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EXTRACTED VERSION

General Report of Weapons Tests

Ground-Motion Studies on Operations IVY and CASTLE

Sandia Corporation
Albuquerque, New Mexico

February 1955

NOTICE

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Ground motion produced by Mike shot of Operation Ivy (Project 6.5) was measured as three components of acceleration at four ground ranges between 8000 and 114,000 ft. Gauges were in sand below the water table at depths of about 17 ft. Similar measurements were made on a massive concrete instrument shelter at about 30,000 ft from Ground Zero. Ground-motion data derived from shot 3 of Operation Castle (Project 1.7) are presented in Chap. 2. These data, because of the low yield of the shot, are inadequate for correlation with the results of other tests.

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FOREWORD

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ABSTRACT

Ground motion produced by Mike shot of Operation Ivy (Project 6.5) was measured as three components of acceleration at four ground ranges between 8000 and 114,000 ft. Gauges were in sand below the water table at depths of about 17 ft. Similar measurements were made on a massive concrete instrument shelter at about 30,000 ft from Ground Zero.

A rough empirical relation was derived for scaled peak ground-transmitted acceleration as a function of scaled ground range and compared with similar data from Operation Greenhouse. The peak vertical acceleration produced by incidence of the air shock in the vicinity of the gauge station was related empirically to the peak air overpressure. These relations are necessarily rough because of the few reliable data available, but are probably adequate for estimating effects of megaton weapon bursts. The acceleration data were converted to velocity-time and displacement-time information.

Ground-motion data derived from shot 3 [redacted] of Operation Castle (Project 1.7) are presented in Chap. 2. These data, because of the low yield of the shot, are inadequate for correlation with the results of other tests.

Procedures employed for correction of acceleration data integrated to velocities and displacements are discussed in Appendix B.

PREFACE

Ground-motion studies conducted as Project 6.5 of Operation Ivy yielded useful information of limited scope because complete data were not recovered. It was considered desirable to extend and supplement the data from Mike shot of Operation Ivy with several close-in, ground-motion measuring stations of Operation Castle (Project 1.7).

The data from Project 6.5 of Operation Ivy have been delayed in processing. Consequently, it is convenient and pertinent to combine the reports on the original and supplementary studies as Chaps. 1 and 2 of a single report.

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Weapons effects studies concerned with damage to structures include observations of ground motion, to certain aspects of which underground structures are sensitive. Limitations imposed by instrument characteristics have usually restricted the measured parameter to acceleration. Velocity and displacement information has been derived by iterated integration of acceleration-time data. Direct measurement of velocities or displacements is feasible for small-charge experiments wherein durations of phenomena can be resolved by practical gauges.

Energy from an explosion is coupled to the earth either directly or as a secondary effect through ground incidence of an air shock. Direct coupling is most obvious in underground bursts in which secondary coupling is usually negligible because energy in the air shock is relatively smaller. Surface bursts involve both direct and secondary coupling, the first being probably predominant close to Ground Zero, where the two effects are essentially undifferentiable. At more remote distances from Ground Zero, the directly coupled energy effects outrun those derived from local incidence of air shock and become separated in time. Secondary air-coupled effects are propagated at velocities characteristic of air-shock velocity, which decreases with distance, approaching acoustic air speeds. Transmission of directly coupled effects through the ground is at seismic velocities, which are generally several times acoustic air velocities and tend to increase with ground range because of refraction through deeper, higher velocity strata. Effects from directly coupled energy are attenuated by angular dispersion as well as by frequency dispersion. Ground-acceleration frequencies are consequently relatively low and probably decrease with ground range. The lower frequency portion of the motion becomes stronger in the particle velocity data and often predominates in the displacements. Secondary coupling effects, on the other hand, result from a shock wave which retains a steep front and is attenuated less rapidly than the ground-transmitted motion. These effects are characterized in general by relatively higher frequencies and peak accelerations than the directly coupled motion, but resultant particle velocities and displacements may be comparatively small because of the short periods of the frequencies involved.

Ground motion from explosions centered well above the ground involves only air-shock coupling. Effects caused by incidence of air shock in the immediate vicinity of a measurement station predominate at all ground ranges. At stations remote from Ground Zero, effects derived from incidence of the air shock at or near Ground Zero may be distinguishable from those caused by local incidence, but the ground-transmitted signals are usually negligible because attenuation due to coupling, dispersion, and transmission over large distances within the earth greatly exceeds that to which the locally incident air shock has been subjected.

Measurements of ground motion produced by high explosives, usually represented by accelerations, have been included in the Office of Scientific Research and Development Underground Explosion Effects program,[1] the Underground Explosion Test Program at Dugway

Proving Ground,[2,3] Operation Jangle at Nevada Test Site,[4] and Project Mole.[5,6] These studies were concerned principally with underground explosions, but Project Mole, in particular, included observation of underground effects from several surface and above-surface shots.

Studies of ground motion have been a part of weapons effects programs for all nuclear tests. Data for these studies were derived principally from air (or tower) bursts[7–10] although one surface and one underground shot were included in Operation Jangle.[11,12] There is good correlation between the peak acceleration induced by local incidence of air shock and peak overpressure for air-burst weapons. This correlation probably holds true for surface and subsurface bursts also, although in the latter case the overpressure and the consequent ground motion are negligible.

Acceleration induced by incidence of the air shock directly above instrumentation has a dominant vertical component. Ground-transmitted acceleration, from subsurface bursts or air-shock induction near Ground Zero, has a horizontal radial component of the same magnitude or greater than the vertical and is characterized by predominance of long-period surface waves (Rayleigh waves) at large ground ranges. Correlation of acceleration data from nuclear shots in accordance with scaling laws is hindered by the very complex nature of these data. The nonlinear nature of the mechanical properties of soil and its heterogeneity are reason enough to make scaling of motion parameters far from simple.

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CHAPTER 1

GROUND MOTION FROM MIKE SHOT OF OPERATION IVY

1.1 PURPOSE

Observation of the ground motion produced by Mike shot of Operation Ivy was undertaken primarily to furnish information concerning these effects for super bomb detonation, but its most useful purpose was expected to be the prediction of motion of instrumentation shelters and other structures for future tests in the Pacific Proving Grounds. Except for possible comparison with data from Easy and ___ shots of Operation Greenhouse, it was not anticipated that ground motion of a coral atoll would correlate particularly well with or be significant to weapons effects in likely target areas.

1.2 PLAN OF THE EXPERIMENT

Project 6.5 of Operation Ivy was planned to furnish data concerning vertical, radial, and tangential components of ground acceleration at six stations ranging from about 8000 to 114,000 ft from Ground Zero of Mike shot. The depth of this instrumentation was to be determined by local subsurface conditions with the restrictions that gauges should be below the water table and, if feasible, well within a massive layer of coral rock or sand. These requirements were included to minimize effects of discontinuities close to the instruments.

1.3 CHOICE OF INSTRUMENT STATIONS

General location of instrument stations (i.e., the 650-stations) for ground-motion observations was dictated by location of Sandia Laboratory recording shelters (i.e., the 600-stations). Specific instrument locations were selected on the basis of subsurface conditions as determined by exploratory borings. The site map, Fig. 1.1, includes enlarged maps of the islands on which ground-motion instrumentation was located.

Ideally, and instruments for ground-acceleration measurement should be placed along a single radial line at such depth that they could be considered to be within a continuous homogeneous medium. Pertinent information on subsurface conditions at Eniwetok was limited to logs of several borings made on Engebi, Muzin, and Aomon during Operation Greenhouse. The original expectation that gauge assemblies could be placed within coral rock strata at least 10 ft thick on the reef side of the islands was abandoned after discussion with Holmes and Narver engineers and with geophysicists from the U. S. Geological Survey. Consequently it was decided

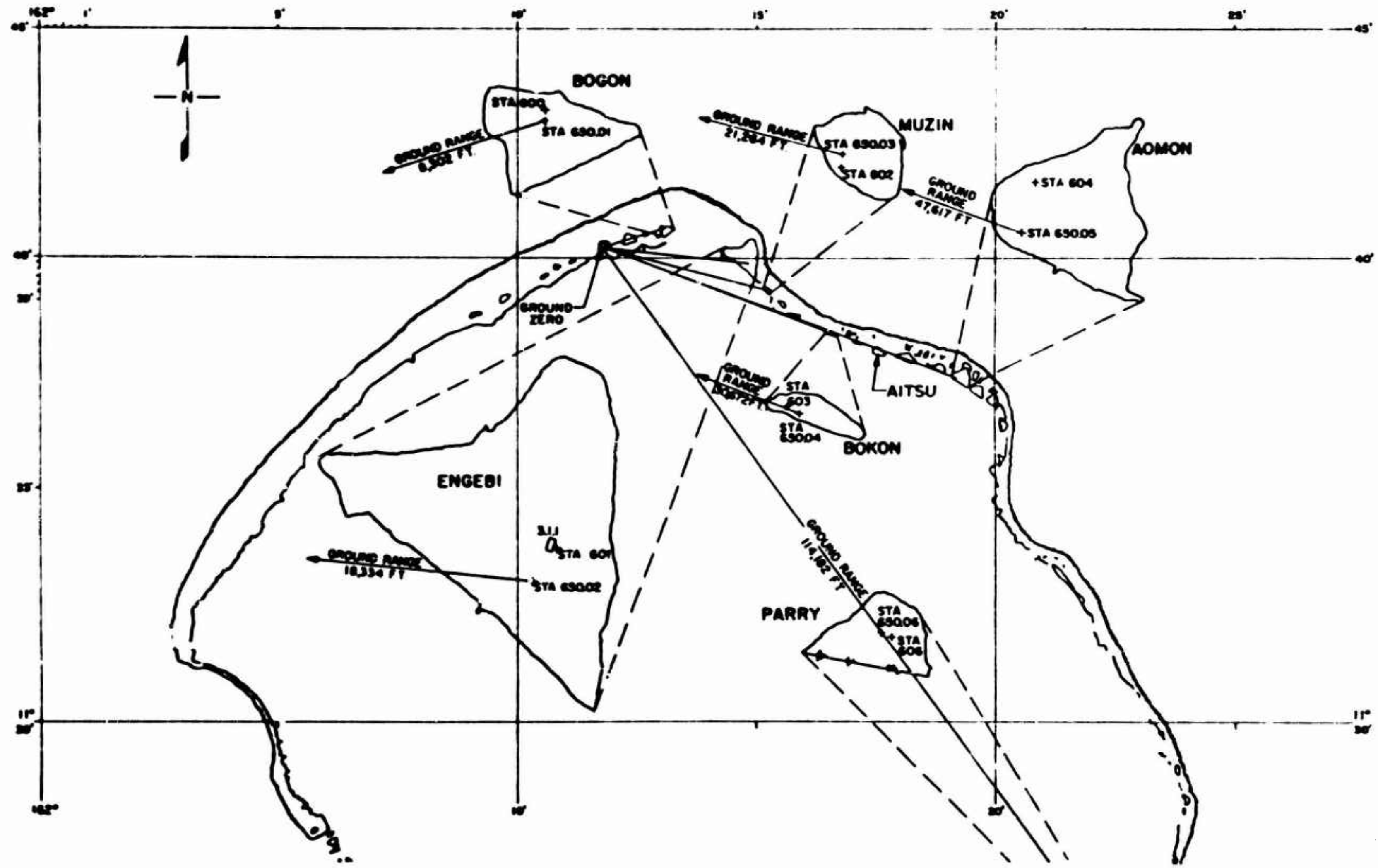

Fig. 1.1—Site map and ground-motion station detail for Mike shot, Operation Ivy (Eniwetok Atoll).

that the gauges should be placed within the relatively homogeneous coral sand at least 5 ft below zones of cemented sand or fragmented coral blocks. These conditions were more likely to be realized on the various islands and were expected to provide reasonably consistent data.

Nine borings for exploration and gauge installation were made during August 1952. Three were for exploration purposes at sites where no previous subsurface data were available, and six were for later use during gauge installation. Exploratory borings were extended about 5 ft below elevations chosen for gauges on the basis of conditions observed during exploration. This procedure prevented placing the gauges directly above a soil discontinuity. Sand samples and cores were taken in each boring, and logs of all borings were kept (Fig. 1.2). Instrument borings were cased with 10-in. pipe to the chosen gauge elevation, and the upper ends of the casings, projecting about 1 ft above the surrounding sand, were plugged and identified by station numbers (Fig. 1.3). Suitable conditions for instrumentation were encountered at depths between 16.5 and 17.5 ft at all stations. Surveys, made after all gauge borings were completed, established the coordinates and ground range of each 650-station.

1.4 INSTRUMENTATION

End instruments used for ground-motion measurements were Wiancko accelerometers.[1] Three of these gauges were mounted with mutually perpendicular response axes in a watertight case (Fig. 1.4). The volume and weight of the assembly were adjusted to give it a density approximately equal to that of the coral rock at Eniwetok. This assembly was about 25 per cent more dense than the surrounding material as a result of the change from rock to sand.

Carrier power and accelerometer signals were transmitted between end instruments and recording shelter by buried four-conductor shielded cables. The output of the accelerometers was amplified and recorded on magnetic tapes. A description of the recording equipment and its performance is included in reference 2.

1.4.1 Set Range and Calibration of Accelerometers

Accelerometer set ranges were derived with the aid of Los Alamos Scientific Laboratory (LASL) memorandum J-9122, which included an estimate of the ground acceleration as a function of ground range. This estimate was based on scanty data from shot of Operation Greenhouse[3] scaled to the anticipated Mike yield. Energies were assumed to scale as the square root of the yield, and the very low burst height of Mike was assumed to make the fraction of energy coupled to the ground 50 times greater than it was for The magnitude of this factor (50) was questioned, but, since no data were available for verifying the scaling procedure, the LASL estimate was used.

Individual accelerometers were chosen in response ranges slightly above the estimated set range. All were damped approximately to 0.65 critical, and response over their full range was within 2 per cent of linearity. Each accelerometer was calibrated to set range in the field on its assigned recording channel shortly before installation of the gauge assembly in the ground. Details of the calibration procedure and calibration-signal circuitry are given in reference 2.

1.4.2 Installation of Instruments

Tidal fluctuation of the ground water caused invasion of loose sand through open bottoms of the cased instrument borings, essentially filling all holes to the water line during the three-month period between drilling and gauge installation. It was necessary to clean out all holes preliminary to placing the accelerometers. Gauge assemblies, as shown beside the casing in Fig. 1.3, were placed and oriented with respect to Ground Zero by means of positioning pipes and were bonded to the surrounding sand by cement grout. Casings were removed from each hole after the grout had set, special care being taken not to disturb orientation of the gauges.[2]

Water seeped into two of the gauge units before Mike shot. One of these units, at Station 650.02, was removed, rehabilitated, and replaced in satisfactory operating condition. The other, at Station 650.04, could not be similarly reconditioned because all drilling equipment had been

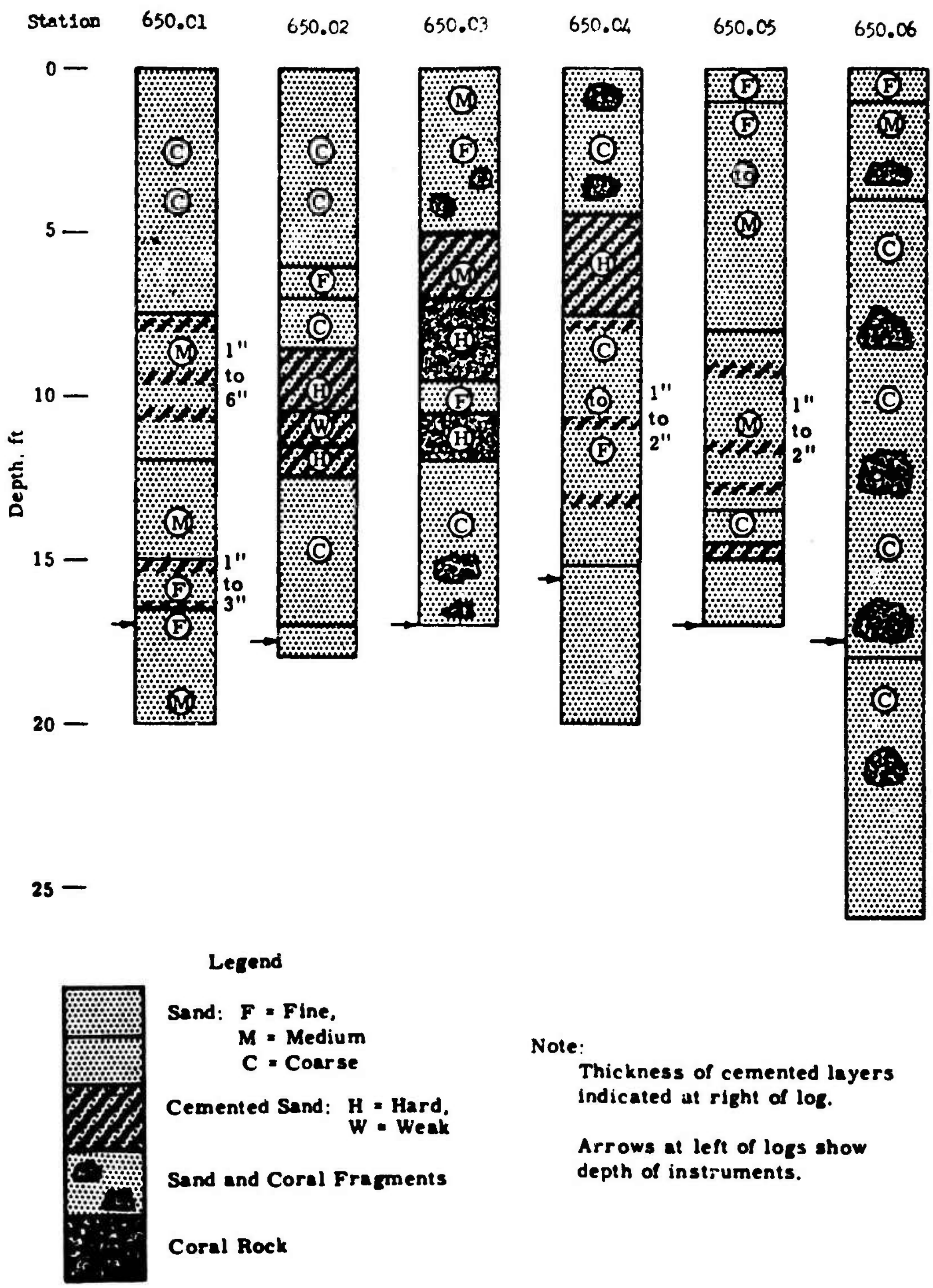

Fig. 1.2—Logs of borings for ground-motion instrumentation, Operation Ivy (Eniwetok Atoll).

