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CALCULATED CONCRETE TARGET DAMAGE BY MULTIPLE ROD IMPACT AND PENETRATION

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The effect of enhanced crater formation has been demonstrated experimentally when multiple and delayed shaped charge jets impact and penetrate concrete. The concept for enhancement utilizes a single follow-on jet at the centerline of holes produced by multiple precursor jets penetrating the surrounding the region. Calculations of the 3D crater enhancement phenomena have been conducted with multiple rods to simulate the steady state portion of the multiple jet penetration process. It is expected that this analysis methodology will be beneficial for optimization of the multiple jet crater enhancement application. We present calculated results using ALE3D where the model uses the standard Gruneisen equation of state combined with a rate dependent strength model including material damage parameters. This study focuses on the concrete material damage model as a representation of the portion of the target that would eventually be ejected creating a large bore-hole. The calculations are compared with the experimental evidence and limitations of the modeling approach are discussed.

INTRODUCTION

Previous experiments have demonstrated the effect of multiple jet impact and penetration on the borehole diameter in concrete targets [1 2 3]. A fundamental theory of single jet penetration is that the target hole-volume is proportional to the energy deposited in the target by the jet. Additionally, the target material-properties such as strength have a primary influence on the hole-volume made by the jet energy. The jet material and penetration velocity are lesser influences for a given jet energy. The multiple-jet concept enhances the crater-volume formation by simultaneous penetration of jets into a target followed by a delayed jet penetration of the central encircled-volume left by the first set of jets. This configuration of jet application further enhances the borehole volume. The approach utilizes stress-wave interactions with free surface effects on the preliminary holes bored by the multiple arrays of jets. The free surfaces of the multiple jet holes help to generate tensile failure stresses in the target.

The computational approach for evaluating the hole-volume enhancement utilizes the ALE3d code [4]. All ALE3D calculations have been conducted with constant velocity and constant diameter rods which are used to simulate the steady state portion of the shaped charge (SC) jet penetration process. Borehole size comparisons are related to the energy per unit length of the penetrating rod. The target material model uses the standard Gruneisen equation-of-state with the Holmquist rate dependent strength model that includes material damage parameters for concrete [5]. Previous calculations of SC penetration into concrete with an elastic plastic constitutive model were compared with penetration experiments with a focus on the evaluation of flow stress, porosity, and EOS [6]. The current focus is on 3D simulations combined with the material damage model.

The constitutive model for concrete has the equivalent strength expressed as a function of the pressure, strain rate, and damage. The damage is accumulated as a function of plastic strain and plastic volumetric strain, eq. (1). The denominator is the plastic strain to fracture subject to constant pressure eq. (2).

$$D = \sum(\Delta\varepsilon_{\mathrm{p}} + \Delta\mu_p)/(\varepsilon_p^f + \mu_p^f) \tag{1}$$

$$(\varepsilon_p^f + \mu_p^f) = D1(P^* + T^*)^{D2} \tag{2}$$

The equivalent plastic strain is separated from the plastic volumetric strain as a contribution to the damage. The constants D1 and D2 are determined for the given material. The equivalent plastic strain is measured to be rate dependant and is a significant parameter we used for computation evaluation. The constants for the model were all applied as best determined by Holmquist et. al.

DESCRIPTION OF MULTI-JET ANALYSIS CONFIGURATIONS

The study objective was to utilize a high fidelity concrete material model in a 3D computation to numerically evaluate the multi-jet enhancement (MJE) effect for target material excavation. The first part of the study considers a 5 MJE configuration (runs 1A-1C) while the second part considers a 6 MJE configuration (runs 2A-2C) as listed in Table 1. All computations were conducted with 6 km/sec cylindrical aluminum rods to simulate the steady state penetration of a SC jet. The first set of MJE computations consisted of the following three runs: (1A) unitary rod with diameter of 0.7 cm, (1B) four 0.7 cm rods surrounding a central 0.7 cm rod, and (1C) a unitary rod with diameter 1.565 cm providing the same energy as the 5 rods in run 1B.

Table I. Jet configurations tested and calculated. The effective borehole diameter illustrates the material excavation enhancement from the multi-jet configuration.

run	# of penetrators	penetrator diameter	energy joule/cm	tested configuration	effective hole dia	energy/vol joule/cc
1A	1	0.700 cm	37,400	sc	4.8 cm	2066
1B	4 1	0.700 cm 0.700 cm	187,000	4 x sc sc	30 cm	265
1C	1	1.565 cm	187,000	analysis	12 cm	1653
2A	5 1	0.700 cm 1.400 cm	336,660	5 x sc sc	30-40 cm (35 cm)	350
2B	5 1	0.700 cm 1.400 cm	336,660	analysis	38 cm	296
2C	1	2.100 cm	336,000	analysis	16 cm	1671

The single jet hole-diameter has been compared to the effective-diameter for MJE configurations in previous experiments. The run 1A configuration computed the steady state hole-size produced from a unitary SC jet by using a constant velocity cylindrical rod. The calculations show that a 0.7 cm diameter rod at 6 km/s produces a hole diameter of 4.8 cm with an energy per unit hole volume (E/V) of 2066 j/cc. The calculated hole damage from a typical unitary rod penetration is shown in Figure 1.

