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AMPLITUDE AND FREQUENCY
CHARACTERISTICS OF ELASTIC
WAVE TYPES GENERATED BY
UNDERGROUND NUCLEAR EXPLOSIONS

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ABSTRACT

Elastic wave studies yield useful information about the amplitude and frequency characteristics of the ground motion caused by underground nuclear explosions. This information provides a valuable data base which can be incorporated into analytical and predictive studies.

Elastic wave types were identified on seismograms recorded from three Pahute Mesa (Boxcar, Stinger, and Rickey) and two Yucca Flat (Zaza and Lanpher) detonations utilizing the basic information contained in the seismogram; i.e., the first arrival times and particle motion characteristics. The amplitude characteristics of the identified elastic wave types were determined to vary with yield, source-recording station distance, and frequency. The surface wave and the direct P and S wave modes appear to scale approximately as the first power of yield, whereas refracted and reflected P and S wave modes scale approximately as the 0.6 power. Within each body wave subset, the refracted wave amplitude decays most rapidly and the reflected wave amplitude least rapidly with distance. The surface wave decays at about the same rate as the reflected wave over the distance considered. Amplitude spectra of the P, S, and surface wave time windows all peak at different spectral frequencies for

stations on rock (BPF line and Beatty, Nevada); approximately 0.8-1.0 Hz for the P wave window, 0.35-0.65 Hz for the S wave window, and 0.25-0.50 Hz for the surface wave window. The peak amplitude of body wave window spectra occurs at higher spectral frequencies for the two Tonopah, Nevada stations (especially Tonopah Motel). The frequency of the spectral peak for each wave mode time window shifts slightly from higher to lower values with increase in yield, but is essentially constant with increase in propagation distance over the distance range 22.2 - 79.1 km. The latter fact shows that reduction of high frequencies by the low-pass filtering action of the earth is essentially insignificant over this distance range.

Recommendations are made to extend the results of this report in order to develop the capability to predict the important characteristics of ground motion, resulting from underground nuclear explosions, in terms of specific elastic wave types, source parameters, ground motion parameters, and station site geology.

CHAPTER 1

INTRODUCTION

1.1 GENERAL BACKGROUND

The primary purpose of identifying and analyzing elastic wave types on seismograms from underground nuclear explosions is to gain physical insight into the amplitude-frequency composition of observed ground motion. The correlation of amplitude and frequency characteristics of observed ground motion with specific elastic wave types (P, S, and surface waves), although a complex multiparameter problem, is a necessary step in the development of the capability to identify and to predict the important characteristics of ground motion in terms other than the peak amplitude on the seismogram. Also, it provides a means to determine the physical influence of varying geological and geophysical parameters at the source, along the transmission path, and at the recording site on the elastic wave types, and consequently the ground motion, generated by an underground nuclear explosion.

Detonations Boxcar, Rickey, Stinger, Lanpher and Zaza provide an adequate data sample for correlating the amplitude and frequency characteristics of measured seismic data with elastic wave types. The events were detonated in two well-known geologic provinces of

Nevada Test Site (NTS), Yucca Flat and Pahute Mesa. The source medium was tuff for all the events except Boxcar which was detonated in rhyolite. The events had a fairly wide range between the highest and lowest yield. The events were adequately instrumented, with velocity meters being deployed over a wide distance range (4.4 - 528.0 km). Also, many recording station sites were common to all five events. All of these factors combine to provide the type of data sample needed to achieve the objectives of this report.

1.2 IDENTIFICATION OF ELASTIC WAVE TYPES

Identification of the elastic wave types on a seismogram of an underground nuclear explosion is a key step in the sequence of steps needed to correlate the amplitude and frequency characteristics of measured seismic data with specific elastic wave types. Travel time information, particle motion diagrams (hodographs), and the radial-vertical component product waveform individually and collectively provide useful information which can be used to identify elastic wave types on a seismogram (Sutton, 1967 and Hays, 1968). Travel time data provide the identity and propagation velocity of the first arrival, the least ambiguous and most useful travel time information on the record. The first arrival is always a P wave (compressional body wave). Travel time data also provide a

close estimate of the expected arrival time of the S wave (shear body wave) having a travel path corresponding to that of the first arrival and information which can be related to the physical parameters of the sequence of layers comprising the earth's crust and the upper mantle. This information is important, for the crust and upper mantle constitute the transmission path for elastic wave types generated by underground nuclear explosions and recorded over the distance range 4.4 - 528.0 km. Hodographs and the radial-vertical component product waveform provide a valuable diagnostic tool, as well as a quick check, for identifying the body waves (P and S) and the Rayleigh (surface) wave on seismograms. The characteristics of the hodograph and the product waveform can be related directly to the particle motion characteristics expected on the basis of theoretical considerations.

On the basis of travel time data, hodographs, and component product waveforms, the time history of a typical seismogram can be divided into three windows:

1. A P wave window (beginning with the first arrival and extending to the first S wave arrival).
2. An S wave window (beginning at the first S wave arrival; i.e., at a time about 1.7 times the first arrival time, and extending to the onset of the surface wave train).

3. A surface wave window (from the onset of the long period surface wave train to the end of the significant motion of the seismogram).

Each of these time windows can be analyzed individually and amplitude and frequency characteristics of the ground motion displayed in each time window can be interpreted in terms of the specific wave mode window. Characteristics of the two body wave windows can be related to specific wave phases; i.e., direct wave, refracted wave, and reflected wave.

Investigations by many people (Gutenberg, 1954, Romney, 1959, Jordan, et. al, 1965, Julian and Anderson, 1968, and Lehmann, 1969 and others) have shown that the identification of specific elastic wave phases on a seismogram is not a simple process. One reason is that the real earth is so complex that the approximating model is always greatly simplified by comparison. Consequently, the model of the earth never incorporates adequately factors such as: 1) horizontal and vertical anisotropy of velocity and elastic properties caused by spatial variation in the geological processes of sedimentation and vulcanism, 2) the effect of variable shallow low velocity layers, and 3) variation in the structural attitude of acoustic impedance contrast interfaces caused by tectonic activity. Nevertheless, the identification process in practice usually reduces to a simplified iterative procedure which is valid on a macroscopic

scale. That is, the parameters of the model are defined on the basis of the observed travel time data, then the model is used as the basis for identifying specific elastic wave types. Data from several detonations serve to refine the model and to provide a statistical basis for defining the uncertainty connected with the identification procedure.

