Source Scaling of Single-Fired and Delay-Fired Explosions Constrained by In-Mine and Regional Seismograms

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Abstract

This work quantifies seismic coupling as a function of charge weight for single-fired (simultaneously detonated) explosions observed in the mine and at regional distances. These single-fired explosions are contrasted to standard production shots from the same mine. Production shots include cast blasts to remove overburden and coal shots to fracture the resource. The blasts were conducted in a mine in NE Wyoming. The data sets consist of measurements in the mine (100-10000 m) and at regional distance (360 km) using a seismic array near Pinedale, Wyoming (PDAR). The single-fired explosions ranged in size from 5500 to 50000 lbs. Peak amplitude measured at a single element of the regional array are modeled by a power law dependent on explosive weight. Similar scaling constants were determined for each of the dominant regional phases: Pn – 0.84±0.14; Pg – 0.84±0.09; and Lg – 0.91±.08. Spectral ratios of observations from different explosions observed at the same station document the frequency dependence of the source scaling relations. Spectral ratios using in-mine observations are consistent with those using regional data. The empirical source ratio is matched with a Mueller-Murphy source model replicating both the increase in long period spectral level and the accompanying decrease in source corner frequency with increasing charge weight. The coal and cast blasts that make up the production shots ranged in size from 77,000 to 4,738,230 lbs. Peak amplitudes from the largest production shots are comparable to those from the largest single-fired explosion. This dramatic decrease in amplitude for production shots (factor of 60-300) can be explained in terms of destructive interference between waveforms from individual boreholes introduced by delay firing. Shot specific models of delay firing suggest that peak amplitudes for the production shots are insensitive to the total amount of explosives in the blast. Peak amplitude data supports this modeling result.

Introduction

Quantification of the coupling of explosion energy into seismic waves from mining explosions provides the first step in understanding and controlling these motions so that acceptable ground motion levels are experienced in the mine and surrounding area. The development of mathematical and physical models that capture these scaling relations provide a basis from which shot designs can be modified in cases where the ground motion accompanying a blast is unacceptable. The ground motion from mining explosions result from the effect of the individual borehole as well as the spatial and temporal effects of multiple boreholes. It is sometimes useful to separate the effect of the individual borehole from that of the spatial-temporal array of explosions in quantifying these different effects.

The ground motions generated in and around the mine property are of primary concern to the mining community. These near-source waves continue to propagate and are observed at quite great distances from the mine as well, despite the fact that the amplitudes of the waves are greatly decreased by attenuation and geometrical spreading. Typically mining explosions can be well observed at regional distances (100-1000 km) providing additional data for studying and constraining the source coupling and characterization of delay-fired explosions.

We will relate both local, in-mine, and regional seismic recordings of mining explosions to the coupling of energy from a single explosion and the modifications introduced by multiple boreholes detonated in space and time typical of delay-firing. The single-fired explosions provide constraints on the frequency dependent scaling introduced by the individual explosion. These results are then used to interpret observations from delay-fired explosions to quantify the primary effects of multiple boreholes.

Unique to this work is the comparison of empirical data from in-mine (100-10000 m) with that observed at regional distance (360 km). The scaling relations are found to be consistent between the two data types although the bandwidth of the regional data is more restrictive.

Experimental Design

The location of the cooperative mine was the Powder River Basin in NE Wyoming (Figure 1). The mine (Figure 2) conducts large scale cast blasting for the purposes of removing overburden (Martin and King, 1995). Once the coal is exposed it is fractured with smaller explosions which we label coal shots. Extensive seismic and videographic instrumentation was deployed in-mine for purposes of characterizing the explosions. Regional seismic observations of the explosions were made at the Pinedale Seismic Array (PDAR) some 360 km to the southwest of the mine (Figure 1). Seismic data from within the mine will be compared to seismic data recorded at PDAR for purposes of constraining the different types of explosive sources.

In order to separate the spatial and temporal effects of the delay-fired cast and coal shots from the coupling effects of individual explosions a series of contained, single-fired explosions were conducted within the mine. There were seven contained, single-fired explosions with total explosive weight ranging from 5500 to 50000 lbs. (Figure 2). Typical boreholes at the mine are loaded with approximately 5000 to 8000 lbs. of explosives and so the larger shots involved the simultaneous detonation of multiple boreholes. The number of individual boreholes in any one explosion was between 1 and 10. The source characteristics are summarized in Table 1.

