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BUGGY

MASTER

ANALYSIS OF
GROUND MOTION

Issuance Date: December 12, 1969

Environmental Research Corporation
Alexandria, Virginia

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ANALYSIS OF GROUND MOTION**BUGGY I EVENT**

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ABSTRACT

The Buggy I event was a Plowshare nuclear row-charge cratering experiment detonated in Area 30, on the Nevada Test Site. Seismic ground motions from Buggy I were monitored by the USC&GS. Data processing and post-shot analyses were performed by ERC.

The close-in (< 12 km) Buggy I seismic data have been analyzed to determine if any azimuthal asymmetries are present in the seismic radiation pattern. The conclusion, based on peak amplitude, BPF amplitude and energy density data, is that no measurable asymmetries are in evidence in the seismic data.

The distant seismic data from Buggy I have been compared with measurements from previous tests to determine if a single equivalent charge could be postulated for prediction purposes. It is concluded that the Buggy I data are unlike those expected on the basis of a single charge cratering experiment and are very similar to those which would be expected from a single contained shot with the yield of one of the elements of the Buggy I row.

CHAPTER 1

INTRODUCTION

1.1 GENERAL BACKGROUND

Project Buggy I was a nuclear row-charge cratering experiment conducted on Chukar Mesa in the central portion of Area 30 on the Nevada Test Site. It was one of a series of experiments being conducted by the Atomic Energy Commission as part of the Plowshare Nuclear Excavation program, the objective of which is the development of a technology of nuclear explosives as a tool for civil excavation projects.

The Buggy I site occupies a topographic flat at an elevation of about 5,200 feet on the flank of Forty Mile Canyon. Overburden material varies in thickness from about 4.5 to 10 feet near the site location (Lutton and Hunt, 1967). Basalt flows with small amounts of soil, tuff, rhyolite, and breccia are interlayered to form the site media. The upper basalt unit is about 330 feet thick and consists of five flows ranging in thickness about 15 to 145 feet separated by thin zones of breccia. Each flow characteristically consists of a dense unit with less than five percent porosity grading upward to a vesicular basalt with as much as 30 to 40 percent porosity (Tewest, 1967).

The gently dipping strata at the site have been subjected to mild fault deformation and extensive jointing.

Buggy I was detonated on March 12, 1968. The experiment consisted of five nuclear explosives of 1.1 kt each, at a depth of 135 feet, spaced 150 feet apart. The line of charges was on a true bearing of about S 70° E. The Nevada State coordinates of the end charges were N 821,828; E 586,631, and N 822,040; E 586,070.

1.2 OBJECTIVES AND SCOPE OF THE POST-SHOT REPORT

Environmental Research Corporation, under contract to the Nevada Operations Office (NVOO) of the U.S. Atomic Energy Commission, is responsible for providing pre- and post-shot safety evaluations of selected nuclear events. Responsibilities pertaining to Buggy I were to provide the Effects Evaluation Division of the USAEC/NVOO with the following:

1. An instrumentation plan designed to monitor ground motions.
2. Predictions of ground motion at each proposed instrument station to determine the optimum recording level of the seismic instruments.
3. Post-shot processing of seismic data (time-histories, band-pass filtering, etc.).
4. Post-shot analysis of seismic data comparing Buggy I results with predicted ground motions and with results of other similar or related experiments.

The primary objectives of this post-shot report are to present amplitude and frequency characteristics of ground motions generated by a nuclear multiple-charge cratering experiment and to compare these characteristics with the results of single-charge cratering and single-charge contained experiments.

Material presented in Chapters 2 and 3 includes the data and the analyses which have been carried out. Chapter 2 contains descriptions of the instrumentation employed for the Buggy I experiment and discussions of the types of data utilized in the analyses. Chapter 3 describes analyses performed to determine the asymmetry effects of Buggy I at relatively close-in distances and the amplitude and frequency characteristics of ground motions recorded at more distant stations. Both peak amplitude and amplitude-frequency (band-pass filter) spectra were utilized in the analyses. Although a completely suitable close-in data sample was not available from Buggy I, the results of the asymmetry investigation indicate an absence of asymmetric ground motions. The analysis of the longer distance data includes comparisons with ground motion data from the single-charge cratering experiment Cabriolet and with data from single-charge contained events. The comparative analysis indicates a pronounced similarity between the results of Buggy I and the results of a single-charge contained event with a yield less than the combined yield of the

five Buggy I charges. The significant conclusions drawn from the Buggy I ground motion analyses are summarized in Chapter 4.

1.3 REVIEW OF INTERFERENCE EFFECTS

A basic question raised by the Buggy I experiment (and repeatedly raised by row-charge experiments in general) pertains to whether row-charge seismic motions can be reliably predicted by adding the motions, with appropriate phase adjustments, which result from the individual charges constituting the row. An analysis of the results of the Dugout HE experiment (Loux and Murphy, 1968) did not lead to firm conclusions with regard to this question although hydrodynamic considerations suggested that direct addition of the motions from individual charges to obtain the total seismic motions of the row is invalid. Because the hydrodynamic considerations applied to the analysis of Dugout results are equally pertinent to the Buggy I experiment, the fundamental ideas are reviewed here.

1.3.1 Hydrodynamic Considerations

Usually, individual charges of a row detonation are deliberately spaced so that intersection of the expanding stress fronts reinforces the pressures by more than simple addition. The intersections of the fronts occur at angles increasing from 0° at initial intersection to 180° at longer distances and time.

Thus, the nature of the reinforcement may also change during the process, with strong possibilities of discontinuous shock fronts such as the "Mach reflections" found in some metals by Fowles and Isbell, (1965).

The hydrodynamic calculations of the non-linear interactions of shock fronts are identical in principle to the calculations presented in the Interoceanic Canal Ground Motion Report, (ERC, 1967). The calculations, in three sequential steps, are described as follows:

1. A one-dimensional hydrodynamic calculation with spherical symmetry from which particle velocities at one-fourth the charge spacing were used as input to the next calculation.

2. A two-dimensional calculation with cylindrical symmetry (along the axis of the row) and a fixed surface at the plane midway between charges from which particle velocities at a radius of one-half the charge spacing were used as input to the third calculation.

3. A two-dimensional calculation in a plane perpendicular to the line of charges and having a free surface at ground level.

Details of the calculation are not sufficiently realistic that output numbers may be used with confidence (for example, all plastic-brittle effects are ignored). However, two qualitative conclusions for a row-charge have been fully confirmed by experiment:

1. Particle motions as calculated from the first two stages exhibit approximate symmetry about the charge axis and hence produce a straight, uniform channel.

2. Particle motions at and near the ground surface are significantly more horizontal than those calculated for single charge craters.

A third quantitative conclusion, not supported by experiment, is that particle velocities broadside to the row are roughly 50% larger than expected from a single charge. Data from Buggy I suitable for comparison with hydrodynamic model calculations were not available.

