VIBRATIONS FROM INSTANTANEOUS AND MILLISECOND-DELAYED QUARRY BLASTS

By Wilbur I. Duvall, Charles F. Johnson, Alfred V. C. Meyer, and James F. Devine

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by

Wilbur I. Duvall,[1] Charles F. Johnson,[2] Alfred V. C. Meyer,[2]
and James F. Devine[2]

ABSTRACT

Nineteen quarry blasts were instrumented with particle-velocity gages mounted in a uniform soil overburden, back of one face in a quarry in Iowa. Three components of particle velocity, radial, vertical, and transverse, were recorded at each of eight stations back of each blast. Distances from blast area to gage stations ranged from 150 to 3,000 feet. Eleven of the quarry blasts employed millisecond delays, and eight were instantaneous blasts. Charge weight per hole was 200 pounds, and the charge weight per delay interval, including the instantaneous blasts, ranged from 100 to 3,000 pounds.

Analysis of the data from these tests shows that the particle velocity, V, produced at distance, D, by a quarry blast of charge per delay interval, W, can be represented by an equation of the form,

$$V = K W^b D^{-n},$$

where b and n are exponents, and K is the intercept constant which is a measure of the level of vibration. The value of K for a millisecond-delayed blast employing one hole per delay interval is about 42 percent larger than the value of K for a single-hole blast. The value of K for a multiple-hole millisecond-delayed blast is about the same as that for an instantaneous blast when the charge per delay for the millisecond blast is equal to the total charge for the instanteneous blast. The vibration level from millisecond-delayed blasts employing one hole per delay is shown to be independent of the length of the delay interval and the number of delay intervals over the range of the variables tested: 9, 17, and 34 milliseconds and 3, 7, and 15 delays per blast.

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INTRODUCTION

The Bureau of Mines and the cooperating quarrying industry are conducting a long-range research program on vibrations from quarry blasting and the effect of these vibrations upon structures. The initial phases of this research program were concerned with instrumentation studies, calibration of portable seismographs, review of literature on vibrations from quarry blasting, and the effect of these vibrations upon structures. Four reports have been prepared on these initial studies (8, 9, 14, 22).[3]

In the 1940's and 1950's, millisecond-delayed blasting became an accepted technique for reducing vibrations from blasting, and a better method for breaking rock. The main variables associated with a millisecond-delayed blast are the delay interval, the number of delay intervals, and the number of holes per delay interval. Although previous work by other investigators has shown that millisecond-delayed blasts produce smaller vibration levels than those produced by instantaneous blasts employing the same total charge, the effect of these variables on the vibrations produced by millisecond-delayed blasts is not thoroughly understood.

Experimental determinations have been made of the charge per delay in a millisecond-delayed blast, W_d, and the total charge in an instantaneous blast, W_i, that will produce the same vibration level at the same distance. The equivalent weight ratio, R_W, is defined as

$$R_W = W_d/W_i. \tag{1}$$

Experimentally determined values of R_W range from 0.55 to 1.63 and have an average of 0.67 (10, 13, 16, 19, 20, 21, 25). Apparently no systematic study has been made to determine if the value of R_W is affected by such variables as the length of the millisecond-delay interval, the number of delay intervals, the number of holes per delay, and the distance from the blast area.

The effect of distance and charge weight on the vibration level is basic to all quarry blasting vibration studies. Many types of propagation laws or equations have been proposed. However, the most common one is of the form:

$$A = k\, W^b D^n, \tag{2}$$

where A is the peak amplitude of particle displacement, velocity, or acceleration, W is the charge weight, D is the distance, and k, b, and n are constants to be determined for a given site and shooting procedure. Both theoretical and experimental methods have been used to estimate values of both b and n. Typical values found in the literature for b range from 0.4 to 1.0 and for n from minus 1 to minus 2; the larger negative value of n is associated with particle acceleration (1, 4, 6, 15, 17, 18, 21, 24-27).

Statistical methods have been used for studying the correlation between the amplitude of the vibration and other variables associated with quarry

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[3]Underlined numbers in parentheses refer to references given at the end of this report.

blasting. These correlation studies usually are made on data obtained from a quarry where a seismograph was used to monitor each blast. Thus, only one amplitude and frequency measurement is obtained at one distance for each blast. Distance and charge weight per delay vary from one blast to the next. Correlation studies are based upon the assumption that the amplitude of vibration, A, is dependent upon the charge per delay, W, the distance, D, and the frequency, F, by the following equation:

$$A = k\, W^b\, D^n\, F^e, \tag{3}$$

where k, b, n, and e are constants determined by statistical procedures (2, 3, 5). These studies are inherently difficult because the results may be influenced by other variables about the blast that were not controlled or randomized.

From the foregoing literature studies the following problems were selected for study: (1) Determining the propagation law for the amplitude of vibrations produced by both instantaneous and millisecond-delayed quarry blasts, (2) determining if the level of vibration at various distances from the blast area is controlled by either the length of the delay interval or the number of delay periods in a millisecond-delayed quarry blast, (3) and comparing vibration levels from instantaneous blasts with those from millisecond-delayed blasts.

To study ground vibrations produced by blasting requires that at least one of the quantities, particle displacement, velocity, or acceleration, be recorded as a function of time. The quantity most often measured is particle displacement because of the ease with which it can be recorded by means of a portable seismograph. Also, particle acceleration often is measured using portable accelerographs. The use of particle velocity to study vibrations from quarry blasting has received little attention in the past.

A study of the published data on vibration levels that produce damage to residential structures showed that the particle velocity of the vibration was a better measure of damage than either the displacement or acceleration (9). Therefore, particle velocity was recorded.

To obtain reliable data with a minimum of experimental effort requires that the variables under study be controlled in a known manner and that other factors that might affect the results be maintained constant or randomized. The variables selected for study in this investigation were delay interval, number of delay periods, distance, and charge weight. Charge weight was varied by number of holes and not by charge per hole. The factors held constant were charge per hole, hole size, burden, spacing, face height, type of explosive, rock type, and overburden. To obtain the desired degree of control, a quarry in relatively flat terrain, having uniform overburden extending back of a working face for 1,000 feet or more, was selected. Also, close cooperation with the quarry operator was required so that the tests could be conducted as planned.

The test program was planned around a simple factorial experiment with the length of the millisecond-delay interval as one variable and the number of delays as the other variable. Instantaneous blasts were obtained by making the delay interval less than 1 millisecond. Vibration levels were obtained by measuring particle velocity of the ground in three mutually perpendicular directions (radial, vertical, and transverse), at six to eight distances behind the blast area. To keep the amount of drilling required within reasonable limits, only one hole per delay interval was used in the millisecond-delayed blasts. Thus, the number of delay intervals is one less than the number of holes for each millisecond-delayed blast.

This report describes the test site, the equipment, and the experimental procedures used in performing these factorial designed blasting tests and presents the data together with an analysis of the data and the conclusions drawn.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to the Weaver Construction Co. for the use of the quarry at Alden, Iowa, for conducting the blasting tests. Specific acknowledgments are due Wood Weaver, president of the Weaver Construction Co., for suggesting use of his quarry and for making the necessary arrangements for the tests. The assistance given by Robert Lau, superintendent of the Alden quarry, and Ed Ites, driller and blaster, is greatly appreciated. Financial support of this investigation was supplied in part by the following: Liberty Mutual Insurance Companies, Association of Casualty and Surety Companies, The National Board of Fire Underwriters, National Association of Mutual Casualty Companies, and The National Crushed Stone Association.

TEST SITE

The Weaver Construction Co., Alden limestone quarry, hereafter called the Weaver quarry, is one-half mile east of Alden, Iowa. The limestone to the west of the quarry is overlain by 6 to 12 feet of black reworked glacial till. The overburden increases to about 60 feet southwest of the quarry. The rock exposed at the face is a light-tan, argillaceous, loosely jointed, 30-foot section of Gilmore City limestone. The upper 10 feet exhibits weathering and crossbedding effects. The floor of the quarry consists of a more massive oolitic limestone. There is virtually no structural dip in this area. Figure 1 shows a mining area of the quarry. The relatively flat area northwest of the face extends into the town of Alden, where this investigation was made.

INSTRUMENTATION

The instrumentation consisted of a 36-channel, direct-writing recorder, 24 channels of linear-integrating amplifiers, 12 channels of carrier amplifiers, and velocity and acceleration gages. The recorder, amplifiers, and auxiliary equipment are housed in a mobile laboratory, a 2-1/2-ton van-body truck (fig. 2). The ac power to operate this equipment is supplied by a 5-kw gasoline-powered generator housed in a small trailer. A 36-channel input

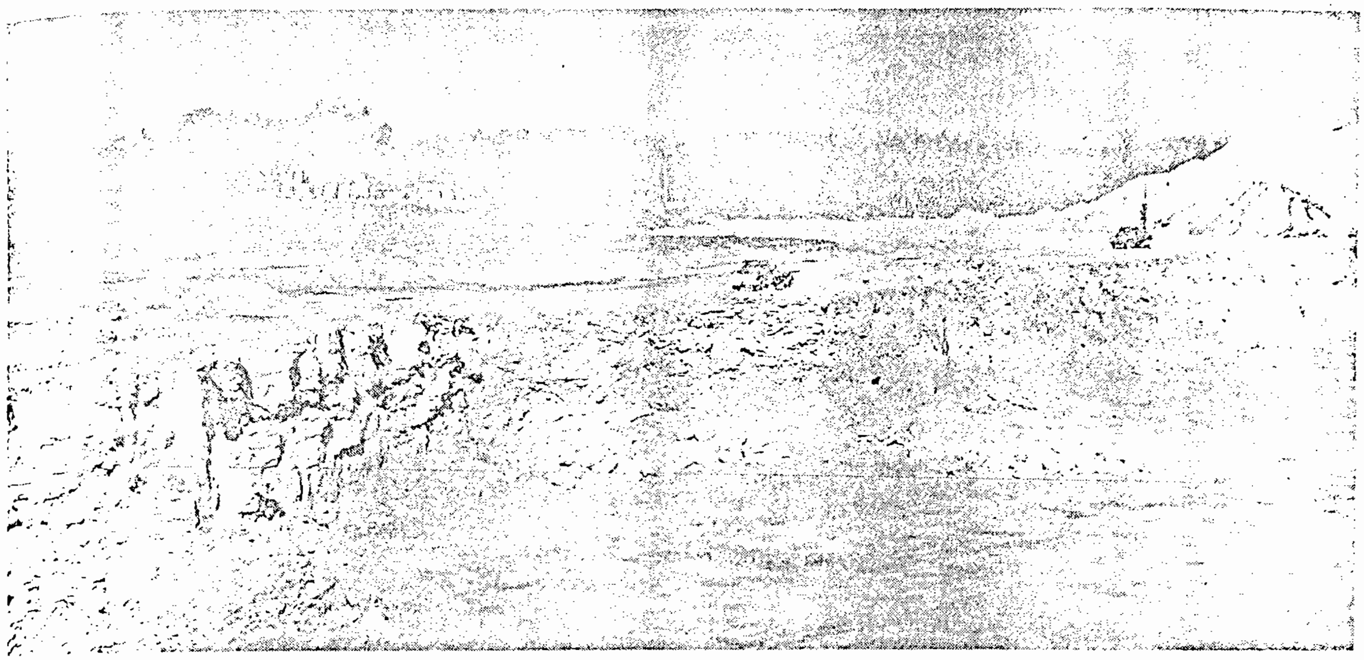

FIGURE 1. - Photograph of Quarry Face.

panel was constructed on the side of the van body so that the cables from the gages could be plugged into appropriate channels. Each channel from the input panel is wired permanently to an amplifier and a recording channel.

The galvanometers in the recorder have a natural frequency of 3,500 cycles per second (cps) and are fluid damped, and their flat frequency response (within ±5 percent) ranges from 0 to 2,100 cps. The linear-integrating amplifiers can be used either as linear or integrating amplifiers. The flat frequency response (within ±3 percent) of these amplifiers ranges from 2 to 10,000 cps. A typical response curve for one of the linear amplifiers is shown in figure 3. Each amplifier has a 20-step attenuator for changing the gain in increments of about 3 decibels (db) for a total change of 60 db.