Table 1: Shot Characteristics

Shot Number	Shot Size (lb.)	Number of Boreholes
S1	5500	1
S2	5500	1
S3	5500	1
S4	6000	1
S5	12000	3
S6	16000	4
S7	50000	10

Source Types

Three distinct types of explosive sources were quantified during this study. The contained, single-fired explosions, cast blasts and coal shots. The cast blasts and coal shots each involve delay-firing of multiple boreholes with the seismic waves reflecting these source effects. Figure 3 illustrates the peak amplitudes of the regional P waves at PDAR for the three types of explosions. The single-fired explosions show a clear relationship between total amount of explosives and regional seismic amplitude. The coal and cast shots show no relationship between peak amplitude and total amount of explosives although the coal shots generally produce peak amplitudes that are less than those from the cast shots. The goal of this study is to quantify the relationship between peak amplitude and charge weight for the single-fired shots and then explain the insensitivity of peak amplitude with explosive charge for the coal and cast shots.

Video images of the different types of explosions are combined with in-mine waveforms to illustrate some of the physical characteristics of the explosions in Figures 4 (contained, single-fired), 5 (cast blast) and 6 (coal shot). The single-fired explosion in Figure 4 is from the largest shot, 50000 lbs.(S7), which involved the simultaneous detonation of ten boreholes. The in-mine seismic data is simple and relatively short in duration (~0.5 s). The cast blast explosion (Figure 5) consists of an eight row shot with a total of 704 boreholes and 4,738,230 pounds of explosives. Uphole delay times of 35 ms are used between holes in a row and downhole delays of 125, 300, 500, 700, 900, 1200, and 1400 ms in an echelon pattern from the front row. Explosive loads for individual boreholes averaged near 6730 lbs. The delay pattern extends over 4.5 s and the near-source seismograms extend to beyond 7 s, reflecting the combined effects of shot timing and material casting. The third source type, coal shots (Figure 6), consist of boreholes emplaced in the coal for purposes of fragmenting the resource. The coal shot in Figure 6 is typical of these types and included 57 boreholes with a total of 77,000 lbs. of explosives. The average borehole contains approximately 1350 lbs. of explosives, much smaller than the explosive charge weight for the cast blast boreholes. The duration of the in-mine P wave at 1.25 s is intermediate between that observed for the single-fired explosion and the cast blast.

Both the regional amplitudes (Figure 3) and the in-mine waveforms and video (Figures 4-6) capture the effects of total charge size and temporal and spatial finiteness. In an attempt to separate these different effects, the single-fired shots were first used to quantify the effect of shot size on the seismic data.

Single-Fired Charges and Seismic Coupling

An example regional seismogram from PDAR of the largest single-fired explosion, S7, is reproduced in Figure 7. Inspection of the waveform identifies three regional arrivals: P_n; P_g; and L_g. P_n is the head wave traveling at the upper mantle velocity of 7.9 to 8.2 km/s. P_g is the crustal guided P wave traveling at 5.5 to 6.2 km/s. L_g represents the crustal guided shear energy traveling at 3.5 to 3.7 km/s. These are the regional phases used in quantifying source coupling.

Peak amplitudes for each of the regional phases were determined for the single-fired explosions of different charge weight and plotted as a function of charge weight in Figure 8. The data can be fit with a power law relation.

$$Amplitude = AW^b$$

Estimates of A and b were made for each element of PDAR and each of three predominant regional phases, P_n, P_g, and L_g. The models are superimposed on the data in Figure 8. Similar scaling constants (b values) were determined for each of the dominant regional phases, Pn – 0.84±0.14, Pg – 0.84±0.09, and Lg – 0.91±.08. The b values determined for these chemical explosions in Wyoming are in close agreement with the scaling results of Vergino and Mensing (1983) for P_n waves from nuclear explosions in Nevada. The apparent similarity of these magnitude-yield results and the inability to distinguish waveforms from chemical and nuclear explosions (Denny, 1994; Stump *et al.,* 1999) suggests that chemical explosions can be used to calibrate regions and stations. Yang *et al.* (1999) studied close-in seismic observations from smaller single-fired cylindrical explosions and found similar scaling laws with b between 0.73 and 0.94.

