EFFECT OF CHARGE WEIGHT ON VIBRATION LEVELS FROM QUARRY BLASTING

By James F. Devine, Richard H. Beck,
Alfred V. C. Meyer, and Wilbur I. Duvall

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CONTENTS

ILLUSTRATIONS

TABLES

TABLES--Continued

EFFECT OF CHARGE WEIGHT ON VIBRATION LEVELS FROM QUARRY BLASTING

by

James F. Devine,[1] Richard H. Beck,[1] Alfred V. C. Meyer,[2] and Wilbur I. Duvall[3]

ABSTRACT

The radial, vertical, and transverse components of particle velocity were recorded by Bureau of Mines investigators along gage arrays extending in one or two directions for 145 to 3,170 feet at five quarrys. Of the 39 quarry blasts, 12 were instantaneous blasts, 5 were of the one hole per delay type, using millisecond delayed caps, and 22 were multiple hole per delay type employing millisecond delay detonating fuse connectors. Charge weight per hole ranged from 8 to 1,500 pounds, and the charge weight per delay interval, including the instantaneous blasts, ranged from 25 to 4,620 pounds.

Statistical analysis of the particle velocity-distance data shows that the square root of the charge weight per delay interval can be used as a scaling factor in a propagation equation of the form

$$V = H\left(\frac{D}{W^{\frac{1}{2}}}\right)^{-\beta}$$

where V is the peak particle velocity produced at a distance, D, by a quarry blast of charge weight per delay interval, W, and H and β are constants for each component of velocity for each quarry site.

INTRODUCTION

Previous Bureau of Mines investigations of vibrations from instantaneous and millisecond delayed quarry blasts (1-2)[4] showed that the radial, vertical,

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[4]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

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and transverse components of the peak particle velocity of ground vibrations could be represented by an equation of the form

$$V = HW^{b}D^{-\beta}, \tag{1}$$

where V is the peak particle velocity, W is the charge weight per delay interval or total charge weight for an instantaneous blast, D is the distance from blast area, and H, b, and β are constants for a given site and component. Equation 1 for any one component implies that H, b, and β are independent parameters that have to be determined for each quarry site and shooting procedure. Therefore, three constants must be determined before equation 1 can be used for predictions of vibration levels.

Equation 1 is simplified if a relationship exists between b and β such that the charge weight per delay interval, W, raised to some power, α, is a scaling factor. For this condition, equation 1 becomes:

$$V = H\left(\frac{D}{W^{\alpha}}\right)^{-\beta}, \tag{2}$$

where

$$\alpha = b/\beta. \tag{3}$$

To determine the applicability of equation 2 to particle velocity-distance data requires a large amount of data from different sites which have different propagation parameters H, b, and β. Statistical methods can then be used to determine if W^{α} is a scaling factor and, if so, to determine the value of α.

This Bureau of Mines report presents a summary of propagation data for the radial, vertical, and transverse components of the peak particle velocities of ground vibrations produced by millisecond-delayed or instantaneous quarry blasts. Data from 39 blasts at five quarries, where the maximum charge weight per delay interval is accurately known, are included. The maximum charge weight per delay interval for these blasts ranges from 25 to 4,620 pounds. The particle velocity data were obtained for a distance range from 145 to 3,170 feet from the blast area.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to the following companies for permitting the blasting tests at their quarries: Weaver Construction Company, Alden, Iowa; Northern Ohio Stone Company, Flat Rock, Ohio; New York Traprock Company, Clinton Point, N. Y.; and the Chemstone Corporation, Strasburg, Va. They also wish to thank Charles Croker, blasting consultant, and the Ohio Valley Construction Company for their cooperation in conducting the Washington, D.C. tests.

TEST SITES

The Iowa site is located at a quarry in central Iowa, near the town of Alden. The rock exposed at the face of this quarry is a light tan, argillaceous, loosely jointed limestone of the Gilmore City formation. The upper 10 feet exhibits weathering and crossbedding effects. There is virtually no structural dip in this area. The overburden, in which the gages were mounted, consists of 6 to 12 feet of black reworked glacial till.

The Washington, D.C., site was located at the east approach of the Theodore Roosevelt Bridge over the Potomac River. The rock is dark greenish-gray gneissoid diorite with hornblende. The surface of the bedrock sloped eastward away from the blast area. The arenaceous clay overburden, which was approximately 5 feet thick at the working area, increased to approximately 40 to 50 feet thick at station 7 of the gage array.

The third site was in a quarry located near Poughkeepsie, N.Y., which is situated in a tilted and jointed dolomite of the Stockbridge group. The overburden varies from 2 to 50 feet, depending on the direction from the blast area.

The Ohio site, a quarry near Flat Rock, Ohio, is located in a hard, flat-lying, thickly bedded gray limestone of the Columbus formation. The working face consisted of an upper level which contained 15 feet of slightly fractured and weathered limestone and a lower level which consisted of 20 feet of hard, unfractured limestone. The overburden is uniformly 9 feet thick. The gage boxes were buried below the normal level of plowing in a field directly behind the quarry.

The fifth site was located near Strasburg, Va. The rock consists of thick-bedded, bluish-gray, fine to medium coarsely crystalline dolomite, and limestone of compact texture, blue or dove colored, and coarsely fossiliferous. The beds dip approximately 30° to the southeast.

INSTRUMENTATION AND EXPERIMENTAL PROCEDURE

The recording instrumentation used in this investigation, described in detail in previous reports (1-2), consisted of velocity gages, linear amplifiers, and a 36-channel direct-writing oscillograph. For each measurement station the gages were mounted either on pins driven in the sides and bottom of a square hole dug in the overburden, or in an aluminum box buried in a square hole in the overburden as described in a previous report (4).

Figure 1 is a plan view of the Iowa test site showing the blast areas and gage locations. The gage array for each shot consisted of six to eight 3-component gage stations placed directly behind the blast area extending away from the blast. The gage array was moved frequently to keep it directly behind the blast area. Except for two tests the gage arrays remained approximately parallel to each other throughout the test program. Different symbols have been used in figures 1 to 5 to show which gage stations were used to record a particular blast.

The blast areas and gage array of the Washington, D.C., site are shown in figure 2. The gage stations at this site were not moved at any time, but the gage boxes were removed after each blast and replanted for the next blast. Seven 3-component gage stations were used for all the blasts at this site.

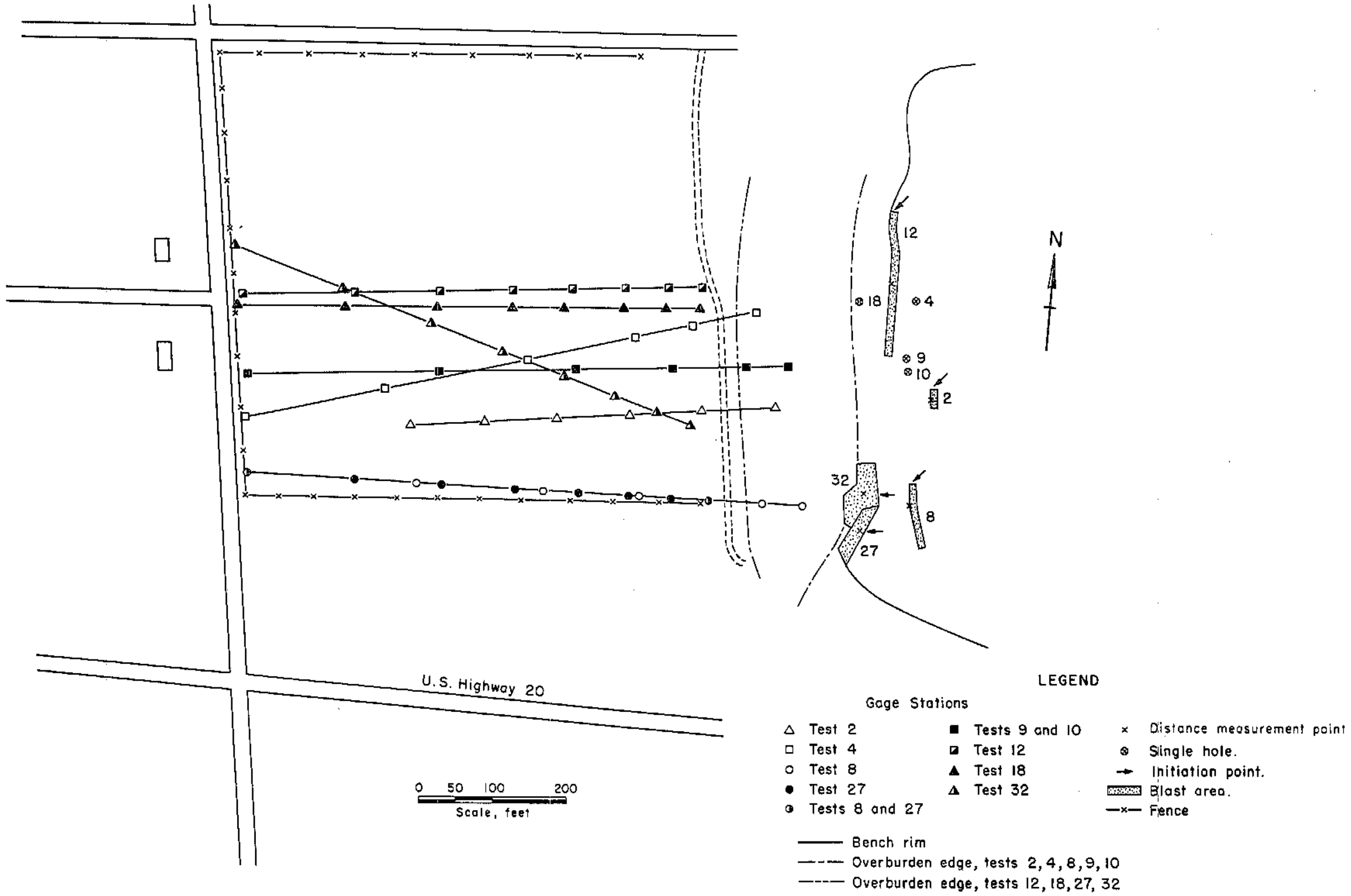

FIGURE 1. - Plan View of Iowa Test Site.

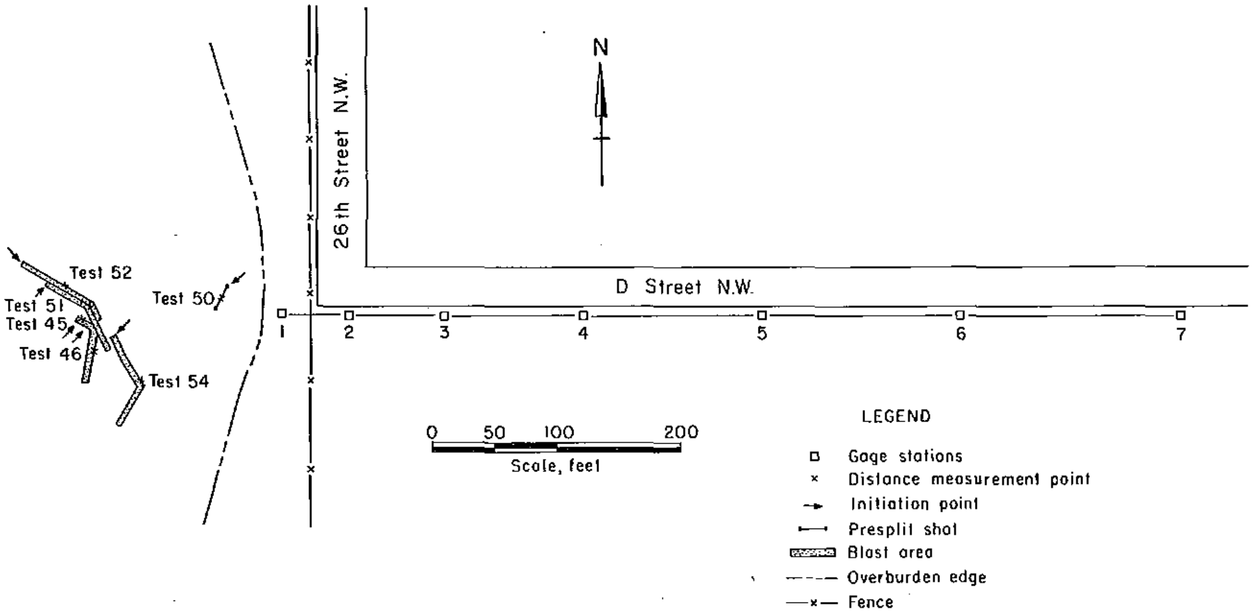

FIGURE 2. - Plan View of Washington, D.C., Test Site.