Recordings are made on 12-inch-wide, direct-writing photographic paper driven at a speed of 17.31 inches per second. Timing lines are recorded at every 10-millisecond interval. As the accuracy of the timing lines depends upon the accuracy of the ac power supply, one galvanometer is used to record a 100-cps standard oscillator having an accuracy of 1 cps.

Each channel of the recording system is calibrated before each test at the attenuator setting to be employed. A signal generator and microvolter supply the input voltage, and the output deflection of the galvanometer is photographically recorded.

Velocity gages having a natural frequency of 4.75 cps, a damping coefficient of 65 percent of critical damping and an average sensitivity of 95 millivolts (mv)/in/sec were used in these tests. Each velocity gage was calibrated on a shaking table before it was used and periodically thereafter. Normally

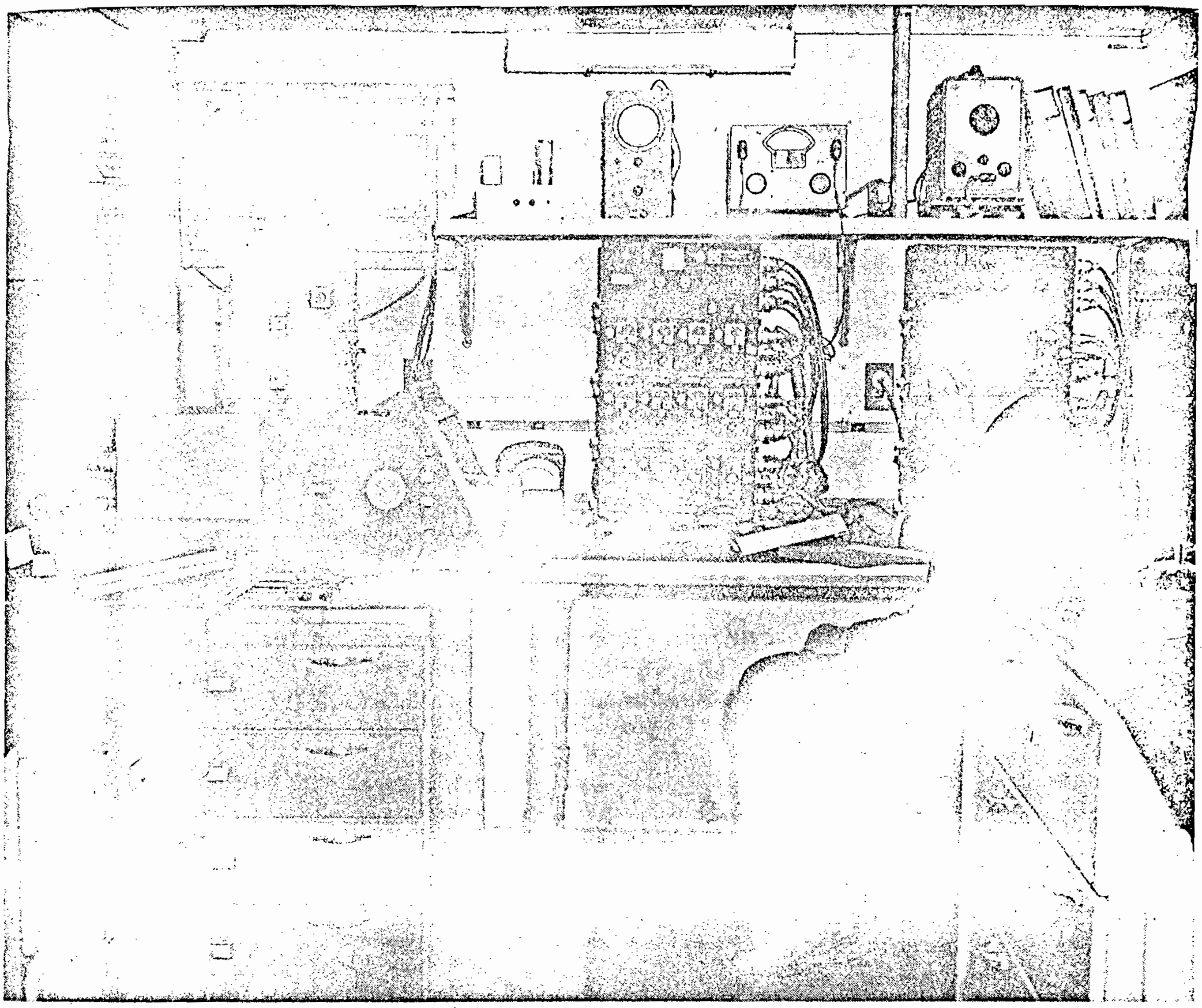

FIGURE 2. - Photograph of Recording Instrumentation.

the sensitivity and frequency response of these gages do not vary more than 2 percent from the specifications of the manufacturer. Gages found to deviate more than this amount were returned to the manufacturer for repair and recalibration. A typical response curve for one of the velocity gages is given in figure 4. The velocity gages can be adjusted to respond to vertical or horizontal motion.

A series of preliminary tests was performed to determine a satisfactory method for mounting small gages to the surface of the ground. The method established for this series of tests was as follows: A hole about 9 inches deep and 12 inches on each side was dug in the topsoil. The bottom surface and two adjacent vertical sides were planed smooth with a spade so that three mutually perpendicular surfaces were formed; one of the vertical surfaces was normal to the direction to the shot point. One-half-inch-diameter steel pins, 12 inches long, pointed at one end, and a steelplate welded to the other end,

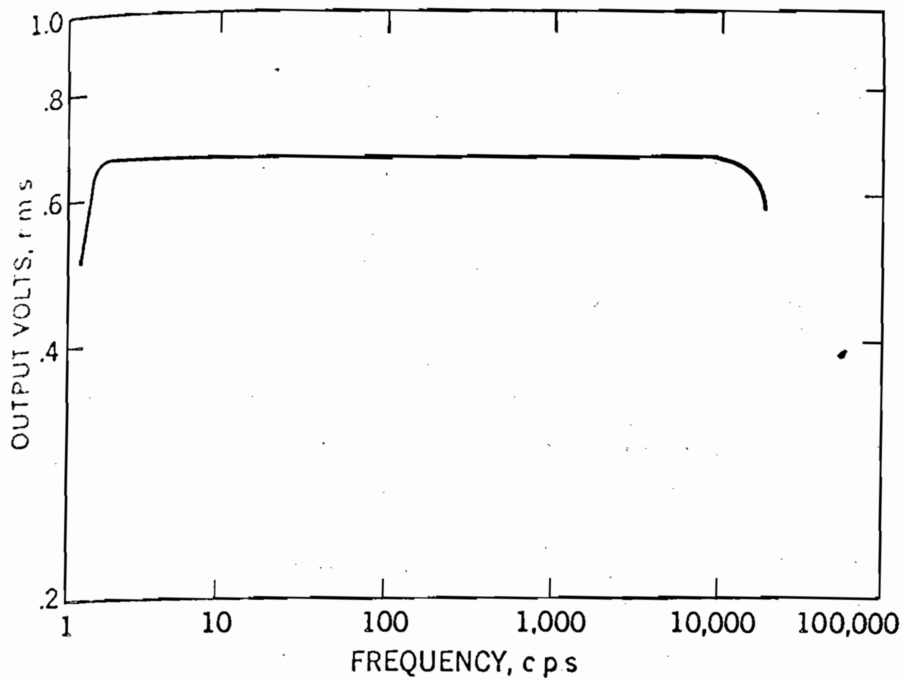

FIGURE 3. - Frequency Response of Linear Amplifiers.

were driven into each of the three mutually perpendicular surfaces of the hole. The velocity gages were fastened to the metal plates by four screws. Figure 5 is a photograph of three velocity gages in place for recording. Waterproofed connectors were used to join the gage-output cables to the lead-in cables going to the recording truck. Polarized cable connectors were used so that positive and negative voltages could be associated with a given direction of particle velocity.

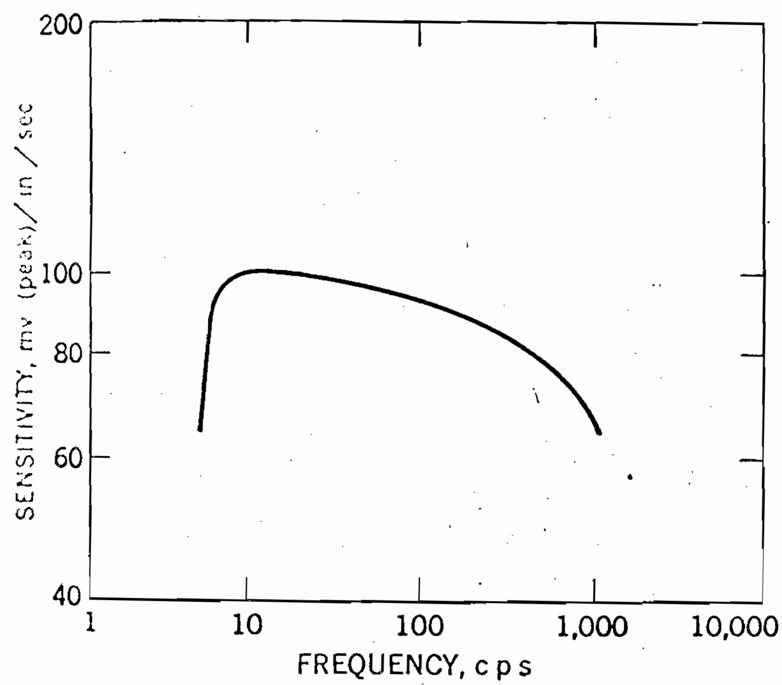

FIGURE 4. - Frequency Response of Velocity Gages.

EXPERIMENTAL PROCEDURE

The Weaver quarry was chosen as the test site because a flat area having homogeneous overburden of uniform thickness extended a thousand feet or more back from the working face. The face was about 30 feet high, and the overburden at the face was 6 to 8 feet thick.

Detailed information about the rock surface and the overburden was obtained by seismic refraction tests and by a grid of exploration holes drilled to rock. Refraction tests, using one-half pound of explosive and gage arrays that were 70, 100, and 200 feet in length, were conducted to determine depths and seismic propagation velocities at two places in the test area. Arrival times were recorded using vertical velocity gages mounted on pins driven into the soil surface. One channel of the oscillograph recorded the detonation time pulse generated by a contact in the explosive charge. An oscillograph record of each refraction test was made; the amplifiers were set for maximum sensitivity so that the arrival time of the initial signals could be accurately determined.

FIGURE 5. - Photograph of Velocity Gages Mounted to Soil.

Table 1 gives the factorial design and shooting order used for studying the vibration levels from millisecond-delayed and instantaneous quarry blasts. In these tests only a single row of holes was used. Detonating fuse was used to connect the charge holes together in series for the instantaneous blasts. For the millisecond-delayed blasts, either a 9-, 17-, or two 17-millisecond-delay connectors were placed in series with the detonating fuse between the holes of the round. Thus, only one hole per delay was employed in these millisecond-delayed blasts.

TABLE 1. - Factorial design and shooting order

Number of holes	Delay interval, ms.			
	0	9	17	34
	Shot numbers			
3....................	2	19	3	6
7....................	8	20	5	7
15....................	12	21	11	13

In addition to the foregoing 12 quarry blasts, 5 single-hole blasts and 2 multiple-row millisecond-delayed blasts were instrumented. For the two multiple-row blasts, the charge holes were connected together with detonating fuse and 17-millisecond connectors so that the maximum number of holes per delay was 4 for one round and 6 for the other.

In conducting the tests randomization of the order of shooting the quarry rounds and the position along the face was attempted so that these two variables would not bias the results. Complete randomization was not possible because the quarry face had to be mined efficiently, and the multiple-row and 9-millisecond-delayed blasts were added to the program after the other tests had been completed.

Hole diameter, depth, spacing, burden, and loading were held constant for all instrumented quarry blasts. The location of each hole was determined by measurement so that the spacing between holes was 15 feet and the burden on each hole was 10 feet. Each hole was drilled to a depth of 36 feet with a 6-inch-diameter auger drill. The explosive charge loaded into each hole is given in table 2.

