Status Report on Source Properties Important for Discrimination

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STATUS REPORT ON SOURCE PROPERTIES IMPORTANT FOR DISCRIMINATION*

L. A. Glenn
27 March 1995

INTRODUCTION

To begin, we need to discuss what is meant by source properties important for discrimination. Here we are concerned primarily with discriminating earthquakes from explosions by seismic means. We do not distinguish between chemical and nuclear explosions because, for concentrated explosions, these will appear identical except for a factor of two or so in the long-period amplitude (which will not be identifiable at a distant seismic station). Ripple-fired chemical explosions may, in theory, be distinguished from concentrated explosions by the spectral modulation that is produced by the former, however we specifically exclude spatio-temporal organization and other geometric effects and concentrate on material properties that have important influence on characteristics of the seismic signal which might allow explosions to be distinguished from earthquakes. The most prominent of these are the corner frequency of the seismic spectrum, the high-frequency roll-off, and the long-period overshoot.

Both quasi-analytical¹ methods and finite difference numerical solutions of the hydrodynamic equations¹⁻⁶ were used to explore the effects of the:

1. equation of state of the explosion products
2. equation of state of the rock media surrounding the explosion
3. energy and mass density of the explosion source
4. constitutive properties of the surrounding rock media, including
 - a. compressive and tensile strength
 - b. porosity
 - c. dilatancy
 - d. elastic moduli
5. depth of burial (lithostatic overburden)

The calculations performed thus far assumed one-dimensional radial symmetry for the most part so that, in addition to geometric details of the source excluded from consider-

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ation, depth effects on spall are excluded as well. It is also important to understand that many of the factors itemized above are not single-valued parameters, but rather models for which several parameters normally need to be specified. This is obviously the case for the high-temperature equations of state, where tabular constructions are the most accurate representations, but also for the strength, porosity and dilatancy (which turn out to have much more important influence for seismic discrimination purposes. The models employed are not unique and this further complicates any discussion of source properties. For our analysis we have chosen models that offer a wide range of parametric behavior and also that have generally given good agreement with experiment. It must be admitted, however, that field data are relatively sparse and that models that agree well with laboratory-scale experiments do not always perform well at field scale. The main reason for this is probably the inhomogeneous nature of most rock formations. Model parameters are often set via laboratory analysis of rock cores that have dimension of only a few millimeters whereas field-scale modeling considers elements larger by several orders of magnitude. When the rock properties vary considerably between these scales good agreement in results should not be expected.

MATERIAL MODELS

The most important rock material properties are the strength, gas porosity, and possibly the dilatancy. We found that the high-temperature equations of state for both the explosion products and the rock have relatively little influence on the spectral characteristics of the seismic signal. We generally 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 even the rock quite accurately. The elastic moduli are also known accurately via wave speed measurements. By contrast, and as noted above, it is difficult to obtain unambiguous strength or porosity data due mainly to the spatial inhomogeneities inherent at most sites.

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

$$\sqrt{3J'_2} \leq Y = (1 - D)\bar{Y} + \beta D\bar{Y} \quad (1)$$

where $J'_2 \equiv \frac{1}{2}\sigma'_{ij}\sigma'_{ij}$, σ' is the deviatoric stress tensor, β is a constant, and D is a scalar function of the volumetric component of the void strain tensor⁷. 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. In three

dimensions, the cracks are free to rotate with the deforming media (with one dimensional radial symmetry, no such rotation is obviously possible) and frictional contact on sliding crack surfaces is allowed. Typically, $D = \epsilon_{ii}^V / \epsilon_{max}^V$ and ϵ_{max}^V is assumed to be on the order of 10^{-2} . Also,

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

Y_0 is the unconfined compressive strength, Y_u is the ultimate compressive strength, T is temperature, and $T_m(p)$ is the melting point.