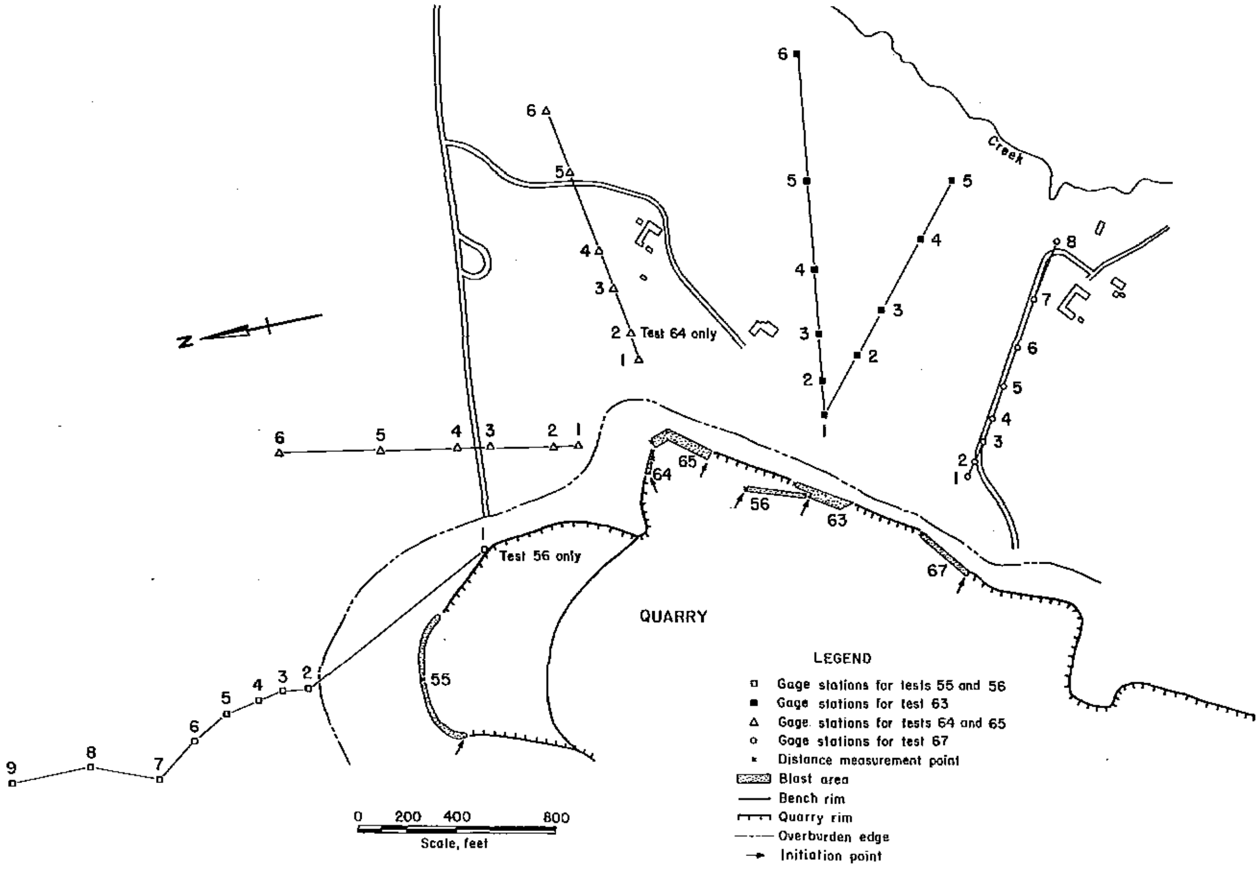

FIGURE 3. - Plan View of New York Test Site.

Figure 3 is a plan view of the New York site with the blast areas and gage stations shown. For three of the blasts at this site, two gage arrays extending in different directions from the blast were used. Six 2-component stations were used for each array. One shot was recorded by vertical gages only and the remaining two shots were recorded by an eight-station, 3-component gage array.

One eight-station 3-component gage array was used to record each of the blasts at the Ohio site, as shown in figure 4. Two of the blasts were detonated on the same day so the gage boxes were not moved for tests 78 and 79.

At the Virginia site, shown in figure 5, the eight 3-component gage boxes were placed on either of two gage arrays for all the blasts. As the data were collected it became obvious that the data from line 1 would not combine with the data from line 2. Therefore, the two lines and corresponding blast areas were considered as separate sites and have been called Va-1 and Va-2 throughout this report.

The blasting pattern and method of blast initiation varied considerably from quarry to quarry. These patterns consisted of single hole shots, single hole per delay shots, multiple hole per delay shots with all holes in a delay group connected with detonating fuse, and instantaneous multiple hole shots with all holes connected with detonating fuse. Two or more of these patterns were used at most of the sites. Table 1 gives a summary of the quarry blast data.

For the millisecond delayed blasts, the delay interval varied from 5 to 26 milliseconds. In a previous report (2) it was shown that the vibration level is independent of the delay interval if the delay interval is from 9 to 34 milliseconds. Therefore, the maximum charge weight per delay was considered as the charge weight for each shot. The vibration levels resulting from those shots that employed 5 millisecond delay connectors were not appreciably different from the vibration levels from shots containing longer delays and therefore, were included in the data analysis.

EXPERIMENTAL DATA

The peak particle velocity was determined by measuring the maximum amplitude of each record trace and multiplying this value by the calibrated sensitivity of the instrumentation (2). The maximum amplitude was measured regardless of the frequency, direction, and where it occurred during the record. The frequency of the pulse having the maximum amplitude was determined for each record trace. Tables 2 through 7 present the peak particle velocities and associated frequencies recorded at each gage station from each blast. When the peak particle velocity is the result of two frequencies, one superimposed on the other, both frequencies are listed in the tables, with the predominant one appearing first. Distances from shot to gage, also given in tables 2 through 7, were determined by measuring the distance from each gage to the center of the blast holes having the maximum charge weight per delay interval.

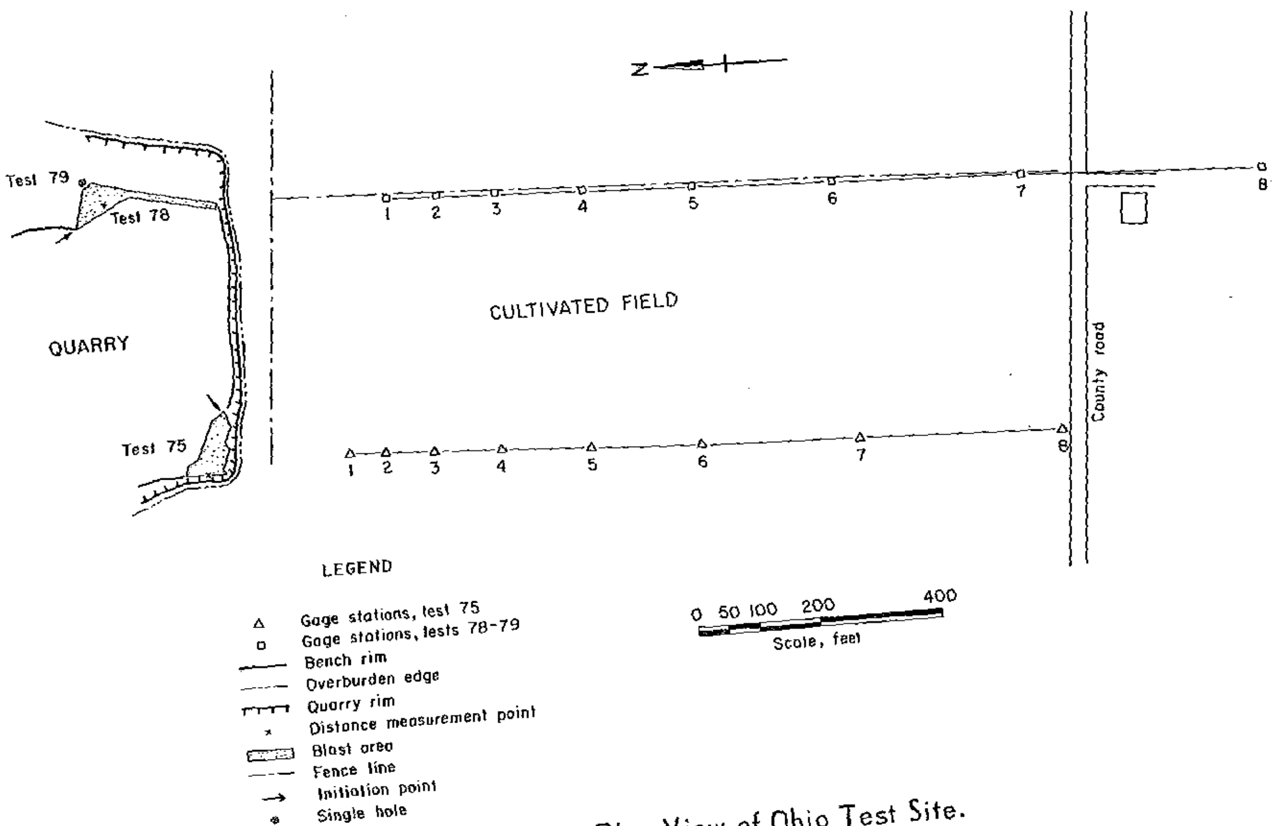

FIGURE 4. - Plan View of Ohio Test Site.

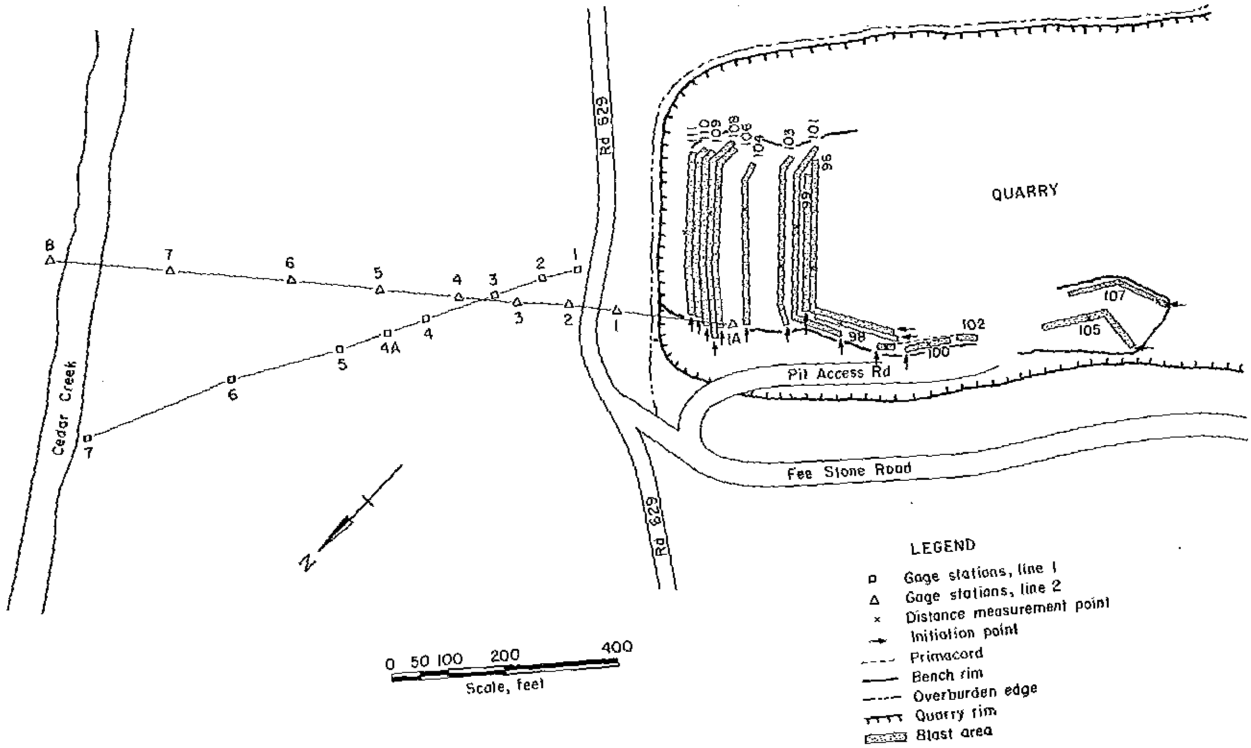

FIGURE 5. - Plan View of Virginia Test Site.

