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SEISMIC WAVEFIELD CALIBRATION

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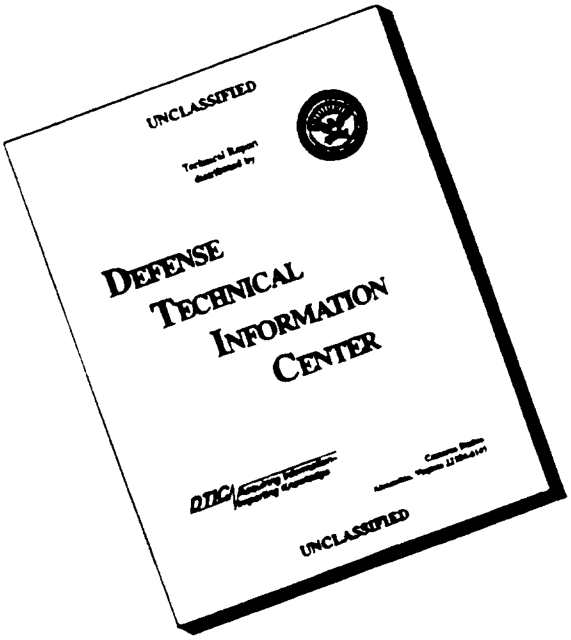
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The use of regionally recorded Rayleigh waves to estimate isotropic moment and psi-infinity for the purpose of yield estimation is investigated. These seismological parameters and their variability are consistent with other investigations. Psi-infinity shows less variability than isotropic moment as a yield estimator. Preliminary results on wave propagation in the Korean peninsula are also presented.

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Summary

This report consists of two sections. The first is a compilation of work done under this contract as well as previous contracts on the estimation of isotropic moment, M_I, and ψ_{in} from regional Rayleigh wave data in the 0.5 - 5.0 Hz band. The data set of 24 independent estimates are combined with a tabulation of 104 estimates provided by Dr. Marv Denny to investigate the scatter in the relationships between M_I and ψ_∞ to yield, Y. Because of the nature of our data sets, it was not possible to investigate the sensitivity of these relations to depth of burial and shotpoint material properties. Since the combined data set consisted of both nuclear and chemical explosions, the relationship was also studied in terms of these major subsets. The data set seems adequate for implementing a yield estimation module for sparsely recorded explosions.

The second section of the report presents the results of a very preliminary analysis of regional Lg wave propagation on the Korean peninsula. The attenuation is greater than that of the central United States. However, the array data set suffers from the limitation of effectively being a single station estimate.

Variability in M_I, ψ_∞ vs Y from Regional Surface Waves

by L. Malagnini, R. B. Herrmann, G. I. Al-Eqabi and K. D. Hutchenson

ABSTRACT Variability in the relation of yields of small explosions to seismological source parameters is investigated by studying the short-period, fundamental mode Rayleigh waves recorded at a 0 - 200 km distance range from point and spatially distributed chemical explosions. The data set includes long linear array and single station observations. Surface-wave time histories are analyzed for source and propagation path parameters. Since the source medium is not well known, observed variability in the empirical moment - yield relation may be indicative of scatter to be expected in a test ban treaty monitoring effort when only a few observations along an uncalibrated path exist. Our source parameter estimates and their variability are consistent with those determined from a larger data set. Observations indicate that the isotropic moment, M_I and ψ_∞ are related to yield, Y, as

$$M_I(dyne-cm) = 1.06\,x\,10^{18} Y(tons) \quad \psi_\infty(m^3) = 0.385 Y(tons)$$

1. Introduction

The study of explosions is a very important topic in the seismological literature because of interest in monitoring underground nuclear explosions. An early theoretical study of buried explosive sources was that of Sharpe (1942). Since then, other studies have been published on source-time functions and spectra of underground nuclear explosions from both theoretical and observational viewpoints (Haskell, 1967; Mueller and Murphy, 1971; von Seggern and Blandford, 1972; Aki *et al.*, 1974; Burdick and Helmberger, 1979; Glenn *et al.*, 1987; Denny and Goodman, 1990; Murphy, 1977, 1991; Johnson and McEvilly, 1994).

