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Seismic Models for Near-Surface Explosion Yield Estimation in Alluvium and Sedimentary Rock

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Abstract

Seismic ground-motion data provide valuable constraints on explosion characteristics, such as yield and height-of-burst/depth-of-burial (HOB/DOB). This study investigated a range of seismic amplitude features and their efficacy in minimizing errors associated with yield estimation. Using a set of explosion recordings from experiments conducted in alluvium and sedimentary rock geologies, we investigated the effectiveness of three different seismic feature types over a range of different frequencies. Using both velocity and displacement data, we investigated the zero-to-peak (ZTP) amplitude of the first arriving *P* wave, the peak-to-peak (PTP) amplitude of the first arriving *P* wave, and the P_{rms}Prms amplitude over various time windows starting with the *P* wave. These three basic features were measured on both vertical component only data and the vertical–radial vector sum. In total, there were 56 different combinations investigated. Our seismic models combine the effects of scaled range and scaled HOB/DOB on the observed seismic features. The results show that the vertical–radial vector sum of the ZTP amplitudes measured on displacement seismograms most consistently produce models with the smallest difference between predicted amplitude values and observed amplitude values when accounting for both alluvium and sedimentary rock lithology. The improvement in fit to the data when incorporating the difference in source lithology is significant. If an alluvium lithology is assumed for a sedimentary rock lithology, the difference in yield could be up to ~ 3.0~3.0times the appropriate yield in the far field.

Introduction

To accurately estimate the yield of near-surface explosions using information from local seismic data, robust seismic amplitude model systems must incorporate the effects of lithology and the vertical emplacement of the source relative to the ground surface. To date, there have been relatively few controlled experiments that systematically vary the height-of-burst/depth-of-burial (HOB/DOB) of known explosions in different lithology types to quantify the combined effect of these two factors. The observation that lithology can significantly affect the amplitudes and character of recorded seismic waveforms has been well documented for surface and deeply buried explosions (Perret and Preston, 1958; Adams *et al.*, 1961; Carder and Mickey, 1962; Gupta and Hartenberger, 1981). Similarly, the fact that vertical source emplacement, that is, HOB/DOB, can significantly influence the seismic energy recorded at local distances has also been observed by both the underground nuclear monitoring community and the geotechnical blasting community (Kitov *et al.*, 1997; Flynn and Stump, 1988; Saadat *et al.*, 2014). However, to date, the most common seismic amplitude prediction models primarily depend only on yield and distance from the source (e.g., Murphy and Lahoud, 1969; Medearis, 1979; Gupta and Hartenberger, 1981; Saadat *et al.*, 2014).

Recent studies have attempted to quantify the effect of lithology and HOB/DOB on a variety of local-distance seismic observables with the intention of minimizing the uncertainty in subsequent yield estimations (Koper *et al.*, 2002; Bonner *et al.*, 2013; Ford *et al.*, 2014). Using aboveground explosions in alluvium, Koper *et al.* (2002)developed scaling laws and explored the effectiveness of functional relationships between yield and three observed waveform properties: the peak displacement of the first arriving *P* wave, the low-frequency asymptote of the displacement spectrum, and the corner frequency of the displacement spectrum. Bonner *et al.* (2013) studied surface-wave generation from both aboveground and belowground explosions detonated in alluvium and sedimentary rock lithologies to develop a technique to predict peak particle velocities that could be used to estimate seismoacoustic yields. The effect of yield, HOB/DOB, and range on the peak displacement of the first arriving *P* waves was modeled by Ford *et al.* (2014) for a set of shots in alluvium lithology to simultaneously estimate yield and HOB/DOB source parameters.

The objective of this study is to determine the most robust seismic feature model with the tightest model parameter confidence intervals using a suite of observed measurements to accurately predict the variation of seismic amplitudes due to differences in yield, range, geological conditions of the source, and HOB/DOB of the source to inform future predictive forensic yield analyses. There is a recognized need for validation of these types of empirical relationships that relate yield to variations in emplacement and source conditions in differing geological media. The preferred seismic model could therefore become a powerful tool when characterizing yield and HOB/DOB for future explosions of unknown size and emplacement.

To this end, we investigate the efficacy of three types of seismic features measured on observational data collected across two different lithologies: alluvium and sedimentary rocks. On both velocity and displacement data, we investigate the zero-to-peak (ZTP) amplitude of the first arriving *P* wave, the peak-to-peak (PTP) amplitude of the first arriving *P* wave, and the P_{rms}Prms amplitude over various time windows starting with the *P*-wave arrival. These three basic seismic feature types are combined with a variety of different band-pass filters and measured over both vertical component only data and the vertical–radial vector sum. In total, there are 56 different combinations of seismic features, band-pass filters, and input data components investigated in this study. Comparisons between these 56 different seismic features show that the vector sum of the ZTP amplitude of the *P* wave on the vertical and radial seismic components integrated to displacement most consistently produces models with the smallest difference between model-predicted amplitude values and observed amplitude values when accounting for both alluvium and sedimentary rock source lithology.