1.3.2 Linear Considerations

Linear theory assumes independent seismic waves originating on spherical surfaces surrounding each charge. These waves are non-interacting and may be added directly by taking into account their appropriate phase differences. The phase differences are

least broadside to the row and greatest in-line with the row, leading to asymmetries which should remain, in theory, for infinite distances. Other ground motion characteristics caused by variations in the earth's seismic transmission paths can make it difficult at longer distances, to distinguish the asymmetries caused by the source configuration.

Close-in Buggy I data were examined for asymmetry effects. The material presented in Chapter 3 relative to possible asymmetry effects includes a discussion of interference phenomena expected on the basis of strictly linear theory.

CHAPTER 2

COLLECTION AND PROCESSING OF BUGGY I SEISMIC DATA

2.1 INSTRUMENTATION

The instrumentation plan for Buggy I was designed with the following objectives in mind:

1. To provide seismic data suitable for the delineation of any asymmetries in the seismic radiation pattern.
2. To produce seismic data suitable for comparison with data collected previously from single charge cratering and contained events.

To accomplish these objectives, seismic instruments were located (1) on two lines radiating from the event (one perpendicular and the other in-line with the row of charges), (2) on an arc south and west of the site, and (3) at stations which have recorded a number of other events. Figure 2-1 shows the location of the instruments on the arc and the two radiating lines, while Figure 2-2 shows the location of instruments which have recorded other events. Table 2-1 provides important station information including identification of the station abbreviations used in Figures 3-7 and 3-8.

Figure 2-1. Map Showing Close-in Instrument Stations for the Buggy I Event.

Figure 2-2. Map Showing Distant Instrument Stations for Buggy I Event.

TABLE 2-1. SUMMARY OF BUGGY I INSTRUMENT STATIONS

Station	Station Abbreviation	Station Environment	Instrument Type	Horizontal Distance (km)	Angle From Row Charge Axis
441	---	Hard Rock	L-7	2.69	90°
447	---	" "	L-7	2.69	0°
456	---	" "	L-7	2.69	75°
461	---	" "	L-7	2.69	0°
458	---	" "	L-7	2.97	45°
459	---	" "	L-7	2.98	31°
443	---	" "	L-7	6.37	85°
449	---	" "	L-7	6.37	0°
444	---	" "	L-7	11.1	75°
450	---	" "	L-7	11.1	0°
CP-1	---	" "	L-7	30.5	7°
Beatty	B	Alluvium	L-7	36.0	39°
SE-2	---	Hard Rock	L-7	83.0	15°
454	---	" "	L-7	99.5	88°
Alamo	ALH	" "	NC-21	115.0	40°
Alamo	ALA	Alluvium	NC-21	115.0	40°
SE-4	---	"	L-7	116.0	18°
Tonopah Church	TCH	Hard Rock	NC-21	139.0	39°
Tonopah South St.	TSS	" "	L-7	139.0	39°
Tonopah Motel	TMT	Alluvium	NC-21	139.0	39°
SE-6 (Las Vegas)	---	"	NC-21	150.0	20°
SE-6 (Las Vegas)	---	"	L-7	150.0	20°

The U. S. Coast & Geodetic Survey was responsible for the deployment of Buggy I instruments. Two types of instruments were used; (1) NC-21 velocity meters and (2) L-7 velocity meters, both of which record three orthogonal components of particle velocity on magnetic tape. Table 2-2 shows the frequency range over which the effective amplitude response of these instruments is flat, (USC&GS, 1967; USC&GS, 1968).

TABLE 2-2. FREQUENCY RANGE OF RECORDED GROUND MOTION DATA AFTER PROCESSING.

Instrument Type	Frequency Range, Hz	
	Low	High
NC-21	1.0**	45*
L-7	0.1	45*

*Varies with filter setting.

**0.3 Hz after application of an analog correction circuit.

2.2 CALCULATION OF PEAK AMPLITUDES FROM SEISMOGRAMS

Acceleration and displacement traces are derived by differentiation and integration of the velocity traces with respect to time. Peak values of ground motion are determined for each component of recorded ground motion. In addition, peak values of the magnitude of the resultant vector motion are obtained.

The peak values of the vertical (Z), radial (R), and transverse (T) component and the peak resultant vector (V) of acceleration,

displacement, and velocity are tabulated in Tables 2-3 through 2-8. Arrival time data are given in these tables where the times are measured from shot time. Arrival time data given in parentheses represent time after first motion. The period data listed in the tables are periods associated with the peak amplitudes which have been measured visually on the paper records.

2.3 BAND-PASS FILTER DATA

Band-pass filtering of a seismogram is a technique developed to analyze the peak particle velocity recorded from nuclear events as a function of frequency. The velocity traces of a seismogram are passed through twelve narrow band-pass filters to obtain information relating to the frequency content of the seismic signal. A discussion of the filter characteristics can be found in Lynch (1965). The peak amplitude of the output from each filter is plotted as a function of the center frequency of the filter and the points are connected, giving a continuous curve called the BPF curve. Band-pass filter curves from the Buggy I event are shown on Figures 2-3 through 2-7.

TABLE 2-3. PEAK SURFACE ACCELERATION AT STATIONS ON HARD ROCK

STATION/ INSTRUMENT	DISTANCE (km)	FIRST ARRIVAL TIME (sec)	COMPONENT	PEAK ACCELERATION (g)	TIME OF PEAK (sec)	PERIOD (sec)
441 L-7	2.69	0.80	Z	2.51×10^{-2}	1.65	0.20
		0.80	R	3.93×10^{-2}	2.65	0.48
		0.80	T	2.67×10^{-2}	2.96	0.30
			V	4.55×10^{-2}	1.65	--
443 L-7	6.37	1.80	Z	6.18×10^{-3}	17.36	0.14
		1.80	R	5.94×10^{-3}	31.90	0.06
		1.80	T	8.21×10^{-3}	18.80	0.21
			V	1.02×10^{-2}	31.90	--
444 L-7	11.1	2.90	Z	2.89×10^{-3}	16.25	0.26
		2.90	R	2.78×10^{-3}	16.05	0.25
		2.90	T	2.03×10^{-3}	16.25	0.21
			V	3.22×10^{-3}	16.20	--
450 L-7	11.1	2.70	Z	2.22×10^{-3}	21.35	0.19
		2.70	R	2.63×10^{-3}	21.43	0.25
		2.70	T	2.92×10^{-3}	21.45	0.33
			V	2.95×10^{-3}	22.76	--
Alamo NC-21	115.0	--	Z	5.38×10^{-5}	(6.71)	0.27
		--	R	5.87×10^{-5}	(3.29)	0.35
		--	T	4.56×10^{-5}	(19.08)	0.60
			V	6.07×10^{-5}	(6.70)	--
Tonopah Church NC-21	139.0	--	Z	1.63×10^{-4}	(0.45)	0.25
		--	R	1.57×10^{-4}	(2.40)	--
		--	T	1.48×10^{-4}	(2.20)	0.05
			V	1.89×10^{-4}	(0.45)	--
Tonopah South St. L-7	139.0	25.90	Z	2.19×10^{-4}	26.43	0.27
		25.90	R	1.53×10^{-4}	27.45	0.25
		25.90	T	1.05×10^{-4}	26.63	0.17
			V	2.28×10^{-4}	26.43	--