TABLE 1. - Quarry blast data

Site	Test no.	Total no. of holes	Hole depth, feet	Face hgt., feet	Total charge, pounds	Max. charge per delay, pounds	Charge per hole, pounds	No. of delay intervals	Length of delay, millisec	Burden, feet	Spacing, feet
Iowa.....	2	3	36	30	600	600	200	0	[1]0	10	15
	4	1	36	30	200	200	200	0	0	10	-
	8	7	36	30	1,400	1,400	200	0	0	10	15
	9	1	36	30	200	200	200	0	0	10	-
	10	1	36	30	200	200	200	0	0	10	-
	12	15	36	30	3,000	3,000	200	0	0	10	15
	18	1	36	30	200	200	200	0	0	10	-
	27	13	36	30	2,600	800	200	3	17	10	15
	32	21	36	30	4,263	1,218	203	3	17	10	14
D.C......	45	3	20	20	110	37	37	2	25(cap)	4	6
	46	13	20	20	403	31	31	12	25(cap)	4	6.5
	50	9	20	-	70	70	7.8	0	0	-	2.5
	51	13	20	20	403	31	31	12	25(cap)	4	6
	52	13	20	20	325	25	25	12	25(cap)	4	6
	54	13	18	20	308	25	24 avg	12	25(cap)	4	6
New York.	55	35	-	28- 54	21,578	920	920	34	17,26	22	20
	56	13	-	83-104	18,471	1,522	1,100-1,522	12	26	22	20
	63E	18	-	67- 73	19,933	1,249	1,039-1,249	17	26	23	20
	63SE	-	-	-	-	-	-	-	-	-	-
	64N	6	-	-	1,200	200	200	5	26	10-15	20
	64E	-	-	-	-	-	-	-	-	-	-
	65N	28	55-60	50- 55	28,810	1,405	700-1,405	27	26	21	20
	65E	-	-	-	-	-	-	-	-	-	-
	67	12	76-82	70- 76	14,576	1,355	1,100-1,355	11	26	22	22
Ohio.....	75	36	24	23	6,430	1,072	180	9	9	12	10
	78	36	56	54	16,520	4,620	459	12	9	14	11
	79	1	56	54	468	468	468	0	0	10	-
Va.-1....	96	84	20	18	3,350	1,120	40 avg	2	5	8	5
	99	49	20	18	1,950	968	40 avg	1	5	8	5
	101	78	20	18	3,200	1,600	40 avg	1	5	8	5
	103	59	20	18	2,150	589	35 avg	3	5	8	5
	104	60	15-20	15- 20	2,425	1,330	40 avg	1	9	8	6
	106	61	20	18	2,350	1,380	40 avg	1	9	8	5
	108	60	20	18	1,950	1,600	20-35	1	5	10	6
	109	51	20	12- 14	1,700	865	33 avg	1	5	8	5-7
	110	51	20	18	1,750	360	32 avg	4	5	8	6
	111	48	20	18	1,600	367	33 avg	4	5	8	6
Va.-2....	98	31	20	18	1,250	605	40.3 avg	1	5	8	5
	100	16	22-12	20- 10	475	475	25-35	0	0	8	5
	102	16	10-20	8- 18	450	343	25-35	1	5	8	5
	105	42	4-20	4- 20	1,325	1,325	25-35	0	0	10	5
	107	42	6-20	6- 20	1,250	1,250	25-35	0	0	8	5

[1]The length of the delay is considered to be zero if the shot consisted of a single hole, of one hole per delay, or of multiple holes per delay tied together with detonating fuse.

TABLE 2. - Particle velocity and frequency data for the Iowa site

Test	Distance, 100 ft	Scaled distance, ft/lb$^{\frac{1}{2}}$	Radial		Vertical		Transverse	
			Particle velocity, in/sec	Frequency, cps	Particle velocity, in/sec	Frequency, cps	Particle velocity, in/sec	Frequency, cps
2..	2.13	8.69	-	-	1.74	50	0.789	50
	3.13	12.8	1.47	25	1.17	25	.699	50
	4.13	16.9	.923	20	.680	40	.384	30
	5.13	20.9	.680	16	.363	100	.199	25
	6.13	25.0	.694	20	.324	40	.201	20
	7.13	29.1	.511	16	.241	50	.228	16
4..	2.20	15.6	1.45	24	1.08	167	.456	36
	3.10	22.0	.597	26	.418	-	.192	42
	3.89	27.6	.403	29	.280	200	.185	14
	5.38	38.2	.325	21	.144	125	-	-
	7.38	52.3	.150	21	.0898	133	.068	71
	9.32	66.1	.0792	56	.0502	66	.044	20
8..	1.45	3.88	-	-	8.76	15	1.65	25
	2.00	5.35	6.92	15	5.45	14	.900	50
	2.74	7.33	4.65	14	2.27	50	.932	20
	3.70	9.89	1.94	50	2.11	50	.859	30
	5.00	13.4	2.00	50	1.20	50	.614	50
	6.75	18.0	1.45	50	.780	30	.381	50
	9.07	24.3	.694	28	.350	20	.344	18
9..	1.62	11.5	1.88	37	1.79	71	.450	17
	2.20	15.6	1.10	31	.977	83	.245	83
	3.22	22.8	.475	42	.448	71	.269	71
	4.55	32.3	.340	30	.238	125	.182	20
	6.42	45.5	.169	36	.157	125	.103	20
	9.03	64.0	.0811	23	.0710	83	.0589	31
10..	1.62	11.5	2.34	50	1.64	71	.757	50
	2.20	15.6	1.30	38	.892	111	.450	36
	3.22	22.8	.567	31	.448	71	.223	56
	4.55	32.3	.386	30	.219	31	.182	26
	6.42	45.5	.195	45	.137	105	.101	22
	9.03	64.0	.0957	21	.0676	83	.0500	25
12..	2.60	4.75	-	-	4.72	25	2.41	25
	3.06	5.58	5.10	16	2.73	25	1.57	20
	3.64	6.64	4.15	12	2.00	25	1.24	25
	4.36	7.96	3.77	20	2.64	25	1.01	30
	5.18	9.45	3.64	20	1.65	29	1.47	25
	6.18	11.3	2.19	22	.866	25	1.09	22
	7.36	13.4	1.49	20	.548	20	1.25	25
	8.88	16.2	.903	15	.420	30	-	-

TABLE 2. - Particle velocity and frequency data for the Iowa site--(Con.)

Test	Distance, 100 ft	Scaled distance, ft/lb$^{\frac{1}{2}}$	Radial		Vertical		Transverse	
			Particle velocity, in/sec	Frequency, cps	Particle velocity, in/sec	Frequency, cps	Particle velocity, in/sec	Frequency, cps
18..	2.20	15.6	1.66	22	0.998	25	0.778	33
	2.67	18.9	.713	13	.850	83	.696	26
	3.24	23.0	.780	18	.347	38	.621	26
	4.10	29.1	.634	19	.342	32	.279	18
	4.76	33.8	.630	27	.205	28+114	.355	18
	5.79	41.1	.266	24	.105	23+143	.239	20
	7.04	49.9	.215	18	.126	22	.243	18
	8.53	60.5	.131	14	.0965	27	.146	15
27..	2.14	7.56	4.48	12+125	-	-	1.13	10+50
	2.63	9.29	1.08	100	2.39	125	3.08	100
	3.21	11.3	1.80	12+75	1.38	50	.859	12+83
	3.90	13.8	1.91	25	1.25	133	1.06	12
	4.75	16.8	1.52	26	.744	28+100	.788	17
	5.75	20.3	1.54	29	.786	25+100	-	-
	6.95	24.6	.729	12	.504	25+100	.345	12
	8.40	29.7	.387	18	.228	10	.237	7.5
32..	2.55	7.31	4.32	8.5	1.33	85	1.15	11+100
	3.05	8.74	1.80	14	-	-	.835	52
	3.65	10.5	1.58	20+86	1.15	80	1.15	15
	4.40	12.6	1.79	16+80	1.37	10+86	.849	14+60
	5.30	15.2	1.28	16	.742	35	.988	18
	6.35	18.2	1.02	19	.522	40+75	.448	19+100
	7.65	21.9	1.04	17+72	.406	75	.438	115
	9.24	26.5	.533	18+75	.328	76	.164	20

TABLE 3. - Particle velocity and frequency data for the D.C. site

Test	Distance, ft	Scaled distance, ft/lb$^{\frac{1}{2}}$	Radial		Vertical		Transverse	
			Particle velocity, in/sec	Frequency, cps	Particle velocity, in/sec	Frequency, cps	Particle velocity, in/sec	Frequency, cps
45..	160	26.3	0.625	91	0.909	71	0.659	83
	290	47.7	.415	67	.404	35	.281	77
	546	89.8	.118	27	.133	100	.274	83
	705	116	.114	40	.0857	59	.0940	111
	882	145	.0531	40	.0690	83	.0339	50
46..	154	27.6	.426	71	.517	63	.398	63
	207	37.2	.297	77	.347	77	.249	71
	283	50.8	.290	63	.207	36	.140	71
	393	70.6	.148	45	.114	100	.0834	112
	537	96.4	.110	56	.0685	63	.0857	50
	697	125	.0935	48	.0425	71	.0583	63
	875	157	.0294	56	.0396	63	.0301	45
50..	176	21.0	1.27	59	1.04	59	.389	43
	286	34.2	.405	43	.465	42	.184	143
	430	51.4	.264	36	.261	35	.159	33
	590	70.5	.155	30	.116	42	.137	36
	765	91.4	.0689	30	.0785	30	.0471	37
51..	155	27.8	.344	67	.373	31	.291	43
	209	37.5	.348	63	.417	40	.278	50
	286	51.3	.373	43	.258	59	.170	100
	396	71.1	.186	38	.136	134	.0966	25+140
	540	96.9	.128	36	.0804	36	.0761	31
	700	126	.101	40	.0517	71	.0613	56
	877	157	.0366	59	.0417	67	.0335	27
52..	175	34.3	.186	111	.418	29	.189	36
	229	44.9	.212	71	.242	35	.179	33
	306	60.0	-	-	.156	45	.0995	45
	416	81.6	.0878	40	.0803	130	.0658	29
	560	110	.0581	33	.0726	28	.0649	27
	720	141	.0477	32	.0380	29	.0477	45
	897	176	.0253	33	.0335	37	.0219	24
54..	176	35.2	.446	100	.471	71	.212	71
	250	50.0	.466	63	.334	67	.271	28
	359	71.8	.183	33	.210	37	.128	23+143
	502	100	.126	27	.128	91	.0739	40
	661	132	.0814	26	.0745	33	.0839	45
	837	167	.0560	29	.0489	63	.0309	36