Current research emphasis is directed toward the problems inherent in monitoring a comprehensive test ban treaty (CTBT), with a necessary emphasis on small yield explosions. This is complicated by the need to discriminate a wider class of events:

- Earthquakes
- Cavity Collapses
- Chemical Explosions
    - Point Sources
    - Distributed Sources
    - (with associated surface phenomena)
- Nuclear Explosions
    - Coupled
    - Decoupled

The discrimination process for a CTBT is even more challenging because the numbers of earthquakes and chemical explosions increase with smaller source size, reflecting earthquake recurrence rates and mining practice. Industrial and research chemical explosions encompass a variety of purposes, from refraction/reflection seismology to strip mining, spanning a range of yields from fractions of a kilogram to fractions of a kiloton, and having different source-time functions, from spatially and temporally point sources to multi-deck, multi-row strip-mine blasts. Moreover, some of the seismic signals generated by chemical explosions are characterized by mostly lateral movement of mass (spall) that complicates interpretation of the seismic signal.

Nuclear events are characterized by a point source, but the seismic signal can also be perturbed by spall generated by shallow nuclear explosions. The detonation of explosions in properly sized cavities can reduce the observed seismic signal. This complicates discrimination by reducing the likelihood of detection and by moving the event into a population of smaller events for which discrimination may be more difficult (Denny and Goodman, 1990; Glenn *et al.*,, 1987).

Effective seismic source discrimination must rely on fundamental differences in the source process. Well tamped explosive point sources can be satisfactorily modeled by an isotropic source of pressure applied inside a spherical cavity of an equivalent elastic radius. What is still not clear about underground explosions is the amount of the variability of remote estimates of the size of an explosion when close-in seismic recordings, in situ radiochemical measurements or shot-point material properties are unknown. This may be the norm in a CTBT environment.

Seismological parameterization of explosion size can be made in terms of the isotropic moment, M_I, and reduced displacement potential, $\psi(t)$ at large time, $t = \infty$, ψ_∞ (Denny and Johnson, 1991), which are related by

$$\psi_\infty = \frac{M_I}{4\pi\rho\alpha^2} \tag{1}$$

Here ρ and α are the density and the compressional-wave velocity of the medium at the source. The determination of M_I from seismic waveforms requires assumptions about the spatial and temporal features of the source as well as propagation medium physical parameters. Since $\psi_\infty = R_c^3/3$, where R_c is the elastic radius, it may be a more stable yield estimator than M_I. M_I can be obtained from seismic observations after accounting for wave propagation effects, while $\psi(t)$ can be estimated directly from data recorded in the elastic region about the shot point.

Werth *et al.* (1962) noted that fairly large variations in the observed reduced displacement potential (RDP) result in very little change in the distant signal. A comparison between RDP functions determined from nuclear explosions detonated in four different media was made by Werth and Herbst (1963) who presented data scaled to 5 kT by using a cube-root amplitude-time scaling law for point sources in infinite homogeneous media (Werth *et al.*, 1962). Their study noted variability of about an order of magnitude between the estimates of ψ_∞ for the different data sets. The scaled event in alluvium was characterized by the smallest value of ψ_∞ ($420m^3$), whereas the one carried out in tuffs resulted in the largest value ($5120m^3$). The greater source of variability for their results, shown in Table 1, is perhaps related to the explosion depths, i.e. their position with respect to the water table. GNOME in water saturated salt (their ψ_∞ values are the largest ones among the scaled, available estimates), whereas FISHER was detonated in non-saturated alluvium (the smallest value of ψ_∞), and HARDHAT in (dry) granite. The amount of overshooting in the observed RDP in the four different explosions showed a strong dependence on the mechanical characteristics of rocks at the shot point. As pointed out by Denny and Johnson (1991), a great number of variables relate the seismological source size to event yield: depth of burial, gas porosity, density, compressional- and shear-wave velocities of the host rock. The resulting estimates of yield made with seismological observations are likely affected by large uncertainties.

Given this background of problems of nuclear explosion monitoring, our study focuses on a related topic, that of yield estimation. We tabulate estimates of M_I and ψ_∞ as a function of yield for chemical explosions in the range of 0.01 - 65 tons, based on observations of short period surface waves in the 0.5 - 5.0 Hz frequency band. Since the data sets were not originally generated for source yield studies, their inferred relation to yield will necessarily reflect these many uncertainties, and thus provide an initial step toward understanding the limitations of remote source size estimates.

2. Experiments

This section briefly discusses our estimation of M_I and shallow earth structure from an analysis of short period Rayleigh waves generated by shallow explosions in three distinct regions: the northeastern United States, the central United States, and in northern Italy. The shallow velocity structures affecting the Rayleigh wave are metamorphosed paleozoic, glacial till covered paleozoic and quaternary alluvium, respectively, for the three regions. Thus the data sets form a strong test on the relation between M_I and Y.