TABLE 2-4. PEAK SURFACE ACCELERATION AT STATIONS ON ALLUVIUM

STATION/ INSTRUMENT	DISTANCE (km)	FIRST ARRIVAL TIME (sec)	COMPONENT	PEAK ACCELERATION (g)	TIME OF PEAK (sec)	PERIOD (sec)
Beatty L-7	36.0	7.40	Z	9.14×10^{-4}	14.60	0.22
		--	R	--	--	--
		--	T	--	--	--
			V	--	--	--
Alamo NC-21	115.0	--	Z	6.97×10^{-5}	(6.90)	0.25
		--	R	1.17×10^{-4}	(11.53)	0.30
		--	T	1.10×10^{-4}	(10.86)	0.35
			V	1.21×10^{-4}	(11.50)	--
SE-4 L-7	116.0	20.00	Z	8.43×10^{-5}	20.38	0.20
		20.00	R	6.66×10^{-5}	23.57	0.15
		20.00	T	5.90×10^{-5}	23.55	0.21
			V	9.41×10^{-5}	22.35	--
Tonopah Motel NC-21	139.0	--	Z	2.06×10^{-4}	(0.62)	0.27
		--	R	2.07×10^{-4}	(1.05)	0.25
		--	T	--	--	--
			V	2.37×10^{-4}	(0.60)	--
SE-6 NC-21	150.0	--	Z	9.26×10^{-5}	(1.30)	0.20
		--	N/S	7.98×10^{-5}	(20.74)	0.43
		--	E/W	7.83×10^{-5}	(21.21)	0.41
			V	9.26×10^{-5}	(1.35)	--
SE-6 L-7	150.00	26.30	Z	9.50×10^{-5}	27.52	0.15
		26.30	N/S	7.60×10^{-5}	46.80	0.25
		26.30	E/W	8.83×10^{-5}	47.93	0.43
			V	9.90×10^{-5}	27.52	--

TABLE 2-5. PEAK SURFACE DISPLACEMENT AT STATIONS ON HARD ROCK

STATION/ INSTRUMENT	DISTANCE (km)	FIRST ARRIVAL TIME (sec)	COMPONENT	PEAK DISPLACEMENT (cm)	TIME OF PEAK (sec)	PERIOD (sec)
441	2.69	0.80	Z	1.63×10^{-1}	2.52	0.82
L-7		0.80	R	4.62×10^{-1}	2.57	1.03
		0.80	T	2.35×10^{-1}	3.80	0.74
			V	4.80×10^{-1}	2.57	--
461	2.69	--	Z	1.03×10^{-1}	(0.81)	2.16
L-7		--	R	2.40×10^{-1}	(2.49)	0.80
		--	T	1.47×10^{-1}	(2.86)	0.73
		--	V	2.68×10^{-1}	(2.49)	--
458	2.97	1.20	Z	8.51×10^{-2}	2.70	0.75
L-7		1.20	R	1.84×10^{-1}	5.10	0.60
		1.20	T	1.90×10^{-1}	3.49	0.80
			V	2.22×10^{-1}	5.10	--
459	2.98	1.10	Z	6.44×10^{-2}	8.60	0.58
L-7		1.10	R	1.84×10^{-1}	2.45	0.96
		1.10	T	1.71×10^{-1}	3.22	0.87
			V	1.85×10^{-1}	2.47	--
443	6.37	1.80	Z	2.86×10^{-2}	21.05	1.20
L-7		1.80	R	3.45×10^{-2}	18.35	3.96
		1.80	T	2.87×10^{-2}	20.30	0.90
			V	3.73×10^{-2}	22.00	--
449	6.37	2.00	Z	3.38×10^{-2}	10.20	0.95
L-7		2.00	R	5.35×10^{-2}	12.10	1.08
		2.00	T	5.18×10^{-2}	12.30	2.23
			V	7.06×10^{-2}	11.60	--
444	11.1	2.90	Z	1.07×10^{-2}	21.57	1.05
L-7		2.90	R	1.05×10^{-2}	19.45	2.30
		2.90	T	9.80×10^{-3}	21.65	0.73
			V	1.45×10^{-2}	21.61	--
450	11.1	2.70	Z	1.24×10^{-2}	31.40	1.10
L-7		2.70	R	1.64×10^{-2}	25.30	1.60
		2.70	T	1.55×10^{-2}	28.13	1.00
			V	1.98×10^{-2}	25.40	--

STATION/ INSTRUMENT	DISTANCE (km)	FIRST ARRIVAL TIME (sec)	COMPONENT	PEAK DISPLACEMENT (cm)	TIME OF PEAK (sec)	PERIOD (sec)
CP-1	30.5	5.60	Z	2.74×10^{-3}	21.58	2.75
L-7		5.60	R	3.60×10^{-3}	21.68	1.60
		5.60	T	2.28×10^{-3}	21.30	2.00
			V	4.34×10^{-3}	21.68	--
454	99.5	18.30	Z	3.59×10^{-4}	47.47	2.49
L-7		18.30	R	3.74×10^{-4}	27.95	4.52
		18.30	T	3.98×10^{-4}	60.23	1.80
			V	5.26×10^{-4}	60.30	--
Alamo	115.0	--	Z	3.39×10^{-4}	(27.11)	1.63
NC-21		--	R	6.02×10^{-4}	(29.00)	0.75
		--	T	5.21×10^{-4}	(20.82)	1.12
		--	V	6.55×10^{-4}	(29.00)	--
Tonopah	139.0	--	Z	4.62×10^{-4}	(1.35)	0.12
Church		--	R	3.03×10^{-4}	(1.47)	0.75
NC-21		--	T	3.36×10^{-4}	(20.96)	0.87
		--	V	4.58×10^{-4}	(1.35)	--
Tonopah	139.0	25.90	Z	5.00×10^{-4}	26.43	0.29
South St.		25.90	R	3.93×10^{-4}	27.42	0.42
L-7		25.90	T	3.93×10^{-4}	57.84	5.29
			V	5.00×10^{-4}	26.42	-