Experimental Series

Overview

Seismic data from four different controlled explosive-source test series are included in this study. They are Humble Redwood I (HR1), Humble Redwood II (HR2), Humble Redwood III (HR3), and the Sayarim 2011 series (SAY). These tests were conducted in two different types of subsurface lithologies: alluvium and sedimentary rock (Table 1). The sections below present detailed descriptions for each of these four test series.

Humble Redwood I and Humble Redwood II

The HR1 and HR2 series collected seismic and overpressure data from a series of 13 controlled high explosive experiments conducted at the Kirtland Air Force Base in New Mexico (Foxall *et al.*, 2008, 2010, 2011; Marrs *et al.*, 2009, 2012). Seven ammonium nitrate fuel oil (ANFO) explosions were associated with HR1 (Table 2). Individual shot locations, although clustered together horizontally, were not collocated to avoid emplacing shots in predisturbed sediments. The HOB of the shots ranged from $+5.0$ to -5.0 m, in which positive values indicate height above ground level and negative values indicate depth below ground level. Yields for all explosions in HR1 were equal to 539.8 kg trinitrotoluene (TNT) equivalent. The far-field seismic sensors that recorded the HR1 shots included three-component Güralp CMG-40T broadband seismometers, three-component Sprengnether S-6000 short-period seismometers, and one three-component Güralp CMG-3TB borehole broadband seismometer (Fig. 1 and Table 3). The strong-motion accelerometer data were not used in this study.

Six ANFO explosions were associated with HR2 (Table 4). Individual shot locations were also clustered together horizontally, but not collocated. The HOB of the shots ranged from -0.6 to -10.0 m (Table 4). Yields for all explosions in HR2 ranged from 90.8 to 753.9 kg TNT equivalent. The far-field seismic sensors that recorded the HR2 shots included three-component Güralp CMG-40T broadband seismometers and three-component Güralp CMG-3T broadband seismometers (Fig. 2 and Table 5). The strong-motion accelerometer data and data from the seismic array installed by Weston Geophysical to the northeast of the shot locations are not used in this study.

Raw seismic data were corrected to physical units by multiplying by the system sensitivity factor. As an interesting note, a comparison between the amplitudes of seismic waveforms recorded on the western stations with those recorded on the eastern stations show a noticeable path effect for post-*P*-wave phases. Amplitudes to the west are observed to be generally larger than those to the east for the same event, especially for the late arriving acoustic arrivals (Fig. 3; Ford *et al.*, 2014). The *P* phases generally do not display this amplification. The amplitude difference seems to coincide with differences in the fault-bounded physiographic provinces of the seismic station locations. For example, west of the Hubbell Springs fault is the Albuquerque basin, characterized by deep alluvial sediments, whereas the Hubbell Bench province is located to the east of the fault and is characterized by Permian sandstones and mudstones, Pennsylvanian limestones, and Precambrian basement overlain by a narrow and thinning surficial alluvium layer that pinches out to the east between E4 and ANMO (Figs. 1 and 2; Grant, 1981; Bedsun and Logan, 1984; Logan *et al.*, 1986; Foxall *et al.*, 2011). This marked difference in lithology could account for the differences in observed amplitudes on either side of the shot locations. Additionally, we note that all sources and seismic sensors, with the exception of the U.S. Geological Survey borehole station ANMO of the IU network, were located on alluvial deposits with estimated subsurface velocities of less than $\sim 800 \mathrm{m/s}$~800 m/s (Foxall *et al.*, 2011). ANMO is overlaid by 6 m of alluvial overburden followed by 94 m of fractured granite.

Humble Redwood III (HR3)

The HR3 experiment consisted of a series of five ANFO explosions (Bonner *et al.*, 2013). Shots 1 and 2 were detonated in the same alluvial test site as the HR1 and HR2 experiments, while the remaining three were detonated in a limestone outcrop 6.5 km directly to the east of the HR1 and HR2 experiments (Fig. 4). The yields of all explosions in this test series were equal to 90.6 kg TNT equivalent (Table 6). Two of the shots, one in each type of geology, were detonated aboveground while the other three were detonated belowground. Shot 5 was detonated in the cavity produced by shot 4. Most of the HR3 seismic stations had three-component sensors. Forty-two Sercel L-22 seismometers, 14 Sercel L-4C 3D seismometers, 6 Güralp CMG-40T broadband seismometers, and 1 STS-2 broadband seismometer were deployed for the HR3 experiment (Fig. 4 and Table 7). Each of the shot locations were surrounded by a semicircle array. The 21-station WC array surrounded the alluvium shot location whereas the 21-station WG array surrounded the sedimentary rock shot location (Fig. 4).

