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EFFECT OF SIMULTANEOUS AND SEQUENTIAL DETONATION ON EXPLOSIVE-INDUCED FRACTURE

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ABSTRACT

Tests were conducted in samples of polystyrene to study the effects of detonation delay on explosively induced fracturing. Two explosive charges in separate emplacement holes were fired at several choices of delay. The effect of free surfaces was minimized to make the experiments a study of blast-induced fracturing in a confined mode, i.e., deeply buried. All fractures formed on radial planes with respect to the emplacement holes. Simultaneous firing connected emplacement holes and produced fractures strongly oriented in the plane of the holes. Delayed firings in the second hole tended to suppress fracturing in the general direction of the first shot hole but to enhance fracturing away from the first hole. The effect was most dramatic in the "medium" delay firings; i.e., where the delay time was comparable to the dilatational wave transit time between holes. Using total surface area of cracks as a measure of damage, it was found that no choice of delay, including zero delay, could enhance the per-hole damage above that produced by an isolated shot. For medium delays, in fact, the total damage was measurably reduced.

INTRODUCTION

In situ processing schemes for energy and other mineral resources recently have received increased attention. Usually, a scheme involves modifying the resource in place to increase its permeability or its available surface area. A proposed method for this type of modification is explosive blasting [1-3]. However, despite considerable study of explosives and blasting near to a free surface [4-10], not a great deal is known about confined explosive blasting, where free surfaces do not come into play. Some work has been done [2,11-13], but more is needed on the effects of charge type, size, number, geometry, and timing on confined explosive fracturing. The work reported here concerns the effect of the timing of multiple detonations in separate holes on explosive fracturing in an experimental situation where free surfaces do not have a dominant effect.

For near-surface blasting, sequential detonation in multiple holes is commonly used to minimize ground vibration effects. There is also some evidence for enhancement of fragmentation from sequential detonation in near-surface blasting [8,14]. For confined blasting, the effect of sequencing has not been experimentally studied. However, one can

imagine that the second shot of a confined sequence might interact with a partially reflecting boundary in the plane between charges if fractured rock has a lower acoustic impedance than unfractured rock. This interaction could produce tensions, and therefore enhance fragmentation. This concept has been verified by a simple one-dimensional computer calculation [15]. Unfortunately, in such a calculation the rock is treated as a continuum. If, in the real world, the system is fracture-dominated, with fractures that have lengths comparable to emplacement hole spacing, hole size, and stress pulse length, then a continuum calculation is not reliable. Therefore, an experiment was designed to vary the delay between the detonations of two charges in separate holes, and to study the induced fracturing with statistical methods, with the hope of finding a method of enhancing damage.

EXPERIMENTAL TECHNIQUE

A number of transparent materials were considered for the experiments. Polystyrene, a transparent polymer, was chosen because its brittleness and several of its other properties suggested that it would be a reasonable analogue of a geologic material such as coal. However, the differences in the inherent flaw distributions in rock and in plastic suggest that the results of these experiments be applied to rock with caution.

To minimize the influence of the free surface, the charge was made as small as possible, and the samples were immersed in sodium silicate liquid for impedance matching. The density, dilatational wave speed and shear wave speed of the polystyrene used are approximately 1.05 g/cm³, 0.23 cm/μsec, and 0.12 cm/μsec, respectively. The density and wave speed of the sodium silicate are 1.54 g/cm³ and 0.22 cm/μsec. Test samples of the polystyrene were cast into cylindrical blocks, 250 mm in diameter by 180 mm long. Larger blocks could have precluded the need for the impedance matching medium. However, they also would develop a proportionally larger locked-in stress field during thermal curing. The present sample size results in a stress field which does not noticeably influence the fracture pattern. To check the effect of shear reflections at the polystyrene-sodium silicate interface on the growth of fractures, one sample was cast with an additional 50-mm thick jacket of epoxy around its circumference.