TABLE 4. - Particle velocity and frequency data for the New York site

Test	Distance, 100 ft	Scaled distance, ft/lb$^{1/2}$	Radial: Particle velocity, in/sec	Radial: Frequency, cps	Vertical: Particle velocity, in/sec	Vertical: Frequency, cps	Transverse: Particle velocity, in/sec	Transverse: Frequency, cps
55..	4.68	15.5	-	-	0.737	28	-	-
	5.68	18.8	-	-	.478	40	-	-
	6.70	22.1	-	-	.263	50	-	-
	8.05	26.6	-	-	.245	40	-	-
	11.4	37.7	-	-	.164	36	-	-
	17.1	56.5	-	-	.203	38	-	-
56..	10.7	27.4	-	-	.347	49	-	-
	19.3	49.4	0.174	12.5	.0775	20	0.148	11
	20.3	51.9	.0716	64	.0560	40+100	.101	40
	21.3	54.6	.0537	51	.0457	63	.101	60
	22.7	58.2	.0768	40	.0746	80	.0891	9+60
	24.3	62.2	.0582	50	.0631	100	.0699	63
	26.3	67.3	.0571	50	.0499	45	.0953	50
	28.5	73.1	.0439	40	.0464	42	.0567	8.5+33
	31.7	81.3	.0909	40	.0861	40	.0862	49
63E.	3.00	8.50	1.24	29	1.34	25	-	-
	4.25	12.0	1.16	43	1.46	17	-	-
	6.00	17.0	.880	23+50	.835	18	-	-
	8.50	24.1	.588	25	.620	12.5	-	-
	12.0	34.0	.281	10	.344	12	-	-
	17.0	48.2	.194	14	-	-	-	-
63SE	3.00	8.50	1.24	29	1.34	25	-	-
	5.70	16.1	.549	38	.581	9	-	-
	7.70	21.8	.732	16+51	.618	13+22	-	-
	10.9	30.9	.228	22	.207	33	-	-
	13.5	38.4	.166	50	.245	38	-	-
64N.	3.00	21.3	.627	26+110	.438	25+133	-	-
	4.00	28.4	.397	20	.303	32+77	-	-
	6.50	46.1	.101	17+100	.137	25+100	-	-
	7.80	55.3	.156	17	.0818	29+100	-	-
	10.9	77.3	.106	15+74	.0520	22	-	-
	15.0	106	.0322	11+83	.0357	16	-	-
64E.	3.90	27.7	.17	29	.13	25	-	-
	5.00	35.5	-	-	.052	17	-	-
	6.90	48.9	.0854	25	.051	23+50	-	-
	8.50	60.3	.114	18	.0737	25	-	-
	11.8	83.7	.033	12.5	.035	10	-	-
	14.4	102	.019	12	.018	12	-	-
65N.	3.00	8.00	0.657	39	.705	42	-	-
	4.00	10.7	.658	17	.634	42	-	-
	6.49	17.3	.258	22	.202	18	-	-
	7.80	20.8	.258	18	.121	23+71	-	-
	10.9	29.1	.220	8.5+40	.124	20	-	-
	15.0	40.0	.177	10	.0676	8.5	-	-

TABLE 4. - Particle velocity and frequency data for the New York site--(Con.)

Test	Distance, 100 ft	Scaled distance, ft/lb$^{1/2}$	Radial		Vertical		Transverse	
			Particle velocity, in/sec	Frequency, cps	Particle velocity, in/sec	Frequency, cps	Particle velocity, in/sec	Frequency, cps
65E.	3.00	8.00	2.08	25	1.80	38	-	-
	6.00	16.0	.966	43	.760	42	-	-
	7.65	20.4	.718	13+26	.358	83	-	-
	10.9	29.1	.207	12+43	.125	9+33	-	-
	13.6	36.3	.133	12+57	.105	10+31	-	-
67..	2.95	8.02	1.49	33	1.63	37	1.46	56
	3.55	9.65	1.86	10	1.33	43	1.16	25
	4.40	12.0	.977	10	.676	50	.560	12.5
	5.40	14.7	.456	7.2	.518	20+67	.517	77
	6.75	18.3	.387	18	.311	45	.388	83
	8.35	22.7	.311	50	.211	50	.269	12.5
	10.3	28.0	.146	9+59	.158	50	.141	63
	12.8	34.8	-	-	.128	50	.124	50

TABLE 5. - Particle velocity and frequency data for the Ohio site

Test	Distance, 100 ft	Scaled distance, ft/lb$^{1/2}$	Radial		Vertical		Transverse	
			Particle velocity, in/sec	Frequency, cps	Particle velocity, in/sec	Frequency, cps	Particle velocity, in/sec	Frequency, cps
75..	2.32	7.09	2.17	26	1.79	59	2.19	50
	2.93	8.96	2.34	29	1.49	50	1.41	36
	3.74	11.4	2.19	42	1.14	56	1.68	50
	4.82	14.7	.909	66	1.31	45	.967	29
	6.30	19.3	.764	36	.896	75	.560	36
	8.10	24.8	.794	28	.950	83	1.02	71
	10.7	32.7	.407	30+100	.401	42	.418	28
	14.0	42.8	.309	16	.0867	12	.348	15
78..	4.60	6.76	2.06	19	2.85	22	2.32	11
	5.41	7.96	2.19	28	1.86	26	1.67	28
	6.40	9.41	2.01	25	1.31	33	1.18	15
	7.82	11.5	1.72	19	.912	27	.861	12
	9.62	14.1	1.47	25	.786	50	.834	25
	11.9	17.5	1.09	50	.674	42	.788	15
	15.0	22.0	.590	13	.373	29	.936	13
	18.9	27.9	.307	25	.278	16	.263	22
79..	4.96	23.0	0.401	36	0.611	31	0.395	18
	5.78	26.8	.384	31	.278	28	.334	24
	6.76	31.3	.341	29	.134	42	.251	22
	8.19	37.9	.287	28	.147	33	.246	22
	9.98	46.2	.235	24	.101	42	.261	25
	12.3	56.8	.152	22	.0806	36	.182	20
	15.3	71.1	.120	18	.0546	28	.156	20
	19.3	89.4	.0669	25	.0422	17	.0474	25

TABLE 6. - Particle velocity and frequency data for the Virginia site line 1

Test	Distance, 100 ft	Scaled distance, ft/lb$^{\frac{1}{2}}$	Radial		Vertical		Transverse	
			Particle velocity, in/sec	Frequency, cps	Particle velocity, in/sec	Frequency, cps	Particle velocity, in/sec	Frequency, cps
96	4.12	12.3	0.962	38	-	-	0.886	27
	4.75	14.2	1.39	23	1.54	31	1.62	26
	5.60	16.7	1.03	19	.683	34	-	-
	6.88	20.5	-	-	.423	35	.900	24
	8.45	25.2	.772	14	.334	23	.378	24
	10.40	31.0	.383	11	.314	17	.301	12.5
	13.10	39.1	.471	25	.159	100	.285	39
99	3.95	12.7	1.85	33	1.67	38	1.92	22
	4.56	14.7	1.20	36	1.33	36	1.42	25
	5.42	17.4	0.861	25+100	.628	63	1.53	25
	6.67	21.4	-	-	.824	38	.845	29
	8.24	26.5	.692	21	.406	36	.472	38
	10.20	32.8	.328	20	.342	18	.328	18
	12.90	41.5	.334	25	.215	36+100	.313	25
101	3.88	9.70	1.64	68	1.81	28	1.90	22
	4.52	11.3	1.09	25	1.14	31	1.57	23
	5.42	13.5	1.17	25+75	1.02	50	2.25	28
	6.70	16.7	-	-	.714	31	.764	25+50
	8.29	20.7	.946	17	.461	26	.616	22
	10.30	25.7	.938	16	.340	20	.434	16
	13.00	32.5	.358	25+63	.198	83	.347	77
103	3.56	14.6	.840	80+17	1.09	38	1.25	26
	4.18	17.2	.773	60	.580	67	1.09	22
	5.02	20.7	.602	71	.500	87	1.01	25
	6.29	25.9	-	-	.243	100+20	.474	24
	7.85	32.3	.346	21	.318	24	.493	25
	9.83	40.5	.223	14	.249	18	.232	17
	12.50	51.4	.195	28	.0929	71	.353	24
104	3.10	8.49	-	-	1.24	26	-	-
	3.76	10.3	0.558	57	1.04	24	1.89	30
	4.64	12.7	.786	25	.863	50	1.38	29
	5.93	16.2	-	-	.456	30	1.10	35
	7.51	20.6	.634	18	.434	26	.860	36
	9.50	26.0	.296	13	.285	22	.276	19
	12.25	33.6	.384	23	.129	56	.535	28

TABLE 6. - Particle velocity and frequency data for the Virginia site line 1--Continued

Test	Distance, 100 ft	Scaled distance, ft/lb$^{1/2}$	Radial		Vertical		Transverse	
			Particle velocity, in/sec	Frequency, cps	Particle velocity, in/sec	Frequency, cps	Particle velocity, in/sec	Frequency, cps
106	2.86	7.71	2.08	38	1.40	21	-	-
	3.50	9.43	1.98	26	1.42	26	2.00	21
	4.38	11.8	.922	36	1.09	38	1.61	25
	5.65	15.2	-	-	.600	36	1.58	31
	7.24	19.5	.566	29	.529	26	1.18	36
	9.21	24.8	.435	10	.384	23	.348	21
	12.00	32.2	.323	23	.161	40	.363	22
108	2.50	6.68	1.42	31	1.43	29	2.17	26
	3.15	8.42	1.52	24	2.01	33	1.44	28
	4.00	10.7	1.13	29	.959	29	1.41	40
	5.32	14.2	-	-	.727	33	.657	31
	6.02	16.0	1.02	22	.977	26	1.70	24
	6.90	18.4	.711	22	.448	31	.628	33
	8.87	23.8	.387	12	.263	17	.338	17
	11.60	31.0	.270	23	.124	31	.392	22
109	2.14	7.28	2.19	42	1.55	45	1.26	17
	2.78	9.46	1.09	25	1.12	27	1.85	29
	3.62	12.3	.736	67	.766	31	1.29	27
	4.88	16.6	-	-	.373	56	.597	33
	5.55	18.9	.863	31	.800	22	.958	31
	6.43	21.9	.387	25	.334	25	.628	36
	8.44	28.7	.223	45	.264	25	.240	17
	11.20	38.1	.273	26	.105	50	.286	25
110	2.13	11.2	1.10	31	1.06	42	1.14	33
	2.78	14.6	.420	23	.472	48	1.09	30
	3.68	19.4	-	-	-	-	.675	27
	4.97	26.2	.680	29	-	-	-	-
	5.67	29.8	.484	33	.283	22	.345	34
	6.56	34.5	.245	10	.144	25	.235	43
	8.52	44.8	.181	14	.0847	17	.112	63
	11.3	59.4	.124	67	.120	100	.142	21
111	2.00	10.2	1.12	38	1.01	43	1.45	31
	2.64	13.5	.465	31	.712	71	1.23	33
	3.50	17.9	.539	35	.581	53	.627	71
	4.80	24.5	.871	30	.518	48	.420	31
	5.50	28.0	.570	34	.278	21	.285	34
	6.40	32.6	.290	11	.211	26	.328	40
	8.38	42.7	.155	9	.0884	13	.143	40
	11.1	56.6	.280	24	.121	42	.195	24

