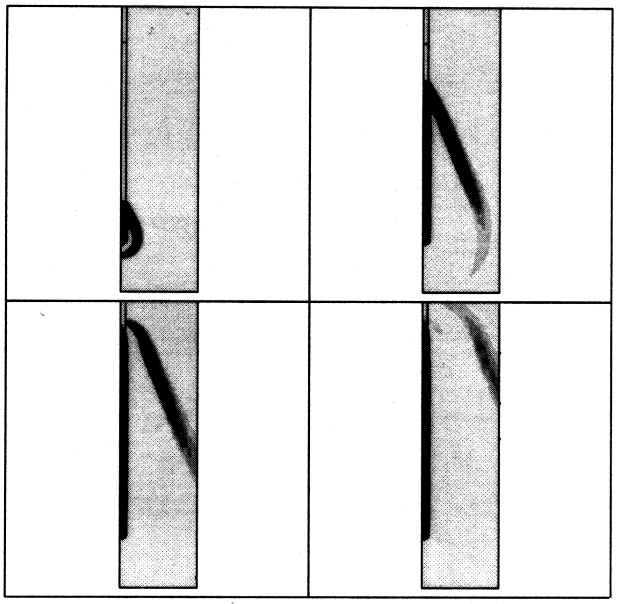

Figure 2—Explosive Detonation and shock wave interacting with air deck at time 0.2 ms, 0.8 ms, 1.2 ms, and 1.6 ms. The grey-scale (light-to-dark) pressure range is from 0.0 to 3.0×10^9 dyne/cm^2. Pressures above and below the range are the same shade as the upper or lower limits

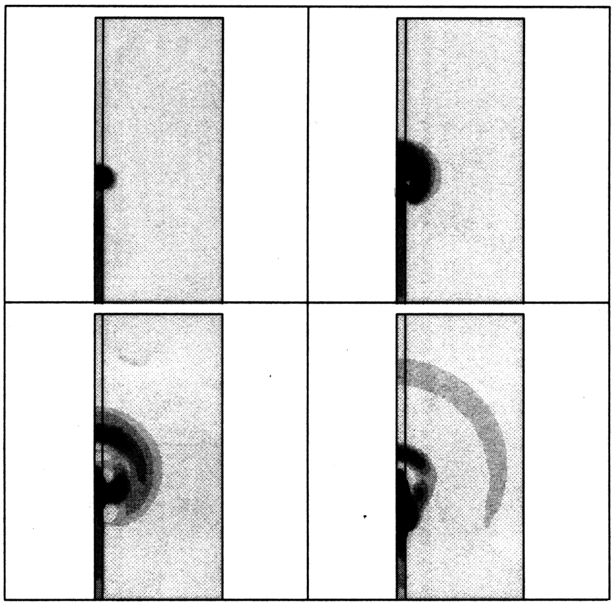

Figure 3—Shock wave reflecting off of, and interacting with, stemming column at time 10.8 ms, 11.0 ms, 11.2 ms, and 11.6 ms. The grey-scale (light-to-dark) pressure range is from 0.0 to 100.0×10^6 dyne/cm^2. Pressures above and below the range are the same shade as the upper or lower limits

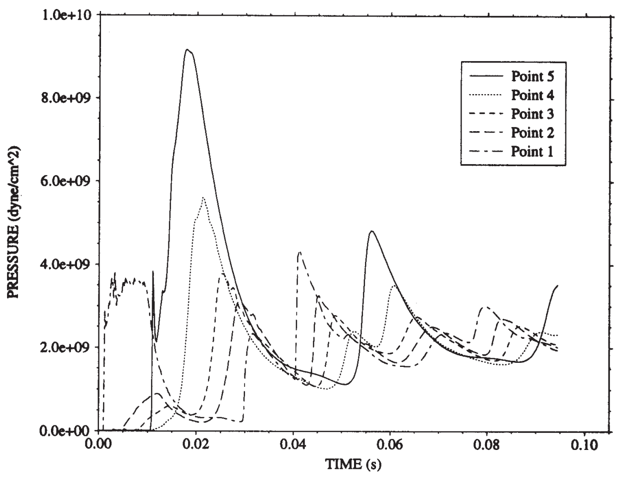

Figure 4—Pressure at centreline of borehole versus time. See Figure 1 for location of measurement points

