Numerical Modelling of the Effect of Loading and Timing in Wall Control Applications

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ABSTRACT

The stress field around detonating charges in wall control boreholes was calculated using the AUTODYN™ code to examine the effect of loading and delay. Fully coupled low density explosives produced less damage than decoupled explosives when total energy per borehole was kept the same. Decoupling results in reverberation of the explosion products in the borehole creating multiple impacts of the rock and accumulating damage. Small delays, of the order of few milliseconds between wall control holes do not appear to cause significant problems in splitting the rock between the charges. If however the delay is substantial, venting of gases influences the semi-static tensile field between the charges and consequently, changes in damage between the boreholes are observed.

1. INTRODUCTION

When a charge detonates inside a borehole, a number of cracks are driven from the borehole into the rock. In production blasts, where fragmentation is the issue, one tries to maximize crack development and growth. However when the charge is close to a final wall, the growth and the direction of cracks must be controlled. Typically, one wants crack growth along the plane joining adjacent boreholes and crack minimization in all other directions. In other words one would like neighbouring boreholes to cooperate in developing cracks joining the boreholes, while cracks in the direction of the final wall must be minimized. Wall control is a common practice; however its theory is often debated, as it ultimately has to examine the question of what causes cracks in blasting. The contribution of the stress wave versus gas penetration has been argued for a number of years. According to the experimental work by Brinkmann (1990), cracking is basically related to stress wave propagation while breakout of burden is controlled by gas penetration. Similar experimental findings were reported by Olsson, Nie, Bergqvist and Ouchterlony (2002). Thus, it is possible to use a stress wave propagation model to investigate parameters assisting in the preferential growth of cracks, during wall control applications. The effect of gas penetration in driving new cracks can be ignored as long as it is recognised that gases could penetrate cracks, especially in blasts with significant burden (Ouchterlony, 1996). However gases do not cause new cracks to develop.

In terms of wall control, the following parameters have been identified as important:

- explosive coupling
- explosive detonation velocity
- spacing between boreholes
- timing between boreholes and
- burden

In general, as decoupling increases, the borehole pressure is reduced and the crack length decreases; high VOD explosives result in a large number of fine cracks close to the borehole; crack length around a borehole increases with spacing and delay time between boreholes, while for relatively large burdens crack length is independent of burden (Olsson et al. 2002). Thus trends have been established; however best practices have not been determined since the limits of the above mentioned trends are unknown. For example, decoupling explosives has been recognised as beneficial. It is rather clear that decoupling produces less unwanted damage than decking. Other technologies, such as the use of low density explosives (Silva & Katsabanis, 2000), may offer advantages over decoupling. Instantaneous initiation has been recommended as beneficial; however vibration from simultaneous initiation of several charges can be excessive and result in damage. Thus short delays may offer a benefit, especially in vibration sensitive environments.

The purpose of this paper is to examine the application of wall control concepts using a stress wave propagation code and identify practical improvements. In this capacity the code is used as a laboratory to examine processes of importance to the crack propagation between boreholes. Simplifications are made, treating the rock as a continuum initially elastic and later elasto-plastic material.

It has been indicated by previous work (Berg & Preece, 2004; Preece & Chung, 2003; Wu et al., 2004) that AUTODYN^{TM} (Century Dynamics, 2005), a non-linear explicit hydrodynamic analysis code, is a reliable tool for carrying out numerical modeling of hydrodynamic, wave propagation and projectile impact problems. A 2D version of the code (AUTODYN-2D) was used to model the effect of explosives loading, timing and free faces of wall control blastholes on blast induced damage.

