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PROGRESS REPORT:
CONTROLLED BLASTING CALCULATIONAL STUDIES

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PROGRESS REPORT: CONTROLLED BLASTING CALCULATIONAL STUDIES*

Abstract

Although commercial explosives are widely used for excavation, rock blasting techniques are primarily developed by an empirical approach. More quantitative knowledge of the explosive blasting process is required if design procedures are to be placed on a firm physical basis. Lagrangian finite-difference computer codes capable of calculating high-explosive detonation, shock wave propagation, and the displacement and fracturing of surrounding rock are ideally suited for application to blasting design problems.

Computer calculations are being conducted for cylindrical explosive charges in three different types of rock. Since data on the properties of commercial explosives were inadequate, extensive detonation tests have been undertaken to characterize four typical formulations. Properties of the rock media were chosen to match the dense high-strength materials often encountered in field blasting. Calculations have been performed for both one-dimensional and two-dimensional cylindrical symmetry. The one-dimensional calculations are intended to model free-field shock transmission and rock fracturing, thereby enabling effectiveness comparisons for the various explosives. Two-dimensional calculations simulate realistic blasting events, with a vertical cylinder of explosive emplaced beneath a horizontal free surface. The two-dimensional configurations have also been used to study more sophisticated design techniques, including directional detonation of the explosive charge (top or bottom initiation), effects of an inclined presplit or fracture plane in the rock, and shock wave attenuation by a "buffer zone" of broken rock. Results of these calculations provide new insight into the overall dynamics of the blasting process, and indicate several profitable areas for future design research. Experimental

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data are now needed to verify the calculations and further improve the rock mechanics models incorporated in the codes.

I. INTRODUCTION

The efficient use of high explosives as a construction tool requires the ability to predict and control the location and degree of rock fracturing. In conventional practice, explosive emplacement designs have been established by means of empirical experience and field tests for each rock type and explosive. Sophisticated controlled blasting techniques, which utilize smaller subsidiary detonations and presplit planes to control overbreak and precisely fix the cut dimensions, have also been developed with a largely empirical approach. The few analytic and experimental studies conducted in the past have been somewhat descriptive in nature, due to the inability to precisely model or measure the high-pressure inelastic rock behavior and complex stress histories near an explosive detonation. The application of finite-difference computer programs offers a means to overcome these difficulties and place blasting design on a more rigorous basis.

Recognizing the need for controlled blasting technology improvement and the great potential of these computer programs for simulating high-explosive blasting effects, the U.S. Army Corps of Engineers Explosive Excavation Research Laboratory (EERL) proposed a comprehensive four-phase research program to the National Science Foundation. The first phase involved hydrodynamic code calculations to simulate typical controlled blasting situations. Upon award of a research grant, EERL arranged for calculational support from the Lawrence Livermore Laboratory (LLL), Earth Sciences Division. The program plan for the grant and a description of the computer codes were presented at a conference on excavation technology.¹ This report summarizes the results obtained from these calculations to date.

The effects of buried explosive detonations in a solid environment may be simulated by hydrodynamic computer codes which calculate shock

propagation. The computational methods are capable of modeling regimes of material behavior which include explosive energy release, fluid flow, elastic solid, and plastic flow or brittle failure of a solid. The available codes include SOC73^{2,3} (one-dimensional spherical, planar, or cylindrical symmetry) and TENSOR^{4,5} (two-dimensional cylindrical or planar symmetry), which have been successfully used to calculate phenomena such as high-explosive and nuclear cratering,^{6,7} and shock propagation and rock fracturing from contained nuclear detonations.^{8,9}

The rock mechanics models used in these codes have undergone considerable recent development incorporating improved failure and damping descriptions.³ These physical models, previously developed for the SOC73 code, have been integrated into the two-dimensional TENSOR code as part of the current research effort.¹⁰ The new two-dimensional code is being used for the calculations described in this report. Modeling techniques of both the one- and two-dimensional codes are continuously modified as improved physical understanding and additional experimental data become available.

