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SENSITIVITY OF THE CLOSE-IN SEISMIC SOURCE FUNCTION TO ROCK PROPERTIES

FRED N. APP

Geophysics Group, EES-3
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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Sensitivity of the Close-in Seismic Source Function to Rock Properties.

Fred N. App
Geophysics Group - Earth and Environmental Sciences Division
Los Alamos National Laboratory

ABSTRACT

The objective of this investigation is to determine and evaluate how rock properties near the origin of an explosion influence the close-in seismic source function. This is work in progress that represents one step in the systematic investigation of parameters important in the remote identification of underground nuclear tests. In this study, the "overshoot" and "steady state value" of the reduced displacement potential, and the "corner frequency" and "rolloff" of the reduced velocity potential spectrum are the properties of the source function used as principal measures of effect. A series of one-dimensional, spherically symmetric calculations are made with the computational mesh divided into six phenomenological regions. Material properties are modified in selected regions to evaluate source function sensitivities.

Following are some tentative conclusions. 1) Differences in the high pressure cavity gas thermodynamics can affect coupling but do not have much effect on the waveshape or spectral characteristics of the source function. 2) The source function is relatively insensitive to differences in rock properties within the solid material, hydrodynamic region (in the scaled range 2 to 10 m/kt^{1/3}). 3) The source function is relatively insensitive to the volumetric response properties of the solid rock (rock + water) in all pressure regimes. 4) Total energy coupling to the elastic field and the spectral characteristics of the transmitted waveform are very sensitive to both the gas porosity and rock shear strength; gas filled porosity is important outside the hydrodynamic region (from about 10 m/kt^{1/3} to the elastic radius), whereas the effect of shear strength is greatest beyond the cavity region (from about 20 m/kt^{1/3} to the elastic radius). 5) There is a suggestion that each source function property has its own degree of sensitivity to the type of coupling and the types of materials present at a site.

There are some interesting implications to the above conclusions. Since the very close-in material properties (within the hydrodynamic region) mainly affect coupling without affecting waveform or spectral characteristics, variations in the high pressure response properties are not likely to cause a problem in discriminating between intrinsically different types of events. Material properties in the inelastic region outside the hydrodynamic region, and particularly outside the cavity region, have a greater effect on waveforms and thus can affect both discrimination and yield estimation performance. The source function may be most sensitive to shear strength, a poorly known, and difficult to obtain, material property; unusual events may correlate more closely with this parameter than any other. The results of this study suggest the possibility that, at some level, the source function properties may be used to constrain the size and type of energy release without foreknowledge of the material properties at the origin.

I. INTRODUCTION

The objective of this study is to determine and evaluate how rock properties near the origin of a tamped explosion influence the close-in seismic source function, (i.e., the amplitude and spectral content of the signal where it first decays to an elastic wave in the free-field), using computer modeling as the principal analytical tool. The study is limited to effects close-in rather than at regional or teleseismic distances. Perhaps the work that comes closest to this in terms of utilizing the characteristics of waveforms is that of Taylor and Dowla (1991). They used spectral matching techniques to determine yield in the absence of specific geologic information. However, the key to the success of the technique is that the spectral shape at seismic distances is sensitive to the near-source geology. In the work being reported here, the goal is to identify how the spectral shape is influenced by the geologic properties, so in a sense it compliments the Taylor and Dowla work, however, yield effects are not a focus of this study.

The source function is described by four properties of the potential that satisfies the spherical wave equation (the reduced displacement or reduced velocity potential). These are the "steady state value", the "rolloff", the "overshoot" and the "corner frequency" (Denny and Johnson, 1991). Specifics on how these properties are applied in this study are discussed in the Approach Section. The emphasis here is on the close-in region with the expectation, based on the aforementioned work of Taylor and Dowla, that it also is relevant to the seismic regime. The study is limited to one dimension and does not address secondary effects such as spall. It is but one step in the systematic investigation of parameters important in the remote identification and yield estimation of underground nuclear tests.

The study has spawned a number of ideas on expanded modeling efforts that may prove valuable in resolving verification and proliferation issues, and these are advanced as specific recommendations at the end of this report.

II. PHYSICS OF THE CODE

The calculations reported herein were performed using a Los Alamos modified version of the Sandia National Laboratory TOODY finite difference Lagrangian stress wave code (Swegle, 1978). The basic approaches to solving the difference equations for conservation of momentum and energy are described in the above reference; however, some of the analytical techniques employed that are most relevant to this study are reiterated here.