1.3 OBJECTIVES OF THIS REPORT

The primary objective of this report is to determine the amplitude and frequency characteristics of the ground motion observed from five specific underground nuclear explosions and to correlate these characteristics with specific elastic wave types generated by the explosions.

The chapters which follow describe various functional analyses designed to meet the objective of this report. Chapter 2 describes the amplitude characteristics of elastic wave types generated by the Boxcar, Rickey, Stinger, Zaza, and Lanpher detonations. Regression equations which express the particle velocity amplitude as a function of yield and source-recording station distance are defined in Chapter 2. Chapter 3 identifies the frequency characteristics of the elastic wave types generated by the Boxcar, Rickey, Stinger, Zaza, and Lanpher detonations. Fourier amplitude spectra are obtained for the P, S, and surface wave time windows from seismograms of selected stations such as Beatty, Tonopah Church, Tonopah Motel, and the BPF line, all in Nevada.

CHAPTER 2

AMPLITUDE CHARACTERISTICS OF ELASTIC WAVE TYPES

2.1 GEOLOGIC SETTING OF THE BOXCAR, RICKEY, STINGER, LANPHER AND ZAZA EVENTS

The Nevada Test Site (NTS) lies north and east of the Las Vegas Valley-Walker Lane shear zone, near the thickest part of the Paleozoic Cordilleran miogeosyncline and east of an area characterized by large plutons of Mesozoic age (Ekren, 1968). Alluvium-filled basins constitute about 20 percent of the area. Paleozoic and uppermost Precambrian sedimentary rocks total about 40,000 feet in thickness and form approximately 30 percent of the outcrops. The remainder comprises primarily volcanic rocks and related intrusive igneous masses of Tertiary age.

Detonations Boxcar, Rickey, Stinger, Lanpher, and Zaza are located in NTS (see Figure 2-1) in two well-known geologic provinces, Yucca Flat and Pahute Mesa. Zaza and Lanpher are located on Yucca Flat, whereas Boxcar, Rickey, and Stinger are located on Pahute Mesa.

Yucca Flat (Figure 2-2) is a broad intermontaine valley blanketed by a variable thickness of semi-to-consolidated alluvium up to 2,000 feet thick. This alluvium effectively conceals the underlying Tertiary volcanic tuffs and lava flows. It also conceals the older

Figure 2-1. Map Showing Location of the Boxcar, Rickey, Stinger, Lanpher and Zaza Events and Selected Instrument Stations

(after Stead, 1968)

Figure 2-3. Diagrammatic Geologic Cross-Section of Pahute Mesa, Nevada Test Site

Paleozoic dolomites, shales, and quartzites. The terrain surrounding the valley is structurally complex and consists of a variety of volcanics, sediments, and small granite stocks. The major fault in the area is Yucca Fault, along which very recent movements have occurred. This fault clearly breaks through and offsets all the rocks.

Pahute Mesa structurally represents one of the major volcanic calderas of NTS. Pahute Mesa is underlain by complex volcanic sequences of rhyolitic and quartz-latic composition, several thousand feet in thickness (see Figure 2-3). Numerous normal faults occur throughout the area and have throws of several hundred feet.

2.2 TRAVEL TIME DATA FROM THE BOXCAR, RICKEY, STINGER, LANPHER AND ZAZA EVENTS

Figure 2-4 shows the first arrival time (T) as a function of station distance (Δ) for all instrument stations which recorded the Boxcar, Rickey, Stinger, Lanpher and Zaza detonations and had first arrival time information. In addition, first arrival times measured at Faultless stations in the distance range 150-550 km were included to increase the sample size in this distance range.

The first arrival times, despite some scatter, can be approximated by two straight line segments; the first in the interval 0-150 km and the second in the interval 150-550 km. The first of these lines has a best-fit equation, determined by least squares analysis, of

Figure 2-4. First Arrival Time Versus Distance for the Boxcar, Rickey, Stinger, Lanpher and Zaza Events (Data from Faultless in the 150-550 km range are included also)

$$T_1(\Delta) = \left(\frac{\Delta}{5.69} + 0.53 \right) \pm 0.67 \quad (2-1)$$

where T_1 is the travel time (sec), Δ is the station distance (km), 5.69 is the inverse slope of the line and corresponds to the wave propagation velocity (km/sec), 0.67 (sec) is the standard error of estimate (a measure of the scatter in the data).

Equation 2-1 represents the arrival time of the compressional wave, designated P_g in conventional earthquake terminology, which is called the "direct" wave. This wave propagates in the upper layers of the crust. In reality, the wave does not travel a straight line from the source to the receiver, as shown schematically in Figure 2-4, but is refracted at the interface between the Paleozoic sedimentary rocks and the underlying crystalline granite rocks.

The second line segment has the equation

$$T_2(\Delta) = \left(\frac{\Delta}{7.85} + 7.50 \right) \pm 5.0 \quad (2-2)$$

where T_2 and Δ are defined above, 7.85 is the velocity (km/sec), and 5.0 is the standard error of estimate (sec). This equation was not determined by least squares analysis, but was determined subjectively on the basis of the Faultless data due to the relatively small number of first arrival times available in this distance

range from the five events and the fairly large scatter in the data. Equation 2-2 represents the arrival time as a function of station distance for a compressional wave, designated P_n in conventional earthquake terminology, which has been critically refracted along the crust-mantle interface, i.e., the Mohorovicic (M) discontinuity. This equation provides an estimate of the arrival time of the refracted wave.

