AN ANALYSIS OF THE SEISMIC SOURCE CHARACTERISTICS OF EXPLOSIONS IN LOW-COUPLING DRY POROUS MEDIA

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ABSTRACT

The dependence of seismic source coupling of underground nuclear explosions on the characteristics of the explosion source medium is an important consideration in any assessment of nuclear test monitoring capability. In particular, while experience has indicated that normal depth explosions in almost all hardrock and water saturated emplacement media (i.e., “good-coupling” media) are roughly consistent with a single m_b/yield relation for any fixed tectonic source region, explosions in dry, porous media, such as the dry tuffs and alluvium found above the water table at the Nevada Test Site (NTS), are typically observed to have m_b values at a given yield that are lower than those in hardrock by about 0.50 ± 0.25 magnitude units. With the exception of the complex cavity decoupling evasion scenario, which is not always feasible, explosions in such low-coupling media define the lower bound on the detection capability required to successfully monitor small, clandestine underground nuclear tests. However, at the present time no fully reliable seismic source model is available to support quantitative analyses of broadband data recorded from such explosions. The technical objectives of this program are to develop a “Mueller/Murphy” frequency dependent seismic source model for underground nuclear explosions in dry, porous media and to then apply this model to a quantitative assessment of seismic yield estimation capability for such explosions as functions of explosion yield and depth of burial, as well as detailed physical properties of the source medium such as compressional wave velocity and percent by volume of air-filled porosity.

Our analyses during the past year have focused on seismic data recorded at the Lawrence Livermore National Laboratory (LLNL) regional network station MNV (Mina Nevada) from nuclear explosions conducted above and below the water table at the Yucca Flat testing area of NTS. P wave spectra over the frequency band 0.5 to 10 Hz have been estimated for a sample of 63 explosions conducted in dry, porous media above the water table at Yucca Flat. The measured gas-filled porosities (Gp) at the working points of these explosions range from near zero to almost 30%, while the associated yield values extend over approximately two orders of magnitude around a mean yield of about 10 kt. Since these explosions were conducted over a fairly narrow range in scaled depth centered on 150 m/kt$^{1/3}$, we analyzed the frequency dependent source scaling as functions of yield and Gp alone. Somewhat surprisingly, it was found that the derived dependence of the observed spectral amplitudes on Gp is essentially independent of frequency over the range 0.5 to 10 Hz, with the logarithm of the spectral amplitude at a fixed frequency decreasing with increasing Gp as -0.024 Gp. That is, the effect of Gp on the seismic source spectrum can be expressed as a frequency independent factor that indicates, for example, that the spectral amplitude levels decrease uniformly by about a factor of 5 as Gp increases from 0% to 30%. In order to compare these results with the well-documented seismic source for explosions conducted below the water table in saturated media, we collected data from a selected sample of explosions conducted below the water table at Yucca Flat and scaled their corresponding station MNV P wave spectra to a yield of 10 kt and a depth of 323 m (i.e., 150 m/kt$^{1/3}$) using the Mueller/Murphy source scaling model. The resulting average spectrum was then divided by the P wave spectra for 10 kt explosions in dry, porous media predicted as a function of Gp using the statistically derived scaling relations. The results of this analysis indicated that the seismic source function for a 10 kt explosion in a dry, porous medium with a Gp value of 25% is expected to be very similar to the corresponding Mueller/Murphy source function for a 10 kt explosion at the same depth in saturated tuff, divided by a frequency independent factor of about 7. In particular, in contrast to some previously published results, both source function estimates show a high frequency rolloff inversely proportional to the square of the frequency. Work is continuing on deriving quantitative estimates of the statistical uncertainty in these results and their implications for general source modeling as functions of yield and source medium Gp value.

OBJECTIVES

The technical objectives of this research program are to develop an analytic approximation for a frequency dependent seismic source model for underground nuclear explosions in dry, porous media analogous to the Mueller/Murphy model for explosions in hardrock and water-saturated media, and to then apply this model to a quantitative assessment of seismic monitoring capability relative to explosions in such media. This is being accomplished by conducting source scaling analyses of broadband seismic data recorded from explosions in such media at NTS to define their frequency dependent source coupling characteristics relative to the already well-documented seismic source coupling of corresponding explosions in "good-coupling" media at that same test site. The ultimate objective is to improve U.S. operational nuclear test monitoring capability by providing a reliable seismic source model that can be used to quantitatively address seismic detection, identification and yield estimation capability as functions of yield, depth of burial and the physical characteristics of the source medium for small underground nuclear tests which might be conducted in such low-coupling media.

RESEARCH ACCOMPLISHED

It has long been recognized that normal depth explosions in almost all hardrock and water-saturated emplacement media (i.e. "good-coupling" media) are roughly consistent with a single m_b/yield relation for any fixed tectonic source region. In fact, the only media which are known to give consistently different results for fully tamped explosions are saturated clay or water and dry, porous media, such as the dry tuff and alluvium found above the water table at NTS. These observations are summarized in Figure 1, where it can be seen that the average m_b value for explosions of fixed low yield in saturated clay or water is expected to be higher by about 0.50 ± 0.25 magnitude units, while that for explosions in dry, porous media is expected to be lower by about 0.50 ± 0.25 magnitude units relative to that for explosions of the same yield in good-coupling media. It follows that, with the exception of cavity decoupled explosions, which are not always technically feasible, small explosions in dry, porous media pose the greatest challenge to effective seismic monitoring.