Fig. 1.3—Top of an instrumentation boring and a gauge assembly. The gauge assembly will be placed in the casing at a depth of 16.5 to 17.5 ft.

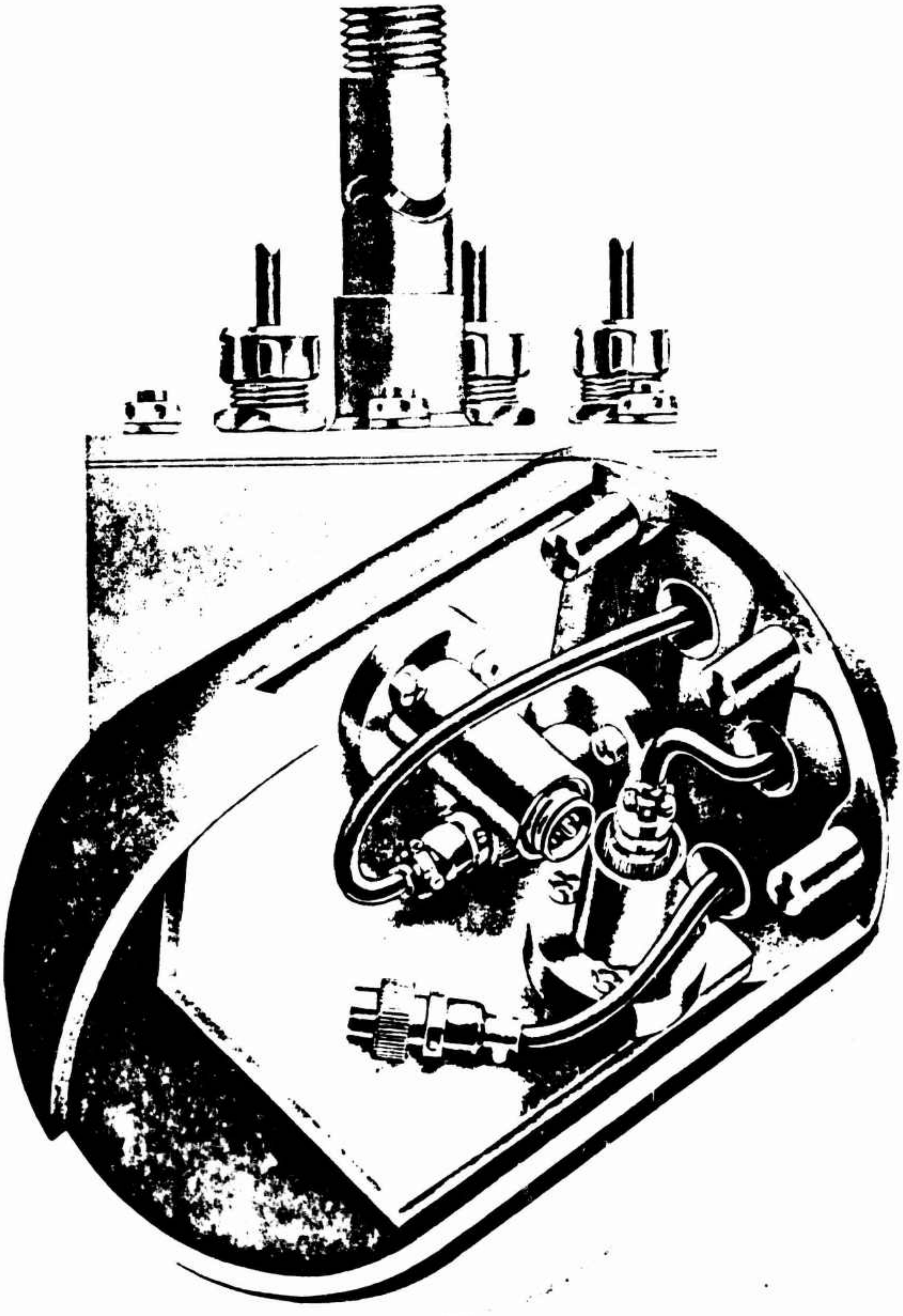

Fig. 1.4—Accelerometer mounting and case assembly.

removed from Eniwetok before the failure was detected. Three spare accelerometers, which were installed on the roof and rear and side walls of the recording shelter, Station 603, to respond to vertical, radial, and tangential components of acceleration, were connected to the information channels assigned to Station 650.04.

1.5 DATA ANALYSIS

1.5.1 Accelerations

Acceleration-time data were obtained from all component instruments at five stations. No data were recovered from Station 650.05 on Aomon as a result of failure of the recorder tape-transport mechanism.[2] Only the initial portion of the recorded data at Station 650.01 on Bogon was useful because incidence of the air shock at the recorder shelter, Station 601, reactivated the cal-step timer with consequent recording of spurious signals.

Pertinent sections of the acceleration-time data are presented in Appendix A, Figs. A.1 to A.11. Each of these figures includes, in addition, velocity-time and displacement-time data derived by integration. Ground-transmitted signals and those produced by local incidence of air shock are separated by appreciable time intervals for all stations beyond Engebi and are plotted as separate parameter-time graphs. The data from local incidence of the air shock at Station 650.02 are reproduced on an expanded time scale for clarity.

Acceleration-time data from Station 650.01 are compared in Fig. A.1 with data (dashed curves) from a recorder channel which monitored the carrier power supply to the gauges. The carrier power was apparently stable until 1.436 sec after zero time, when reactivation of the cal-step timer is thought to have occurred. Signals recorded on the accelerometer traces after this time follow details of the carrier monitor record. Data from Station 650.01 are good until 1.436 sec and false thereafter. A vertical dashed line on each parameter-time curve for this station indicates the end of the valid portion of the curve.

The ground-transmitted acceleration presented for Station 650.06 on Parry in Fig. A.11 does not represent the initial arrival which occurred at about 7.35 sec, but a later, stronger signal, probably the first pulse reflected from basement rock. Weaker reflected pulses arrived later, but they are not included because the signal-to-noise ratio was low as a result of poor set-range estimation.

Arrival times, peak accelerations, and acceleration frequencies comprise the information available directly from the recorded data. Air-overpressure data from Project 6.1 stations[4] are also pertinent to study of ground motion since most of the acceleration data show a readily distinguishable air-shock induced signal. Data from Station 650.01 in which the motion is derived indistinguishably from both sources are the only exceptions observed. Data from Bokon, Station 603, are compared with overpressure data from Aitsu because no air-pressure records were obtained from Bokon.

Arrival times for both air overpressure and ground acceleration are compared in Table 1.1. Zero time on the records from Parry was derived from the cal-step signal at −15 sec (Ref. 4) because no zero time signal was recorded at that site. Absolute times on Parry records are considered good only to about 0.1 sec. Interval timing on these records is, however, as good as that for the other stations since the timing-channel frequency was recorded satisfactorily. Overpressure arrival was determined to have been 83.75 sec after zero time. Ground-acceleration data were adjusted to assumed simultaneous arrival of overpressure and air-shock induced ground motion.

Arrival times plotted as a function of ground range show the anticipated branched curve (Fig. 1.5). Arrival of the air-shock induced accelerations corresponds closely with the curve for arrival of air overpressure. This curve indicates an initial propagation velocity greater than 6000 ft/sec, decreasing beyond 20,000 ft to an apparent velocity of about 1230 ft/sec. Ground-transmitted accelerations are propagated with a velocity of nearly 18,000 ft/sec beyond Station 650.01 and with a velocity of 6300 ft/sec out to that station. The latter pattern is consistent with seismic refraction under the conditions shown by deep drilling at Elugelab and Parry—a deep interface between massive basalt and overlying water-filled sand containing

Table 1.1 — ARRIVAL-TIME DATA

Station number	Site name	Ground range, ft	Air-over-pressure arrival, sec	Acceleration arrivals					
				Ground-transmitted			Air-shock induced		
				Vert., sec	Rad., sec	Tang., sec	Vert., sec	Rad., sec	Tang., sec
615.02	Bogon	8,250	1.36						
650.01	Bogon	8,302		1.39	1.39	1.40	*	*	*
611.01	Engebi	15,900	5.18						
650.02	Engebi	18,334		1.83	2.00	2.36	6.67	6.68	6.67
650.03	Muzin	21,264		2.24	2.24	2.57	8.54	8.51	8.54
611.02	Muzin	21,412	8.71						
603	Bokon†	30,226		3.00	3.00	3.00	15.30	15.29	15.30
613.01	Aitsu	36,708	25.08						
611.04	Aomon	47,574	28.87						
650.05	Aomon	47,617		No record					
650.06	Parry‡	114,182		7.35			83.75		
612.01	Parry	114,240	83.75						

*Source of acceleration at Station 650.01 indistinguishable.

†Acceleration measurements made on roof and rear and side walls of recorder shelter.

‡No true zero time signal. Times derived from −15 sec cal-step initiation and corrected to approximate zero.

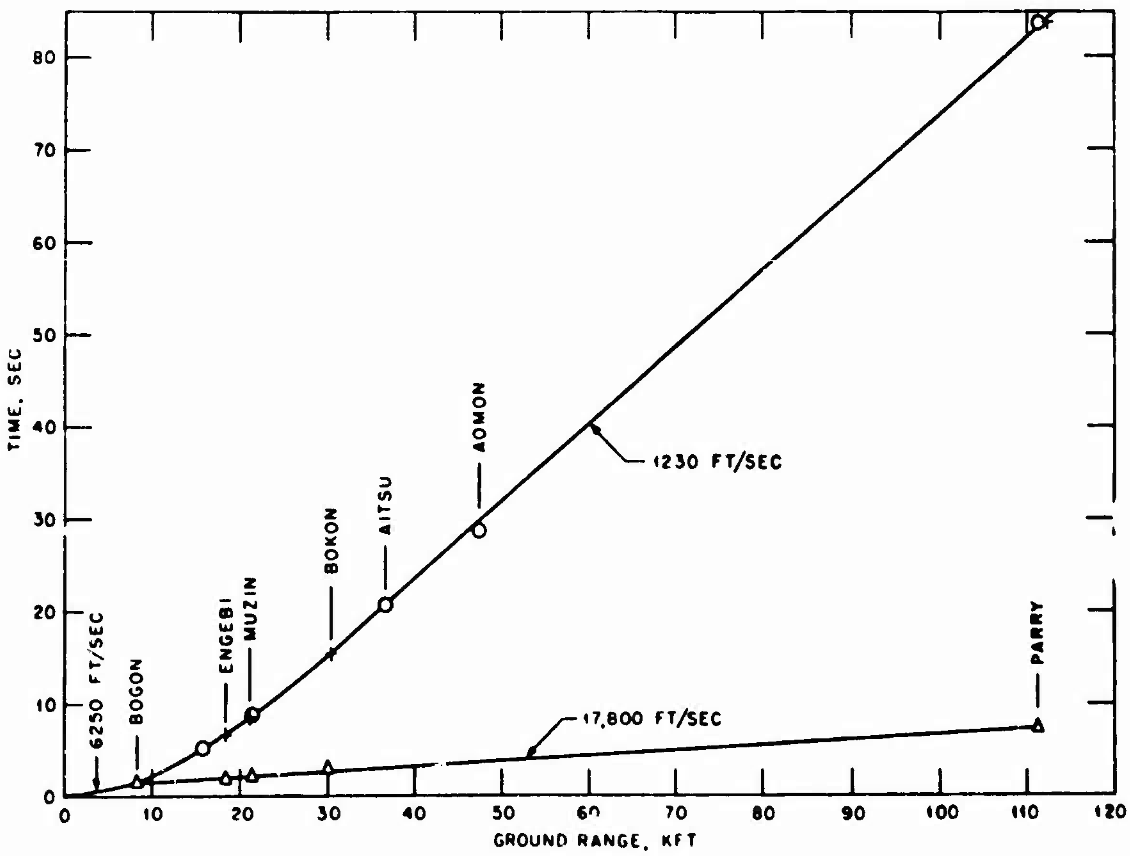

Fig. 1.5 — Arrival times vs ground range for Mike shot, Operation Ivy. ○, air overpressure. +, air-shock induced acceleration. △, ground-transmitted acceleration.

lenticular masses of cemented sand.[5] The data are insufficient to permit detailed seismic analysis, but average depth to basalt is about 3400 ft. Similar data from Easy and   shots of Operation Greenhouse indicated a constant seismic velocity of about 6900 ft/sec (Ref. 3) but did not include information from sufficiently remote stations to include refraction through basement rock.

Table 1.2—GROUND-ACCELERATION AND AIR-OVERPRESSURE DATA

Station number	Ground range, ft	Max. air overpressure, psi	Accelerometers: Component	Accelerometers: Set range, g	Accelerometers: Damped natural freq., cps	Ground-transmitted: Max. pos.,* g	Ground-transmitted: Max. neg., g	Ground-transmitted: Freq.,† cps	Air-shock induced: Max. pos.,* g	Air-shock induced: Max. neg., g	Air-shock induced: Freq.,† cps
615.02	8,250	(40)									
850.01	8,302		V	18	165	2.35	3.5	50			
			R	18	182	1.00	3.8	50			
			T	9	128	0.41	0.56	77			
811.01	15,900	18.6									
650.02	18,334		V	4	108	0.26	0.20	2.7	1.34	1.50	21
			R	4	102	0.23	0.27	4.0	0.46	0.45	36
			T	2	73	0.14	0.11	4.2	0.19	0.37	42
650.03	21,264		V	3	106	0.23	0.18	3.0	0.74	2.1	22(8.3)
			R	3	111	0.23	0.17	3.3	0.71	0.46	67(9.4)
			T	2	73	0.12	0.07	4.6	0.16	0.33	67(13)
611.02	21,412	12.4									
603	30,226		V	2	69	0.18	0.15	3.4(1.6)	3.67	2.90	154
			R	2	65	0.16	0.14	3.4(1.8)	3.00	2.96	111
			T	2	79	0.26	0.20	4.5(1.7)	0.85	0.49	128
613.01	38,708	4									
811.04	47,574	2.7									
650.05	47,617						No record				
650.06	114,1o2		V	0.2	40	0.010	0.080	1.4	0.034	0.020	21
612.01	114,240	0.55									

*Positive acceleration has the following directions: up, for all vertical components; in (toward Ground Zero), for all radial components; counterclockwise (as seen from above Ground Zero), for all tangential components.

†Frequencies enclosed in parentheses are those of apparently secondary importance.

Maximum accelerations and acceleration frequencies are compared in Table 1.2. Set ranges in this table refer to the plus-and-minus ranges of linear response to which the end-instrument-recording systems were set. These values were high by factors ranging from 1.7 to 16 except for the accelerometers on the recorder shelter on Bokon, Station 603, which indicated accelerations nearly twice set ranges. Ground-transmitted signals were below set range by factors of 6 to 20, and air-shock induced data indicate that set ranges should have been lower by factors of from 2 to 10. Consequently the factor used to increase the energy fraction directly coupled to the earth because of the low burst height of Mike shot in estimating set range should probably have been about 4 instead of 50. Data from Stations 650.01 and 603 are anomalous because of incompleteness of the record from Station 650.01 and because of measurement of structural response rather than ground motion at Station 603. Peak accelerations quoted for Station 650.06 in Table 1.2 are estimated for first ground-transmitted arrivals and are lower by a factor of 2 than those for the first reflected signals included in Fig. A.11.

Ground-transmitted accelerations were analyzed by a logarithmic plot of peak-scaled accelerations as a function of scaled ground range (Fig. 1.6). Scaling was according to the expressions

$$A_1 W_1^{1/3} = A_2 W_2^{1/3} \quad \text{and} \quad \frac{R_1}{W_1^{1/3}} = \frac{R_2}{W_2^{1/3}}$$

where W is the radiochemical yield expressed in pounds of TNT. Data included are from Stations 650.01, 650.02, and 650.03 only and represent maxima of the initial refracted signal. Data

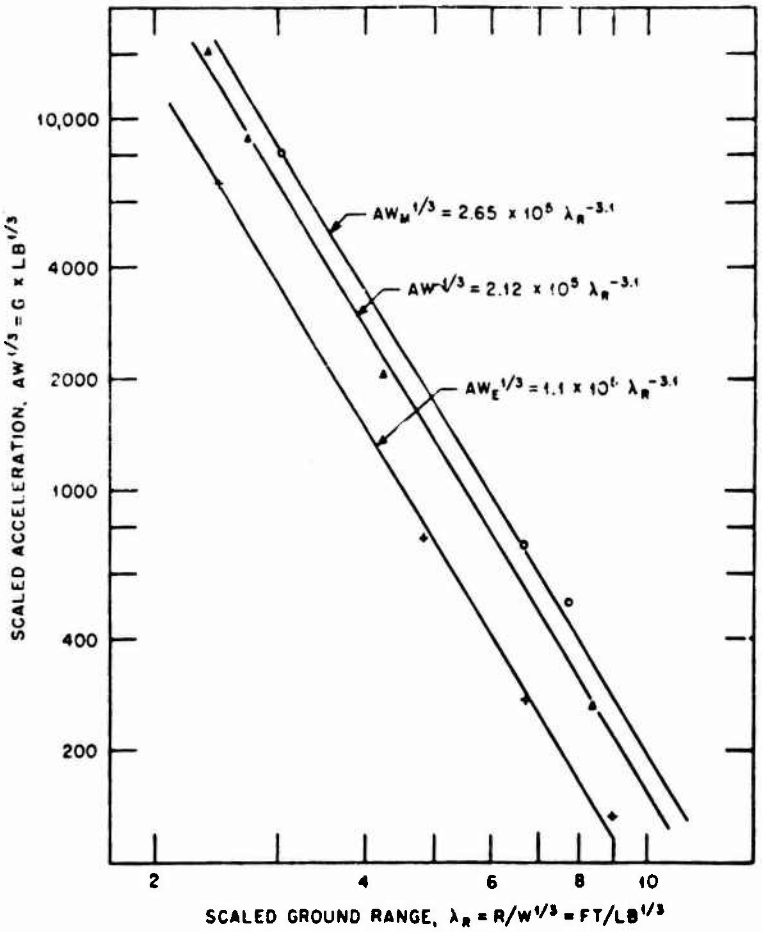

Fig. 1.6—Ground-transmitted acceleration as a function of ground range. O, Ivy Mike shot. +, Greenhouse Easy shot.

from Station 603 are omitted for irrelevancy because they represent motion of a massive structure on a semielastic earth rather than soil particle motion. Low signal-to-noise ratio and uncertainty of the magnitude of early refracted signals led to omission of Station 650.06 data also.