A variety of models predicting damage have assumed that the rock is an homogeneous and isotropic mass. Of course this does not represent reality; however, for rocks with very little jointing, the assumption is justified. Models built on these assumptions typically use damage mechanics to describe the role of micro-fractures and their activation and growth due to the stress waves. Typical of these efforts are the models by Grady (1985), Kuzmaul (1987) and Liu (1996). These models described rock failure as a result of bulk tensile strain. Currently, a model by Riedel, Thoma and Hiermaier (RHT) has been developed for use in concrete and has been coded in the AUTODYN^{TM} code (Century Dynamics, 2005). The model rectifies some of the deficiencies of previous models describing damage of brittle materials due to the propagation of a compressive wave and was used in the current work. Since a calibration of the RHT model is currently unavailable for rocks, the existing calibration for high strength concrete was used (Riedel, 2000). Rock was considered similar to high strength concrete having a uniaxial compressive strength of 140MPa.

2. CONCRETE MODELLING

In hydrodynamic codes, a stress tensor in the material is separated into two components: uniform hydrostatic pressure and shearing deviatoric stress. In a state of thermodynamic equilibrium, the equation of state governs the relation between local hydrostatic pressure, specific volume and specific energy (Century Dynamics, 2005). This equation is solved simultaneously with the energy equation to obtain the hydrostatic pressure component. In this effort, the polynomial equation of state was used with constants representing concrete (Century Dynamics, 2005).

The response of the concrete under dynamic loading is a complex nonlinear and strain-rate-dependent process. The RHT model (Riedel, 2000) considers pressure hardening, strain hardening, strain rate hardening, third invariant dependence for compressive and tensile meridians, and cumulative damage (strain softening). The material model uses three strength surfaces: an elastic limit surface, a failure surface and the residual strength surface for the crushed material. Often there is a cap on the elastic strength surface.

3. EXPLOSIVE MODELLING

The explosive charge is modeled by the JWL equation of state (Lee et al., 1968). A low density explosive, with a density of 0.2 g/cm^3 corresponding to an experimental product developed at the laboratory, was used. For comparison with higher density explosives, ANFO with a density of 0.93 g/cm^3 was used. Table (1) lists the JWL parameters of the explosives used for the problem in hand.

The parameters for the low density explosive were calculated from the fit of the adiabat passing through the C-J point, calculated by the Cheetah code on the basis of the chemical composition and density of the explosive. The parameters for ANFO are listed in the AUTODYN™ code library (Century Dynamics, 2005) and have been obtained by cylinder tests.

Table 1. JWL Parameters of Low Density Explosives.

	ρ_0 g/cc	A GPa	B GPa	R_1	R_2	ω	VOD (m/s)	C-J Pressure, GPa
LDE1	0.2	3.596	0.166	4.113	0.725	0.037	2689	0.522
ANFO	0.93	49.46	1.89	3.907	1.118	0.333	4160	5.15

4. RESULTS

4.1 Damage by one borehole

Figure 1 shows the damage zones around a low density explosive and a decoupled explosive with equal energy in a borehole having a diameter of 45mm and a length of 4m. The boundaries around the charge and at the bottom of the charge are non reflective, approximating boreholes incarcerated in an infinite and continuous rock medium. Damage levels larger than 0.5 are considered to be visible fractures.

