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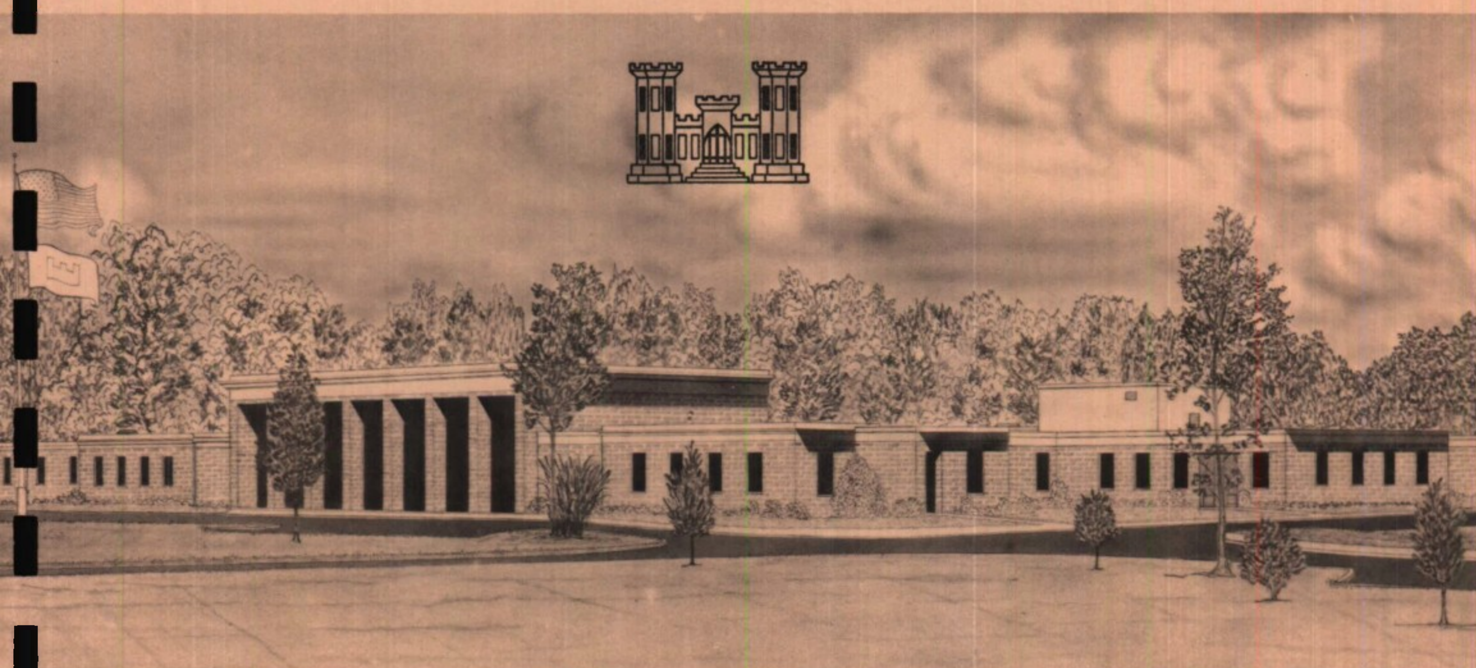
DECOUPLING OF GROUND SHOCK FROM EXPLOSIONS IN ROCK CAVITIES

by

J. L. Drake



January 1974

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Conducted by U. S. Army Engineer Waterways Experiment Station
Weapons Effects Laboratory
Vicksburg, Mississippi

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Foreword

This report is part of a paper presented at the Department of Defense Explosives Safety Board Sponsored 15th Annual Explosive Safety Seminar held in San Francisco, Calif., on 18-20 Sep 1973. The reported research is a generalization of a formulation of a model for stress wave propagation in jointed rock which was sponsored by the Office, Chief of Engineers (OCE), Military Construction Directorate, under Nuclear Construction and Engineering Project A880, work unit, "Vulnerability of Deep Underground Structures in Rock," which was monitored by Mr. D. S. Reynolds, OCE.

This report was written by Mr. J. L. Drake under the general supervision of Mr. L. F. Ingram, Chief, Phenomenology and Effects Division and Mr. W. J. Flathau, Chief, Weapons Effects Laboratory, U. S. Army Engineer Waterways Experiment Station (WES).

