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 hard rock 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 National Security Site (NNSS)—formerly the Nevada Test Site—are typically observed to have, at a given yield, m_b values lower than those in hard rock 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.

Over the past two years, we have been studying the P wave seismic source coupling characteristics of explosions in dry, porous media by analyzing seismic data recorded at the Lawrence Livermore National Laboratory (LLNL) regional network stations from nuclear explosions conducted above and below the water table at the Yucca Flat testing area of NNSS. These data have included a sample of 63 explosions conducted in dry, porous media above the water table at Yucca Flat that sample a range of gas-filled porosities (Gp) extending from near zero to almost 30% and that have a mean yield of about 10 kt and a mean scaled depth of burial of about 150 m/kt$^{1/3}$. The statistical source scaling analyses of these data revealed that the dependence of the observed P wave spectral amplitudes on Gp is essentially independent of frequency over the range of 0.5 to 10 Hz, with the logarithm of the spectral amplitude at a fixed yield decreasing with increasing Gp as -0.024 Gp. That is, the effect of Gp on the P wave seismic source spectrum can be expressed as a frequency independent factor, which greatly simplifies the source scaling analysis. It has been further determined that the theoretical Mueller/Murphy seismic source scaling with yield and source depth of burial determined for explosions in water-saturated tuffs, such as those found below the water table at Yucca Flat, is also applicable to low-yield explosions in dry, porous media. That is, these results indicate that the P wave seismic source functions for underground nuclear explosions in dry, porous media can be well approximated by simply dividing the P wave source functions for the same explosions in saturated tuff predicted by the well-calibrated Mueller/Murphy source model by the derived frequency independent Gp reduction factor. It follows that, given an estimate of Gp for the dry, porous source emplacement medium of an explosion of monitoring interest, a P wave seismic yield estimate for that explosion can be readily determined from the established relations for explosions in good-coupling media by accounting for the expected frequency-independent effect of Gp on the radiated P wave amplitude.

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 hard rock 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 dry, porous media at NNSS 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 physical characteristics of the source medium for small underground nuclear tests that might be conducted in such low-coupling media.

RESEARCH ACCOMPLISHED

Observational data from multiple, globally distributed nuclear test sites strongly indicate that low-frequency seismic source coupling efficiency is very similar for all explosions in good-coupling media (i.e., hard rock or water-saturated media). Saturated clay or water and dry, porous media are the only media in which fully tamped explosions produce m_b/yield results that are consistently different from those obtained in good-coupling media. At a fixed yield, the m_b/yield results for saturated clay or water are higher on average by about 0.5 units m_b (and therefore provide no special monitoring challenge); for dry, porous media, they are lower on average by about 0.5 units m_b. This reduced coupling for the latter is illustrated in Figure 1, where m_b/yield data for selected explosions conducted in dry, porous tuff and alluvium above the water table at NNSS are compared with the nominal NNSS m_b/yield relation for explosions in good-coupling media. It can be seen that these observed data fall below this good-coupling m_b/yield relation by nearly a full order of magnitude in some cases and that the offset appears to increase with increasing air-filled porosity (Gp)—percent by volume, measured at shot depth. While this observed reduction in seismic coupling is not as pronounced as that for the cavity decoupling evasion scenario, which is expected to be as much as two orders of magnitude lower than that for good-coupling media, it is large enough to significantly affect nuclear test monitoring strategy. Thus, there is a need for a quantitative seismic source model for explosions in such media.