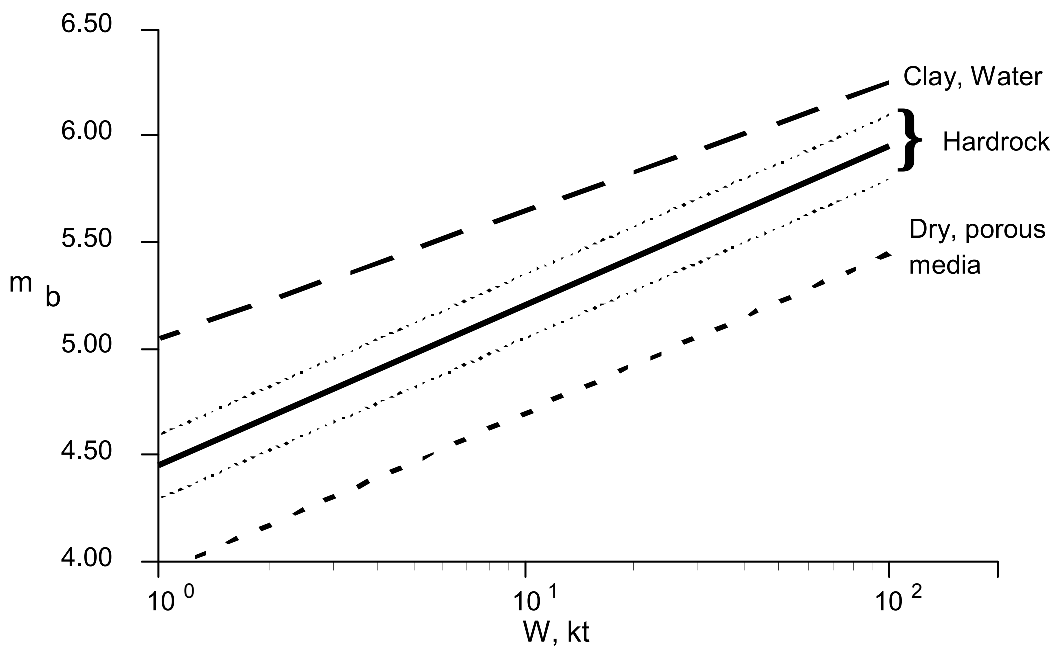

Figure 1. Comparison of m_b/yield relations for fully tamped underground nuclear explosions in a fixed tectonic source environment, illustrating the effects of source medium on seismic coupling. It can be seen that the average m_b value for explosions of fixed low yield in dry, porous media is expected to be lower by about 0.50 ± 0.25 magnitude units relative to that for explosions of the same yield in hardrock media.

During the first year of this two year study program, our analyses have focused on broadband data recorded from NTS explosions at the four near-regional stations of the LLNL seismic network. We currently have digital data recorded at those stations from some 150 NTS explosions, approximately 100 of which were underground nuclear tests conducted above the water table in dry, porous media. These data are generally of excellent quality, as is illustrated in Figure 2 which shows a record section of data recorded from selected Yucca Flat explosions at LLNL station MNV. In this figure, the top ten traces correspond to recordings of low yield (W < 20 kt) explosions in dry, porous media above the water table (above W.T.) at Yucca, while the bottom three traces represent recordings of larger (~140 kt) explosions conducted in saturated tuffs below the water table (below W.T.) at Yucca. It can be seen that the broadband signal to noise ratios are generally quite high, even for the smaller explosions in low coupling media.

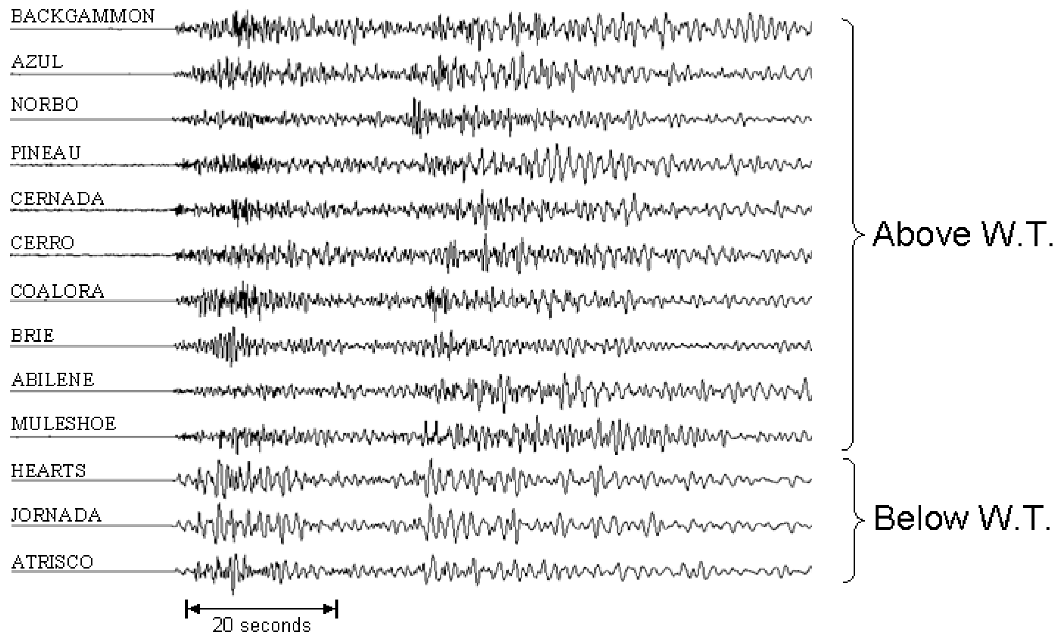

Figure 2. Data recorded from selected Yucca Flat explosions at LLNL station MNV. The top ten traces correspond to recordings of low yield (W < 20 kt) explosions in dry porous media above the water table (above W.T.) at Yucca, while the bottom three traces are recordings of larger explosions conducted in saturated tuff below the water table (below W.T.) at Yucca.