COL G. H. Hilt, CE, was Director of WES during the preparation and publication of this report. Mr. F. R. Brown was Technical Director.

Contents

Notation

a	Initial cavity radius
c	Compressional wave speed
c_e	Detonation velocity
F	Arbitrary function
k	A constant
P_e	Detonation pressure
r	Radial coordinate
$\tilde{r}$	Dimensionless radial coordinate
t	Time
u	Radial particle displacement
v	Radial particle velocity
v_{max}	Peak particle velocity
v_0	Peak particle velocity of cavity wall for tamped explosion
$v_0(t)$	Particle velocity of cavity wall
$\tilde{v}_0$	Dimensionless particle velocity
$v_0(\rho_\ell)$	Peak particle velocity of cavity wall for decoupled explosions
α	Time constant
$\tilde{\alpha}$	Dimensionless time constant
γ	Ratio of specific heats of the explosion gases
ρ	Density of rock medium
ρ_ℓ	Loading density of explosive
ρ_0	Density of condensed explosive
$(\rho c)_e$	Impedance of explosive
$(\rho c)_r$	Impedance of rock
σ	Peak stress in rock
τ	Reduced time
τ_+	Positive duration of particle velocity

Summary

Decoupling explosive energy by detonating charges in cavities larger than the charge is an effective method for reducing ground shock magnitudes over those of fully contained bursts. The blasting industry deliberately decouples explosives in presplitting, smooth wall, and cushion blasting operations. This method has been explored as a possible method for concealment of underground nuclear explosions. Decoupling can be an effective means of significantly reducing the energy coupled into the earth by accidental explosion of magazines.

This paper presents an analysis of ground motions generated by decoupled explosions in rock cavities. A simplified elastic solution is used to calculate particle motion magnitudes and time histories produced by an explosion in rock as a function of the initial cavity radius and the loading density of the explosive. Loading density is defined as the total explosive weight divided by the initial cavity volume. Initial cavity conditions were estimated from the adiabatic expansion of the explosive products as an ideal gas for slightly decoupled conditions, and empirical data were used to extrapolate initial cavity conditions to low loading densities.

Results compare favorably with data obtained from decoupling experiments in three different rock types where sources ranged from small high-explosive charges to low-yield nuclear explosions. Spatial attenuation of peak particle velocity or strain and positive duration of particle motion are dependent upon the initial cavity size and magnitude of motion on the loading density.

DECOUPLING OF GROUND SHOCK FROM EXPLOSIONS IN ROCK CAVITIES

Introduction

1. Decoupling explosive energy by detonating charges in cavities larger than the charge is an effective method for reducing ground shock magnitudes over those of fully contained bursts. The blasting industry deliberately decouples explosions iin presplitting, smooth wall, and cushion blasting operations. This method has been explored as a possible method for concealment of underground nuclear explosions. Decoupling can be an effective means of significantly reducing the energy coupled into the earth by accidental explosions of magazines.

2. This report presents an analysis of ground motions produced by decoupled explosions in rock cavities. A simplified elastic solution is used to calculate particle motion magnitudes and time histories produced by an explosion in rock as a function of the initial cavity radius and the loading density of the explosive. Initial cavity conditions were estimated from the adiabatic expansion of the explosive products, and empirical data from decoupling experiments were used to extrapolate initial cavity conditions to low loading densities. This presentation is not intended to be a rigorous solution of the decoupling problem but rather a semi-empirical method which is relatively simple and accurate for estimating ground motions from explosions in cavities.

Elastic Solution

3. The general solution to the elastic wave equation in spherical coordinates is (see reference 1 for example):

$$u(r,t) = \frac{\partial}{\partial r} \frac{1}{r} F\left(t - \frac{r - a}{c}\right) \qquad (1)$$

where

u = radial particle displacement

r = radial coordinate

t = time

a = initial cavity radius

c = compressional wave speed

$F(\tau)$ is an arbitrary function of the argument $\tau = t - \left[(r - a)/c\right]$, which is the reduced time. Expressions for particle strain, velocity, stress, etc., can be written directly from equation 1.