The code assumes that the Mie-Gruneisen equation for pressure (P) is valid, i.e.,

$$P = P_H + \Gamma\rho(\epsilon - \epsilon_H)$$

where Γ , the Gruneisen ratio¹, is assumed to be a function of density (ρ), as are P_H and ϵ_H , which represent the pressure and specific internal energy along some reference curve. The quantity $\epsilon - \epsilon_H$ is the specific thermal energy. For this study, a requirement is that

$$\Gamma = \Gamma_0(\rho_0/\rho)$$

where Γ_0 is the Gruneisen ratio at ambient density ρ_0 ; i.e., the $\Gamma\rho$ term in the Mie-Gruneisen equation is constant at all densities.

For this study, the reference pressure and specific internal energy are taken from a reference curve that is derived using a technique developed by Butkovich (1973) in which the compressibility of the composite material (rock and water) is determined by the relative proportions of each component and their respective compressibilities. If the material is unsaturated (air as a third component), the reference curve is adjusted to account for the presence of the air voids and their irreversible removal with increased confining stress, using the Herrmann (1968) P- α model.

¹ The Gruneisen ratio is a thermodynamic quantity which accounts for the specific heat of a material and its coefficient of volumetric expansion in relating shock pressure to internal heat generation.

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For material vaporization, a special expanded material equation of state is used that essentially reduces to the perfect gas law for very expanded materials, i.e.,

$$P = (\gamma - 1)\rho(\epsilon - \epsilon_s)$$

where γ is the ratio of specific heats of the perfect gas and ϵ_s is the sublimation energy. When density is equal to the ambient density of the solid material, the vapor equation is continuous with the Mie-Grüneisen equation for solid materials:

$$P = \Gamma_0 \rho \epsilon$$

At intermediate expansions that lie between these two extremes, the equation can be regarded as a variable gamma law gas equation of state in which gamma is a function of specific volume, internal energy and sublimation energy. There are no claims of theoretical correctness for this treatment - it is a computationally convenient method for treating vaporization that has proven adequate for many classes of problems addressed with the code, but certainly is inadequate in any detailed treatment involving the influence of specific components of the cavity gases on cavity pressure, such as water vapor.

Shear deformation and failure are determined from Hooke's Law relating shear stress to shear strain, with the maximum supportable stress differences limited according to user-supplied failure envelopes. Rock damage is modeled as a weakening in shear with the accumulation of inelastic shear strain.

III. APPROACH

The first step is to perform a single material, 1-D, spherically symmetric calculation of wave propagation from an underground explosion in a medium that is generally well characterized, and for which there are response data validated by experiment. A saturated, or nearly saturated, rock is preferred in order to maximize energy coupling to the elastic field. The Tunnel Beds Tuff of Area 12 at the Nevada Test Site (NTS) meets these criteria. The above calculation is the "baseline" against which other calculations, using other properties, are compared. App and Brunish (1991) and Brunish and App (1992) modeled selected Area 12 tunnel events using response

models similar to the models used here and obtained reasonable agreement with the measured waveforms.

The 1-D, spherical model is divided into six regions, as depicted in Figure 1. The in-situ (overburden) pressure is 6.4 MPa (64 bars), consistent with a depth of burial (DOB) of about 400 m in Rainier Mesa of the NTS. The yield is invariant in this study and is consistent with a 400 m DOB for a "contained" event². The inner, immovable boundary of the computational mesh is located 5 m from the center of the sphere. All of the energy is deposited into a 1 m thick shell with an outer radius of 6 m. All rock within this volume is "instantaneously" vaporized. The volume vaporized is consistent with a scaled vaporization radius of about $2 \text{ m/kt}^{1/3}$, had the energy been deposited at the center of the sphere rather than in a shell³. The outer boundary of the "hydrodynamic" region is 20 m from the source (i.e., 25 m from the center of the sphere). It is roughly equivalent to a scaled range of $10 \text{ m/kt}^{1/3}$. This is the region where shock dynamics dominate. For the baseline calculation, peak stress at the outer edge of this region is about 1 GPa (10 Kb). The "cavity" region extends to 40 m ($\sim 20 \text{ m/kt}^{1/3}$) from the source and roughly represents the volume occupied by the fully grown, explosion-produced cavity. In much of the literature, material properties listed as "working point" (WP) properties actually are properties averaged over this region. Peak dynamic stress at the outer edge of this region is about 400 MPa (4 kb). The strength dominated "inelastic" region extends to 100 m. It is a region of strong inelastic deformation where material strength is especially important in shaping the waveform. The "transitional" region doesn't represent any specific phenomenological regime, but rather defines the inner and outermost bounds for a transition from strongly inelastic to primarily elastic response (i.e., elastic radius) for various rock types. For the baseline case, the transition occurs at about 225 m. In the elastic region (everything beyond 300 m), the response is purely elastic except for some minor absorption caused by the artificial viscosity treatment used in the code.