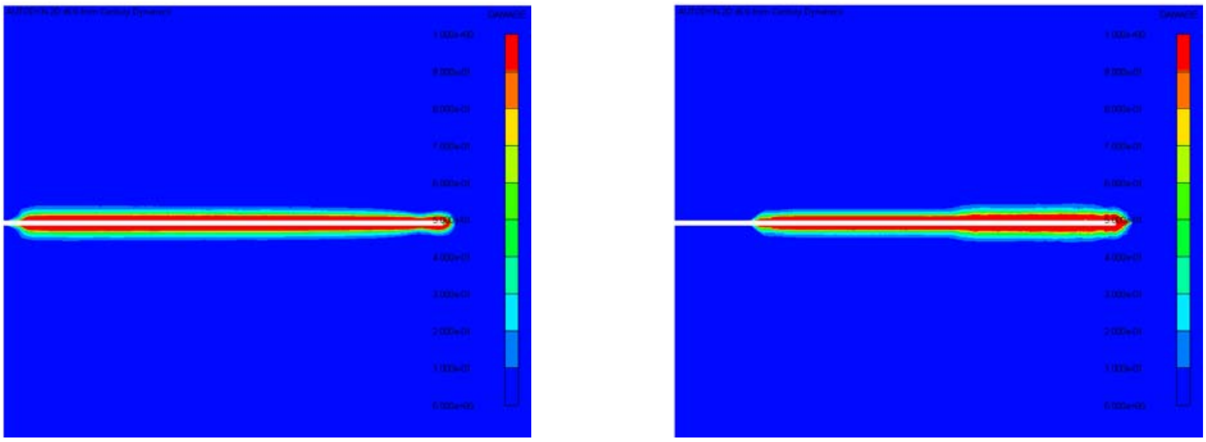


Fig. 1. Damage with (a) fully coupled and (b) decoupled charge.

Damage is slightly more pronounced in the case of the decoupled charge, at the bottom of the hole. Close to the top of the hole, damage appears to be less but this is due to the shorter time simulated. The reason for the added damage at the bottom is the reverberation of the shock wave in the borehole as a result of the impact of the detonation products with the wall of the borehole. This creates secondary loading of the rock mass and additional damage.

Figure 2 shows the difference in the pressure – time records, calculated at the centre of the borehole in both cases. The peak pressure of 350 MPa, in the case of the fully coupled charge, corresponds to the detonation pressure of the low density explosive, while the peak pressure of 4GPa, in the case of the decoupled explosive, corresponds to the detonation pressure of the decoupled ANFO explosive. The second peak in the case of the decoupled explosive is the calculated impact pressure once the products of detonation fill the volume of the borehole.

Subsequently there are a few more reverberations in the decoupled charge record, before the semi-static pressure becomes equal to 250 – 300 MPa in the case of both explosives. In both cases the semi static equilibrium pressure is the same; however the paths to the constant value are different. The reverberations result in several rapid loading and unloading cycles accumulating damage.

Reducing the reverberation of the pressure pulse in the borehole, or its peak amplitude, would be beneficial. A variety of materials have been proposed to practically reduce damage. Such materials are sand in the case of cushion blasting and B-Gel^{TM} in the case of dimensional stone quarries (Lownds, 2000). These materials absorb some of the impact energy but their effectiveness, once compressed, is debatable (Katsabanis, 2001).

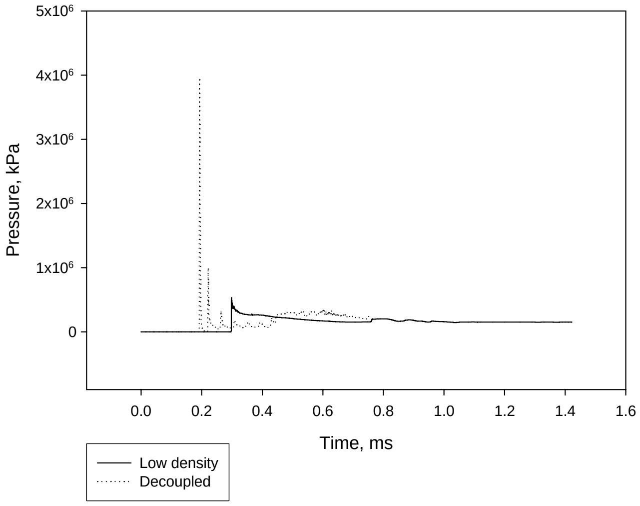


Fig. 2: Pressure time histories at the centre of the charge.

4.2 Effect of delay

It is known that simultaneous initiation is very important in achieving a clean fracture connecting neighbouring boreholes. It is also recognized that vibrations, both near and far field, generated by the simultaneous blasting of several boreholes can be severe and also cause damage. Rustan (1996) has proposed the use of micro-sequential contour blasting. The technique essentially means firing wall control boreholes at intervals of 1-2ms to achieve reduction of vibration and adequate damage between the boreholes. Rustan (1996) had some successful experimental results; however there is considerable debate on the effect of delay time on the quality of the final wall.

