INCORPORATING THE EFFECTS OF DAMAGE-INDUCED SECONDARY SEISMIC RADIATION INTO NUMERICAL MODELS FOR UNDERGROUND EXPLOSIONS

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ABSTRACT

Secondary seismic radiation is generated by rock fracture in the “damage zone” of an underground nuclear source and by frictional sliding on preexisting fractures in the “non-linear elastic zone” at larger distances from the shot point. This radiation is important for two reasons: (1) Johnson (1997, 1998) has shown that it can make an important contribution to the far-field seismic signal, and (2) Sammis (1998) has argued that it can significantly weaken the granulated rock behind the shock front in the damage zone. This weakening is due to a mechanism called acoustic fluidization originally proposed by Melosh (1979) to explain long-run-out landslides, the fluid morphology of extraterrestrial impact craters, and the low coefficient of effective friction inferred for the San Andreas fault. Such weakening has been shown to be necessary if computer models are to simulate the pulse-broadening observed in the near-field of nuclear explosions in hard rock (Rimer et al., 1987; Rimer et al., 1998). This paper outlines a procedure to incorporate acoustic fluidization into the numerical codes used to simulate underground explosions.

Key Words: seismic sources, discrimination.

OBJECTIVE

The objective of this research project is to understand the physics of rock fragmentation and subsequent deformation in the source region of a nuclear explosion detonated in crystalline rock. Rock fragmentation in the source region is relevant to research in support of the Comprehensive Nuclear-Test-Ban Treaty because it directly affects the seismic radiation observed in both the near and far field in at least two important ways:

1) The fragmentation process itself generates secondary high-frequency P and S waves that may affect seismic discrimination and yield estimates which use high-frequency local crustal phases.

2) Fragmentation behind the advancing shock front leaves a weakened region that is thought to produce the pulse-broadening observed in seismic radiation. A quantitative understanding of this observed pulse broadening is important if the frequency content of the seismic signal is to be used for discrimination and yield estimates.

RESEARCH ACCOMPLISHED

Generation of secondary radiation by the damage process has been modeled by Lane Johnson and the author [Johnson, 1996,1997; Sammis, 1998; Johnson and Sammis, 1999]. We found that secondary seismic energy approaches 10% of the primary radiation.

The micromechanical damage mechanics developed by Ashby and Sammis [1990] has been successfully integrated into the spherically symmetric numerical simulation code at s-cubed through a collaboration between Rimer, Stevens and the author [Rimer et al, 1998] Although these simulations gave a good description of the extent of the fracture damage near the source (as evidenced by Russian fracture measurements at their hard rock sites), they were unable to explain the observed seismic pulse broadening.

The problem is that the Ashby and Sammis [1990] damage mechanics is not applicable in the post-failure regime where the rock fractures and granulate. While it gives a good description of damage nucleation and failure surface, it breaks down and does not give an adequate description of the post-failure behavior of the damaged rock. In the s-cubed simulations [Rimer et al., 1998], we assumed that once an element failed, its strength fell to the level given by friction. This assumption was based on the behavior of granular layers tested under simple shear in the laboratory which are observed to deform according to a simple frictional rheology [Dieterich, 1981; Biegel et al., 1989; Marone and Kilgore, 1993; Sammis and Steacy, 1994;]. However, in order to simulate the observed pulse broadening, Rimer et al.[1998] found that they had to reduce the coefficient of friction in the granulated rock to μ=0.02, far below the value of μ=0.6 commonly observed in the laboratory. The problem may lie in the fact that the laboratory measurements of friction in granular layers are made at very low sliding velocities on the order of microns per second whereas deformation rates in the nonlinear region of a nuclear source are very high and dynamic effects may be important.

A physical solution to this dilemma may lie in the "acoustic fluidization" of the granulated rock in the source region [Sammis, 1998]. Acoustic fluidization is a phenomenon proposed by Melosh [1979] to explain long run-out landslides on earth and the fluid-like morphology of large extraterrestrial impact craters. Melosh [1996] has recently proposed acoustic fluidization as the mechanism which explains the "heat flow paradox" in which the absence of a heat flow anomaly on the San Andreas fault implies that it slips at a very low effective coefficient of friction. This interpretation is supported by recent computer simulations of faulting in a granular medium by Mora and Place [1998].