The size of the polystyrene samples imposed restrictions on the design of the explosive charges used in the tests. The size and effective chemical

energy of the charges had to be small enough not to pulverize or break a polystyrene sample into pieces, yet the charge had to detonate reproducibly at low amplitudes. The charge designed to satisfy these requirements consisted of a 38-mg mixture of PETN and an inert substance in a ratio of 9:1 with a density of 0.21 g/cm³. The explosive was contained in a 5.1-mm diameter by 8.9-mm long polystyrene tube with an aluminum cap on one end and a 0.039-mm diameter by 1.02-mm long gold bridgewire at the other end. The effective available chemical energy was about 229 joules with a volume burn pressure of about 0.18 GPa.

The experimental configuration is shown in Fig. 1. The explosive charges were placed in two 8.8-mm diameter holes that were parallel to and equally spaced from the longitudinal axis of the plastic block. The holes were drilled entirely through the sample to improve symmetry. Most of the experiments

Fig. 1. Schematic drawing of the experiment.

were conducted with a 38-mm hole spacing, because preliminary experiments showed that this was optimum for the observation of interaction effects. Smaller spacing obscured results because of high fracture densities, and larger spacing resulted in little interaction. A few experiments were done at other spacings to look at the effect of spacing. Each charge was placed halfway down its emplacement hole and stemmed from both ends with sodium silicate. The loaded sample was immersed in the tank of sodium silicate. Two capacitive discharge units having 6- μ F capacitors charged to 2500 volts were used to ignite the bridgewire-explosive charges. A pulse delay unit was used for precisely timed sequential detonations. Wave forms of current vs. time for each bridgewire were recorded for every shot to check the reproducibility of charge ignition. No

TABLE 1. Emplacement Hole Spacing and Delay Time

Sample No.	Hole Spacing (mm)	Delay Time (μ sec)	Category
38 (50-mm epoxy jacket)	38.1	0	Simultaneous
44	38.1	0	Simultaneous
55	38.1	12.4	Short delay
50	38.1	16.0	Short delay
45	38.1	20.0	Medium delay
49	38.1	20.0	Medium delay
47	38.1	40.0	Medium delay
51	38.1	80.0	Long delay
42	38.1	>>10 ⁶	Long delay
43 (single hole)	---	---	---
41	25.4	13.5	Medium delay
48	25.4	>>10 ⁶	Long delay
39	50.8	0	Simultaneous
46	50.8	26.7	Medium delay

other active measurements were made during the experiment. After the shot, cracks were measured, and a statistical technique was used to study and interpret the results.

RESULTS

General Observations

A total of fourteen experiments were conducted. A list of the shots, with sample number, emplacement hole spacing and detonation delay time, is given in Table 1. Nine shots used a hole spacing of 38.1 mm. In one shot (sample 43), a single charge was emplaced in a hole drilled in the center of the sample. Of the remaining four shots, two used 25.4-mm and two used 50.8-mm hole spacings. The results reported here emphasize the 38.1-mm hole spacing, because enough were fired at this spacing to establish statistically relevant conclusions.

Several delay times were studied. They are defined as simultaneous, short delay, medium delay,

Fig. 2. Coordinate system used in crack mapping. In a sequential detonation, hole 1 is the hole fired first.

and long delay (see Table 1). Simultaneous is no delay. A short delay is a time less than or equal to the dilatational wave transit time between emplacement holes (16.35 μ sec for the 38.1-mm hole spacing). A medium delay is a time greater than the wave transit time between holes, yet less than the estimated time for maximum crack growth caused by the first detonation. A long delay is greater than the estimated time for maximum crack growth caused by the first detonation. For the 38.1-mm hole spacing, delay times of 12.4 and 16.0 μ sec are short delays, 20.0 and 40.0 μ sec are medium delays, and 80.0 μ sec is a long delay.

Figure 2 defines a reference system for discussing the relationship between crack patterns and emplacement holes. Figure 3 shows examples of crack patterns for three delays: simultaneous, medium (20 μ sec), and long (many minutes), all for 38.1-mm hole spacing. Observations of the crack patterns of all fourteen tests reveal the following trends:

- 1) All cracks radiate outward from the emplacement holes in planes normal to the x-y plane (Fig. 3). This observation suggests that circumferential tension is the only cause of crack growth.