The results for each data set are summarized in Table 1. Within each data set there is more than one estimate of M_I or ψ_∞. The individual estimates are averaged in a logarithmic sense. If an individual estimate of a parameter is x_i, then the logarithmic mean of N observations is defined as

$$\bar{x} = 10^{\mu} \qquad (2)$$

where

Table 1. Source Parameters From Short-Period Rayleigh Waves

ID	Y (T)	M_I (dyne-cm)	$ERR\,M_I$	$ERR\,\overline{M_I}$	ψ_∞ (m^3)	$ERR\,\psi_\infty$	$ERR\,\overline{\psi_\infty}$	Ref
Distributed Chemical Source								
111891	14.56	$6.0\,10^{19}$	2.82	1.59	19.0	2.59	1.53	Hutchenson (1994)
111991	13.23	$2.7\,10^{19}$	3.31	1.70	8.9	3.09	1.65	Hutchenson (1994)
112191	29.44	$1.75\,10^{20}$	1.96	1.29	55.1	1.74	1.23	Hutchenson (1994)
090892	49.89	$1.99\,10^{20}$	2.85	1.39	73.2	2.89	1.39	Hutchenson (1994)
091192	64.62	$1.64\,10^{20}$	3.22	1.44	60.3	3.27	1.45	Hutchenson (1994)
Point Chemical Source								
Ferrara	0.01	$6.8\,10^{15}$	1.02		0.016	1.02		Malagnini *et al* (1996)
10279	1.25	$7.0\,10^{18}$	1.45	1.24	0.98	1.47	1.25	Hutchenson (1994)
SP4-POS	1.0	$1.4\,10^{18}$		1.06	0.20		1.06	Al-Eqabi (1994)
SP6-POS	1.0	$2.2\,10^{18}$		1.07	0.38		1.07	Al-Eqabi (1994)
SP6-NEG	1.0	$1.7\,10^{18}$		1.05	0.27		1.05	Al-Eqabi (1994)
SP3B-POS	1.0	$3.6\,10^{18}$		1.10	0.54		1.10	Al-Eqabi (1994)
SP3A-NEG	1.0	$1.6\,10^{18}$		1.07	0.20		1.07	Al-Eqabi (1994)
SP1-POS	1.0	$1.8\,10^{18}$		1.08	0.29		1.08	Al-Eqabi (1994)
SP1-NEG	1.0	$1.5\,10^{18}$		1.10	0.22		1.10	Al-Eqabi (1994)
SPC2-NEG	0.5	$1.0\,10^{18}$		1.08	0.14		1.08	Al-Eqabi (1994)
SP13-NEG	1.0	$1.5\,10^{18}$		1.08	0.28		1.08	Al-Eqabi (1994)
SP4A-POS	1.0	$2.0\,10^{18}$		1.15	0.23		1.15	Al-Eqabi (1994)
SP15-POS	1.0	$2.0\,10^{18}$		1.10	0.24		1.10	Al-Eqabi (1994)
SP17-NEG	1.0	$5.1\,10^{18}$		1.10	0.64		1.10	Al-Eqabi (1994)
SP19-NEG	1.0	$2.4\,10^{18}$		1.09	0.45		1.09	Al-Eqabi (1994)
SP19-POS	1.0	$1.7\,10^{18}$		1.08	0.28		1.08	Al-Eqabi (1994)
SP20-POS	1.0	$2.2\,10^{18}$		1.05	0.30		1.05	Al-Eqabi (1994)
SP23-NEG	1.0	$4.7\,10^{18}$		1.09	0.65		1.09	Al-Eqabi (1994)
SP26-NEG	1.0	$3.6\,10^{18}$		1.12	0.47		1.12	Al-Eqabi (1994)

EVID: Event identification used in the primary references
Mean M_I and ψ_∞ are obtained by taking the anti-logarithm of their logarithmic averages. $ERR\,M_I$ and $ERR\,\psi_\infty$ are multiplicative factors obtained as 10^σ, where σ is the standard deviation of their logarithms.
$ERR\,\overline{M_I}$ and $ERR\,\overline{\psi_\infty}$ are multiplicative factors obtained by the relation 10^{σ_μ}, where σ_μ is the standard deviation of the mean of their logarithms.