TABLE 2. - Explosive charge per hole

Explosive	Stick size		Number of sticks	Total, lb
	Diameter, inches	Weight, pounds		
Hi Cap.....................	5	25	5	125
Nitramon Type A...........	5	22.5	2	45
Nitramon Primer...........	5	22.5	1	22.5
Pelletol..................	-	7.5	-	7.5
Grand total............	-	-	-	200

Each instrument array and blast area was mapped by a stadia survey (fig. 6). The location of each quarry blast is identified by test number, and the area of rock breakage is indicated by broken lines. All instrumentation for the blasts was kept on the same side of the quarry as the working face. The instrument arrays were placed along the straight lines shown on the map. Each test array was directly behind the blast area and approximately

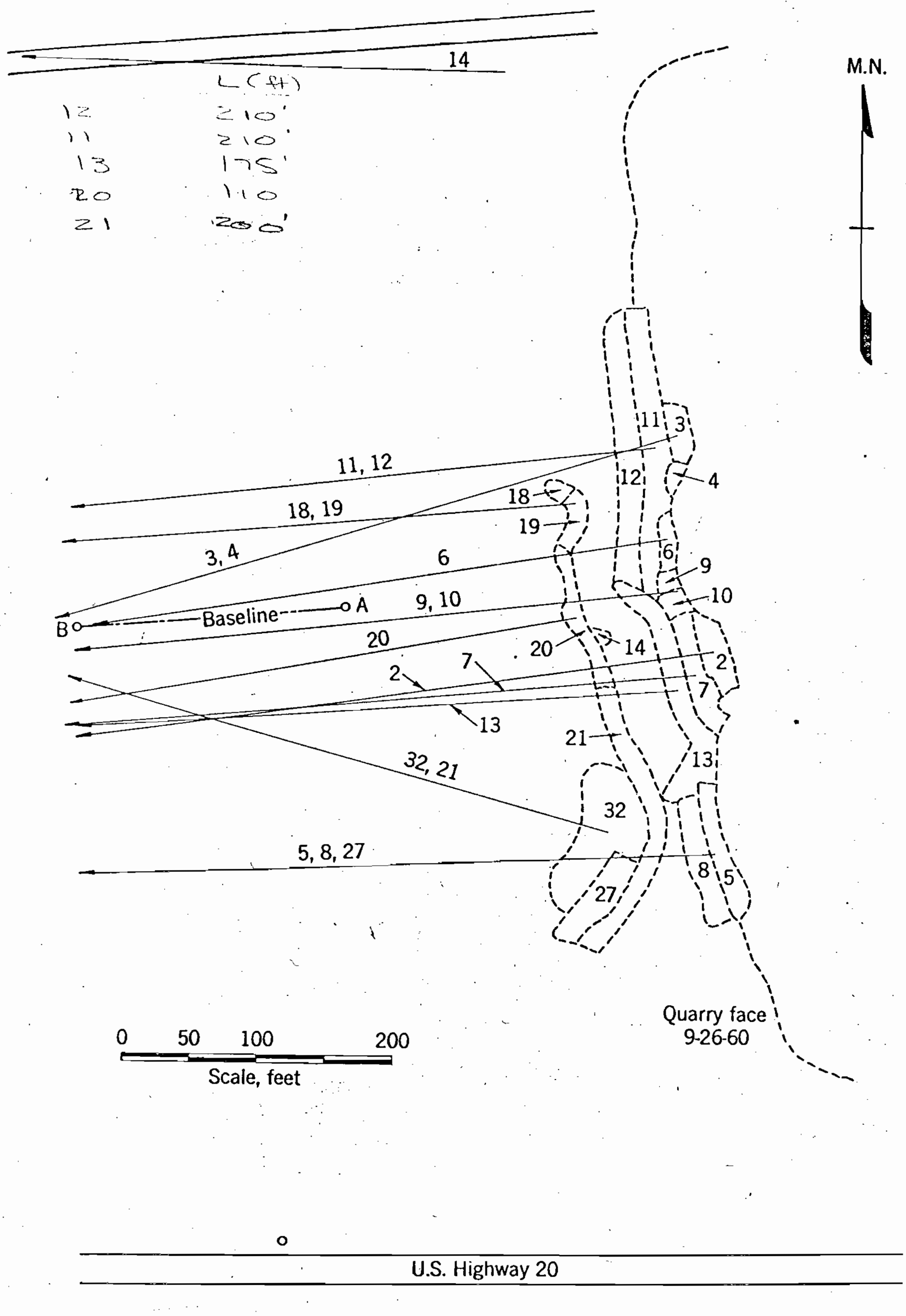

FIGURE 6. - Map of Test Area Near Quarry Face.

perpendicular to the face. The gaps between the blast areas shown on the map represent the rock quarried when no vibration studies were conducted. The spacing of the eight gage stations for each array was measured from the center of the blast area. A hole was dug at each gage station to a depth great enough to permit driving the gage-mounting pins into firm soil. The field had been under cultivation, and the holes ranged from 9 to 18 inches deep. The gages were connected to the amplifiers by separate shielded cables through the truck-input panel. A complete system check and calibration of the instrumentation was conducted before each test. Each blast was fired upon command by a telephone operator, who alerted the instrument operator 10 seconds before the blast.

EXPERIMENTAL DATA

Five refraction tests were conducted to determine the propagation velocity and thickness of the overburden and the propagation velocity of the upper layers of the limestone at the Weaver quarry. The arrival time for the first seismic pulse at each gage position was measured for each of the refraction tests. From these data, a time-distance plot was compiled, and the propagation velocity of each layer was obtained by computing the reciprocal of the slope for each segment of the time-distance curve. The average propagation velocity determined for the overburden in this manner was 1,250 ft/sec. The velocity of the rock directly beneath the overburden averaged 7,000 ft/sec. When the length of the refraction array was extended from 100 to 200 feet, a deeper rock layer with a propagation velocity of 13,500 ft/sec was identified.

The average thickness of overburden was determined from the time-distance plots by the use of the following relationship (_7_):

$$Z = (T_0 V_1 /2)/(1 - V_1^2/V_2^2)^{1/2} , \qquad (4)$$

where

Z = overburden thickness,

T_0 = intercept time of the first rock layer slope on the time-distance plot,

V_1 = velocity of the overburden,

and

V_2 = velocity of the first rock layer.

The overburden thickness computed by the use of this relationship ranged from 8.5 to 12 feet. The thickness of the overburden was verified by a series of 12 holes drilled throughout the instrumented area. The thickness of the overburden determined in this manner ranged from 3.5 to 9 feet, except for one hole in the southwestern corner of the test area where the depth to rock was 21 feet. The overburden thickness from the test drilling averaged 7.5 feet, which is in fair agreement with the refraction results. The propagation velocities and thicknesses of the various layers of soil and rock are summarized in table 3.

TABLE 3. - Refraction test data

Test	Length of array, feet	Overburden		First rock layer		Second rock layer
		Velocity, ft/sec	Thickness, feet	Velocity, ft/sec	Thickness, feet	Velocity, ft/sec
1.......	70	1,250	12	7,000	-	-
2.......	70	1,250	12	7,000	-	-
3.......	100	1,250	8.5	7,000	-	-
4.......	200	1,250	11	7,000	17	13,500
5.......	200	-	-	7,500	-	13,500

Twenty-four particle-velocity-versus-time records were obtained from each of the 19 quarry blasts. Examples of these records are shown in figures 7 through 10. Time is indicated by 10-millisecond timing lines. Each trace on the record is identified as to component of particle velocity and distance from blast area to gage. Thus, R, V, and T represent the radial, vertical, and transverse components, respectively. The center trace on each of these records is the 100-cps output of the standard oscillator.

The arrival time for the first seismic pulse at each gage was measured from an arbitrary zero time. From these data, a time-distance plot was compiled for each shot, and the propagation velocity was determined from the resulting slope. A typical curve is shown in figure 11. The average propagation velocity determined in this manner was 15,250 ft/sec, which is greater than that obtained in the refraction tests. Table 4 summarizes the quarry-blasting tests conducted and gives the propagation velocity obtained in each test.

TABLE 4. - Summary of quarry-blasting tests and propagation velocities

Test	Propagation velocity, ft/sec	Number of holes	Holes per delay	Delay, ms	Charge/delay, pounds	Total charge, pounds
2.........	15,660	3	3	0	600	600
3.........	15,250	3	1	17	200	600
4.........	15,100	1	1	0	200	200
5.........	14,600	7	1	17	200	1,400
6.........	15,370	3	1	34	200	600
7.........	15,620	7	1	34	200	1,400
8.........	14,000	7	7	0	1,400	1,400
9.........	15,925	1	1	0	200	200
10.........	15,625	1	1	0	200	200
11.........	16,300	15	1	17	200	3,000
12.........	15,500	15	15	0	3,000	3,000
13.........	16,375	15	1	34	200	3,000
14.........	14,800	1	1	0	100	100
18.........	15,000	1	1	0	200	200
19.........	14,800	3	1	9	200	600
20.........	16,250	7	1	9	200	1,400
21.........	15,370	15	1	9	200	3,000
27.........	13,600	13	4	17	800	2,600
32.........	14,600	21	6	17	1,218	4,263

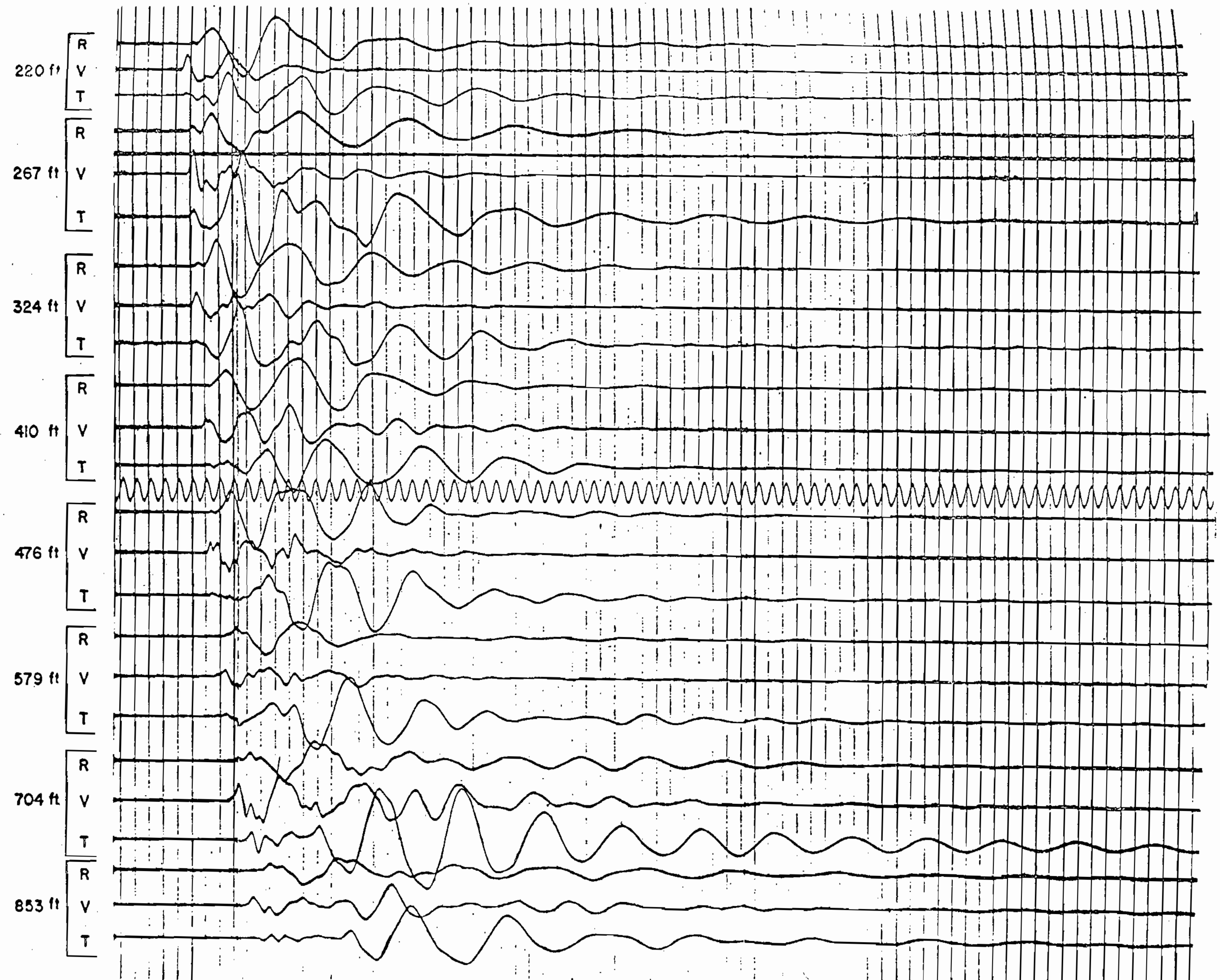

FIGURE 7. - Vibration Records for 1-Hole Blast.