Simple spectral ratios utilizing the spectra from different single-fired explosions provides a mechanism for quantifying variations in spectral shape that can be attributed to the source function (Stump *et al.,* 1999).

The spectrum from an individual explosion is represented as:

$$U_{kij}(f) = R_{ki}(f)\, P_k(f)\, S_j(f) \qquad (1)$$

where $U_{kij}(f)$ is the spectrum of the k^{th} component (1- vertical, 2- radial, 3- transverse, k = 1 for PDAR) at the i^{th} receiver (PDAR array elements) from the j^{th} source (1-7, Table 1). $R_{ki}(f)$ is the receiver function for the i^{th} receiver or array element and is assumed to be the same for each source. $P_k(f)$ is the regional propagation path effect. $S_j(f)$ is the source function for the j^{th} explosion.

$R_{ki}(f)$ and $P_k(f)$ are assumed to be identical for each source and thus taking the ratio of $U_{kij}(f)$ for two different sources eliminates the local receiver effect and regional propagation path contributions retaining only the ratio of the two source functions.

$$\frac{U_{ki1}(f)}{U_{ki2}(f)} = \frac{R_{ki}P_kS_1}{R_{ki}P_kS_2} = \frac{S_1}{S_2} \qquad (2)$$

The ratio of the spectra removes both the regional wave propagation path and the strong local receiver effects. What remains is the frequency dependent source scaling relation for the explosion source function. Equation 2 can be extended to multiple component as well as array data. Averaging over individual components for near-source estimates and over array elements for the regional data at PDAR produces average source estimates.

The first example spectral ratio is for two sources (S4 & S3) of identical yield. Spectral ratios were estimated for each array element at PDAR and a mean formed (Figure 9). Additionally spectral ratios were estimated using a single, three-component station from within the mine. These different data sets provide the opportunity to compare near-source and regional source estimates and extend the source comparison to higher frequency (using in-mine data). The spectral ratios at local and regional distances in Figure 9 are consistent. They both indicate that the spectra from the two shots are nearly identical (ratio of 1) as expected for two identically prepared and executed explosions. The rise in spectral ratio above 10 Hz for the regional data is accompanied by an increase in standard deviation. The higher bandwidth in-mine data indicates that the ratio remains flat to higher frequencies.

Two sources of different charge size, S6 (16000 lb.) and S7 (50000 lb.), are compared in Figure 10(left). The spectral ratios for both P and L_g provide similar estimates of the source scaling as a function of frequency. The ratios are flat at long periods with the relative size indicative of the factor of three differences in absolute charge weight. The corner frequency of the larger explosion is below 4 Hz where the ratio begins to decay and then reached a plateau at the corner frequency of the smaller explosion, 7 Hz.

The empirical source scaling relation in Figure 10 (left) can be compared to theoretical scaling relations for contained explosions. One such model was developed based upon first principles and observations from contained nuclear explosions (Mueller and Murphy, 1971). The Mueller-Murphy explosion source function was used to model the spectral ratios determined for the single-fired chemical explosion sources in this study. The shots were detonated in interbedded shales and limestones. The assumed near-source material properties were: α = 2.4 km/s (compressional velocity); β = 1.0 km/s (shear velocity); ρ = 2.0 gm/cm^3(density). The source corner frequencies and related elastic radii in the model were estimnated following the procedure of Yang *et al.* (1999). This model was used to calculate source spectra for S7 (50000 lbs.) and S6 (16000 lbs.). Both of these shots had the same emplacement depth of 29 m. The resulting models of source spectra were used to form a theoretical ratio, which is plotted in Figure 10 (right). The long-period level, corner frequency of S7, corner frequency of S6 and high frequency level is in close agreement between the empirical results and the model. These results suggest that the Mueller-Murphy model can be used in modeling single-fired contained chemical explosions providing the starting point for investigating multiple explosions in time and space such as the coal and cast shots introduced earlier.

Delay-Fired Explosions

The primary difference between the single-fired explosions and the coal and cast shots is the timing of the individual explosions in the blast design. One simple way of studying these effects is to model the timing of the cast or coal shots as a series of impulses with the design delay times. The explosion is modeled as a convolution of this impulse response with an individual borehole source model such as the Mueller-Murphy model introduced earlier.