TABLE 7. - Particle velocity and frequency data for the Virginia site line 2

Test	Distance, 100 ft	Scaled distance, $ft/lb^{1/2}$	Radial		Vertical		Transverse	
			Particle velocity, in/sec	Frequency, cps	Particle velocity, in/sec	Frequency, cps	Particle velocity, in/sec	Frequency, cps
98	3.94	16.0	1.61	38	1.76	54	1.67	42
	4.78	19.4	0.679	36	.788	36	.794	40
	5.69	23.1	.829	36	.917	83	1.28	28
	6.72	27.3	.550	75	.346	85	.692	23
	8.13	33.0	.517	36	.233	83	.592	28
	9.70	39.4	.381	15	.142	20	.338	15
	11.80	48.0	.106	11+75	.0929	93	.119	77
	13.90	56.5	.105	28+100	.0991	100	.0788	100
100	5.52	25.3	1.06	33	.693	37	.611	33
	6.36	29.2	.328	50	.267	42	.380	33
	7.27	33.3	.573	24	.173	33	.328	37
	8.31	38.1	.442	23	.230	23	.409	28
	9.71	44.5	.333	25	.121	25	.293	23
	11.30	51.8	.258	66	.178	20	.204	25
	15.50	71.1	.0640	24	.0484	20+110	-	-
102	4.77	25.8	.672	37	.281	50	.280	35
	5.61	30.3	.246	45	.185	56	.211	45
	6.51	35.2	.430	31	.136	63	.469	36
	7.57	40.9	.196	30	.113	36	.261	27
	8.96	48.4	.173	32	.0579	42	.153	28
	10.50	56.8	.110	23	.0484	22+56	.0681	43
	14.70	79.5	.0306	42	.0285	50	.0299	39
105	8.25	22.7	.995	29	1.15	33	.536	29
	10.00	27.5	.873	26	-	-	.497	26
	11.00	30.3	.581	83	.424	22+250	.421	22
	12.40	34.1	.598	22	.283	19	.464	26
	14.00	38.5	.310	12	.217	17	.240	19
107	9.47	26.8	.483	28	.670	30	.552	29
	10.30	29.0	.253	55	.278	46	.248	38
	11.20	31.6	.549	26	.216	71	.403	33
	12.20	34.5	.323	22	.257	25	.341	25
	12.80	36.1	.435	31	.173	27	.280	25
	13.60	38.4	.347	25	.366	22	.235	19
	15.20	42.9	.161	12	.130	19	.140	16
	17.30	48.9	.171	50	.0571	17+120	-	-

DATA ANALYSIS

For each test, the peak particle velocity recorded at each gage position was plotted by component on log-log coordinates as a function of distance from the blast area. Good linear grouping of the data was obtained, indicating that the particle velocity-distance data for each set of data can be represented by a straight line. The method of least squares was used to obtain a measure of the spread in the data, and to determine the slope and intercept of the best fit straight line through each set of data (5).

The straight lines are shown plotted through the midpoints of the data in figures 6 to 8. Because of the large amount of data, it is not possible to show each data point. The standard deviation of the data about each straight line is shown as a vertical line near the center of the data. The straight lines in figures 6 to 8 can be represented by a general propagation equation of the form

$$V = K_{ij} D^{-\beta_{ij}}, \qquad (4)$$

i site
j test # @ site

where V = peak particle velocity,

D = travel distance,

β_{ij} = exponent of D or the slope of the straight line through the jth set of data at the ith site,

and K_{ij} = velocity intercept at unit travel distance for the jth set of data at the ith site.

The letter i represents the site, and varies from 1 to 6, whereas the letter j represents a test at each site, and varies from 1 to k_i where k_i is the total number of tests at any given site.

As written, equation 4 indicates that for each component the slope, β_{ij}, varies with each shot at each site. However, it is apparent from figures 6 to 8 that the slopes, β_{ij}, may not vary significantly from shot to shot for a given component at each site. Therefore, analysis of variance tests were performed on the data to determine if significant differences in β_{ij} exist for a given compnent at each site. A summary of these tests is given in table 8. * The calculated F_1 values are all larger than the table values; thus, there are significant differences between the sets of data and one straight line can not represent all the test data for each component at each site. Because the calculated values of F_2 are all smaller than the F_2 table values, there are no significant differences in the slopes for the different tests at each site for each component. Thus, an average slope, β_i, can be used for each component at each site. These average slopes are given in table 8.

To determine if significant differences in slope exist because of site effect, the data from all sites were grouped together by component, and an analysis of variance test performed. The results are summarized on the last line for each component in table 8, and show that there is a significant difference in slope with site for two of the components. No attempt was made to combine the data by component, or to use an average slope at all sites for the transverse component.

? * ie significant differences existed for Kij data => one line NO!

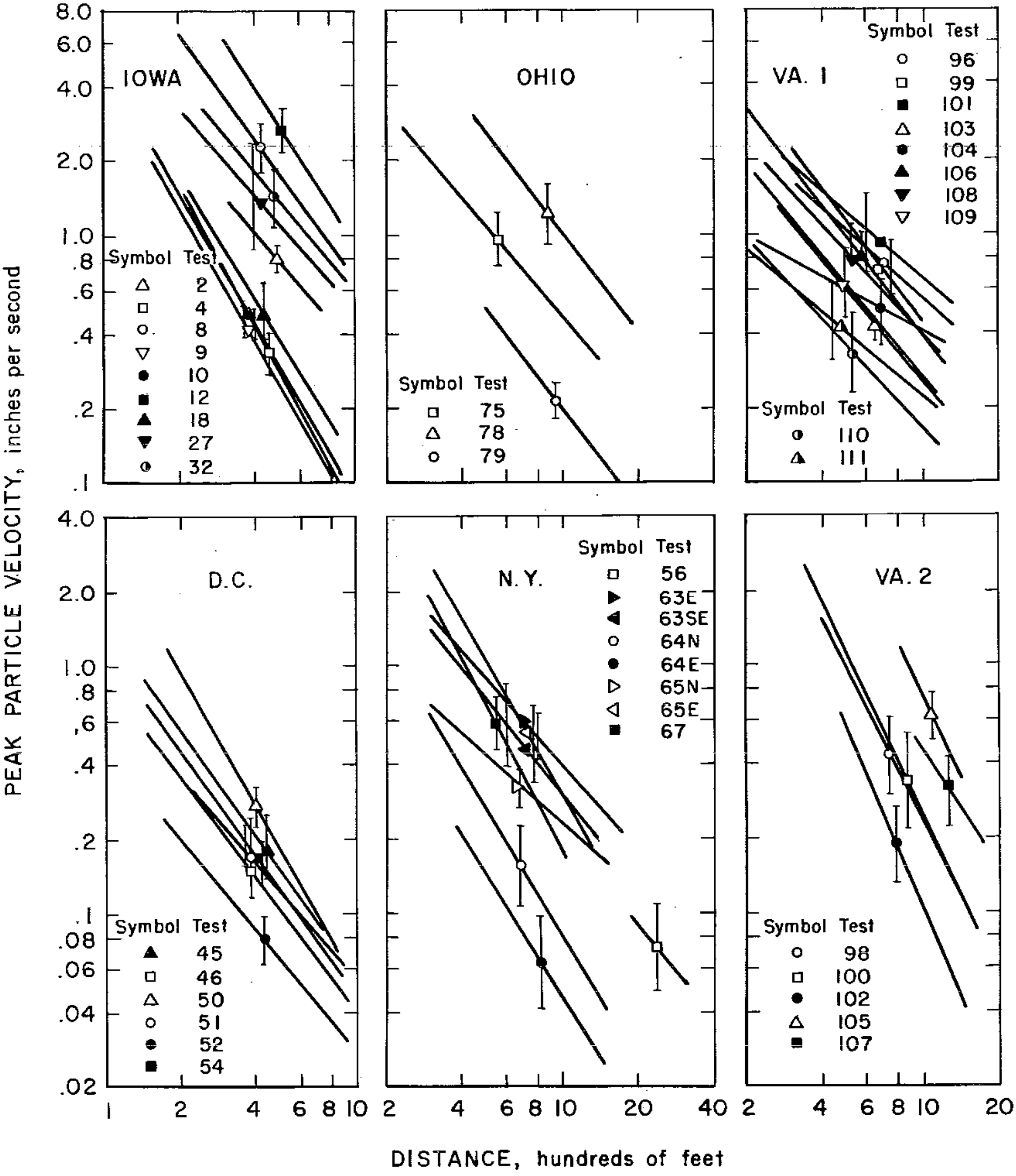

FIGURE 6. - Peak Particle Velocity Versus Distance, Radial Component.

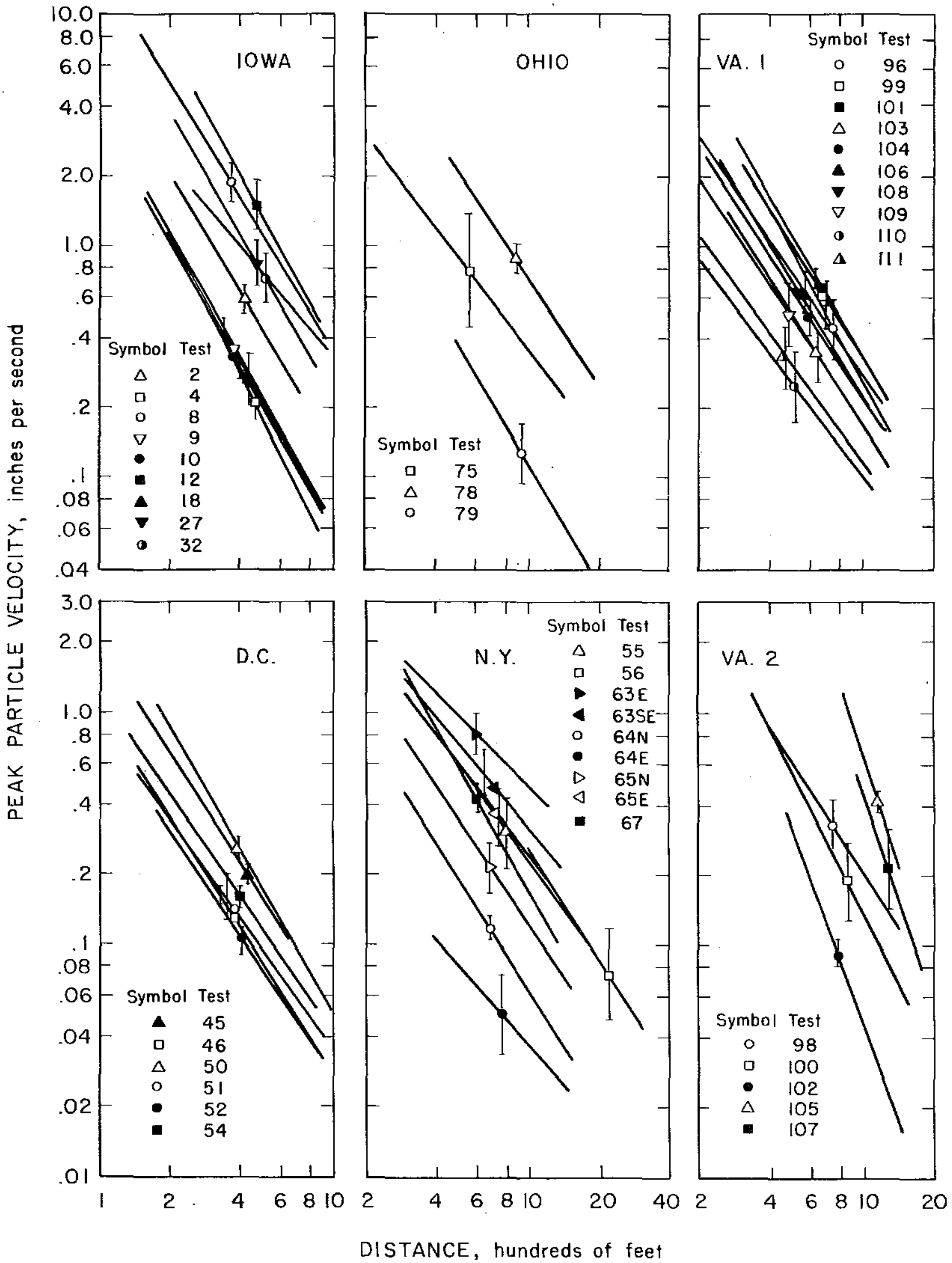

FIGURE 7. - Peak Particle Velocity Versus Distance, Vertical Component.