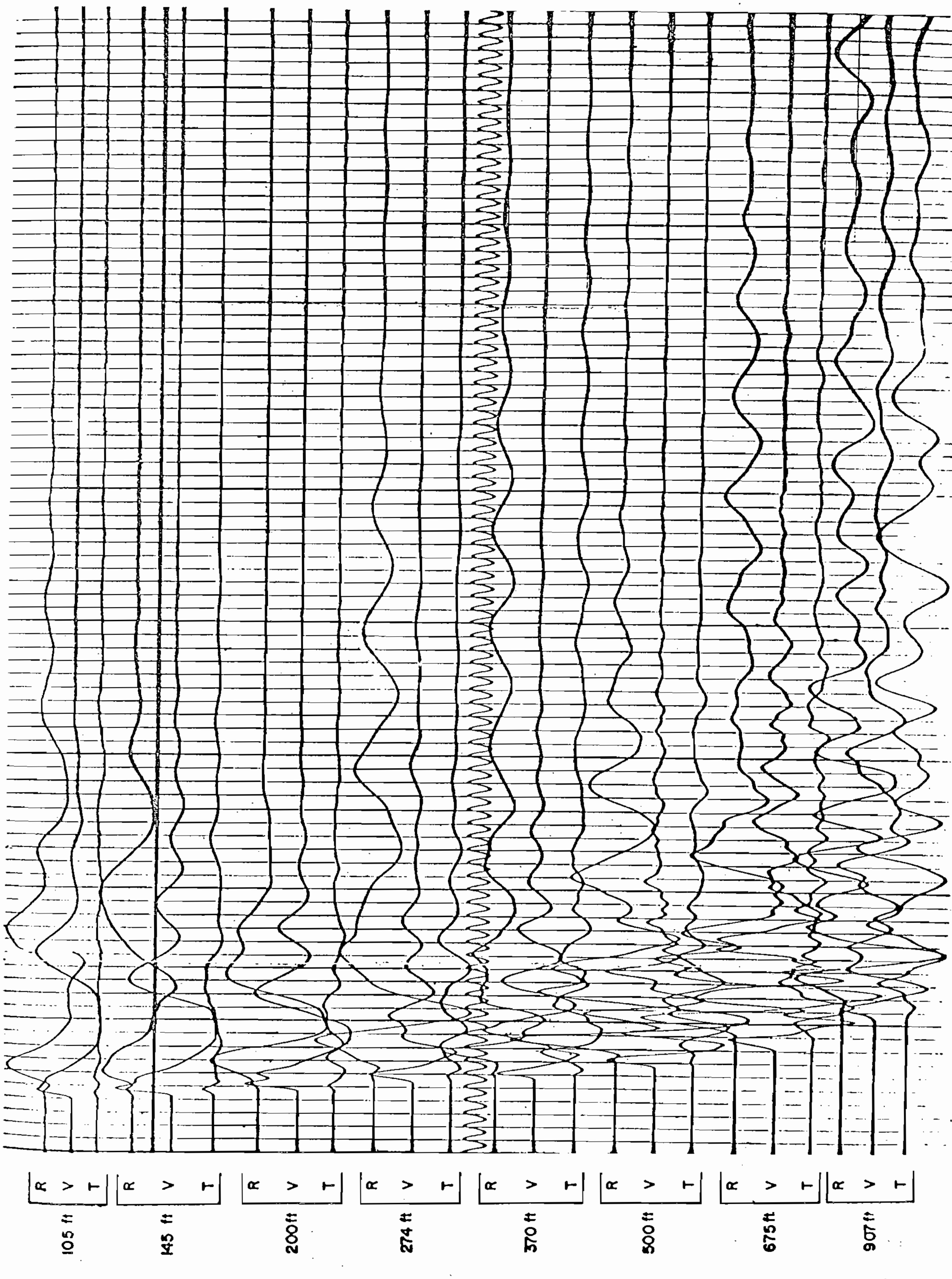

FIGURE 8. - Vibration Records for 7-Hole Instantaneous Blast.

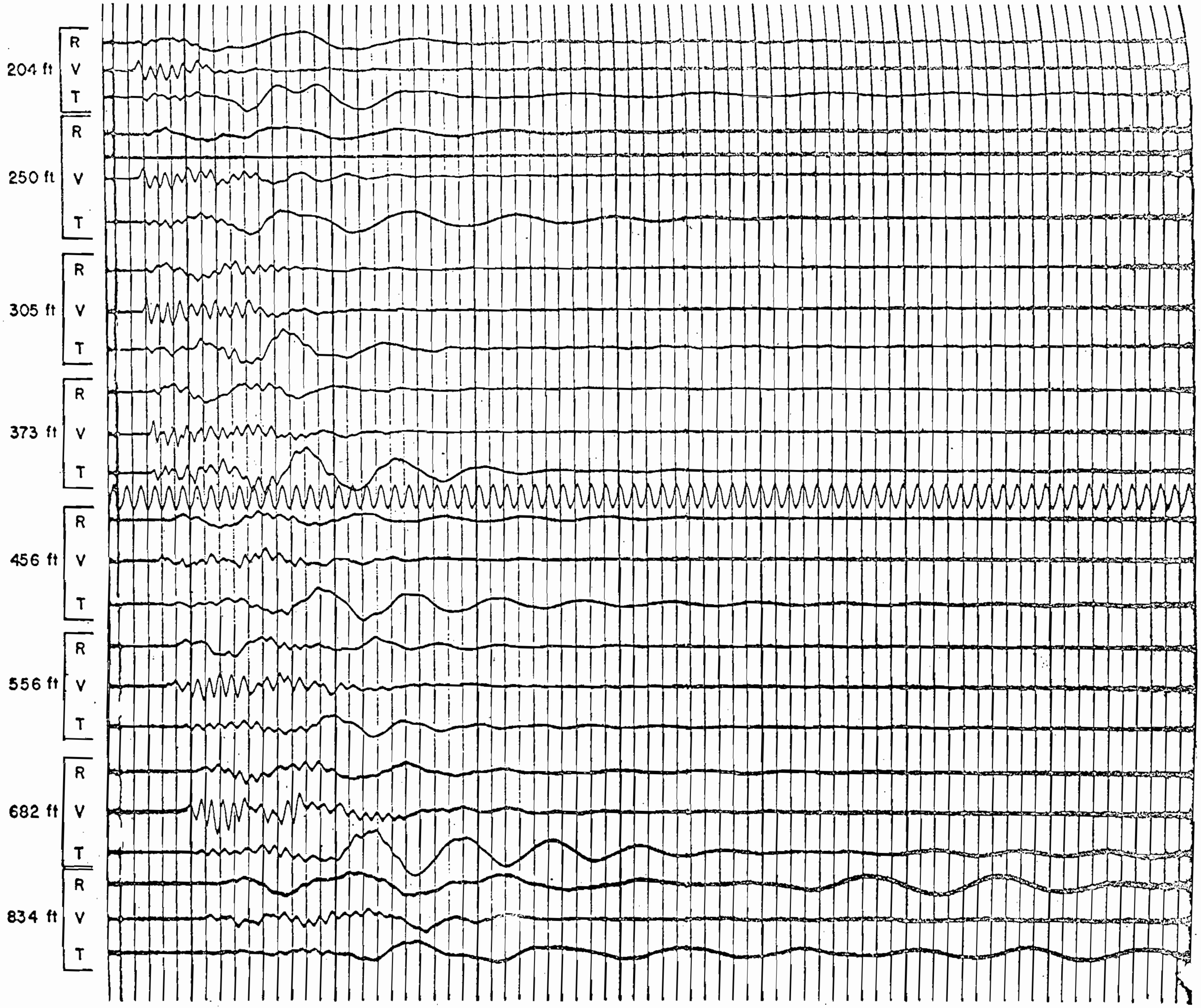

FIGURE 9. - Vibration Records for 7-Hole, 9-Millisecond-Delayed Blast.

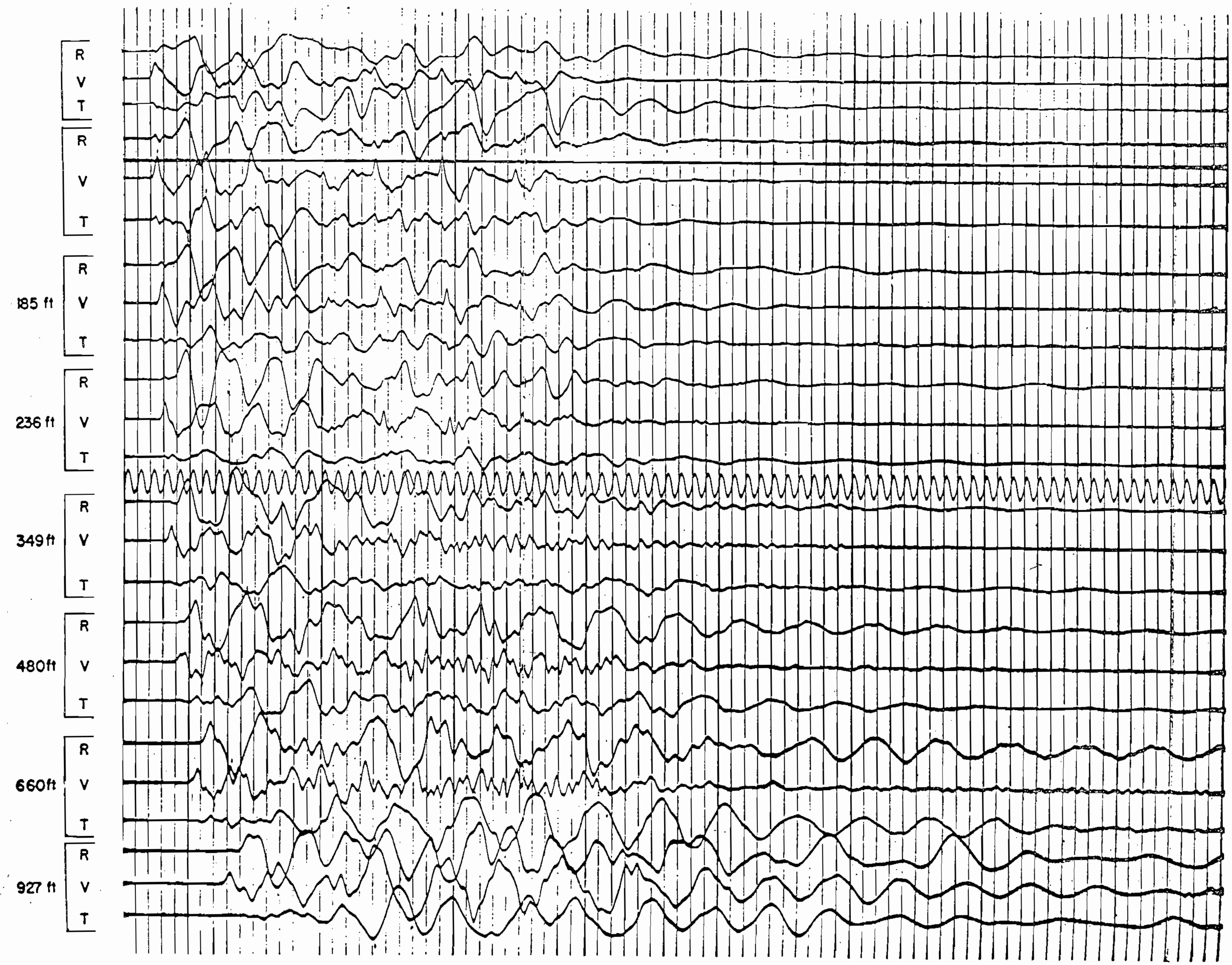

FIGURE 10. - Vibration Records for 7-Hole, 34-Millisecond-Delayed Blast.