A cast shot similar to that documented in Figure 5, was represented as a series of impulses based upon design delay times with a duration near 4.5 s (Figure 11-top). The Fourier transform of this impulse series illustrates the predicted effect of constructive and destructive interference on the seismic data (Figure 11-bottom). It is only at the very lowest frequencies (less than 0.10 Hz) that the total size of the shot is reflected in the amplitude data. At frequencies commonly observed in-mine and at the regional distances, 1-20 Hz, the model predicts that amplitudes will be reduced by a factor of 60-300 below those expected if all the explosives were simultaneously detonated. This effect is commonly known and provides the primary motivation for using delay-firing. A second cast model is included in Figure 11, one which is exactly half the size of the first but with the same timing between holes in a row and between rows. The time function has a shorter duration. Comparison in the frequency domain illustrates that only at the very lowest frequencies are the amplitudes reduced by 50%. At frequencies typical of the in-mine and regional observations, 1-20 Hz, the model predicts that the amplitudes from the two shots should be nearly identical. This simple superposition model is consistent with the lack of any amplitude dependence with total explosive size for both the cast and coal shots (Figure 3). The offset in peak amplitude between the coal and cast shots can be partially explained in terms of the difference in single borehole charge weights for the coal (1350 lbs.) and cast (6730 lbs.) based upon the Mueller-Murphy source model.

Conclusions

Single-fired, coal, and cast explosions at a single mine in NE Wyoming have been quantified as sources of in-mine and regional seismic waves. Consistent source scaling relations were developed using in-mine and regional data illustrating the dominant effect of energy coupling at the blast. The Mueller-Murphy source model is shown to reproduce the effect of coupling for single-fired explosions. Complex timing effects from delay-firing are modeled as impulse responses illustrating significant destructive interference (factor of 70-300 for cast shots) in the frequency band of 1-20 Hz. This aspect of the model predicts an insensitivity of peak amplitudes in the 1-20 Hz band to total amount of explosives in a delay-fired blast.

Acknowledgements

This project would not have been possible without the interest, support and encouragement of Robert Martin. The authors would like to dedicate this work to his memory. Vindell Hsu provided the regional data from PDAR and was supportive of this work. David Anderson helped with the video processing and Rong-Mao Zhou completed the impulse response analysis. This work was performed under the auspices of the US Department of Energy by Los Alamos National Laboratory under Contract W-7405-ENG-36. Additional support for this work came from the Defense Threat Reduction Agency under contract DSWA01-98-C-0131 at Southern Methodist University.

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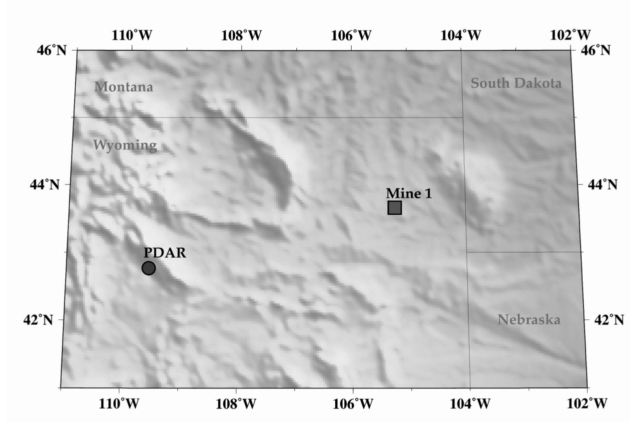

Figure 1: Map illustrating the location of the mine in the Powder River Basin of NE Wyoming. The regional seismic array near Pinedale, Wyoming (PDAR) is approximately 360 km from the mine.

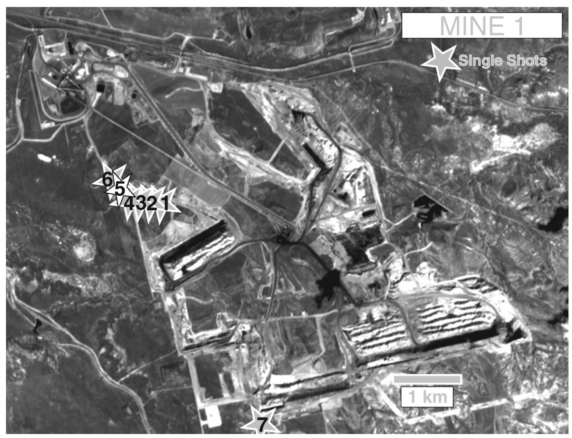

Figure 2: Overhead imagery of the mine where all the explosions were detonated. The pits and processing facilities can be identified. The locations of the seven, single-fired explosions are designated.