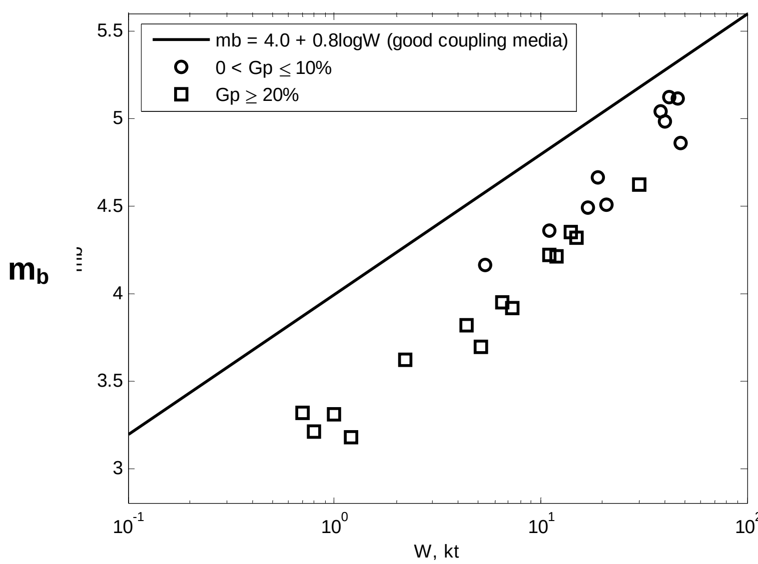

Figure 1. Comparison of observed m_b/yield data for explosions conducted in dry, porous tuff and alluvium above the water table at NNSS with the nominal NNSS m_b/yield relation for explosions conducted in good-coupling media. Gp denotes the measured air-filled porosity (percent by volume) at the detonation point.

Theoretical investigations of the seismic source characteristics of underground nuclear explosions have been ongoing since the initiation of underground testing in 1957. The most ambitious of these have attempted to proceed according to “first principles,” that is, by beginning at the point and instant of detonation and calculating outward in space and time using nonlinear finite difference codes based on fundamental physical laws. However, because of the complex nature of the response of real earth materials over the enormous range of pressures encountered in tamped underground nuclear explosions, it has yet to be demonstrated that such theoretical simulation models are fully capable of accurately reproducing all of the observed variations in seismic coupling. For this reason, an alternative approach has been pursued in parallel to the formal one in which measured ground-motion data from explosions have been used to infer simple analytic approximations to the nuclear seismic source function as well as scaling laws to describe the dependence of the source characteristics on variables such as explosion yield, depth of burial, and emplacement medium. One such approximate source model that has been extensively tested and verified against a wide variety of observed seismic data is that proposed by Mueller and Murphy some 40 years ago (Mueller and Murphy, 1971; Murphy, 1977). This research resulted in the formulation of seismic source models for underground nuclear explosions in granite, saturated tuff/rhyolite, salt, and sandstone/shale media. The models have proved to be remarkably consistent with seismic observations from underground nuclear explosions conducted in conjunction with the U.S., Former Soviet Union, French, and Chinese nuclear testing programs (Murphy and Barker, 2001; Murphy et al., 2001). However, because it was generally believed at the time of the original Mueller/Murphy model formulation that only low-yield nuclear explosions could be conducted in dry porous media at potential testing locations within the Soviet Union, explosions in such media were considered to be of secondary importance with respect to nuclear test monitoring, and consequently, no attempt was made at that time to derive and validate a corresponding approximate “Mueller/Murphy” seismic source model for underground nuclear explosions in low-coupling, dry, porous media. More recently, U.S. nuclear monitoring requirements have expanded to focus more on global monitoring of possible smaller, clandestine nuclear tests. Such low-yield tests could well be conducted in low-coupling media in many countries of potential monitoring interest. Therefore, there is a need for an appropriate seismic source model for explosions in such media that can be used to quantitatively assess nuclear monitoring capability.

The seismic source scaling analysis conducted in this study has focused on broadband digital data recorded from NNSS explosions at the four near-regional stations of the LLNL seismic network. Because the available data sample from LLNL station MNV (Mina, Nevada; $\Delta \approx 240$ km) is the most complete, it was used for the statistical scaling analysis; and selected data from the other three LLNL stations were used to test the robustness of the seismic source scaling inferred from the MNV data. This MNV data sample consists of recordings from 63 underground nuclear explosions conducted above the water table in dry, porous media at the Yucca Flat testing area of NNSS. The distribution of the measured Gp values for these 63 explosions is summarized in Figure 2, where it can be seen that the values range from near zero to almost 30%, with a mean value of about 15%. The corresponding explosion yields range from about 0.5 to 40 kt, with a mean value of around 10 kt, and the associated scaled depths of burial are fairly tightly clustered around a mean-scaled depth of about 150 m/kt$^{1/3}$.