To determine the peak particle velocity from amplitude measurements on the record the following relationship was employed:

$$V = \frac{E_c\ d_r}{d_c\ S}, \qquad (5)$$

where

V = peak particle velocity, in/sec;
E_c = the peak calibration voltage input to the amplifier, volts;
d_c = the peak deflection resulting from the application of E_c, inches;
S = peak gage sensitivity, volts/in/sec;

and

d_r = trace deflection obtained from the record by measuring from the zero or datum line to the peak of the pulse with maximum amplitude, inches.

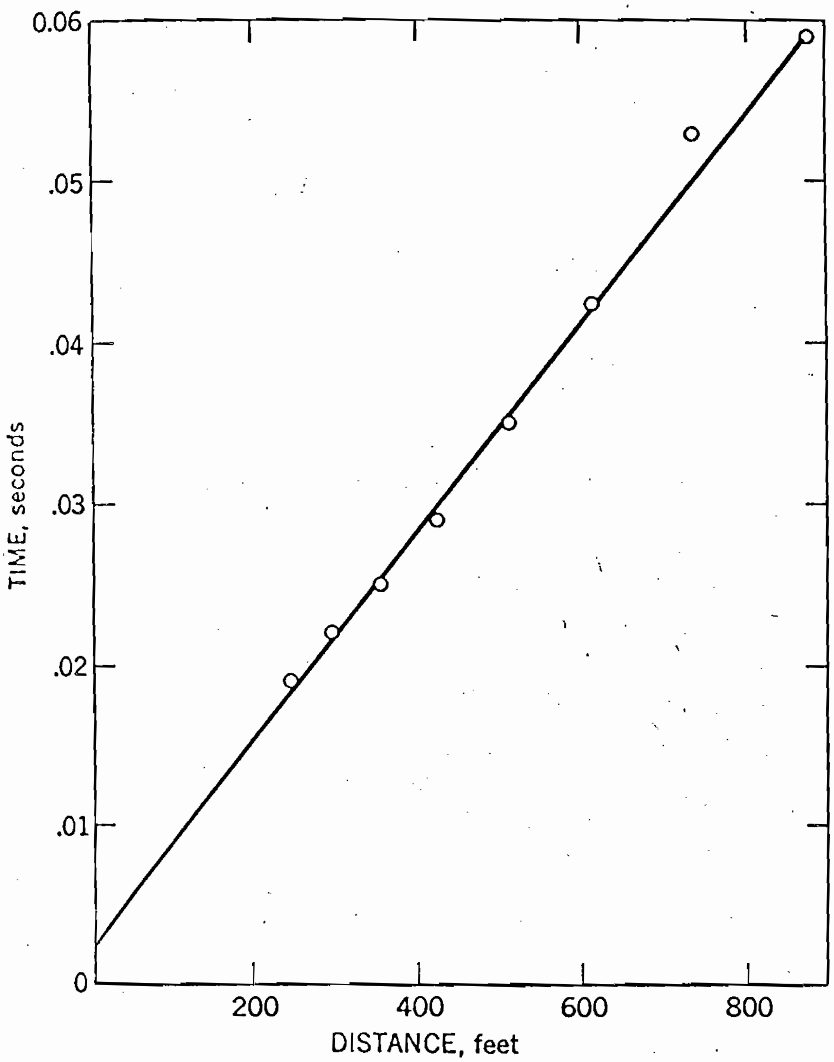

FIGURE 11. - Propagation Velocity From Shot 21.

The seismic pulse having the maximum amplitude was selected for measurement regardless of the frequency, regardless of the direction, and regardless of where it occurred during the record. The frequency of the seismic pulses ranged from 7 to 300 cycles per second. When the peak amplitude appeared to be a resultant of one wave superimposed on another, the frequency of each wave was noted. Tables 5 through 9 present the particle-velocity and frequency data for the 19 shots of this series. Particle-velocity data obtained at distances of 150 feet or less were erratic and are not included.

The duration of the seismic activity for the instantaneous shots averaged 200 milliseconds and for the millisecond-delayed blasts averaged 200 milliseconds plus the product of the length of the delay interval and the number of delays.

TABLE 5. - Particle-velocity and frequency data for 1-hole blasts

Test	Distance, 100 feet	Radial		Vertical		Transverse	
		Velocity, in/sec	Frequency, cps	Velocity, in/sec	Frequency, cps	Velocity, in/sec	Frequency, cps
4...	2.20	1.45	24	1.08	167	0.46	36
	3.10	.60	26	.42	-	.19	42
	3.89	.40	29	.28	200	.19	14
	5.38	.33	21	.14	125	-	-
	7.38	.15	21	.09	133+25	.068	71
	9.32	.079	56	.05	66	.044	20
9...	1.62	1.9	37	1.8	70	.45	17
	2.20	1.1	31	.98	85	.24	85
	3.22	.48	42	.45	70	.27	70
	4.55	.34	30	.24	125	.18	20
	6.42	.17	36	.16	125	.10	20
	9.03	.08	23	.07	85	.06	31
10...	1.62	2.3	50	1.65	70	.76	50
	2.20	1.3	38	.89	110	.45	36
	3.22	.57	31	.45	70	.22	56
	4.55	.39	30	.22	31	.18	26
	6.42	.19	45	.14	105	.10	22
	9.03	.096	21	.067	85	.05	25
18...	2.20	1.66	22	.99	25	.78	33
	2.67	.71	13	.84	83	.68	26
	3.24	.79	18	.35	38	.64	26
	4.10	.62	19	.34	32	.28	18
	4.76	.63	27	.20	28+114	.36	18
	5.79	.27	24	.11	23+145	.24	20
	7.04	.22	18	.13	22	.25	18
	8.53	.13	14	.10	27	.15	15
14...	5.40	-	-	.095	77	-	-
	5.70	-	-	.100	22	-	-
	6.15	-	-	.063	50	-	-
	6.80	-	-	.060	50	-	-
	7.65	-	-	.046	90	-	-
	8.88	-	-	.041	67	-	-
	10.45	.	.	.036	80+15	-	-
	12.60	-	-	.019	59	-	-
	15.30	-	-	.033	18	-	-
	18.70	-	-	.011	20	-	-
	22.95	-	-	.016	20	-	-
	29.05	-	-	.009	31	-	-

TABLE 6. - Particle-velocity and frequency data for 3-hole blasts

Test	Delay interval, ms	Distance, 100 feet	Radial		Vertical		Transverse	
			Velocity, in/sec	Frequency, cps	Velocity, in/sec	Frequency, cps	Velocity, in/sec	Frequency, cps
2.......	0	2.13	-	-	1.75	50	0.79	50
		3.13	1.46	25	1.15	25	.70	50
		4.13	.92	20	.67	40	.38	30
		5.13	.70	16	.36	100	.20	25
		6.13	.68	100	.32	40	.20	20
		7.13	.51	30	.24	50	.23	16
		8.13	.37	15	.24	10	-	-
19.......	9	2.20	1.2	20	1.1	20	.36	16
		2.67	.99	12	1.3	20+100	.38	22
		3.24	1.1	16	.37	100	.38	16
		4.10	.88	15	.23	31+290	.32	17
		4.76	.73	19	.20	140	.52	18+110
		5.79	.40	19	.15	120	.20	19
		7.04	.33	17	.18	20+100	.27	18
		8.53	.17	14	.07	120	.12	17
3.......	17	1.50	1.8	40	1.8	40	1.3	100
		2.30	.7	45	1.0	35	1.5	35
		3.20	.45	50	.34	100	.57	15
		4.00	.29	50	.20	100	.36	16
		5.50	.23	40	.14	200	-	-
		7.50	.12	18	.098	80	.24	24
		9.50	.059	50	.076	26	.12	17
6.......	34	1.77	2.8	40	2.6	100	.68	55
		2.29	1.0	26	.80	125	.46	55
		3.41	.63	28	.37	120	.34	60
		4.72	.53	70	.28	125	.21	50
		6.55	.25	22	.094	165	.16	24
		9.10	.10	29	.12	22	.074	11

TABLE 7. - Particle-velocity and frequency data for 7-hole blasts

Test	Delay interval, ms	Distance, 100 feet	Radial		Vertical		Transverse	
			Velocity, in/sec	Frequency, cps	Velocity, in/sec	Frequency, cps	Velocity, in/sec	Frequency, cps
8.......	0	1.45	-	-	8.8	15	1.6	25
		2.00	6.8	15	5.45	14	.90	50
		2.74	4.6	14	2.3	50	.93	20
		3.70	1.94	50	2.1	50	.86	30
		5.00	2.00	50	1.19	50	.61	50
		6.75	1.45	50	.78	30	.38	50
		9.07	.70	28	.35	20	.34	18
20.......	9	2.04	1.70	11	1.08	100	.98	30
		2.50	.68	12	.75	110	.59	14
		3.05	.71	125	.68	110	.67	16
		3.73	.53	16	.50	125	.52	16
		4.56	.41	14	.26	100	.37	16
		5.56	.22	20	.21	125	.21	20
		6.82	.30	110	.19	130	.21	16
		8.34	.15	20	.12	130	.14	12
5.......	17	1.60	-	-	3.42	50	1.70	85
		2.15	2.62	40	2.12	33	1.02	45
		2.89	1.45	40	1.02	62	.60	30
		3.85	.95	33	.64	40	.30	50
		5.15	.64	30	.41	31	-	-
		6.90	.39	42	.33	50	.20	38
		9.22	.16	25	.10	48	.15	21
7.......	34	1.85	1.7	30	1.2	23+100	.72	55
		2.36	1.1	30	.46	25+100	.32	42
		3.49	.56	16	.35	27+100	.26	17
		4.80	.32	18	.20	120	.20	20+12
		6.60	.19	18	.10	31+150	.13	20
		9.27	.091	30	.092	19	.068	21

TABLE 8. - Particle-velocity and frequency data for 15-hole blasts

Test	Delay interval, ms	Distance, 100 feet	Radial		Vertical		Transverse	
			Velocity, in/sec	Frequency, cps	Velocity, in/sec	Frequency, cps	Velocity, in/sec	Frequency, cps
12.......	0	2.60	-	-	4.7	25	2.4	25
		3.06	5.1	16	2.7	25	1.6	20
		3.64	4.2	12	2.0	25	1.24	25
		4.36	3.9	20	2.6	25	1.00	30
		5.18	3.6	20	1.65	29	1.47	25
		6.18	2.2	22	.86	25	1.1	22
		7.36	1.5	20	.55	20	1.2	25
		8.88	.9	15	.42	30	-	-
21.......	9	2.49	1.7	10	.84	110	1.2	25
		2.98	1.1	60	.71	150	.60	25
		3.57	.54	50	.40	150	.79	20
		4.27	.92	12	.64	50	.77	25
		5.12	.64	35	.53	110	.33	16
		6.13	.84	12	.38	120	.46	25
		7.33	.45	13	.25	150	.25	12
		8.78	.18	20	.16	50	.23	20
11.......	17	2.08	1.2	100	1.9	62	1.5	52
		2.98	.83	29	.62	71	.72	29
		3.78	.69	15+54	.40	140	.37	38
		5.28	.45	71	.27	200	.24	100
		7.28	.18	50	.14	44+143	.12	13+167
		9.28	.094	16+114	.081	100	.079	16+50
13.......	34	2.85	1.33	24	.88	24	.43	35
		3.37	1.00	26	.58	28	.45	24
		3.96	.66	24	.39	35	.31	24
		4.67	.49	23	.35	60	.28	20
		5.50	.48	22	.26	62	.14	21
		6.48	.32	22	.14	23	.10	50
		7.63	.23	24	.13	23	.14	22+55
		9.10	.12	24	.11	24	.082	26