- 2) Crack fronts as seen in the crack plane are smooth curves approximating semicircles.
- 3) Cracks occur along the entire length of an emplacement hole, with a maximum density at the position of the explosive charge.
- 4) For simultaneous shots, holes are interconnected, and crack patterns are strongly oriented in the plane containing the hole axes.
- 5) For long delays, little interaction is apparent, although there is some preferred crack orientation.
- 6) For medium delays (particularly 20- μ sec at 38.1-mm spacing) there is a dramatic inhibition of crack initiation at the second hole in the two quadrants facing the first hole.

Quantification of Crack Patterns

The exact crack pattern for any one shot is quite complex and not reproducible, consistent with the random character of the fracturing process. Nevertheless, a way is needed of displaying and quantifying results so that trends may be seen and general conclusions may be drawn. To quantify the crack patterns, all cracks were assumed to be perfect semi-

FIG. 3. Comparison of photographs of three samples (a-c) with corresponding computer-derived images (d-f). Images are oriented with hole 2 above hole 1, as in Fig. 2. Samples shown are (a,d) simultaneous detonation, sample 14; (b,e) 20-sec delay, sample 45; and (c,f) infinite delay, sample 42.

circles lying in radial planes around the emplacement holes [based on observations (1) and (2) above]. Furthermore, the crack positions were reduced to two dimensions by ignoring their z-dependence [based on observation (3) above]. Crack patterns were projected into the x-y plane by sighting through the blocks in a direction parallel to their longitudinal axes and marking on a transparent sheet the position of the tip of each crack in the pattern. Figures 3d-f are drawn from computer-generated images of quantified crack patterns.

Given the position of a crack tip at (x_i, y_i) in the coordinate system of Fig. 2, crack parameters length L , area A , and orientation θ were calculated as follows:

$$L = [(x_i - x_0)^2 + (y_i - y_0)^2]^{1/2} - r_0$$

$$A = \frac{1}{2} \pi L^2$$

$$\theta = \tan^{-1} \frac{y_i - y_0}{x_i - x_0}$$

where (x_0, y_0) are the coordinates of the appropriate hole, and r_0 is the hole radius (4.4 mm).

It is then possible to compute total number,

length, and area of cracks in a sample and to produce length, area, and orientation distributions of the crack parameters. Furthermore, similar experiments can be combined to determine estimates of the true totals and true distributions.

Special cases were handled individually: all but two of the two-hole tests produced one rectangular crack connecting the lengths of the shot holes. The area counted was the full rectangular one, with half attributed to hole 1 and half to hole 2. Cracks which intersected the top or bottom of the test sample were truncated semicircles. The free surface had no obvious effects on the shape of these cracks, and the areas were calculated accordingly. Cracks which intersected the sides of the sample, on the other hand, undoubtedly had a free surface effect since most passed entirely through the sample. The epoxy-jacketed sample, number 38, showed a distinctly reduced maximum crack length, confirming that the large cracks in the other samples were artifacts of the free surface. Based on estimates of crack growth velocities and the timing of shear wave reflections from the free surface, and supported by the appearance of cracks in sample 38, it was decided to truncate arbitrarily all cracks with $L > 50$ mm to $L = 50$ mm for the analysis. Typically, two to

Fig. 4. Crack data for a model single shot as generated by combining the crack data for first shot holes in each of the three long delay samples (42, 48, 51). In the graphs in this figure, and in Figs. 5 and 6 as well, a point represents the mean number (or total area or total length) of all cracks in a 30° interval of angle (or a 2.5-cm^2 interval of area or a 0.5 interval of length). The associated error bar measures one standard deviation above and below the mean. Symmetry in the angular distributions about 90° and 270° is an artifact of the analysis scheme (see text).

three cracks were truncated for each shot hole; four of twenty-seven holes had no cracks truncated; one hole (sample 42, hole 1) had five cracks truncated. None of our conclusions are affected by this truncation, but their statistical uncertainty would become somewhat larger without the truncation.