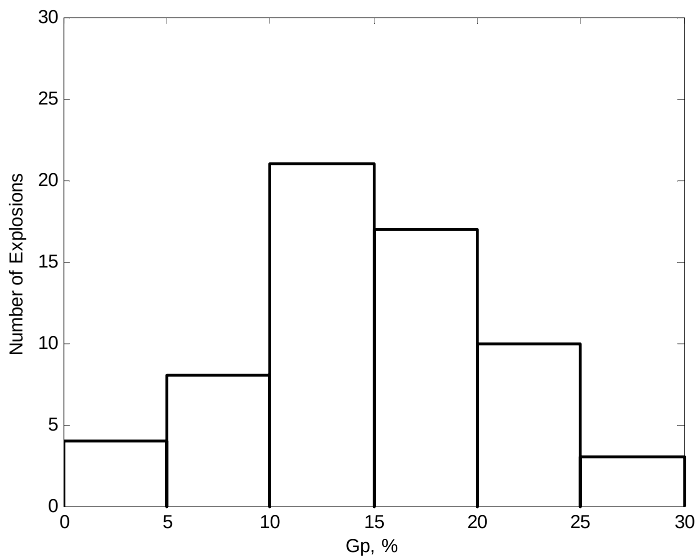

Figure 2. Distribution of observed gas-filled porosity (Gp) values for the selected sample of 63 Yucca Flat explosions recorded at station MNV.

P wave spectra corresponding to the seismic data recorded at MNV from the 63 selected Yucca Flat explosions have been estimated over the frequency band from 0.5 to 10 Hz, using the initial 10 seconds of the recorded P waves. These spectra have been smoothed to an effective resolution of about 0.25 Hz to provide the P wave spectral amplitude data used in the scaling analysis. Since these data were recorded at a fixed station from explosions in the same Yucca Flat testing area of NNSS, it has been assumed that the frequency dependent propagation path effects are essentially the same for all events and that, consequently, the scaling of these observed P wave spectra should reflect the scaling of the associated P wave source functions.

With regard to the statistical scaling model, because these selected explosions were conducted over such a narrow range in scaled depth, source depth is approximately proportional to the cube root of the yield, and any depth dependence of the seismic source is absorbed into the yield dependence for this sample of explosions and cannot be independently estimated through statistical analyses. Therefore, the observed P wave spectra from these explosions, P(ω), have been represented by the simple functional form

$$P(\omega) \quad = \quad k(\omega)\, W^{a_1(\omega)}\, 10^{a_2(\omega) G_P}\, , \tag{1}$$

where W is the explosion yield; Gp the percent gas-filled porosity of the emplacement medium at shot depth; and k, a_1, and a_2 are frequency dependent scaling coefficients to be estimated from the observed spectral data via least squares analysis using the linearized form of Equation (1):

$$\log P(\omega) \quad = \quad \log k(\omega) \quad + \quad a_1(\omega) \log W \quad + \quad a_2(\omega)\, G_P\ . \tag{2}$$

Note that the assumed functional dependence of the P wave spectral amplitudes on Gp in Equation (2) is simply a generalized, frequency dependent version of that employed previously by Vergino and Mensing (1990) in their analysis of narrowband m_b(Pn) data. Although alternative functional dependencies could certainly be considered, it has been found that this simple relation provides a good description of the observed variations in P wave spectral amplitude level as a function of Gp. A somewhat unexpected result of this statistical analysis has been the finding that the dependence of P wave spectral amplitude on Gp is essentially independent of frequency over the entire analysis band extending from 0.5 to 10 Hz. This fact is confirmed in Figure 3, which shows a comparison of the prediction σ values (i.e., the standard deviations of the logarithms of the ratios of predicted to observed spectral amplitudes) as a function of frequency obtained using the statistically derived frequency dependent Gp scaling coefficients and a frequency independent Gp scaling in which the coefficient on Gp was held fixed at the average of the derived frequency dependent values. 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 statistical uncertainties of the least squares solution. The average value of the Gp scaling coefficient (i.e., a_2 in Equation [2]) in this case is -0.024, which agrees quite well with the coefficient value of -0.027 obtained previously by Vergino and Mensing (1990) in their analysis of the m_b(Pn) magnitude measure scaling dependence on Gp. This result greatly simplifies the seismic source modeling analysis for explosions in dry, porous media in that it implies that for any fixed explosion yield and source depth of burial, the P wave spectral amplitudes expected for different values of Gp are offset from one another by frequency independent constant values, decreasing by a factor of about 5 as Gp varies from near zero to 30%.