Corresponding information from Easy Operation Greenhouse[3] is included in the graph of Fig. 1.6. All three sets of data fit approximately straight lines with negative slopes. These lines are parallel and may be represented by the equation

$$AW^{1/3} = K\lambda_R^{-3.1} \tag{1.1}$$

where A is peak acceleration in g units, W is the radiochemical yield in pounds of TNT, and λ_R is the scaled ground range in ft/lb$^{1/3}$. The units of K are approximately g-ft^3/lb$^{1/3}$. The coefficient K has the following values:

Mike shot	2.65×10^5
Easy shot	1.1×10^5

Differences in scaled height of burst between the three shots are included in the values of the coefficient K. A cursory study suggests that in fact K may be represented as a constant modulated by a negative exponential of the 1.5 power of the scaled height of burst. However, the data are hardly strong enough to support an analytical expression of such complexity.

Equation 1.1 yields reasonable estimates for vertical or radial ground-transmitted accelerations within the scaled ground-range limits $2.5 \leq \lambda_R \leq 10$ when the proper coefficient K is used. For near surface bursts, between zero burst height and a scaled height of 0.14 ft/lb$^{1/3}$, K may be estimated roughly between 2.66×10^5 and 2.1×10^5 without excessive increase in the acceleration error. In any event the error in derived accelerations will probably be less than ±50 per cent and should be adequate for estimating set ranges and possibly for rough estimates of damage.

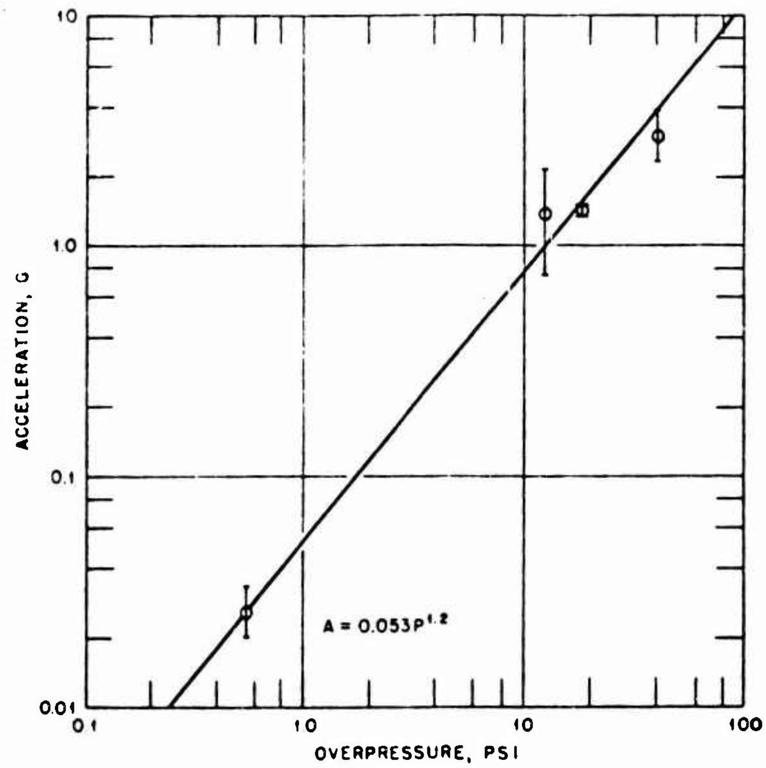

Fig. 1.7—Air-shock induced acceleration as a function of incident overpressure for Mike shot, Operation Ivy.

Absolute values of maximum positive and negative vertical accelerations induced by incidence of air shock above the gauges are plotted as a function of peak air overpressure in Fig. 1.7. The end points of the vertical line segments represent the positive and negative peaks, negative being the greater at all stations. Overpressures are mean peak values[4] except at Station 650.01, where an estimate was made by extrapolation since dependable overpressure data were not obtained at Bogon.

Peak accelerations induced at Station 603 by air shock are higher by a factor of about 7 than would be expected from interpolation of the ground-motion data. The straight line fitted to the data in Fig. 1.7 represents the equation

$$A = 0.053p^{1.2} \qquad (1.2)$$

in which acceleration is in g units and overpressure is in psi.

Acceleration data from four air-burst tests of Operation Tumbler-Snapper[6] show an analogous relationship expressed by

$$A = 0.32p^{0.89} \tag{1.3}$$

Differences in soil conditions at the Pacific Proving Grounds (Eq. 1.2) and Nevada Test Site (Eq. 1.3) are probably the primary cause of the differences in coefficients and exponents in the two equations.

The acceleration-time curves (Figs. A.1 to A.11) are of a complex periodic form. All show some distinct frequencies and apparent interference effects which influence the curve. Frequencies derived directly from the curves are included in Table 1.2. Frequencies enclosed in parentheses are those of apparently secondary importance. The ground-transmitted motion is characterized by two major frequency ranges: one of about 50 cps at Station 650.01 which, according to Fig. 1.1, involves principally transmission through the shallower materials characterized by a seismic velocity of 6300 ft/sec, and the other of from 2 to 4 cps which involves an appreciable proportion of travel over a refraction path within the 18,000 ft/sec basement rock. These frequencies are consistent with those observed in seismic exploration.

The frequency of the air-shock induced motion is generally similar at all stations, ranging from 20 to 70 cps except for the higher ones in Station 603 measurements which probably result from response of structural elements.

Directions of the various components of motion are consistent. The initial vertical acceleration pulse is upward for the ground-transmitted signal and downward for the air-shock induced one at all stations. Initial radial pulse is outward from Ground Zero for all signals from both sources with the doubtful exception of the ground-transmitted signal at Station 650.03. Initial tangential pulses are less consistent; the pulse from the ground-transmitted acceleration is clockwise for the ground stations, 650.01, 650.02, and 650.03, but is reversed for the shelter station, 603, and a similar reversal occurs in the air-shock induced signal, which is counterclockwise at all stations except 603.

1.5.2 Velocities

Velocity-time information was derived by integration of data from each measured acceleration component. A detailed description of the integration process is included in Appendix B.

Integrations over time intervals of the order of 5 sec or longer were required even for strong motion portions of the ground-transmitted accelerations. Integration over periods of such length magnifies excessively the influence of very small low-frequency drifts in the primary recorded data. This effect becomes more serious where signal-to-noise ratio is low, even though the noise component of the recorded data may be erased by the integration. The magnification is, furthermore, strongly enhanced when a second integration of the data is performed. The significance of small long-duration extraneous drifts in the primary data to the results of integration is evident if it is realized that an additive correction in acceleration data appears as a linear increase in velocity and as a parabolic increase in displacement. For example, slow sinusoidal or linear changes of the order of a fraction of 1 per cent of carrier voltage can, for long-duration integrations, introduce effects that distort the velocity curve badly and obscure small but real displacements.

Complete correction of data for integration was frequently neither feasible nor possible in this analysis, and all corrections involved some degree of arbitrariness. Consequently, in reviewing results of the first integration of the acceleration-time data, unrealistic or improbable results were often eliminated, and it was always necessary to recognize that precision had been lowered by the integration.

Velocity-time curves for each accelerometer station are included in Figs. A.1 to A.11. These represent the corrected velocity data from which displacements were derived. Data from these velocity curves are compiled in Table 1.3. Maximum velocities enclosed in parentheses represent peak-to-peak values of the higher frequency signals which are reasonably independent of the spurious values introduced by instrument drift. Computed peak velocities and low-frequency components are in some cases introduced by extraneous sources.

Velocities computed for Station 650.01 are probably irrelevant because only the early part of the ground motion was recorded before the circuit failure at 1.436 sec (vertical dashed line in Fig. A.1). Magnitudes of the velocities included in Table 1.3 for this station may be reasonable, but it is highly probable that a very different range of velocities would have been observed had the complete acceleration-time sequence been recorded.

Ground-transmitted velocity curves for Station 650.02 illustrate the effect of long-period minor changes in recorded acceleration which are probably extraneous to ground motion. All three components of velocity at this station, Figs. A.2 to A.4, include one signal of about 3.5 to 4 cps and another signal of either 0.6 or 0.3 cps. The former corresponds to the dominant frequency in the acceleration, and the latter is hardly distinguishable in those data except perhaps as a modulation in the radial and tangential curves. The full significance of these low-frequency effects cannot be appreciated from the velocity data alone, although they do evidently increase the maximum peak-to-peak amplitude of the velocity by factors of from 1.5 to 3. The more serious effect of the anomalies will be noted in displacement data.

There are somewhat similar anomalies evident in the air-shock induced portions of the velocity curves, although here the spuriousness is not so certain; the low-frequency components may well be legitimate ground-transmitted signals comprising part of the late seismic reflection or a Rayleigh wave. However, that portion of the curve, particularly for Station 650.02, which corresponds to the high-frequency acceleration appears only as relatively minor oscillations in the velocities superimposed on much lower frequency signals of amplitudes several times those of the high-frequency component. Because the durations of the damped wave-train associated with incidence of the air shock are short and data were integrated over a correspondingly short period, long-period drifts have little influence on the results. However, the length of the air-shock induced accelerations included in the integration is considerably less than that of the positive phase of the air shock and may not give a complete picture of maximum velocities.

Velocity curves derived for Station 650.03 (Figs. A.5 to A.7) are essentially free of serious extraneous signals. The earlier part of the curves (ground signals) shows no long-period large-amplitude effects. The air-shock portion of the curves includes a 1.1-cps signal, but this is compatible with reflected signal frequencies and its occurrence at about 9 sec after zero time suggests that it may be part of a reflected pulse. The data in Table 1.3 for this station are therefore all valid. Parenthetic values of amplitude represent a superimposed signal in the case of the air-shock induced ground velocities and are approximately the sum of the positive and negative peak velocities of the earlier part of the curves.

Vertical and tangential velocity data from the shelter, Station 603, include a long-period oscillation which might be spurious. A similar long-period effect is not obvious in the radial velocity. The air-shock induced velocities are reasonably free of extraneous signal, although two frequencies are evident. One of about 100 cps may represent reaction of the structural element itself and the other, about 10 cps, oscillation of the structure-foundation system.

Data from Station 650.06 are of no real significance to damage or to structural response. However, these data, in particular those transmitted from Ground Zero through the earth, were used for testing integration procedures. Numerous corrections were made as noted in Appendix B, and only a short portion, including the first reflected signal, was carried through the finally corrected integration. Duration of the data integrated for the air-shock induced curve is short so that effects of spurious signals similar to those which altered ground-transmitted data are not noticeable.

1.5.3 Displacements

Corrected velocity-time data were integrated to displacements. Iteration serves to enhance further the influence of the long-period components at the expense of the short-period signals. In the second integration this effect can result in extinction of the short-period information, making the results worthless. Unfortunately in some instances this result was attained in processing the Operation Ivy acceleration data.

Displacement-time data are included in the graphs of Appendix A as the third curve in each figure. Data from these curves are compiled in Table 1.4. Maximum displacement values in

Table 1.3—GROUND-VELOCITY DATA

			Velocity					
			Ground-transmitted			Air-shock induced		
Station number	Ground range, ft	Component	Max. pos.,* ft/sec	Max. neg., ft/sec	Freq.,† cps	Max. pos.,* ft/sec	Max. neg., ft/sec	Freq.,† cps
650.01	8,302	V	0.41	0.85	42			
		R		0.98	38			
		T	0.009	0.10	62			
650.02	18,334	V	0.90 (0.61)	0.93	3.4 (0.3)	0.29	0.04	22 (7.5)
		R	0.62 (0.87)	0.60	4.0 (0.6)	0.22	0.11	(8.3)
		T	0.33 (0.47)	0.33	3.7 (0.6)		0.25	
650.03	21,264	V	0.53 (0.83)	0.30	1.8	0.80 (0.44)	0.73	1.1
		R	0.57 (0.77)	0.36	3.1	0.63 (0.39)	0.74	1.1
		T	0.17 (0.44)	0.32	3.5	0.37 (0.14)	0.60	1.1
603	30,226	V	0.48 (0.65)	0.63	3.7 (0.3)	0.15 (0.49)	0.40	63 (9)
		R	3.83 (6.48)	2.85	2.4	0.18 (0.35)	0.17	105 (9)
		T	0.33 (0.65)	0.45	3.3 (0.2)	0.056 (0.08)	0.048	111 (12)
650.05	No record							
650.06	114,182	V	0.056 (0.10)	0.048	1.5	0.0080 (0.016)	0.0079	20

*Maximum velocities enclosed in parentheses represent peak-to-peak values of the higher frequency signals.

†Values enclosed in parentheses are those of apparently secondary importance.

Table 1.4—GROUND-DISPLACEMENT DATA

			Displacement*					
			Ground-transmitted			Air-shock induced		
Station number	Ground range, ft	Component	Maximum, in.	Residual, in.	Frequency, cps	Maximum, in.	Residual, in.	Frequency, cps
650.01	8,302	V	0.4					
		R						
		T						
650.02	18,334	V	(−9.1)	(−2.)	(0.15)			
		R	1.2 (−3.2)	0.3 (−1.0)	2 (0.6)			
		T	0.5 (−2.9)	(−0.75)	1.4 (0.6)			
650.03	21,264	V	1.0 (−1.5)	−0.2	0.3 (2)	−1.7	1.05	0.8
		R	1.1 (−1.7)	0.5	0.3 (2)	−2.2	1.0	0.6
		T	0.7 (−0.9)	−0.5	0.5 (2.4)	−1.8	0.0	1.1
603	30,226	V	−5.5	1.9	0.13 (1.6)	−0.15	0.08	3.8
		R	4.8	0.9	0.14 (1.6)	−0.05		7.5
		T	0.9	−1.2	0.29 (1.4)	−0.008	0.005	15
650.05	No record							
650.06	114,182	V	0.13 (0.20)	0.03	1.5 (0.17)	−0.001	>−0.001	18

*Maximum displacement values in parentheses are curve maxima; displacements not enclosed are either maxima or peak-to-peak values which are directly attributable to the measured acceleration.

parentheses are curve maxima and represent in some cases the effect, wholly or in part, of uncorrected spurious instrument or circuit drifts. Displacements not enclosed parenthetically are either maxima or peak-to-peak values which are directly attributable to the measured acceleration. These are not necessarily true maxima because the integration process tends to submerge short-period peaks in long-period oscillations.

No useful information concerning displacement can be derived at Station 650.01. No significant maximum or residual values occur in the data prior to failure indicated by the carrier monitor record.

Information contained in the vertical displacement curve for Station 650.02 appears to be worthless because the 0.3-cps component noted in the velocity data obscures the 3.4-cps data in the curve. The 9-in. negative displacement is probably excessive, and no safe estimate can be made.

Radial and tangential displacements at Station 650.02 are less seriously affected by spurious long-period signals. However, validity of the 3.2-in. maximum radial and 2.9-in. maximum tangential displacements is uncertain, and the 1.2- and 0.5-in. peak-to-peak displacements are probably more reliable information.

Displacements associated with the 20- to 40-cps acceleration produced by incident air shock are negligible and only barely perceptible as an inflection of the curve resulting from longer-period ground-transmitted effects.

The existence or importance of false displacements in the ground-transmitted data for Station 650.03 is not so definite as at Station 650.02. However, the positive pulse of 1.5 sec duration in the vertical and radial displacement curves may be the result of false data. Peak-to-peak amplitudes of the higher frequency signals, or the first inflection representing the integrated first half-cycle of the velocity curve, indicate displacements which are certainly not greater than maximum and may be low. Tangential displacements also include a long-period component, but maxima and peak-to-peak values of higher frequency components of this curve differ very little.

Air-shock induced displacements for all components at Station 650.03 are of very similar shape. There is a negative displacement peak of 1.5 to 2.0 in. between 8.9 and 9.0 sec. None of the curves show the influence of the damped 20- to 80-cps sinusoidal pulse which is so strong in the acceleration curve.

Motion of the shelter, Station 603, shows a long-period displacement dominating all three components of the ground-transmitted effect but reaching a peak at successively later times for vertical, radial, and tangential data. The displacements are large, possibly too large to be realistic, but they suggest a long-period surface wave in which displacement follows a sequence — down, up and out, in and counterclockwise — which is reminiscent of the hydrodynamic wave recognized by Leet after the Trinity test.[7] Lack of coincidence of these large displacements indicates that they are probably not instrumental error, although the amplitudes are large. At this station there is evidence, especially in the radial and tangential displacement, of motion from an independent source at a frequency of about 1.6 cps corresponding to the higher frequency components of the ground-transmitted signal at Stations 650.02 and 650.03.

Air-shock induced displacements from high-frequency accelerations at Station 603 are again negligible, but displacements of the order of tenths of an inch vertically and hundredths of an inch radially and tangentially at 1 cps are evident and do not appear to be spurious.