To answer the question of timing, it is important to understand what causes cracking in the case of wall control applications. In many practical design methods wall control is associated with the hoop stress produced in the case of a statically pressurized cylinder. The superposition of the hoop stresses in the case of neighbouring boreholes is considered to be the reason for the wall control cracks. The static theory has been debated since the events are dynamic; however there is little debate on the effect of borehole pressure on the final outcome. However the borehole pressure is not static but it has a time history. Figure 3 shows the pressure history at a depth of 3 m inside a 45mm diameter borehole with a depth of 4m loaded with a low density explosive.

The profile was generated using an axisymmetric case of one borehole in which the explosive was modelled in an Eulerian grid and the rock was modelled using a Lagrangian grid. Thus, venting of the gases was modelled with sufficient accuracy. The record of figure 3 shows a peak at the detonation pressure which decreases rapidly to a semi static value; equal to the equilibrium pressure in the borehole. However the borehole is not a sealed cylinder and the pressure decays when the rarefaction, caused by venting of the gases, reaches the point where pressure is measured or calculated. In the case of the graph of Figure 3, decay of the semi static level of pressure occurs around 4ms after detonation. This is how long it takes for the detonation wave to reach the end of the charge and the rarefaction from the venting to reach the point of interest. Obviously a slower detonating explosive will result in a longer pressurization time. Eventually, a semi-static field around the charge will be formed with a duration influenced by the venting of detonation gases.

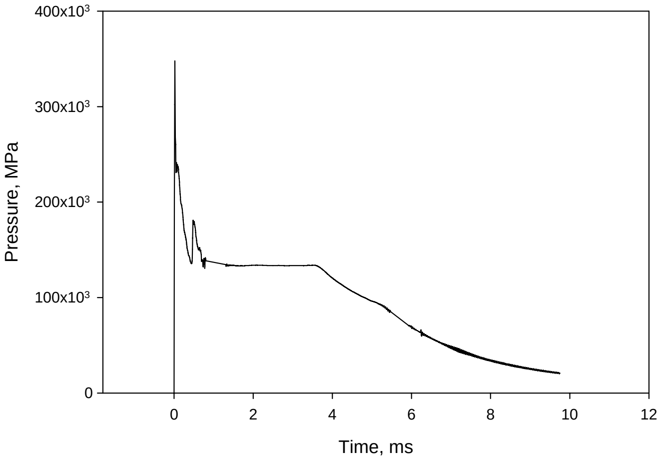


Fig. 3. Pressure time history for low density explosive.

In the case of simultaneous initiation some cracks develop around each borehole and in the early stages there is no cooperation between holes; soon cooperation is established and the preferred direction of failure is the line joining the boreholes. Figure 4 shows the failed material (damage larger than 0.5) for two 45mm diameter boreholes located 600mm apart. The boundaries, as in the case of the rest of the planar simulations in this paper, are considered non reflective. However some reflected waves are generated, something evident in the graphs. The pressure history applied on the wall of each hole is identical to the one of Figure 3.