4. Particle velocity is used in this study because it is the most commonly measured and best understood ground motion parameter. It can be determined by differentiation of equation 1 as:

$$v(r,t) = -\frac{1}{r^2}\left[F'(\tau) + \frac{r}{c}F''(\tau)\right] \tag{2}$$

where a primed notation indicates differentiation with respect to the argument. This expression is an ordinary differential equation which can be easily integrated to determine $F(\tau)$ if the particle motion is specified at some point in the medium. Assuming the particle velocity at the cavity boundary is $v(a,t) = v_0(t)$, then integration of equation 2 gives:

$$F'(t) = -\,cae^{-ct/a}\int_0^t v_0(\eta)e^{c\eta/a}\,d\eta \tag{3}$$

Because of the sensitivity of the decoupling phenomenon to the initial cavity radius, it is convenient to integrate equation 3 by parts to obtain a series expansion in powers of the small term (a/c). This procedure greatly simplifies the resulting expressions for estimating particle velocity at large distances. Noting that

$$\int_0^t v_0(\eta)e^{c\eta/a}\,d\eta = \frac{a}{c}\,e^{ct/a}\left[v_0(t) - \left(\frac{a}{c}\right)v_0'(t) + \left(\frac{a}{c}\right)^2 v_0''(t) + \ldots\right] \tag{4}$$

From (2) and (3) with $\tau = 0$, $v\left(r, \frac{r-a}{c}\right) = \frac{a}{r}\,v(a,0)$ (cf. (8))

assuming the medium was initially quiet at $t \leq 0$, a formula for particle velocity can easily be found by substituting the series in equation 4 into equations 2 and 3 as:

$$v(r,t) = \left(\frac{a}{r}\right)^2 \left[v_0(\tau) + \frac{r-a}{c} v_0'(\tau) - \frac{a}{c}\,\frac{r-a}{c} v_0''(\tau) + \ldots\right] \qquad (5)$$

5. Previous investigations (reference 2) have shown that an input particle velocity function of the form

$$v_0(\tau) = v_0 e^{-\alpha^2\tau^2} \qquad (6)$$

was adequate for describing particle motions from contained explosions. Here it is assumed that the peak particle velocity at the cavity boundary v_0 and the time constant α are functions of the loading density of the explosion. Substituting equation 6 into equation 5 gives:

$$v(r,t) = v_0\left(\frac{a}{r}\right)^2 \left[1 + 2\alpha^2 \frac{r-a}{c}\left(\frac{a}{c} - \tau - 2\alpha^2\tau^2\right) + \ldots\right] e^{-\alpha^2\tau^2} \; ; \; \tau > 0 \qquad (7)$$

Note that the peak particle velocity occurs at $\tau = 0$, which is the arrival of the wave at radius r and is given by:

$$v_{max} = v_0\left[\frac{a^2}{r^2} + \frac{2\alpha^2 a^2}{c^2}\left(\frac{a}{r}\right) + \ldots\right] \qquad (8)$$

Initial Cavity Conditions

6. In general, initial cavity conditions, v_0 and α, are functions of the loading density and detonation characteristics of the explosive as well as the elastic constants of the rock. The initial cavity velocity is proportional to the peak gas pressure in the cavity. Assuming that the adiabatic expansion of an ideal gas can be used to estimate the pressure in the decoupled cavity, the peak velocity at the cavity boundary is given by:

Exact soln with (6) where $\phi(x) = \exp(x^2)\,\mathrm{erf}(x)$

$$v(r,t) = v_0 \frac{a}{r} e^{-\alpha^2\tau^2} + \frac{v_0 c\sqrt{\pi}}{2\alpha r}\left(1 - \frac{a}{r}\right) \times \left[e^{-\alpha^2\tau^2}\phi\left(\frac{c}{2a\alpha} - \alpha\tau\right) - e^{-c\tau/a}\phi\left(\frac{c}{2a\alpha}\right)\right]$$

$$\frac{v_0(\rho_\ell)}{v_0} = \left(\frac{\rho_\ell}{\rho_0}\right)^\gamma \tag{9}$$

where

$v_0, v_0(\rho_\ell)$ = particle velocity parameters for the fully coupled and decoupled charges, respectively

ρ_0, ρ_ℓ = explosive density and loading density, respectively

γ = ratio of specific heats of the explosion gases

Loading density is defined as the weight of the explosive divided by the cavity volume.