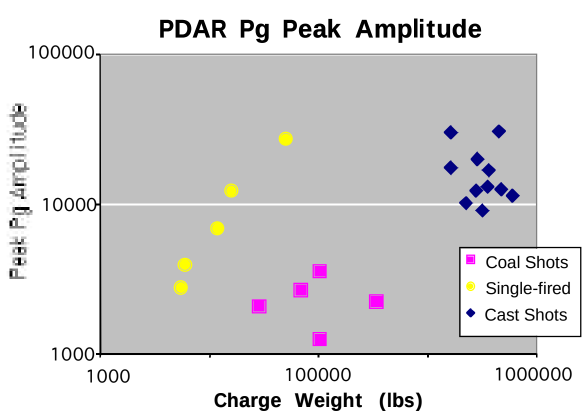

Figure 3: Peak amplitude of Pg energy recorded at PDAR for the contained single-fired explosions (circles), coal shots (squares) and cast shots (diamonds). Only the contained single-fired explosions show an increase in Pg amplitude with increasing charge weight.

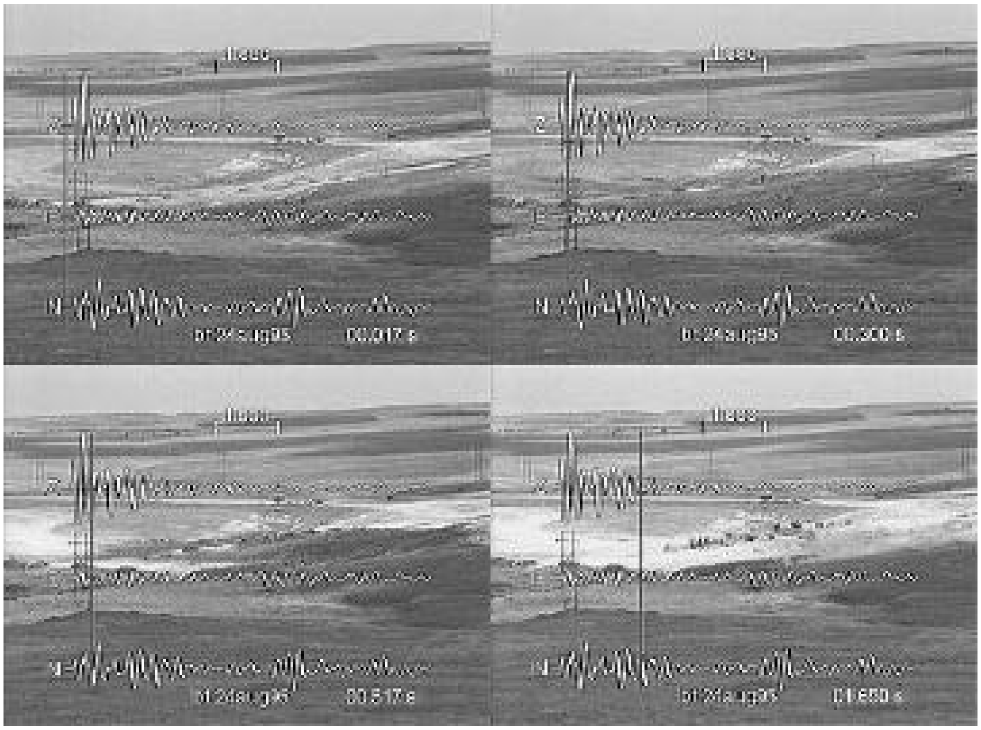

Figure 4: Four video images (0-1.65 s) with local ground motion superimposed and time aligned (vertical line) with the detonation of a contained single-fired explosion of 50,000 lbs. (S7).