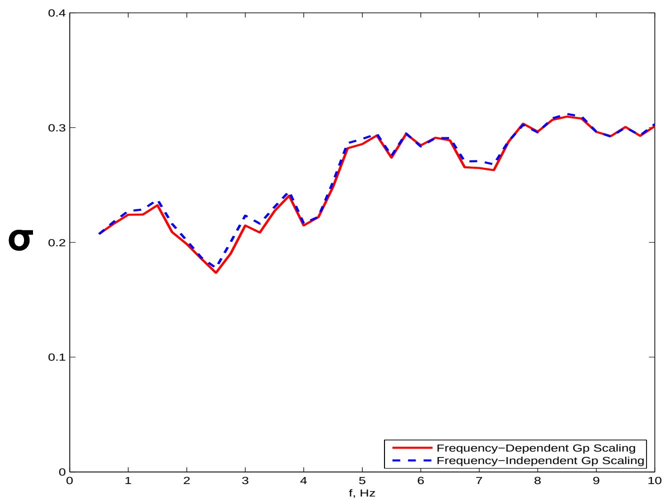

Figure 3. Comparison of prediction standard deviations (σ) as a function of frequency (f) for scaling analyses conducted with frequency dependent (solid line) and frequency independent (dashed line) Gp scaling.

It has been found that this statistically derived scaling model provides quite good predictive capability over the range of source parameters encompassed by the selected sample of explosions. For example, Figure 4 shows comparisons of predicted and observed MNV P wave spectra for explosions of essentially the same yield and significantly different Gp values. Similarly, Figure 5 shows comparisons of predicted and observed MNV P wave spectra for explosions with comparable Gp values (~20%) and m_b(Pn) values (and associated yields) varying over nearly a full order of magnitude. These comparisons confirm that the statistically derived scaling with both yield and Gp are in good agreement with the measured MNV P wave spectral data; consequently, they provide a robust method for estimating the expected MNV P wave spectra corresponding to Yucca Flat explosions in dry, porous media characterized by a range of Gp values at the sample average yield and scaled depth of burial of 10 kt and 150 m/kt$^{1/3}$, respectively.

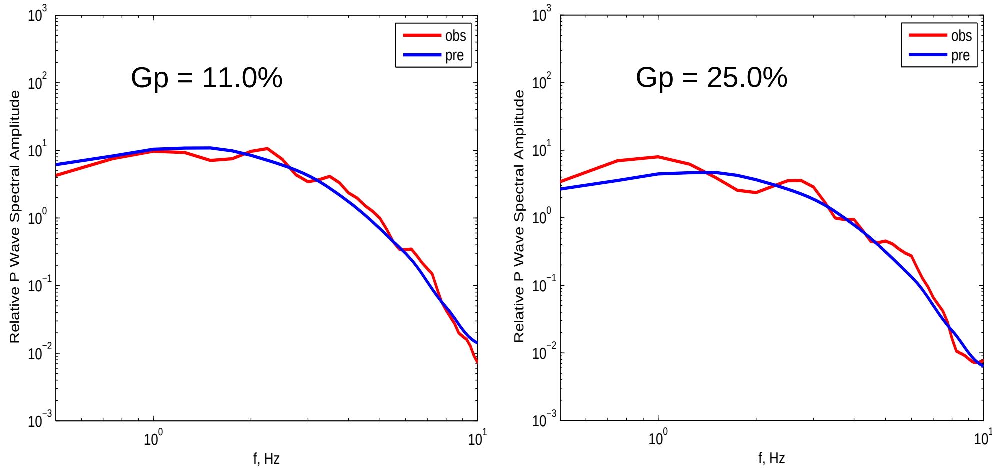

Figure 4. Comparison of predicted and observed MNV P wave spectra for explosions of comparable yield conducted in media with significantly different gas-filled porosity (Gp) values.

In order to provide a basis for the quantitative definition of a general seismic source model for explosions in dry, porous media, MNV P wave spectra derived from selected explosions conducted below the water table in saturated tuff at Yucca Flat have been scaled to the average dry, porous sample yield and depth of burial values of 10 kt and 323 m (i.e., $h/w^{1/3} = 150$ m/kt$^{1/3}$) using the well-documented and validated Mueller/Murphy (1971) seismic source scaling model for underground nuclear explosions in saturated tuff media. A sample of four below the water table (BWT) explosions was selected for this analysis, two of which (Hearts, Jornada) had yields significantly larger than the reference yield of 10 kt, and two of which (Techado, Borrego) had yields significantly smaller than the reference yield of 10 kt. Since these explosions were detonated BWT at Yucca Flat, the two smaller explosions were significantly overburied with respect to the reference scaled depth of burial of 150 m/kt$^{1/3}$; consequently, theoretical scaling for depth effects plays an important role. Figure 6 shows a comparison of the average of the yield scaled MNV spectra for Techado and Jornada with the average of the scaled spectra obtained using all four of the selected BWT explosions. It can be seen that these estimates are very comparable, indicating that the selected sample provides a very robust estimate of the average MNV P wave spectrum expected for a 10 kt explosion at a depth of 323 m in a BWT saturated tuff medium at Yucca Flat.