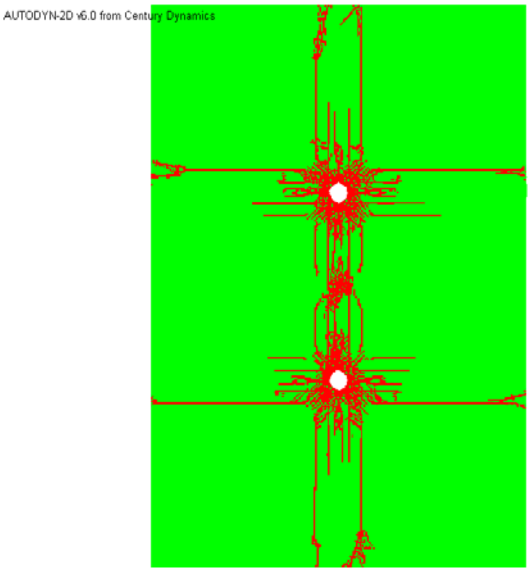
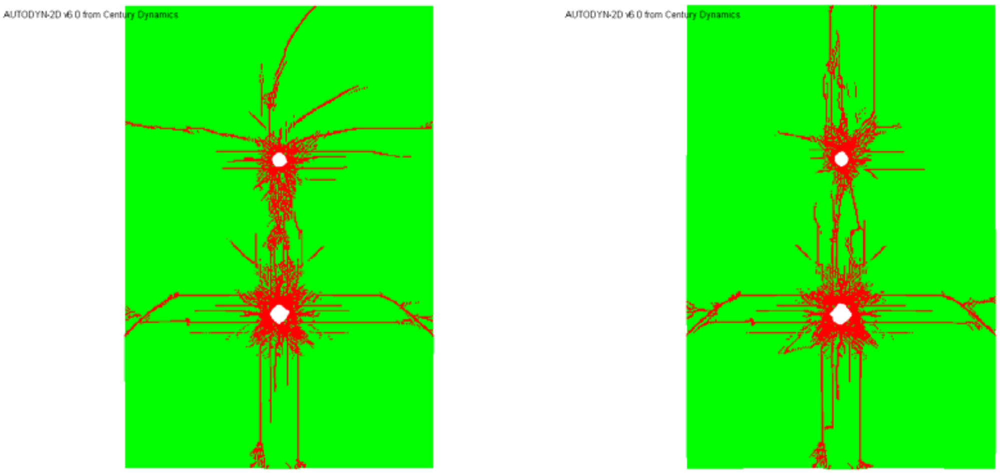


Fig. 4. Material status for simultaneous initiation.

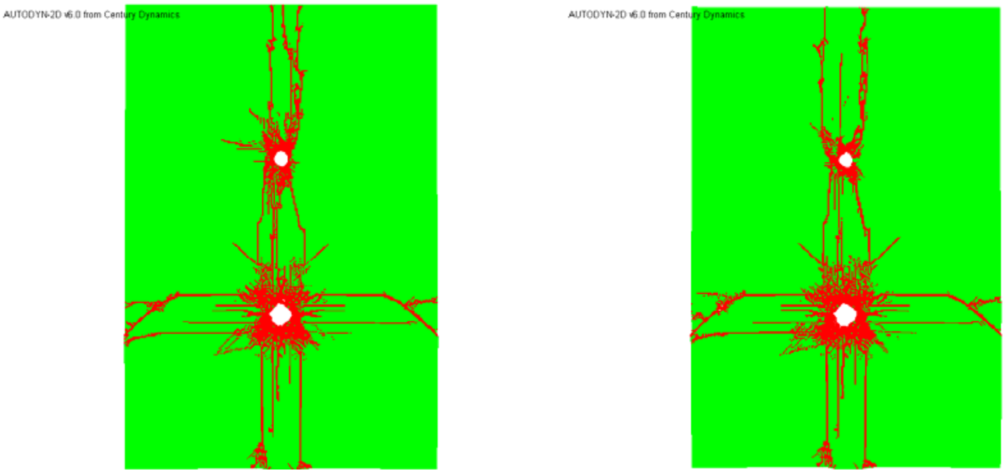
In the case of the delayed initiation there is a departure from the above. If the delay is short, the first hole has established a stress field around it with a compressional component in the radial direction and a tensional component in the tangential direction. The detonation of the second hole then occurs inside pre stressed rock. If the delay is long, the first hole is depressurized and the only influence of the first hole is the damage to the rock mass by it.

Figure 5 shows failed material 2ms after detonation of the second hole, at different delay times between boreholes. The pressure in the borehole is that of Figure 3.