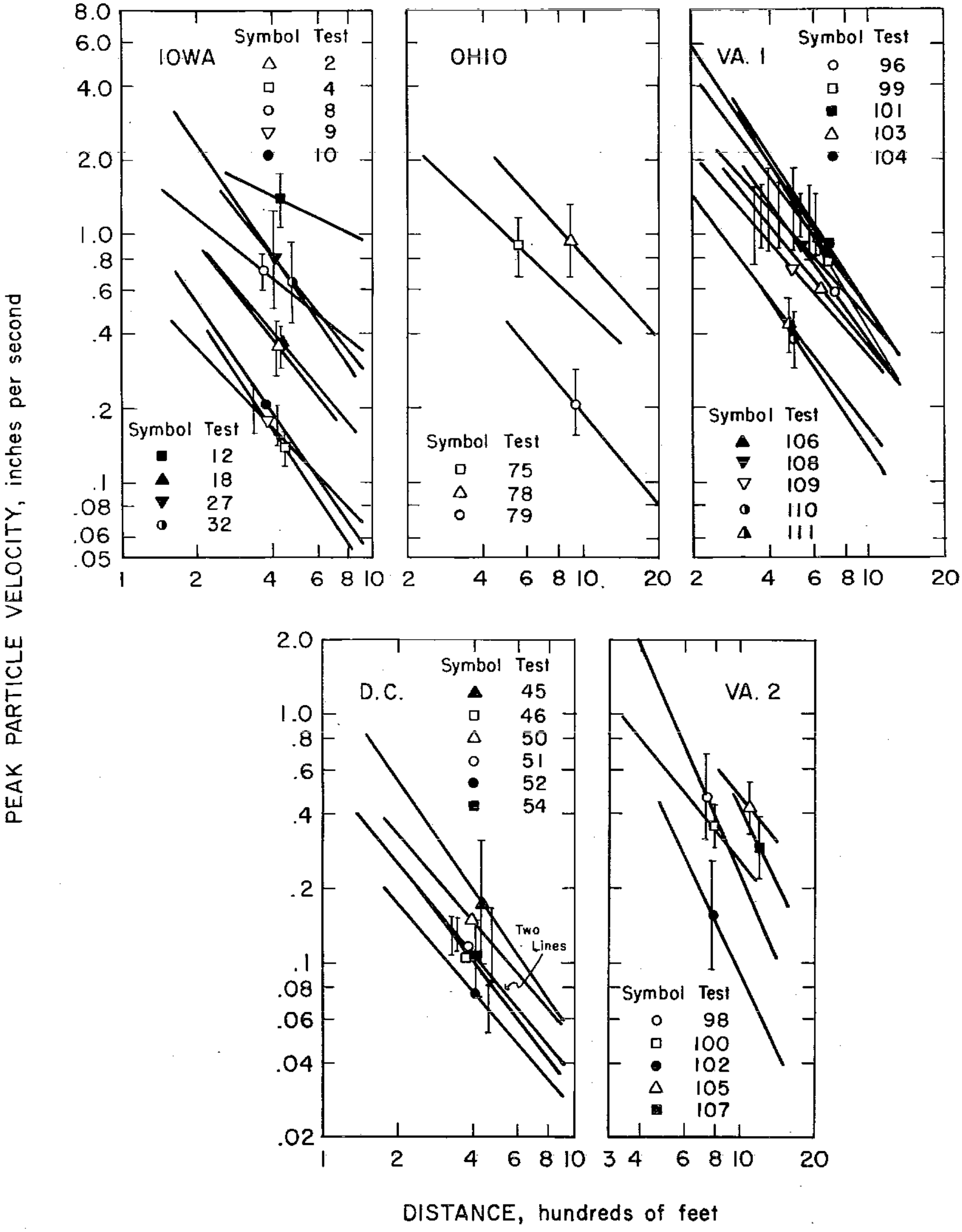

FIGURE 8. - Peak Particle Velocity Versus Distance, Transverse Component.

TABLE 8. - Statistical tests for particle velocity versus distance data

Component	Site	k_i	n[1]	F_1[2] Table[4]	F_1[2] Calculated	F_2[3] Table[4]	F_2[3] Calculated	Average β_i
Radial	Iowa	9	60	1.89	36.91	2.17	1.53	-1.576
	D.C.	6	36	2.26	5.57	2.62	1.04	-1.384
	N.Y.	8	48	2.02	12.94	2.32	1.91	-1.431
	Ohio	3	24	2.93	53.97	3.55	.22	-1.255
	Va. 1	10	62	1.86	7.88	2.11	1.12	-1.086
	Va. 2	5	35	2.34	11.53	2.76	.36	-2.148
	All	41	265	1.38	30.39	1.55	2.26	-
Vertical	Iowa	9	61	1.89	57.83	2.17	1.71	-1.766
	D.C.	6	37	2.24	20.35	2.60	1.24	-1.548
	N.Y.	9	56	1.92	20.50	2.19	1.97	-1.475
	Ohio	3	24	2.93	25.56	3.55	.57	-1.497
	Va. 1	10	71	1.76	9.77	2.05	.40	-1.548
	Va. 2	5	34	2.36	21.64	2.78	1.06	-2.346
	All	42	283	1.38	30.67	1.55	1.69	-
Transverse	Iowa	9	60	1.89	28.26	2.17	2.17	-1.189
	D.C.	6	37	2.24	3.17	2.60	.24	-1.285
	N.Y.	-	-	-	-	-	-	-
	Ohio	3	24	2.93	23.03	3.55	.34	-1.083
	Va. 1	10	70	1.78	7.79	2.07	.49	-1.389
	Va. 2	5	33	2.38	9.67	2.80	.89	-2.064
	All	33	224	1.44	32.16	1.65	1.52	-

[1] Total number of data points.
[2] A calculated value of F_1 greater than the table value means that one line cannot be used to represent all the data.
[3] A calculated value of F_2 less than the table value means that the slopes are not significantly different.
[4] Table values are for a 95 percent confidence interval.

With the assumption that the straight line passes through the midpoint of the data, the average slope, β_i, for each component at each site was used to calculate the intercept, K_{ij}, for each test. To reduce the variance in the intercepts, distances were determined in units of 100 feet. Therefore, K_{ij} is the particle velocity at 100 feet. The values of K_{ij} are summarized in table 9 along with the maximum charge weight per delay interval. It can be seen from this table and from the plots in figures 6 to 8 that the level of vibration generally increases as charge weight per delay increases.

As a result of the statistical tests described above the general propagation equation 4 for each component can now be written as

$$V = K_{ij} D^{-\beta_i} \qquad (5)$$

where V = particle velocity in in/sec,

D = distance in units of 100 ft,

K_{ij} = velocity intercept at $D = 1$,

and β_i = average slope of the j sets of data at the ith site when these data are plotted on log-log coordinates.

Equation 2 written in a generalized form to represent data from different sites, becomes:

$$V = H_i (D/W_{ij}^{\alpha})^{-\beta_i}, \tag{6}$$

where D = distance in units of 100 ft,

W_{ij} = maximum charge weight per delay interval for each test in units of 100 lbs,

and H_i = the velocity intercept at $D/W^{\alpha} = 1$ for all the tests at the ith site.

Comparison of equation 5 with equation 6 shows that the following relationship must exist:

$$K_{ij} = H_i W_{ij}^{\alpha\beta_i}. \tag{7}$$

Equation 7 implies that a log-log plot of the K_{ij} values against the charge weight per delay, W_{ij}, should result in a linear grouping of the data by site and component.

Log-log plots of K_{ij} vs W_{ij} (data given in table 9) were made and are shown in figures 9a, 10a, and 11a. Examination of these plots shows that the data for each site are independently distributed about their own straight line, thus indicating that both the slope, $\alpha\beta_i$, and the intercept, H_i, are functions of site and component. The method of least squares was used to determine the slopes, $\alpha\beta_i$, and intercepts, H_i. These values are given in table 9.

Equation 7 can be rewritten as:

$$(K_{ij})^{1/\beta_i} = (H_i)^{1/\beta_i}\ W_{ij}^{\alpha}. \tag{8}$$

Equation 8 is interpreted as follows: If W^{α} is a scaling factor, then a plot of $(K_{ij})^{1/\beta_i}$ versus W_{ij} on log-log coordinates should result in the data grouping about a series of parallel straight lines having a slope of α. The average values of β_i for each site and component, given in table 8, were used to calculate the quantities $(K_{ij})^{1/\beta_i}$. These values are shown plotted as a function of W_{ij} on log-log coordinates in figures 9b, 10b, and 11b. The method of least squares was used to determine the slopes, α_i, and their variances, S_{α_i}, for the straight lines through the data from each site and component are given in table 10.

TABLE 9. - Summary of K_{ij}, $\alpha\beta_i$, and H_i data

Site	Test	Maximum charge per delay, lbs	Radial			Vertical			Transverse		
			K_{ij}, in/sec	$\alpha\beta_i$	H_i	K_{ij}, in/sec	$\alpha\beta_i$	H_i	K_{ij}, in/sec	$\alpha\beta_i$	H_i
Iowa	2	600	9.88	0.830	2.24	7.61	0.753	2.13	1.99	0.710	0.675
	4	200	3.72	-	-	3.12	-	-	.817	-	-
	8	1,400	22.1	-	-	18.4	-	-	3.35	-	-
	9	200	3.34	-	-	3.77	-	-	.874	-	-
	10	200	3.95	-	-	3.51	-	-	.992	-	-
	12	3,000	35.2	-	-	23.3	-	-	7.94	-	-
	18	200	4.88	-	-	3.60	-	-	2.07	-	-
	27	800	13.3	-	-	12.9	-	-	4.27	-	-
	32	1,218	16.9	-	-	13.2	-	-	4.19	-	-
D.C.	45	37	1.38	0.774	2.52	1.92	0.741	2.96	1.16	0.525	1.22
	46	31	.947	-	-	.997	-	-	.603	-	-
	50	70	1.81	-	-	2.17	-	-	.875	-	-
	51	31	1.08	-	-	1.10	-	-	.624	-	-
	52	26	.586	-	-	.897	-	-	.461	-	-
	54	25	1.15	-	-	1.37	-	-	.637	-	-
N.Y.	55	920	-	0.724	1.09	6.59	0.802	0.861	-	-	-
	56	1,522	6.73	-	-	6.94	-	-	-	-	-
	63E	1,249	9.80	-	-	11.4	-	-	-	-	-
	63SE	-	7.64	-	-	8.76	-	-	-	-	-
	64N	200	2.39	-	-	2.00	-	-	-	-	-
	64E	-	1.31	-	-	1.00	-	-	-	-	-
	65N	1,405	5.01	-	-	3.60	-	-	-	-	-
	65E	-	8.99	-	-	6.81	-	-	-	-	-
	67	1,355	6.58	-	-	6.04	-	-	-	-	-
Ohio	75	1,072	8.40	0.709	1.32	10.1	0.784	1.25	5.77	0.616	1.04
	78	4,620	18.8	-	-	23.2	-	-	10.1	-	-
	79	468	3.53	-	-	3.58	-	-	2.29	-	-
Va.1	96	1,120	6.37	0.696	.906	10.4	0.742	1.45	9.37	0.762	1.54
	99	968	5.89	-	-	12.1	-	-	11.2	-	-
	101	1,600	7.58	-	-	12.7	-	-	13.1	-	-
	103	589	3.23	-	-	6.13	-	-	7.90	-	-
	104	1,330	4.06	-	-	8.08	-	-	11.9	-	-
	106	1,380	5.46	-	-	9.48	-	-	12.6	-	-
	108	1,600	4.91	-	-	8.71	-	-	2.23	-	-
	109	865	3.54	-	-	5.89	-	-	1.90	-	-
	110	360	1.99	-	-	3.18	-	-	1.26	-	-
	111	367	2.28	-	-	3.75	-	-	1.35	-	-
Va.2	98	605	31.8	1.21	4.04	36.3	1.49	2.30	29.2	1.05	3.82
	100	475	34.7	-	-	29.4	-	-	24.6	-	-
	102	343	15.7	-	-	11.8	-	-	11.0	-	-
	105	1,325	106	-	-	120	-	-	58.1	-	-
	107	1,250	71.7	-	-	81.9	-	-	48.8	-	-