TABLE 2-6. PEAK SURFACE DISPLACEMENT AT STATIONS ON ALLUVIUM

STATION/ INSTRUMENT	DISTANCE (km)	FIRST ARRIVAL TIME (sec)	COMPONENT	PEAK DISPLACEMENT (cm)	TIME OF PEAK (sec)	PERIOD (sec)
Beatty L-7	36.0	7.40	Z	3.43×10^{-4}	17.02	1.74
		--	R	--	--	--
		--	T	--	--	--
		--	V	--	--	--
Alamo NC-21	115.0	--	Z	3.04×10^{-4}	(6.91)	0.78
		--	R	5.79×10^{-4}	(31.15)	0.50
		--	T	7.60×10^{-4}	(18.10)	0.85
		--	V	7.60×10^{-4}	(18.15)	--
SE-4 L-7	116.0	20.00	Z	3.40×10^{-4}	22.35	0.73
		20.00	R	2.48×10^{-4}	47.00	1.70
		20.00	T	2.33×10^{-4}	40.95	0.85
		--	V	3.74×10^{-4}	22.32	--
Tonopah Motel NC-21	139.0	--	Z	5.90×10^{-4}	(0.60)	0.35
		--	R	4.10×10^{-4}	(1.02)	0.29
		--	T	--	--	--
		--	V	6.17×10^{-4}	(0.60)	--
SE-6 NC-21	150.0	--	Z	6.10×10^{-4}	(1.35)	0.70
		--	N/S	6.10×10^{-4}	(47.60)	1.25
		--	E/W	6.70×10^{-4}	(27.50)	1.90
		--	V	7.77×10^{-4}	(27.65)	--
SE-6 L-7	150.0	26.30	Z	6.36×10^{-4}	27.57	1.25
		26.30	N/S	7.56×10^{-4}	74.45	2.07
		26.30	E/W	5.68×10^{-4}	74.35	1.23
		--	V	9.27×10^{-4}	74.45	--

TABLE 2-7. PEAK SURFACE VELOCITY AT STATIONS ON HARD ROCK

STATION/ INSTRUMENT	DISTANCE (km)	FIRST ARRIVAL TIME (sec)	COMPONENT	PEAK VELOCITY (cm/sec)	TIME OF PEAK (sec)	PERIOD (sec)
441 L-7	2.69	0.80	Z	1.24×10^0	2.95	0.50
		0.90	R	2.57×10^0	2.25	0.78
		0.80	T	2.33×10^0	3.58	0.93
			V	3.06×10^0	3.58	--
447 L-7	2.69	0.90	Z	1.25×10^0	2.20	0.60
		0.90	R	1.38×10^0	3.80	0.53
		0.90	T	1.77×10^0	3.55	0.65
			V	2.02×10^0	3.55	--
456 L-7	2.69	1.10	Z	1.18×10^0	1.35	0.25
		1.10	R	1.45×10^0	2.43	0.92
		--	T	--	--	--
			V	1.60×10^0	2.40	--
461 L-7	2.69	--	Z	1.15×10^0	(2.58)	0.55
		--	R	2.30×10^0	(2.37)	0.67
		--	T	1.40×10^0	(2.85)	0.68
			V	2.53×10^0	(2.40)	--
458 L-7	2.97	1.20	Z	1.42×10^0	1.83	0.49
		1.20	R	1.74×10^0	4.94	0.55
		1.20	T	2.10×10^0	3.30	0.73
			V	2.17×10^0	4.92	--
459 L-7	2.98	1.10	Z	7.15×10^{-1}	1.60	0.28
		1.10	R	1.39×10^0	4.10	0.62
		1.10	T	1.36×10^0	3.15	0.78
			V	1.67×10^0	4.10	--
443 L-7	6.37	1.80	Z	2.03×10^{-1}	3.25	0.63
		1.80	R	1.69×10^{-1}	2.33	0.80
		1.80	T	2.99×10^{-1}	5.18	0.81
			V	3.13×10^{-1}	5.18	--
449 L-7	6.37	2.00	Z	3.20×10^{-1}	7.20	0.73
		2.00	R	3.61×10^{-1}	5.53	0.85
		2.00	T	3.60×10^{-1}	5.28	0.46
			V	4.18×10^{-1}	5.23	--

STATION/ INSTRUMENT	DISTANCE (km)	FIRST ARRIVAL TIME (sec)	COMPONENT	PEAK VELOCITY (cm/sec)	TIME OF PEAK (sec)	PERIOD (sec)
444 L-7	11.1	2.90	Z	1.31×10^{-1}	3.22	0.30
		2.90	R	1.09×10^{-1}	3.15	0.25
		2.90	T	8.72×10^{-2}	8.50	1.00
			V	1.69×10^{-1}	3.22	--
450 L-7	11.1	2.70	Z	1.02×10^{-1}	7.15	0.37
		2.70	R	1.15×10^{-1}	5.60	0.30
		2.70	T	1.23×10^{-1}	5.70	0.40
			V	1.39×10^{-1}	5.65	--
CP-1 L-7	30.5	5.60	Z	1.69×10^{-2}	6.35	0.22
		5.60	R	2.11×10^{-2}	16.85	0.62
		5.60	T	2.17×10^{-2}	7.62	0.30
			V	2.36×10^{-2}	16.85	--
454 L-7	99.5	18.30	Z	2.48×10^{-3}	19.68	0.32
		18.30	R	1.83×10^{-3}	35.49	0.58
		18.30	T	2.12×10^{-3}	33.75	0.60
			V	2.50×10^{-3}	19.45	--
Alamo NC-21	115.0	--	Z	2.73×10^{-3}	(27.45)	0.50
		--	R	4.37×10^{-3}	(28.85)	0.65
		--	T	4.20×10^{-3}	(19.50)	0.70
			V	4.61×10^{-3}	(19.55)	--
Tonopah Church NC-21	139.0	--	Z	7.08×10^{-3}	(0.70)	0.27
		--	R	3.48×10^{-3}	(1.65)	0.33
		--	T	3.66×10^{-3}	(20.95)	0.32
			V	7.47×10^{-3}	(0.70)	--
Tonopah South St. L-7	139.0	25.90	Z	8.75×10^{-3}	26.52	0.30
		25.90	R	5.53×10^{-3}	27.35	0.42
		25.90	T	3.93×10^{-3}	26.48	0.26
			V	9.46×10^{-3}	26.52	--