Finally, the integrated data from the vertical accelerometer at Station 650.06 on Parry indicate peak-to-peak ground-transmitted displacements at 1.5 cps of about 0.13 in. superimposed upon a 6-sec cyclical variation. Air-shock induced displacements are of the order of 0.001 in.

1.6 DISCUSSION OF RESULTS

Ground-motion measurements of Project 6.5 show unfortunate gaps. Data from the stations nearest to and most remote from Ground Zero are not useful, data from Station 603 are anomalous because instruments were mounted on a structure as an expediency following failure of underground instrumentation, and data from Station 650.05 on Aomon are lacking because of recorder failure.

This study is limited, consequently, to information from two stations, 650.02 and 650.03, which should be pertinent, and a third, 603, of doubtful pertinence. The latter data, although highly significant to the reaction of surface structures of the type used for recorder shelters at Pacific Proving Grounds, can be related to ground motion in this study only by crude extrapolation from shorter ground ranges.

Results from the most remote instrumentation, that on Parry, could at best have been of academic interest and, because of a too optimistic estimate of set range, were burdened by low signal-to-noise ratio and serve principally as tests of integration techniques (Appendix B).

Ground motion of sufficient magnitude to damage underground structures in the Pacific Proving Grounds evidently did not occur at scaled ground ranges ($R/W^{1/3}$ in ft/lb$^{1/3}$) as great as 6.6 (Engebi) where the recorder shelters were intact following Mike shot. However, the earth-covered recorder shelter on Bogon, Station 600, at a scaled ground range of 3, was subjected to such severe motion, probably from incidence of the air shock, that failures were produced in the recording circuitry and steel doors were jammed. Correlation of ground-motion data with damage at these stations is of doubtful significance because of the incompleteness of information from the instrumentation at Station 650.01 near the recorder shelter on Bogon.

1.7 CONCLUSIONS

1. Data from only two of the six stations instrumented were wholly suited to the purpose of the ground-motion study.

2. Information from these two stations and such partially usable data as were available from other stations suggest that, for the Pacific Proving Grounds, maximum ground-transmitted accelerations from weapons burst above ground may be estimated from the empirical equation

$$AW^{1/3} = K\lambda_R^{-3.1}$$

where acceleration is in g units and the scaled ground range λ is derived from $W^{1/3}$, the cube root of the radiochemical yield expressed as pounds of TNT. The coefficient K has values between 2.66×10^5 and 2.1×10^5 for scaled heights of burst between 0 and 0.14 ft/lb$^{1/3}$.

3. Acceleration induced in the ground at Pacific Proving Grounds by locally incident air shock is related to the peak air overpressure by the equation

$$A = 0.053p^{1.2}$$

for accelerations in g units and pressure in psi, with an error of ±30 per cent.

4. Motion of elements of a massive, rigid structure founded on loose water-filled sands may be from 2 to 6 times greater than the motion of the soil, although the frequency of the motion will be similar to the latter, according to data from Station 603. Motion of such structural elements induced directly by air shock appears to be considerably greater than ground motion from the same source and will include a frequency characteristic of the structural element.

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CHAPTER 2

GROUND MOTION FROM SHOT OF OPERATION CASTLE

2.1 PURPOSE

Study of the ground motion produced by burst of megaton-yield weapons near the ground surface was planned for Operation Castle to extend and supplement the incomplete results of Project 6.5 of Operation Ivy. Primarily interest was focused on ground motion closer to Ground Zero than during the previous test and on data to fill the vacancy left by incomplete records from Station 650.01.

2.2 PLAN OF THE EXPERIMENT

The general plan for Project 1.7 included observation of vertical, radial, and tangential components of acceleration in the ground below the water table at ground ranges corresponding to 200-, 100-, and 40-psi air overpressure.

Specific plans required that instrumentation be split between shot to be fired on Eninman Island of Bikini Atoll and the shot to be fired on Eberiru Island of Eniwetok Atoll. This split was dictated partly by available information channels but more critically by the fact that the larger yield burst, was scheduled for an atoll whose subsurface conditions differed to an unknown degree from those which had affected the ground-motion data from Mike shot of Operation Ivy. Since the data from the new project were not expected specifically to overlap those from Mike shot, but were to replace an important partially recorded set of information, it was considered advisable to include check measurements involving insofar as possible subsurface conditions similar to those which prevailed for the previous operation. Such a check test was feasible on the shot, although the estimated yield was in the fractional megaton range.

These considerations were the basis for choice of three accelerometer stations (Fig. 2.1) on Bikini Atoll at a ground range of 2600 ft on Eninman (Station 170.01) and on Reere at ground ranges of 3650 ft (Station 170.03) and 5600 ft (Station 170.02), corresponding to approximately 200-, 100-, and 36-psi air overpressure for the estimated 1-Mt yield. Similar considerations were involved in locating two stations at Eniwetok Atoll on Rujoru at ground ranges of 2450 ft (Station 170.05) and 3000 ft (Station 170.04), corresponding to estimated overpressures of 70 and 40 psi for the predicted Ramrod-shot yield of 0.2 Mt.

Boring logs for islands of the Eninman-Airukiiji complex at Bikini indicated considerable difference between subsurface conditions there and at Eniwetok. However, soil and rock conditions reasonably consistent with those prescribed for Operation Ivy ground-motion stations existed at depths of about 15 ft on Eninman and Reere. Consequently accelerometers at

Stations 170.01, 170.02, and 170.03 were placed at that depth; those at Stations 170.04 and 170.05 on Rujoru were placed at a depth of about 17 ft in agreement with gauge depths adopted for similar stations on Operation Ivy.

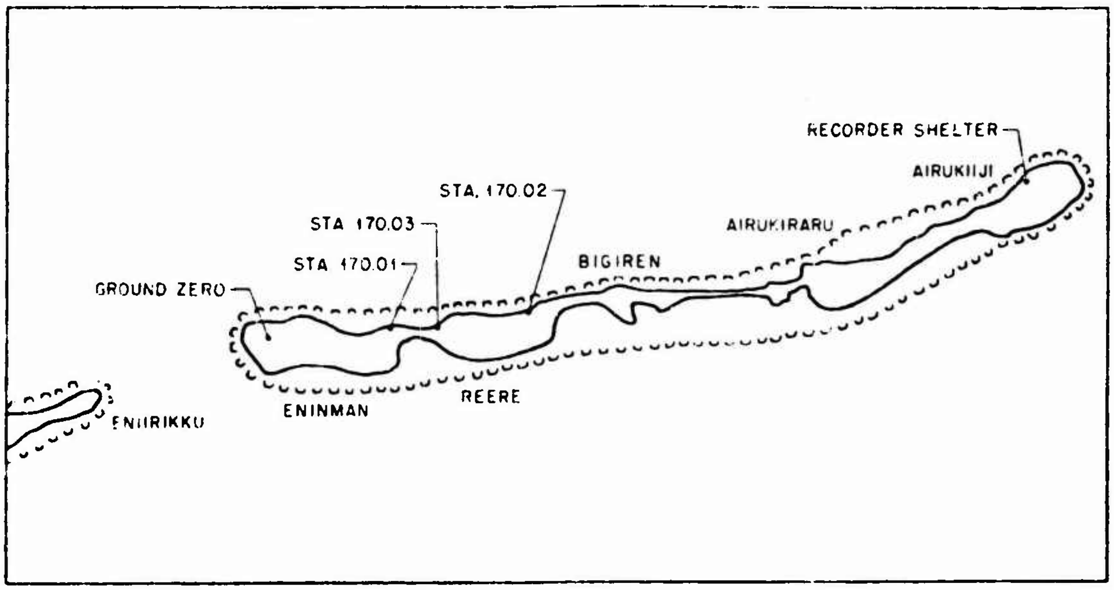

Fig. 2.1 — Site plan showing location of ground-motion stations for , Operation Castle (Bikini Atoll).

2.3 INSTRUMENTATION

End instruments and mounts were essentially the same as those used for Project 6.5 of Operation Ivy. The cases in which the accelerometers were mounted were redesigned to ensure better waterproofing. Instrumentation for recording gauge output consisted of carrier amplifiers and magnetic tape recorders backed up by photographic recorders and is described in the instrumentation report for the Sandia Laboratory projects.[1]

Set ranges for the accelerometers were assigned on the basis of data from Operation Ivy. Initial set ranges were increased shortly before calibration as a result of an increased estimate of yield. Final set ranges for vertical and radial components were 33 g for Station 170.01, 24 g for Station 170.03, and 9 g for Station 170.02. Tangential component ranges were lower.

Calibration procedures and installation were essentially the same as those used during Operation Ivy. The spin-table used for accelerometer calibration was revised to ensure smoother operation.[1]

2.4 DATA ANALYSIS

Eight of the nine acceleration channels for operated satisfactorily. The ninth channel, responding to vertical acceleration at Station 170.01, became inoperative probably because of damage to the cables by water waves from one of the earlier shots. It was not feasible to repair or replace the gauge since it was already in the ground. Consequently no vertical acceleration data were recorded for the close-in station.

The yield of shot was about one-eighth the earlier estimate of 1 Mt and about one-twelfth the estimated yield used for final calibration. The result of low-yield and consequent high set ranges was very low recorded signal amplitudes. A secondary result of the low yield of shot was cancellation of the shot and consequent limitation of the ground-motion data to those from the earlier shot.

Acceleration-time plots are presented in Figs. A.12 to A.14, each of which includes all components observed at one station. It is evident that, except for data from Station 170.01, the signal-to-noise ratio is so low that identification of any portion of the signal except air-shock induced acceleration is uncertain. Ground-transmitted acceleration signals are definite on the records from Station 170.01. Approximate arrival times and peak accelerations were read from the data, and the results are compiled in Table 2.1.

Table 2.1 —ACCELERATION DATA

				Acceleration							
				Ground-transmitted				Air-shock induced			
Station number	Ground range, ft	Set range, g	Component	Arrival time, sec	Max. pos., g	Max. neg., g	Freq., cps	Arrival time, sec	Max. pos., g	Max. neg., g	Freq., cps
170.01	2596	33	V	No record							
		33	R	0.31	0.96	0.47	42	0.63	3.44	4.10	90
		33	T	0.31	1.50	1.27	45	0.65	2.20	4.67	100
170.03	3650	24	V	0.39	0.37	0.25		1.24	0.23	0.55	45
		24	R	0.40	0.13	0.35		1.23	0.62	0.29	
		9	T	0.42	0.11	0.19		1.24	0.24	0.18	
170.02	5599	9	V	0.61	0.17	0.15	38	2.63	0.15	0.51	
		9	R	0.61	0.13	0.12		2.56	0.51	0.25	
		3	T	0.61	0.10	0.10		2.61	0.16	0.25	

The graph of arrival times vs ground range, Fig. 2.2, is a two-branched curve in which the ground-transmitted signal is shown to be propagated with a velocity of slightly over 8700 ft/sec and the air-shock induced signal follows the same pattern as air overpressures, being propagated at velocities which decrease with increasing ground range. The time-distance curve for air-shock induced ground motion is a short range extrapolation of the corresponding one for air-overpressure data, since the station of shortest ground range for which overpressure arrival times are available coincides roughly with the most remote ground-acceleration station.

Air overpressures were measured as part of Project 1.2 by Ballistic Research Laboratories (BRL)[2] and by Sandia Laboratory.[3] Arrival times of the close-in BRL data were not observed, but peak overpressure data were adequately precise for correlation with accelerations. However, precision of acceleration data from two stations, 170.03 and 170.02, was too low to be suitable for correlation, and the results of comparison of peak pressures and accelerations are consequently of little value. They are sufficient simply to indicate that for two stations, 170.03 and 170.02, at overpressures of about 21 and 8.2 psi the air-shock induced vertical accelerations were about 75 and 25 per cent below those predicted by Eq. 1.2 ($A = 0.053p^{1.2}$) derived from Mike-shot data.

Acceleration frequencies could be read from the recorded signals with reasonable confidence in only a few cases. These few observations, which are included in Table 2.1, indicate merely that the frequencies of shot data are similar to those observed at the close-in stations during Mike shot. Noise or other extraneous oscillations obscured the recognizable acceleration frequencies on the records for which no data were included.

Analysis in terms of velocities or displacements was not attempted because the ground motion was too small to produce structural damage and precision of the data was too poor to support integration.

Actual yield of the shot placed the 40-psi ground range at Station 170.01. These data were consequently derived from an overpressure level corresponding approximately to that of Station 650.01 for Mike shot of Operation Ivy and, had they been complete, might have been useful adjuncts to the incomplete Mike-shot data.

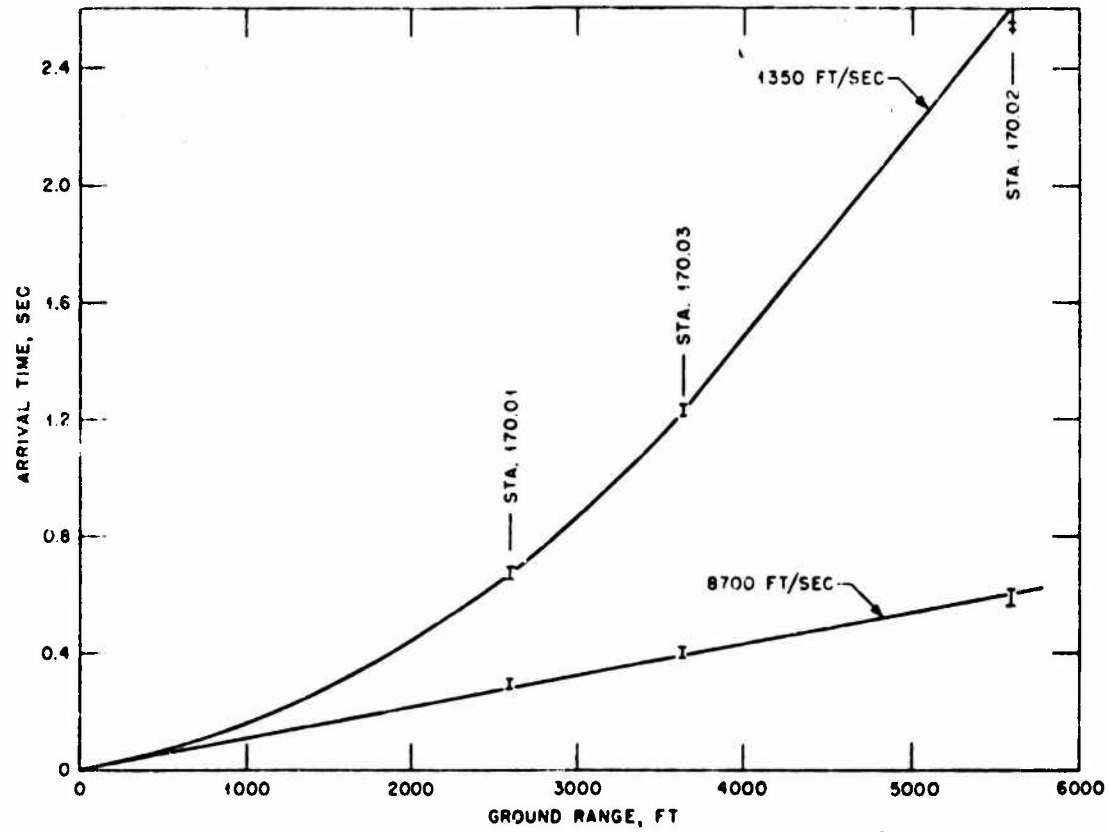

Fig. 2.2—Earth acceleration arrival times vs ground range for shot, Operation Castle.

2.5 CONCLUSIONS

The only conclusion that can be derived from the ground-motion data of Project 1.7 is that they are insignificant. They are inadequate for either correlation with damage or recorder shelter design needs and do not supplement or complete the data from Mike shot of Operation Ivy.

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APPENDIX A

GROUND-MOTION CURVES, OPERATIONS IVY AND CASTLE

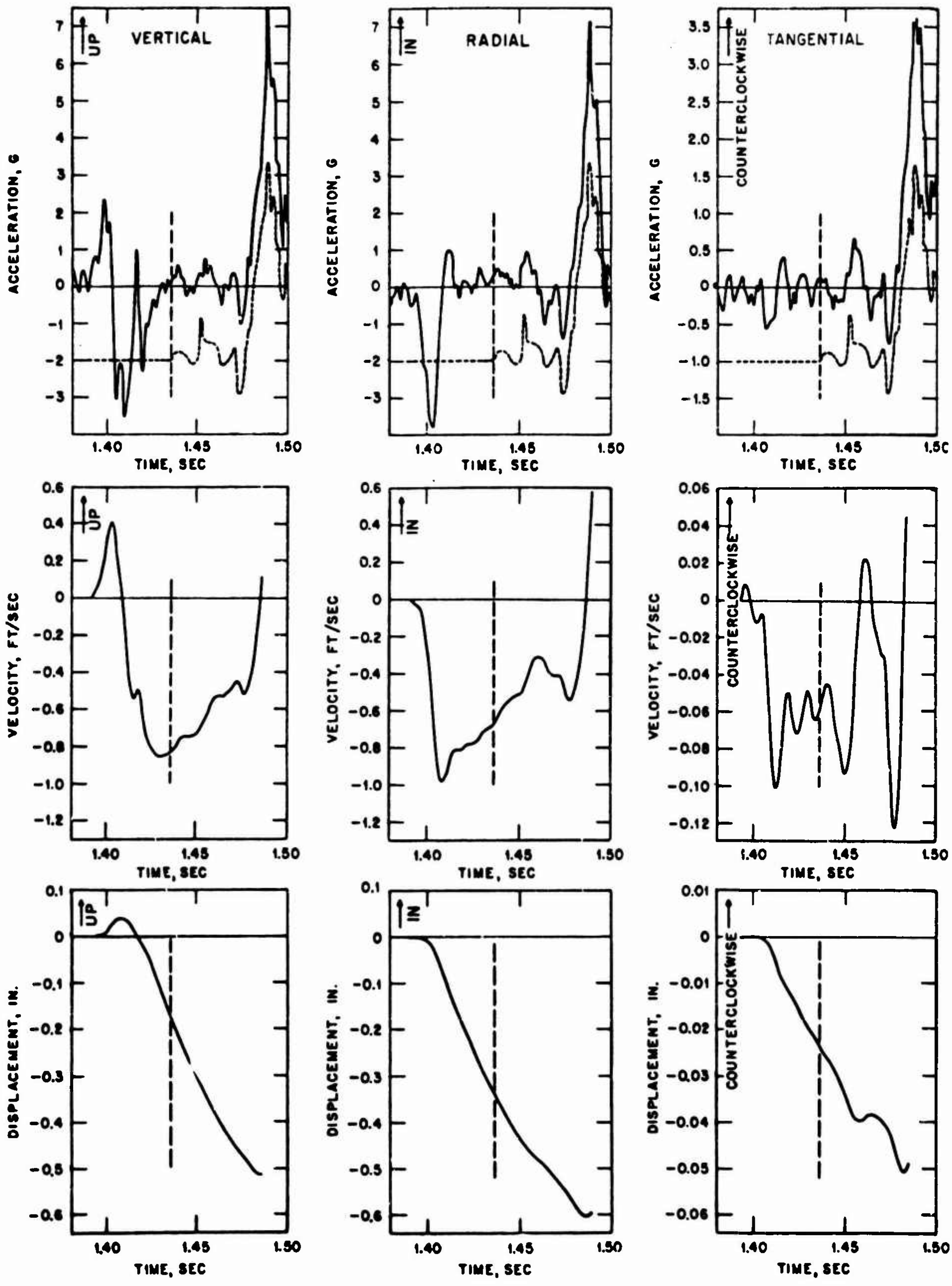

Fig. A.1—Ground motion at Station 650.01 for Mike shot, Operation Ivy (ground range, 8302 ft). Dashed curves are carrier power vs time. The start of anomalous data for each curve is indicated by a vertical dashed line.