A series of calculations are performed, modifying a material property within one or more of the regions and observing the effects (relative

² A "contained" event is an underground nuclear explosion that releases no measureable amount of radiation into the atmosphere.

³ A scaled radius of $2 \text{ m/kt}^{1/3}$ is the rule-of-thumb value used by the containment community in estimating the shock vaporization radius

Figure 1. Geometry of the model. Spherical symmetry - indicated distances are from inner boundary of the energy source region, which is located 5 m from the center of the sphere. Case-by-case source function comparisons are made at the 300 m edit point.

to the baseline case) in the elastic field, using the calculated properties of the reduced displacement potential (RDP) and its derivative, the reduced velocity potential (RVP), as the principal measures of effect. Comparisons are made at the 300 m edit point shown in Figure 1. Table 1 summarizes the cases addressed in this study. Case 1 focuses on energy coupling to the shock wave (energy source region). Case 2 deals only with changes in the hydrodynamic region and the influence of the high pressure EOS on the source function. The remainder of the cases focus on the lower pressure regime and the relative importance of specific response properties in shaping the source function. In Cases 3 through 6, one parameter at a time is changed and substituted into a selected region in order to isolate specific cause and effect relationships. The material descriptions used in Cases 3 through 6 are not intended to represent any particular rock type. In Cases 7 and 8, different rock types are substituted into the selected regions, meaning that more than a single response property is changed for each substitution.

A description and discussion of the RDP and RVP, and their use in describing the seismic source function, can be found in the Denny and Johnson (1991) reference. Briefly, for a spherically divergent wave, the RDP is described as follows:

$$\xi(r,t) = -\partial[\psi(\tau)/r]/\partial r$$

where $\psi(\tau)$ is the RDP, ξ is the displacement, r the range from the source, t is time, and τ is the reduced time ($\tau=t-r/c$), where c is the wave propagation velocity. In physical terms, the RDP is proportional to the volumetric displacement as measured at any single point, and has a constant value beyond the elastic radius (the range at which the wave becomes purely elastic). Similarly, the RVP is described as:

$$\dot{\xi}(r,t) = -\partial[\dot{\psi}(\tau)/r]/\partial r$$

where $\dot{\psi}(\tau)$ is the RVP and $\dot{\xi}$ is the particle velocity.

Figure 2 shows the four properties of the close-in source function that are used in this study as the principal measures of effect. Intuitively, for a given amount of energy coupled into the rock, the steady state value of the RDP should be a strong function of both

TABLE I

Case	Description
	<u>Source Region - Energy Coupling.</u>
1	Source Region - change cavity gas EOS by changing effective gamma for gamma law gas.
	<u>Hydrodynamic Region - Revised Hugoniot.</u>
2a	Hydro region only - change high pressure reference loading curve.
2b	Hydro region only - change loading Hugoniot and unloading adiabat by changing Gruneisen ratio.
	<u>Changes in Initial Bulk Density.</u>
3a	Higher density rock to outer edge of hydro region.
3b	Higher density rock to outer edge of cavity region.
3c	Higher density rock in all regions.
4a	Lower density rock to outer edge of hydro region.
4b	Lower density rock to outer edge of cavity region.
4c	Lower density rock in all regions.
	<u>Effects of Shear Strength.</u>
5a	No shear strength to outer edge of hydro region.
5b	No shear strength to outer edge of cavity region.
6a	No damage to outer edge of hydro region.
6b	No damage to outer edge of cavity region.
6c	No damage for all regions.
	<u>Changes in Rock Type.</u>
7a	Granite to outer edge of hydro region.
7b	Granite to outer edge of cavity.
7c	Granite in all regions.
8a	Alluvium to outer edge of hydro region.
8b	Alluvium to outer edge of cavity region.
8c	Alluvium in all regions.