TABLE 2-8. PEAK SURFACE VELOCITY AT STATIONS ON ALLUVIUM

STATION/ INSTRUMENT	DISTANCE (km)	FIRST ARRIVAL TIME (sec)	COMPONENT	PEAK VELOCITY (cm/sec)	TIME OF PEAK (sec)	PERIOD (sec)
Beatty L-7	36.0	7.40	Z	3.42×10^{-3}	14.70	0.25
		--	R	--	--	--
		--	T	--	--	--
		--	V	--	--	--
Alamo NC-21	115.0	--	Z	3.34×10^{-3}	(9.40)	0.50
		--	R	7.13×10^{-3}	(10.70)	0.35
		--	T	6.54×10^{-3}	(18.35)	0.45
		--	V	7.55×10^{-3}	(19.85)	--
SE-4 L-7	116.0	20.0	Z	4.48×10^{-3}	22.70	0.45
		20.0	R	3.00×10^{-3}	24.53	0.38
		20.0	T	3.20×10^{-3}	37.85	0.50
		--	V	4.48×10^{-3}	22.70	--
Tonopah Motel NC-21	139.0	--	Z	9.77×10^{-3}	(0.70)	0.30
		--	R	7.41×10^{-3}	(1.70)	0.45
		--	T	--	--	--
		--	V	1.08×10^{-2}	(0.70)	--
SE-6 NC-21	150.0	--	Z	4.08×10^{-3}	(1.35)	0.70
		--	N/S	4.31×10^{-3}	(26.55)	0.80
		--	E/W	4.73×10^{-3}	(22.05)	0.45
		--	V	5.91×10^{-3}	(26.95)	--
SE-6 L-7	150.0	26.30	Z	6.00×10^{-3}	27.75	0.60
		26.30	N/S	4.69×10^{-3}	66.35	0.78
		26.30	E/W	4.88×10^{-3}	47.48	0.42
		--	V	6.02×10^{-3}	27.75	--

FIGURE 2-3. PEAK BAND-PASS FILTER PARTICLE VELOCITY VERSUS FREQUENCY

FIGURE 2-4. PEAK BAND-PASS FILTER PARTICLE VELOCITY VERSUS FREQUENCY

FIGURE 2-5. PEAK BAND-PASS FILTER PARTICLE VELOCITY VERSUS FREQUENCY

FIGURE 2-6. PEAK BAND-PASS FILTER PARTICLE VELOCITY VERSUS FREQUENCY

FIGURE 2-7. PEAK BAND-PASS FILTER PARTICLE VELOCITY VERSUS FREQUENCY

CHAPTER 3

COMPARISON AND ANALYSIS OF BUGGY I DATA

In this chapter, two aspects of the Buggy I seismic data are considered. First, data from the close-in stations are examined to determine if there are any asymmetries in the seismic radiation pattern which may be attributed to interference caused by the multi-element source array. The second portion of the analysis consists of a detailed comparison of the distant Buggy I data with appropriately scaled data from single cratering and single contained events.

3.1 INTERFERENCE CONSIDERATIONS

As referenced in Chapter 1, an earlier study of interference effects from the multi-element shot Dugout (Loux and Murphy, 1968) was inconclusive. It was shown that linear interference concepts could not apply exactly since it was apparent that energy radiated from the individual charges interacts in the non-linear region. The point of view was taken, however, that it is still of interest to determine to what extent these concepts provide insight into the problem of predicting seismic motion from row-charge events. In the conclusions of the Dugout report, it was noted that the results of the linear interference analysis had been inconclusive due, to some extent, to the lack of appropriate instrumentation.

The close-in instrumentation plan shown in Figure 2-1 of this report was recommended to provide more complete data for the Buggy I event.

3.1.1 Peak Amplitude Data

As the first step in an effort to determine if asymmetries exist in the seismic radiation pattern of the Buggy I experiment, the peak amplitude data are examined. The peak amplitude of recorded ground motion has historically provided an opportunity to perform economical parameter studies as the initial effort in a study program. If the results of the initial peak amplitude study appear to be significant, more detailed work typically follows.

Close-in peak motions recorded on the line of instruments perpendicular to the Buggy I row of charges (Stations 441, 443 and 444) and on the line of instruments in-line with the row of charges (Stations 447, 449 and 450) are examined (refer to the station location map, Figure 2-1, the tabulation of peak motions, Tables 2-3 through 2-8, and the peak amplitude graphs, Figures 3-8 and 3-9). The three stations on each line are located as pairs. Each pair of stations is equidistant from the center of the row of charges, e.g., Stations 441 and 447 are 2.69 km from the event, Stations 443 and 449 are 6.37 km from the event and Stations 444 and 450 are 11.1 km from the event. It is

evident from the peak amplitude data shown in Table 3-1 that no azimuthal variations of recorded peaks in the close-in distance ranges around Buggy I are indicated.

Although the peak amplitude results do not suggest any asymmetry in the seismic radiation pattern, consideration of the theory of seismic interference phenomena requires that the Buggy I amplitude-frequency spectra be examined to further evaluate the asymmetry effects of the experiment.

3.1.2 Amplitude-Frequency Data

Before examining the amplitude-frequency data, it is of interest to consider what might be expected on the basis of linear theory. If the problem were purely linear and the medium homogeneous, the superposition principle would hold. Harmonic components considered as originating at the individual sources could then be superposed at an arbitrary observation point using phase relations dictated by the spacing of the sources and the velocity of propagation in the medium. In this case, we would anticipate that some wavelengths would be in-phase while other wavelengths would be out-of-phase (with respect to the five sources) for a particular observation point. Consequently, we would expect an interference pattern which would be a function of wavelength and the location of the receiver relative to the orientation of the source array. That is, we would expect an

TABLE 3-1. COMPARISON OF PEAK AMPLITUDES RECORDED AT CLOSE-IN STATIONS
FROM THE BUGGY I EVENT

STATION		447	461	459	458	456	441	449	443	450	444
Distance (km)		2.69	2.69	2.98	2.97	2.69	2.69	6.37	6.37	11.1	11.1
Angle From Row Axis		0°	0°	31°	45°	75°	90°	0°	85°	0°	75°
Resultant Vector Peak Amplitude	Acceleration (g)	--	--	--	--	--	4.55×10^{-2}	--	1.02×10^{-2}	2.95×10^{-3}	3.22×10^{-3}
	Displacement (cm)	--	2.68×10^{-1}	1.85×10^{-1}	2.22×10^{-1}	--	4.80×10^{-1}	7.06×10^{-2}	3.73×10^{-2}	1.98×10^{-2}	1.45×10^{-2}
	Velocity (cm/sec)	2.02×10^0	2.53×10^0	1.67×10^0	2.17×10^0	1.60×10^0	3.06×10^0	4.18×10^{-1}	3.13×10^{-1}	1.39×10^{-1}	1.69×10^{-1}

asymmetric radiation pattern which should be discernable in the data.

Since the differences in distance between the receiver and the individual shots are smallest for stations located broadside (i.e., at 90°) to the orientation of the row, the broadside Buggy I stations (i.e., 444, 443, 441) are used as reference levels in the present case. Figure 3-1 shows the theoretical spectral ratios of broadside amplitudes to those measured in-line, at 30° , and at 45° from the orientation of the row, assuming propagation velocities of 4500 m/sec and 2700 m/sec respectively. It can be seen that pronounced peaks exist in these curves corresponding to those wavelengths at which destructive interference takes place due to differences in travel-time to the observation point for the various sources. Since interference occurs at characteristic wavelengths, as the propagation velocity decreases the peak interference frequency decreases.