Our initial analyses centered on seismic data recorded at the LLNL near-regional ($\Delta \approx 240$ km) station MNV (Mina, Nevada), for which we have the most complete set of data recorded from explosions conducted above the water table in dry, porous media at Yucca Flat. The distribution of gas-filled porosity (percent by volume) values measured at the working points of these 63 explosions is shown in Figure 3, where it can be seen that the values range from near zero to almost 30%. The mean yield of this sample of explosions is close to 10 kt and their distribution with scaled depth is shown in Figure 4, where it can be seen that the values are fairly tightly clustered around a mean scaled depth of about 150 m/kt$^{1/3}$.

P wave spectra corresponding to the data recorded from these explosions at station MNV were estimated over the frequency band 0.5 to 10 Hz, using the initial 10 seconds of the recorded P waves. Because these explosions were conducted over such a narrow range in scaled depth, it is not possible to explicitly address the depth dependence of the seismic source, and the P wave spectral amplitude level, P(ω), has been represented by the simple scaling relation:

$$P(\omega) = k(\omega)\, W^{a_1(\omega)}\, 10^{a_2(\omega)Gp} \qquad (1)$$

where W is the explosion yield, Gp the percent gas-filled porosity at the working point and k, a_1, a_2 are frequency dependent coefficients to be estimated from the observed spectral data via least squares analysis:

$$\log P(\omega) = \log k(\omega) + a_1(\omega) \log W + a_2(\omega)\, Gp \qquad (2)$$

The assumed functional dependence of the P wave spectral amplitudes on Gp was adopted from the scaling relation proposed previously by Vergino and Mensing (1990) in their prior analysis of m_b(Pn) scaling for explosions in dry, porous media at NTS. Although alternate functional forms could be considered, it has been found that this simple relation provides a good description of the observed variations in P wave spectral amplitude as a function of Gp.

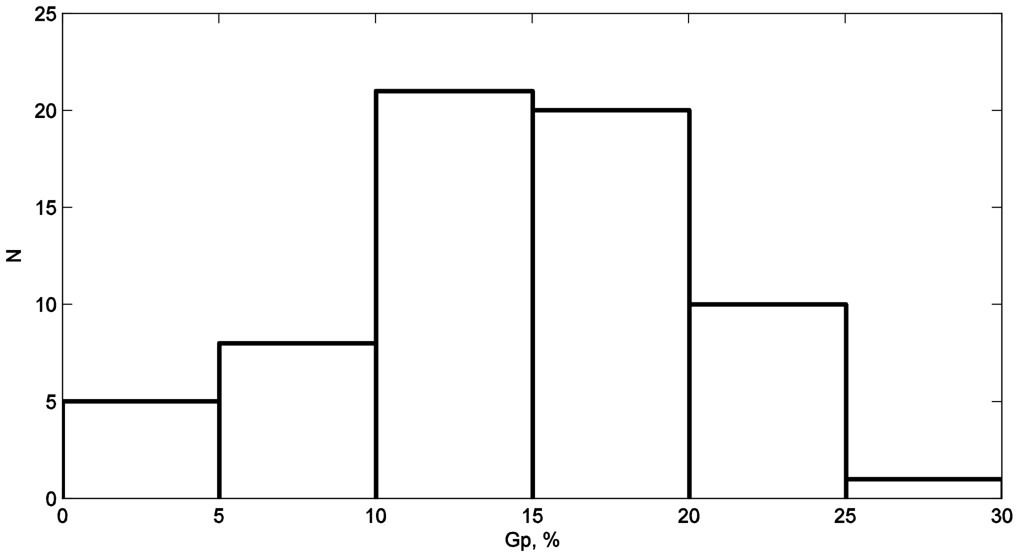

Figure 3. Distribution of observed gas-filled porosity (Gp) values for the selected sample of Yucca Flat explosions recorded at MNV.