Acoustic fluidization occurs when high-frequency acoustic energy produces sufficiently large fluctuation in the normal stress between grains that local slip between grains becomes possible at a very low value of the applied stress. The theory developed by Melosh [1979] is necessarily statistical in nature since the stress fluctuations are spatially and temporally distributed throughout the granular medium. The central equation describing the rheology of a fluidized granular medium is

$$\dot{\varepsilon} = \frac{\tau}{\rho \lambda c} \left[\frac{1 - erf\left(s_c / 2^{1/2} \sigma\right)}{1 + erf\left(s_c / 2^{1/2} \sigma\right)} \right] \quad (1)$$

where:

τ = applied shear stress
ρ = density of the granulated rock
λ = wavelength of the acoustic energy
c = P wave velocity in the granulated rock
S_c = critical pressure amplitude in the P wave acoustic field to relieve the overburden pressure ρgh and allow sliding
= ρgh - τ/μ
σ = variance of the normally distributed random acoustic P wave field.

Note that the strain rate is linear in the applied stress τ so the fluidized granular rock behaves as a Newtonian fluid with viscosity

$$\eta = \frac{\rho \lambda c}{2} \left[\frac{1 + erf\left(s_c / 2^{1/2} \sigma\right)}{1 - erf\left(s_c / 2^{1/2} \sigma\right)} \right] \quad (2)$$

In a strong acoustic field, $\sigma \approx s_c$ and

$$\eta \approx \rho \lambda c \quad (3)$$

Note that the viscosity is lowest for short wavelength acoustic energy (small λ) and that the low value of the P wave velocity (c) in the highly damaged rock also contributes toward lowering the fluidized viscosity.

There are two questions which must be answered before acoustic fluidization can be considered a viable process in the source region: 1) is a fully fluidized granulated layer weak enough to produce the observed pulse broadening and 2) is the acoustic field strong enough to fully fluidize this layer? We begin with question (1). As a preliminary estimate, take ρ = 3 gm./cm^3 and c = 1 km/s as typical values for granulated rock. Assume that the wavelength of the acoustic waves are of the same order as the flaw size that generates them and take λ = 1 cm. If the damaged rock is fully fluidized, the effective viscosity will be $\eta \approx \rho\lambda c = (3)(10^5)(1) = 3x10^5 P$. The hoop strain during the Hardhat explosion at a distance of r=200 m. from the shotpoint was about 7.5x10^{-3} [Rimer et al., 1987]. Since the inflation lasts for about 0.15 s., the strain-rate is about $\dot{\varepsilon} = 5x10^{-2}$ sec^{-1}. If the rock is fully fluidized, the stress required to produce this strain rate is:

$$\sigma = \eta\dot{\varepsilon} = (3x10^5)(5x10^{-2}) = 1.5x10^4 \text{ dynes/cm}^2,$$

or about 0.015 bars. Since this is well below the stress level in the granulated layer, we can conclude that full acoustic fluidization can weaken the granulated layer sufficiently to produce the pulse broadening observed in Hardhat.

The second question is more difficult to answer and is the current focus of our research. In a recent paper [Johnson and Sammis, 1999] we have integrated the seismic moments (shear and dilatational) generated by the myriad of small flaws in the damage regime and shown that they make a significant contribution to the far-field seismic radiation provided that a) there is a preferred orientation to the preexisting flaws or b) there is a non-isotropic prestress, or both. We now need to calculate the integrated contribution of all the flaws to the acoustic field in the granulated zone inside the growing damage front as illustrated in Figure 1. Johnson and Sammis [1999] showed that the damage front moves out with a velocity between the P and S velocity. The bulk of the returning radiation should be trapped in the granulated zone by strong scattering thus extending the time during which the material is fluidized, but this has yet to be quantified. If there were no attenuation, then one can make the following simple geometrical argument that the dilatation will be strong enough to overcome lithostatic pressure. Dilatational stresses at the source must be strong enough to overcome the overburden since dilatational "wing cracks" are formed. At any point inside the spherical damage front (e.g., point P in Figure 1), the radiation from a spherical damage front at r will be independent of r. This is because the $1/r^2$ decrease in pressure is exactly compensated by the r^2 increase in source area. Since the pressure at the source is sufficiently strong, so will be the waves from any subsequent spherical shell. An historical note: this is the same argument used by Olbers in 1823 against a uniform infinite static distribution of stars, and argument subsequently invalidated by the red shift associated with the expanding universe. A quantitative evaluation of the effects of scattering and attenuation on this argument are a current focus of our research program.