The appropriate ratios of observed radial component BPF curves corresponding to the theoretical ratios mentioned above are shown in Figure 3-2. It can be seen by comparing these curves with those shown in Figure 3-1 that although variations exist, no consistent pattern of interference is evident. Before concluding that linear interference concepts are not applicable, a further

FIGURE 3-1. THEORETICAL SPECTRAL RATIOS FOR LINEAR INTERFERENCE MODEL

FIGURE 3-2. BPF SPECTRAL RATIOS BASED ON TOTAL SEISMOGRAMS

complicating factor must be considered, namely, the relationship between wavelength, frequency and velocity. The complication arises in comparing the amplitudes at a given frequency (from a Fourier amplitude or BPF spectra) for a pair of stations since we are, in reality, comparing the contributions due to components of different wavelengths. For example, if we consider the amplitude at a given frequency to be due to the arrival of both compressional and shear waves, more than one wavelength is represented since the velocities of the two waves are different. Since, on the basis of linear theory, we anticipate that interference will be a function of the wavelength of the waves involved, the traditional one-dimensional Fourier transform is not adequate for the delineation of such effects. In order to examine contributions from individual wavelengths in a group of time histories collected at different distances, a two-dimensional Fourier transform must be employed. That is, if we are dealing with a function of space and time $S(x,t)$ (i.e., seismograms measured at an array of stations), we can write

$$S(k,\omega) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} S(x,t) e^{-i(kx+\omega t)} dx dt \quad (3-1)$$

where k is wavenumber and ω is angular frequency. In this representation, $S(k,\omega)$ corresponds to a surface contoured over the k,ω plane and cuts taken parallel to the frequency axis would correspond to a fixed wavelength ($= 2\pi/k$). Contributions from a

given wavelength in-line and broadside to the source array could then be compared to determine if interference is present. In principle, such two-dimensional transforms can be calculated whenever arrays of seismometers are available. In practice, however, problems relating to aliasing and resolution with regard to wavenumber arise just as with frequency in the traditional one-dimensional transform. Thus, with the limited Buggy I data arrays, it was not possible to numerically compute the two-dimensional transforms with the required wavenumber resolution. As a compromise measure, the spectral composition of the recorded seismogram was analyzed as a function of time using the BPF technique. In this approach, if selected portions of a recorded seismogram correspond primarily to a single arrival, then the spectral composition of that time window will correspond to unique wavelengths. The spectral ratios derived from the first second of record following the first arrival on the appropriate radial component seismograms are shown in the upper portions of Figures 3-3 and 3-4 for the frequency range over which they are meaningful (bearing in mind the transient response characteristics of the BPF). These observed ratios are to be compared with the theoretical calculations (Figure 3-1) for a velocity of 4,500 m/sec (assuming that the time window used corresponds to the arrival of a direct compressional wave). The spectral ratios corresponding

FIGURE 3-3. BPF SPECTRAL RATIOS (BROADSIDE/INLINE) BASED ON THE FIRST SECOND OF THE SEISMOGRAMS (UPPER FIGURES) AND THE TENTH SECOND OF THE SEISMOGRAMS (LOWER FIGURES)

FIGURE 3-4. BPF SPECTRAL RATIOS (BROADSIDE/30°, BROADSIDE/45°) BASED ON THE FIRST SECOND OF THE SEISMOGRAMS (UPPER FIGURES) AND THE TENTH SECOND OF THE SEISMOGRAMS (LOWER FIGURES)

to the time interval extending from the tenth to eleventh second following the first arrival are shown in the lower position of Figures 3-3 and 3-4. These observed ratios are to be compared with the theoretical calculations (Figure 3-1) for a velocity of 3,700 m/sec (assuming that the time window corresponds to a surface wave arrival). As with the total BPF curves, some irregularity is evident in the plots, but no consistent pattern of interference emerges.

As a final check on the symmetry of the radiation, an energy calculation was made for the in-line and broadside stations using the recorded traces. It is well known (Bath, 1958) that the energy density at a site is proportional to the integral of the velocity time history squared over the duration of the disturbance, i.e.,

$$E \sim \int_0^T v^2(t) dt \quad (3-2)$$

Now, in the present case, a direct calculation according to equation (3-2) might be misleading due to the substantial high frequency noise components in the recordings. The obvious way to deal with this problem would be to low-pass filter the time series before integrating. For reasons which will become apparent later in this chapter, it was decided to perform this filtering

operation in the frequency domain and to compute the energy density in the frequency domain using an equivalent form of Equation (3-2). Let $V(t)$ be a velocity time history with a Fourier transform $v(\omega) = A(\omega)e^{i\phi(\omega)}$ where $A(\omega)$ is the amplitude spectrum and $\phi(\omega)$ the phase spectrum of $V(t)$. Then by Rayleigh's theorem, Papoulis (1962),

$$\int_{-\infty}^{\infty} v^2(t) dt = 4\pi \int_0^{\infty} A^2(\omega) d\omega \quad (3-3)$$

where we have used the fact that $A(\omega)$ is an even function of ω . That is, the time integral indicated in Equation (3-2) can be formally replaced by an integral over the power spectrum in the frequency domain. One advantage of this alternate formulation lies in the fact that the required low-pass filtering operation can be performed by merely changing the upper limit of integration from infinity to some maximum frequency determined by the frequency range of the data versus the noise. In the present case, judging from the BPF curves, the upper limit was determined to be 10 Hz. Since the velocity at a given station is a vector quantity, the amplitude spectrum of the vector magnitude squared was used in these computations. The results of this analysis are presented in Table 3-2. Again, there is no clear evidence of asymmetry.

TABLE 3-2. ENERGY CALCULATIONS

Station	$\int_0^{10 \text{ Hz}} v^2(f) df, \frac{\text{cm}^2}{\text{sec}}$	
441 (broadside)	1.645×10^1	} R = 2.69 km
461 (in-line)	8.82×10^0	
447 (in-line)	7.02×10^0	
458 (arc)	9.38×10^0	
459 (arc)	6.37×10^0	
443 (broadside)	3.05×10^{-1}	} R = 6.37 km
449 (in-line)	5.739×10^{-1}	
444 (broadside)	5.764×10^{-2}	} R = 11.1 km
450 (in-line)	7.933×10^{-2}	

In conclusion, it may be stated that no significant asymmetries attributable to the source configuration were found in the amplitude-frequency data derived from the close-in instrumentation specifically designed to detect such effects.

3.2 COMPARISON OF BUGGY I DATA WITH DATA FROM SINGLE CRATERING EVENT

Having concluded in Section 3.1 that no measurable asymmetries exist in the seismic radiation patterns from Buggy I, an analysis was performed to determine if the amplitude and frequency characteristics of a multiple-charge cratering experiment are "equivalent" to the characteristics of a single charge

cratering experiment. In this aspect of the study, the far-field Buggy I peak amplitude data and amplitude-frequency data are compared with Cabriolet data obtained from recording stations SE-6, Alamo Alluvium, Tonopah Church, Tonopah Motel and CP-1 (refer to station location map, Figure 2-2).