7. The particle velocity parameter for the fully coupled condition can be estimated from the detonation pressure and the characteristic shock wave impedances of the explosive and rock. The detonation wave in the explosive is partially reflected and partially transmitted by the rock medium. Considering this reflection process to be acoustic, the peak pressure σ in the rock is:

$$\sigma = \rho c v_0 = 2P_e \left[1 + \frac{(\rho c)_e}{(\rho c)_r}\right]^{-1} \tag{10}$$

where

P_e = detonation pressure

$(\rho c)_r, (\rho c)_e$ = characteristic impedances of the rock and explosive, respectively

The impedance of the explosive is taken as the product of the density ρ_0 and the detonation velocity c_e. For most explosives, the detonation pressure can be expressed as:

$$P_e = k\rho_0 c_e^2 \tag{11}$$

where k is a constant less than unity. Combining equation 11 with equation 10, v_0 is given as:

$$\frac{v_0}{c} \approx 2k \frac{c_e}{c} \left[1 + \frac{(\rho c)_r}{(\rho c)_e}\right]^{-1} \tag{12}$$

The constant k was determined as

$$k = \frac{3}{8} \tag{13}$$

by comparing equation 8 with experimental peak particle velocity data from fully coupled experiments in granite (reference 3), salt (references 4 and 5), tuff (reference 6), and alluvium (reference 7).

Comparison with Decoupling Experiments

8. It is convenient to introduce the dimensionless scaled variables

$$\tilde{v}_0 = \frac{v_0}{c} \quad ; \quad \tilde{r} = \frac{r}{a} \quad ; \quad \tilde{\alpha} = \alpha \frac{a}{c} \tag{14}$$

and rewrite the equation for peak particle velocity (equation 8) as:

$$v_{max} = \frac{\tilde{v}_0 c}{\tilde{r}^2} \left(1 + 2\tilde{\alpha}^2\tilde{r} + \ldots\right) \tag{15}$$

This expression was compared with data from decoupling experiments to establish a functional form for $\tilde{\alpha}(\rho_\ell)$ and to verify the dependency of the particle velocity parameter on loading density as given by equation 9.

9. Relative peak strain and particle velocity data from experiments in granite (reference 8), limestone (reference 8), and both nuclear (reference 9) and conventional (reference 10) explosions in salt are shown in fig. 1 as a function of the relative loading density of the explosive. These data follow equation 9 quite nicely for an overall value of the ratio of specific heats of the explosion gases of 1.2 over a large range of relative density. Considering that several different explosive types (both nuclear and chemical) were used, the scatter in the data is quite acceptable.

10. Values of peak particle velocity calculated using equation 15 are compared with experimental data from the Cowboy (reference 10)