At low pressures, and for generally porous rocks, the scalar part of the stress tensor is based on the well-known $p - \alpha$ concept⁸:

$$p(\nu, e) = p_m(\nu/\alpha, e)/\alpha = p_m(\nu_m, e_m)/\alpha \quad (3)$$

and

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

where $\nu = 1/\rho$ is the specific volume, and the subscript m refers to the matrix material in which the pores are embedded. For efficient solution we have employed a quadratic form of the Grüneisen equation for p_m in (3) and a piecewise linear representation of the "crush curve" (4). The parameter α is related to the gas porosity, Ψ , and is defined by the relation

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

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 $p_m(\rho, T)$. No specific representation was made for saturated or partially saturated porous media other than to adjust the tabular equation of state and Grüneisen parameters accordingly, assuming a homogeneous mixture of rock and water, and to reduce the strength in accordance with laboratory data. Effective stress theories have sometimes been used to deal with saturated rock media, but we have not found these to provide any better agreement with experiment.

Equations (3) and (4) apply to loading for $p < p_c$, but to unloading only when $p < p_{el}$; in this small, but important, range the pore volume behaves in strictly elastic fashion. In the range $p_{el} \leq p < p_c$, unloading occurs at constant gas porosity.

The results obtained with this model were described in detail when applied to an analysis of the Non-Proliferation Experiment(NPE) and a nearby nuclear explosion⁵. Numerous simulations were made and compared with experiment. We found that the

asymptotic (long period) value of the reduced displacement potential, ϕ_∞ , for explosions with the ANFO blasting agent used in the NPE, was larger than that derived for a tamped nuclear explosion of the same yield by a factor of 1.9, in good agreement with the experimental results derived from free-field particle velocity measurements, and also with $m_b(P_n)$ data from the Livermore Nevada Network (LNN). Beyond the corner frequency, the spectra calculated for the chemical and nuclear explosions were indistinguishable, also in good agreement with experiment. It was found possible to match the spectral characteristics by varying both the yield strength and the gas porosity, but the strength required to obtain this match was considerably less than measured in laboratory experiments with small cores pulled from the vicinity of the emplacement. As noted above, however, previous experience has shown that laboratory measurements on core-sized rock samples may not be representative of the extant rock mass from which the samples derive.

Further studies with this model have pointed out some difficulties⁹. We have found that the amplitude of the long-period seismic signal is extremely sensitive to the value assigned to p_{el} , an unfortunate circumstance since this parameter is normally not very well defined by experiment. Another problem with this *standard* form of the $p - \alpha$ model is the discontinuous unloading modulus that derives 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. The effect of this artifact is to significantly reduce the long-period amplitude of the reduced displacement potential and to thereby induce an artificial overshoot in the Fourier spectrum. When the model was modified to allow smooth transition of unloading bulk moduli from the fully porous to the fully compacted states, the artificial overshoot disappeared.

Laboratory experiments on porous rock samples that are repeatedly loaded and unloaded, at various stress levels in the partially compacted state, exhibit much more complex unloading behavior than the simple models described above. We found that *ad hoc* representations of this behavior had a significant influence on the shape of the seismic spectrum, especially at long periods. These shape factors may be important for discrimination purposes, so we are planning to implement a physically based porosity model that includes more accurate representation of the unloading/reloading process and also better accounts for effects of partial saturation.

Finally, we should remark on some recent work done in collaboration with the Moscow Engineering Physics Institute¹⁰ under the auspices of the International Science and Technology Center. This work describes a model of brittle failure in which the influence of dilatancy plays an important role. Normally, the effect of increasing the compressive strength of rock is to reduce the amplitude of the seismic signal. For granitic rocks,

where inelastic dilatancies of up to 20% have been observed dynamically, increasing the strength can be shown to increase the amplitude. Although this behavior appears counter-intuitive, recall that the maximum amplitude of the reduced displacement potential is proportional to the change in volume in the inelastic region induced by the explosion. Large dilatancies can therefore overcompensate for the increasing strength, with the net effect being increased seismic amplitude. Additional work is required to provide experimental confirmation, and to examine the effects of dilatancy on the spectral shape.

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