II. CONSTITUTIVE RELATIONS

In order to implement hydrodynamic calculations, it is necessary to have an accurate description of the material behavior or "equation of state" for all the media included in the problem. This characterization should extend up to the maximum pressure levels achieved during the calculation. High-explosive properties of interest include the initial density, detonation velocity, energy release, Chapman-Jouguet point, and the expansion adiabat of the gaseous products. These properties may be formulated in terms of the Jones-Wilkins-Lee (JWL) equation of state,¹¹ which is calculated from experimental data on the detonation of metal-encased explosive spheres and cylinders.

Accurate equations of state are currently available for a variety of military high-energy explosives.¹² In conjunction with the current calculational research, the Organic Materials Division at the Lawrence Livermore Laboratory is determining equations of state of four commercial

blasting explosives.¹³ These include ANFO and ammonium nitrate slurry explosives of a type increasingly used in commercial blasting applications.¹⁴ Equation of state tests for ANFO and dynamite have been completed.¹³ Experimental measurements on the additional ammonium nitrate slurry explosives are currently in progress. Basic properties and JWL coefficients* are summarized in Table 1. Nitromethane and "Diamond Ore" slurry, which were used in some preliminary calculations, are included for comparison. The "Diamond Ore" slurry is a nonideal high-energy aluminized ammonium nitrate slurry explosive used in certain military experiments; it is the only slurry formulation for which appropriate equation of state data were available prior to this project.¹⁵

The equations of state derived during this study are expected to be valuable not only for the current series of calculations, but also for future research in the rapidly-expanding field of commercial explosives applications. The explosives were selected to typify various commercial blasting materials; however, no endorsement of a specific product is intended or implied.

In addition to the explosive equation of state, it is necessary to characterize the rock media used in the calculations. Required data include the initial density and elastic properties, volumetric compressibility of intact rock and of fully-compacted rock, and shear strength as

* The JWL equation of state has been developed to describe the pressure-volume-energy behavior of high-explosive detonation products, as observed in metal acceleration experiments. Application of the JWL equation of state requires a knowledge of the bulk density, detonation velocity, total energy release, and Chapman-Jouguet compression of the explosive, plus the JWL coefficients for the following equation:

$$P = A_1 \left(1 - \frac{W_1}{R_{11} V/V_0} \right) e^{-R_{11} V/V_0} + B_1 \left(1 - \frac{W_1}{R_{21} V/V_0} \right) e^{-R_{21} V/V_0} + \frac{W_1 E}{V/V_0}$$

where P = pressure (Mbar), E = energy content (Mbar-cc/cc), V/V_0 = specific volume of detonation products/initial specific volume of explosive. In addition, for a nonideal two-phase explosive (Diamond Ore AANS), a second set of JWL coefficients must be determined. Also needed are the energy release for the first phase (initial detonation) and second phase of the burn, the delay time " ϕ " between detonation front arrival and beginning of the second phase burn, and ramp time or duration " θ " for the second phase burn.

Table 1. Basic physical properties and Jones-Wilkins-Lee (JWL) coefficients for explosives used in controlled blasting study.11-13

Explosive	Gelled nitromethane (Proj. ESSEX ^a)	Aluminized ammonium nitrate slurry (Proj. Diamond Ore ^b)	Ammonium nitrate fuel oil (ANFO)	Unigèl dynamite
Bulk density ρ_0 (g/cm ³)	1.21	1.59	0.782	1.262
Detonation velocity (m/sec)	6210	4100	5000	5760
Total energy release (Mbar-cc/cc)	0.045	0.096 ^b	0.029	0.051
Chapman-Jouguet pressure (kb)	120	—	50	120
Chapman-Jouguet compression μ_{cj}	0.34614	0.32154	0.34364	0.40154
Ramp time θ for phase 2 (μ sec)	∞	50.0	∞	∞
Delay time ϕ for phase 2 (μ sec)	∞	0.0	∞	∞
Energy release for phase 1 (Mbar-cc/cc)	0.045	0.020	0.029	0.051
Energy release for phase 2 (Mbar-cc/cc)	0.0	0.076	0.0	0.0
R_{11}	4.9	4.4	4.3	4.4
R_{12}	1.0	4.25	1.0	1.0
A_1 (Mbar)	3.180	1.622844	1.02987	1.90698
A_2 (Mbar)	0.0	0.63249	0.0	0.0
B_1 (Mbar)	0.06378	0.002555	-0.00574	0.075771
B_2 (Mbar)	0.0	0.012907	0.0	0.0
W_1	0.38	0.32	0.28	0.23
W_2	0.0	0.4	0.0	0.0
R_{21}	1.4	1.2	1.2	1.4
R_{22}	1.0	1.0	1.0	1.0