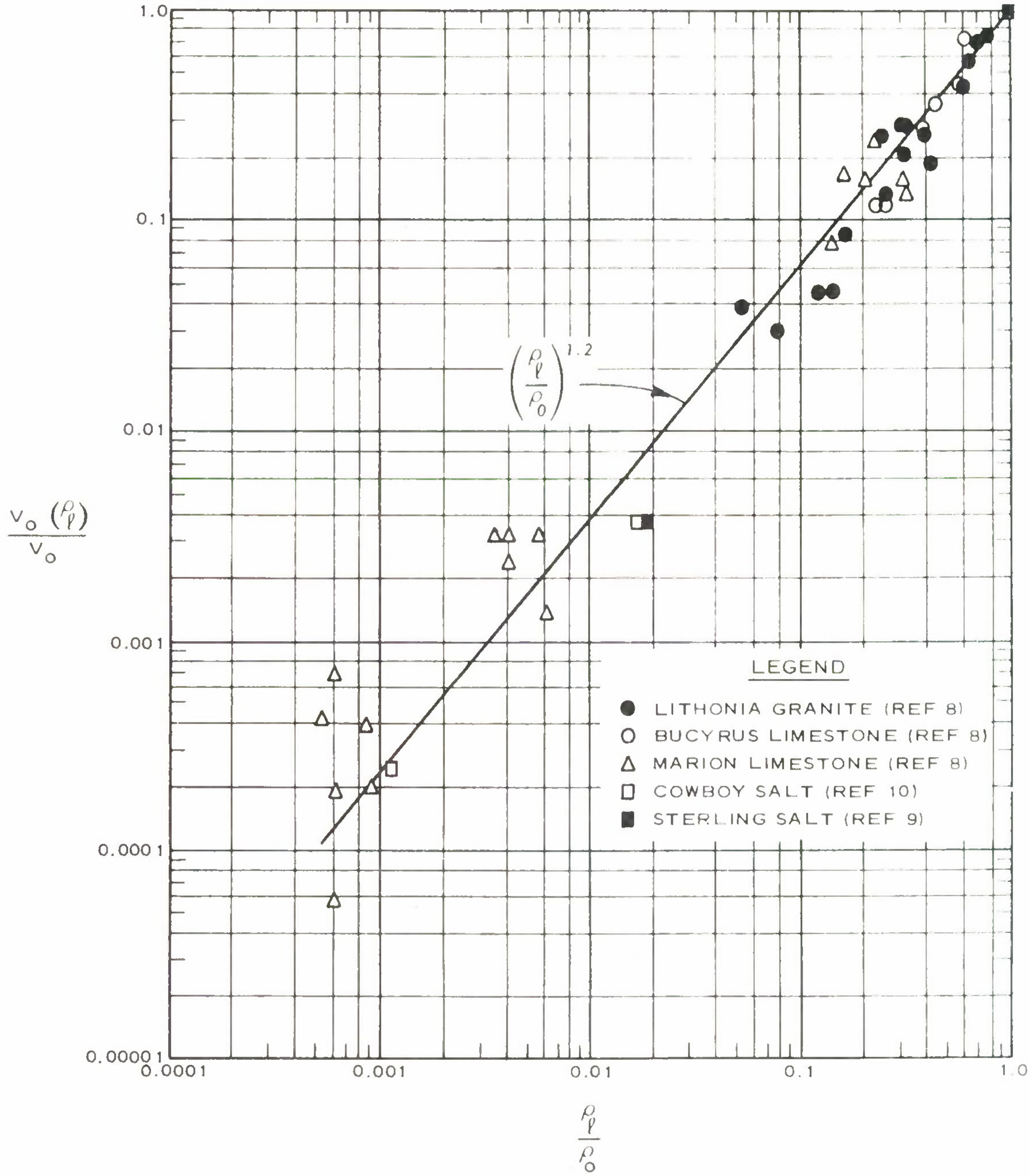

Fig. 1. Relative peak particle velocity versus relative loading density

high-explosive experiments in rock salt (see fig. 2). The calculated curves are in good agreement with data over a range of relative loading densities from 0.1 percent to fully coupled. Note that the (a/r) term becomes more and more dominant as the relative loading density decreases, indicating the increasing influence of $\tilde{\alpha}$.

11. The time constant parameter $\tilde{\alpha}$ is difficult to determine with any degree of confidence. Data as reported by the Bureau of Mines (reference 8) were taken from long cylindrical explosives, which adds uncertainty in the reported periods. Values from the Cowboy experiments (reference 4) suggest that

$$\tilde{\alpha} = 0.08\left(\frac{\rho_0}{\rho_\ell}\right)^{1/3} \tag{16}$$

which is verified by data from coupled explosions in tuff (reference 6).

Conclusions

12. A simplified elastic theory is presented for calculating particle motion magnitudes and time histories produced by an explosion in rock as a function of the initial cavity radius and loading density of the explosive. Initial cavity conditions estimated from the adiabatic expansion of the explosive products compared favorably with data obtained from decoupling experiments in three rock types where sources ranged from small high-explosive charges to low-yield nuclear explosions. An average ratio of specific heats of the explosion gases of $\gamma = 1.2$ was found to fit experimental data over a range of loading densities from 0.05 to 100 percent of the condensed explosive. The scaled time constant was found to vary as the inverse cube root of the relative loading density.