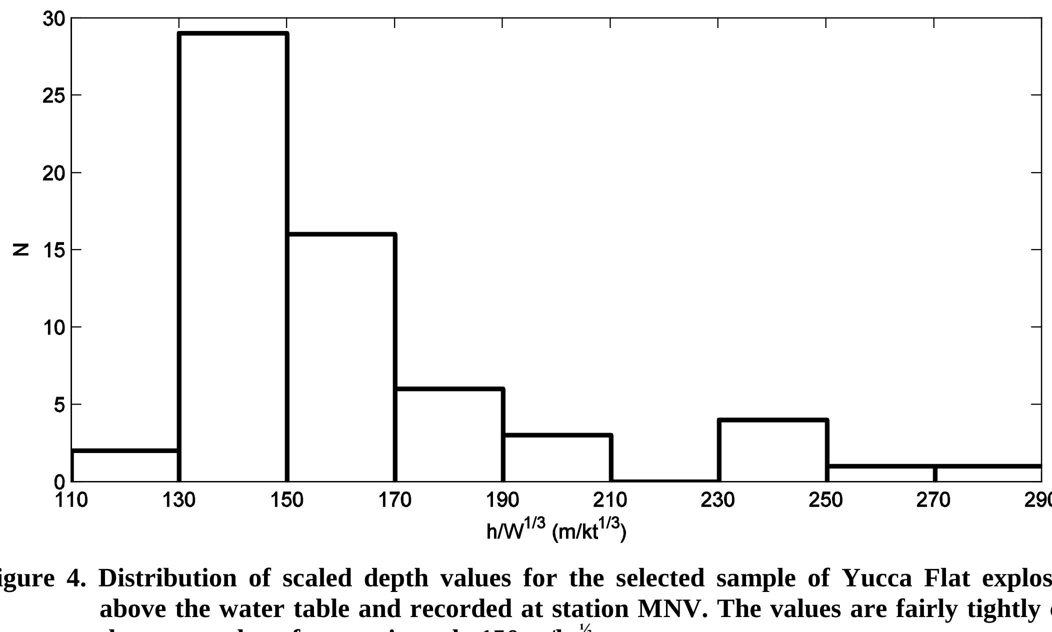

Figure 4. Distribution of scaled depth values for the selected sample of Yucca Flat explosions conducted above the water table and recorded at station MNV. The values are fairly tightly clustered about the mean value of approximately 150 m/kt$^{1/3}$.

A somewhat surprising result of our scaling analysis has been the finding that the dependence of P wave spectral amplitude on Gp is essentially independent of frequency. This fact is confirmed in Figure 5 which shows a comparison of the prediction σ values as a function of frequency obtained using the statistically derived frequency dependent scaling and a frequency independent scaling in which the coefficient on Gp was held fixed at the average of the frequency dependent values.

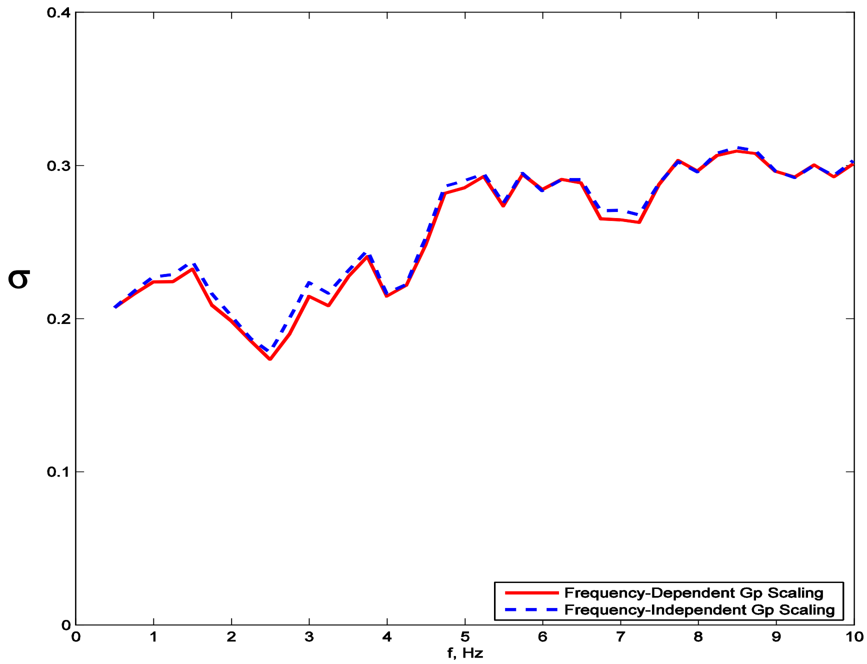

Figure 5. Comparison of prediction standard deviations (σ) as a function of frequency (f) for scaling analyses conducted with frequency dependent (solid) and frequency independent (dashed) Gp scaling. These results indicate that the scaling with Gp is essentially independent of frequency.

It can be seen that the results obtained using these two models are essentially identical, confirming that the Gp scaling is independent of frequency within the uncertainties in the statistically derived scaling coefficients. The average value of the a_2 coefficient in this case is -0.024, which compares with the coefficient values of -0.027 obtained by Vergino and Mensing (1990) from their analysis of the m_b(Pn) scaling dependence on Gp. This finding results in a very significant reduction in the complexity of the source scaling in that it means that the entire P wave source spectrum scales in the same way over the analyzed frequency range from 0.5 to 10 Hz, decreasing by about a factor of five at a fixed yield as Gp varies from near zero to 30%.

It has been found that this statistical scaling model provides quite good predictive capability over the range of source parameters encompassed by the selected sample of explosions. This fact is illustrated in Figures 6 and 7 which show, respectively, comparisons of predicted and observed P wave spectra for explosions of the same yield with significantly different Gp values, and for explosions of the same Gp value (~20%) with m_b(Pn) values (and associated yields) varying over nearly a full order of magnitude. These comparisons confirm that the derived scaling with both yield and Gp are in good agreement with the measured P wave spectral data. In fact, the scaling with Gp appears to be precise enough to identify likely errors in the reported Gp values. An example of this is shown in Figure 8, where the comparison on the left is for the prediction obtained using the reported Gp value of 29% (the highest value in our sample of explosions), while the comparison on the right is for the prediction obtained using a reduced Gp value of 15%. Clearly the fit is much better using the reduced value and the frequency independent nature of the discrepancy strongly points to the Gp variable.