Insufficient data were available to establish a propagation velocity for the shallow alluvium layer, which occurs intermittently over NTS, and the intermediate layer (Conrad discontinuity) which some investigators have noted. Consequently, the velocity of 5.69 km/sec is assumed to be the velocity from the surface to just above the Moho.

The values of velocity indicated above for P_g and P_n are comparable with the results obtained at NTS by other investigators, such as Diment, et. al. (1961), Stuart, et. al. (1964), and Hill, et. al. (1967). Differences in the values of velocity reported are related to factors such as: 1) the physical character of shallow crustal layers, 2) the depth and structural attitude of the M discontinuity, and 3) regional tectonic features which introduce azimuthal variations in the travel times.

2.3 IDENTIFICATION OF BODY WAVE PHASES

Travel time curves can be calculated as a function of station distance for P and S wave phases, assumed to have traveled a direct ray path (P_g and S_g), a critically refracted ray path (P_n and S_n), and a ray path corresponding to a reflection (P_mP and S_mS) from the M discontinuity (see Figure 2-4). The formulae which apply for a two layer earth model are as follows:

$$T(\Delta) = \sqrt{\frac{\Delta^2 + h^2}{V_1^2}} \quad \text{Direct Wave} \quad (2-3)$$

$$T(\Delta) = \sqrt{\frac{\Delta^2 + (2H-h)^2}{V_1^2}} \quad \text{Reflected Wave} \quad (2-4)$$

$$T(\Delta) = \frac{\Delta}{V_2} + \frac{2H-h}{V_1} \sqrt{1 - \frac{V_1^2}{V_2^2}} \quad \text{Refracted Wave} \quad (2-5)$$

In each formula, Δ is the surface distance (km) of the recording station from the source, H is the depth (km) of the M discontinuity, h is the depth of burial (km) of the nuclear device, V_1 is the propagation velocity in the crust and V_2 is the propagation velocity (km/sec) at the top of the mantle. The P wave propagation velocities are determined from the analysis of the first arrival time data. Propagation velocities of the S waves traveling a corresponding ray path are estimated on the basis of theoretical and observational evidence that S waves propagate with a velocity of about 0.6 that of P waves for most earth materials (Dobrin, 1960).

A chart containing the theoretical time-distance graphs for the P and S wave modes, assumed to have traveled a direct ray path (P_g and S_g), a critically refracted ray path along the M discontinuity (P_n and S_n), and a ray path corresponding to a reflection from the Moho (P_mP and S_mS), was prepared on the same time scale as the particle velocity seismograms. This chart was used as a guide to estimate the arrival time of the onset of each wave mode over the distance range 4.4 - 528.0 km. Significant characteristics of the recorded ground motion, such as a sharp change in dominant frequency, a rapid increase in amplitude on a particular seismograph component or of the total vector motion, in conjunction with hodographs and component product waveform characteristics (Hays, 1968), heavily influenced the interpretative aspect of the wave mode identification and provided first order corrections in the technique.

Corrected particle velocity seismograms, obtained from NC-21 and L-7 recording systems data, were used in the mode identification process. Particle displacement and particle acceleration records are both very useful, however, and were used in a supplemental role in all cases, when available.

2.4 AMPLITUDE CHARACTERISTICS OF ELASTIC WAVE TYPES

The amplitude of the particle velocity associated with each of the six identified body wave phases (P_g , P_n , P_mP , S_g , S_n , S_mS) and the surface wave mode was measured on each particle velocity seismogram available from the five events over the distance range 4.4 - 528.0 km. The resultant vector amplitude which coincides in time with the identified onset of the elastic wave mode was selected for measurement. The resultant vector was selected because the objective is to relate the peak vector motion on the seismogram to the peak vector motion of specific elastic wave types. In all cases, the value of amplitude assigned to a specific wave mode was limited to the peak value of the vector occurring within one cycle of the identified onset time of the wave. This limiting interval provided a means for maintaining consistency in the amplitude assignment procedure.

It should be noted that the identification of elastic wave phases in this distance range (4.4 - 528.0 km) is not a simple process. Each seismogram must be analyzed both as an individual entity and collectively with others to establish the identification of the body wave phases. Consideration must be given to factors such as interfering wave arrivals, particularly in the distance range around the initial point (about 60 km) where the reflected and critically refracted waves arrive almost simultaneously.

2.4.1 Amplitude as a Function of Yield and Distance

The ground motion recorded at a given recording site corresponds to the superposition in time of seismic waves which have traveled from the energy source to the receiver along a great number of travel paths. Consequently, the amplitude of a specific wave type recorded at an individual station is a complex function of variables related to 1) the source region, 2) the transmission path, and 3) the recording site. Source variables include the yield of the device, the depth of burial, the nature of the emplacement hole, and physical parameters (rock type, elastic properties, moisture content, propagation velocity, etc.) of the source and near-source media. Transmission path variables include the physical parameters of each individual transmission path between the source and receiver, the source to receiver distance, the geometrical travel path, and the propagating elastic wave type. Recording site variables include the physical parameters (thickness, elastic properties, rock type, etc.) of the near-surface materials, geophone-earth coupling, and instrument response characteristics.

Analytic studies conducted by Werth, et. al. (1962), Springer (1966), Davis and Murphy (1967), Murphy and Lahoud (1968), Trembly and Berg (1968), Long and Berg (1969) and others indicates that the explicit functional form which would relate the amplitude of a seis-

mic wave to the variables mentioned above is very complex and beyond the current development of the art. Experience (Murphy and Lahoud, 1968) has shown that one practical approach to the problem is to hold all but two primary independent variables, yield (W) and source to receiver distance (R), constant and to relate amplitude to them through the power law formulation

$$A(W,R) = K W^m R^{-n} \quad (2-6)$$

This functional relationship provides a good first approximation even though error is introduced by consideration of only two independent variables of the physical system.