Some Relevant Properties of the Close-in Source Function

1. The "corner frequency" of the RVP spectrum
2. The "rolloff" of the RVP at high frequencies.
3. The "steady state" value of the RDP
4. The "overshoot" of the RDP

EXAMPLE

RVP SPECTRUM

REDUCED DISPLACEMENT POTENTIAL

Figure 2. Example of four relevant properties of the source function RDP and RVP. These are the four properties selected for use as "measures of effect" for this study.

rock shear strength and gas porosity, while the overshoot⁴ should correlate most strongly with shear strength. The corner frequency and rolloff should correlate strongly with compressibility and shear strength. The objective of this type of sensitivity study is to quantify the cause and effect relationships between material properties and source function properties. This is a start in that direction.

In the example of Figure 2, scalar quantities are shown for the source function properties. For the specific cases addressed in this report only the waveforms and spectra are shown, and there is no attempt to pick scalar quantities other than the steady state value of the RDP. For now, the emphasis is on qualitative differences rather than on absolute values.

An important concept in the formation of the source function properties is that of the coupling of the source energy to the surrounding medium. Kurtz (1975) separates the coupling of energy from a fully tamped explosion to the surrounding medium into two phases. Phase 1 is the prompt coupling of energy associated with the formation of the shock wave. Vaporization, melt and the high pressure EOS of the cavity gases play a dominant role in Phase 1 coupling, i.e., the energy that remains behind in the cavity is unavailable to the shock wave. Phase 2 is associated with the coupling of energy from the shock wave to the elastic field wherein energy losses to the medium due to compaction and other inelastic processes are important. The concept of two distinctly different phases of coupling is important in the analysis of calculations made in the course of this study.

IV. RESULTS

Baseline Case Tuff compared with Alluvium and Granite.

In order to provide a frame of reference for the various case-by-case comparisons discussed below, results of calculations using three very different materials are first introduced. Table II shows the physical properties of granite and alluvium compared to the baseline tuff. Figure 3 shows the reference failure envelopes and loading curves

⁴ Overshoot is often used to describe the difference between the long period and peak spectral amplitudes of the RVP. In this report, it is used to describe the difference between the long period (steady state) and peak values of the RDP in the time domain.

TABLE II
Physical Properties
Tunnel Beds Tuff, "Good Quality" Granite and "Area 3" Alluvium

	Tuff	Granite	Alluvium
Bulk density (Mg/m ³)	1.847	2.730	1.710
Grain density (Mg/m ³)	2.450	2.750	2.471
Water content (Wt%)	21.5	0.4	10.9
Total porosity (%)	40.8	1.1	38.3
Saturation (%)	97.3	100.0	48.6
Gas porosity (%)	1.09	0.0	19.7
Longitudinal sound speed (m/s)	2200	4000.0	1600
Initial crush pressure (MPa)	3.0	not applicable	1.2
Full crush pressure (MPa)	600.0	not applicable	30.0
Unconfined strength-stress difference (MPa)	15	5	~0
Max strength-stress difference (MPa)	30	252	10
Damage	<p><u>For tuff</u> there is a linear decrease in shear strength with accumulated inelastic shear strain - considered fully damaged (near zero unconfined strength) at 10 % strain. The accumulated inelastic shear strain exceeds 10% to a range of about 60 m (full damage radius). <u>For alluvium</u>, same damage mechanism as for tuff but the material is considered fully damaged at 1 % strain. The "full damage radius" is about 80 m. <u>For granite</u> it is assumed that there is no strain induced damage</p>

Figure 3. Comparisons of response properties of Area 3 alluvium, Tunnel Beds Tuff and "good quality" granite. The failure envelopes are for undamaged rock.

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for the three materials. The tuff response properties are based on the Brunish and App (1992) work referenced earlier. It is a zeolitic, nearly saturated, moderately weak ash flow tuff. The alluvium properties are based on a special study by Brunish and App (1989) for the MERLIN event in NTS Area 3. It is a dry, weak, granular material with poor cohesion. The granite properties are generic and are not meant to represent granite from any specific site. They are chosen to represent a "good quality" granite⁵, as described in a mining related report by Hoek and Brown (1980). It is dense, saturated, and very strong in shear at elevated confinement pressures. It has a relatively low unconfined strength, a reflection of the presence of joints. The granite and alluvium are meant to represent extremes with respect to mechanical properties for the more abundant rock types found at shallow depths (upper couple kilometers of the earth crust).

Figure 4 is a waveform comparison (particle velocity and RVP) at the 300 m edit point. The granite particle velocity waveform is very impulsive compared to that for either alluvium or tuff. The tuff waveform (baseline case) has a peak amplitude about equal to that of granite but has a considerably longer period. The peak amplitude in alluvium is substantially less than that for either granite or tuff. Figure 5 shows the RVP spectrum and the RDP waveform for the same three rock types. The RVP corner frequency and rolloff are similar for the tuff and alluvium. Because the granite waveform is more impulsive, its spectrum is broader and flatter than the other two. In terms of the steady state values and overshoot, all three are vastly different from one another.