Incorporation of acoustic fluidization into the source model requires that failed elements are assigned the viscosity given by eqn. (2) or (3). This is very different from our previous assumption that the strength falls to friction which amounts to specifying a yield surface and relaxing the displacement field by radial-return to this surface. One interesting consequence of a viscous model is that the standard scaling relations no longer necessarily hold.

CONCLUSIONS AND RECOMMENDATIONS

Our recent success in incorporating micromechanical damage mechanics into numerical simulations of explosions in crystalline rock [Rimer et al., 1998] has demonstrated that the weakening associated with crack growth and fragmentation is not sufficient to produce the pulse broadening observed in the seismic radiation. Last year, we [Sammis, 1998] proposed that acoustic fluidization [Melosh, 1979] of the fragmented rock behind the shock front might produce the additional weakening required to fit the observed radiation. We show here that preliminary estimates of the effective viscosity of the fully fluidized fragments are consistent with the stress and strain-rates in the nonlinear regime of the Hardhat explosion calculated by Rimer et al. [1987].

The one remaining question is whether there is sufficient acoustic energy in the granulated rock to achieve full fluidization. In a recent paper [Johnson and Sammis, 1999], we have developed the methodology to calculate the secondary seismic radiation generated by the myriad of small growing fractures which comprise the "damage" in damage mechanics. The next step is to calculate the amplitude of this secondary radiation behind the shock front taking into account scattering and attenuation. A simple geometrical argument suggests that there should be sufficient acoustic energy. Equations (2) and/or (3) can then be used to assign a viscosity to the failed elements.

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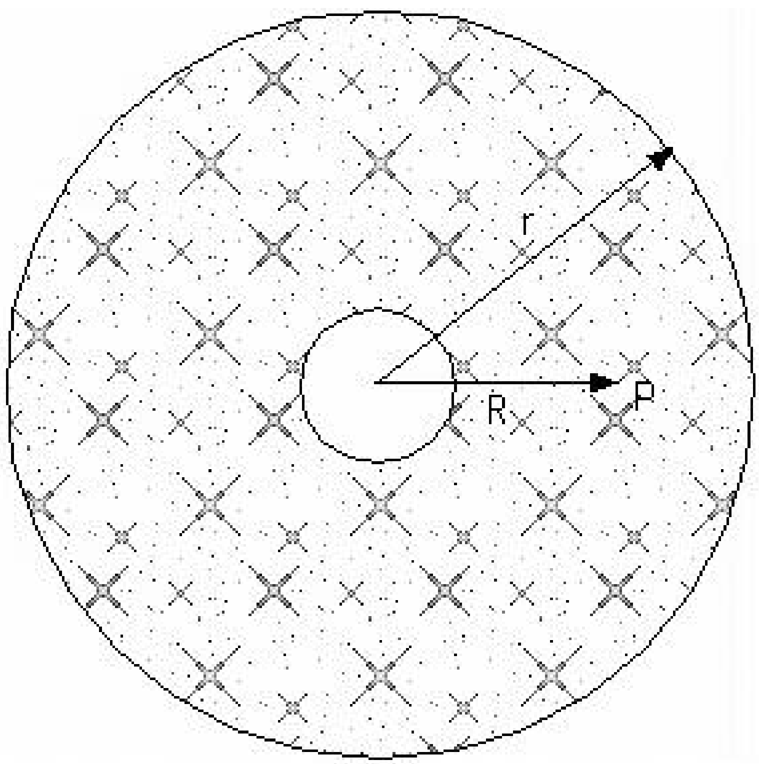

Figure 1. Geometry of fragmented zone. Field point P is at distance R from the shotpoint. The active damage front is at a distance r(t) from the shotpoint at time t.