Errors introduced by considering only two independent variables are reflected in the statistical measures of uncertainty determined for the final results. This approach is clearly an approximation to the actual physical system, although several of the system variables can probably be correctly considered to be negligible or even eliminated in some cases. For example, instrument response can be eliminated, as all the velocity seismograms have been corrected for instrument response. Also, the emplacement procedures used for NC-21 and L-7 instruments cause the seismograph-earth coupling to be nearly perfect; therefore, this variable can be considered to be negligible. The

same geological medium (tuff) at the source of all events except Boxcar (rhyolite) may eliminate the source geological environment as a significant variable for four of the events; although, the physical properties of tuff sometimes vary over a fairly wide range. When amplitudes measured at the same station are compared, the geological and geophysical parameters of the station site can be eliminated as a variable.

Table 2-1 lists the values of m and n , the two exponents in equation 2-6 which describe the variation of the vector particle velocity amplitude with yield and range respectively. These values were determined by multiple regression analysis of the sample set triple (wave mode amplitude-yield-station range) derived from each particle velocity seismogram from the five events. Statistical measures of uncertainty (95% confidence interval and standard error of estimate) are also shown in Table 2-1.

Evaluation of the data and statistics shown in Table 2-1 leads to the following conclusions:

- The particle velocity amplitude of each elastic wave type shows a closer functional dependence (i.e., the confidence limit on the exponent is smaller) on yield than on distance. This observation is consistent with results reported by Hannon (1964), White (1965), Davis and Murphy (1967), Sutton, et. al. (1967), Long and Berg (1969) and others which show that factors such as absorption and scattering, which occur as a function of the crustal structure along the transmission path, and amplitude amplification,

TABLE 2-1

YIELD AND RANGE EXPONENTS, 95% CONFIDENCE INTERVAL
AND STANDARD ERROR OF ESTIMATE DERIVED FROM REGRESSION
ANALYSIS OF WAVE MODE AMPLITUDE DATA
FIVE EVENTS

STATION LITHOLOGY	SAMPLE SIZE	WAVE MODE	YIELD EXPONENT(m) AND 95% CONFIDENCE INTERVAL	RANGE EXPONENT(n) AND 95% CONFIDENCE INTERVAL	STANDARD ERROR (σ)
Hard Rock	34	P _g	1.00 ± 0.28	1.76 ± 0.35	2.27
	31	S _g	0.77 ± 0.21	1.89 ± 0.26	1.81
	17	P _n	0.59 ± 0.29	3.02 ± 0.68	1.71
	17	S _n	0.59 ± 0.26	1.98 ± 0.60	1.61
	33	P _m P	0.63 ± 0.24	1.52 ± 0.38	2.01
	32	S _m S	0.65 ± 0.19	1.50 ± 0.26	1.71
	31	Surface Wave	0.87 ± 0.16	1.75 ± 0.18	1.56

*Range on Distance: 4.4-528.0 km,

Alluvium	41	P _g	1.05 ± 0.31	1.83 ± 0.55	2.57
	42	S _g	0.78 ± 0.19	1.62 ± 0.34	1.78
	19	P _n	0.47 ± 0.39	2.49 ± 2.04	2.14
	19	S _n	0.53 ± 0.46	-----	2.60
	41	P _m P	0.80 ± 0.19	-----	1.76
	41	S _m S	0.59 ± 0.21	-----	1.81
	37	Surface Wave	0.80 ± 0.25	1.58 ± 0.46	2.12

*Range on Distance: 16.2-176.8 km,

*Note: Distance Range is 60-528 km for the refracted wave modes.

which occurs as a function of the shallow low velocity layers at the station site, introduce more scatter in the amplitude data than a change in source parameters.

- The surface wave and the direct P and S wave modes scale approximately as the first power of yield, whereas the refracted and reflected P and S wave modes scale approximately as the 0.6 power. The relatively greater scaling with yield for the low frequency surface wave is consistent with observations by Molotova (1964) and Lynch (1969). No physical reason is known at this time, however, to explain the apparent first power scaling of the direct P and S waves.
- The attenuation rate (determined from the exponent on range) of the particle velocity amplitude is different for each wave mode. Within each body wave subset, the refracted wave mode attenuates most rapidly and the reflected wave mode least rapidly with distance; a result expected from theoretical considerations (Heelan, 1953).
- The cylindrically expanding surface wave decays less rapidly with distance than all the body wave modes except the reflected wave mode. The comparatively slow decay rate of the reflected wave is due partly to the fact that beyond the initial point, total internal reflection occurs; that is, a normal mode of propagation results rather than a leaking mode. This leads to higher amplitudes in the distance range between 60-150 km (Cerveny, 1965). Also, the trapped reflected wave acts as a cylindrically expanding wave.

The amplitudes for each wave mode were normalized to a common yield, 200 kt, using the yield exponents shown in Table 2-1. The scaled amplitudes for the hard rock stations are plotted in Figure 2-5. The derived multiple regression mean and the one sigma lines are superposed for reference on the normalized amplitude data of each wave mode.

Figure 2-5. Vector Particle Velocity Amplitude (normalized to 200 kt) of Each Wave Mode Versus Range (Hard Rock Stations - Five Events)

2.4.2 Amplitude Attenuation of Elastic Wave Types Measured at Hard Rock Stations Recording the Boxcar Event

The variation with station range of the total vector particle velocity amplitude was determined for each identified wave mode for the Boxcar stations located on hard rock. This data subset was selected for two reasons: 1) hard rock stations represent a sample in which the extremely important and variable station site physical properties which lead to amplitude amplification are minimized, and 2) Boxcar hard rock particle velocity stations represent approximately 50% of the total 5-event hard rock sample, a possible biasing factor in the analysis above.

Figure 2-6 shows, in summary form, the mean regression lines and the one-sigma lines for the resultant vector particle velocity of each wave mode as a function of distance. Careful analysis of the mean regression lines and the associated statistics shows that the various wave modes behave differently over the distance range 16.2-528.0 km. The direct P waves tend to have the most significant amplitude at distances less than 40 km. The maximum contribution of the refracted P waves occurs between 60 and 110 km. The surface waves have the greatest amplitude from about 110-300 km. The reflected P wave has the greatest amplitude for distances greater than about 300 km. The magnitude of uncertainty associated with each regression line, however, indicates that any one of the wave

Figure 2-6. Vector Particle Velocity Amplitude of Each Wave Mode Versus Range (Hard Rock Stations - Boxcar Event)

arrivals could contribute the peak particle velocity at a given distance.

