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Lewis A. Glenn

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THE INFLUENCE OF ROCK MATERIAL MODELS ON SEISMIC DISCRIMINATION OF UNDERGROUND NUCLEAR EXPLOSIONS

L. A. Glenn

Lawrence Livermore National Laboratory, Earth Sciences Division, Livermore, California 94550

We found that the spectral characteristics of the seismic signal from underground explosions were mainly determined by the rock material strength and the gas porosity. Both the unloading characteristics and the amplitude of the "elastic toe" are important parameters in the porous model.

INTRODUCTION

Physical models of explosion sources are needed to explain the variations in performance of existing discriminants in different regions and to help develop more robust methods for identifying underground explosions. In a previous study (1), we used numerical simulations to assess the sensitivity of explosion source functions to material properties including the equations of state of explosion products and rock media surrounding the explosion, and the constitutive properties of the rock, including compressive and tensile strength and porosity. The calculated explosion spectra were compared with experimental results derived from free-field particle acceleration and regional seismic data from nuclear- and chemical-explosion experiments conducted on Rainier Mesa of the Nevada Test Site. We found that the high-temperature equations of state for both the explosions and the rock had relatively little influence on the spectral characteristics of the seismic signal. The most important rock material properties are the strength (which largely determines the corner frequency) and the gas porosity. A modified p - α model was used to describe the porous rock, but we have recently deduced that this model does not adequately represent the unloading behavior, which was found to have significant

influence on the shape of the seismic spectrum, especially at long periods. Another important parameter in the porous model is the amplitude of the "elastic toe" below which the pressure behaves in strictly elastic fashion. This parameter is normally not very well defined by experiment, but was observed to have an important effect on the long period amplitude. In what follows we discuss these latter results in some detail.

MATERIAL MODELS

We employed tabular equations of state for both the explosion device and the surrounding rock (at least above the melting point), that were fitted to previously obtained shock Hugoniot and elastic-wave data. The shock-wave data are relatively insensitive to small-scale inhomogeneities, so that it is generally possible to determine the high-pressure properties of the rock quite accurately. The elastic moduli are also known accurately via wave speed measurements. By contrast, it is difficult to obtain unambiguous strength or porosity data due mainly to spatial inhomogeneities inherent at most field sites.

In our model, the compressive strength of the rock depends on the pressure, temperature, and on a damage parameter that measures the degradation due to tensile or shear failure. Specifically,

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$$\sqrt{3J_2} \leq Y = (1-D)\bar{Y} + \beta D\bar{Y} \quad (1)$$

where $J_2 = (1/2)\sigma' \cdot \sigma'$, σ' is the deviatoric stress tensor, β is a constant, typically 0.25, and D is a scalar function of the volumetric component of the void and equivalent plastic strain tensors (2); typically, $D = \min\{(\epsilon_{ii}^V + \epsilon_{ii}^P) / \epsilon_{mx}, 1\}$ and the order of ϵ_{mx} varies between 0.01 and 0.1. Tensile fracture is allowed along three orthogonal axes, and cracks are allowed to open and close; once opened, however, the tensile strength normal to the plane of opening is zero. The generalized compressive strength is:

$$\bar{Y} = \left[Y_0 + \frac{p}{a + \left(\frac{p}{Y_u - Y_0} \right)} \right] \max \left[(1 - T/T_m)^b, 0 \right] \quad (2)$$

Y_0 is the unconfined compressive strength, Y_u is the ultimate compressive strength, and $T_m(p)$ is the melting temperature. p is the pressure and the parameters a (the cohesion) and b are constants.

At low pressures, and for generally porous rocks, the scalar part of the stress tensor is based on the well-known p - α concept (3):

$$p(v, e) = p_m(v/\alpha, e)/\alpha = p_m(v_m, e_m)/\alpha \quad (3)$$

and

$$\alpha = \alpha(p) \quad (4)$$

where $v = 1/\rho$ is the specific volume, e is the specific internal energy, and the subscript m refers to the matrix material in which the pores are embedded. The parameter α is related to the gas porosity, Ψ , and is defined by the relation

$$\alpha \equiv v/v_m = \rho_m/\rho = (1 - \Psi)^{-1} \quad (5)$$

At ambient pressure, $\alpha = \alpha^0$, the initial value, and at some high pressure, p_c , the pores will be completely crushed and $\alpha(p_c) = 1$. For $p > p_c$, the Grüneisen form, p_m , employed in equation (3) smoothly transitions into the tabular form $p_m(\rho, T)$. Equations (4) and (5) apply to loading for $p < p_c$, but to unloading only when $p < p_{el}$; in this small, but important, range (termed the elastic toe) the pore volume behaves in strictly elastic

fashion. In the range $p_{el} \leq p < p_c$, unloading occurs at constant gas porosity. No specific representation was made for saturated or partially saturated porous media other than to adjust the tabular equation of state and Grüneisen and strength parameters accordingly, assuming a homogeneous mixture of rock and water. Effective stress theories have also been used to deal with water-filled pore structures, but we have not found these to provide any better agreement with experiment.