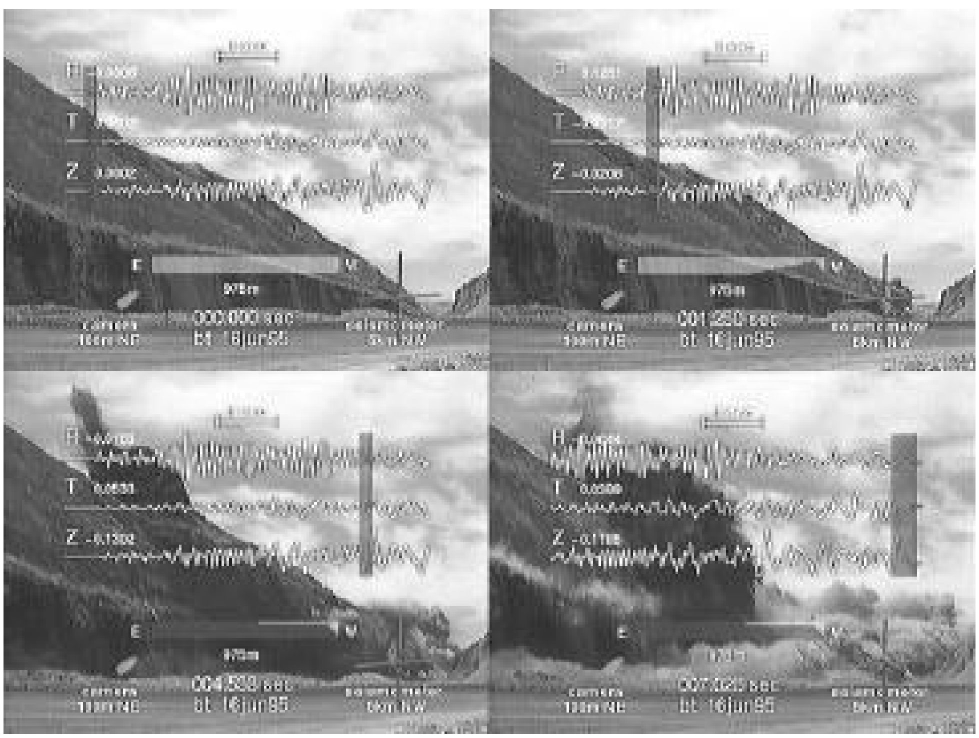

Figure 5: Four video images (0-7.025 s) with local ground motion superimposed and time aligned (vertical bar) with the detonation of a cast blast containing 4,780,230 lbs. of explosives.

Figure 6: Four video images (0-1.267 s) with local ground motion superimposed and time aligned (vertical line) with the detonation of a coal shot containing 77,000 lbs. of explosives.

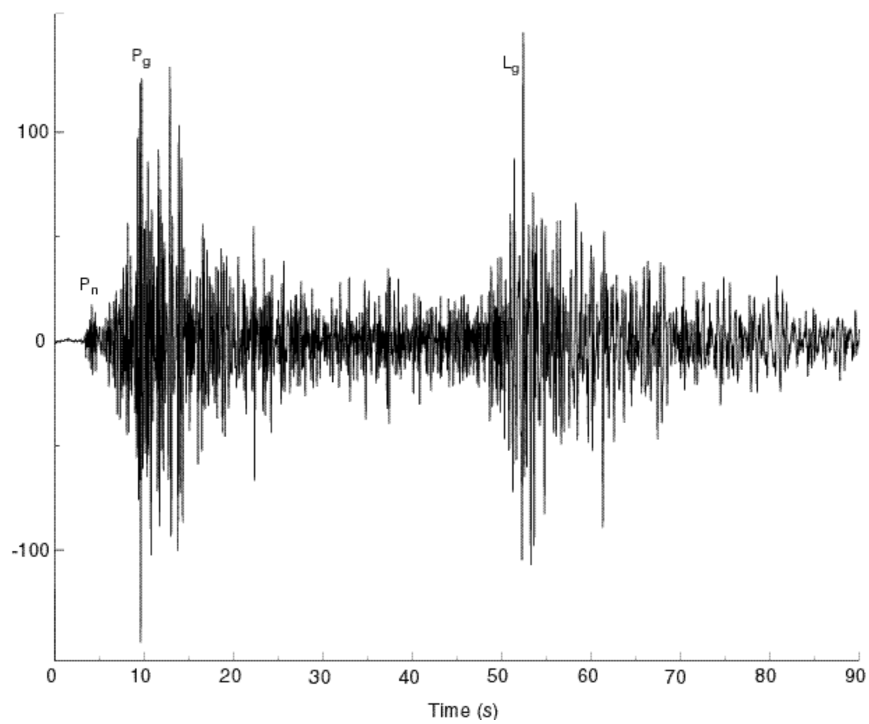

Figure 7: Regional seismogram observed at PDAR (Figure 1) from the contained, single-fired 50,000-lbs. explosion (S7) depicted in Figure 4. The three regional arrivals Pn, Pg and Lg (shear) are identified.