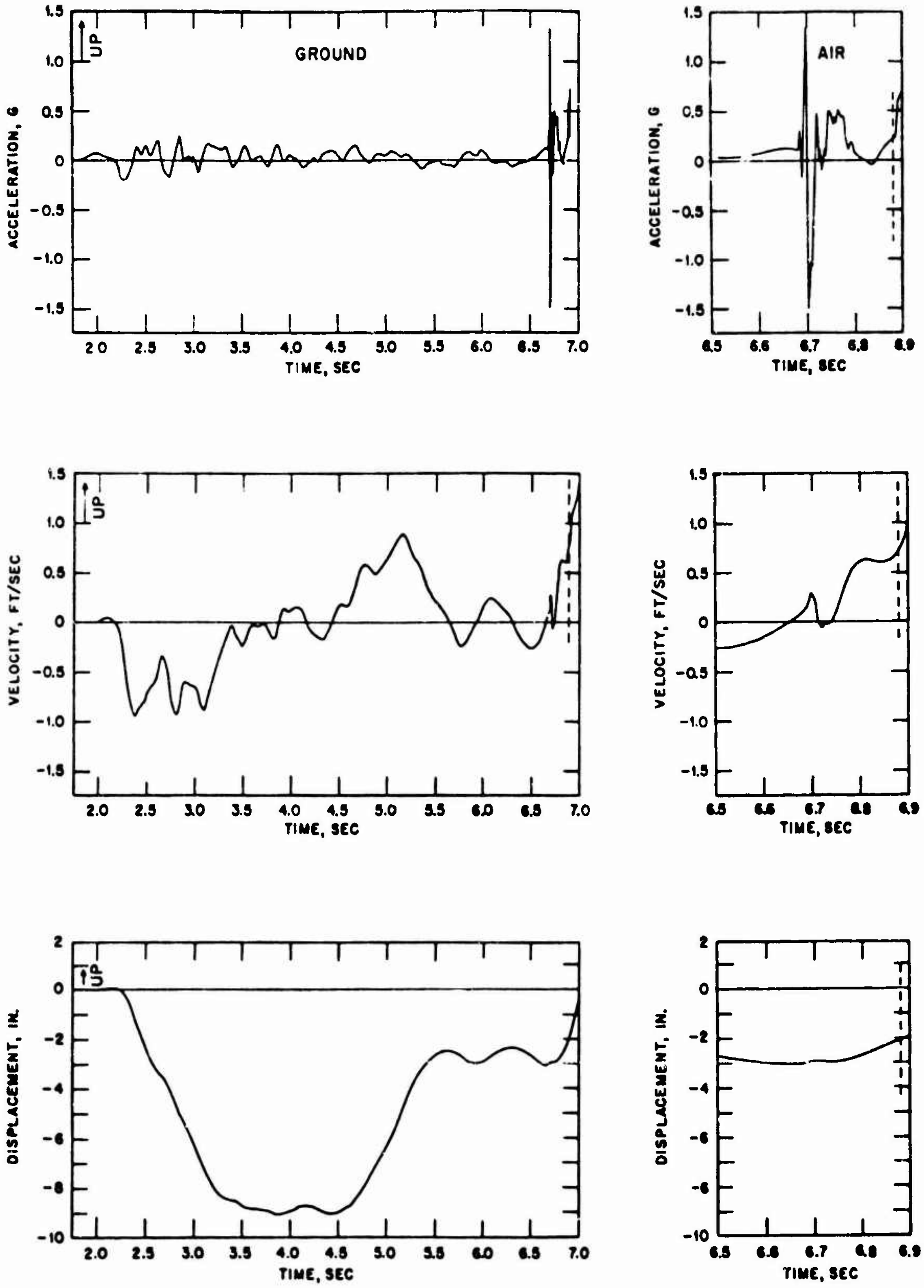

Fig. A.2—Vertical ground motion at Station 650.02 for Mike shot, Operation Ivy (ground range, 18,334 ft).

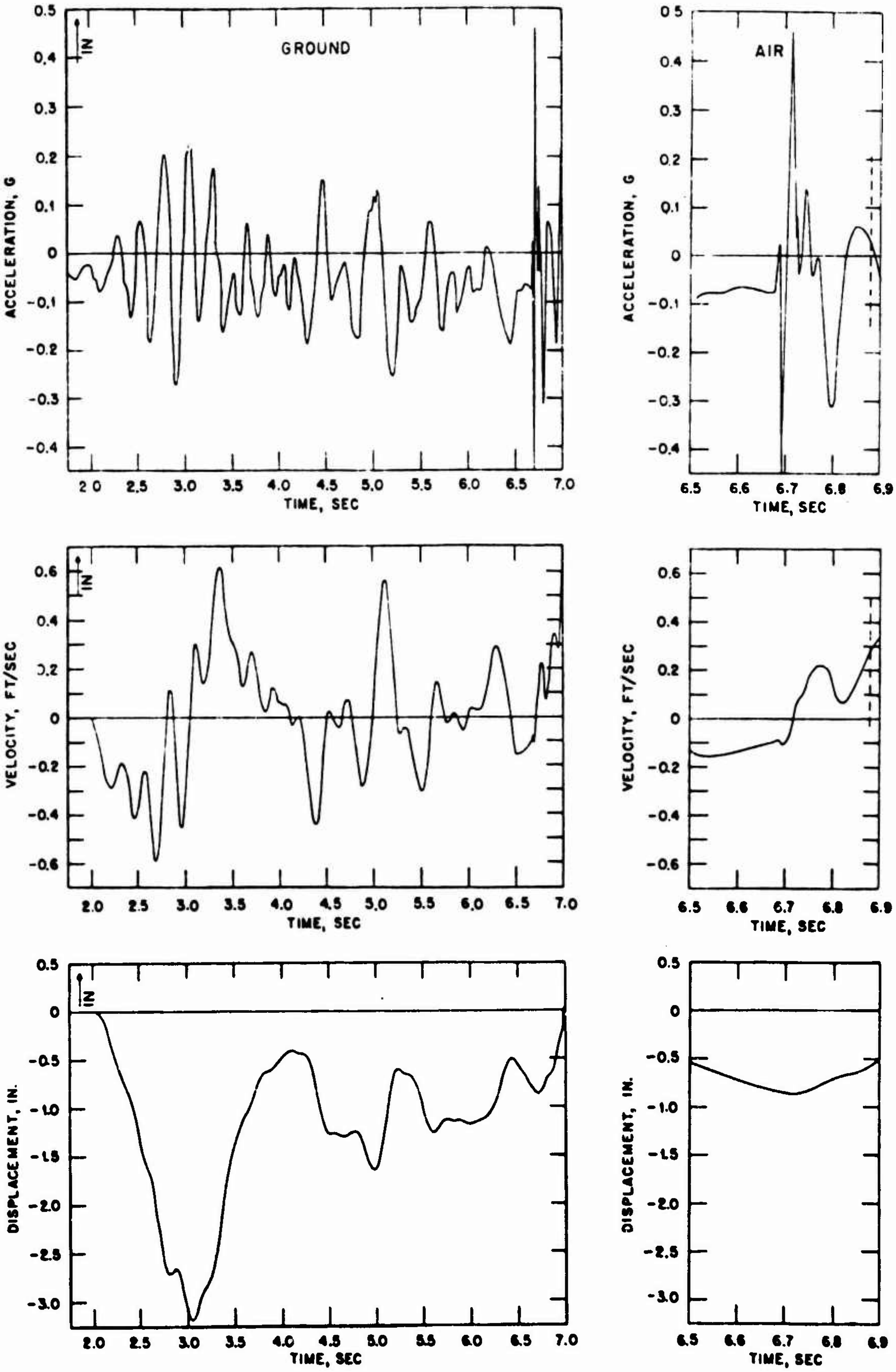

Fig. A.3—Radial ground motion at Station 650.02 for Mike shot, Operation Ivy (ground range, 18,334 ft).

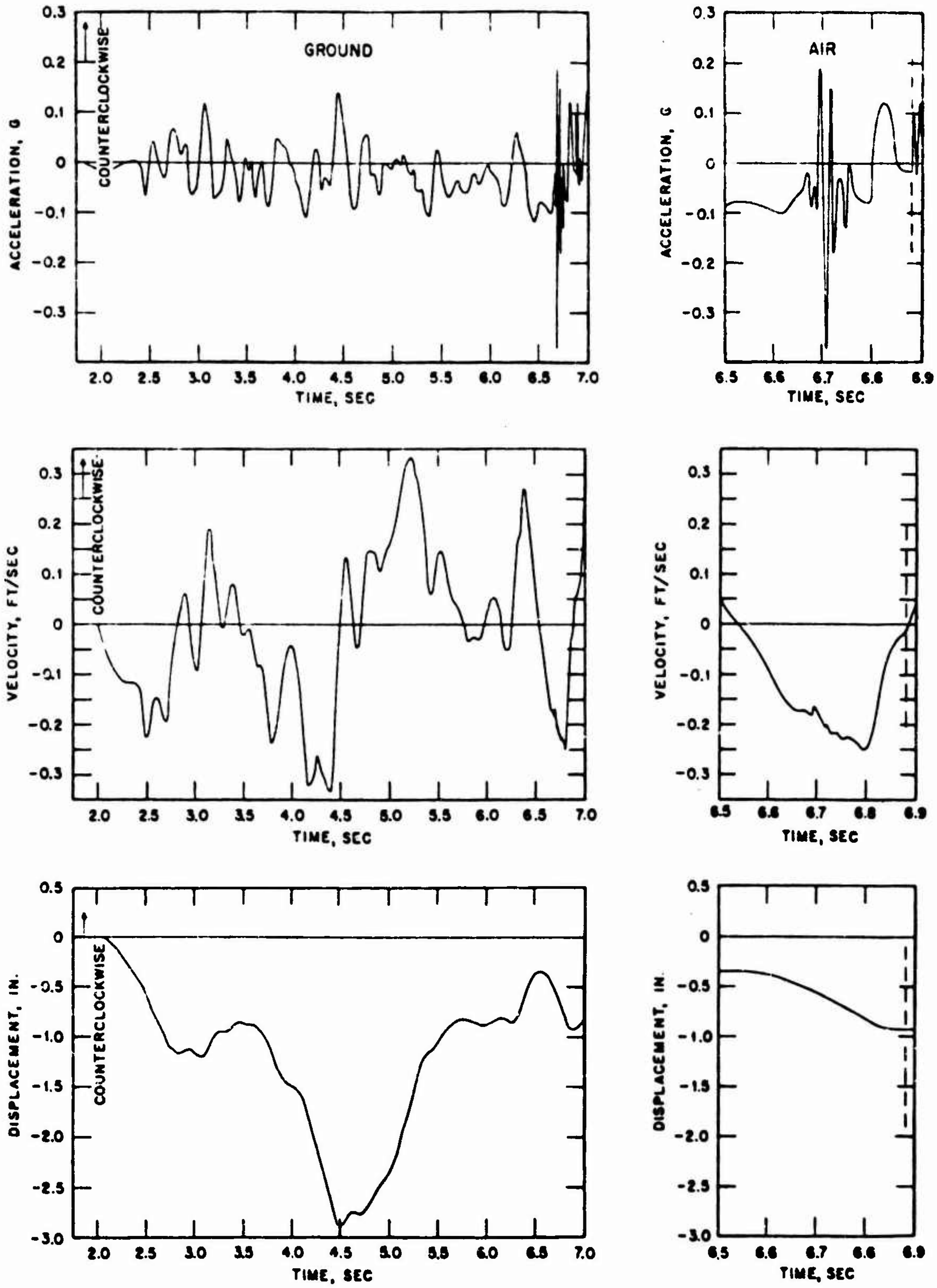

Fig. A.4 —Tangential ground motion at Station 650.02 for Mike shot, Operation Ivy (ground range, 18,334 ft).

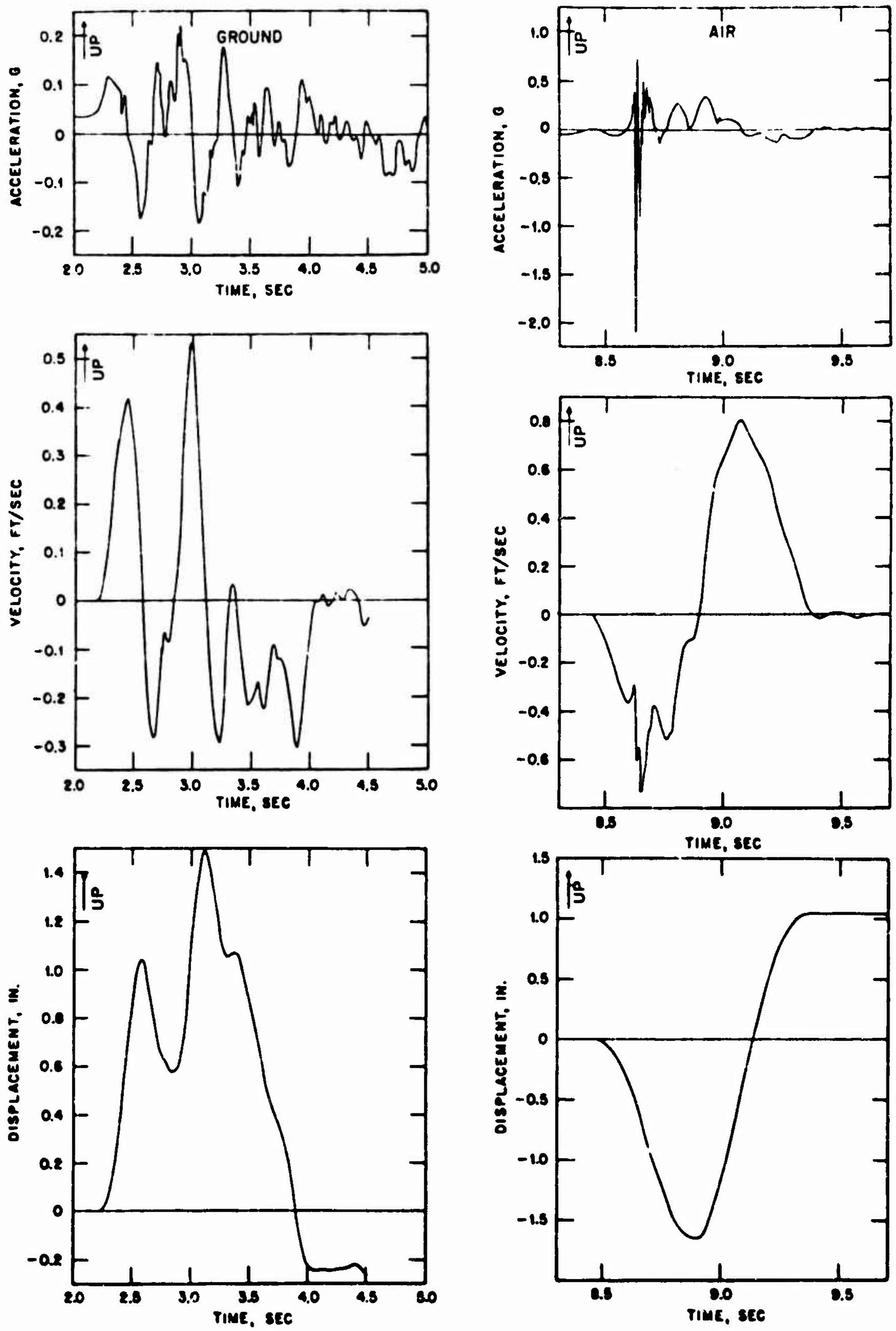

Fig. A.5 — Vertical ground motion at Station 650.03 for Mike shot, Operation Ivy (ground range, 21,264 ft).