3.2.1 Peak Amplitude Data

The objective of peak amplitude comparisons is to determine if there are similarities in the levels of ground motion resulting from a multiple-charge cratering experiment and from a single-charge cratering experiment. The Cabriolet peak amplitudes were scaled to 1.1 kt and 5.5 kt using the yield scaling factors contained in Murphy and Lahoud (1968). In addition, the distance exponents in the same report were used to scale for differences in source-to-station distances between Buggy I and Cabriolet. The stations examined were the common stations CP-1, Tonopah Church, Tonopah Motel, Alamo Alluvium, and SE-6.

The ratios of observed Buggy I peak amplitudes to scaled Cabriolet peaks were calculated and plotted on semi-logarithmic graphs as shown in Figure 3-5. It can be seen that there is considerable variation in the ratios above and below unity. The variation in results and relative scarcity of common-station data, preclude any definitive statements about differences or similarities between Buggy I and Cabriolet. A comparison of the

FIGURE 3-5. PEAK AMPLITUDE RATIOS OF BUGGY I TO CABRIOLET SCALED TO 1.1 KT (CIRCLES) AND CABRIOLET SCALED TO 5.5 KT (SQUARES)

total Buggy I peak amplitude data sample with contained event regression equations to be discussed in Section 3.3.1, provides additional information pertaining to the effective yield of Buggy I. Studies of amplitude-frequency data presented in Sections 3.2.2 and 3.3.2 will also provide information on the effective yield of the row-charge experiment.

3.2.2 Amplitude-Frequency Data

The radial component band-pass filter curves for Buggy I (solid lines) and Cabriolet (dashed lines) are shown in Figure 3-6 for the station SE-6, Alamo Alluvium, Tonopah Church, and CP-1. It can be seen from these figures that at all four stations, Cabriolet data are higher than Buggy I data at low frequencies ($f < 1$ Hz) whereas, in some cases (Tonopah Church and SE-6), Buggy I data are substantially higher in the high frequency range ($f > 1$ Hz). It is important to note that the data were not adjusted for differences in yield (the Cabriolet yield was 1.9 kt and the total yield of the Buggy I simultaneous devices was 5.5 kt.)

In light of the above observations, it is of some interest to compare the Buggy I amplitude-frequency data with what we would anticipate from 1.1 kt and 5.5 kt single cratering shots. Using a recently developed analytical formulation, (Mueller (1969)),

FIGURE 3-6. COMPARISON OF BUGGY I (SOLID LINE), CABRIOLET (DASHED LINE) AND SCALED CABRIOLET (DOTTED LINE) BPF CURVES

it is possible to scale a measured amplitude spectrum for differences in both yield and depth of burial of the shot. On the basis of this formulation, the measured Cabriolet data were scaled to yields of 1.1 and 5.5 kt for a depth of burial of 135 feet (Buggy I depth of burial). These results are shown as dotted lines on Figure 3-6). In some cases (SE-6, Tonopah Church, Alamo Alluvium), the Cabriolet amplitude-frequency data scaled to 1.1 kt at 135 feet come into very close agreement with the observed Buggy I data at low frequencies (< 1 Hz). In general, however, it may be stated that none of the scaled Cabriolet curves are very similar to the observed Buggy I data.

A quantitative comparison is provided by the energy ratios computed using equation (3-3). Strictly speaking, these ratios correspond to ratios of the energy radiated into the elastic region (over the measured frequency range) for the two shots only in the case when the transmission path is identical for both shots. Consequently, the energy calculations were not made for station CP-1 where the percentage difference in distance for the two shots was substantial. As referenced above, the energy calculations were made in the frequency domain by making use of Rayleigh's theorem. This approach is convenient in the present case because our analytic scaling formulation allows us to scale the Fourier amplitude spectrum for yield and depth of burial.

Table 3-3 shows the calculated energy ratios of Cabriolet scaled to 1.1 kt and 135 feet depth of burial and Cabriolet scaled to 5.5 kt and 135 feet depth of burial to Buggy I for the stations SE-6, Alamo Alluvium, and Tonopah Church. A good deal of scatter exists in the values of the ratio for a given yield; in particular, the values at Tonopah Church are consistently a factor of two or more larger than the average of the values at the other two stations. However, in comparing the various yields, it is clear that Cabriolet scaled to 5.5 kt and 135 feet depth of burial gives a large discrepancy and that on the basis of an attempt to equalize the radiated elastic energy (in the recorded frequency range) from the two shots, we would require a Cabriolet yield somewhat greater than 1.1 kt but less than 1.9 kt which was the Cabriolet yield.

Thus, the Buggy I amplitude-frequency data do not compare very well with scaled data from the single shot cratering event Cabriolet with regard to general spectral shape. Further, the energy calculations seem to indicate an effective yield for Buggy I closer to 1.1 kt than 5.5 kt.

TABLE 3-3. ENERGY RATIOS

Station	Cabriolet (Unscaled) Buggy I	Cabriolet (1.1 kt @ 135') Buggy I	Cabriolet (5.5 kt @ 135') Buggy I
Alamo Alluvium	1.95	.73	23
Tonopah Church	3.4	1.17	56
SE-6	1.37	.44	27
Average	2.36	.78	35

3.3 COMPARISON OF BUGGY I DATA WITH DATA FROM SINGLE CONTAINED EVENTS

It was shown in Section 3.2 that Buggy I data do not compare well with scaled data from the single cratering event, Cabriolet. This is particularly true with regard to the general shape of the amplitude-frequency spectra. Further, it was shown, based on peak amplitude and amplitude-frequency comparisons and energy calculations that the Buggy I effective yield may be closer to 1.1 kt. For these reasons, the measured Buggy I data were next compared with predictions based on NTS experience assuming 1.1 and 5.5 kt contained events. It should be noted that "contained" in this context implies a depth of burial (in feet) of approximately $350-450W^{1/3}$ where W is the yield in kt.

3.3.1 Peak Amplitude Data

The following equations, obtained from Murphy and Lahoud, (1968) were used to compare Buggy I observed peak amplitudes with peak amplitudes resulting from contained events:

For Locations on Hard Rock

$$a = 1.57 \times 10^{-1} W^{.656} R^{-1.68} \quad \sigma = 2.54 \quad (3-4)$$

$$d = 3.78 \times 10^{-1} W^{.852} R^{-1.39} \quad \sigma = 2.19 \quad (3-5)$$

$$u = 3.36 \times 10^0 W^{.770} R^{-1.51} \quad \sigma = 2.42 \quad (3-6)$$

For Locations on Alluvium

$$a = 9.00 \times 10^{-2} W^{.624} R^{-1.36} \quad \sigma = 2.13 \quad (3-7)$$

$$d = 4.49 \times 10^{-1} W^{.767} R^{-1.14} \quad \sigma = 2.20 \quad (3-8)$$

$$u = 5.10 \times 10^0 W^{.635} R^{-1.31} \quad \sigma = 1.97 \quad (3-9)$$

Symbol notation and units for equations (3-4) through (3-9) are:

a = peak surface particle acceleration in units of gravity (g)

d = peak surface particle displacement in centimeters (cm)

u = peak surface particle velocity in centimeters per second (cm/sec)

W = yield in kilotons

R = slant distance in kilometers

σ = standard error of estimate

The above equations, obtained from a statistical analysis of peak vector amplitude data measured from 99 underground nuclear events, represent a valid source of contained event peak amplitude information. Figures 3-7 and 3-8 show peak amplitude versus slant distance graphs containing all Buggy I observed data compared with regression lines representing Equations (3-4) through (3-9.) Two regression lines, one calculated for 1.1 kt and one for 5.5 kt, are included on each graph. (For identification of station symbols on these figures, see Table 2-1, page 2-4).