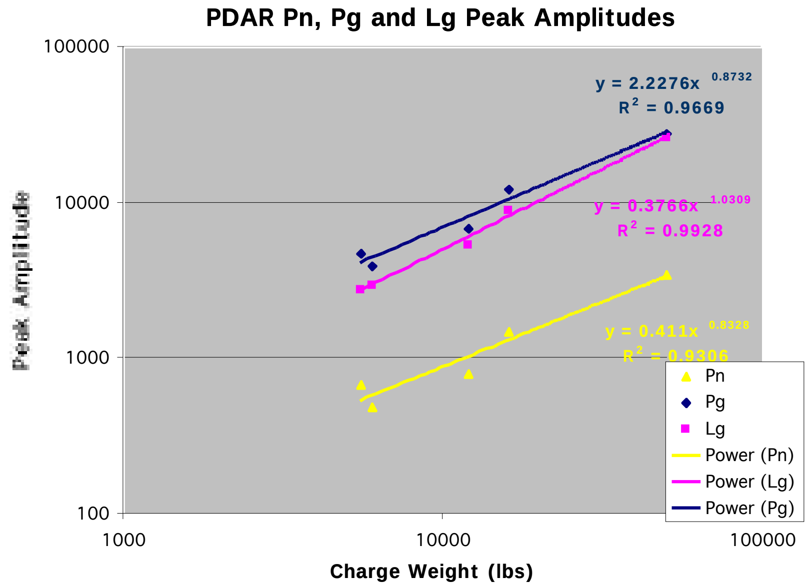

Figure 8: Peak amplitude data for the regional phases Pn, Pg and Lg observed at PDAR (Figure 1) plotted against charge weight for the contained single-fired explosions. Power law fits to each phase are included illustrating the similarity of yield scaling for the different phases.

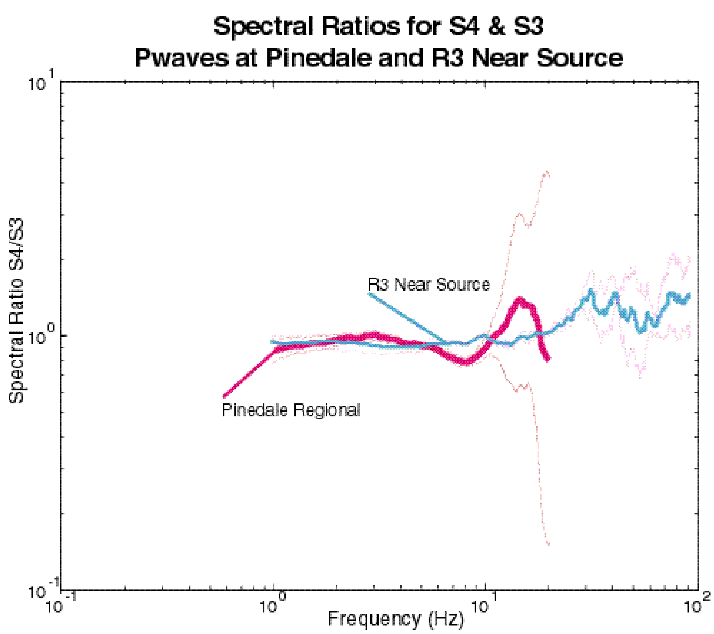

Figure 9: Spectral ratios between two identical single-fired explosions (S4 - 6000 lbs. & S3 - 5500 lbs.). The thick line is the ratio estimated using the regional data from PDAR. The thin line is the ratio using a single, three-component station (broader frequency band) from within the mine which extends to higher frequency. Dotted lines are the ± 1 standard deviation limits.