As suggested above, one normally considers granite and alluvium as representing two extremes in properties for crustal rocks (with tuff somewhere in between). Granite and alluvium do represent extreme cases for Phase 1 coupling with granite the most efficient medium (see table below); however, with regard to the overall effect on the close-in source function (combined Phases 1 and 2), tuff represents a much more extreme case than granite.

⁵ A "good quality" rock is defined as having unweathered fractures spaced 1 to 3 m apart.

Figure 4. Particle velocity and RVP waveform comparisons for tuff, granite and alluvium at 300 m.

Figure 5. RVP spectrum and RDP waveform comparisons for tuff, granite and alluvium at 300 m.

The partitioning of energy for the three cases is tabulated below.

	Tuff (baseline)	Granite	Alluvium
% of total energy coupled into rock (Phase 1 coupling).	40.7	47.1	33.6
% of Phase 1 <u>coupled</u> energy transmitted beyond 300 m (Phase 2 coupling).			
Internal	6.9	2.8	0.1
Kinetic	3.0	1.0	0.1
Steady State RDP (m ³).	5110	1860	320

Phase 1 coupling is determined by editing the amount of energy remaining in the cavity after shock wave formation and subtracting it from the total energy. For tuff and alluvium, Phase 1 coupling efficiency is in close agreement with values estimated by Butkovich (1974) from his analysis of melt volumes from nuclear explosions; however, the Phase 1 coupling for granite is low compared to his estimate for "high density" rock. The Phase 2 coupled internal and kinetic energies are obtained by summing the energy in all computational zones beyond 300 m. They should be used with caution because there are some energy losses due to less-than-perfect energy conservation in the code as the signal propagates into a larger and larger volume of material. Nevertheless, it is evident that the percentage of the total energy that gets transmitted into the elastic field as a seismic signal is very small (kinetic energy beyond 300 m). The internal energy of the material beyond 300 m reflects the final state of equilibrium of the material after passage of the main stress wave and after adjustments to cavity growth are complete⁶.

Case 1 - Source Region - Energy Coupling.

Case 1 specifically addresses the issue of Phase 1 coupling. It compares the baseline case with a calculation that uses a revised high pressure EOS. The input energies and the properties of the solid

⁶ The convention used in this report is that internal energy is positive in compression.

rock are identical for the two cases. For the revised EOS, the initial vapor pressure is 2.5 times greater than for the baseline. This is accomplished by increasing the effective gamma of the gamma law gas at high pressures. Figure 6 shows the early-time cavity conditions. As the shock wave develops and the cavity begins to form, the vapor pressures decrease and become very nearly equal by 0.3 ms problem time. There is no physical basis for the revised EOS - the point of the change is simply to demonstrate the sensitivity of the source function properties to variations and uncertainties in the high pressure regime (>20 GPa). Figures 7 and 8 compare the results of the two calculations. The amplitude of the RDP waveform is about 42% greater for the revised EOS than for the baseline case. Phase 1 energy edits in the calculations show that 59% of the total energy remains behind in the cavity for the baseline case compared to only 40% for the revised EOS. This means there is considerably more energy available to the shock wave for the revised EOS. The higher RDP for the revised EOS case is due almost entirely to the increased Phase 1 coupling.

This example suggests that early time, high pressure cavity gas thermodynamics can affect coupling, and therefore yield estimation, but do not significantly affect the shape of the waveform or spectral characteristics of the source function.

The remainder of the cases deal primarily with Phase 2 coupling mechanisms, but the Phase 1 coupling efficiency for each case is printed in the lower right-hand-corner of the RDP plots.

Case 2 - Hydrodynamic Region - Revised Hugoniot.

Case 2 addresses the sensitivity of results to the high pressure response properties in the strong shock regime outside the vaporization region. The vapor EOS is unchanged. For Case 2a, only the reference loading curve (and therefore the shock Hugoniot) is changed (Figure 9 - upper plot). The two loading curves represent three and six degree polynomial fits to the same basic experimental data set. The main motivation here is to justify the use of the computationally more convenient cubic form, but the comparison also serves to indicate sensitivity to such differences whatever their origin may be. The lower plot of Figure 9 shows the calculated load/unload response at a point 5 m from the energy source. There is very little difference in the release behavior at near ambient density after going through a load-unload cycle. Figures 10 and 11

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Figure 6. Case 1 - cavity conditions to 2 ms for two gas equations-of-state. Top - pressure vs time; bottom - "effective" gamma-1 vs specific volume. Values at zero time are not shown - first edit time is 0.1 ms.