The footprint of the HR3 experiment encompasses three distinct physiographic provinces. As with HR1 and HR2, the lithology west of the Hubbell Springs fault and inferred Sandia fault is characterized by the deep alluvial Albuquerque basin. The lithology east of the Hubbell Springs fault and south of the Tijeras fault is composed of the Hubbell Bench province with thick sedimentary layers overlain by a narrow and thinning veneer of alluvium that pinches out just to the east of seismic station E4 (Fig. 4; Grant, 1981; Bedsun and Logan, 1984; Logan *et al.*, 1986; Foxall *et al.*, 2011). To the east of the Manzano fault are the raised Manzano and Manzanita Mountains consisting of relatively undeformed Precambrian rocks capped by flat-lying Pennsylvanian limestones.

Sayarim (SAY)

In 2011, the Geophysical Institute of Israel partnered with the Comprehensive Test Ban Treaty Organization to detonate three explosive charges in the Sayarim Military Range in the Negev desert, Israel (for more details see Bonner *et al.*, 2013). Two of the charges were composed primarily of ANFO, while a third was a smaller explosion composed of composition B. The yield for shot 3 is the largest of any of the shots investigated in the current study (Table 8; Gitterman and Hofstetter, 2012). All shots were assembled directly on the ground surface, therefore HOB differences reflect differences in the center of mass of the explosive shots. Nine three-component Sercel L-4C 3D temporary seismic stations were deployed for the Sayarim experiment (Table 9 and Fig. 5).

At the Sayarim testing site, the top 0.5–1 m subsurface layer is composed of soft and loose sediments. Below the surface layer lies 85–100 m of Quaternary alluvial conglomerates, with *P*-wave velocities between 1130 and $2020\ \mathrm{m/s}$, underlain by consolidated limestone, chalk and chert rocks, with *P*-wave velocities between 3750 and $4120\ \mathrm{m/s}$ (Gitterman *et al.*, 2005; Bonner *et al.*, 2013).

Seismic Features

Overview

Three different seismic features are measured on both velocity and displacement seismograms: the root mean square (rms) amplitude within a specified time window starting with the *P* phase (P_{rms}), ZTP amplitude of the first arriving *P* phase, and the PTP amplitude of the first arriving *P* phase. Detailed descriptions of these three seismic features (P_{rms}, ZTP, and PTP) are in the sections that follow.

We first pick the arrival of the *P* phase by hand on the unfiltered velocity seismograms. Displacement seismograms are obtained by removing the trend and mean of the velocity seismograms and then integrating to displacement. The *P*-phase arrivals on the displacement seismograms are then re-picked on unfiltered traces.

Seismic features on velocity and displacement seismograms are measured for single-component vertical-only (VV) data and calculated for vertical–radial (VR) vector sum quantities using

$$\mathrm{VR} = \sqrt{\mathrm{VER}^2 + \mathrm{RAD}^2}, \quad (1)$$

in which VER is the amplitude of the seismic feature on the vertical component and RAD is the amplitude of the seismic feature on the radial component.

P_{rms} Amplitude

The P_{rms} amplitude is a measure of the amplitude of the waveform over time windows starting with the *P*-wave arrival. The P_{rms} amplitude is calculated using

$$\mathrm{rms} = \sqrt{\frac{\sum x_i^2}{n}}, \quad (2)$$

in which x_i refers to the waveform amplitude at sample i, and n refers to the total number of samples within the time window. We determine the P_{rms} amplitude across three different window lengths (0.25, 0.33, and 0.50 s) on data filtered using one-pass (causal) two-pole Butterworth filters of various passbands. A complete listing of the window length and filter combinations is given in Table 10. We limit the length of the windows to a maximum of 0.5 s to reduce possible bias caused by subsequent seismic phases observed in the wavetrain. Nevertheless, we recognize that window length may impact the measurements for explosions larger than those included in this study if their source duration is longer than 0.5 s.

ZTP Amplitude

The ZTP amplitude is the peak amplitude of the first quarter cycle of the first arrival. To determine the ZTP amplitude, we band-pass filter the waveform then measure the amplitude of the first peak of the first arrival and subtract it from the amplitude at the *P* pick. We apply two possible band-pass filters to the data (Table 11). An example of the ZTP amplitude measurement from a typical velocity seismogram is shown in Figure 6.

PTP Amplitude

The PTP feature is a measure of the maximum amplitude of the first complete cycle of the *P* phase. Before determining the PTP amplitude, the data are first band-pass filtered using one of two possible filters (Table 11). An example of the PTP amplitude measurement from a typical velocity seismogram is shown in Figure 6.

Nomenclature

In the descriptions that follow, the various seismic features will be referred to in the text with abbreviations as follows:

$$[\mathrm{FeatureType}][\mathrm{DataType}][\mathrm{FilterType}]\_[\mathrm{ComponentType}].$$

[FeatureType][DataType][FilterType]_[ComponentType].