In order to provide a basis for quantitative evaluation of the seismic source for explosions in dry, porous media, we theoretically scaled MNV *P*-wave spectra derived from data recorded from explosions conducted below the water table (BWT) at Yucca Flat to the average sample values of W = 10 kt, h = 323 m (i.e., $h/W^{1/3} = 150$ m/kt$^{1/3}$) of the dry, porous sample using the Mueller/Murphy (1971) scaling model. Figure 9 shows a comparison of the resulting scaled spectra for an explosion much larger than 10 kt (Jornada) and an explosion smaller than 10 kt (Techado). It can be seen that these scaled spectra are comparable, indicating that we have a good reference level for a 10 kt explosion at a depth of 323 m in saturated tuff.

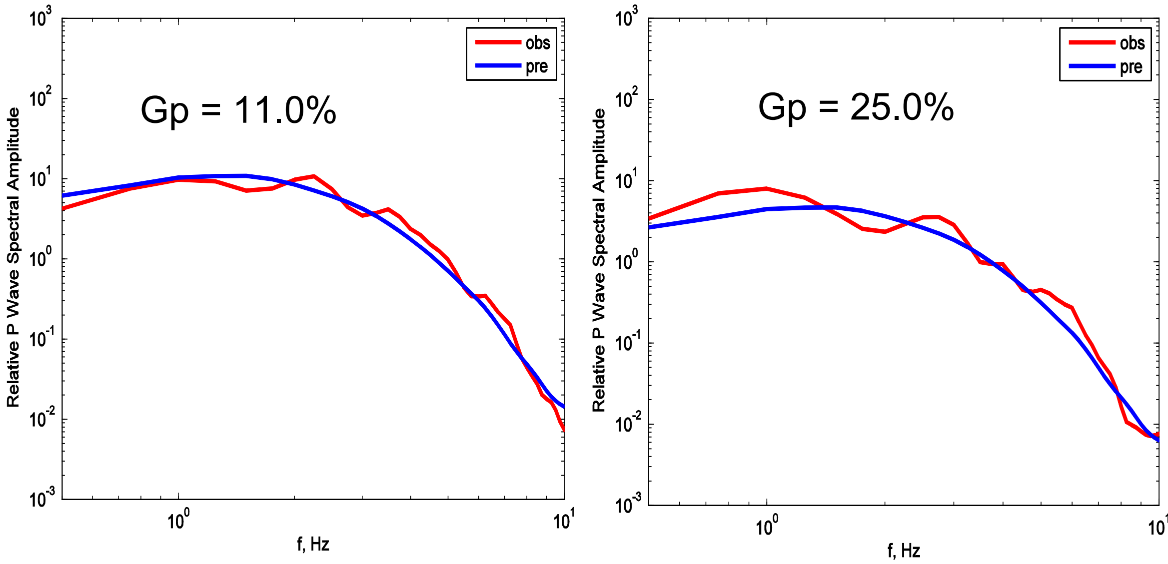

Figure 6. Comparison of predicted and observed MNV P wave spectra for explosions of comparable yield conducted in media with significantly different gas-filled porosity (Gp) values.