$$\mu = \frac{1}{N}\sum \log x_i \,. \tag{3}$$

The standard error in logarithmic space is defined as

$$\sigma = \left[\sum(\log x_i - \mu)^2/(N-1)\right]^{1/2}, \tag{4}$$

which corresponds to a multiplicative error $ERR_x = 10^\sigma$. Finally, the standard error of the mean value of the logarithms is

$$\sigma_\mu = \sigma / N^{1/2}, \tag{5}$$

which corresponds to a multiplicative error in $\bar{x}$ of $ERR_{\bar{x}} = 10^{\sigma_\mu}$. The choice of logarithm space for averaging is based on modeling the observed time histories $o(t)$ in terms of the synthetic Green's functions $g(t)$ by the relation $o(t)=\bar{x}g(t)$. Note that σ indicates the scatter of individual observations and σ_μ indicates the scatter is the estimate of the mean.

2.1 Maine, northeastern U. S.

Al-Eqabi (1994) analyzed short-period Rayleigh waves generated in the fall of 1984 as part of a U. S. Geological Survey refraction study to investigate the structure and tectonic evolution of the northern Appalachian Mountains in Maine (Murphy and Luetgert, 1986, 1987). The surface waves were well observed in the 0 - 50 km distance range in the 1 - 5 Hz frequency band. Because of the frequency band and the high velocity metamorphosed paleozoic structure having little deep sediment cover, observed waveforms are well dispersed, coherent and easily modeled. Aspects of the interpretation of the surface-wave data set are presented in Herrmann and Al-Eqabi (1991) for data processing and Al-Eqabi and Herrmann (1993) for inference of laterally varying earth structure. Al-Eqabi (1994) succeeded in modeling the waveforms in terms of Q_β^{-1} and laterally varying velocity models.

Figure 1 compares the observed and predicted waveforms for the data set SP6POS (Al-Eqabi, 1994) using a point center of expansion with a step source time function at shallow depth for the source. The waveform fit as a function of time and distance served as a validation of the inferred model. Since recording instrument calibration was known, M_I is obtained by comparing observed and predicted peak amplitudes as a function of distance for the assumed step source time function. A step is used rather than a more realistic form (Murphy, 1977, 1991; Sharpe, 1942) since the frequencies observed are assumed to be in the flat part of the spectrum at low frequencies for these 0.5 and 1.0 ton explosions.

To test this assumption, Figure 2 compares observed and predicted peak amplitudes of traces bandpass filtered about various center frequencies. The agreement between observed and predicted waveforms in terms of phase, peak amplitude and shape provides confidence in the inferred medium parameters. The absolute ratio of peak amplitudes of the observed and predicted surface wave in different frequency bands provided a check on the earth model, as well as the assumption of the step source time function in the explosion model. The source spectra estimates based on these time domain filtered amplitudes indicate that the step source time function was adequate for this data set. The isotropic moment estimates given in Table 1 were obtained by taking a log-mean of the M_I estimate at each distance from a comparison as shown in Figure 2. The ψ_∞ were inferred using (1) and the derived velocity model for 14 shots recorded along 17 profiles. The log-standard error factor for the level is also given.