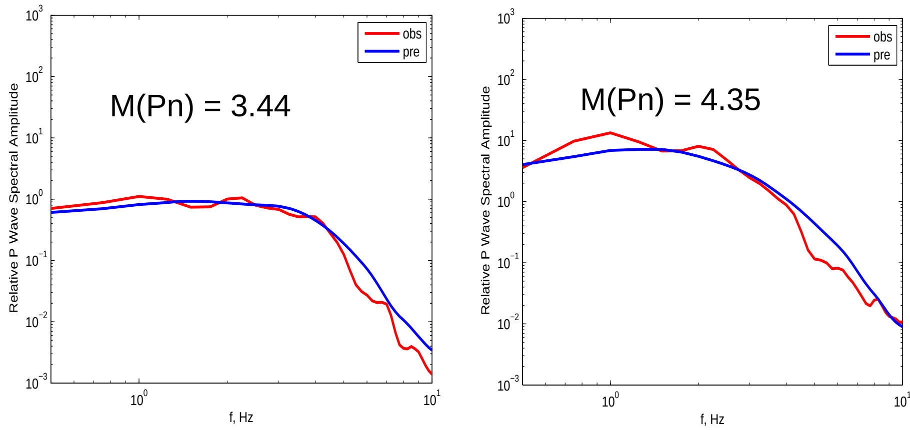

Figure 5. Comparison of predicted and observed MNV P wave spectra for explosions of different yield conducted in media with comparable gas-filled porosity values (Gp ≈ 20%).

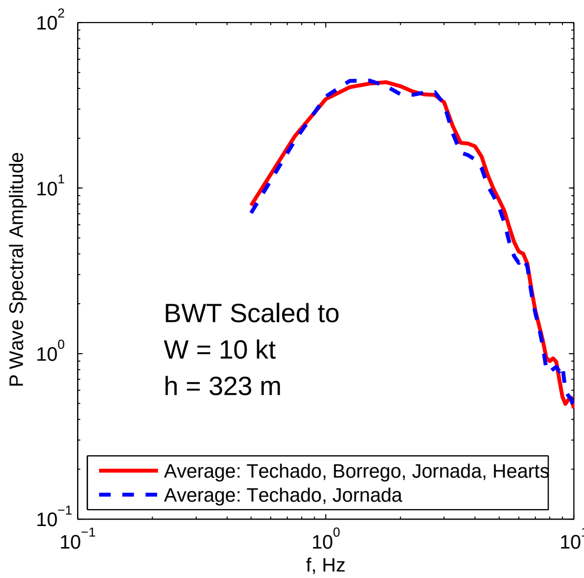

Figure 6. Comparison of the average station MNV scaled P wave spectrum at 10 kt for Techado and Borrego with that corresponding to a larger sample of below the water table (BWT) explosions.

Taking the ratio of the average observed saturated tuff scaled MNV P wave spectrum from Figure 6 to the corresponding predicted MNV P wave spectra for explosions with a yield of 10 kt and depth of 323 m in dry, porous media obtained using the statistically derived scaling model gives the P wave source spectral ratio estimates for Gp values of 5% and 25%, as shown in Figure 7. Note that these source spectral ratios are approximately independent of frequency over the analyzed band from 0.5 to 10 Hz. This implies that the P wave seismic source functions for explosions in dry, porous media have a corner frequency and high-frequency rolloff rate comparable to that of the corresponding Mueller/Murphy saturated tuff P wave source function, at least at the sample average yield and depth values of 10 kt and 323 m. This inference is confirmed in Figure 8, which shows a comparison of the results of dividing the theoretical Mueller/Murphy P wave source function for the reference explosion in saturated tuff by the source spectral ratio estimate corresponding to Gp = 25% in Figure 7 with that obtained by simply dividing that same source function by a frequency independent constant value of 6.5. It can be seen that these two estimates of the P wave source function for a 10 kt explosion at a depth of 323 m in dry, porous media are very comparable, showing the same corner frequency and ω^{-2} rolloff above the corner frequency as the corresponding saturated tuff source function. That is, the P wave source function for an explosion with a yield of 10 kt and a depth of 323 m in a dry, porous medium can be well approximated from the corresponding theoretical Mueller/Murphy P wave seismic source function for the same explosion in saturated tuff by simply dividing by a frequency independent constant.