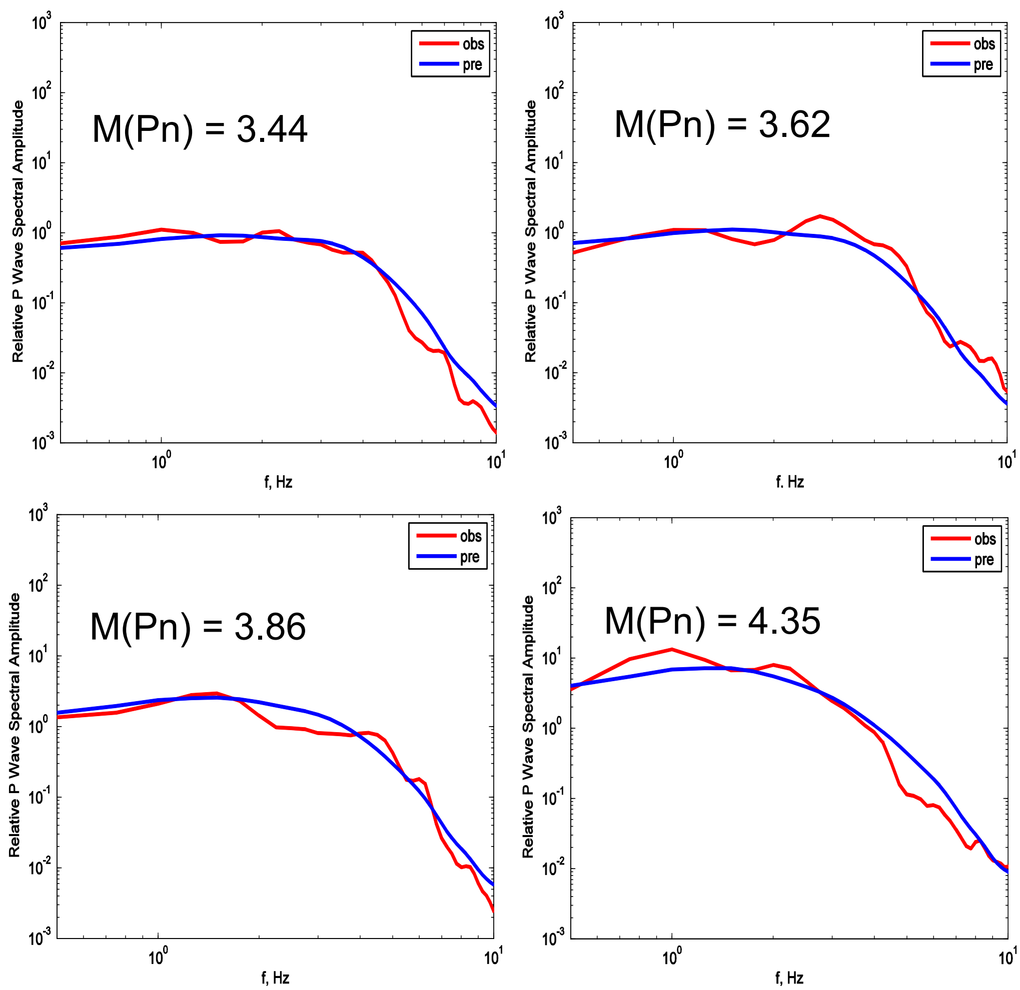

Figure 7. Comparison of predicted and observed MNV P wave spectra for explosions of different yields conducted in media with comparable (Gp ≈ 20%) gas-filled porosity values.

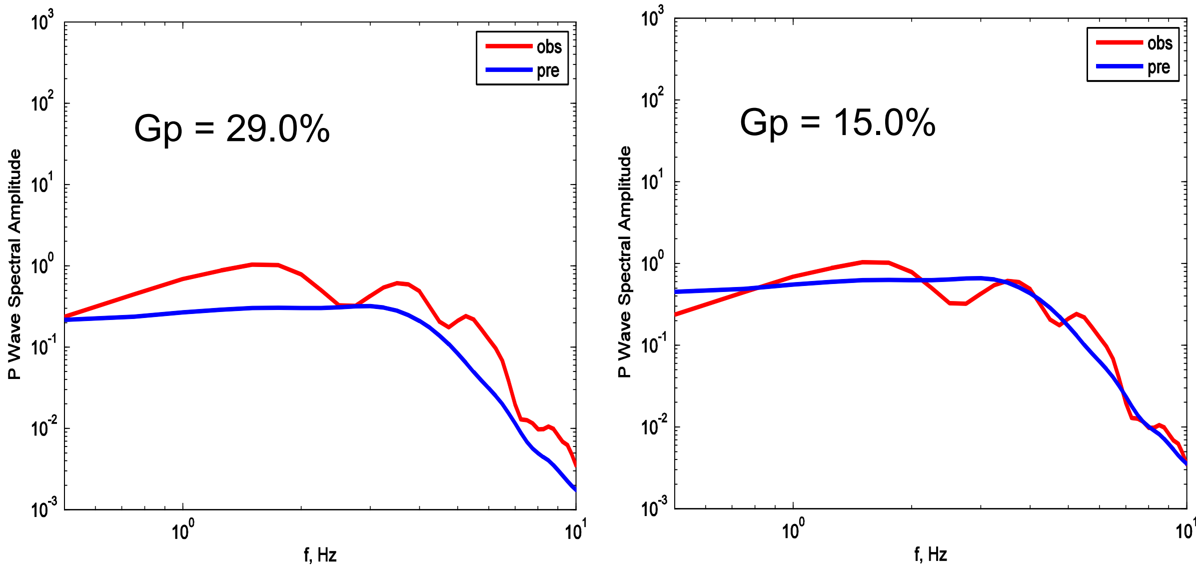

Figure 8. Comparison of observed MNV P wave spectra for an explosion with reported gas-filled porosity (Gp) of 29% with predicted spectra for Gp values of 29% (left) and 15% (right). It can be seen that the derived scaling relations are precise enough to identify likely errors in the reported Gp values.