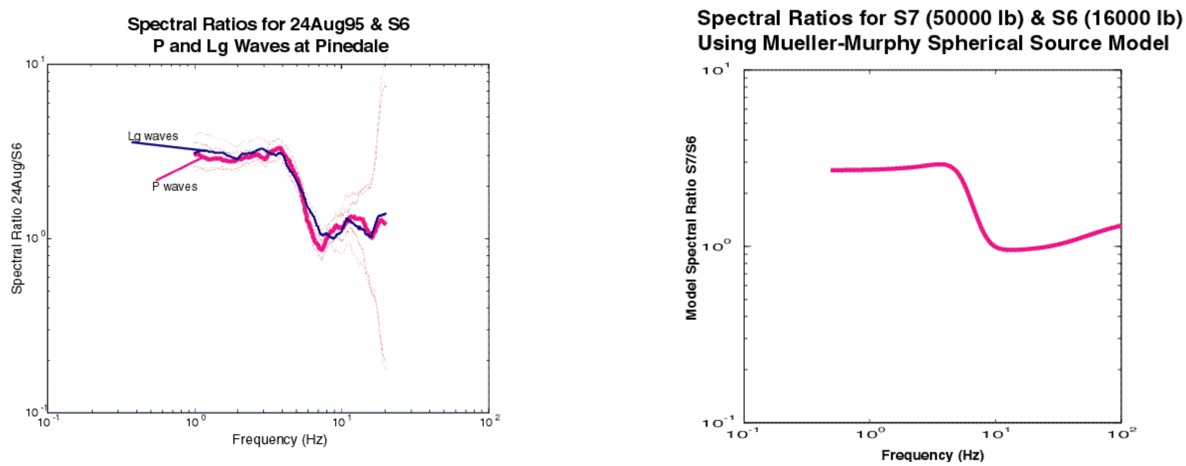

Figure 10 left: Spectral ratios (P and Lg regional phases) between two contained single-fired explosions, S7-50000 lbs. and S6-16000 lbs. illustrating the empirical frequency dependent scaling. Right: The theoretical source spectral ratio for the two explosions based upon the Mueller-Murphy source model.

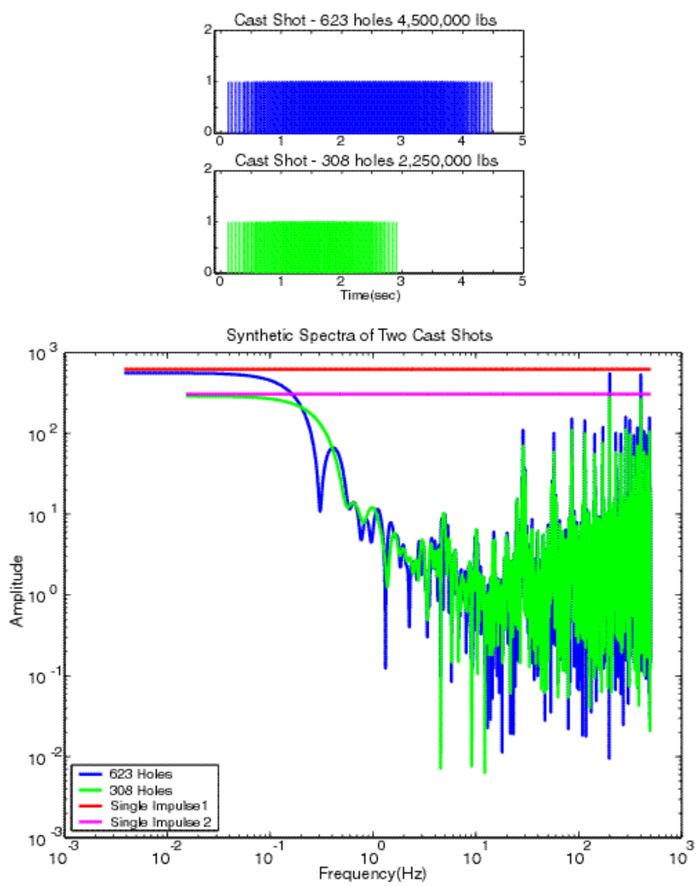

Figure 11: Design impulse response time function (top of figure) for a cast shot of 4,500,000 lbs.(top) and 2,250,000 lbs. (second). Timing between holes in a row and between rows of the two shots are identical. The Fourier spectra of the two time series are compared in the lower portion of the figure. Spectral levels of the two sources are identical in the 1-20 Hz band.