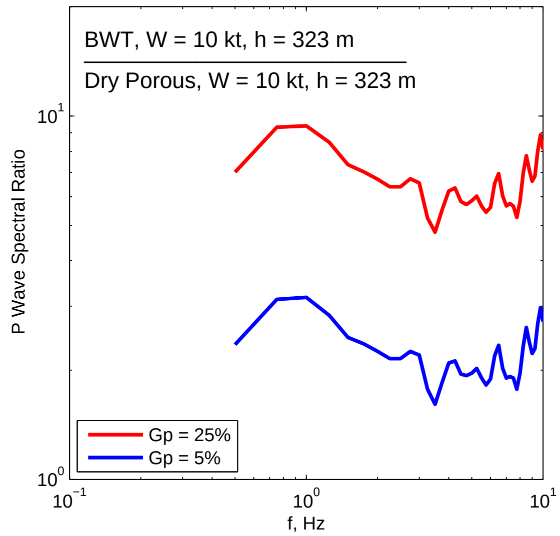

Figure 7. Spectral ratios of the estimated station MNV P wave spectrum for a 10 kt explosion at a depth of 323 m in saturated tuff to the corresponding MNV predicted spectra for 10 kt explosions in dry, porous media characterized by Gp values of 5% and 25%.

With reference to Figure 7, it can be seen that this reduction factor (RF) that maps the Mueller/Murphy saturated tuff source into the corresponding dry, porous media source for the reference explosion is given approximately by the relation

$$RF = 1.75 * 10^{0.024\, G_p} . \qquad (3)$$

Note that this factor does not go to 1 in the limit as Gp approaches zero. This means that explosions in dry, porous media couple less well than BWT explosions, even in the limit of very small Gp values. That is, the absence of water results in a decrease in seismic source coupling efficiency, even in the absence of any appreciable air-filled porosity.

Given the observed strong correlation between the inferred seismic source for an explosion with a yield of 10 kt and a depth of 323 m in dry, porous media with the corresponding theoretical Mueller/Murphy seismic source predicted for the same explosion in saturated tuff, it is reasonable to ask whether the Mueller/Murphy seismic source scaling with yield and source depth of burial determined for explosions in saturated tuff might not also be generally applicable to explosions in dry, porous media, particularly for the lower yield explosions of principal interest in nuclear test monitoring. This hypothesis has been tested by comparing the prediction σ values as a function of frequency obtained by scaling the nominal W = 10 kt, h = 323 m MNV P wave spectrum for explosions in dry, porous media using both the statistical yield scaling model and the Mueller/Murphy yield and depth scaling model derived for explosions in saturated tuff, for all explosions in the selected analysis sample with yields less than or equal to 20 kt (i.e., 48 of the 63 selected explosions). In both cases, the effects of variations in Gp were accounted for using the previously validated frequency independent Gp scaling relation. The prediction σ results as a function of frequency obtained using these two source scaling models are shown in Figure 9, where it can be seen that they are very similar over the entire frequency range from 0.5 to 10 Hz. This indicates that the theoretical Mueller/Murphy source scaling for explosions in saturated tuff is indeed applicable to low-yield explosions in dry, porous media.