Figure 7. Case 1 - particle velocity and RVP waveform comparisons at 300 m for two different cavity gas EOS treatments.

Figure 8. Case 1 - RVP spectrum and RDP waveform comparisons at 300 m for two different cavity gas EOS treatments.

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Figure 9. Case 2a - comparisons of high pressure volumetric response for two different loading reference curves.

Figure 10. Case 2a - particle velocity and RVP waveform comparisons at 300 m for two different loading reference curves.

Figure 11. Case 2a - RVP spectrum and RDP waveform comparisons at 300 m for two different loading reference curves.

show that the calculated results overlay, suggesting that details of the loading response curve are unimportant and that a cubic fit to data is entirely adequate in describing the solid P-V response of the rock. With the exception of this one case, all calculations discussed in this report use a cubic fit to P-V response data generated using Butkovich's (1973) techniques.

For Case 2b, the Hugoniot is changed by increasing the Gruneisen ratio (Γ_0) from 0.4 to 2.0. The value of 0.4 used for the baseline calculation is somewhat lower than is normally used for geologic materials. The reason for using such a low value is related to computational convenience and the specific form of the vapor EOS (that uses Γ_0) in the TOODY code. On the other hand, a value of 2.0 is on the high side, so we are covering a range in excess of what would normally be expected for geologic materials. Figure 12 shows the resulting response curves. Now the release behavior is different from that of the baseline case, which should have some effect on cavity growth. Figures 13 and 14 show that at 300 m the effects are minor and any differences that are present appear to be due primarily to increased Phase 1 coupling.

Although Case 2 certainly is not exhaustive in exploring all parameter space regarding high pressure effects (for example, phase changes are ignored, including those for water), the results do suggest that the seismic source function is relatively insensitive to details of the solid rock Hugoniot.

Cases 3 and 4 - Changes in Initial Bulk Density.

Figures 15 and 16 show the effect of substituting higher density material into selected regions of the model. The in-situ bulk density is increased from its value of 1.85 Mg/m³ for the baseline tuff to 2.7 Mg/m³. This is achieved by decreasing the total porosity from 41% by volume to nearly zero. Because of the decreased water to rock ratio, the loading reference curve of the high density rock is considerably stiffer than that of the baseline tuff. The gas-filled porosity (GFP) is unchanged between the two cases (about 1% GFP). Figure 16 shows that the changes in source function properties are quite small, even when all of the baseline tuff is replaced by the higher density material. The source function obviously is insensitive to differences in the volumetric response characteristics of saturated or nearly saturated rocks at both high and low pressures.

Figure 12. Case 2b - comparisons of high pressure volumetric response for same loading reference curve but using two different Gruneisen ratios.

Figure 13, Case 2b - particle velocity and RVP waveform comparisons at 300 m using two different Gruneisen ratios with same reference curve.

Figure 14. Case 2b - RVP spectrum and RDP waveform comparisons at 300 m using two different Gruneisen ratios with same reference curve.

Figure 15. Case 3 - particle velocity and RVP waveform comparisons at 300 m for substitution of higher density material into selected regions.

RVP SPECTRUM

REDUCED DISPLACEMENT POTENTIAL

Figure 16. Case 3 - RVP spectrum and RDP waveform comparisons at 300 m for substitution of higher density material into selected regions.

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Figures 17 and 18 show the effect of substituting lower density material into selected regions. The reduced density is obtained by increasing the GFP from 1% to 20%. The rock to water ratio remains unchanged, therefore the loading reference curve for the solid component of the rock (rock plus water - no air) also is unchanged. The effects on the source function properties are significant. Both Phase 1 and Phase 2 coupling play a role here. The Phase 1 coupling efficiency is 34% for the lower density rock vs 41% for the baseline tuff. With material substitution only into the hydrodynamic region, it appears that about all of the observed differences are due to the decrease in Phase 1 coupling. For substitution into the cavity region, about half is due to Phase 1 and half to Phase 2. Beyond the cavity region, differences in GFP have a strong effect on Phase 2 coupling and on both the amplitude and spectral characteristics of the source function

Cases 3 and 4 show that the effect of density alone on the source function properties is relatively small unless the density change is accompanied by a change in gas-filled porosity.