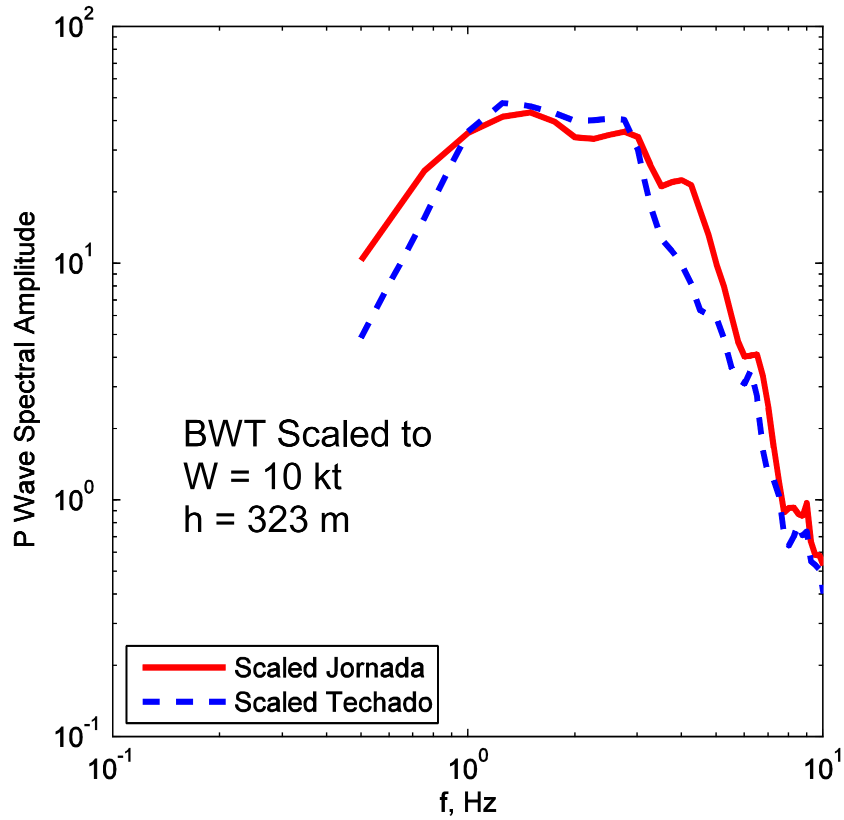

Figure 9. Comparison of station MNV scaled P wave spectra for explosions in saturated tuff below the water table at Yucca Flat with yields significantly larger (Jornada) and smaller (Techado) than the mean yield of approximately 10 kt of the sample of explosions in dry, porous media. It can be seen that the application of the Mueller/Murphy scaling relations brings these two into very good agreement.

Figure 10 shows ratios of the average saturated tuff P wave spectral estimate for a 10 kt explosion at 323 m depth to the corresponding average spectra predicted for the same explosion in dry, porous media with Gp values of 5 and 25%, using the statistically derived scaling laws. It can be seen that these source spectral ratios are approximately independent of frequency over the analyzed band from 0.5 to 10 Hz. Note also that an explosion in a dry, porous medium with very low Gp is not the same as an explosion of the same yield and depth in saturated tuff. That is, the absence of water has some effect on seismic coupling, even for media with very low air-filled porosity values.

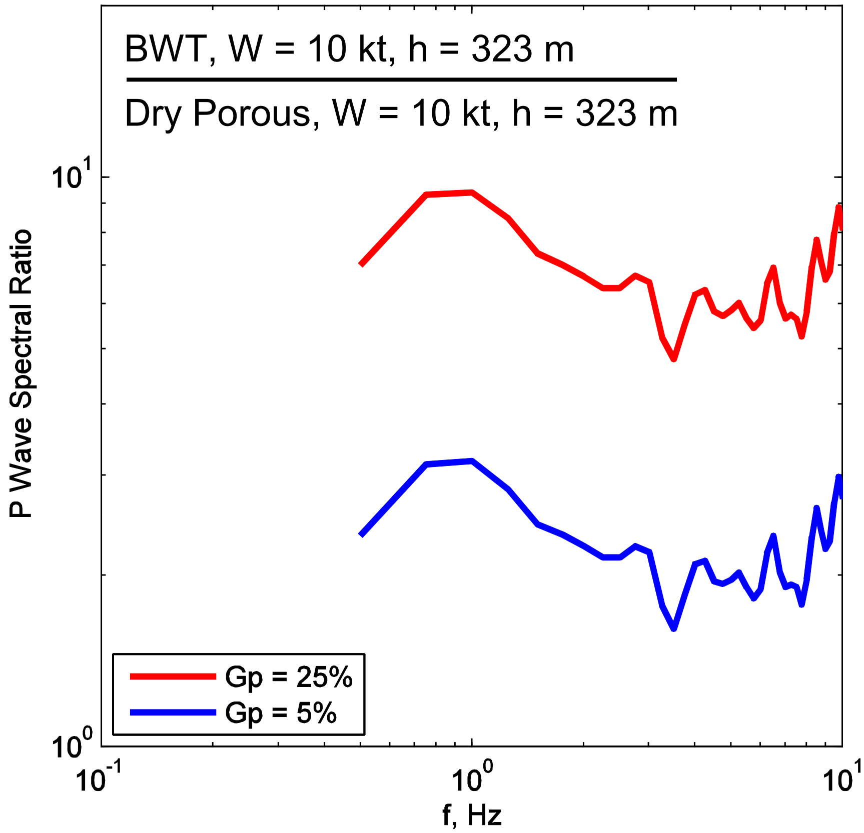

Figure 10. Spectral ratios of the estimated station MNV P wave spectrum for a 10 kt explosion at a depth of 323 m in saturated tuff to the corresponding MNV predicted spectra for 10 kt explosions in dry, porous media characterized by Gp values of 5% and 25%.

Dividing the Mueller/Murphy seismic source function predicted for a 10 kt explosion at a depth of 323 m in saturated tuff by the experimental source spectral ratios shown in Figure 10 gives estimates of the corresponding seismic source functions for the same explosions in dry, porous media. The result for a Gp value of 25% is shown in Figure 11, where it is compared with the result of dividing the Mueller/Murphy saturated tuff source by a frequency independent factor of 6.5. It can be seen that this simple frequency independent shift brings the two source function estimates for a 10 kt explosion at a depth of 323 m in a dry, porous medium characterized by a Gp value of 25% into excellent agreement. In particular, both estimates show about the same corner frequency and a common inverse frequency squared rolloff at high frequency, contrary to the conclusions of some previous studies (e.g., Taylor and Dowla, 1991) which suggested that the rolloff rate is expected to be higher for explosions in dry, porous media.