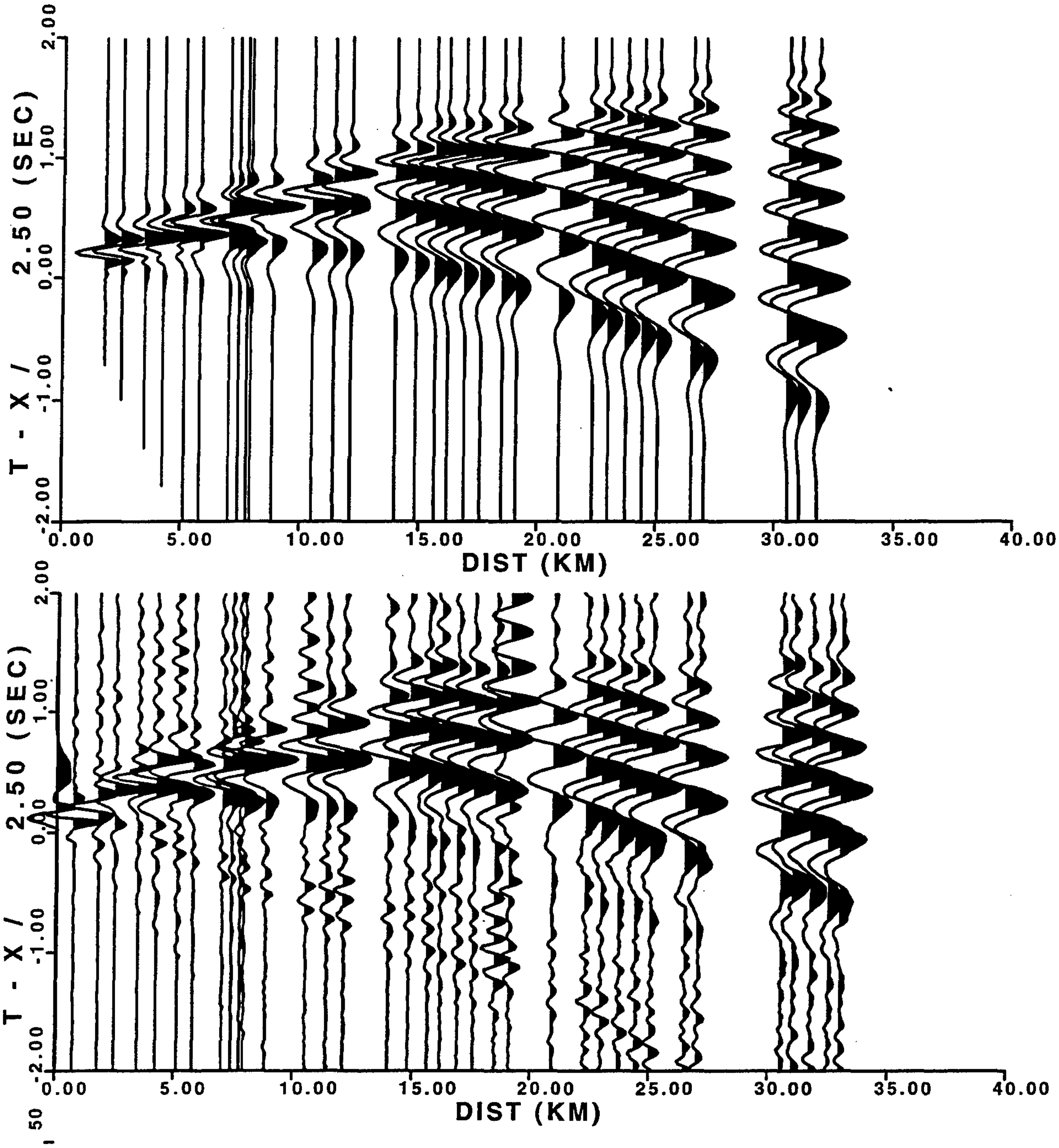

Figure 1. Comparison of observed (bottom) and predicted (top) traces for the SP6POS profile of the Maine experiment. All traces are bandpass filtered between 0.5-5.0 Hz. All traces are scaled to have the same peak amplitude.

2.2 Ferrara, Italy

Malagnini *et al.* (1996) discuss an experiment performed in the Po River flood plain near Ferarra, northern Italy. As in the Maine experiment, surface