Cases 5 and 6 - Effects of Shear Strength.

Figures 19 and 20 show the influence on the source function of a material with zero shear strength within the hydrodynamic and cavity regions. Within the aptly named hydrodynamic region, shear strength plays almost no role. Even in the cavity region, the effect is very small. A calculation was made in which all material was assumed to have zero shear strength. The amplitudes were much larger and the problem had not reached static equilibrium by 1 sec, so the waveforms for that calculation are not included in Figures 19 and 20. Suffice it to say that the shear strength of Tunnel Beds Tuff within the cavity region has an insignificant effect on the properties of the source function; the shear strength outside the cavity region plays the dominant role.

Figures 21 and 22 show the effect of ground shock damage on the source function. In this context, damage is defined as a reduction in the rock shear strength due to ground shock conditioning. Such weakening is known to occur in Tunnel Beds Tuff - the baseline material. In this case, the substitute material is identical to the baseline tuff except it is not allowed to damage. The effect is most noticeable on the overshoot and corner frequency, and then only

Figure 17. Case 4 - particle velocity and RVP waveform comparisons at 300 m for substitution of lower density (higher gas-filled porosity) material into selected regions.

Figure 18. Case 4 - RVP spectrum and RDP waveform comparisons at 300 m for substitution of lower density (higher gas-filled porosity) material into selected regions.

Figure 19. Case 5 - particle velocity and RVP waveform comparisons at 300 m for substitution of zero strength material into selected regions.

Figure 20. Case 5 - RVP spectrum and RDP waveform comparisons at 300 m for substitution of zero strength material into selected regions.

PARTICLE VELOCITY

REDUCED VELOCITY POTENTIAL

Figure 21. Case 6 - particle velocity and RVP waveform comparisons at 300 m for substitution of "no-damage" material into selected regions.

Figure 22. Case 6 - RVP spectrum and RDP waveform comparisons at 300 m for substitution of "no-damage" material into selected regions.

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when the replacement material is substituted into the cavity region and beyond. The effect is minimal for substitution only into the hydrodynamic region. For the case of material damage, the material is continually weakening as the cavity grows outward. When rebound occurs, the resistance to inward motion is considerably less than if the rock still possessed its original shear strength; thus there is more inward motion; i.e., more overshoot. The effect is not so much a damage effect per se as it is an effect simply of material shear strength. A material that is originally very weak, and without damage, should exhibit the same large overshoot behavior. In the particular example chosen here, the steady state value of the RDP is relatively unaffected.

These examples do not represent the most extreme cases for the effect of cavity region shear strength since the baseline Tunnel Beds Tuff is initially fairly weak anyway. It is probably generally true, however, that the strength of rock outside the immediate cavity region has a far greater effect on the properties of the source function than the strength of the rock within the cavity region.

Cases 7 and 8 - Changes in Rock Type.

Cases 2 through 6 varied one response material property at a time in order to focus on specific cause and effect relationships. For Cases 7 and 8, specific rock types are substituted in the targeted regions, the main difference being that more than one response property is changed to reflect the true differences between rock types. The subject rocks are the same ones used above in the "tuff vs. alluvium and granite" comparisons.

Figures 23 and 24 show the results for substitution of granite into the selected regions. The main difference between granite and the earlier "high density" material of Case 3 is that the shear strength is increased to be representative of "good quality" dense rock. Also, the granite is not allowed to "damage". As shown in Figure 24, substitution into the hydrodynamic region has little influence on the source function characteristics. However, both the overshoot and corner frequency are strongly effected when granite is substituted into the cavity region. The steady state value of the RDP is most strongly effected in the "all granite" case, which is in marked contrast to the previous "all high density material" case (Figure 16). This again implies that shear strength of material beyond the cavity has a dominant influence on the steady state value of the RDP.

Figure 23. Case 7 - particle velocity and RVP waveform comparisons at 300 m for substitution of "good quality" granite into selected regions.

Figure 24. Case 7 - RVP spectrum and RDP waveform comparisons at 300 m for substitution of "good quality" granite into selected regions.

Figure 25. Case 8 - particle velocity and RVP waveform comparisons at 300 m for substitution of Area 3 alluvium into selected regions.

Figure 26. Case 8 - RVP spectrum and RDP waveform comparisons at 300 m for substitution of Area 3 alluvium into selected regions.