In order to make realistic comparisons, selected Buggy I data were adjusted based on known systematic deviations of observed data from the mean statistical equations. Separate statistical analyses of contained event data were run using only data recorded at those stations which, from past experience, were known to deviate from the mean sample. Correction factors were derived and applied to the Buggy I observed motions at Beatty Alluvium, Tonopah Church, Tonopah Motel, SE-2 and SE-6. The Tonopah Church (hard rock) factors were applied at the Tonopah South Street station due to the proximity of these stations to each other and also due to the absence of a statistical sample at the South Street station. Table 3-4 contains all the factors which were applied. It should be noted that the station

FIGURE 3-7. COMPARISON OF BUGGY I PEAK AMPLITUDE DATA WITH PREDICTIONS FOR 1.1 KT AND 5.5 KT SINGLE-CONTAINED EVENTS, HARD ROCK STATIONS

FIGURE 3-8. COMPARISON OF BUGGY I PEAK AMPLITUDE DATA WITH PREDICTIONS FOR 1.1 KT AND 5.5 KT SINGLE-CONTAINED EVENTS, ALLUVIUM STATIONS

TABLE 3-4. STATION MULTIPLICATIVE FACTORS APPLIED TO OBSERVED
BUGGY I PEAK AMPLITUDE DATA

STATION	FACTOR		
	ACCELERATION	DISPLACEMENT	VELOCITY
Beatty Alluvium	--	8.3×10^{-1}	--
Tonopah Church	6.4×10^{-2}	--	1.8×10^{-1}
Tonopah Motel	6.9×10^{-2}	3.1×10^0	3.9×10^{-1}
SE-6	--	--	1.2×10^0

correction factors vary somewhat with yield. However, since the factor differences between 1.1 kt and 5.5 kt are negligible, the quantities shown in Table 3-4 represent an average for the two yields. Examination of Figure 3-7 (stations on hard rock) indicates an effective yield of Buggy I greater than 1.1 kt but less than 5.5 kt. Examination of Figure 3-8 (stations on alluvium) indicates an effective yield equal to or less than 1.1 kt. These observations are in essential agreement with the conclusions drawn from the frequency analysis discussed in Section 3.2.2 of this report. It is interesting to refer to the peak amplitude discussion contained in Section 3.2.1. The conclusion was drawn that no definitive statements could be made about differences or similarities between Buggy I and Cabriolet. However, it may be significant that at four of the five stations shown on the peak

displacement ratio graph in Figure 3-5 (page 3-16), observed Buggy I peak amplitudes are closer in magnitude to Cabriolet scaled to 1.1 kt than to Cabriolet scaled to 5.5 kt.

Having examined the Buggy I peak amplitude data in comparison with contained event peak motion regression equations, the Buggy I amplitude-frequency spectra at two stations were studied.

3.3.2 Amplitude-Frequency Data

Amplitude-frequency data comparisons could be made with confidence only at stations SE-6 and Tonopah Church where single station prediction equations are available. These comparisons are shown in Figure 3-9. The predictions for the 1.1 kt contained event fit the measured Buggy I data better than any of the individual scaled Cabriolet curves. That is, the seismic motion from this five-shot cratering event is more like that from a single contained event than that from a single cratering event. The physical explanation of these observations is not clear at this time. Apparently, the effects of the multi-element source array have counteracted the influence of the shallow depth of burial, yielding a resultant seismic frequency content more characteristic of much deeper, buried, single shots.

In conclusion, all available evidence indicates that the Buggy I row charge event generated far-field motions characteristic

FIGURE 3-9. COMPARISON OF OBSERVED BUGGY I BPF CURVES WITH BPF PREDICTIONS FOR A 1.1 KT SINGLE-CONTAINED EVENT, STATIONS SE-6 AND TONOPAH CHURCH

of a 1.1 kt single contained shot. It is unfortunate that Buggy I did not record at other stations where reliable amplitude-frequency prediction equations were available. A more firm conclusion would be of greater significance with regard to the engineering application of row charges.

CHAPTER 4

SUMMARY AND CONCLUSIONS

Seismic data from the Buggy I row-charge cratering event were analyzed to determine the elastic wave radiation characteristics of a multi-element source configuration. The close-in ($R \leq 12$ km) measurements were examined to determine if any azimuthal asymmetries exist in the seismic radiation pattern while the distant ($R > 12$ km) data were compared with measurements from previous tests to determine if a single equivalent charge could be postulated and used for prediction of ground motion parameters for future row-charge detonations.

Studies of the close-in data centered on a comparison of peak amplitudes, BPF amplitudes and energy densities at stations broad-side and in-line with respect to the orientation of the row of charges, as well as at a series of stations situated on an arc covering one quadrant centered on the middle element of the row-charge. All three of the above mentioned criteria confirmed the fact that no measurable azimuthal asymmetries exist in the Buggy I seismic data. These observations seem to rule out the possibility of using strictly linear concepts, such as superposition, in the prediction of ground motion effects from row-charge nuclear excavation detonations.

The distant seismic data from Buggy I have been compared with suitably scaled observations from both single cratering (Cabriolet) and single contained detonations. The comparative criteria were again peak amplitudes, BPF amplitudes and energy densities. Comparisons with scaled and unscaled measurements from the single cratering detonation, Cabriolet, indicate an equivalent single cratering yield for Buggy I which is somewhat less than 5.5 kt (total simultaneous energy release of the five Buggy I elements) and somewhat more than 1.1 kt (the energy release associated with a single Buggy I element). In general, however, the spectral composition of the Buggy I measured seismograms is not compatible with the Cabriolet measurements scaled to any yield. On the other hand, comparison of both the peak amplitude and BPF predictions made using equations based on single contained detonations indicates that the Buggy I data compare quite well with predictions for a 1.1 kt contained detonation. Unfortunately, no theoretical model yet exists which can adequately explain this observation and consequently, great caution must be exercised in attempting to extrapolate these conclusions to predictions for higher yield row-charge events. In any case, however, it appears that a prediction assuming a single contained detonation with a yield equal to the sum of the yields of the individual charges will be conservative.

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