Run 1B illustrates the enhancement of MJE configurations. This configuration uses five rods that are the same as the single rod in run 1A and produced a 30 cm hole with a E/V of 265 J/cc. Each rod had the same diameter (0.7 cm) and velocity (6 km/s). The distance from the center rod to the array of four was 10.77 cm. Experiments of the MJE configuration show that the calculated damage parameter represents material which would eventually be ejected from the target assuming some "excavation" energy is imparted to this fragmented material in the hole-boring process. Thus, we calculate an equivalent effective volume using the damage parameter as a variable by calibrating the EFMIN parameter until the damage matched the experiment. This allows for a larger fraction of plastic strain for fracture damage to develop in the material based on the supposition was that the strain-rate aspects of the damage parameter may be significantly larger for the higher strain rate of a jet erosion process. We then use this same parameter value for all the calculations as a predictor for the excavation result. With this parameter set, the 1.565 cm diameter unitary rod with the same energy as run 1B produced a 12 cm diameter hole with an E/V of 1653.

For the single rod penetration into the target, the associated damage diameter is not excavated hole diameter. The material between the hydrodynamic hole-diameter (dark center hole) and the damage diameter (light blue ring) remains intact. A logical conclusion is that the damaged material remained locked in place by the compression of the hydrodynamic hole boring process.

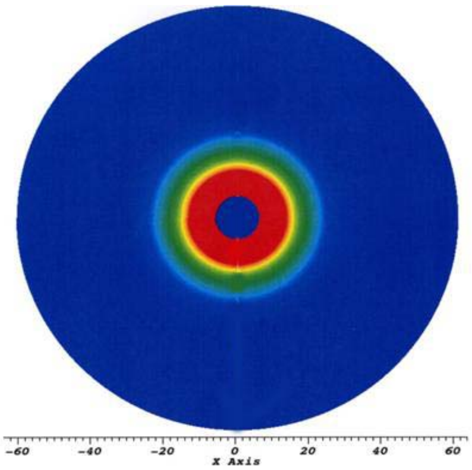

Figure 1. Single rod penetration calculation into 120 cm diameter concrete showing the damage parameter. Red represents a maximum damage of 1.0 or fully damaged material - a cross-sectional area of 570 cm^2. Dark blue center is the excavated hole.

The second part of MJE study consisted of the following three equal energy configurations: (2A) experimental results from five 12.7 cm SC's surrounding a central 25.4 cm SC, (2B) computation of five 0.7 cm rods surrounding a central 1.4 cm rod, and (2C) computation of a unitary rod with diameter 2.1 cm providing the same energy as the 6 rods in run 2B. For this configuration we also increased the ring hole-radius from a starting value of 10.8 cm radius to 17.8 cm radius as shown in Figure 2. The increase in radius allowed for the assessment of the extent of target damage from the MJE.

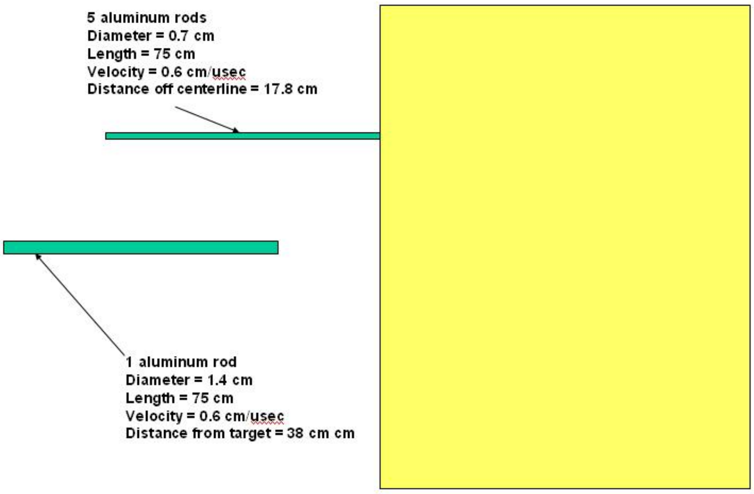

Figure 2. Five 0.7 cm diameter rods equally spaced on a 17.8 cm radius configuration and arriving simultaneously with one central 1.4 cm diameter rod arriving at 70 μs later.