EXPLOSION SIMULATIONS

Figure 1 illustrates the effect of the ultimate yield strength on the seismic spectra when the porosity is zero. The yield-scaled magnitude of the reduced velocity potential spectrum, $|i\omega\Phi|/W$, is plotted as a function of yield scaled frequency, $fW^{1/3}$, where $f = 2\pi\omega$, and Φ is the Fourier transform of the reduced displacement potential, ϕ . The heavy gray curve is the lognormal average computed from free-field velocity data from 7 gages employed on a nuclear test conducted at Area 12 (Rainier Mesa) of the Nevada Test Site. The medium is partially saturated tuff. All the gages were located at ranges beyond $257 \text{ m/kt}^{1/3}$. The dotted gray curves represent ± 1 standard deviation from the mean. The black curves are calculated spectra obtained from spherical one-dimensional Arbitrary Lagrange Eulerian (ALE) explosion simulations made with the AFTONRS code (4,5), in which the overburden pressure was 4 MPa, roughly half the value in the experiment. (Figure 2 shows that doubling the overburden pressure has insignificant effect on the spectra). It is observed that the corner frequency decreases with decreasing strength, and that a good fit to the experimental corner is obtained with $Y_u = 5 \text{ MPa}$ (solid black curve). Although the amplitude is too high in this case, it will be shown that this can be remedied by a slight increase in porosity.

It should also be noted that the corner frequency was relatively invariant with respect to variations of parameters other than the strength. The effect of gas porosity is shown in Fig. 2. In this case, the overburden pressure was fixed at the nominal

FIGURE 1. Effect on the seismic spectra of varying the ultimate yield strength.

experimental value of 8 MPa and the ultimate compressive strength was 5 MPa. A quite good fit to the experiment is observed for $0 < \Psi < 0.01$; the experimental peak particle velocity data are also bounded by the calculated values in this porosity range. At higher values of Ψ the long-period amplitude is apparently much lower; in Fig. 2, for example, with $\Psi = 0.05$, $\phi_{t \rightarrow \infty} = |i\omega\Phi|_{\omega \rightarrow 0}$ is roughly an order of magnitude greater than with $\Psi = 0$. The difference is much less near the corner frequency. This result has been traced to a problem with the standard form of the p - α model, which yields a discontinuous unloading modulus near the point (p_{el}, α_{el}) . For $p_{el} - \delta p_{el}$, where $\delta p_{el} \rightarrow 0$, unloading occurs at the bulk sound speed in the *in situ* porous medium, whereas for $p_{el} + \delta p_{el}$, and because α remains constant in this region, the unloading bulk sound speed turns out to be very nearly that of the fully compacted medium. A simple modification of equation (3) remedies the (presumably unphysical) situation. If equation (3)

FIGURE 2. Effect on the seismic spectra of varying the gas porosity.

is slightly modified to read

$$p = A(\alpha)p_m/\alpha \quad (6)$$

$$\text{where } A = a + (1-a) \left(\frac{\alpha - \alpha_0}{1 - \alpha_0} \right)^n, \quad (7)$$

$a \equiv (c_0/c_m)^2$, c is the sound speed, and n is a constant < 1 , the unloading bulk modulus transitions smoothly from the fully porous to the fully compacted state. The effect of making this change can be seen in Fig. 3. It is observed that, with the modified model, the steep gradient in the region $0.3 < fW^{1/3} < 3 \text{ m/kt}^{1/3}$ no longer obtains and the effect of increased porosity is similar to that of increasing the yield strength, except that, in this case, the corner frequency is unaffected. High frequency attenuation is also unaffected by the modified p - α model. As expected, both figures 2 and 3 evidence increased attenuation of high frequencies as the gas porosity is increased.

FIGURE 3. Effect on the seismic spectra of modifying the p - α porosity model to eliminate discontinuous unloading near the elastic limit.

Apart from the unloading discontinuity problem near the point (p_{el}, α_{el}) , there is another difficulty with either version of the porous model, i.e., the amplitude of the long-period seismic signal is quite sensitive to the value assigned to p_{el} itself. This is unfortunate, since this parameter is normally not very well defined by experiment. For example, and with the modified model, with $\Psi=0.15$ and $p_{ovb} = 8$ MPa, increasing p_{el} from 11.8 MPa to 19.6 MPa resulted in $\phi_{t \rightarrow \infty}$ doubling from 163 to 317 m^3/kt .

CONCLUDING REMARKS

The most important elements in simulating the seismic response to underground explosions are the representation of material strength and gas porosity. We found it possible to match experimental seismic

spectra and peak velocity data, but the strength that provided the match was roughly an order of magnitude less than that determined via laboratory analysis of core samples taken from the vicinity of the test site. This is not an unusual occurrence and derives from the fact that the rock media in which testing takes place are generally quite inhomogeneous, so that laboratory measurements on core-sized samples may not be representative of the extant rock mass from which the samples derive. We note that this is an inherent limitation in employing simulations to the monitoring function, i.e., simulation of explosions at unidentified (clandestine) locations implies an imperfect knowledge of the *in situ* material properties and emplacement geometry.

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