Feature types can be one of ZTP, PTP, or P_{rms}. Data types can either be D for displacement or V for velocity. Filter types are the numeric codes found in Table 10 for P_{rms} measurements or Table 11 for ZTP and PTP measurements. Component types can be either VV for vertical-only components or VR for vertical–radial vector sum quantities. For example, a ZTP measurement on vertical–radial vector sum displacement data filtered between 1.0 and 5.0 Hz would be ZTPD11_VR.

Model and Inversion Procedure

Seismic Model

Seismic scaling relations traditionally relate observed seismic amplitude features to distance and yield using the familiar power-law functional form

$$A = KW^{n}R^{-m}, \qquad (3)$$

(3)A=KWnR−m,

in which A is the amplitude of the seismic feature, W is the yield of the source, R is the distance to the source, and K, n, and m are constants (Murphy and Lahoud, 1969).

Secondary variables, however, such as HOB/DOB, can significantly influence the character of the observed waveform, and should be incorporated into the above scaling relation. Figure 7 shows the approximately hyperbolic tangent relationship observed between a generic seismic amplitude feature and the HOB/DOB of the source. Equation 3 can be modified to include the full effect of HOB/DOB on the observed seismic feature amplitudes

$$A=KW^{n}R^{-m}e^{l\times\tanh(H\times k+j)},\quad(4)$$

(4)A=KWnR−meI×tanh(H×k+j),

in which l, k, and j are additional constants and H is the HOB/DOB of the explosive source. Alternatively, equation (3) can be modified to include only a simplified form of the assumed hyperbolic tangent function

$$A=KW^{n}R^{-m}e^{l\times\tanh(H)}.\quad(5)$$

(5)A=KWnR−meI×tanh(H).

Prior dimensional analyses have derived scaling laws for explosions (i.e., relationships between various observables and the initial conditions of the explosion event) in the hydrodynamic region (Bridgman, 1937; Parkin, 1958; Sauer *et al.*, 1964). These analyses have shown that for relationships that include parameters with dimensions of length, the lengths must be scaled by a function of the yield, for example, displacement amplitude measurements (d), distance (R), and HOB/DOB values should be scaled when used in these scaling laws. These analyses have also shown that for scaling laws that include parameters with dimensions of velocity, for example, velocity amplitude measurements (v), these parameters should not be scaled by a function of the yield. Therefore, in the subsequent scaling relationships we scale d, R, and H as $D_{S}=d/W^{1/E}$, $R_{S}=R/W^{1/E}$, and $H_{S}=H/W^{1/E}$, in which E reflects the assumed energy scaling law. In the case of cube-root scaling $E=3$ and in the case of square-root scaling $E=2$. In geotechnical research and regulations, in which peak particle velocity is one of the preferred measurements, square-root scaling is generally applied for explosive line charges or cylindrical charges (e.g., Kohler and Fuis, 1992; Krauthammer, 2008; Leidig *et al.*, 2010), however, in underground nuclear explosion research, cube-root scaling is almost exclusively employed (e.g., Perret and Bass, 1975). It is to be expected that at large distances, the point-source assumption would hold and cube-root scaling would be preferred. At shorter distances, however, the geometry of the charge may play a greater role in defining the shock front and square-root scaling may be indicated. We consider the scaling relationships and rewrite equation (4) as follows:

$$D_{S}=K_{1}(R_{S})^{\beta_{2}}e^{\beta_{3}\tanh(\beta_{4}H_{S}+\beta_{5})},\quad(6)$$

(6)DS=K1(RS)β2eβ3tanh(β4HS+β5),

in which K_{1}, β_{2}, β_{3}, β_{4}, and β_{5} are constants in the displacement model and

$$v=K_{2}(R_{S})^{\alpha_{2}}e^{\alpha_{3}\tanh(\alpha_{4}H_{S}+\alpha_{5})},\quad(7)$$

(7)v=K2(RS)α2eα3tanh(α4HS+α5),

in which K_{2}, α_{2}, α_{3}, α_{4}, and α_{5} are constants in the velocity model. By taking the base-10 logarithm of both sides of the equations, we can obtain the linearized form of the seismic models as

$$\log_{10}(D_{S})=\beta_{1}+\beta_{2}\log_{10}(R_{S})+\beta_{3}\tanh(\beta_{4}H_{S}+\beta_{5}),\quad(8)$$

(8)log10(DS)=β1+β2log10(RS)+β3tanh(β4HS+β5),

in which $\beta_{1}=\log_{10}(K_{1})$ for the displacement model and

$$\log_{10}(v)=\alpha_{1}+\alpha_{2}\log_{10}(R_{S})+\alpha_{3}\tanh(\alpha_{4}H_{S}+\alpha_{5}),\quad(9)$$

(9)log10(v)=α1+α2log10(RS)+α3tanh(α4HS+α5),

in which $\alpha_1=\log_{10}(K_2)$ for the velocity model. Similarly, the simplified form of the HOB/DOB model, shown in equation (5), can be written as

$$\log_{10}(D_S)=\beta_1+\beta_2\log_{10}(R_S)+\beta_3\tanh(H_S) \quad (10)$$

(10)log10(DS)=β1+β2log10(RS)+β3tanh(HS)

for the displacement model and

$$\log_{10}(v)=\alpha_1+\alpha_2\log_{10}(R_S)+\alpha_3\tanh(H_S) \quad (11)$$

(11)log10(v)=α1+α2log10(RS)+α3tanh(HS)

for the velocity model. By inspection, equations (8) and (9) can be seen to be of the same form as the seismic model of Ford *et al.* (2014). The reason for applying the simplified model to a subset of the data in this study will be detailed in a subsequent section.