Damage appears to be affected by the delay time. If the delay time is short, heavier visible damage is seen between the boreholes and the later firing hole develops an elliptical damage zone with the major axis in the direction between the boreholes. Previous work (Tawadrous & Katsabanis, 2007) has shown that damage from blasting in a pre stressed environment follows the direction of the major principal stress. Apparently the early detonating hole gives rise to such an environment. If the delay is long, the first hole vents and the stress field decreases. As a result, the later firing hole receives no contribution from the earlier firing hole. At the delay of 5ms the damage between the boreholes has decreased. The increased amount of failed material around the first borehole is the result of the longer simulation time.



(a) 1ms (b) 2ms



(c) 3ms (d) 5ms

Fig. 5. Material status with delays of 1ms, 2ms, 3ms and 5ms.

Another important factor is the damage caused by the detonation of the first hole. Damage creates anisotropy in the rock, influencing the damage pattern from the detonation of the second hole. This can be clearly seen in Figures 5 (c) and (d), where the failed material zones around the second hole appears to be reduced, compared to those of the shorter delay times. In reality, the first hole produces cracks which are long enough and interfere with the stress waves created by the detonation of the charge in the second hole.

It is worth examining the effects of a different pressure time history of the explosive in the borehole on damage. Figure 6 shows a pressure time history at a point in the charge close to the collar.Venting here occurs earlier and the pressure pulse has a smaller duration than the pulse of Figure 3. Figure 7 shows the failed material between the boreholes at delays of 0ms (simultaneous initiation) 0.5ms 1ms and 2ms. The graphs are calculated at a time of 2ms after the detonation of the last hole.

When simultaneous initiation is used, the result is very similar to that of Figure 4. Stress waves cooperate in creating failure between the boreholes. Clearly split is achieved at the earlier delay times but there is little cooperation between charges when the delay is 2ms. The graphs also indicate that there may be an optimum delay between boreholes, providing maximum damage between the boreholes. This agrees with the graphs of Figure 5 as well as with the experimental work discussed by Rustan (1996). The reason for such optimum will be investigated in forthcoming work.

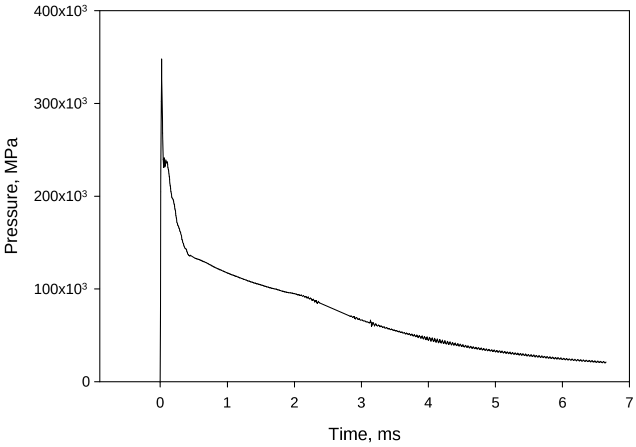


Fig. 6. Pressure - time close to collar of borehole.

Apparently the shape of the pulse and its duration are of importance. They are both affected by the time it takes for the detonation wave to reach the end of the charge, as well as from the time of rarefaction due to expansion to reach the point of interest. Thus the following parameters would have an influence:

- Detonation velocity
- Distance of the point of interest
- Stemming
- Point of initiation

As far as the detonation velocity is concerned, a higher detonation velocity would mean shorter pulse duration than in the case of a fully coupled low density explosive. Thus a low density explosive would offer the possibility of implementing a short delay between holes to decrease vibration levels by the blast.

The location of the point of interest is a very important issue. In the case of a point close to the surface the duration of the pulse cannot be long as rarefaction by venting is immediate. Thus small deviations from instantaneous initiation would result in lack of cooperation between holes and not a well defined final wall. As the boreholes become deeper and as the point of interest is deeper in the borehole cooperation is favoured and a damage zone connecting the boreholes can be formed.