13. Combining the results of the elastic calculation for peak particle velocity and estimates of coupling effects on initial cavity parameters, a formula for predicting particle velocity magnitudes is found as:

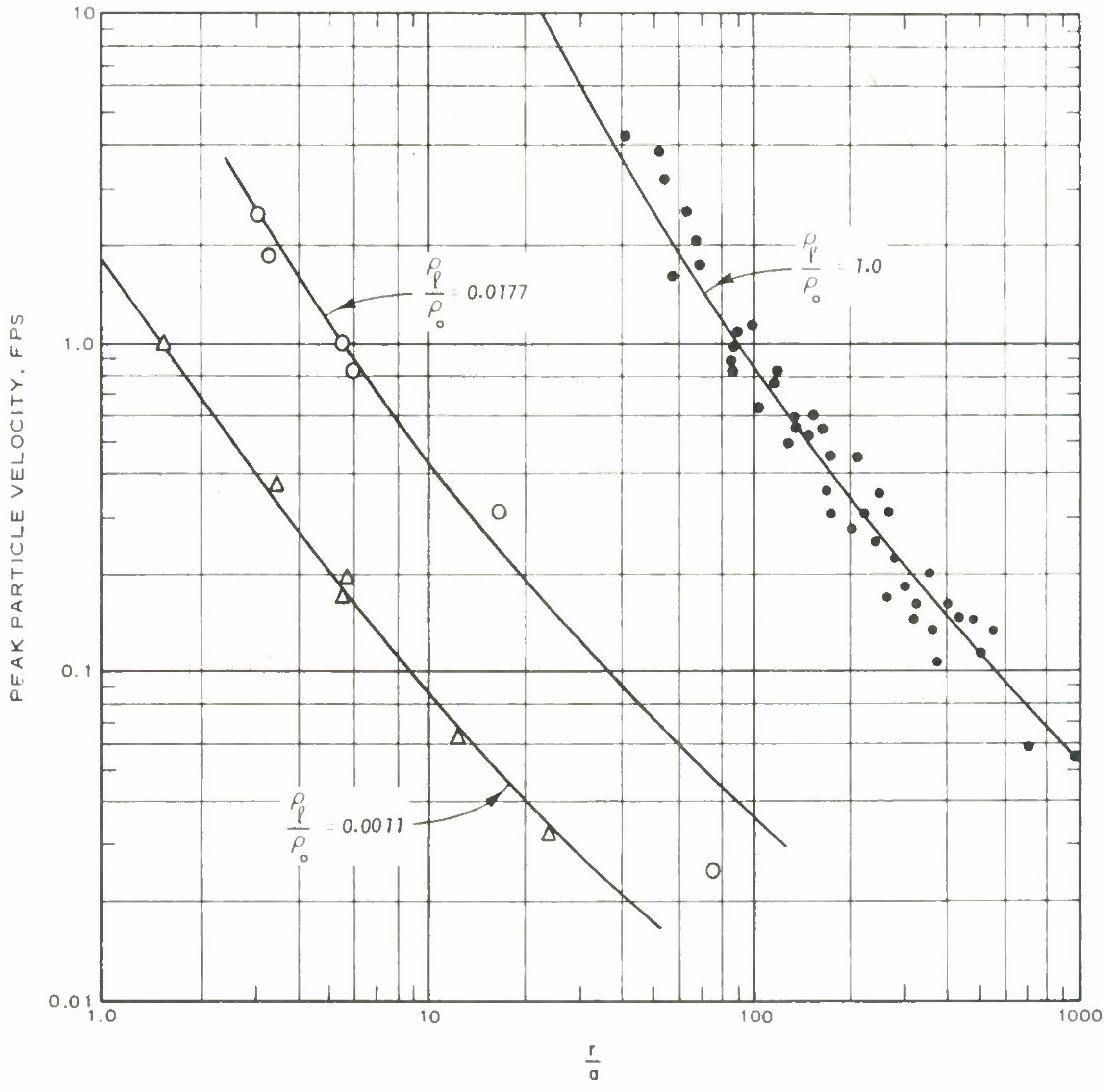

Fig. 2. Peak particle velocity for Project Cowboy

$$v_{max} = v_0 \left(\frac{\rho_\ell}{\rho_0}\right)^\gamma \left[\left(\frac{a}{r}\right)^2 + 0.0128 \left(\frac{\rho_0}{\rho_\ell}\right)^{2/3} \left(\frac{a}{r}\right)\right] \tag{17}$$

where v_0 can be calculated from the detonation velocity and initial density of the explosive by the expression given in equation 12. It can be seen that for $\gamma = 1.2$ the peak particle velocity decreases inversely as the cavity radius to the 1.6 power at close ranges and decreases inversely as the cavity radius to the 0.6 power at large distances from the detonation. The $1/r$ term becomes more dominant for low relative values of the loading density.