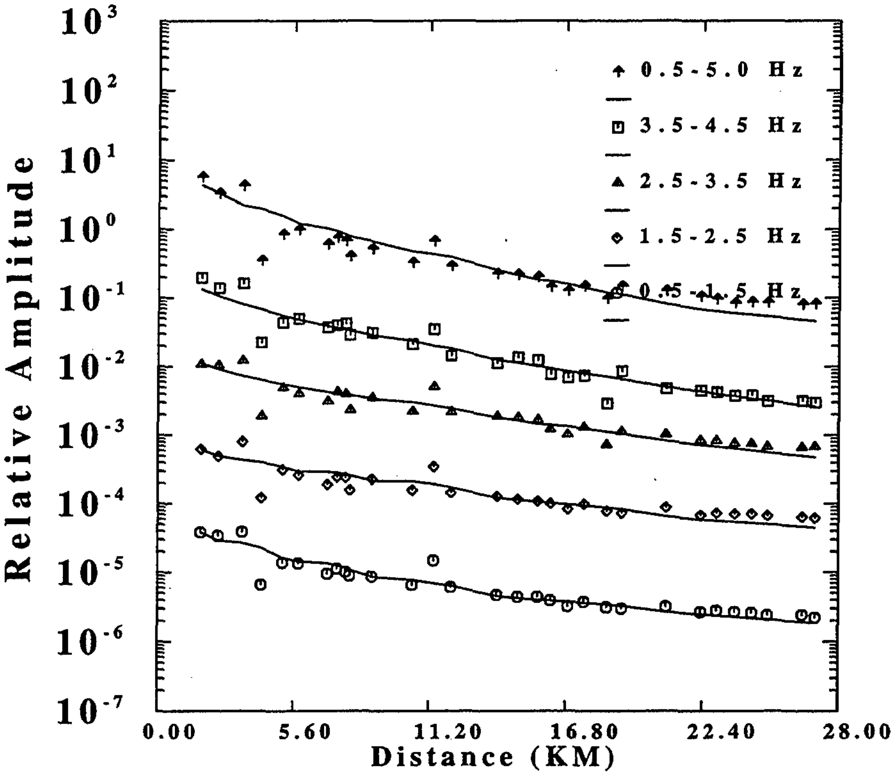

Figure 2. Comparison of observed (symbols) and predicted (lines) peak amplitude as a function of distance and the SP6POS profile of the Maine experiment in different bandpass frequency bands. The ratio of observed to predicted amplitudes estimates the source spectrum in each frequency band.

wave data were observed by an array, but in this case the source and array were in low velocity quaternary alluvium. In terms of wave propagation, this means that the observed surface waves are multi-mode in the observed frequency band of 1-5 Hz and that scattering and lateral wave propagation due to the development of the alluvial plain, may make modeling difficult since there will be difficulty in identifying the mode for a given dispersion. The source to receiver distance is on the order of 100 wavelengths near 1 Hz, compared to 10 wavelengths for the simpler Maine data sets.

Figure 3 compares the observed and model predicted trace at a distance of 2.61 km from the shot point. The early part of the surface wave signal is modeled well. The latter part that is not modeled may be due to multipathing. The general agreement in phase and envelope shape provides confidence in the velocity and Q model. Figure 4 compares the observed and predicted bandpass filtered ground velocities as a function of distance. The ratio of observed to predicted amplitudes was used to estimate the frequency dependent source spectrum, which was approximately fit by a step in pressure, but which may require some overshoot. The character of amplitude versus distance in the observed data may be indicative of multipathing or modal interference, and contributes to the estimated error in the isotropic moment. The M_I and ψ_∞ are given in Table 1.

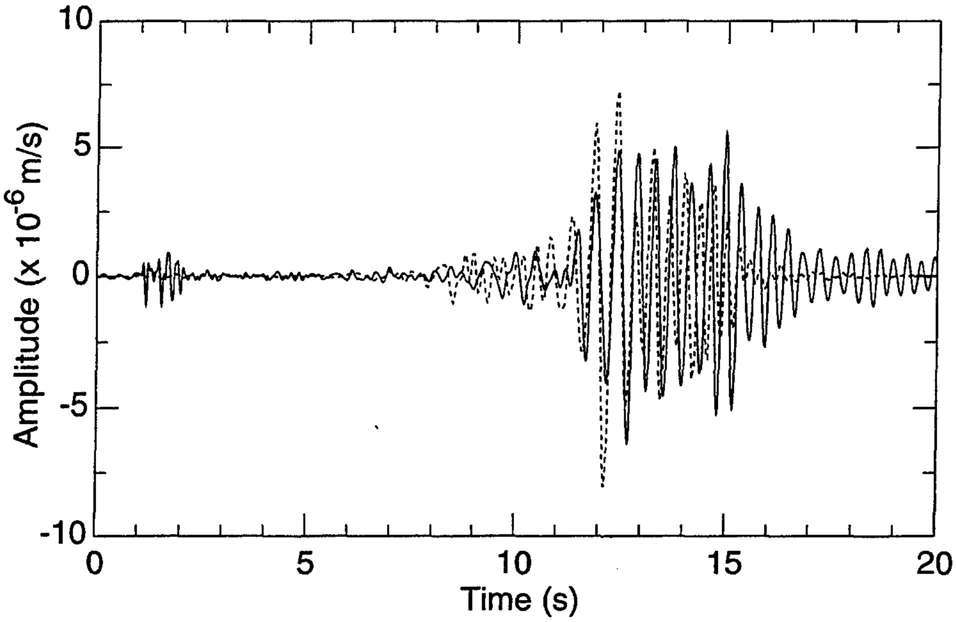

Figure 3. Comparison of observed (solid) to synthetic (dashed) vertical component ground velocity at a station 2.61 km from the Ferrara shotpoint. Traces have been bandpass filtered between 0.5 and 5.0 Hz for comparison.

