ACOUSTIC FLUIDIZATION OF CRUSHED ROCK BEHIND THE SHOCK FRONT BY DAMAGE-INDUCED SECONDARY SEISMIC RADIATION

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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 and Sammis [2000] have shown that it can make an important contribution to the far-field seismic signal, and (2) Sammis [1998] has argued that it can also 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 shows how the secondary radiation calculations of Johnson and Sammis [2000] can be used to calculate the intensity of the high frequency acoustic field behind the shock front and, thereby, to quantitatively assess the strength reduction due to acoustic fluidization.

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 important 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 that 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 the far field. A quantitative understanding of this observed pulse broadening is important if the frequency content of the far-field 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, 1997; Johnson and Sammis, 2000]. They report 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 appears to be that while the Ashby and Sammis damage mechanics gives a good description of compressive failure, it does not give an adequate description of the post-failure behavior of the damaged rock. In the s-cubed simulations, it was assumed that the strength of the rock fell to the level given by friction once it failed. 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 found that he 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. 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 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

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

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
= $\rho gh - \tau/\mu$
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

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

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

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

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 secondary acoustic field strong enough to fully fluidize this layer? We begin with question (1). As a preliminary estimate, take ρ = 3 gm./cm^3, 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 is $\sigma = \eta\dot{\varepsilon} = (3x10^5)(5x10^{-2}) = 1.5x10^4$ dynes/cm^2 ≈ 0.015 bars. Since this is well below the stress level in the granulated layer (Rimer, personal communication), we can conclude that acoustic fluidization can weaken the granulated layer sufficiently to produce the pulse broadening observed at Hardhat.

The second question is more difficult to answer and has been the focus of our current research. As a first step toward calculating the strength of the acoustic field in the granulated zone, Johnson and Sammis [2000] have converted the motions that occur on individual preexisting cracks into seismic moment tensors which may then be used to calculate secondary elastic waves that are radiated into the far field. This crack motion may be separated into sliding motion on the original shear crack that contributes a shear moment per unit volume of

$$m_s = \frac{9}{2}\frac{\lambda+2\mu}{\lambda+\mu}\frac{K_{Ic}}{(\pi a\cos\chi)^{1/2}}\frac{D_0}{\sin\chi\cos^2\chi}\left[\left(\frac{D}{D_0}\right)^{1/3}-1\right]^{1/2} \tag{4}$$

and a tensile opening of the growing "wing cracks" that contributes a tensile moment per unit volume of

$$m_t = \frac{3}{2}\frac{(\lambda+2\mu)^2}{\mu(\lambda+\mu)}\frac{K_{Ic}}{(\pi a\cos\chi)^{1/2}} D_0\left[\left(\frac{D}{D_0}\right)^{1/3}-1\right]^{5/2} \tag{5}$$

In these expressions:

λ and μ = Lame elastic constants
K_{Ic} = Critical stress intensity factor (a material property).
a = Half-length of the preexisting cracks
χ = Geometrical crack orientation factor
D_0 = Initial damage = $\frac{4}{3}\pi(a\cos\chi)^3 N_v$
D = Current damage = $\frac{4}{3}\pi(l + a\cos\chi)^3 N_v$
l = Length of tensile wing cracks
N_v = Number of initial shear cracks per unit volume

While the contribution from an individual crack is small, we found that the combined effect of many cracks in a large region of increased damage can generate secondary waves that are comparable in amplitude to the primary waves generated by the explosion. We performed the numerical integration over the areas of active damage using the following procedure:

- The region surrounding the source was divided into a large number of small volume elements
- The equivalent elastic method [Johnson, 1996, 1997] was used to calculate the principal stresses within each volume element as a function of time.
- The increase in damage (if any) within each volume element was determined using the Ashby and Sammis [1990] theory.
- The increase in damage was converted to a moment tensor using the above equations.
- The displacements at a given receiver location were calculated by summing the contributions from every volume element where there was an increase in damage.
- The vector displacements generated at the receiver location by the secondary waves from all volume elements were summed.

In Johnson and Sammis [2000] we estimated the secondary P and S wave energy in the far field generated by the damage process. We are now working on the high-frequency energy radiated back toward the source. The wavelength of this secondary radiation is determined by the size of the activated flaws that nucleate the damage and can be as short as millimeters. However, this radiation is incoherent and may not propagate beyond the active damage zone. More likely, the wavelength of the secondary radiation that propagates back toward the source will be determined by the width of the active damage zone that must be determined by further modeling. In any event, strong non-linear scattering (which we are also working on) of this inward traveling secondary radiation by the fragmented rock will probably produce the required stochastic acoustic field.

CONCLUSIONS AND RECOMMENDATIONS

Acoustic fluidization appears to be a promising mechanism to weaken the fragmented rock behind the shock front of nuclear explosions detonated in crystalline rock, and thus offers a physical solution to the long-standing mystery of the pulse broadening observed by Rimer et al. [1987]. The nearest natural analog to buried explosions is the formation of a large extraterrestrial craters which show clear morphological evidence for the fluidization of the fragmented rock in the form of flat crater floors, central peaks, and wave-like ring structures [Melosh and Gaffney, 1983, Melosh et al., 1992].

We have recently developed the theoretical tools required to test the significance of acoustic fluidization in the source region of nuclear explosions. The spatial extent of source fragmentation can be calculated using the damage mechanics developed by Ashby and Sammis [1990] that has been implemented in the s-cubed source code. These calculations can be verified using Russian fracture measurements in hard rock nuclear explosions. The s-cubed code can also estimate the width of the active damage region and hence the dominant wavelength of the secondary radiation. The strength and frequency content of the secondary acoustic emissions from the nucleation and growth of fractures behind the shock front can also be calculated using the techniques developed by Johnson[1996, 1997] and Johnson and Sammis [2000]. We are currently working to put these elements together for a quantitative estimate of the role of acoustic fluidization in the highly damage source region of underground explosions and its effect on the waveforms of seismic radiation in the near and far field.

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