Table 2-2 lists the attenuation rates and statistics for the Boxcar data. As expected, the distance exponents and associated statistics compare well with corresponding values listed in Table 2-1.

TABLE 2-2

REGRESSION EQUATION, 95% CONFIDENCE INTERVAL AND
STANDARD ERROR OF ESTIMATE DERIVED FROM REGRESSION
ANALYSIS OF WAVE MODE/AMPLITUDE DATA,
HARD ROCK STATIONS - BOXCAR EVENT

WAVE MODE	PARTICLE VELOCITY (VECTOR) REGRESSION EQUATION	STANDARD ERROR(σ)	SAMPLE SIZE
P_g	$u = 3.53 \times 10^8 R^{-1.81 \pm 0.60}$	2.52	15
S_g	$u = 3.43 \times 10^9 R^{-2.02 \pm 0.38}$	1.82	15
P_n	$u = 2.77 \times 10^{15} R^{-3.12 \pm 0.59}$	1.49	8
S_n	$u = 4.84 \times 10^9 R^{-2.03 \pm 0.97}$	1.93	8
$P_m P$	$u = 1.25 \times 10^7 R^{-1.49 \pm 0.30}$	1.73	16
$S_m S$	$u = 6.25 \times 10^7 R^{-1.64 \pm 0.29}$	1.71	15
Surface	$u = 1.32 \times 10^8 R^{-1.67 \pm 0.21}$	1.47	16
Note: u is in cm/sec R is in km			

2.5 CAUSES OF SEISMIC WAVE ATTENUATION WITH DISTANCE

When a seismic wave propagates through the crust and upper mantle of the earth, several physical mechanisms act to attenuate the wave with increase in distance. These physical processes may be summarized as follows:

1. Absorption of seismic energy along the path from the source to the station site.
2. Geometrical divergence of the wave front along the path between the source and the station.
3. Diffraction and scattering of energy by local inhomogeneities in the propagation medium.
4. Partition of energy at interfaces encountered along the travel path.

The observed attenuation of a seismic wave traveling through the earth is the resultant of contributions from all these mechanisms. Little can be done to isolate the relative influence of each mechanism in real earth materials, particularly as the frequency dependence of the attenuation at various depths within the earth is not well known. Theoretical considerations show that spherically expanding waves (body waves) should attenuate as R^{-1} and cylindrically expanding waves (surface or trapped waves) as $R^{-\frac{1}{2}}$ in an infinite, homogeneous, isotropic, and perfectly elastic medium (Grant, 1965). These exponents account only for geometric spreading factors and do not include the effects of absorption which occur be-

cause the assumption of perfectly elastic behavior does not hold for the materials of the crust and upper mantle. Furthermore, the rate of amplitude decay actually depends upon the specific travel path which the energy follows between the source and receiver. Consequently, a refracted (leaking mode) arrival would be expected to decay more rapidly than a reflected (trapped mode) arrival (Ewing, et. al., 1957). All these factors combine to cause decay rates of the order $R^{-2.0}$ and $R^{-1.5}$ to be observed for body and surface waves propagating in real earth materials instead of R^{-1} and $R^{-1/2}$.

The change in pulse form of a propagating seismic wave can be described by means of linear transform theory. The seismic pulse can be expressed in terms of its complex frequency spectrum

$$S(f) = |A(f)| e^{-i\phi(f)} \quad (2-7)$$

where $A(f)$ is the amplitude spectrum, and $\phi(f)$ is the phase spectrum, both functions of frequency (f). Changes in pulse form with distance traveled can then be thought of as due to a change in the amplitude spectrum (amplitude distortion), a change in the phase spectrum (phase distortion) or to a simultaneous change in both spectra. The amplitude distortion is due to frequency dependent spatial attenuation, whereas the phase distortion is due to dispersion. (Dispersion means that each frequency component contributing to the pulse travels

at a different velocity.) The spatial attenuation constant (α) of naturally occurring rocks has been studied more intensively than dispersion (see White, 1965, for a detailed list of references). Investigators have shown that the attenuation constant is approximately a linear function of frequency. Until recently, no general consensus existed as to the character of the phase distortion in body waves, other than the belief that dispersion, if present, is small. Gupta (1968) showed that the propagation of P and S waves is dispersive whenever the elastic medium considered departs from an infinite, homogeneous, isotropic, and ideally elastic medium and especially when the linear dimensions of inhomogeneity attain the same order of magnitude as the wavelength of the seismic wave involved. The dispersive effects are generally small, but are not always negligible. For example, Gupta (1968) showed that, for propagation normal to a layered structure, shorter period body waves travel faster than longer period body waves and possibly account for some unexplained observations in investigations of explosion and earthquake phenomena.

Chapter 3, which follows, will describe the frequency characteristics of elastic wave types observed at several selected Nevada stations (BPF line, Beatty, Tonopah Church, Tonopah Motel) from the five detonations.

CHAPTER 3

FREQUENCY CHARACTERISTICS OF ELASTIC WAVE TYPES

3.1 GENERAL BACKGROUND

The Fourier transform was used to determine the frequency characteristics of selected time windows of the particle velocity ground motion recorded at selected stations. The Fourier transform was selected as the frequency analysis technique for three main reasons:

1. It provides more detail on the amplitude spectrum of a seismogram than other frequency analysis techniques such as band-pass filter or pseudo-relative velocity.
2. Selected time windows which correlate with P, S, and surface wave time windows on the seismogram can be analyzed easily.
3. It has a well-known physical and mathematical interpretation (Bracewell, 1965).