COMPARISON OF THE FOUR MJE TESTS AND CALCULATION

In Table 1 we compare jet or rod configuration, diameter and energy per unit length. This provides the basis of evaluating the enhancement of crater volume formation. The shock wave interactions from the MJE configuration provide the mechanism whereby the damaged concrete can be excavated even though it is beyond the bore-hole radius produced by a single rod penetration. The single rod hydro-dynamically excavated hole-diameter is about 7 times the rod diameter. The excavated hole produced by the four jet outer ring forms a square pattern with an effective diameter of 12.8 cm as shown in Figure 3. The damage cross-section of the MJE configuration is much larger than the equivalent energy rod configuration of run 2A. The apparent specific benefit of separate distributed charges is that a much larger hole is excavated as previously reported [1].

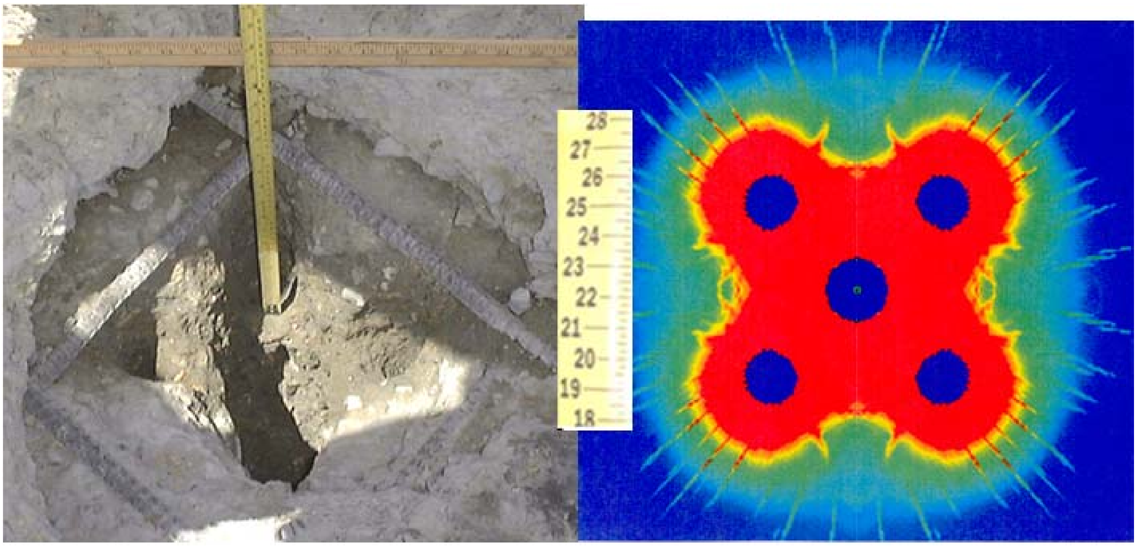

Figure 3. Comparison on the same scale between the excavation by four charges plus one on center and the calculation in concrete. The red boundary represents the full damage concrete, about 625 cm^2 cross-section area

COMPARISON OF THE FIVE MJE TESTS AND CALCULATION

The relatively reasonable match between calculations and test in the part 1 of this study led us to evaluate this damage model against a different test using the five charge MJE configuration. The five 12.7 cm diameter circumferential charges were located at a radius of 15.8 cm. The 25.4 cm diameter central charge was located behind the five outer charges. All six charges were initiated simultaneously. The damage to the concrete target (12 rebar on 12 inch centers) is shown on the left in Figure 4. The calculated result is shown on the right. As with the run 1B configuration, the light blue fringe of material damage in the calculation closely matches the excavation observed in the experiment.

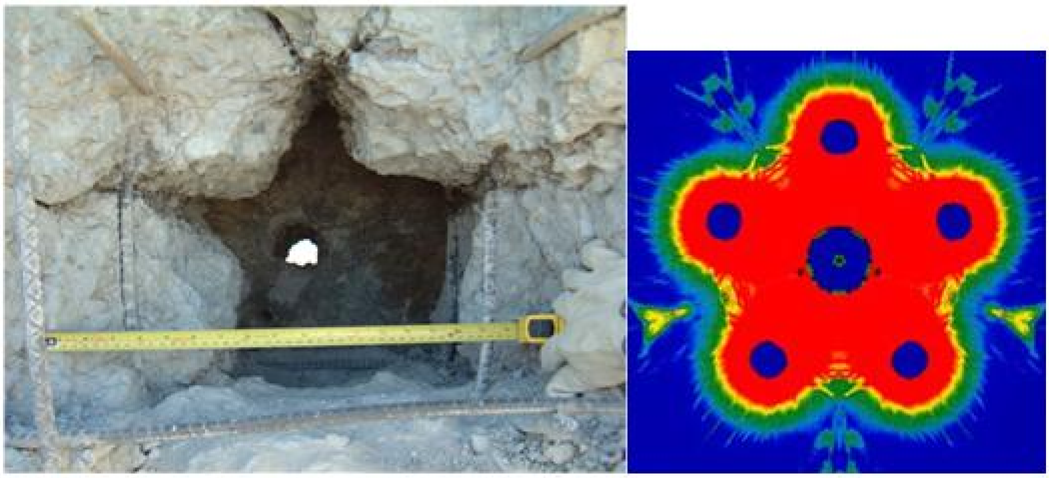

Figure 4. Five jet/rod configuration on the same scale shows the damage frontier closely match between the excavation and the calculation.