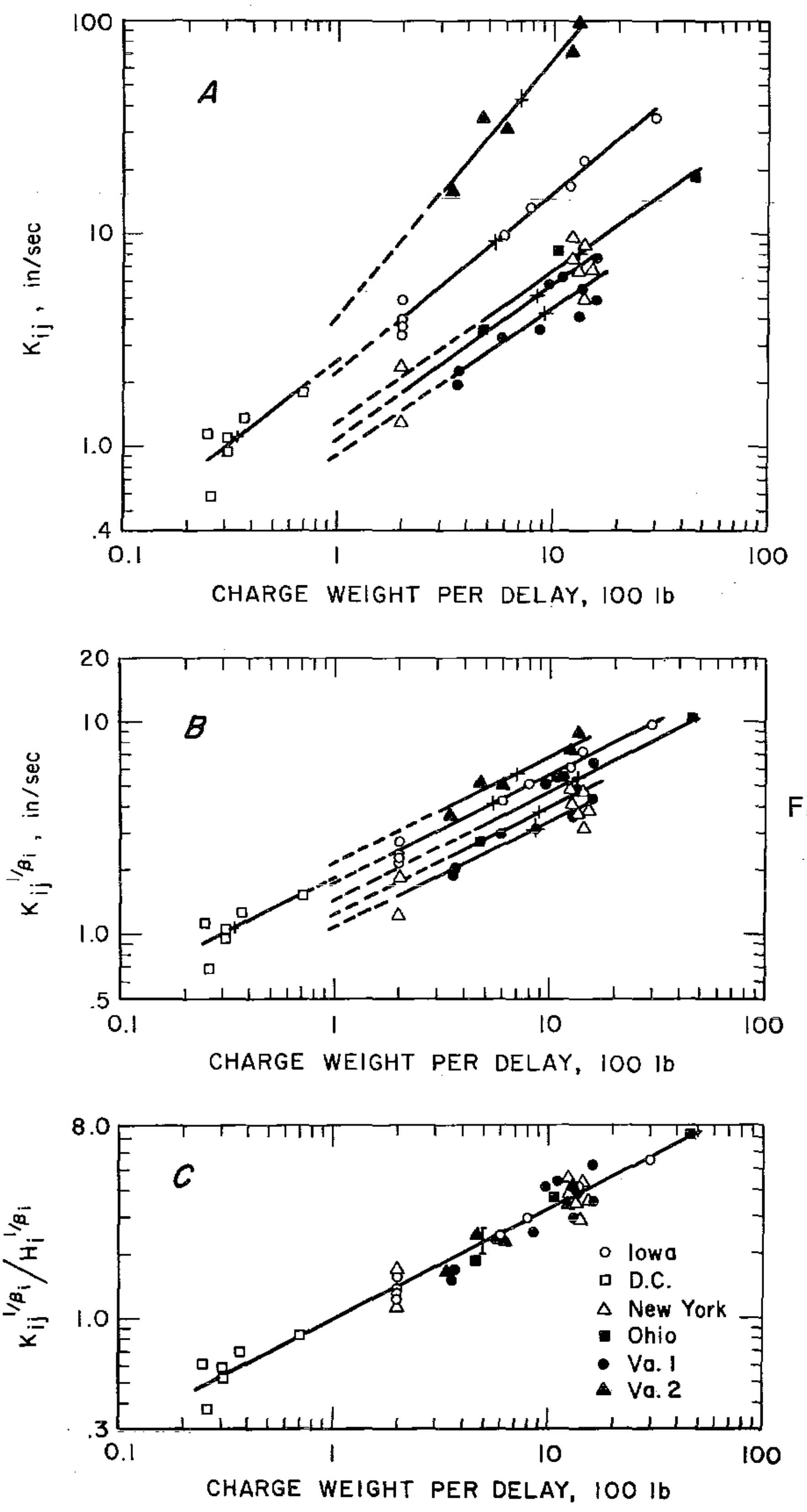

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FIGURE 9. - Particle Velocity Intercepts Versus Charge Weight per Delay, Radial Component.

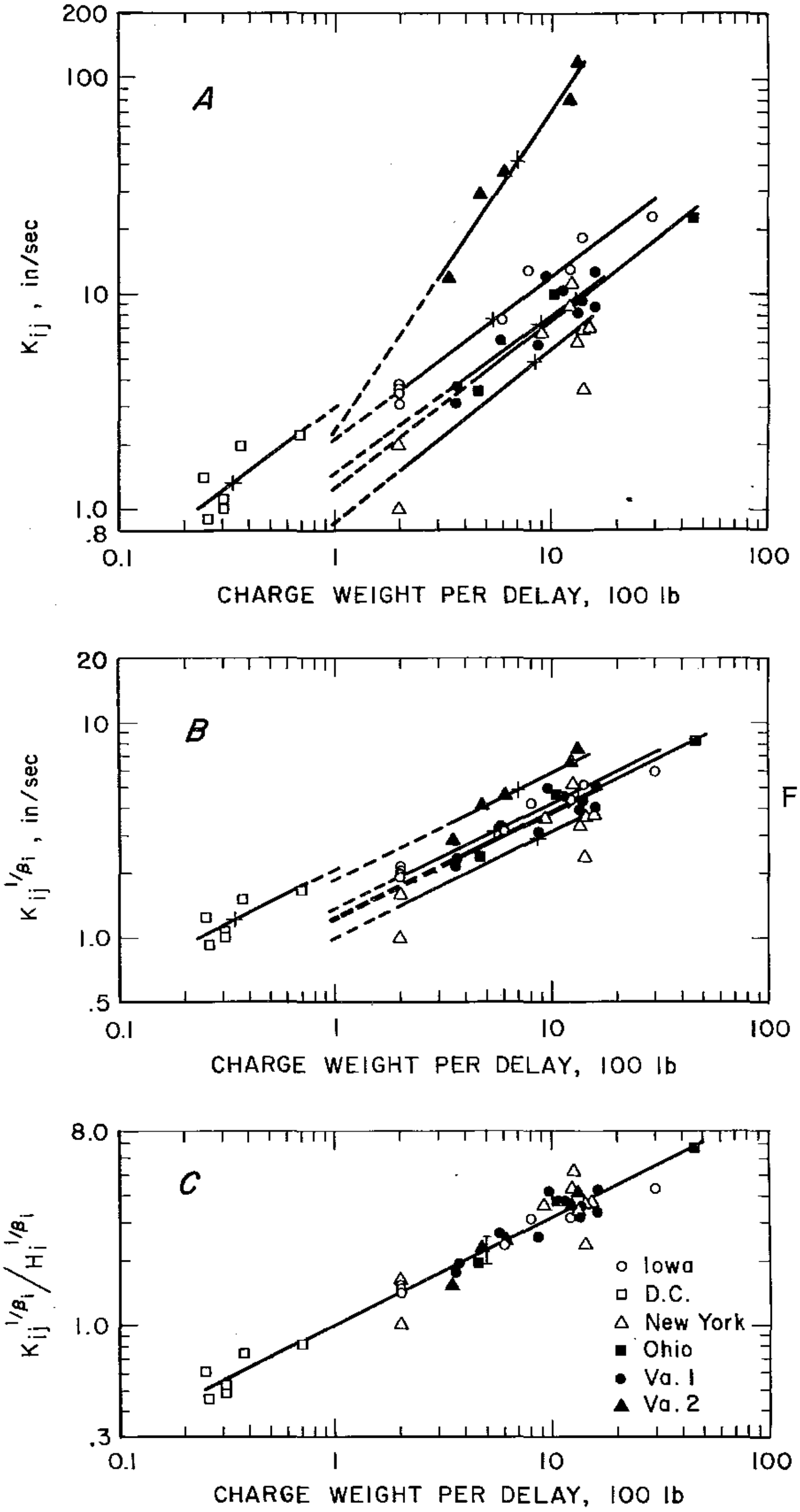

FIGURE 10. - Particle Velocity Intercepts Versus Charge Weight per Delay, Vertical Component.

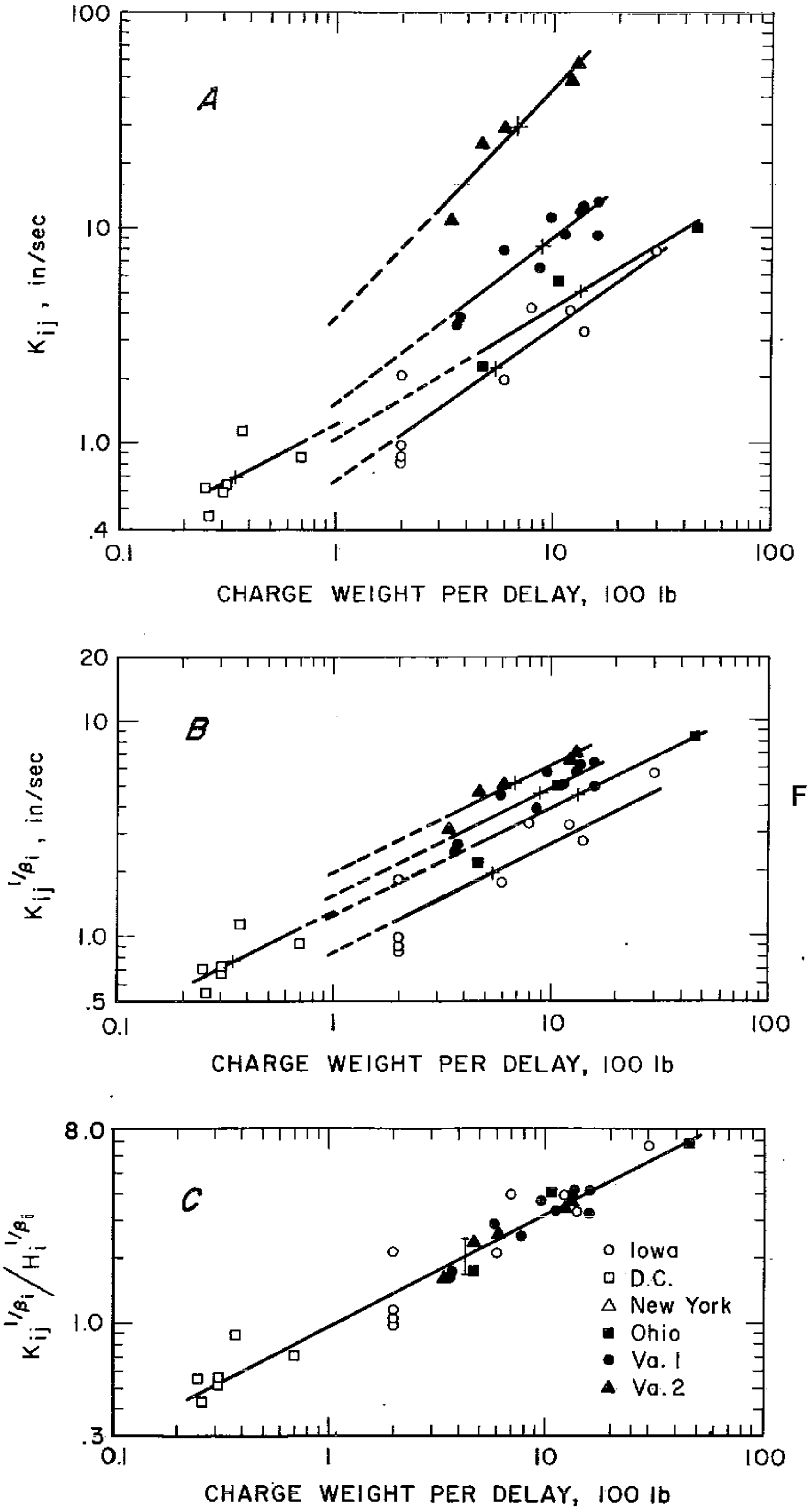

FIGURE 11. - Particle Velocity Intercepts Versus Charge Weight per Delay, Transverse Component.