The Fourier transform enables a function of time (the seismic signal) to be transformed into a complex function of frequency. The frequency domain representation can be resolved into an amplitude and a phase spectrum. The amplitude spectrum of a seismic

signal has more general usefulness than the phase spectrum even though it is highly oscillatory. This lack of smoothness is overcome easily, however, by convolving the amplitude spectrum with a smoothing operator, a procedure routinely followed by most people who use the Fourier amplitude spectrum or power spectral density functions. This smoothing procedure was followed in the examples which follow.

3.2 FREQUENCY CHARACTERISTICS OF THE BPF LINE STATIONS

Stations of the BPF line (BPF 601 - BPF 606) which recorded the Boxcar event were selected for Fourier analysis. These six stations are approximately in-line with the Boxcar source, and represent one of the travel paths at NTS which is relatively simple geologically. These stations were selected to determine the effect of the progressive increase in source-recording station distance (22.2 - 79.1 km) on the propagating elastic wave modes generated by Boxcar. The source is a constant for this analysis. The station factor can probably be considered to be approximately constant, as all BPF stations are located on hard rock (station 601 is located on rhyolite, others are on bedded or welded tuff.)

Figure 3-1 pictures the radial component of particle velocity for each of the six BPF stations. Three non-overlapping wave mode windows are shown for each radial component waveform. The

Figure 3-1. Wave Mode Windows of the Radial Component Particle Velocity Seismograms Recorded by the BPF Stations - Boxcar Event

P wave window begins with the first arrival on the seismogram and ends at the onset time of the first S wave. The S wave window begins with the onset of the S wave and ends with the onset time of the surface wave. The surface wave window begins with the onset of the surface wave motion and continues until all significant excursions diminish. These wave mode windows are necessarily generalized and vary in length and complexity according to: 1) the distance of the station from the source, 2) the station site geology, and 3) the many complex geological and geophysical parameters of the earth's crust which impress their signature upon the propagating waves. The P wave window, for example, contains the direct wave, the wave critically refracted from the M discontinuity, and the reflection from the M discontinuity, in an order which depends upon the source-station distance. Other reflections and refractions from shallower geological and geophysical interfaces are also present. In addition, converted waves (waves which travel almost the entire propagation path as a P or S wave and then convert to the other wave type) may be present also and would be part of the P wave window. Except for converted waves, the makeup of the S wave window would be analogous to the P wave window. All three windows, P, S and surface wave, however, may be complexly affected by reverberation of body waves between shallow near-surface layers.

The smoothed Fourier amplitude spectra for each of the three wave mode windows and the total seismogram window (beginning of P wave window to end of surface wave window) are shown in Figure 3-2. The basis conclusions which these data provide are as follows:

- ① The maximum amplitude of the P, S, and surface wave mode window amplitude spectra occurs at different frequencies; approximately 0.8 Hz for the P wave window spectra, 0.5 Hz for the S wave window spectra, and 0.25 Hz for the surface wave window spectra. This phenomenon is related to the well known fact that the various elastic wave types propagate with different wave velocities and, consequently, different characteristic frequencies.
- ② The maximum amplitude occurs at essentially the same frequency for each of the three wave mode window spectral sets. That is, the loss of high frequency through the low pass filtering action of the earth is essentially insignificant over this distance range (22.2 - 79.1 km), a relationship noted by Werth, et. al. (1963).
- ③ The spectral bandwidth (defined as the spectral width at the 6 db attenuation points) varies both with wave mode time window and with station distance. The S wave window has the largest spectral bandwidth, approximately 1.0 - 1.7 Hz. The spectral bandwidths of the P and surface wave windows are approximately 0.85 Hz and 0.31 Hz, respectively. The spectral bandwidth varies unsystematically with distance. Also, the Fourier amplitude is larger in some cases at greater distances than at shorter distances. These examples of variability reflect the influence of the variation in physical properties along the transmission path and at the station sites on the propagating waves.

3.3 FREQUENCY CHARACTERISTICS OF THE BEATTY (HR) SEISMOGRAMS

Seismograms recorded at the Beatty (HR) station for the five events were selected for Fourier analysis. The objective of this analysis was to determine the variation in the amplitude spectra caused by the range in yield and the differences, if any, in the source environment parameters (Yucca Flat versus Pahute Mesa).

Figure 3-2. Smoothed Fourier Amplitude Spectra of Identified Wave Mode Windows, BPF Stations - Boxcar Event

The source-station distance is comparable (50.6 - 66.4 km) for all five events. The station factor is roughly equivalent for all seismograms, varying only in accordance with the sequence and angle of incidence of the various wave arrivals.

Figure 3-3 shows the radial component of particle velocity recorded by the Beatty (HR) station. The wave mode windows are identified on each seismogram waveform.

The smoothed amplitude spectra for each of the three wave mode windows and the total seismogram window are shown in Figure 3-4. The data on this figure support the following conclusions:

- The frequency of the maximum amplitude of each wave mode window spectrum varies with yield. The greatest amplitude correlates with the highest yield. The frequency of the maximum amplitude varies with yield; shifting progressively to the low end of the frequency spectrum with increase in yield, as noted by Lynch (1969) and others.
- The P, S, and surface wave mode windows exhibit amplitude spectra which peak at distinctively different spectral frequencies. The P wave window spectral peak occurs between 0.85 - 1.0 Hz with the lowest value of frequency correlating with the highest yield event. The S wave window spectral peak occurs between 0.35 - 0.65 Hz and the surface wave window spectral peak occurs between 0.35 - 0.50 Hz, also with the lowest value of frequency correlating with the highest yield event, Boxcar.
- The amplitude spectra from Pahute Mesa events (Boxcar, Rickey, and Stinger) exhibit different attenuation characteristics than the spectra obtained from Yucca Flat (Zaza and Lanpher) events. The amplitude of the wave mode window spectra for Pahute Mesa events decays more

Figure 3-3. Wave Mode Windows of the Radial Component Particle Velocity Seismograms Recorded at Beatty (HR)

Figure 3-4. Smoothed Fourier Amplitude Spectra

rapidly than Yucca Flat event spectra for frequencies between the peak spectral frequency and 3.0 Hz and less rapidly between 3.0 - 8.0 Hz. The explanation for this phenomenon must lie in basic differences in the geological and geophysical parameters of the source environment as well as in the transmission path to Beatty.