TABLE 9. - Particle-velocity and frequency data for multiple-hole millisecond-delayed blasts

Test	Variables	Distance, 100 feet	Radial		Vertical		Transverse	
			Velocity, in/sec	Frequency, cps	Velocity, in/sec	Frequency, cps	Velocity in/sec	Frequency, cps
27..	13 holes;	2.14	4.5	12.5+125	-	-	1.1	10+50
	17 ms	2.63	1.1	100	2.4	125	3.1	100
	delay;	3.21	1.8	12.5+75	1.4	50	.84	12+85
	4 holes/	3.90	1.9	25	1.2	135	1.1	12
	delay.	4.75	1.5	26	.73	28+100	.79	17
		5.75	1.6	29	.77	25+100	.075	17
		6.95	.74	12	.50	25+100	.35	12
		8.40	.37	18	.23	10	.23	7.5
32..	21 holes;	2.55	4.32	8.5	1.34	85	1.16	11+100
	17 ms	3.05	1.80	14	-	-	.84	52
	delay;	3.65	1.58	20+85	1.15	80	1.14	15
	6 holes/	4.40	1.79	16+80	1.37	10+85	.85	14+60
	delay.	5.30	1.28	16	.74	35	.99	18
		6.35	1.02	19	.52	40+75	.45	19+100
		7.65	1.04	17+70	.41	75	.44	115
		9.24	.53	18+75	.33	75	.17	20

DATA ANALYSIS

Propagation Law

To determine how the level of vibration decreases with distance from the blast area, graphs of peak particle velocity and distance were constructed on log-log coordinates for each test and each component of velocity. The graphs (figs. 12-14) show that good linear grouping of the data was obtained. Therefore, a straight line through each set of data represents an equation of the form:

$$V = k\ D^{-n}, \tag{6}$$

where

V = peak particle velocity, in/sec;
D = distance, 100 feet;
k = intercept or velocity at 100 feet;

and

n = exponent or slope of the straight line on log-log coordinates.

The method of least squares was used to determine the values of k and n for each set of data. The data were grouped by component of velocity, and an analysis of variance test was performed to determine if significant differences existed among the values of k and n (23). The results of these tests on each group of data showed that the values of n were not significantly

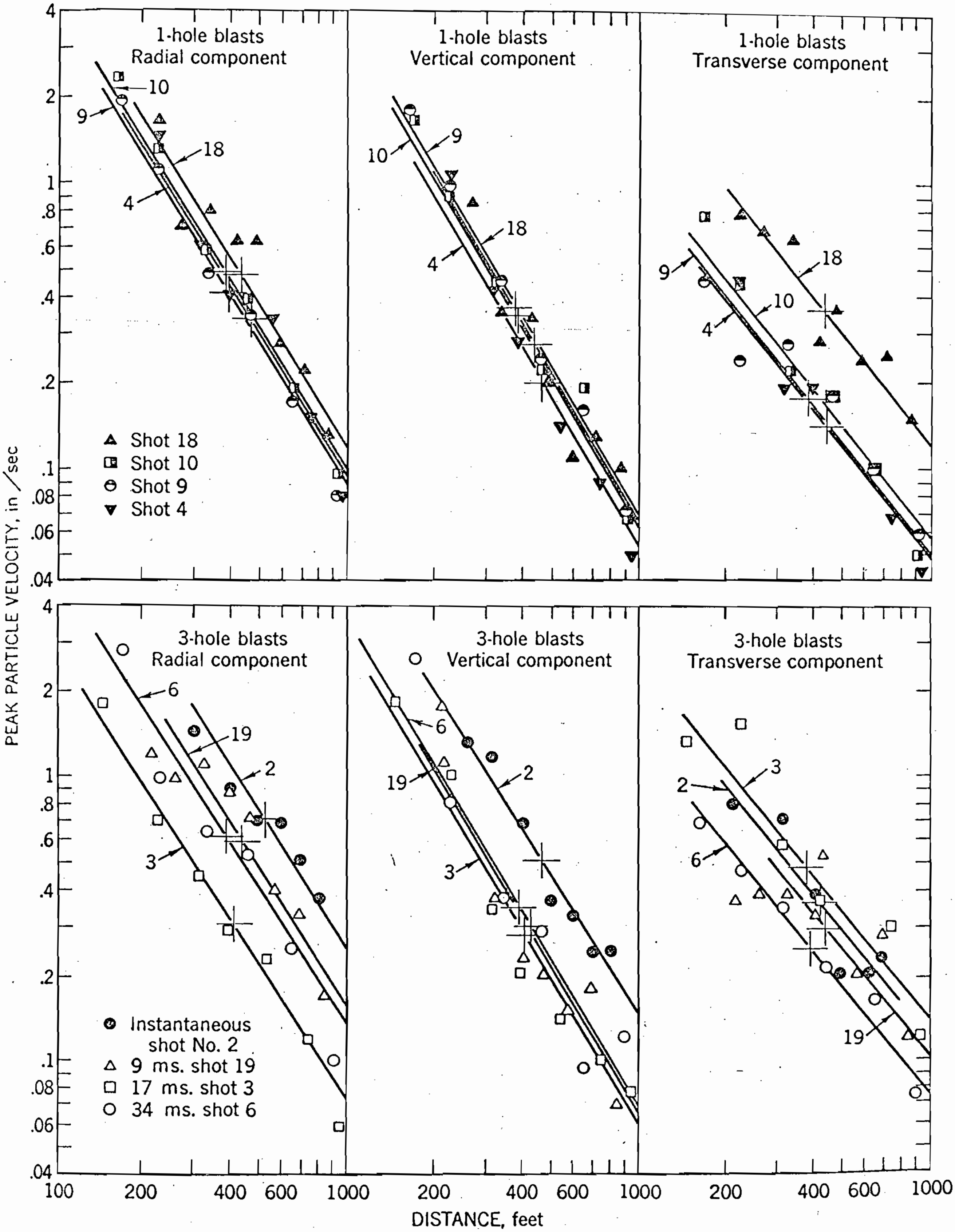

FIGURE 12. - Particle Velocity Versus Distance for 1- and 3-Hole Quarry Blasts.

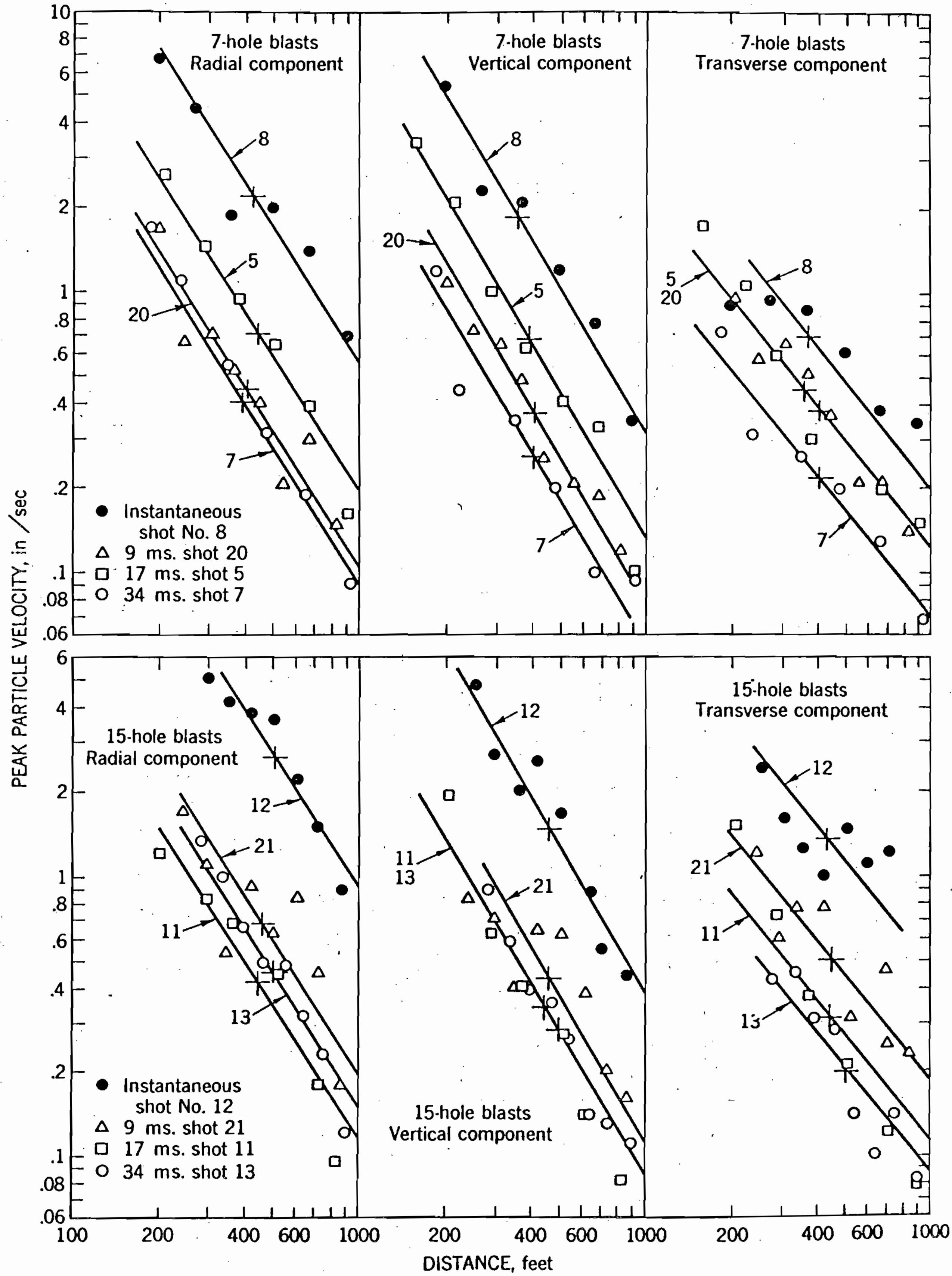

FIGURE 13. - Particle Velocity Versus Distance for 7- and 15-Hole Blasts.