^aThe nitromethane equation of state was derived for a special formulation of gelled nitromethane with particulate sand inclusions; this explosive was used during field tests of the Project ESSEX program.

^bAn aluminized ammonium nitrate slurry explosive (AANS) with particulate sand inclusions, used during previous Diamond Ore field experiments; characterized by a nonideal "two-phase" burn which is approximated by releasing 21% of the explosive energy in the initial detonation and the remaining energy over a 50 μ sec interval.

a function of confining pressure. Once a particular test site has been selected, this information is normally obtained from geophysical field measurements, and from laboratory compressibility and triaxial (strength) tests, high-pressure Hugoniot measurements, etc. Data have been accumulated for a broad spectrum of rock types, densities, and porosities.

A method recently developed by T.R. Butkovich uses simple mixture theory to simulate the complete equation of state of a rock-water-air matrix.¹⁶ This method, which requires only the rock grain density, porosity, water content, and initial (elastic) bulk modulus as input, accurately reproduces the equations of state for a wide variety of silicate rocks. Constitutive relations of the rock media were generated using this method for these general studies, since no specific blasting sites have yet been selected.

During the course of this study, the Butkovich method has been extended to encompass nonsilicate rock compositions such as limestone and marble (calcium carbonate), dolomite (magnesium carbonate), clay minerals, and rocks of mixed composition. The techniques developed were used to generate equations of state for three commonly-encountered rock types: Sandstone (silicate composition), basalt (silicate), and limestone (calcium carbonate). Use of the artificial equation of state generator offers the considerable advantage of permitting the selection of any desired range of physical properties for each of the various rock types.

Since this investigation is directed primarily toward defining relative explosive effects, all three of the media selected were of similar gross physical properties: high density, low porosity, and relatively high strength. These characteristics might typify a compacted, high-strength, unweathered rock formation. The choice of basically similar physical parameters enables us to examine the more subtle influences of differences in the explosive and rock equations of state.

The physical properties assumed in the calculations for each of the three rock types are listed in Table 2. The sandstone parameters are

Table 2. Properties of media for controlled blasting calculations.

Medium	Bulk density ρ_o g/cm ³	Grain density ρ g/cm ³	Water content by weight Z_w wt%	Degree of saturation S %	Total porosity ϕ_p %	Initial bulk modulus k kbar	Sonic velocity V_s m/sec	Poisson's ratio σ	Tensile strength K_T bar
Sandstone	2.5417	2.68	1.25	50	6.34	97.2	2652	0.24	≈70
Basalt	2.7970	2.95	0.86	40	6	240.6	3810	0.28	≈70
Limestone	2.5680	2.70	1.17	50	6	206.1	3680	0.28	≈70
Sand S (crushed bulked sandstone)	2.0354 ^a	2.68	1.25	10.16	25	40.8	1800	0.3	0

^aBulked by approximately 25% relative to intact sandstone material.

representative of the densest and least porous sandstone formations encountered at the Trinidad and R.D. Bailey excavation sites (U.S. Army Corps of Engineers), for which extensive geophysical data are available.¹⁷⁻¹⁹

The grain densities and other properties of basalt and limestone are typical of the respective rock types, but do not refer to any specific site or sample.