2.3 Central US

Hutchenson (1994) also performed a study directed toward defining shallow shear-wave velocity and Q, but used data from a regional seismic network and a field-deployment of digital recorders. This meant that Q could not be estimated by the decay of amplitude with distance along a linear profile, but had to be inferred by its effect on the envelope of the observed single-trace surface wave signal. Other than the one 1.25 ton point explosion set off in alluvium for a 1991 U. S. Geological Survey refraction survey, the other sources were production shots from coal strip mines ranging in size from 13 - 64 tons, being sufficiently large to have some unknown shaping effect on the effective source time function and frequency content of the signal due to non-isotropic effects of the source and time between the first and last hole fired in these spatially distributed sources.

The data sets for a given explosion also represented two distance ranges: 0-10 km for the portable recorders, and 30 - 200 km for the regional network. The explosions were used to break the overburden rock lying over bituminous coal seams strip mined in the Illinois Basin.

Figures 5 and 6 compare the fits between observed and predicted wave forms for the event of 080992 recorded by the regional and portable network stations. The large amplitude fundamental mode surface-wave arrival is well

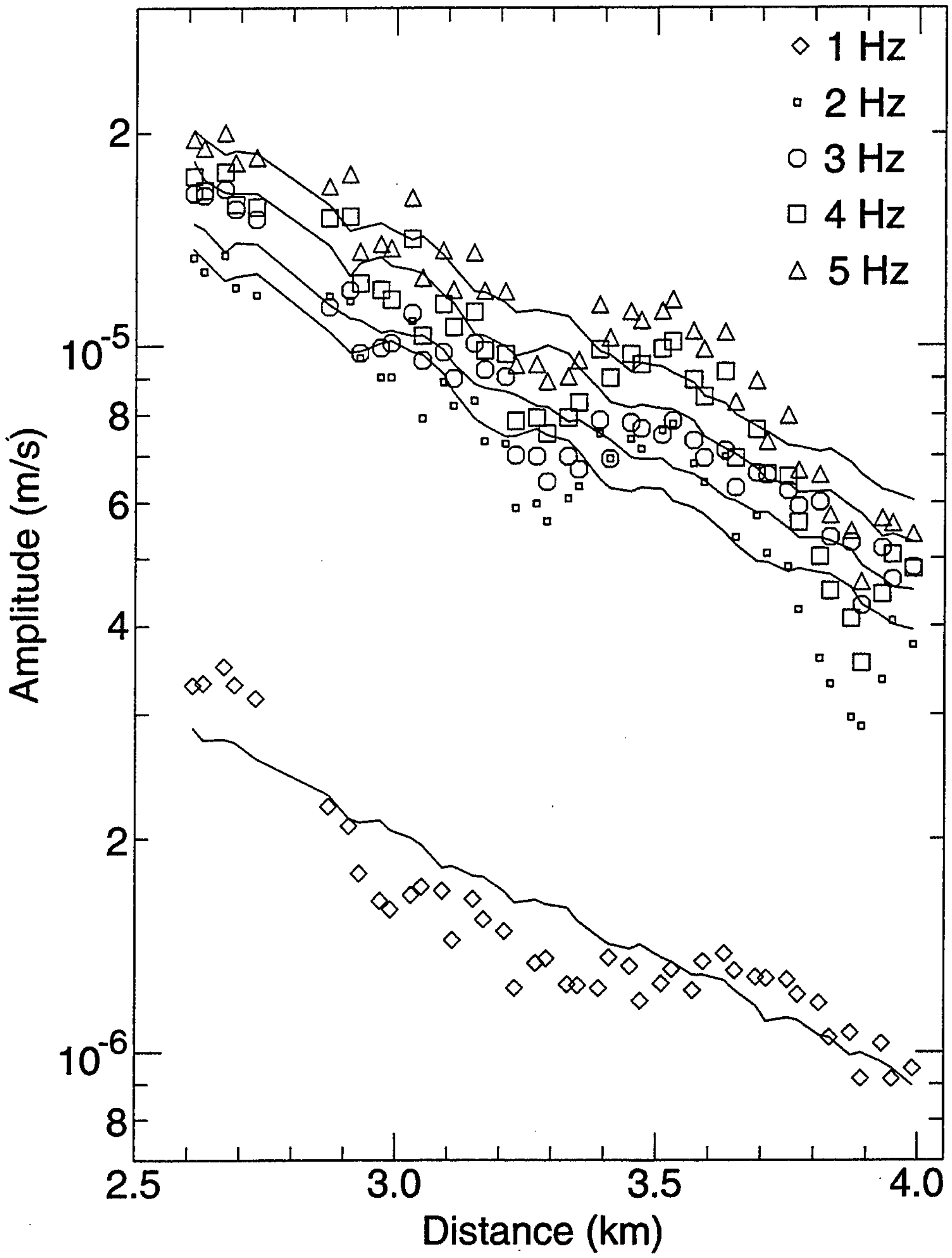

Figure 4. Comparison of observed (symbols) and predicted (lines) filtered ground velocities for the Ferrara, Italy, profile. Vertical scaling is arbitrary. Filtering consisted of a 2nd order Butterworth lowpass filter with corner f_c+0.5 Hz, followed by a 2nd order Butterworth highpass filter with corner f_c-0.5 Hz. The vertical separation at different filter frequencies is due to the excitation of the fundamental mode.