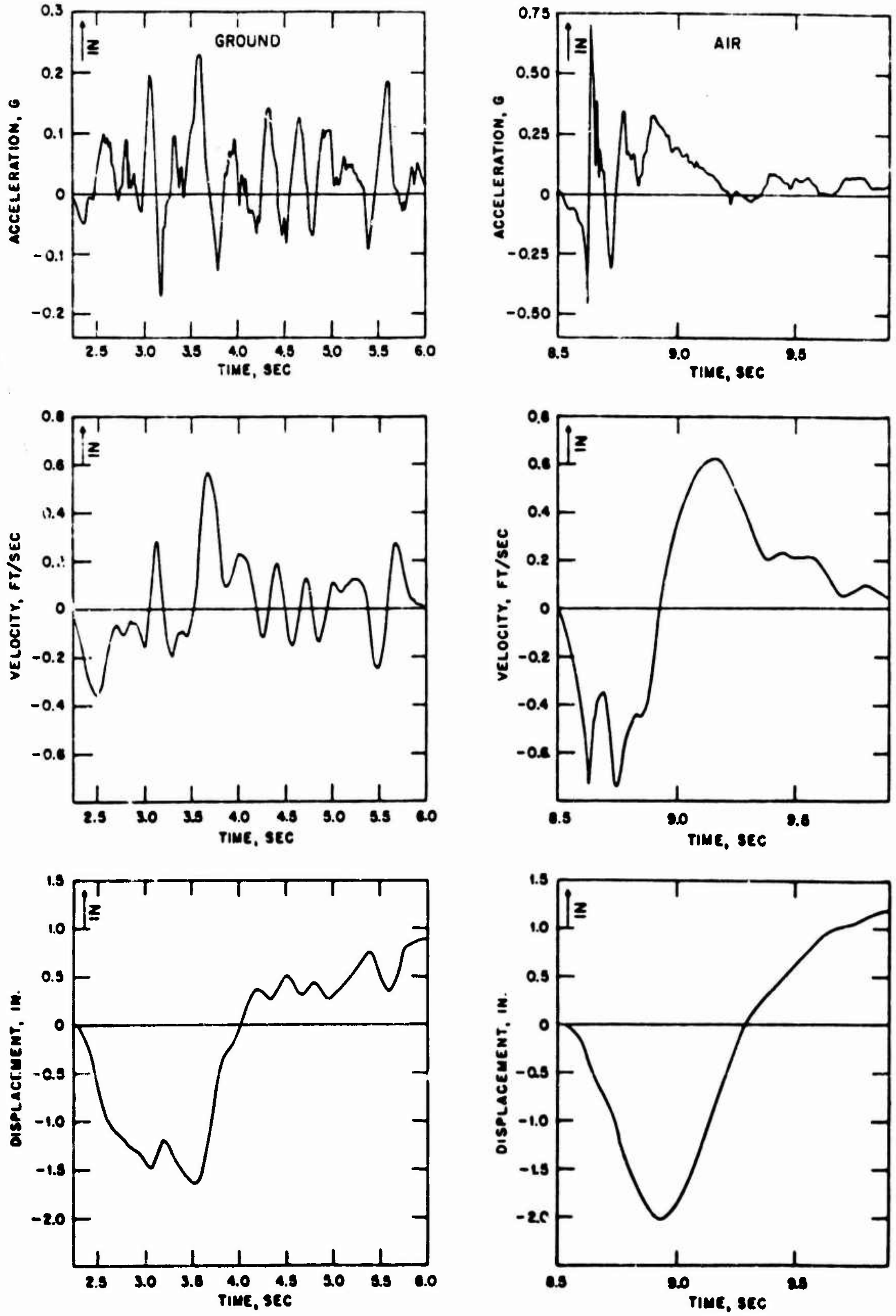

Fig. A.6 — Radial ground motion at Station 650.03 for Mike shot, Operation Ivy (ground range, 21,264 ft).

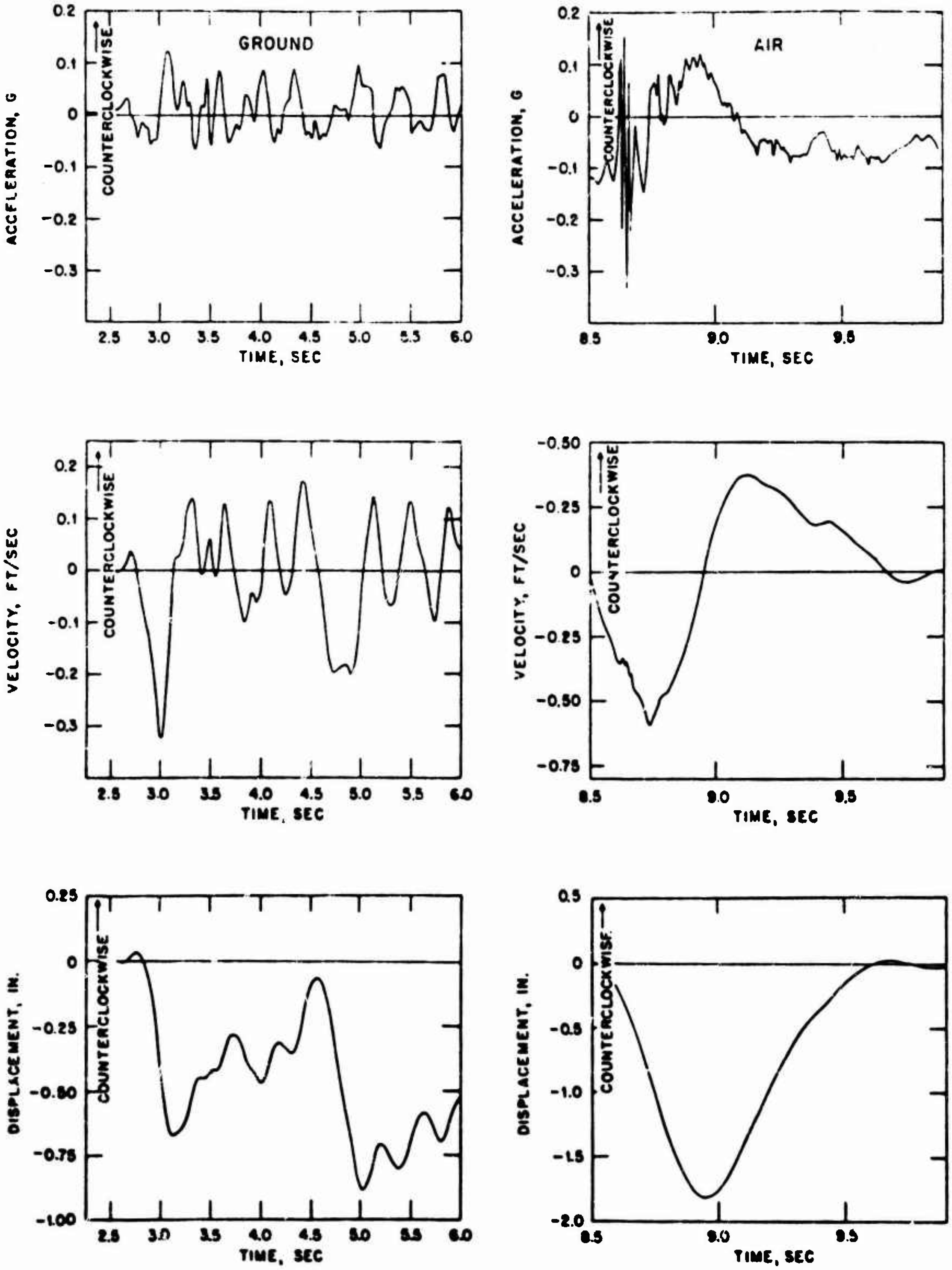

Fig. A.7—Tangential ground motion at Station 650.03 for Mike shot, Operation Ivy (ground range, 21,264 ft).

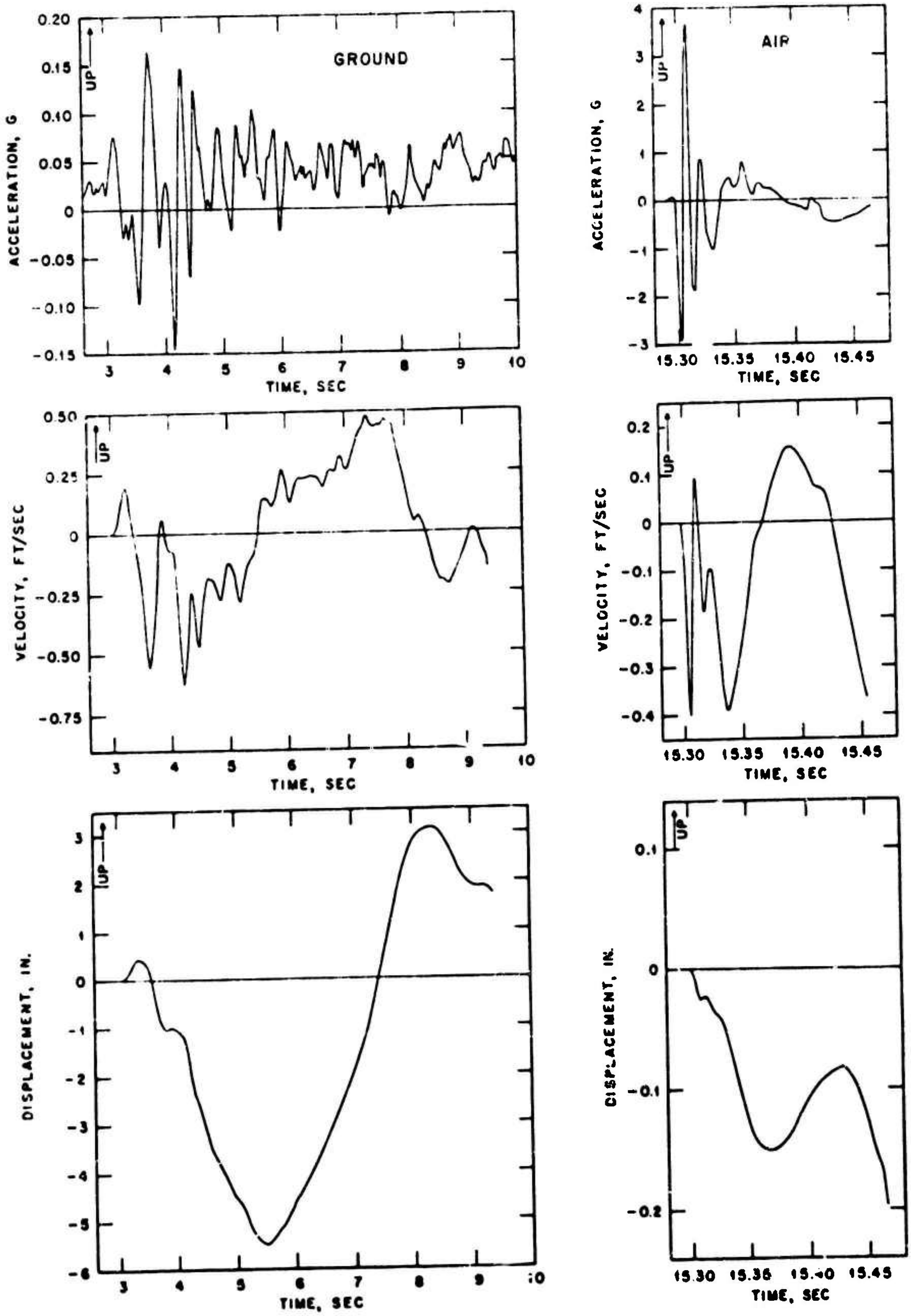

Fig. A.8 — Vertical motion of shelter at Station 603 for Mike shot, Operation Ivy (ground range, 30,226 ft).

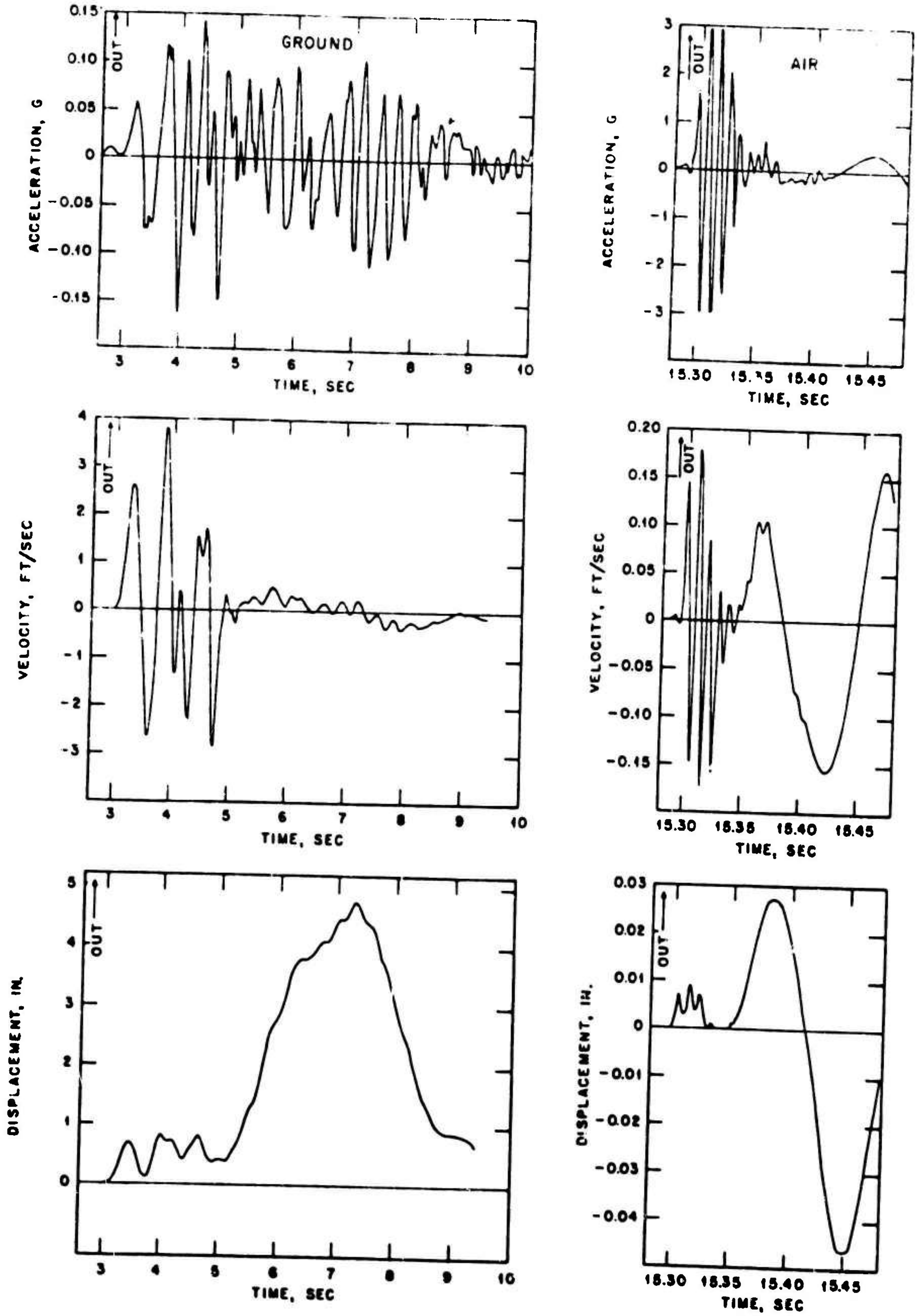

Fig. A.9 —Radial motion of shelter at Station 603 for Mike shot, Operation Ivy (ground range, 30,226 ft).

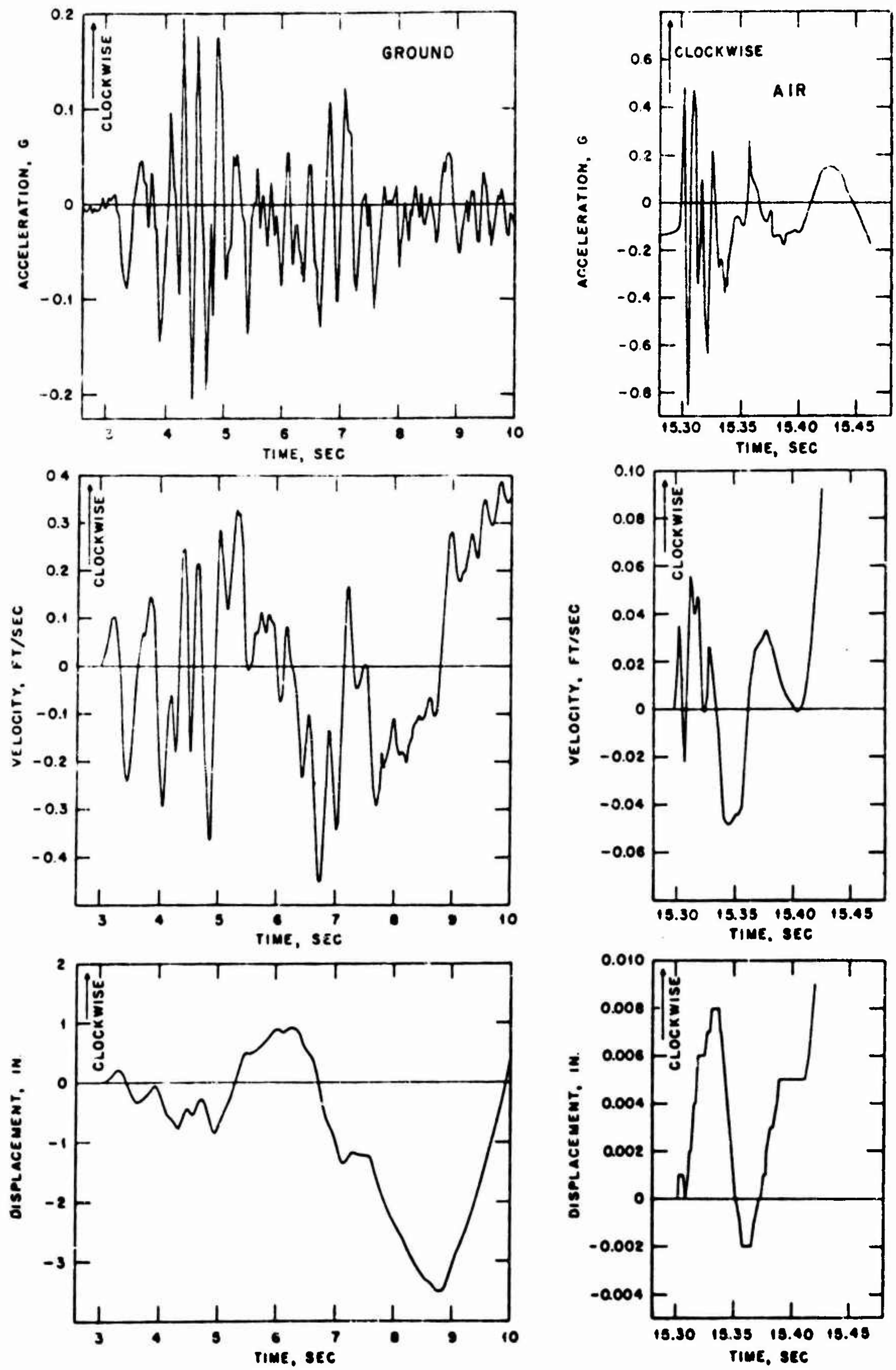

Fig. A.10—Tangential motion of shelter at Station 603 for Mike shot, Operation Ivy (ground range, 30,226 ft).