The grain densities, bulk densities, and water contents listed in Table 2 have been used in conjunction with the modified Butkovich technique to generate equations of state. In each case, the volumetric compressibility " μ " as a function of pressure^{*} and the shear strength " K " as a function of mean confining pressure are determined. The compressibility curves are shown in Fig. 1 (sandstone), Fig. 2 (basalt), and Fig. 3 (limestone). The solid curves represent the original compressibility behavior of the intact rock matrix, while the dashed curves show the compressibility of fully-compacted rock (all air voids removed, unloading and reloading behavior after release from high pressure). An example of the shear strength " K " as a function of mean confining pressure is presented in Fig. 4 (intact sandstone). The other rocks have strengths which vary by less than 15% from the curve shown in Fig. 4.

^{*}Volumetric compressibility μ is defined as

$$\mu = \frac{V_o}{V} - 1$$

where V_o = initial specific volume of the in situ rock at zero pressure
 V = specific volume at a pressure " P ".

Fig. 1. Compressibility of sandstone as a function of pressure; unloading fully-compacted curve is shown as dashed. (a) Complete loading and unloading curves. (b) Low pressure range, expanded.

Fig. 2. Compressibility of basalt as a function of pressure; unloading fully-compacted curve is shown as dashed. (a) Complete loading and unloading curves. (b) Low pressure range, expanded.

Fig. 3. Compressibility of limestone as a function of pressure; unloading fully-compacted curve is shown as dashed. (a) Complete loading and unloading curves. (b) Low pressure range, expanded.

Fig. 4. Shear strength of intact sandstone as a function of mean pressure.

A concept of controlled blasting design under investigation by EERL involves "buffer zones" of rock previously fractured by small-charge detonations. The scope of this study includes calculation of the shock attenuation by broken and bulked material in the buffer zone. Therefore, an additional equation of state is needed. The sandstone medium has been selected for this purpose. Buffer zone properties are expected to vary considerably with depth and emplacement design; however, attenuation of the initial shock and reflected tensile wave near the ground surface are of greatest importance in protecting intact rock or a presplit surface beyond the buffer. The buffer zone material near the surface is always bulked and relatively porous. For this reason, the sandstone described previously has been bulked or increased in volume by about 25% to simulate the crushed buffer region. Grain density and water content are unchanged. These assumptions produce a material of porosity approximately midway between the intact sandstone and fine-grained sand. The physical properties are listed in Table 2 (Sand S).

The compressibility curves and shear strength of this crushed material are presented in Figs. 5 and 6, respectively. The greater initial air void porosity is evident in Fig. 5 from a comparison of the initial loading and "fully-compacted" compressibility curves. The volume of the fully-compacted sand "S" material is actually identical to the volume of fully-compacted sandstone (Fig. 1), although the appearance of the compacted P- μ curves for the two media differs due to the modified initial volume " V_0 ". Since the material is assumed to be crushed and broken, it has no tensile strength.

III. PRELIMINARY CALCULATIONAL RESULTS

The four equations of state discussed above are being used in the one-dimensional (SOC73) calculations; the equations of state for sandstone and crushed sandstone have been adopted for the two-dimensional (TENSOR) calculations. The one-dimensional configurations consist of a cylindrical explosive charge of infinite length emplaced in an essentially infinite

Fig. 5. Compressibility of crushed bulked sandstone (Sand S) as a function of pressure; unloading fully-compacted curve is shown as dashed. (a) Complete loading and unloading curves. (b) Low pressure range, expanded.

Fig. 6. Shear strength of crushed bulked sandstone (Sand S) as a function of mean pressure.

medium (one-dimensional cylindrical symmetry). The two-dimensional events utilize a long, vertically-oriented cylinder of explosive emplaced beneath a free surface. Details of the individual calculations are presented below. The overall sequence of calculations is summarized in Table 3, which shows the scope and current status of the project.