3.4 FREQUENCY CHARACTERISTICS OF THE TONOPAH SEISMOGRAMS

Seismograms recorded at the two Tonopah stations (Church and Motel) were Fourier analyzed to determine the variation in the amplitude spectra caused by differences in yield and in the source environment (Yucca Flat versus Pahute Mesa) for the five events. The source-station distance, which ranges from 109.3 - 149.2 km, is approximately constant for each of the two source environment data sets; i.e., 109.3 - 120.0 km for Pahute Mesa events and 147.6 - 149.2 km for Yucca Flat events. Thus, within each data set, the station factor is approximately constant.

Figures 3-5 and 3-6 show the radial component particle velocity seismograms recorded at Tonopah Church and Tonopah Motel respectively. Tonopah Church is a hard rock station, whereas Tonopah Motel is located on a tailings pile, approximately 30 feet in thickness, directly across the street from the Church station (i.e., the two stations are only 450 feet apart). Wave mode time windows are identified on each of the seismograms.

p3466

The smoothed amplitude spectra for each of the three wave mode windows are shown in Figures 3-7 and 3-8 for Tonopah Church and Tonopah Motel respectively. The data of these figures support

Figure 3-5. Wave Mode Windows of the Radial Component Particle Velocity Seismograms Recorded at Tonopah (Church)

Figure 3-6. Wave Mode Windows of the Radial Component Particle Velocity Seismograms Recorded at Tonopah (Motel)

Figure 3-7. Smoothed Fourier Amplitude Spectra of Identified Wave Mode Windows, Station - Tonopah (Church)

Figure 3-8. Smoothed Fourier Amplitude Spectra of Identified Wave Mode Windows, Station - Tonopah (Motel)

the following conclusions:

- The seismograms of both Tonopah stations have spectra with higher amplitudes at the high frequency end of the spectrum than those recorded at Beatty or the BPF line stations.
- The Motel seismograms have wave mode spectra with higher amplitudes at the high frequency end of the spectrum than the Church seismograms; this phenomenon reflects the natural resonance condition of the Motel site favoring high frequencies (Davis and Murphy, 1967).
- The body wave (P and S) amplitude spectra are quite different at Motel from those of Church even though the travel paths from source to station are virtually identical. The surface wave spectra are quite similar, by contrast. These differences in the body wave amplitude spectra illustrate the effect which the presence or absence of a thin (30 feet) surface layer can have on the amplitude spectra of ground motion caused by body waves. The similarity of the surface wave spectra shows that the characteristic wavelength of the surface wave at these propagation distances is much greater than the dimensions of the thin layer at the Motel site; therefore, the layer has negligible effect on the surface wave spectra.
- The peak spectral amplitude occurs at different frequencies as a function of the yield, the specific wave mode windows analyzed, and the recording site. The peak amplitude increases as the yield increases and shifts slightly toward the low frequency end of the spectrum. The Church amplitude spectra show spectral peaks at 1.0 - 1.25 Hz for the P wave window, 0.80 - 1.12 Hz for the S wave window, and 0.25 - 0.40 Hz for the surface wave window. The Motel spectra, by contrast, have spectral peaks for corresponding wave mode windows at 1.35 - 6.45 Hz, 0.80 - 6.45 Hz and 0.25 - 0.40 Hz respectively. The P wave window spectra of Motel are characterized by several nearly equal spectral peaks, especially for the Pahute Mesa events, representing the response of the layer to several input pulses corresponding to the various wave modes.

- The amplitude decay characteristics of the Tonopah Church spectra vary with the wave mode window under consideration and the geological province. The amplitude decays 20 db (a factor of 10) from the peak spectral amplitude more rapidly with increase in frequency for the Yucca Flat events than for the Pahute Mesa events. The 20 db amplitude decay is most rapid for the surface wave window, and is followed by the S and P wave windows in that order with Yucca Flat event spectra decaying more rapidly. The difference in decay rate between spectra of the two geological provinces is related to the longer travel path to Tonopah for the Yucca Flat events, whereas the difference in decay rate of the various wave mode windows is complexly related to factors such as the characteristic wavelengths of the pulses making up the time window and the order and number of discrete wave arrivals in each wave mode window.

In summary, many physical processes and factors contribute to the observed differences in the amplitude spectra of selected wave mode windows. These variables, which control the shape of the wave form measured at a seismograph station and, consequently, the characteristics of the amplitude spectrum, may be summarized as follows:

1. the shape of the original pulse, especially as affected by the yield of the event;
2. the geological and geophysical parameters of the source region which affect the coupling of energy into the elastic region;
3. geometrical spreading of the propagating elastic wave types;

4. differential frequency dependent absorption of the propagating elastic wave types by an inhomogeneous, anisotropic and imperfectly elastic earth;
5. the influence of geological and geophysical parameters along the transmission path (as for example, a major fault zone);
6. local geological and geophysical parameters at the station site which cause wave reverberation, interference, and natural resonance conditions to occur.

Much additional work remains to be done to advance the understanding of the effect of these variables on the amplitude spectra recorded from underground nuclear explosions.

CHAPTER 4

SUMMARY AND RECOMMENDATIONS FOR ADDITIONAL STUDY

The analyses of this report provides additional physical insight into the amplitude and frequency composition of observed ground motion. The physical influence of varying geological and geophysical parameters at the energy source, along the transmission path, and at the site of the recording station on the amplitude and frequency characteristics of ground motion is demonstrated to be very complex. A preliminary determination of the correlation of the amplitude and frequency characteristics of ground motion and specific elastic wave types (P, S, and surface waves) is made for seismic data observed from 5 Nevada Test Site events (Boxcar, Rickey, Stinger, Zaza and Lanpher). These results enhance the ability to identify and to predict the important characteristics of ground motion resulting from underground nuclear explosions.