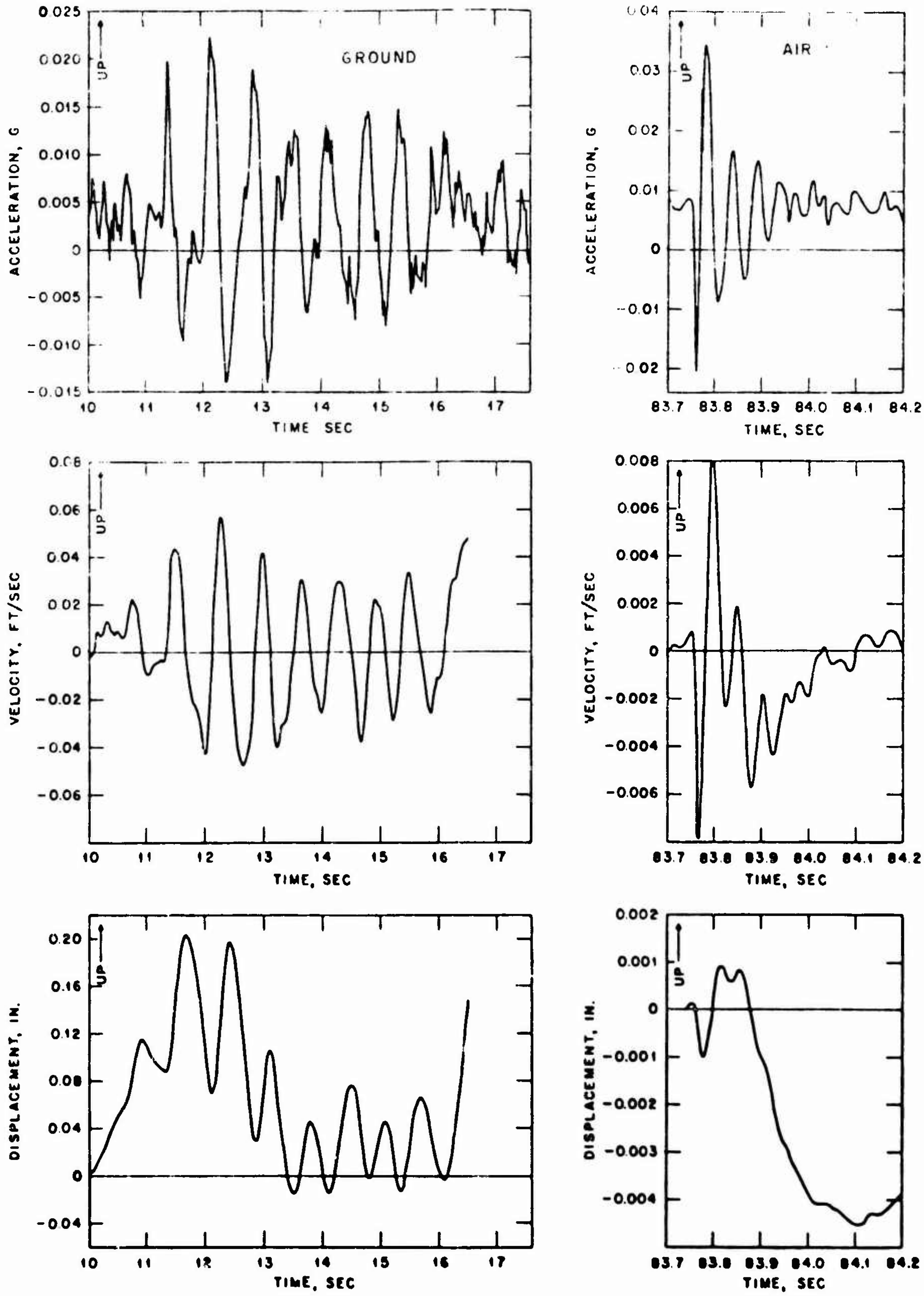

Fig. A.11—Vertical ground motion at Station 650.06 for Mike shot, Operation Ivy (ground range, 114,182 ft).

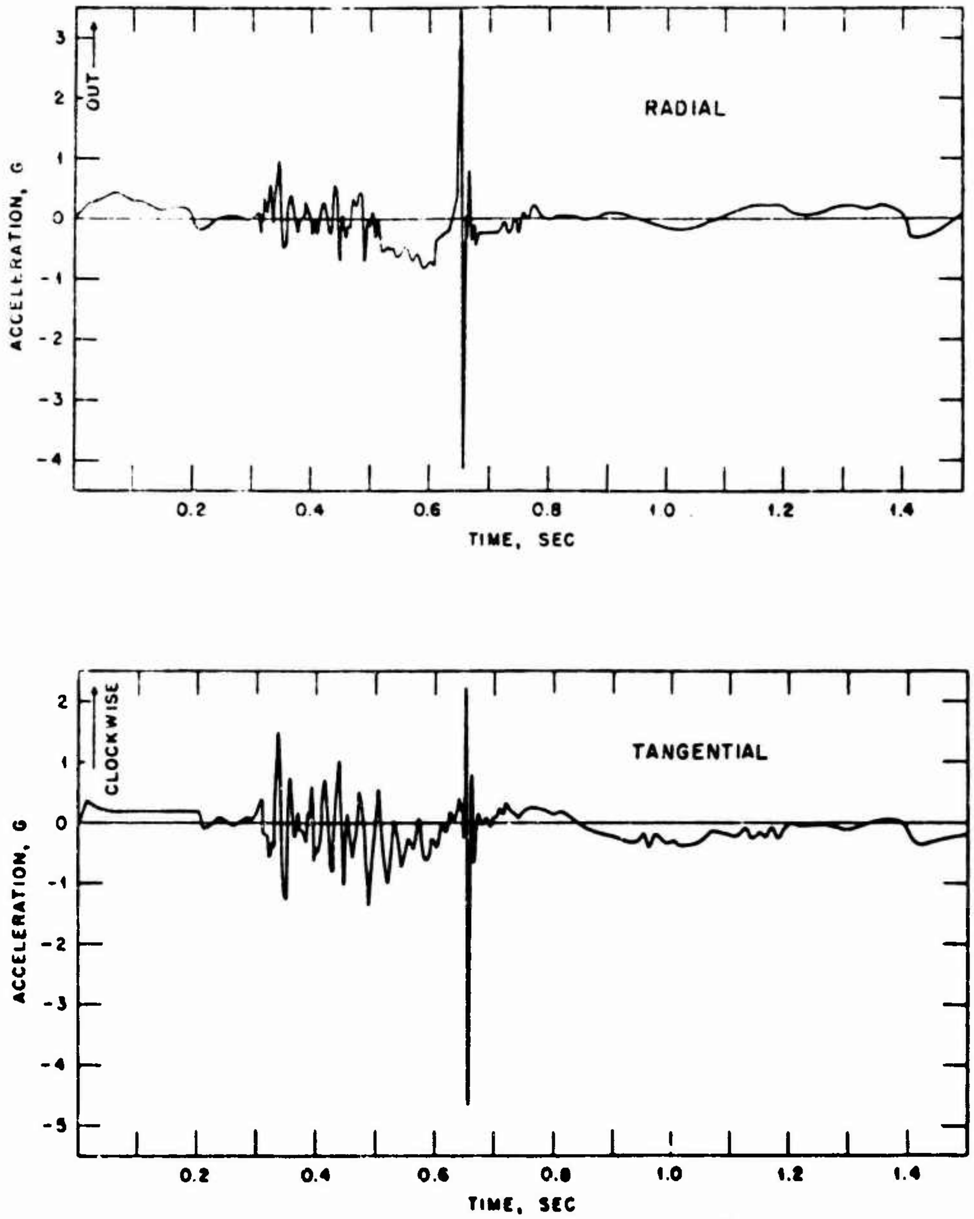

Fig. A.12—Ground acceleration at Station 170.01 for shot 3, Operation Castle (ground range, 2596 ft).

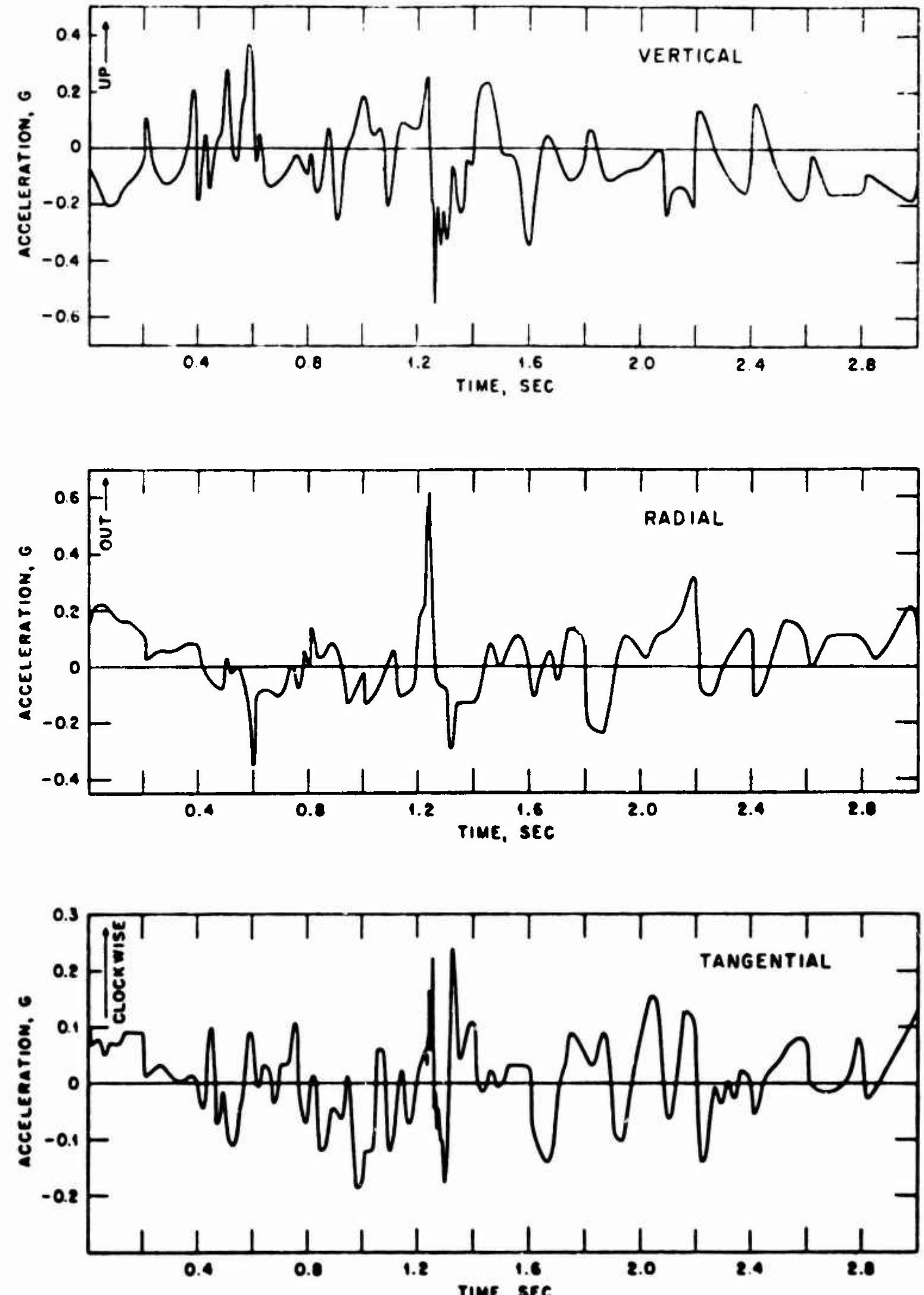

Fig. A.13—Ground acceleration at Station 170.03 for shot, Operation Castle (ground range, 3650 ft).

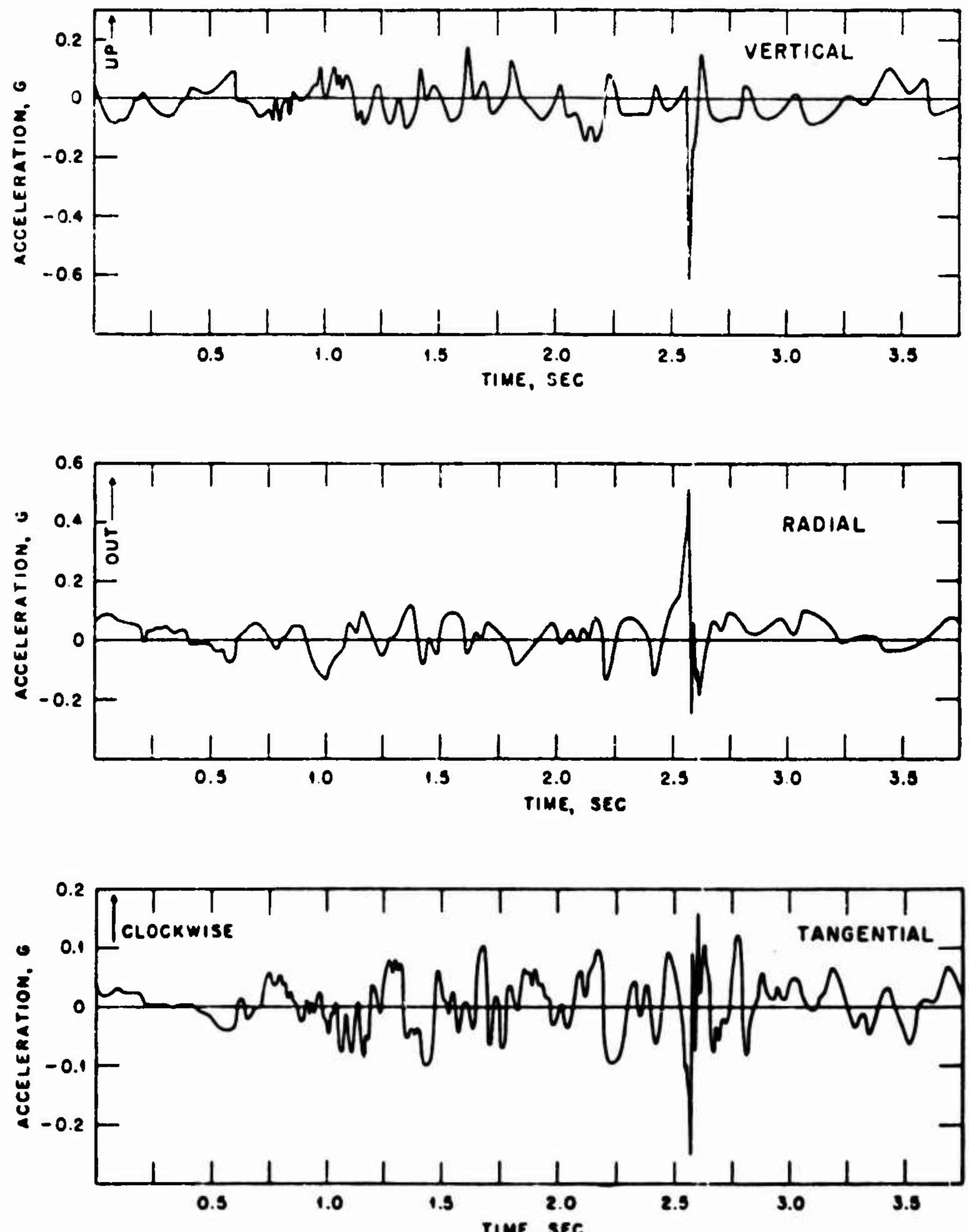

Fig. A.14—Ground acceleration at Station 170.02 for shot 3, Operation Castle (ground range, 5599 ft).

APPENDIX B

DATA PROCESSING

By George N. Landes and William R. Perret

B.1 NORMAL PROCESSING

Ground motion from large-yield explosions is observed as acceleration because instrument response favors this over direct observation of velocity or displacement. Required information concerning velocity and displacement must be derived through iterated integration of the acceleration-time data.

As observed during Operation Ivy, output of the accelerometers was recorded as a modulated carrier frequency on magnetic tape. This information was played back through a system which produced a photographic record. That record was in turn translated on Telereaders into displacements of the information trace from a reference trace as a function of time with precision of ±0.003 in. and ±0.0001 sec. These data were recorded in digital form on IBM cards and converted according to pretest calibration data to accelerations as a function of time.

B.2 TYPES OF ERROR

Several types of error may be superimposed upon the data during recording and reduction. These errors are additive and, although small enough to be neglected in the raw data, may under some conditions have a serious effect on integrated results. Two of these errors — noise and drift — are inherent to the recording and reduction circuitry. Noise is a short-period random phenomenon. Drift is a long-period low-amplitude effect which may be linear or sinusoidal. A sinusoidal drift may be of sufficiently long period compared to the interval over which integration is performed to appear as a constant or roughly linear or parabolic error. The third type of error — shift — is a constant which usually results from reader error in identifying the zero or balance point of the record trace but may also be a quasi-permanent change in the balance position of the trace caused by very strong transients.