Validation of Scaling Model

A straightforward way to determine the theoretical validity of the cube-root scaling model versus the square-root scaling model is to perform an analysis of the yield and distance exponents using a subset of the data for which all other parameters besides yield and distance are approximately constant within the dataset (Murphy and Lahoud, 1969). For example, again assuming the basic power-law functional form and assuming HOB/DOB and lithology parameters are approximately constant, we can write the scaled displacement (d) and velocity (v) relationships as

$$\frac{d}{W^{1/E}}=K_1\left(\frac{R}{W^{1/E}}\right)^{-C_1}, \quad (12)$$

(12)dW1/E=K1(RW1/E)−C1,

$$v=K_2\left(\frac{R}{W^{1/E}}\right)^{-C_2}. \quad (13)$$

(13)v=K2(RW1/E)−C2.

Combining terms to emphasize similarity with equation (3), these equations can be written as

$$d=K_1W^{(C_1+1)/E}R^{-C_1}, \quad (14)$$

(14)d=K1W(C1+1)/ER−C1,

$$v=K_2W^{C_2/E}R^{-C_2}. \quad (15)$$

(15)v=K2WC2/ER−C2.

Assuming an idealized treatment of transient energy release, dimensional analysis imparts that although K_1 and K_2 are constants, C_1 and C_2 are not constant except in the region where the medium behaves elastically and the blast wave is not supersonic (Adams *et al.*, 1961). For this study, we assume that our measurements are taken in this region and that C_1 and C_2 are constant.

Equating the original n and m exponents in equation (3) to the C_1 and C_2 exponents in equations (14) and (15), shows that the following theoretical relationship for the displacement model parameters, within their error estimates, should hold true:

$$n=\frac{m+1}{E} \quad (16)$$

(16)n=m+1E

(Murphy and Lahoud, 1969) and similarly, for the velocity model parameters:

$$n=\frac{m}{E}. \quad (17)$$

(17)n=mE.

To assess the validity of the scaling assumptions, we compare our computed n and m exponent values obtained from a subset of the measured data, for which all independent variables except yield and distance are held approximately constant, with the theoretical relationships described in equations (16) and (17) within the 95% confidence intervals.

Unconstrained Nonlinear Optimization

The constants in the seismic models in equations (8)–(11) are determined by performing an unconstrained nonlinear optimization that minimizes the error objective function between the observed amplitudes and the model predicted amplitudes using the simplex search method of Lagarias *et al.* (1998).

A scale-independent error objective function is necessary because we are directly comparing displacement (smaller amplitude) and velocity (larger amplitude) models. To remove any possible bias caused by inherent differences in the absolute values of the errors, we use the mean absolute percentage error (MAPE) as our error function. MAPE is determined using

$$\mathrm{MAPE} = \left(\frac{100}{n}\right)\sum_{i=1}^{n}\frac{|y_i - y_P|}{y_i}, \qquad (18)$$

in which n is the number of data points, y_P is the predicted value, and y_i is the observed value. MAPE allows for a comparison of the fit between two models in which the proportional size of the errors is of more importance than the absolute value of the error itself. If the fit between model and observed data is perfect, the MAPE will be zero.

For each of the seismic features in this study, we iterate over ~ 2000 different starting points over the range of possible values because the optimization is sensitive to the choice of starting parameters. This approach reduces the possibility that the inversion will get trapped in a local minimum. Through this optimization procedure, we identify the seismic feature that has minimal scatter between predicted values and observed data, and the tightest model parameter confidence intervals that could be used for future yield estimation with minimal error.

Optimization Results

Alluvium Source Lithology

We determine models for a total of 56 different displacement and velocity seismic features. We compare ZTP, PTP, and P_{rms} measurements that are filtered using one of 12 different band-pass filters. The alluvium models are created using data with good signal-to-noise ratio obtained from HR1, HR2, and HR3 shots detonated in alluvium. From the HR1 and HR2 experiments we use data from all shots, whereas from the HR3 experiment we use data only from shots 1 and 2, which were detonated in alluvium. Data from stations located in all three physiographic provinces were included in the analysis. For the HR3 experiment, we also treat the 21-station WC semicircle array and 21-station WG semicircle array recordings as array-averaged data points to avoid preferentially overweighting those distances in the optimization procedure. Data from station W5 from all experiments were excluded due to large known site amplification issues (Ford *et al.*, 2014).