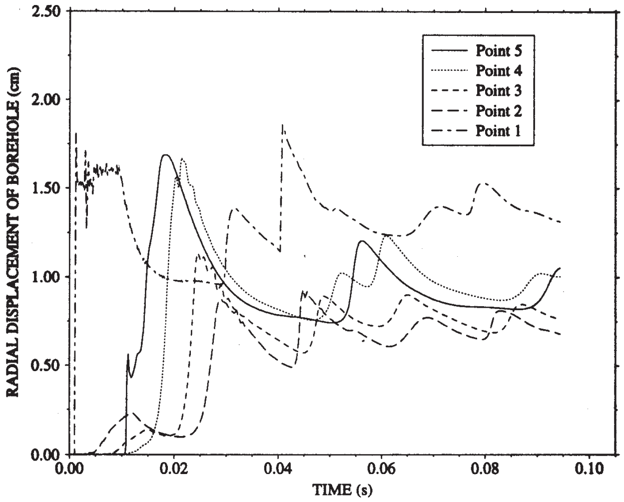

Figure 5—Radial displacement of borehole versus time. See Figure 1 for location of measurement points

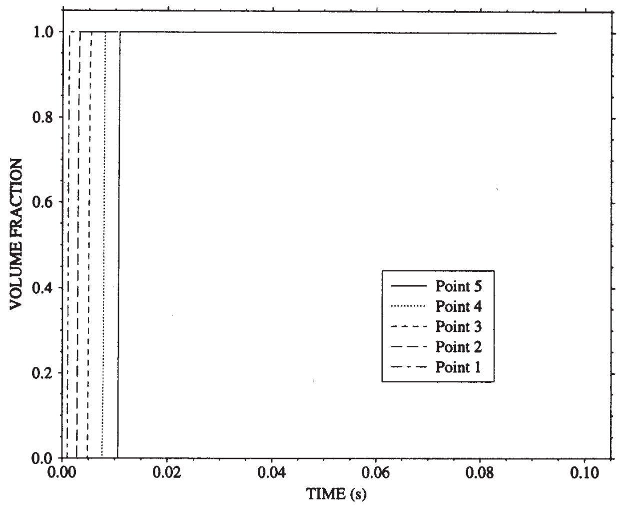

Figure 6—Volume fraction of explosive gas versus time. Values calculated at borehole centreline of locations defined by Figure 1

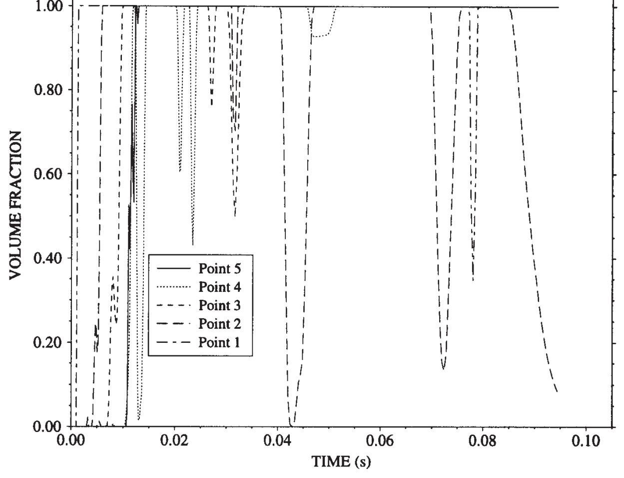

Figure 7—Volume fraction of explosive gas versus time. Values calculated at edge of borehole at locations defined by Figure 1

Conclusions

A 2-D numerical model of the interaction of an explosive with air-decking has been performed using the ALE code ALEGRA developed at Sandia National Laboratories. This simulation demonstrates the ringing effect of the shock wave in the borehole. As a result of this ringing effect, the pressure in the borehole fluctuates for several cycles until an equilibrium pressure is reached. This pressure fluctuation results in a fluctuation of borehole stress and expansion and may contribute to the damage of the rock mass. It is also shown that the volume fraction of the air is nominal after the explosive gases fill the borehole. The air tends to be compressed in front of the explosive and against the wall of the borehole where it circulates along this boundary.

This study is an initial attempt at numerically modelling the effect of air-decking in presplitting. This study demonstrates the capability and benefits of using ALEGRA to model this phenomenon. Future work is needed to more fully investigate the explosive/rock interaction when an air-deck is used in presplitting. Some of this work includes performing the simulation in 3-D. It also includes the incorporation of a rock damage model into the simulation which would show the extent of damage from the blast. From this extension, a parameter study will be done to determine the most beneficial ratio of air-decking to explosive. The effect of different explosives will also be investigated. ALEGRA will also allow for the modelling of different material for use as stemming such as drill cuttings or gravel. Data from these simulations can also be used to investigate the ejection of the stemming material.

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