Figure 25 and 26 show the results for substitution of alluvium into the selected regions. There are two significant differences between alluvium and the previously discussed "low density" material of Case 4. The alluvium has a much lower shear strength and it has a reduced resistance to pore crush. Similar to the results of the "low density" case (Figure 18), effects due to substitution into the hydrodynamic region are due almost entirely to decreased Phase 1 coupling. Substitution into the cavity region results in a substantial change in the steady state RDP, overshoot and corner frequency. The most pronounced effects on the source function properties occur in the "all alluvium" case, due to the combination of low pressure compaction of the gas porosity and low shear strength.

The effect of material substitutions into the cavity region on overshoot and corner frequency is both interesting and unexpected. In the narrow sense, the observed effect partially refutes the general conclusion from Cases 5 and 6 that strength properties of material within the cavity region are of little importance. In a broader sense, it further demonstrates that different source function properties are affected in different ways by changes in material properties.

V. CONCLUSIONS AND IMPLICATIONS

The study has not been exhaustive in treating all of the material properties that potentially could effect the source function, although I do believe that this study includes most of the more important ones. Following are some tentative conclusions. 1) Differences in the high pressure cavity gas thermodynamics can affect coupling but do not have much effect on the waveshape or spectral characteristics of the source function. 2) The source function is insensitive to differences in rock properties within the solid material, hydrodynamic region (between 2 and 10 scaled meters). 3) The source function is relatively insensitive to the volumetric response properties of the solid rock (rock + water) in all pressure regimes. 4) Total energy coupling to the elastic field and the spectral characteristics of the transmitted waveform are very sensitive to both the gas porosity and rock shear strength; gas-filled porosity is important outside the hydrodynamic region (from about 10 scaled meters to the elastic radius), whereas the effect of shear strength is greatest beyond the cavity (from about 20 scaled meters to the elastic radius). 5) There is a suggestion that each source function

property has its own degree of sensitivity to the type of coupling and the types of materials present at a site.

There are some interesting implications to the above conclusions. Since the very close-in material properties (within the hydrodynamic region) mainly affect coupling without affecting waveform or spectral characteristics, variations in the high pressure response properties are not likely to cause a problem in discriminating between intrinsically different types of events. Material properties in the inelastic region outside the hydrodynamic region, and particularly outside the cavity region, have a greater effect on waveforms and thus can affect both discrimination and yield estimation performance. The source function may be most sensitive to shear strength, a poorly known, and difficult to obtain, material property; unusual events may correlate more closely with this parameter than any other. The results of this study suggest the possibility that, at some level, the source function properties may be used to constrain the size and type of energy release without foreknowledge of the material properties at the origin.

VI. RECOMMENDATIONS

Following are recommendations for further close-in modeling work, based on insights and impressions gained in the course of this study.

1) Phase 1 coupling remains an issue, even if it relates primarily to explosive yield, and not as much to discrimination. Radiochemistry analysis on melt puddle samples (for both independent yield determination and estimates on total energy expended in melt rock), combined with modelling and CORRTEx⁷ observations, may be useful in determining the efficiency of Phase 1 coupling as a function of field measurable quantities such as gas porosity, density, and mineralogy. CORRTEx measurements taken in the hydrodynamic region should be relatively unaffected by Phase 2 decoupling.

2) The effect of the very near field, high pressure EOS on both Phase 1 and Phase 2 coupling should be addressed using models that include a more complete description of the phase changes and hysteretic effects, to assure that the simpler treatment used in this study did not overlook some important aspects.

⁷ CORRTEx is a method for yield verification in which the outgoing shock from a nuclear test is tracked in time and space.

3) Shear strength is identified as being very important in shaping the source function. Efforts in the development of more physics-based models for describing shear behavior and damage in rocks should be encouraged, including work that currently is in progress with effective stress laws and in fracture growth and nucleation. Such efforts should go far toward putting our "beliefs" regarding the shear behavior of various rock types on a firmer scientific footing.

4) A systematic comparison of the results and conclusions of this study, and similar studies in the future, should be made with source functions derived from measurements made at regional and teleseismic distances. Special care should be taken that the explosion sites are well characterized with regard to gas-filled porosity and, to the extent possible, shear strength.

5) Secondary close-in effects due to layering, and such processes as spall, should be systematically analyzed to establish their relative contributions to the source function.

6) Discrimination between effects of yield and material properties on the basis of waveform measurements alone would constitute a valuable capability in nuclear test verification. It seems worth the effort to expand and focus further work in determining the extent to which the shape and amplitude of the close-in signal may be used to constrain the size and type of energy release without foreknowledge of the rock properties at the origin of the explosion.

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