4.1 SUMMARY

The basic analyses and the results described in the preceding chapters are summarized below.

1. Amplitude Characteristics of Elastic Wave Types

The peak (vector) particle velocity of six body wave phases (direct P, direct S, refracted P, refracted S, reflected P, and

reflected S) and one surface wave (Rayleigh) was determined from examination of seismograms from three Pahute Mesa (Boxcar, Rickey, and Stinger) and two Yucca Flat (Zaza and Lanpher) underground nuclear explosions. Multiple regression analyses were performed to relate the amplitude of a specific elastic wave type to yield and the source-station distance. These analyses lead to the following conclusions:

- ① The various elastic wave types behave differently over the distance range considered (4.4 - 528.0 km). The behavior is complexly related to source, transmission path, and recording site variables.
- ② The surface wave and the direct P and S wave types scale more directly with yield (i.e., the yield exponent is closer to unity) than the refracted and reflected body wave types. The latter four wave types appear to scale in approximately the same manner with yield (i.e., the yield exponent is approximately 0.6).
- ③ Each of the elastic wave types attenuate differently with distance. Within each body wave subset, the refracted wave attenuates most rapidly and the reflected wave least rapidly with distance. The surface wave attenuates at about the same rate as the reflected wave over the distance range considered.

2. Frequency Characteristics of Elastic Wave Types

The frequency characteristics of three wave mode time windows (i.e., P, S, and surface wave) were determined by use of the Fourier transform for selected stations recording the Boxcar, Rickey, Stinger, Zaza, and Lanpher events. Selection of these stations, which included the BPF line, Beatty, Tonopah Church, and

Tonopah Motel, permitted the station site variables (geophone-earth coupling, instrument response, and the geological and geophysical parameters of the near surface materials underlying the station) to be considered as a constant for analyses involving a common station. The following results were obtained:

- The P, S, and surface wave mode time windows have amplitude spectra which exhibit maxima at different spectral frequencies for stations on hard rock; approximately 0.85-1.0 Hz for the P wave window, 0.35-0.65 Hz for the S wave window, and 0.35-0.50 Hz for the surface wave mode window. (Note: slightly higher values occur for the Tonopah Church station).
- The body wave (P and S) amplitude spectra for Tonopah Motel are quite different than those for Tonopah Church, even though the travel paths from source to station are virtually identical. The surface wave spectra are quite similar, by contrast. P and S wave mode window spectra for Tonopah Motel have spectral peaks at 1.35-6.45 Hz and 0.80-6.45 Hz respectively as compared to spectral peaks at 1.0-1.25 Hz and 0.80-1.12 Hz for Tonopah Church. Surface wave window spectral peaks occur at 0.25-0.40 Hz for both Tonopah stations. The difference in the body wave spectra illustrate the significant effect which the presence or absence of a thin (30 feet) surface layer can have on the amplitude spectra of ground motion caused by body waves. The similarity of the surface wave spectra shows that the characteristic wavelength of the surface wave at these propagation distances is much greater than the dimensions of the thin layer at Tonopah Motel and, consequently, is not significantly affected.
- The frequency of the peak spectral amplitude of each wave mode window spectrum varies with yield. The greatest amplitude correlates with the highest yield; the frequency of the peak spectral value shifts progressively to the low frequency end of the spectrum with increase in yield.
- The maximum spectral amplitude occurs at essentially the same frequency for each of the three wave mode spectral sets. Thus, the loss of high frequencies by the low pass

filtering action of the earth is essentially insignificant over the distance range (22.2-79.1 km) considered in this report.

- The amplitude spectra from Pahute Mesa events exhibit spectral attenuation characteristics for each wave mode which are different from corresponding spectra of Yucca Flat events. The Pahute Mesa spectra attenuate more rapidly for frequencies between the peak spectral frequency and 3.0 Hz and less rapidly between 3.0-8.0 Hz.
- The spectral bandwidth (bandwidth in frequency at the 6 db attenuation points) varies complexly both with yield and distance reflecting the effect of transmission path and source variables. A typical range of values observed at Beatty (HR) is: P wave window; 1.0-2.0 Hz, S wave window; 0.5-1.2 Hz, surface wave window; 0.2-0.5 Hz.

4.2 RECOMMENDATIONS FOR ADDITIONAL STUDY

The objective of the wave mode study is to develop the capability to predict the amplitude and frequency characteristics of ground motion in terms of specific elastic wave types, ground motion parameters, source parameters, and station site geology. Continued development of the study to meet the stated objective will be accomplished by application of a continuous feedback loop study process. Figure 4-1 illustrates this process schematically. Each phase of the developing study builds on results of earlier phases. At the same time, each new phase provides data which continuously update, correct, and refine the accomplishments of earlier phases. This process guarantees internal consistency of results. Also, it should be noted that this process permits certain elements of individual phases to be developed in parallel

Figure 4-1. Sequence of Steps in the Development of the Wave Mode Study

with the development of other phases and incorporated at the appropriate time.

Some of the subjects recommended for future detailed study in order to extend the statistical basis of the results of this report and to attain the primary objective are:

1. the amplitude and frequency characteristics of elastic wave types at close-in distances (0-40 km);
2. the amplitude and frequency characteristics of elastic wave types measured at selected stations (Tonopah, NRDS, SE-6, Beatty, etc.) from a large number of events;
3. the amplitude and frequency characteristics of the reflected and refracted waves for NTS data in the region between the initial point and the critical distance (60-150 km);
4. mechanisms for generation of surface waves and the dispersion characteristics of surface waves over a distance range of about 550 km;
5. the value of the frequency and medium dependent loss parameter and its relation to seismic wave absorption and scattering for NTS data;
6. the significance of converted wave modes on seismograms of underground nuclear explosions.

Emphasis will continue to be placed on developing results which will be useful to other continuing studies such as; synthetic seismograms, analysis of seismic anomalies, amplification of ground motion, and individual event post-shot reports. Specific application will be made to predictions of ground motion to the extent possible.

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