fit, as are some of the higher frequency, higher mode data. For each of the ten waveforms, there are separate estimates of the velocity-Q model and isotropic moment.

For each source, then logarithmic means for M_I and ψ_∞ as well as multiplicative error factors are given in Table 1. The large values of the multiplicative factors relative to the other data sets are indicative of the scatter in this data set.

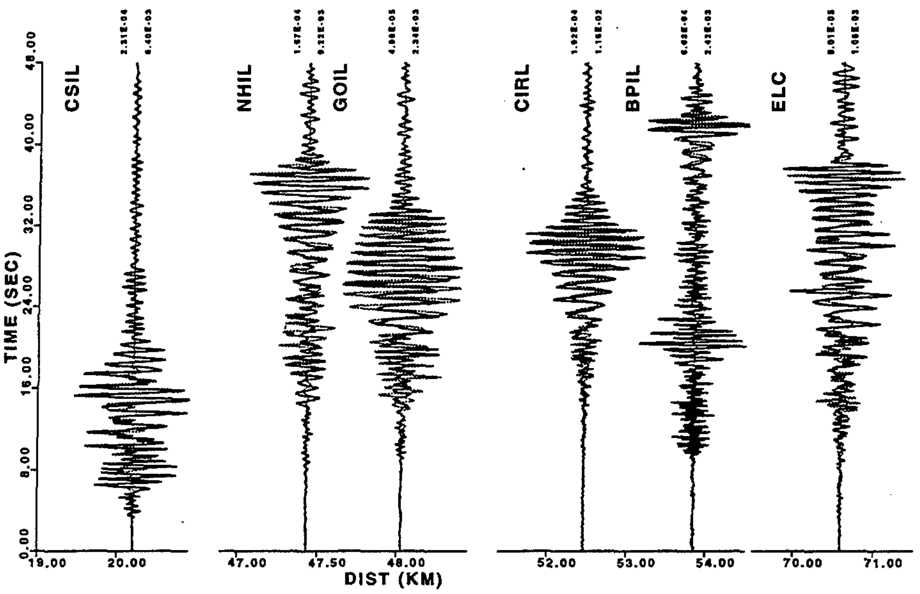

Figure 5. Comparison of the observed (solid) and predicted (dotted) for the Illinois Basin event of 080992 for regional network data in the 20 - 75 km distance range.

2.4 Summary

Since it was assumed that both M_I and ψ_∞ will be directly proportional to yield Y, the estimates of these parameters are normalized by yield in Figures 7 and 8 (solid symbols) to highlight the variability of the estimates. The error estimates of Table 1 are not plotted though for clarity. The yields used for the chemical explosions are the actual amounts used and were provided by the shooters. Since there was insufficient information available on the exact type of chemical used, no attempt was made to use an equivalent energy yield for comparison to nuclear yields. In addition, little was known about the depth of burial, degree of containment or material properties to apply the detailed analysis of Denny and Johnson (1991).

Denny and Johnson (1991) note that to a first order approximation, M_I and ψ_∞ are linear functions of yield Y. This is supported by our data set, which covers 4 orders of yield.

Of the events studied, the Ferrara shot of 0.01 tons is lower than expected in terms of yield normalized moment, but fits better in terms of ψ_∞. This is not unexpected because of the very low P-wave velocity of the shot medium.

An important issue is the variability of measurements. The analysis of the Maine refraction data (Al-Eqabi, 1994) shows a significant spread in M_I