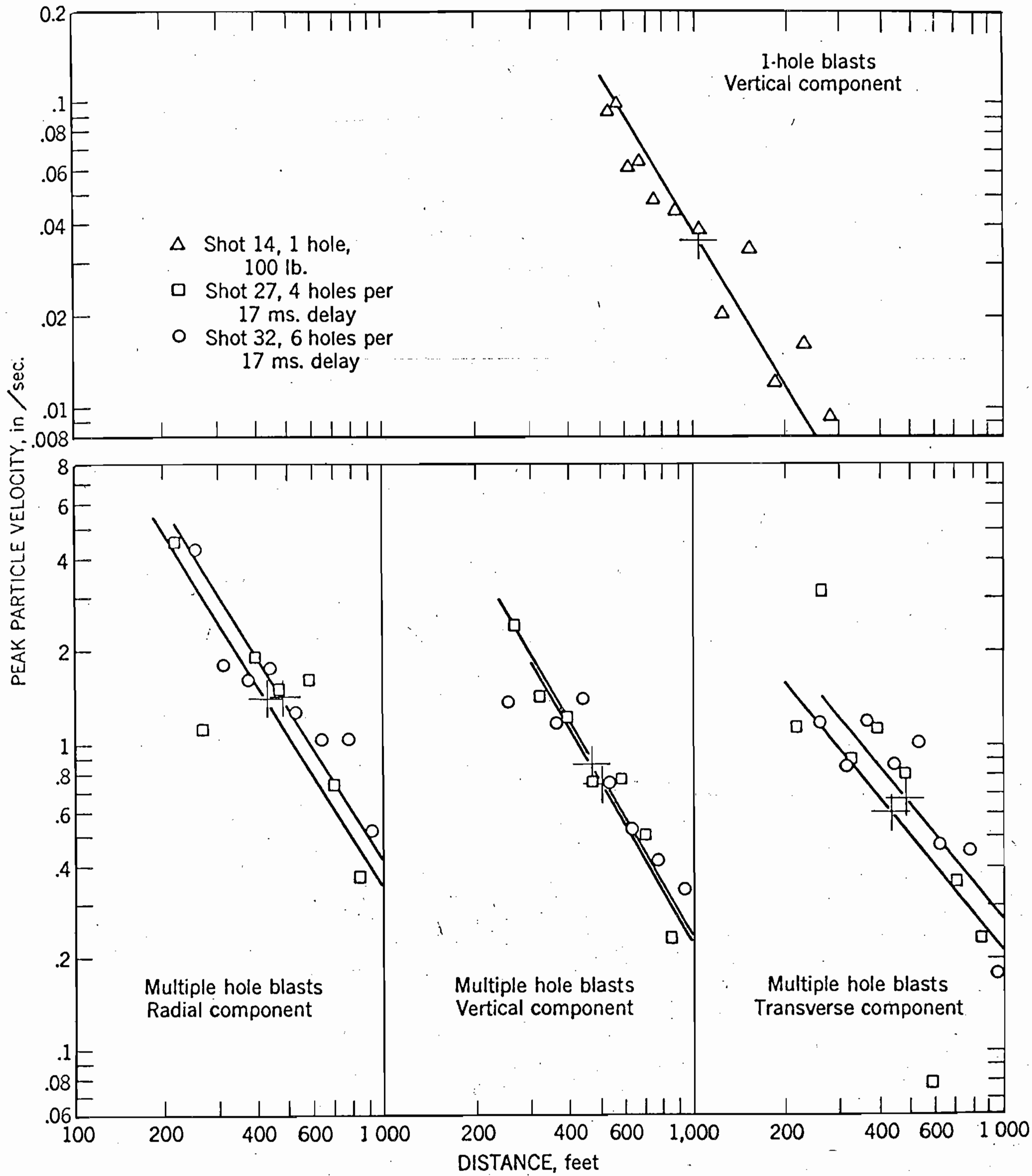

FIGURE 14. - Particle Velocity Versus Distance for a 1-Hole and 2-Multiple-Row Quarry Blasts.

different but that the values of k were significantly different for a confidence limit of 95 percent. Therefore, the average value and the standard error of n for each component was determined. These values, together with the average standard deviation about regression, are given in table 10. A second analysis of variance test showed that the average values of n for the three groups of data (grouped by component) were significantly different at the 95-percent confidence limit. Thus, the average value of n for each component was used to calculate for each set of data a new particle velocity intercept at 100 feet. These intercepts for each component for each test are given in table 11, and the average standard error of these intercepts for each component is given in the last column of table 10.

TABLE 10. - Average n and standard deviations

Component	Average n	Standard deviation about regression, percent	Average standard error of intercepts, percent
Radial...............	1.628 ± 0.043	±27	±30
Vertical.............	1.741 ± .049	±32	±27
Transverse...........	1.279 ± .063	±35	±40

TABLE 11. - Particle-velocity intercepts at 100 feet

Shot	Number of holes	Delay interval, milliseconds	Charge/delay, pounds	Particle-velocity intercepts		
				Radial in/sec	Vertical in/sec	Transverse in/sec
14......	1	0	100	-	2.15	-
4......	1	0	200	4.03	2.88	0.94
9......	1	0	200	3.62	3.70	.98
18......	1	0	200	5.24	3.48	2.39
10......	1	0	200	4.24	3.44	1.12
2......	3	0	600	10.8	7.76	2.28
8......	7	0	1,400	23.9	17.9	3.74
12......	15	0	3,000	38.6	22.1	8.99
19......	3	9	200	6.66	3.72	1.93
20......	7	9	200	4.53	4.35	2.35
21......	15	9	200	8.24	6.33	3.60
3......	3	17	200	2.99	3.16	2.65
5......	7	17	200	8.10	7.04	2.42
11......	15	17	200	4.83	4.61	2.14
6......	3	34	200	5.81	3.90	1.45
7......	7	34	200	4.14	3.06	1.30
13......	15	34	200	6.41	4.71	1.61
27......	13	17	800	14.4	12.3	3.79
32......	21	17	1,218	18.2	12.7	4.83

The particle-velocity intercepts in table 11 are a measure of the vibration level for each test and are the values of k in the following equations:

$$V_r = k_r D^{-1.63}, \quad (7)$$

$$V_v = k_v D^{-1.74}, \quad (8)$$

and

$$V_t = k_t D^{-1.28}, \quad (9)$$

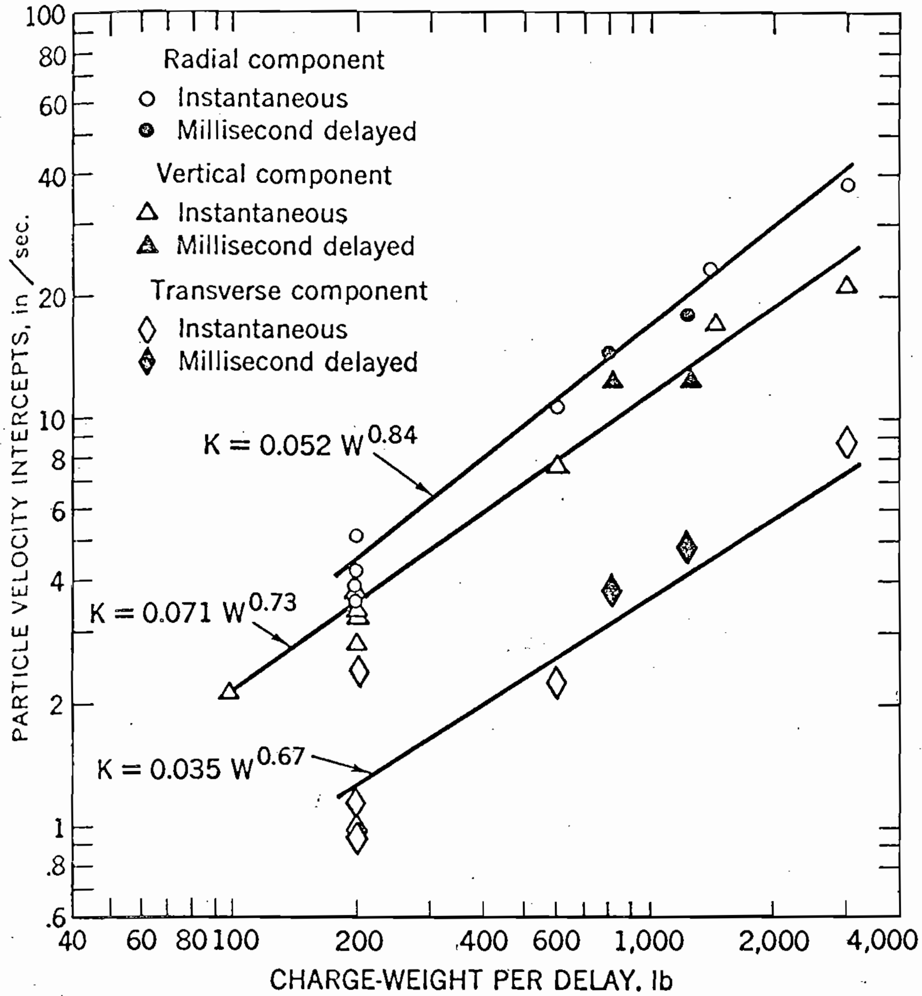

FIGURE 15. - Effect of Charge Weight on Level of Vibration.

where V is the particle velocity in in/sec, and D is the distance from the blast area to the gage expressed in hundreds of feet. The values of k in equations (7) to (9) can be used to study how the vibration level varies with other variables such as charge weight, delay interval, and number of delay periods.

Effect of Charge Weight on Vibration Level for Instantaneous Blasts

The data from the instantaneous blasts were studied to determine the effect of charge weight on the level of vibration. The particle-velocity intercepts at 100 feet were plotted on log-log coordinates as a function of charge weight (fig. 15). For each component, linear grouping of the data was obtained. Thus, a straight line through each group of data represents an equation of the form:

$$k = K W^b, \tag{10}$$

where

k = velocity intercept at 100 feet, in/sec;
K = charge weight intercept at 1 pound, in/sec;
W = charge weight, pounds;

and

b = exponent of W and also slope of the straight line on log-log coordinates.

The method of least squares was used to determine the values of b and K for each group of data. The resulting equations are

$$k_r = 0.052 W^{0.84}, \tag{11}$$

$$k_v = 0.071 W^{0.73}, \tag{12}$$

and

$$k_t = 0.035 W^{0.67}. \tag{13}$$

Substitution of equations (11) into (7), (12) into (8), and (13) into (9) gives

$$V_r = 0.052\ W^{0.84}\ D^{-1.63}, \tag{14}$$

$$V_v = 0.071\ W^{0.73}\ D^{-1.74}, \tag{15}$$

and

$$V_t = 0.035\ W^{0.67}\ D^{-1.28}. \tag{16}$$

Equations (14) to (16) can be used to estimate the maximum radial, vertical, and transverse components of particle velocity generated at various distances from instantaneous quarry blasts of different total charge weight at the Weaver quarry. These equations should be applicable over a distance ranging from 150 to 3,000 feet, and a total charge weight ranging from 100 to 3,000 pounds. The average standard deviation about regression for equations (14) to (16) is 40 percent; therefore, the observed value should not be more than twice or less than one-half of the estimated value at least 95 percent of the time.

Equations (14) to (16) are difficult to handle because the charge weight and the distance occur in the equation with different exponents. Simplification can be achieved if charge weight, raised to some power, can be shown to be a scaling factor. By rearranging terms, equations (14) to (16) can be expressed as

$$V_r = 0.052\ \left(\frac{D}{W^{0.512}}\right)^{-1.63}, \tag{17}$$

$$V_v = 0.071\ \left(\frac{D}{W^{0.421}}\right)^{-1.74}, \tag{18}$$

and

$$V_t = 0.035\ \left(\frac{D}{W^{0.521}}\right)^{-1.28}. \tag{19}$$

The charge weight, raised to some power, appears in the equation as a divisor of the distance, and as such can be considered a scaling factor. The exponent of W varies from 0.421 to 0.515; thus, the square root of W may be the scaling factor. However, there are not sufficient data to support this conclusion statistically within reasonable confidence limits. Therefore, it is recommended that equations (17) to (19) be used as given.

Effect of Delay Interval and Number of Holes

The nine quarry blasts employing delays of 9, 17, and 34 milliseconds and 3, 7, and 15 holes were used to study the effect of delay interval and number of holes on the vibration level. Examination of the curves in figures 12 and 13 shows that, in general, millisecond-delayed blasts resulted in lower vibration levels than instantaneous blasts employing the same total number of holes. Closer examination of these curves shows that the relative vibration levels for the millisecond-delayed blasts appear to be randomly distributed with respect to either the delay interval or the number of holes.

The particle-velocity intercept for any one blast is a measure of the vibration level; therefore, an analysis of variance test on these intercepts was performed to determine if significant differences exist between intercepts. Each component of particle velocity was considered separately.

Table 12 gives, in factorial design, the intercepts for the radial, vertical, and transverse components of particle velocity for the millisecond-delayed blasts. From these data the sum of the squared deviations for the row means, the column means, and the total were calculated and are given in table 13. For the radial component the ratios of the row and column mean squared deviations to the residual mean squared deviation are 0.276 and 0.240, respectively. The corresponding values of these ratios for the vertical component data are 1.01 and 0.46 and for the transverse component data are 0.57 and 3.5. For only 2 and 4 degrees of freedom, these ratios would have to exceed 6.94 before the row and column effects could be considered significant at the 95-percent confidence level. Therefore, from the present data the tentative conclusion is that the level of vibration from a millisecond-delay blast employing only one hole per delay is not controlled significantly by either the delay interval or the number of delay periods.