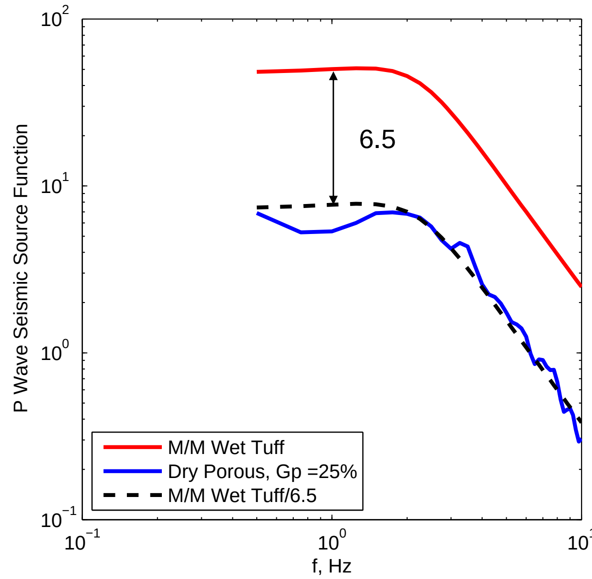

Figure 8. Comparison of the P wave source function estimate for a 10 kt explosion at a depth of 323 m in a dry, porous medium characterized by a Gp value of 25% with the corresponding Mueller/Murphy source function for the same explosion in saturated tuff.

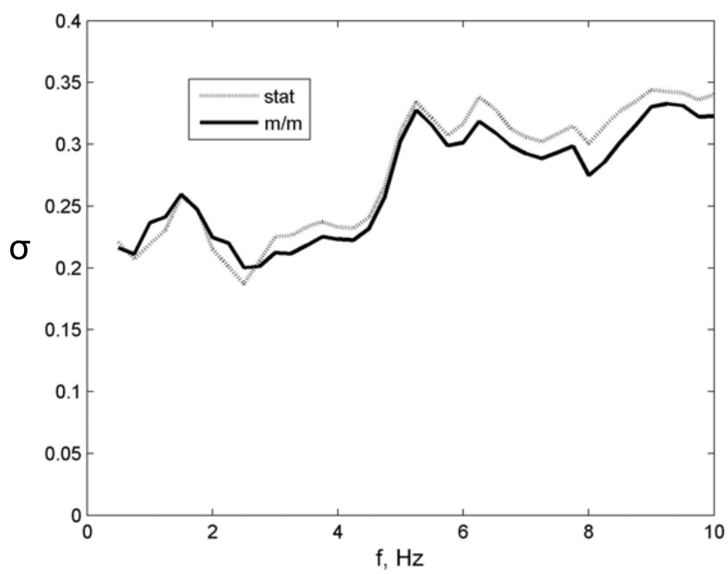

Figure 9. Comparison of prediction standard deviations (σ) as a function of frequency obtained using the statistical yield scaling model (stat) and the Mueller/Murphy (m/m) yield and depth scaling model for explosions in saturated tuff, evaluated over all explosions in the selected dry, porous sample and with yields less than or equal to 20 kt.

In fact, it can be seen from Figure 9 that the prediction σ values obtained using the Mueller/Murphy source scaling are actually uniformly slightly lower than the corresponding σ values obtained using the statistically derived source scaling model for all frequencies above about 2.5 Hz. This initially puzzling observation can be explained by the fact that the Mueller/Murphy model has an additional degree of freedom in that it explicitly accounts for variations in actual scaled depths between explosions relative to the sample average scaled depth of 150 m/kt$^{1/3}$. That is, although the scaled depths of most of the selected explosions in the dry, porous media sample cluster fairly tightly around the mean value of 150 m/kt$^{1/3}$, there are a few outlier events; these are modeled more accurately, particularly at high frequencies, by accounting for the effects of variations in scaled depth using the Mueller/Murphy saturated tuff source scaling model. This fact is illustrated in Figure 10, which shows comparisons of Mueller/Murphy predicted and observed MNV P wave spectra for the two outlier explosions characterized by scaled depths that are the most different from the average value of 150 m/kt$^{1/3}$ (i.e., h/W$^{1/3}$ = 452 m/kt$^{1/3}$, left, and h/W$^{1/3}$ = 281 m/kt$^{1/3}$, right). In these figures, the Mueller/Murphy predictions corresponding to both the nominal scaled depth of 150 m/kt$^{1/3}$ and the actual scaled depths are shown; it can be seen that in both cases the predictions are improved by incorporating the Mueller/Murphy predicted source depth scaling, particularly at high frequencies.

The analysis results presented above indicate that the P wave seismic source functions for underground nuclear explosions in dry, porous media can be well approximated by dividing the P wave source functions for the same explosions in saturated tuff predicted by the well-calibrated Mueller/Murphy P wave source model by the frequency independent reduction factor given by Equation (3). The uncertainty in such source predictions is quantified by the frequency dependent σ values derived for the Mueller/Murphy model prediction results shown in Figure 9 above.