Additionally, if more than one type of instrument was collocated at the same location for an experiment–shot combination, we preferentially choose the broadband instrument measurement over the short-period instrument measurement. The reason for choosing the broadband instrument was because investigations into the data showed that the 2 Hz Sprengnether S-6000 instruments affected the magnitude of the observed amplitude measurements (Fig. 8). For the HR1 experiment, in which the 2 Hz Sprengnether seismometers were collocated with broadband instruments, the Sprengnether seismometers recorded lower amplitudes for the same shots when compared with the broadband instruments. This is most probably due to the fact that the broadband instruments are able to accurately record more of the lower frequency energy than the short-period instruments. Although the observed bias due to instrumentation capabilities is significant, the HR3 data show that natural variation within any one lithology type may be on the same order as the differences between the instrument types (Fig. 9). Therefore, data from all instrument types from HR3 are included because the instruments in that experiment were not collocated with the broadband sensors. Similarly, short-period instruments from the HR1 experiment that did not have a collocated broadband instrument were also included in the analysis.

We computed the MAPE for all 56 measurement cases and summarize the results graphically in Figure 10 and in table form in the Ⓔ electronic supplement to this article. The results show two general observations. The first is that ZTP measurements generally outperform all other types of measurements in alluvium source lithology and have a smaller range of goodness-of-fit values based on variations to the initial measurement, such as the premeasurement filter corner. The second observation comes from a comparison between the single-component VV models and two-component VR models for the same seismic feature. The goodness-of-fit comparisons between the two models can be quantified using

$$Y=\epsilon_{VV}-\epsilon_{VR}, \quad (19)$$

in which ϵ_{VV} is the MAPE value for the VV model and ϵ_{VR} is the MAPE value for VR model for a particular seismic feature type. Positive values of Y would indicate that the VR model produces a better fit to the data; whereas negative values of Y indicate that the VV model produces a better fit to the data. A comparison across all the seismic features shows that alluvium velocity-type VR models generally produce better fitting models to the data than VV models, but that displacement-type models produce mixed results (Fig. 11).

Sedimentary Rock Source Lithology

The sedimentary rock models are created using data with good signal-to-noise ratio obtained from the SAY experiment and HR3 shots 3 and 4, which were detonated in limestone. Shot 5 was excluded because it was detonated within the cavity of an earlier shot and thus had a modified amplitude signature (Stroujkova *et al.*, 2014). Interestingly, although data from stations located in all three physiographic provinces were included as in the alluvium case, only stations E1 and ST5 contributed seismic observables to the analysis because the remainder of the signals from stations within the Albuquerque basin did not rise above the noise. We determine models for a total of

56 different displacement and velocity seismic features for ZTP, PTP, and P_{rms} measurements filtered using one of 12 different band-pass filters.

In the sedimentary rock models, we observe that there does not appear to be one type of seismic feature that outperforms the rest, that the range of MAPE values is much greater than that seen in the alluvium lithology within any one seismic feature type, and that the overall fit to the data is poorer as illustrated by the higher MAPE values (Fig. 12). This is most probably due to the fact that there are much fewer data points to constrain the HOB/DOB relationship in the sedimentary rock geology than in the alluvium geology. Because SAY shots 1 and 3 have almost identical weighted HOBs, there are essentially only four independent HOBs sampled. This is much less than that in the alluvium lithology case. Additionally, a comparison between VV models and VR models for the same seismic feature using Y shows that there is a strong preference for VR-type models over VV-type models in sedimentary lithology (Fig. 13).

Preferred Seismic Feature and Models

For both the alluvium and sedimentary rock source geologies, confidence intervals of the five-parameter model were calculated from the t distribution with the appropriate number of degrees of freedom, determined from the number of data points, using the residuals between the described seismic model and the observed data to estimate the variance–covariance matrix for the model parameters (Seber and Wild, 2003). The results showed that although all parameters for the alluvium five-parameter model were significant, the 95% confidence intervals of parameters β_3–β_5 of the sedimentary rock five-parameter model were unacceptably high and uninformed, because they include $\beta_3=0$, $\beta_4=1$, and $\beta_5=0$. Systematic removal of parameters β_4 (producing a four-parameter model), β_5 (producing an alternative four-parameter model), and both β_4 and β_5 (producing the three-parameter model described in this article), showed that only the three-parameter model produced model parameters within the confidence intervals. Therefore, we chose the three-parameter model functional form to avoid overfitting the sedimentary rock data in the current study, although the observational data from the alluvium geology have suggested that parameters β_4 and β_5 may ultimately become necessary when fitting data from future experiments that include a more complete exploration of HOB/DOB parameter space. As a visual example of the wide range of acceptable five-parameter model coefficients for sedimentary rock lithology, we present a comparison between the data and the top performing three- and five-parameter models produced from the optimization scheme in Ⓔ Figures S1 and S2.