TABLE 12. - Factorial design for studying the effect of the length and the number of millisecond-delay intervals

Particle-velocity intercepts, in/sec					
Delay interval, ms.................		9	17	34	Mean
Component	Number of holes				
Radial..........	3	6.66	2.99	5.81	5.15
	7	4.53	8.10	4.14	5.59
	15	8.24	4.83	6.41	6.49
Mean.........	....	6.48	5.31	5.45	5.74
Vertical........	3	3.72	3.16	3.90	3.59
	7	4.35	7.04	3.06	4.82
	15	6.33	4.61	4.71	5.22
Mean.........	....	4.80	4.94	3.89	4.54
Transverse......	3	1.93	2.65	1.45	2.01
	7	2.35	2.42	1.30	2.02
	15	3.60	2.14	1.61	2.45
Mean.........	....	2.63	2.40	1.45	2.16

Comparison of Millisecond-Delayed Blasts With Instantaneous Blasts

The level of vibration resulting from an instantaneous blast has been shown to depend upon the number of holes in the round or the total charge weight, see equations (14) to (16). Also, the level of vibration from millisecond-delayed blasts employing only one hole per delay interval has been shown to be independent of the number of delay intervals or the length of the delay interval. Thus, the level of vibration from millisecond-delayed blasts must depend mainly upon the charge size per delay or the number of holes per delay. Therefore, the vibration level from a millisecond-delayed blast should correspond closely to an instantaneous blast employing the same number of holes as the number of holes per delay in the millisecond-delayed blast.

TABLE 13. - Analysis of variance for particle-velocity intercepts

Source of variation	Sum of squares	Degrees of freedom	Mean square
Radial component:			
Row means..................	2.8023	2	1.4012
Column means..............	2.4376	2	1.2188
Residual..................	20.2943	4	5.0736
Total..................	25.5342	8	-
Vertical component:			
Row means..................	4.2917	2	2.1458
Column means..............	1.9423	2	.9712
Residual..................	8.4668	4	2.1167
Total..................	14.7008	8	-
Transverse component:			
Row means..................	0.3758	2	0.1879
Column means..............	2.3290	2	1.1645
Residual..................	1.3121	4	.3280
Total..................	4.0169	8	-

Shots 4, 9, 10, and 18 were one-hole instantaneous blasts. Therefore, the vibration levels from these blasts can be compared with vibration levels from the millisecond-delayed blasts employing one hole per delay. For the single hole blasts the average particle velocity intercept at 100 feet, k_i, and its standard deviation σ_i, were calculated for each component from the data given in table 11. For the millisecond-delayed blasts the average particle velocity intercept at 100 feet, k_d, for each component are given in table 12, and their standard deviation, σ_d, were calculated from the total sum of the squares given in table 13. These values are summarized in table 14. Ratios of k_d/k_i and σ_d/σ_i were calculated and are given in table 14. Examination of the data indicates that millisecond-delayed blasts employing one hole per delay produce on the average a vibration level 42 percent greater than that produced by a single-hole instantaneous blast. Also, the spread in the data for the millisecond-delayed blasts is about 2.5 times greater than that for the single hole blasts. The foregoing differences between single hole and millisecond-delayed blasts cannot be shown to be significant at the 95-percent confidence level. However, they do indicate a trend that has important implications.

TABLE 14. - Average particle velocity intercepts for single hole and millisecond-delayed blasts

Component	Single hole blasts		Millisecond-delayed blasts		Ratios	
	k_i	σ_i	k_d	σ_d	k_d/k_i	σ_d/σ_i
Radial................	4.28	0.688	5.74	1.786	1.34	2.596
Vertical..............	3.38	.349	4.54	1.356	1.34	3.883
Transverse............	1.36	.691	2.16	.709	1.59	1.026
Average............	-	-	-	-	1.42	2.502

The particle velocity produced by an instantaneous blast has been shown to be given by an equation of the form,

$$V_i = K_i W_i^b D^{-n}. \tag{20}$$

Assuming that the exponent b is the same for a millisecond-delayed blast and that W is the charge per delay gives

$$V_d = K_d W_d^b D^{-n}. \tag{21}$$

The equivalent weight ratio R has been defined as W_d/W_i for the condition that $V_i = V_d$ at equal distances. Thus, from equations (20) and (21),

$$K_i W_i^b = K_d W_d^b. \tag{22}$$

Solving equation (22) for the equivalent weight ratio gives

$$R = \frac{W_d}{W_i} = [\frac{K_i}{K_d}]^{1/b}. \tag{23}$$

From equation (10),

$$k_i = K_i W_i^b, \tag{24}$$

$$k_d = K_d W_d^b. \tag{25}$$

The values of k_i and k_d given in table 14 were determined for a constant charge weight of 200 pounds. Therefore, setting $W_i = W_d$ and dividing equation (24) by (25) gives

$$\frac{k_i}{k_d} = \frac{K_i}{K_d}. \tag{26}$$

Substitution of equation (26) into (23) gives

$$R = (\frac{k_i}{k_d})^{1/b}. \tag{27}$$

Values of k_i/k_d can be obtained from table 14 for each component, and values of b can be obtained from equations (14) to (16). Evaluating equation (27) gives 0.706, 0.669, and 0.501 for the radial, vertical, and transverse components, respectively. The average of these values is 0.625 which is very close to 0.67, the average value of R found in the literature.

Quarry blasts 27 and 32 employed millisecond delays with a maximum of 4 and 6 holes per delay. The vibration levels from these blasts are compared with instantaneous blasts by plotting the particle-velocity intercepts at 100 feet as a function of charge size per delay on the same graph as used for the instantaneous blasts (fig. 15). Examination of the data points in figure 15 shows that the vibration levels from millisecond-delayed blasts are about the same as those from instantaneous blasts where more than one hole per delay interval was used. Furthermore, the spread in the millisecond-delayed blast data is about the same as the spread in the instantaneous blast data. Apparently a millisecond-delayed blast employing two or more holes per delay produces a more uniform vibration level than one employing only one hole per delay. Considerably more data on millisecond-delayed blasts employing two or more holes per delay are needed to substantiate these conclusions statistically.

CONCLUSIONS

Vibration measurements made with particle-velocity gages mounted in a uniform soil overburden back of a quarry face have demonstrated that propagation equations of the form,

$$V = K W^b D^{-n},$$

can be used to represent the peak particle velocity as a function of distance and charge weight. The exponents b and n vary with component of velocity (radial, vertical, and transverse) but are independent of other variables studied. The spread in the peak particle velocity data about its regression line for any one quarry blast averages 27, 32, and 35 percent for the radial, vertical, and transverse components, respectively.

The vibration levels from millisecond-delayed blasts employing only one hole per delay interval tend to show more spread from shot to shot than do instantaneous blasts or millisecond-delayed blasts employing more than one hole per delay interval. For the range of the variables studied, the number of delay intervals or the length of delay interval does not control the vibration level in any systematic manner for millisecond-delayed blasts employing one hole per delay interval. The level of vibration from these blasts averages about 42 percent greater than that from a single-hole blast; thus, some constructive interference among the individual wave trains is indicated for the millisecond-delayed blasts employing one hole per delay interval.

The level of vibration and the spread from shot to shot for millisecond-delayed blasts employing more than one hole per delay interval is approximately the same as that obtained from instantaneous blasts if the charge weight per delay for the millisecond-delayed blasts is equal to the total charge weight for the instantaneous blasts.

REFERENCES

1. Adams, W. M., R. G. Preston, P. L. Flanders, D. C. Sachs, and W. R. Perrett. Summary Report of Strong Motion Measurements, Underground Detonations. J. Geophysical Res., v. 66, No. 3, March 1961, pp. 903-942.

2. Birkenhauer, Henry F. An Analysis of Displacements Caused by Quarry Blasts. Seismological Observatory, John Carroll Univ., Cleveland, Ohio, May 1957, 48 pp.

3. Birkenhauer, Henry F., Robert Ennis, and Judeth Van Hamm. Statistical Evaluation of Quarry Blast Parameters. Pres. at meeting Eastern Section, Seismological Soc. of America, Cincinnati, Ohio, November 1961; Earthquake Notes, v. 32, Nos. 3, 4, 1961, p. 23.

4. Carder, D. S., and W. K. Cloud. Surface Motion From Large Underground Explosions. J. Geophysical Res., v. 64, No. 10, October 1959, pp. 1471-1487.

5. Cooper, Mary Jo. Multiple Regression Analysis of Vibrations From Small Blasts. Pres. at meeting Eastern Section, Seismological Soc. of America, Cincinnati, Ohio, November 1961; Earthquake Notes, v. 32, Nos. 3, 4, 1961, p. 23.

6. Crandell, F. J. Transmission Coefficient for Ground Vibrations Due to Blasting. J. Boston Soc. Civil Eng., April 1960, pp. 152-168.

7. Dix, C. Hewitt. Seismic Prospecting for Oil. Harper and Bros., New York, N.Y., 1952, p. 246.

8. Duvall, Wilbur I. Design Criteria for Portable Seismographs. Bureau of Mines Rept. of Investigations 5708, 1961, 6 pp.

9. Duvall, Wilbur I., and D. E. Fogelson. Review of Criteria for Estimating Damage to Residences From Blasting Vibrations. Bureau of Mines Rept. of Investigations 5968, 1962, 19 pp.

10. Fish, B. G. Short Delay Blasting. Mine and Quarry Eng., November 1949, pp. 339-344.

11. _____. Fundamental Considerations of Seismic Vibrations From Blasting. Mine and Quarry Eng., May 1951, pp. 111-114.

12. _____. Seismic Vibrations From Blasting--Reduction by Means of Short Delay Initiation. Mine and Quarry Eng., June 1951, pp. 189-192.

13. _____. Seismic Vibrations From Blasting--Solution of the Problem in Specific Cases. Mine and Quarry Eng., April 1951, pp. 217-222.

14. Fogelson, D. E., and C. F. Johnson. Calibration Studies of Three Portable Seismographs. Bureau of Mines Rept. of Investigations 6009, 1962, 21 pp.

15. Habberjam, G. M., and John T. Whetton. On the Relationship Between Seismic Amplitude and Charge of Explosive Fired in Routine Blasting Operations. Geophysics, v. 17, No. 1, January 1952, pp. 116-128.

16. Hancock, J., and W. Taylor. Short Delay Detonators. Mine and Quarry Eng., June 1948, pp. 175-181.

17. Hudson, D. E., J. L. Alford, and W. D. Iwan. Ground Accelerations Caused by Large Quarry Blasts. Seismological Soc. of America Bull., v. 51, No. 2, April 1961, pp. 191-202.

18. Ito, Ichiro. On the Relationship Between Seismic Ground Amplitude and the Quantity of Explosives in Blasting. Reprint From Memoirs of the Faculty of Eng., Kyoto Univ., v. 15, No. 11, April 1953, pp. 579-587.

19. Johansson, C. H., and Ulf Langefors. Short Delay Blasting in Sweden. Mine and Quarry Eng., September 1951, pp. 287-293.

20. Leet, Don L. Vibrations From Delay Blasting, Seismological Soc. of America Bull., March 1948, pp. 9-20.

21. Morris, G. The Reduction of Ground Vibrations From Blasting Operations. Engineering, Apr. 21, 1950, pp. 430-433.

22. Meyer, A. V. C., and W. I. Duvall. Calibration Study of a Peak-Reading Accelerograph. Bureau of Mines Rept. of Investigations 6026, 1962, 6 pp.

23. Ostle, B. Statistics in Research. Iowa State Coll. Press, Ames, Iowa, 1956, pp. 133-137.

24. Ricker, Norman. The Form and Nature of Seismic Waves and the Structure of Seismograms. Geophysics, v. 5, No. 4, October 1940, pp. 348-366.

25. Teichmann, G. A., and R. Westwater. Blasting and Associated Vibrations. Engineering, April 12, 1957, pp. 460-465.

26. Thoenen, J. R., and S. L. Windes. Seismic Effects of Quarry Blasting. Bureau of Mines Bull. 442, 1942, 83 pp.

27. Willis, D. E., and James T. Wilson. Maximum Vertical Ground Displacement of Seismic Waves Generated by Explosive Blasts. Seismological Soc. of America Bull., v. 50, No. 3, July 1960, pp. 455-459.

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