14. The predicted particle velocity time history has an abrupt rise followed by an exponentially decaying pulse which has a positive duration of:

$$\tau_+ = \frac{c}{2\alpha^2 r} + \frac{a}{c} = \frac{a}{c}\left[1 + 78\left(\frac{\rho_\ell}{\rho_0}\right)^{2/3}\left(\frac{a}{r}\right)\right] \tag{18}$$

which has a component due to the cavity size and a second term which decreases with range and is independent of the initial cavity radius. This result is verified by the Cowboy (reference 4) and Sterling (reference 9) decoupling experiments in salt where decoupled periods decreased to the value of a/c . A rise time can be added to the predicted pulse without difficulty. It is shown, in reference 1 that the rise time parameter for fully coupled charges is dependent upon the rock jointing patterns and is independent of the explosive size.

Literature Cited

1. U. S. Army Engineer Waterways Experiment Station, CE, "Feasibility of Modeling Cavity Behavior in Jointed Rock Masses," Contract Report No. 1-135, Nov 1965, Vicksburg, Miss.; prepared under Contract No. DA-22-079-eng-225, by N. M. Newmark and Associates, Urbana, Ill.

2. Drake, J. L., "Mathematical Model for Describing Stress Wave Propagation in a Jointed Rock Mass," Technical Report N-73-7, Oct 1973, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

3. Murrell, D. W. and Carleton, H. D., "Operation Mine Shaft; Ground Shock from Underground and Surface Explosions in Granite," Technical Report N-73-2, Apr 1973, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

4. Nicholls, H. R., Hooker, V., and Duvall, W. I., "Project Cowboy, Dynamic Rock Mechanics Investigations," APRL Report No. 38-3.2, 1 Sep 1960, U. S. Bureau of Mines, Applied Physics Research Laboratory, College Park, Md.

5. Murphey, B. F., "Particle Motions Near Explosions in Halite," Journal of Geophysical Research, Vol 66, No. 3, Mar 1961, pp 947-958.

6. Swift, L. M. and Wells, W. M., "Close-In Earth Motions, Project Hobo," Report No. UCRL 6397, Mar 1961, Stanford Research Institute, Menlo Park, Calif.

7. Kintzinger, P. R., "Air Vent Phase I, Project I, Earth Particle Motion," Research Report SC-RR-64-549, Oct 1964, Sandia Corporation, Albuquerque, N. Mex.

8. Atchison, T. C., Duvall, W. I., and Pugliese, J. M., "Effects of Decoupling on Explosion-Generated Strain Pulses in Rock," Report of Investigations RI-6333, 1964, U. S. Bureau of Mines, Washington, D. C.

9. Perret, W. R., "Free Field Ground Motion Study, Project Sterling," Research Report SC-RR-68-410, Oct 1968, Sandia Laboratories, Albuquerque, N. Mex.

10. Herbst, R. F., Werth, G. C., and Springer, D. L., "Use of Large Cavities to Reduce Seismic Waves from Underground Explosions," Journal of Geophysical Research, Vol 66, No. 3, Mar 1961, pp 959-978.

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Decoupling explosive energy by detonating charges in cavities larger than the charge is an effective method for reducing ground shock magnitudes over those of fully contained bursts. The blasting industry deliberately decouples explosives in presplitting, smooth wall, and cushion blasting operations. This method has been explored as a possible method for concealment of underground nuclear explosions. Decoupling can be an effective means of significantly reducing the energy coupled into the earth by accidental explosion of magazines. This paper presents an analysis of ground motions generated by decoupled explosions in rock cavities. A simplified elastic solution is used to calculate particle motion magnitudes and time histories produced by an explosion in rock as a function of the initial cavity radius and the loading density of the explosive. Loading density is defined as the total explosive weight divided by the initial cavity volume. Initial cavity conditions were estimated from the adiabatic expansion of the explosive products as an ideal gas for slightly decoupled conditions, and empirical data were used to extrapolate initial cavity conditions to low loading densities. Results compare favorably with data obtained from decoupling experiments in three different rock types where sources ranged from small high-explosive charges to low-yield nuclear explosions. Spatial attenuation of peak particle velocity or strain and positive duration of particle motion are dependent upon the initial cavity size and magnitude of motion on the loading density.

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