The one-dimensional calculations are being conducted for a cylindrical line charge 5 in. (12.7 cm) in diameter, detonated at the center and burned to the outer edge. Results of one-dimensional preliminary trial calculations using the Diamond Ore slurry explosive (AANS) and military-type explosives have been presented at the Army Numerical Analysis Conference.²⁰ Results for some of the commercial explosive formulations are now available as well.

The final calculational suite of 15 problems includes five explosive types, in combination with each of the three media (Table 3). An additional calculation for ANFO explosive in sandstone is intended to define free-field attenuation effects due to the crushed buffer zone.* When completed, these calculations will produce a detailed picture of stress wave propagation, cavity growth, radius of failure, and energy partition into the rock for each explosive type and medium. Thus, the relative efficiencies of the various explosives may be quantitatively compared.

The shock-front peak pressures as a function of range[†] R for all three rock types are shown in Fig. 7 (ANFO and AANS explosives) and Fig. 8 (Unigel dynamite explosive). Note that the calculated values given in these and subsequent figures apply only to the dense, low-porosity high-strength rocks encompassed by the study. Significant changes would be expected for other media.

* A cylindrical line charge emplaced in sandstone is surrounded at a radius of several feet by a cylindrical ring of crushed sandstone. Stress attenuation and fracturing beyond this buffer zone may be observed and compared with the corresponding calculation at the same range for no buffer zone. This configuration is obviously not identical with the actual three-dimensional buffer zone emplacement, but it does give a good idea of attenuation effects using only a one-dimensional calculation geometry.

[†] Range R = distance from center of 5-in. diameter explosive cylinder.

Fig. 7. Peak pressures at shock front as a function of range: 5 in. diam cylinders of Diamond Ore AANS explosive and ANFO explosive in free-field environments of sandstone, basalt, and limestone.

Fig. 8. Peak pressures at shock front as a function of range: 5 in. diam cylinders of dynamite explosive in free-field environments of sandstone, basalt, and limestone.

Table 3. Suite of one-dimensional and two-dimensional controlled blasting calculations: C = completed, results under analysis;
A = awaiting explosive equation of state;
P = preliminary two-dimensional calculation (nitromethane explosive).

One-dimensional cylindrical calculations (SOC73 code).					
Medium \ Explosive	"Diamond Ore" aluminized ammonium nitrate slurry	ANFO	Unigel dynamite ^a	Slurry "A" (Pourvex slurry) ^a	Slurry "B" (Aquanal, an aluminized slurry) ^a
Sandstone	C	C	C	A	A
Basalt	C	C	C	A	A
Limestone	C	C	C	A	A
Sandstone plus bulked buffer zone		C			

Two-dimensional calculations, vertical cylinder of explosive in sandstone (TENSOR code):

Configuration \ Explosive	Nitromethane	Final calculations, nitromethane or selected blasting explosive
Sandstone	P	A
Sandstone with presplit	P	A
Sandstone with buffer zone and presplit	P	A
Sandstone, detonate from top of charge	P	A

^aReference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Atomic Energy Commission to the exclusion of others that may be suitable.

The figures also show pressure attenuation lines of slope $R^{-1/2}$ and R^{-1} . An attenuation rate of $R^{-1/2}$ corresponds with the expected geometric attenuation for a cylindrically-divergent nondissipative elastic wave, while R^{-1} is the attenuation for a spherically-divergent wave. The calculated attenuations are more rapid than $R^{-1/2}$ in all cases; the attenuation rates are faster than R^{-1} at close ranges, but approach R^{-1} at longer ranges.

Peak particle velocities at the shock front have also been calculated, and are plotted in Fig. 9 (ANFO and AANS explosives) and Fig. 10 (Unigel dynamite explosive). Similar attenuation behavior as a function of range

Fig. 9. Peak particle velocities at shock front as a function of range: 5 in. diam cylinders of Diamond Ore AANS explosive and ANFO explosive in free-field environments of sandstone, basalt, and limestone.