One further attempt has been made to increase the significance of the results. It is plausible that the plane of the shot holes in a given sample is a plane of mirror symmetry as regards the distribution of number of cracks, crack area, and crack length; *i.e.*, differences in the crack patterns on the two sides reflect only the random nature of the cracking process. No factor has been purposely introduced in the experiments to distinguish the left- and right-hand sides of the sample. Thus, the data base was effectively doubled by treating each half of an experiment as a separate experiment. In Figs. 4-6, the symmetry about 90° and 270° is an artifact of the mirroring treatment.

To form a basis for shot-to-shot comparison, a model single shot in the two-shot geometry was gen-

TABLE 2. Comparison of Hole 1 and Hole 2

Category	Number of Cracks	Length (cm)	Area (cm ²)
<u>HOLE 1</u>			
Simultaneous	63.2 (12.8)*	97.2(21.6)*	328 (124)*
Short	73.5 (4.9)	105 (11.4)	326 (59.4)
Medium (all spacings)	71.0 (24.2)	109 (40.3)	345 (123)
Medium (38.1-mm spacing, 20-μsec delay only)	73.5 (29.0)	120 (28.4)	399 (1.9)
Long (model single shot)	64.0 (21.2)	116 (9.4)	424 (104)
<u>HOLE 2</u>			
Simultaneous	63.2 (12.8)	97.2(21.6)	328 (124)
Short	77.5 (12.0)	110 (22.1)	338 (60.2)
Medium (all spacings)	54.8 (22.0)	87.0(35.3)	321 (121)
Medium (38.1-mm spacing, 20-μsec delay only)	36.5 (23.3)	58.8(18.9)	233 (17.0)
Long	54.3 (3.5)	87.4 (8.2)	314 (67.8)
<u>SINGLE SHOT (Sample 43)</u>			
Single shot	71	113	388

*Numbers in parentheses are standard deviations.

erated by averaging the first holes of the three long delay samples, these being the holes that should have had essentially no interaction effects. Figure 4 shows, for the model single shot, the angular distribution of number of cracks, crack area, and crack length. The orientation dependence of these crack parameters is not strong. However, there is an indication of increased cracking in the general direction of hole 2, but with a dip directly toward hole 2 (*i.e.*, at 90°). Figure 4 also shows the length and area distributions for cracks for the model hole 1. The peak in areas between 0 and 2.0 cm², and the peak

TABLE 3. Comparison of All Holes

Delay	Hole Spacing (cm)	Number of Cracks	Length (cm)	Area (cm ²)
Medium	2.54	46.0 (11.3)*	60.6(23.7)*	210 (110)*
Long	2.54	65.0 (9.9)	101 (20.6)	301 (18.4)
Simultaneous	3.81	62.8 (16.5)	95.6(25.7)	320 (144)
Short	3.81	75.5 (7.9)	107 (14.6)	332 (49.3)
Medium	3.81	62.3 (26.4)	96.3(33.6)	324 (76.1)
Long	3.81	56.3 (16.9)	102 (19.6)	403 (108)
Simultaneous	5.1	64.0 (0)	100 (18.1)	343 (122)
Medium	5.1	81.4 (6.4)	141 (1.7)	483 (57.3)

*Numbers in parentheses are standard deviations.

in lengths between 0.5 and 1.0 cm occur for all holes in all samples. More subtle changes in the shapes of the distribution curves as indicators of experimental conditions were not sought because of the magnitude in the scatter of the data.

Results for other shot conditions are compared in Figs. 5 and 6 and in Tables 2 and 3. Following Griffith theory, which says that the growth rate of crack area is proportional to the local energy available for cracking, total crack area, rather than length, is used here as the primary indicator of damage. Thus, the orientation dependence of damage is shown in Figs. 5 and 6. For comparison, Tables 2 and 3 give overall damage in terms of number of cracks, crack length, and crack area.