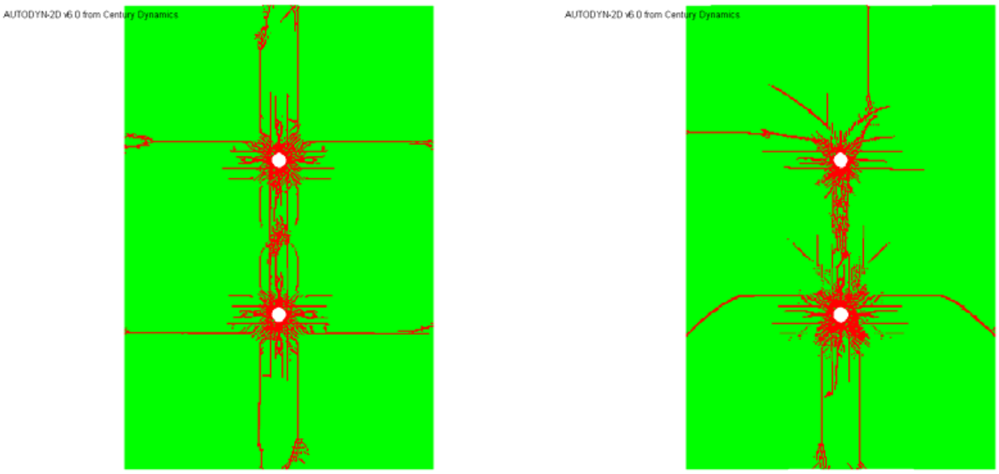
As far as stemming is concerned, its presence increases the duration of the pulses. Although this may be beneficial in guiding damage between boreholes, in practice, it may not be as useful since penetration of gases into the host rock may occur.

Maximum duration of the pressure pulse will be obtained at the bottom of the hole with a bottom-initiated charge. Contrary, in a top-initiated unstemmed hole, gases expand rapidly decreasing the duration of the pressure pulse. The present work suggests that in the later case optimum wall control requires very short delay times between holes or true simultaneous initiation.

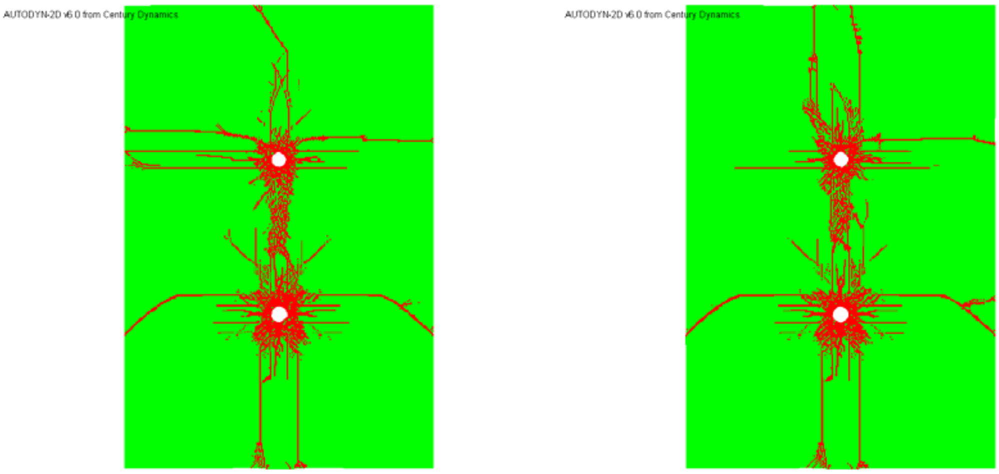
5. CONCLUSION

Numerical modelling has been used to clarify the issues of loading and timing in the case of wall control applications. Decoupled charges appear to introduce some unwanted damage because of the reverberation of the detonation products in the borehole while full coupling with low density explosives appears to result in less damage.

Short delay times can be implemented in wall control applications to minimize vibrations without loss of quality of the final wall. The delay time is a function of the pressure pulse duration which is affected by the venting of the detonation products. The present work has suggested that low density explosives may allow the use of longer delays.



(a) 0ms (b) 0.5ms



(c) 1ms (d) 2ms

Fig. 7. Damage zones by two charges detonating at various delay times.

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