MAXIMUM DAMAGE EXTENT WITH THE FIVE MJE

We increased the circumference radius of the five rods to determine the maximum possible extent of damage from the MJE configuration. It appears that at a radius of 17.8 cm we are near a maximum where the damage is still connected everywhere within the circumference. This illustrates there may be a maximum optimum diameter within which the material is evacuated.

REMAINING ISSUE

The question remains as to the ability of the central penetrator action to evacuate the material from the region damaged by the circumferential penetrators. Figure 5 shows the damage connection between the rod-produced holes for the four-rod calculation of case 1B. It is evident that the damage rapidly connects as the central rod hydro-dynamically erodes the central hole and strains the material around it. This process of material excavation may be crucial to completely excavate the fully-damaged material on a much longer time scale than we calculate here. Single jets do not excavate the material out to the damage diameter. The hydrodynamically bored hole is the result of the eroded penetrator material and the crushed up porous material that is displaced radially. The damaged material outside this limit must remain locked up under the strain of the pressure relieved condition. It is clear that the material can be excavated as illustrated by the referenced MJE experiments. One might ask if the excavation only goes out to the outer position of the hydrodynamic erosion for the holes of the outer circumference. Even so, the benefit of jet multiplicity still remains very significant.

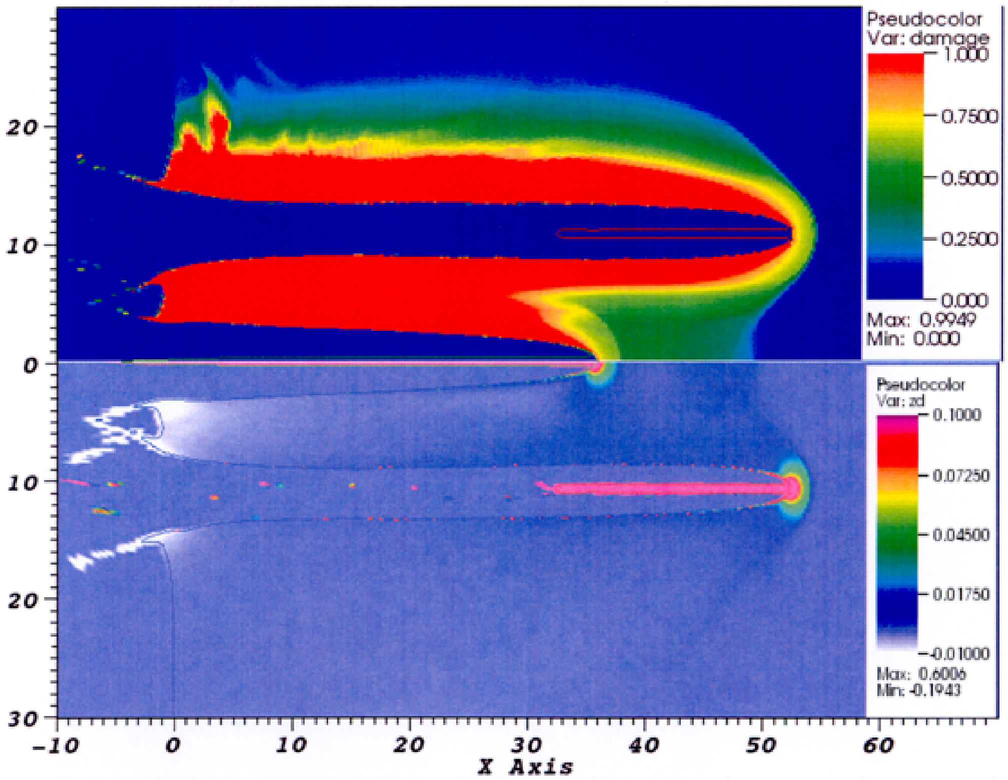

Figure 5. Upper: Cross-sectional view of the development of complete damage in concrete between the central hole and the surrounding pre-formed holes. D = 1, red.
Lower: Relative axial velocity of the materials. Pink is the rod at a positive velocity of 6 km/s, light blue is stationary and white is material being repelled from the block at about 100 m/s.

CONCLUSIONS

These computations confirm that a high fidelity concrete material model in a 3D computation can be used to numerically evaluate the MJE effect for target material excavation. It is expected that this analysis methodology will be beneficial for optimization of the multiple jet crater enhancement application.

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