Figure 5 reveals very clearly that any finite delay between the firing of hole 1 and hole 2 has a pronounced effect on the orientation of damage around hole 2. Figure 5 also suggests that delayed firing may affect the orientation of damage around hole 1 as well. With respect to the model single shot (Fig. 4), the effect of a delay on hole 2 is to increase the damage away from hole 1 but suppress the damage toward hole 1. The net result for a given spacing (Table 2) is little change in overall damage around hole 2, with the notable exception of the crack area around hole 2 at 38.1-mm spacing for medium delay. There, the area seems to be reduced by a statistically significant amount. The effect of a short or medium delay on the first hole (Fig. 5) is either no distinct change or a very slight increase in damage away from hole 2, and a decrease towards hole 2. A small net decrease in overall hole 1 damage for short and medium delays is suggested by the results in Table 2.

For simultaneous shots, where holes 1 and 2 are

Fig. 5. (Following page) Hole 1 and 2 damage distributions for sequential detonations of various timings. Meanings of points and error bars are as in Fig. 4. As in Fig. 4, results were generated by statistically combining the damage distributions of the several individual samples in each category. Members of each category are identified in Table 1. The hole 1 plot for the long delay category is a repeat of Fig. 4b.

Fig. 5. (Caption on preceding page)

Fig. 6. Damage distribution about a hole in a simultaneous test. Meanings of points and error bars are as in Fig. 4. Holes 1 and 2 are not distinguished, but are combined by rotating the hole 2 data by 180°. The direction 90° is always toward the opposing hole; 270° is away from the opposing hole.

in principle indistinguishable, the hole 1 and hole 2 data can be combined by rotating the frame of reference of the nominal hole 2 by 180°. A damage plot so constructed in Fig. 6 reveals a distinctly bimodal distribution with a damage maximum in the plane containing the shot holes (90° and 270°), and a minimum in the plane parallel to the bisector of the shot holes (0° and 180°). Again, overall damage in Table 2 appears slightly lower than for the model single shot.

Hole 1 and hole 2 data are combined in Table 3 to give total shot damage. A weak positive correlation exists between amount of damage and hole spacing. A similar effect has been found for tests on near surface blasting [16]. The correlation may be due to the fact that as hole spacing increases, the distance to the free surface decreases. However, if the correlation exists in the confined case, then further investigation is needed to find the optimum spacing for maximum total damage.

CONCLUSIONS

Effects of simultaneous and sequential multiple explosive detonation have been observed in an experiment where the influence of free surfaces is minimized. In particular, fracture orientation and damage (as measured by fracture surface area) have been observed for holes that are close enough to interact. Simultaneous firing produces fractures that tend to be oriented in the plane of the emplacement holes, with a connecting crack between holes. (This is similar to presplitting in an unconfined configuration.) Long delays produce a preferred orientation of fractures around the second hole, but do not necessarily produce a connecting crack. Medium delays also orient the fractures, with the effect so strong in the second hole that fractures perpendicular to the axis of propagation of the impinging stress wave are almost eliminated.

Compared with the damage produced by a single, isolated shot, any choice of second shot timing seems

to reduce damage at the second hole. The reduction is most prominent in the case of medium delay. Since medium delay corresponds to the dilatational wave transit time between holes, the compressional stress at and following the wavefront from the first shot appears to have inhibited fracture initiation in the vicinity of the second shot. For long delay, second hole damage inhibition in the direction of the first hole is probably attributable to reflection, scattering, or absorption caused by existing fractures.

There is perhaps an optimum spacing for simultaneous firing to produce damage [16], but we have not fully investigated this.

It appears that timing of detonations is only able to reduce and orient damage. This is unfortunate for *in situ* processing schemes because one design tool, charge timing may not be useful. There is, however, a possibility that the use of medium delays to orient fractures in a geologic seam without creating undesired damage elsewhere might be worthwhile. The lack of any increase of damage with delay disagrees with the simple computer experiment described at the beginning of this paper [15]. The disagreement is apparently because the fractured plastic does not act as a continuum with degraded wave impedance. Rather, it acts in a discrete manner, refracting and absorbing energy in a way that redistributes damage instead of increasing it.

In general, this work indicates, as others have, that one must be careful in making the general assumption that fragmentation is proportional to charge energy in all situations of similar geometry [17]. It also demonstrates the usefulness of descriptive statistics to make relevant conclusions in a medium that has a discrete, and to some extent random response, such as a brittle plastic or rock.

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