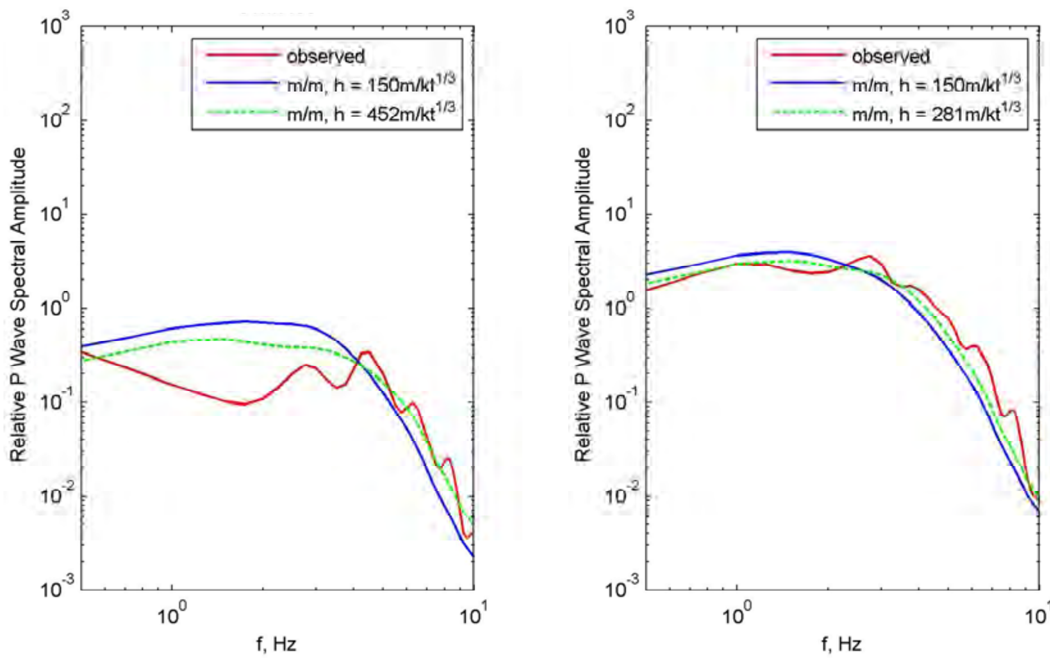

Figure 10. Comparisons of Mueller/Murphy (m/m) predicted and observed MNV P wave spectra for the two explosions characterized by scaled depths that are the most different from the average value of 150 m/kt$^{1/3}$ (i.e., h/W$^{1/3}$ = 452 m/kt$^{1/3}$, left, and h/W$^{1/3}$ = 281 m/kt$^{1/3}$, right). Mueller/Murphy predictions corresponding to both the nominal scaled depth of 150 m/kt$^{1/3}$ and the actual scaled depth are shown to illustrate the predicted depth effect.

CONCLUSIONS AND RECOMMENDATIONS

Over the past two years we have been analyzing P wave seismic source coupling characteristics of underground nuclear explosions in dry, porous media. The technical objectives of this research have been to develop a "Mueller/Murphy" frequency dependent analytic seismic source model for explosions in such media and to apply the model to quantitative assessments of seismic detection, identification, and yield estimation capabilities relevant in nuclear test monitoring. Broadband seismic data recorded at the LLNL regional network stations from 63 nuclear explosions conducted above the water table at the Yucca Flat testing area of NNSS were analyzed and compared to observations and models for explosions in good BWT coupling media. Analyses indicate that the effect of Gp on the P wave seismic source spectrum can be expressed as a frequency independent factor and that the theoretical Mueller/Murphy seismic source scaling with yield and source depth of burial is also applicable to low-yield explosions in dry, porous media after a simple adjustment for this Gp reduction factor. That is, the results of these analyses indicate that the P wave seismic source functions for underground nuclear explosions in dry, porous media can be well-approximated by simply dividing the P wave source functions for the same explosions in saturated tuff, predicted by the validated Mueller/Murphy source model, by a frequency independent Gp RF given by

$$RF = 1.75 * 10^{0.024Gp} \quad . \tag{4}$$

This model predicts that the m_b value at a given yield for an explosion in a medium characterized by a Gp value of 30% will be nearly a full magnitude unit lower than that expected for the same explosion in a good-coupling medium.

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