These errors are significant only in relation to the information signal, and the signal-to-error ratio must be the criterion of importance. Integration is a cumulative process, and errors which are insignificant to raw data may assume dominant proportions in the integral if they persist over sufficiently long periods. Three questions arise concerning the effects of errors on integrated data:

1. How does integration affect the relation between signal amplitude and error?
2. What corrections are feasible?
3. To what extent can corrected results be depended upon to indicate true motion?

B.3 INTEGRATION

Integration of acceleration-time data involves summation of the trapezoidal areas defined by pairs of consecutive data points and the axis of zero acceleration. Magnitudes of elemental areas are derived by multiplying the mean acceleration amplitudes of a pair of adjacent data by the time interval between them. These areas represent incremental velocities, and their cumulative sum represents approximately the instantaneous velocity at the time represented by the last datum included in the summation. Evidently, if adjacent points are sufficiently close, the stepwise summation approximates closely the true area between the acceleration-time curve and zero axis. It is also evident that both stability of the zero balance of the record trace and its proper evaluation within the time span of the integration exercise strong control on the relative error in the result.

B.4 INFLUENCE OF ERRORS

The acceleration-time signal is some undefined function of time to which an error, either constant or a linear or sinusoidal function of time, has been added in recording or reduction. Since the error is added, the effect of integration upon it may be considered independently of the signal. The relative effect of the error on the integrated data can then be estimated roughly.

The integral of a sine function of the form $E \sin \omega t$ is $-(E/\omega) \cos \omega t$, where E is the amplitude and ω is the frequency in radians per second. Consequently the amplitude of the integral (disregarding sign) will be less than E for all values of ω greater than 1. Or, since $\omega = 2\pi f$, where f is frequency in cps, then E/ω will be less than E for all frequencies greater than $1/2\pi$, or approximately $1/6$ cps. This suggests that any sinusoidal error of frequency greater than $1/6$ cps will be diminished in amplitude by integration. But the importance of an error is its relative magnitude with respect to the signal, and relative error will remain unchanged or be diminished by integration only for those components of the signal which have frequencies equal to or greater than the error frequency regardless of its relation to the $1/6$-cps limit.

It is apparent that high-frequency error such as noise will become negligible with respect to signals of normal ground-motion range, less than 40 cps; but even the higher frequency ground-motion signals will be diminished in processing. It is also evident that integrations over short intervals, of the order of a few seconds, will be affected principally by constant or linear errors or by portions of periodic errors which may be approximated by linear or parabolic error functions. Integrations extending over very long intervals will show the influence of sinusoidal errors as such.

A constant error a becomes upon integration $at + b$, and double integration makes it $\frac{1}{2}at^2 + bt + c$. Similarly a linear error, $at + b$, in primary data becomes $\frac{1}{2}at^2 + bt + c$ in the first integral and $\frac{1}{6}at^3 + \frac{1}{2}bt^2 + ct + d$ in the double integral. The significance of these errors becomes evident if it is assumed that the primary data are represented by sine function of amplitude A and frequency f and that there is a constant error a. The relative error is expressed as the ratio of the error at any time t to the maximum signal amplitude. The maximum signal amplitude for the primary data is A; for the once-integrated data, velocity V is A/f; and for the doubly integrated data, displacement D is A/f^2. The relative errors are then for the initial constant error a

$$E_A = \frac{a}{A}$$

$$E_V = (at + b)\frac{f}{A}$$

$$E_D = (\tfrac{1}{2}at^2 + bt + c)\frac{f^2}{A}$$

It is evident that, as t increases, the relative errors E_V and E_D become rapidly greater than

A. If it is assumed that a = 0.001A; that b and c are successively an order of magnitude greater than a, i.e., b = 0.01A and c = 0.1A; and that the signal frequency f is 10 cps, then the relative errors at the end of integration periods of 5 and 10 sec are

For 5 sec	For 10 sec
$E_A = 0.1\%$	$E_A = 0.1\%$
$E_V = 15\%$	$E_V = 20\%$
$E_D = 1625\%$	$E_D = 2500\%$

Similarly a linear error at + b in the primary data would give errors of the order of 100 per cent in the velocities and 10,000 per cent in the displacements. Of course, if all of the error coefficients do not have the same sign, those of opposing sign will counteract each other and reduce the relative error in the integrals, although not usually to extinction.

B.5 CORRECTION PROCEDURE

Evidently, innocuous acceleration errors can become monstrous in their effect on the desired displacement information, and to obtain useful results correction must be made. Direct correction in the primary data is often inadequate; it is difficult, for example, to recognize a zero shift of 0.1 per cent of the peak signal amplitude. Correction can be made, however, in the velocity data by fitting a continuous curve which when added or subtracted will cause the velocity to satisfy both the initial and final conditions that it be zero before and after passage of the transient signal. Sometimes it is necessary to approximate the second condition because of the multiplicity of ground-motion signals which arrive at a station over various refraction and reflection paths, but generally some reasonable form of correction can be applied.

Similar correction would appear to be applicable to displacement data, but, in the absence of independent posttransient measurements of residual displacement, no independent criterion for a thermal condition exists other than the intuitive one that residual displacement should be less than its maximum value and that adjustment of the residual value to nearly zero should not seriously affect amplitudes of early peaks.

B.6 EXAMPLE

The ground-transmitted acceleration data observed at Station 650.06 on Parry for Mike shot provide an extreme example of multiple correction. Signal strength was very low, with consequent poor signal-noise conditions, and duration was very long. Direct integration of the acceleration data between about 7 and 35 sec yields the curve V_1 in Fig. B.1. The noise has been reduced nearly to extinction in the integral, and the curve suggests a strong parabolic increase in velocity and a roughly sinusoidal variation with a period of about 30 sec. Consideration of arrival time, frequency, and magnitudes suggests that the 1.5-cps component of the signal between about 10 and 16 sec may be a reflected pulse from the deep basalt and is probably the strongest part of the true ground motion. This 1.5-cps signal is distinguishable but is minor compared to the parabolic and 30-sec periodic components. A parabolic-error curve (the dashed line in Fig. B.1) was fitted to the velocity curve at three points, and the primary velocity error equation $E_{V_1} = 0.001875t^2 + 0.03375t - 0.325$ was derived from it. The derivative of this equation, converted from feet per second to g units, gives the linear correction function for the acceleration

$$C_{A_1} = -E_{A_1} = -0.00011646t - 0.001048$$

Acceleration data within the interval between 7 and 24 sec were then corrected and integrated to give the curve V_2 in Fig. B.2. This curve, which is plotted on a velocity scale 10 times that

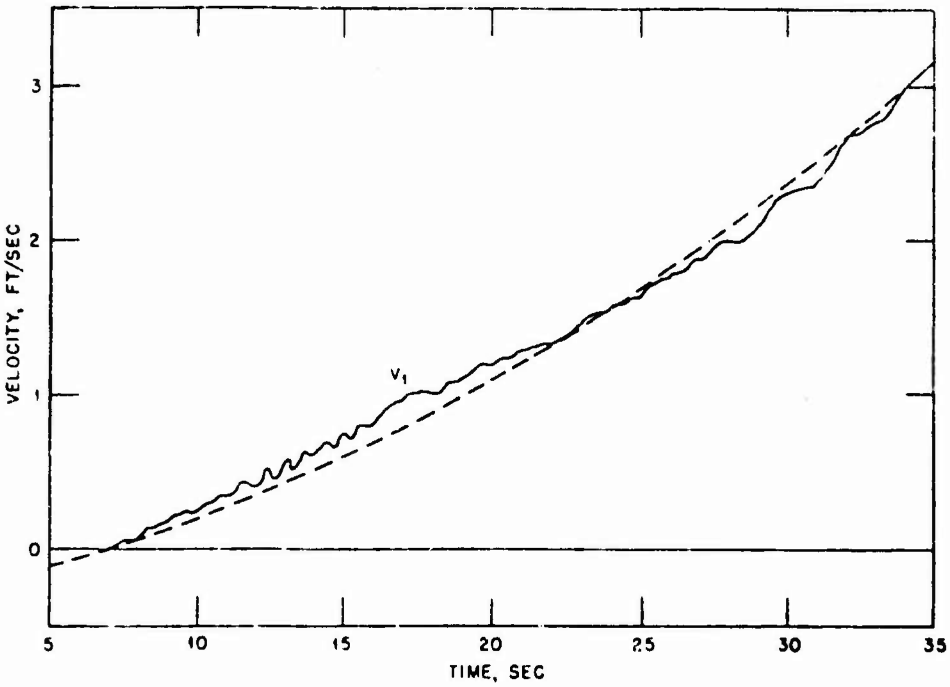

Fig. B.1 — Velocity from uncorrected acceleration-time data.

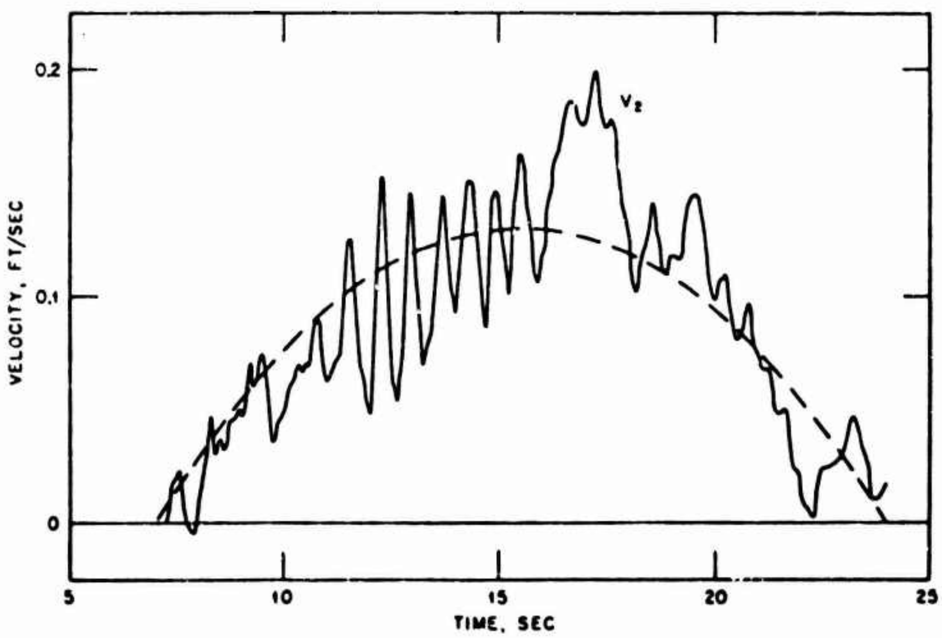

Fig. B.2 — Velocity from acceleration data corrected for linear drift.

of V_1, includes the first half-cycle of the 30-sec periodic component noted in the V_1 curve. A new error curve (the dashed line in Fig. B.2) in which a parabola approximates the half-cycle between 7 and 24 sec was fitted to the V_2 data and evaluated as

$$E_{V_2} = -0.0017995t^2 + 0.05578t - 0.30228$$

The negative derivative of E_{V_2} is the second acceleration correction function

$$C_{A_2} = -E_{A_2} = +0.0001177t - 0.0017323$$

Integration of the newly corrected acceleration over the interval 9.5 to 16.5 sec results in the curve V_3 of Fig. B.3. This curve emphasizes the 1.5-cps signal. However, integration of the

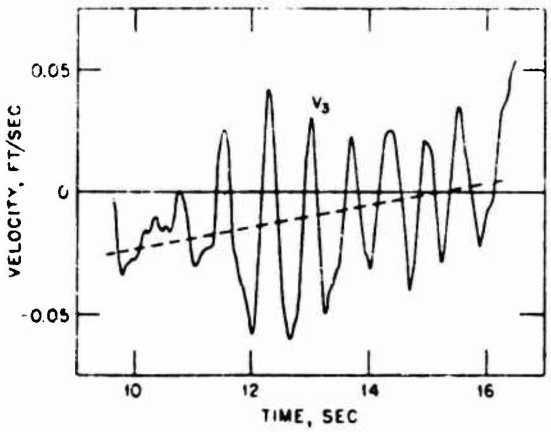

Fig. B.3—Velocity from acceleration data corrected for sinusoidal drift as indicated by dashed line of Fig. B.2.

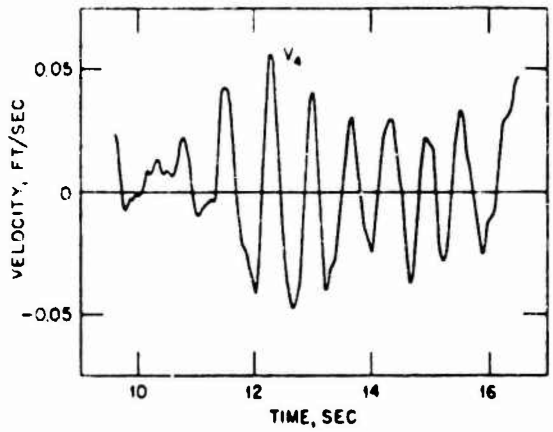

Fig. B.4—Velocity from acceleration data corrected for shift as indicated by dashed lines of Figs. B.3 and B.5.

V_3 data gives the displacement curve D_1 in Fig. B.5, in which the 1.5-cps signal has become submerged in a long-period component which can be approximated between 10 and 16 sec by the parabola shown superimposed on the data. The equation for this error function is

$$E_{D_1} = 0.0258333t^2 - 0.795t + 5.14667$$

which upon differentiation gives the linear error function

$$E_{V_3} = 0.004306t - 0.06625$$

represented by the dashed line in Fig. B.3. This results in a third correction term for the acceleration

$$C_{A_3} = -E_{A_3} = -0.0001337$$

Finally, integration of the acceleration corrected for E_{A_3} between 9.5 and 16.5 sec yields the velocity curve V_4 of Fig. B.4, which in turn gives the displacement curve D_2 of Fig. B.6.

There is still a 5-sec periodic component evident in the displacement curve which undoubtedly affects the maximum values of the curve. However, the 1.5-cps signal is strong, and peak-to-peak amplitudes of this component in the D_2 curve are probably reasonable approximations of maximum excursion of the ground at the instrument station.

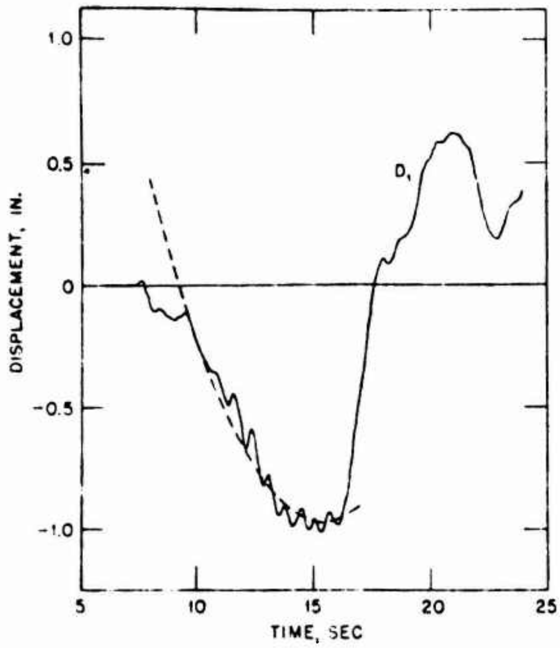

Fig. B.5—Displacement from velocity data of Fig. B.3.

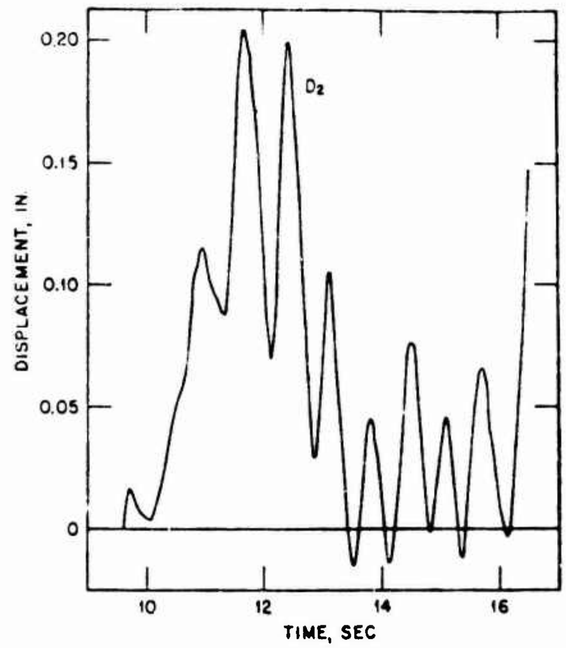

Fig. B.6—Displacement from velocity data of Fig. B.4.

B.7 EVALUATION

Evaluation of corrected doubly integrated acceleration-time data is important. Admittedly the example just described is an extreme case involving data which for practical purposes are useless. The actual accomplishment of the correction process in this case was elimination of features of the raw data which, because of duration or period, were judged to be extraneous to pertinent data. As a result significant portions of the velocity and displacement data could be plotted to scales 20 times those feasible for results of the initial integration. The final displacement curve does not depict true motion but gives a reasonable indication of magnitude and a rough idea of the displacement-time pattern.

Less complex data involving accelerations of damaging magnitude, high signal-noise ratios, short periods of time, and relatively simple signal patterns, such as those from a clean air shock or close-in on an underground explosion, in general can be corrected by the procedures described. Correction of data in this category, if necessary, is usually much less complex, involving only one or two linear corrections in the first integral, and the results are correspondingly more accurate. Data from short-duration clean signals can be fitted to the terminal condition of vanishing velocity with more certainty than complex longer signals. Consequently velocity and displacement components of ground motion can be derived by integration of acceleration data with considerable confidence when the data represent ground motion in the area where signal strength is high and durations are relatively short. Fortunately this area includes all ground ranges in which motion of damaging proportions will exist.