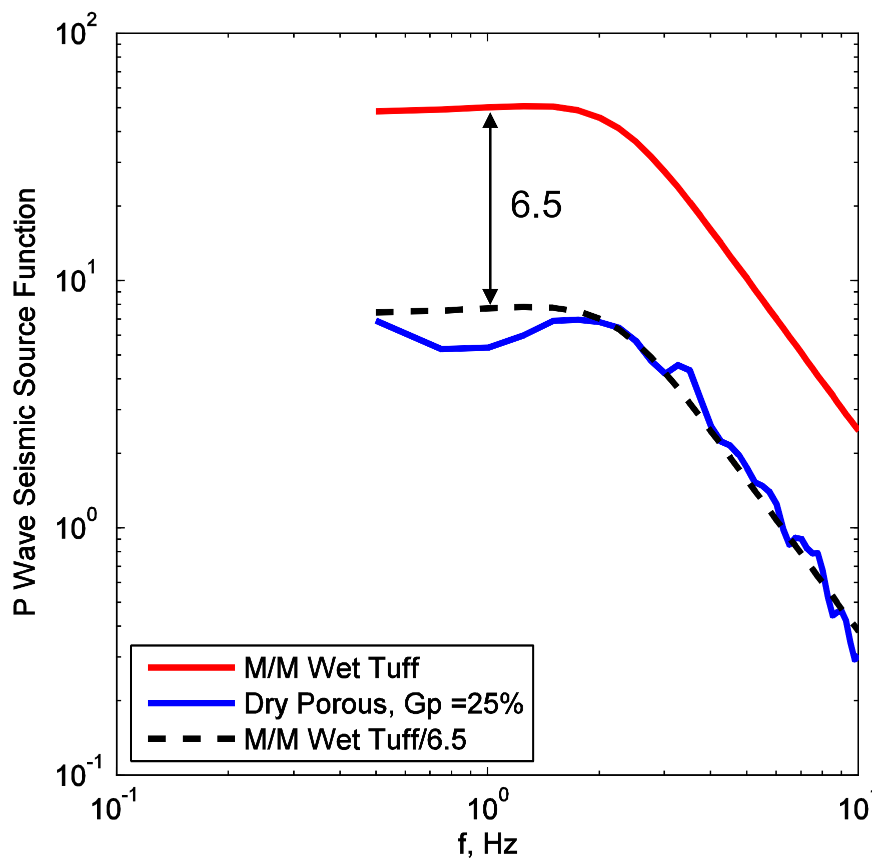

Figure 11. Comparison of the P wave source function estimate for a 10 kt explosion at a depth of 323 m in a dry, porous medium characterized by a Gp value of 25% with the corresponding Mueller/Murphy source function for the same explosion in saturated tuff. It can be seen that these two source function estimates can be reconciled by an essentially frequency independent relative coupling factor of ~ 6.5.

CONCLUSIONS AND RECOMMENDATIONS

The dependence of seismic source coupling of underground nuclear explosions on the characteristics of the explosion source medium is an important consideration in any assessment of nuclear test monitoring capability. While experience has indicated that explosions in almost all hardrock and water-saturated emplacement media are roughly consistent with a single m_b/yield relation in any fixed tectonic source region, explosions in dry, porous media are observed to have low frequency seismic source coupling at a given yield that is as much as an order of magnitude lower than that in hardrock. The objectives of this research study are to develop a "Mueller/Murphy" frequency dependent seismic source model for underground nuclear explosions in such media and to then quantitatively assess the implications of this model with respect to seismic monitoring capability.

Over the past year we have been analyzing seismic data recorded at the LLNL network station MNV from explosions conducted above and below the water table at Yucca Flat. P wave spectra over the frequency band 0.5 to 10 Hz have been estimated for a sample of 63 explosions conducted in dry, porous media above the water table. The measured gas-filled porosities (Gp) at the working points of these explosions range from near zero to almost 30%, while the associated yield values extend over approximately two orders of magnitude around a mean yield of about 10 kt. Statistical scaling analyses of the dependence of the observed spectral amplitudes on explosion yield and Gp indicate that the dependence on Gp is essentially independent of frequency over the entire range from 0.5 to 10 Hz. That is, the effect of Gp on the seismic source spectrum can be expressed as a frequency independent factor that indicates, for example, that the spectral amplitude levels decrease uniformly by about a factor of 5 as Gp increases from 0 to 30%. In order to compare these results with the well-documented seismic source for explosions conducted in water-saturated media, we analyzed data from a selected sample of explosions conducted below the water table at Yucca Flat and scaled their corresponding station MNV P wave spectra to the mean yield and depth of burial of the sample of explosions in dry, porous media using the Mueller/Murphy source scaling model. The results of this comparison indicate that the seismic source function for a 10 kt explosion in a dry, porous medium with a Gp value of 25% is expected to be very similar to the Mueller/Murphy source function for a 10-kt explosion at the same depth in saturated tuff, divided by a frequency independent factor of about 7. In particular, both source function estimates show a high frequency rolloff proportional to ω^{-2}. Current work is focused on deriving quantitative estimates of the statistical uncertainty in these results and on assessing their implications for general source modeling of explosions in dry, porous media.

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