Fig. 10. Peak particle velocities at shock front as a function of range: 5 in. diam cylinders of dynamite explosive in free-field environments of sandstone, basalt, and limestone.

is noted in these plots. Comparison of Figs. 7-10 reveals that the lowest peak pressures for each explosive occur in the sandstone medium, which is the lowest-impedance rock. The lowest velocities are found in basalt, the highest impedance rock, as would be expected.

The differences between rock types are, however, small in comparison to the differences between the explosives. Velocities and pressures at ranges beyond 15 cm (2.3 explosive radii) are always highest for the AANS explosive and lowest for ANFO. The observed differences cannot be fully accounted for in terms of explosive energy content.

Equally distinct deviations between the cavity growth behavior and fracturing effectiveness of the various explosives are also apparent in the calculations. Current research efforts are directed toward correlating these differences with explosive energy content, burn (energy release) characteristics, and explosive-rock impedance properties. There are indications that slurry blasting agents with lower detonation velocity may be superior to high-energy military explosives in rock fracturing applications.

The cylindrically symmetric configuration used in the one-dimensional calculations may be thought of as a cross-section through a line charge of infinite length. Such a configuration is ideal for determining free-field shock propagation and shear failure in an infinite medium. It does not, of course, give direct information concerning free-surface reflections or asymmetric explosive burn effects. Likewise, slippage along a fracture plane and shock interactions at non-normal incidence cannot be simulated in one dimension. Since effects of these types are important in field blasting configurations, two-dimensional calculations are required.

The two-dimensional portion of the controlled blasting study may be divided into two areas: (1) Evolutionary development and modification of two-dimensional rock mechanics computer programs; and (2) application of the programs to calculate physical effects associated with a typical underground explosion geometry. The programs being improved are the TENSOR two-dimensional dynamic code, and TENPLT, an editing and plotting code which presents the results of two-dimensional calculations in a

convenient graphical format. Work has proceeded in both areas of the study simultaneously, with the specific controlled blasting calculations being used as test problems in TENSOR code development.

The basic controlled blasting configuration used in the TENSOR calculations consists of a vertical cylinder of explosive 5 in. in diameter and 16 ft long, with the upper end approximately 9 ft below the ground surface. This charge size corresponds to a total explosive weight of 0.0823 tons and a total energy release of 0.066 tons (278 MJ) for nitromethane. The charge is emplaced in a sandstone medium similar to that used for the one-dimensional calculations. The HE cylinder is, however, detonated at the bottom in these cases. Top-initiated detonations are also being considered in order to examine directivity effects. Calculations presented here use the well-characterized nitromethane explosive (Tables 1 and 3). Either nitromethane or one of the newly-available commercial explosive equations of state will be used to perform calculations for the final report.

Results of the TENSOR calculations have been edited and plotted using the TENPLT code.²¹ Some examples of the TENPLT output are presented in Figs. 11 through 14. Figure 11 shows the initial grid or mesh at the beginning of the calculation. Figure 12 gives the pressure contours in the sandstone at a time 2 msec after the HE detonation is started, while Fig. 13 shows the maximum compressional change in volume ($-\Delta V/V$) which the material has undergone by 2 msec. Both figures reveal that the peak of the shock front is not cylindrically symmetric about the explosive axis but is directed upwards toward the surface. This lack of symmetry results from the bottom initiation of the explosive.

Figure 14a presents the vector velocities in the sandstone material. Finally, Fig. 14b shows the calculated extent of failure (material which has exceeded or is exceeding the shear strength failure surface at 2 msec). Return of the surface-reflected tensile wave is not complete at this time, and further extension of the failed region is still occurring. Similar

Fig. 11. A portion of the original grid for two-dimensional calculations (time = 0 msec.) The nodal points represent the intersection of the K and L grid lines.

Fig. 12. Controlled blasting in a uniform sandstone with nitromethane explosive. Contour plots of pressures at 2 msec (Range: 1 to 1000 bar).