To determine the single best seismic feature when modeling both lithology types, we combine the MAPE values of the alluvium five-parameter model and the sedimentary rock three-parameter model within each feature type for which the model parameters were significant at the 95% confidence interval. Of the features investigated, the ZTPD11_VR seismic feature best minimizes the combined MAPE values. This seismic feature is the vector sum ZTP measurement determined using vertical and radial displacement seismograms filtered between 1.0 and 5.0 Hz. The best-fitting model parameters with the 95% confidence intervals for the alluvium and sedimentary rock models are given in Tables 12 and 13, respectively. The alluvium model included 112 data points and had a MAPE of 17.0 whereas the sedimentary rock model included 44 data points and had a MAPE value of 30.9. For comparison, the model parameters of the Ford *et al.* (2014) five-parameter alluvium model are presented in Table 14.

The β_1 and β_2 parameters primarily model the distance term, whereas the β_3–β_5 parameters primarily model the HOB/DOB term. Both alluvium models compare favorably with each other.

We perform a visual comparison between the above-ground alluvium data and the ZTPD11_VR model assuming a fixed scaled $\mathrm{HOB}=0.40\ \mathrm{m/kg}^{1/3}$ (Fig. 14). The average scaled HOB of the aboveground alluvium measurements is $0.40\ \mathrm{m/kg}^{1/3}$. The model is observed to fit the data well in scaled distance space. We also compare the alluvium data with the ZTPD11_VR model over a variety of fixed scaled distances. In Figure 15, we plot representative data assuming a suite of nine different scaled distances. In this scaled HOB/DOB parameter space, the preferred model again fits most of the data well.

Comparisons using the sedimentary rock models show similar behavior. Assuming a fixed scaled $\mathrm{HOB}=0.44\ \mathrm{m/kg}^{1/3}$, the average scaled HOB of an example set of measurements, we compare the model with the observed data (Fig. 16). The model fits the data well. Similarly, we compare the HR3 and SAY data with the preferred model assuming a set of seven different fixed scaled distances (Fig. 17). Here, it can be observed that the number of data points from various scaled HOB/DOB is significantly less than that of the alluvium lithology.

Validation of Cube-Root Scaling

Because the charge shapes in this study deviated from a theoretical spherical charge, and because some of the seismometers were relatively close to the explosion sources, we thought it is prudent to validate the theoretical cube-root scaling relationship with the inherent point-source assumption in our models. To do so, we kept lithology and HOB/DOB approximately constant and evaluated the theoretical cube-root scaling assumption for the ZTPD11_VR preferred seismic model using equation (16) and a linearized form of equation (3). For the alluvium model, data from alluvium shots with HOB/DOB between -6 to $-10\ \mathrm{m}$ are included to calculate the theoretical yield (n) and distance (m) exponents for comparison in equation (16). For the sedimentary rock model, sedimentary rock shots between 0 and 2 m HOB/DOB are included to similarly calculate the theoretical n and m exponents. The specific HOB/DOB constraints are applied to include the maximum number of measurements for this comparison for each lithology type. The cube-root scaling relationship would be validated for our preferred seismic model if equation (16) were to hold within the 95% confidence intervals. Table 15 shows that within the 95% confidence intervals, cube-root scaling is validated for the ZTPD11_VR model for both alluvium and sedimentary rock. As an interesting side note, we mention that for the alluvium lithology, cube-root scaling was not validated for any of the poorer performing velocity-type measurements, but rather the square-root scaling was indicated by this comparison.

Lithology Yield Bias

The effect of source lithology on the amplitude of seismic features can be seen graphically by comparing the divergence between alluvium and sedimentary rock data around $HOB/DOB=0$ (Fig. 18). To illustrate the importance of lithology when modeling the behavior of seismic signals due to near-surface explosions, we examine the differences in yield between the alluvium and sedimentary rock models. The generic form of our five-parameter seismic model can be written as

$$\log_{10}\left(\frac{A}{W^{1/3}}\right)=Z_1+Z_2\log_{10}\left(\frac{R}{W^{1/3}}\right)+Z_3\tanh\left(\frac{Z_4H}{W^{1/3}}+Z_5\right),\quad(20)$$

(20)log10(AW1/3)=Z1+Z2log10(RW1/3)+Z3tanh(Z4HW1/3+Z5),

in which A is the amplitude measurement of a generic seismic feature, W is the yield, R is the range to the source, H is the HOB/DOB of the source, and the Z coefficients are the five constants associated with a particular lithology model type: β_1–β_5 coefficients for the alluvium model and α_1–α_3 coefficients for the sedimentary rock model, plus assuming the uniform parameters of $\alpha_4=1$ and $\alpha_5=0$. Assuming $H=0\ \mathrm{m}$ for a near-surface explosion, we gather terms and write a modified version of equation (20) as

$$Z_2\log_{10}(W^{1/3})-\log_{10}(W^{1/3})=Z_1+Z_2\log_{10}(R)+Z_3\tanh Z_5-\log_{10}(A).\quad(21)$$

(21)Z2log10(W1/3)−log10(W1/3)=Z1+Z2log10(R)+Z3tanhZ5−log10(A).