Fig. 13. Controlled blasting in a uniform sandstone with nitromethane explosive. Contour plots of maximum volumetric strain $(-\Delta V/V)$ experienced by each zone between 0 and 2 msec (range: 10^{-5} to 10^{-2}).

Fig. 14. Controlled blasting in a uniform sandstone with nitromethane explosive. (a) Vector velocity field at 2 msec (Range: 20-200 cm/sec). (b) Material state: zones that have undergone failure at 2 msec.

calculations have been performed for top-initiated explosive cylinders; results reveal pronounced changes in the stress wave propagation and the failure region, with an inverted or downward-directed shock pattern. Lesser efficiency of tensile wave (surface reflection) breakage near the surface was also observed.

Another goal of the two-dimensional calculations is to examine the effects of presplit surfaces (fracture planes which do not support shear) and of buffer zones (regions of crushed rock) laterally displaced from the main explosive charge. Presplit surfaces are used to assure smooth faces at the sides of a cut, while buffer zones (created by a previous smaller blast) may be utilized to attenuate the stress wave and protect the integrity of a presplit surface beyond the buffer zone. The presplit is computationally simulated by means of a slip line (a frictionless surface which does not transmit shear) at the appropriate location in the problem. Buffer zones are modeled by inserting into the problem a region of the crushed material described earlier.

Two-dimensional calculations are required to fully analyze the buffer zone and presplit effects, since the surface-reflected tensile wave is quite important in fracturing at long ranges. It is hoped that the two-dimensional results will give insight into the relationships between material properties, stress propagation, and failure. This insight, in turn, should enable us to accurately define the desirable properties for a buffer zone and to design more efficient field blasting configurations.

Calculations for presplit and buffer zone plus presplit configurations are currently in progress. Figures 15 through 17 show the 2 msec pressure contours, maximum compression, vector velocities, and extent of fracturing for a bottom-detonated event with simulated presplit (no buffer zone). Comparison of these results with Figs. 12-14 reveals very significant modifications to the stress transmission, vector velocity field, and extent of fracture. Pressures and peak compressions are noticeably decreased beyond the slip surface in the upper portion of the problem, where

Fig. 15. Controlled blasting in a sandstone with pre-split surface, nitro-methane explosive. Contour plots of pressures at 2 msec (range: 1 to 1000 bar).

Fig. 16. Controlled blasting in a sandstone with pre-split surface, nitro-methane explosive. Contour plots of maximum volumetric strain $(-\Delta V/V)$ experienced by each zone between 0 and 2 msec (range: 10^{-5} to 10^{-2}).

Fig. 17. Controlled blasting in a sandstone with pre-split surface, nitromethane explosive. (a) Vector velocity field at 2 msec (Range: 20-200 cm/sec). (b) Material state: zones that have undergone failure at 2 msec.

the shock front crosses the slip at an acute angle. This effect is most apparent in the important spall region close to the ground surface: material motion occurs primarily parallel to the slip surface; stress relief across the slip abruptly truncates pressure contours and reduces peak material compressions to negligible levels. Velocities in the near-surface region beyond the slip are likewise substantially reduced (Figs. 14 and 17). Spall-induced upward motion and material displacement inside the slip are enhanced. Stress relief across the slip also reduces peak shear stresses and halts calculated shear failure beyond the slip, except for a narrow region in the constrained lower section of the grid, where the shock crosses the slip in a more nearly normal direction (Fig. 17b).

IV. SUMMARY

These computations represent a substantial beginning in the effort to make accurate quantitative predictions for controlled blasting. However, only a few material types have been investigated through the one-dimensional calculations; only one geometry and one sandstone medium have thus far been considered in the two-dimensional case. In addition, such phenomena as tensile cracking and spallation have not been studied adequately. The one- and two-dimensional codes are capable of modeling these phenomena, but criteria for assessing tensile damage have not yet been fully established. Correlation with field experimental data is required to improve predictive capability in this area. With a moderate effort to develop these computational tools and apply them to an experimental program, the science of controlled blasting could be greatly advanced.

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