If we define a new constant C as

$$C=Z_1+Z_2\log_{10}(R)+Z_3\tanh Z_5-\log_{10}(A),\quad(22)$$

(22)C=Z1+Z2log10(R)+Z3tanhZ5−log10(A),

we can define the yield as

$$W=10^{\left(\frac{3C}{Z_2-1}\right)}.\quad(23)$$

(23)W=10(3CZ2−1).

We can calculate model-determined yields by inputting the β coefficients for the alluvium model and the α coefficients the sedimentary rock model for the Zcoefficients in equation (21) over a range of assumed R and A values consistent with the alluvium and sedimentary rock models in this study. Comparing the calculated yields for the alluvium model with those of the sedimentary rock model, assuming a scaled distance of $5000\ \mathrm{m/kg^{1/3}}$, shows that

$$\frac{W_{\beta,RS=5000}}{W_{\alpha,RS=5000}}=3.0.\quad(24)$$

(24)Wβ,RS=5000Wα,RS=5000=3.0.

Therefore, assuming an alluvium geology when the lithology was in fact sedimentary rock would produce calculated yields that were up to ~ 3.0 times the appropriate yield in the far field. This difference is significant.

Conclusions

Significant differences are observed in amplitudes of seismic features that propagate from alluvium and sedimentary rock source emplacement types. We specifically look at three basic types of seismic features (ZTP, PTP, and P_{rms}) over both velocity and displacement measurements to investigate which feature produces the most robust predictive estimates. Results from each of the seismic features filtered over a variety of band-pass filters and measured over single-component VV and two-component VR data show that the ZTPD11_VR feature produces models with the smallest difference between model-predicted values and the observed amplitude values. The ZTPD11_VR seismic feature is the vector sum of the ZTP displacement amplitudes of the first quarter cycle of the arriving *P* wave measured on the vertical and radial seismic traces which have been filtered between 1.0 and 5.0 Hz.

For displacement-type models, although the two-component VR models often produced slightly better fitting models for sedimentary rock lithologies compared with the single-component VV models, no such clear cut relationship exists in the alluvium lithology. It is unclear if this is an inherent quality of sedimentary rocks or if this is due to the fact that this lithology type had fewer data points to constrain the model. More observations from this rock type are necessary.
The five-parameter seismic model of Ford *et al.* (2014) compares favorably with the five-parameter alluvium seismic model presented here. However, the 95% confidence intervals for the five-parameter sedimentary rock model show that the number of data points is insufficient to accurately constrain all five parameters. The three-parameter model is therefore necessary to avoid overfitting the sedimentary rock data.

Using an extended underground explosion dataset, Murphy and Lahoud (1969)showed that cube-root scaling of displacement measurements was valid. A similar theoretical comparison between the yield exponents and the range exponents for our more limited dataset also indicated that within the 95% confidence intervals, cube-root scaling held for our preferred displacement-type seismic amplitude feature in both alluvium and sedimentary rock lithology. Interestingly, our dataset samples different yield, range, and scaled range intervals. Further work must be done to investigate if this is a pervasive feature.

Plots of scaled feature amplitudes show that there is a strong divergence between amplitudes measured for shots in alluvium and those measured for shots in sedimentary rocks. Seismic amplitudes for alluvium shots are observed to be larger than seismic amplitudes for sedimentary rock shots at similar scaled distances and HOB. To quantify the effect of source lithology on the predicted yield, we performed a theoretical comparison between the preferred alluvium model and the preferred sedimentary model. This comparison shows that if an alluvium source lithology is assumed for a sedimentary rock source lithology, the difference in yield could be up to 3.0 times the appropriate yield in the far field. This difference is significant and must be calibrated if seismic feature models are to be transported to different source regions.

Future modifications to these models should incorporate additional experimental data that would better illuminate the HOB/DOB relationship for the sedimentary rock model and any future rock types that may come under consideration. The robustness of our predictive models should be verified using data from other rock types to determine if further lithology types should be added to the model library. Additionally, to remove known biases from the data, future test series should include instruments with the widest frequency passband possible, at least 1 Hz but preferably broadband instruments, to exclude observed amplitude biases that should only become more pronounced at higher yields.

Data and Resources

The data used in this study from the Humble Redwood experiments are available to others for research purposes. Requests should be sent to A. J. Rodgers. Data from the Sayarim experiment are limited. For more information on access to the Sayarim data, please see Bonner *et al.* (2013). Figures in this article were created using Matplotlib (Hunter, 2007) and Seismic Analysis Code (SAC; Goldstein *et al.*, 2003). Seismic analysis was performed using SAC.

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