TABLE 10. - Statistical test for $(K_{ij})^{1/\beta_i}$ versus W_{ij}

Component	Site	Slope α_i	S_{α_i}	No. of sites	Σk_i	F_1 [1] Table[3]	F_1 [1] Calculated	F_2 [2] Table[3]	F_2 [2] Calculated
Radial.....	Iowa	0.527	0.026	6	41	2.18	7.64	2.54	0.26
	D.C.	.558	.229	-	-	-	-	-	-
	N.Y.	.506	.089	-	-	-	-	-	-
	Ohio	.568	.105	-	-	-	-	-	-
	Va. 1	.637	.118	-	-	-	-	-	-
	Va. 2	.567	.090	-	-	-	-	-	-
Vertical...	Iowa	.427	.028	6	42	2.16	5.04	2.53	.54
	D.C.	.474	.197	-	-	-	-	-	-
	N.Y.	.546	.119	-	-	-	-	-	-
	Ohio	.523	.113	-	-	-	-	-	-
	Va. 1	.479	.089	-	-	-	-	-	-
	Va. 2	.637	.078	-	-	-	-	-	-
Transverse.	Iowa	.598	.097	5	33	2.38	7.59	2.80	.16
	D.C.	.412	.267	-	-	-	-	-	-
	Ohio	.566	.176	-	-	-	-	-	-
	Va. 1	.550	.087	-	-	-	-	-	-
	Va. 2	.516	.085	-	-	-	-	-	-

[1]A calculated value of F_1 greater than the table value means that one line cannot be used to represent all the data.

[2]A calculated value of F_2 less than the table value means that the slopes are not significantly different.

[3]Table values of F_1 and F_2 are for a 95 percent confidence interval.

An analysis of variance test was performed on the $(K_{ij})^{1/\beta_i}$ vs (W_{ij}) data from all sites, grouped by component to determine if one line could be used to represent all the data by component or if a series of parallel lines could be used to represent the data from each site. These analysis of variance tests are summarized in table 10, and the results show that one line cannot represent all the data for each component, but that an average slope for each component can be used for all sites. These average slopes, α, and their variances, S_α, were computed and are given in table 11. Statistical t tests were performed to determine if the average slopes differ significantly from a theoretical value of 0.5. The results of these t tests, summarized in table 11, show that there is no significant difference between each of the average slopes and the theoretical value of 0.5. Therefore, the theoretical slope of 0.5 was placed through the data as shown in figures 9b, 10b, and 11b. Examination of these figures shows that the value of $(K)^{1/\beta_i}$ at a particular charge weight is a function of the quarry site.

TABLE 11. - Statistical tests for comparison of slope α with theoretical value of 1/2

Component	Degrees of freedom	Average slope α	S_α	Theoretical value	t[1]	
					Table[2]	Calculated
Radial..........	34	0.545	0.034	0.500	2.03	1.32
Vertical........	35	.491	.037	.500	2.03	.24
Transverse......	27	.569	.050	.500	2.05	1.38

[1]A calculated value of t less than the table value means that the slopes are not significantly different.
[2]The table values of t are for a 95 percent confidence interval.

The site effect can be removed by normalizing the data in the following manner. Each side of equation 8 can be divided by $(H_i)^{1/\beta_i}$ to give:

$$(K_{ij})^{1/\beta_i} \;/\; (H_i)^{1/\beta_i} = W_{ij}{}^{\alpha}. \tag{9}$$

Thus, if the quantities $(K_{ij})^{1/\beta_i}$ for any one site and component are divided by the quantity $(H_i)^{1/\beta_i}$ for that site and component, the variation in the level of the intercepts associated with the site effect would no longer exist, as all the intercepts would be unity. A summary of the $(K_{ij})^{1/\beta_i}$, $(H_i)^{1/\beta_i}$, and $(K_{ij})^{1/\beta_i}$ / $(H_i)^{1/\beta_i}$ data is given in table 12. Figures 9c, 10c, and 11c show log-log plots of the quantity $(K_{ij})^{1/\beta_i}$ / $(H_i)^{1/\beta_i}$ versus charge weight per delay. The $(K_{ij})^{1/\beta_i}$ / $(H_i)^{1/\beta_i}$ vs W_{ij} data were combined by component and an analysis of variance test performed to determine any remaining significant differences. The results of this test, as shown in table 13, indicate that one line can be used to represent all the data for one component. Thus the slopes, α, of the straight lines were computed using the data for all sites for each component. These values of α are given in table 13. It should be noted that the slopes given in table 13 are closer to the theoretical value, 0.5, than the average slopes given in table 11. Thus a more accurate slope is obtained by using all the data than by using the data grouped by site.

According to equation 9 the intercepts for the straight lines in figures 9c, 10c, and 11c should be unity. These intercepts were computed and are shown in table 13 to be very close to the theoretical value of one.

If the velocity-distance data are scaled by the square root of the charge weight, the amount of reduction in the spread of the data can be shown graphically by plotting the particle velocity, V, as a function of scaled distance, $D/W^{\frac{1}{2}}$, on log-log coordinates. Figures 12, 13, and 14 are plots of the velocity-scaled distance data. The basic units of distance and charge weight are now feet and pounds. Comparison of these figures with figures 6, 7, and 8 shows that the total spread is reduced considerably and that the velocity level of a shot is no longer a function of the charge weight. Analysis of variance tests were performed on the scaled data by component to determine if one line can be used to represent all the data. The results of these tests are summarized in the F_1 column of table 14, and show that one line cannot represent all the data of one component at the 95 percent confidence level. However, the total spread has been reduced by as much as a factor of 4, as shown by the S_E values given in table 14. The remaining spread in the data is probably a result of such variables as burden, spacing, ratio of length to diameter of charge, and the properties of the soil and rock.

TABLE 12. - Summary of normalizing constants

Site	Test	Radial $(K_{ij})^{1/\beta_i}$	Radial $(H_i)^{1/\beta_i}$	Radial $\frac{(K_{ij})^{1/\beta_i}}{(H_i)^{1/\beta_i}}$	Vertical $(K_{ij})^{1/\beta_i}$	Vertical $(H_i)^{1/\beta_i}$	Vertical $\frac{(K_{ij})^{1/\beta_i}}{(H_i)^{1/\beta_i}}$	Transverse $(K_{ij})^{1/\beta_i}$	Transverse $(H_i)^{1/\beta_i}$	Transverse $\frac{(K_{ij})^{1/\beta_i}}{(H_i)^{1/\beta_i}}$
Iowa	2	4.26	1.75	2.44	3.16	1.36	2.34	1.79	0.845	2.12
	4	2.29	-	1.31	1.92	-	1.42	.844	-	1.00
	8	7.17	-	4.10	5.21	-	3.86	2.77	-	3.29
	9	2.16	-	1.23	2.12	-	1.57	.887	-	1.05
	10	2.39	-	1.36	2.03	-	1.51	.990	-	1.17
	12	9.58	-	5.47	5.93	-	4.39	5.70	-	6.75
	18	2.75	-	1.57	2.05	-	1.52	1.84	-	2.18
	27	5.16	-	2.94	4.26	-	3.16	3.39	-	4.01
	32	6.05	-	3.46	4.81	-	3.19	3.32	-	3.94
D.C.	45	1.26	1.83	.691	1.52	2.06	.741	1.13	1.29	.878
	46	.961	-	.527	1.00	-	.487	.670	-	.522
	50	1.54	-	.844	1.65	-	.803	.905	-	.705
	51	1.06	-	.583	1.05	-	.517	.691	-	.538
	52	.684	-	.375	.93	-	.454	.549	-	.427
	54	1.11	-	.607	1.23	-	.600	.705	-	.549
N.Y.	55	-	-	-	3.60	.933	3.63	-	-	-
	56	3.82	1.08	3.56	3.74	-	3.78	-	-	-
	63E	4.90	-	4.57	5.21	-	5.26	-	-	-
	63SE	4.14	-	3.86	4.35	-	4.39	-	-	-
	64N	1.84	-	1.72	1.60	-	1.62	-	-	-
	64E	1.21	-	1.13	1.00	-	1.01	-	-	-
	65N	3.10	-	2.89	2.39	-	2.41	-	-	-
	65E	4.66	-	4.35	3.67	-	3.71	-	-	-
	67	3.71	-	3.46	3.39	-	3.42	-	-	-
Ohio	75	5.47	1.48	3.71	4.66	1.23	3.78	5.05	1.24	4.06
	78	10.4	-	7.03	8.17	-	6.62	8.41	-	6.75
	79	2.72	-	1.84	2.36	-	1.92	2.16	-	1.73
Va.1	96	5.47	1.24	4.39	4.57	1.21	3.78	5.05	1.53	3.29
	99	5.10	-	4.10	5.00	-	4.14	5.75	-	3.74
	101	6.49	-	5.31	5.16	-	4.26	6.42	-	4.18
	103	2.94	-	2.36	3.22	-	2.66	4.48	-	2.92
	104	3.63	-	2.92	3.86	-	3.19	5.99	-	3.90
	106	4.81	-	3.86	4.26	-	3.53	6.23	-	4.06
	108	4.31	-	3.46	4.06	-	3.35	5.00	-	3.25
	109	3.19	-	2.56	3.13	-	2.59	3.94	-	2.56
	110	1.90	-	1.52	2.12	-	1.75	2.48	-	1.62
	111	2.14	-	1.72	2.34	-	1.93	2.66	-	1.73
Va.2	98	5.00	2.16	2.32	4.62	1.86	2.48	5.10	1.95	2.61
	100	5.21	-	2.41	4.22	-	2.27	4.71	-	2.41
	102	3.60	-	1.67	2.86	-	1.54	3.19	-	1.63
	105	8.85	-	4.10	7.69	-	4.14	7.17	-	3.67
	107	7.32	-	3.39	6.55	-	3.53	6.62	-	3.39

TABLE 13. - Statistical tests for $(K_{ij})^{1/\beta_i}$ / $(H_i)^{1/\beta_i}$ versus W_{ij}

Component	No. of sites	Σk_i	F_1 [1] Table[2]	F_1 [1] Calculated	Slope α	Combined intercept
Radial...........	6	41	2.18	0.24	0.513	0.998
Vertical.........	6	42	2.16	.27	.497	1.01
Transverse.......	5	33	2.38	.25	.516	.976

[1]A calculated value less than the table value means that one line can be used to represent all the data without introducing a significant error.
[2]The table values of F_1 are for a 95 percent confidence interval.

TABLE 14. - Summary of statistical tests for scaled and unscaled velocity-distance data

Component	Site	F_1 (scaled data)[1] Table[2]	F_1 (scaled data)[1] Calculated	S_E (scaled data), percent	S_E (unscaled data), percent
Radial...........	Iowa	1.89	1.43	32	136
	D.C.	2.26	2.76	42	54
	N.Y.	2.02	3.00	53	105
	Ohio	2.93	1.54	27	110
	Va.1	1.86	2.38	40	64
	Va.2	2.34	1.39	45	94
Vertical.........	Iowa	1.89	3.57	29	121
	D.C.	2.24	8.79	28	42
	N.Y.	1.92	5.88	60	118
	Ohio	2.93	1.25	46	138
	Va.1	1.76	2.34	38	65
	Va.2	2.36	2.67	45	116
Transverse.......	Iowa	1.89	6.09	53	122
	D.C.	2.24	1.96	42	48
	Ohio	2.93	1.78	40	101
	Va.1	1.78	1.58	40	69
	Va.2	2.38	1.38	45	89

[1]A calculated value of F_1 less than the table value means that one line can be used to represent all the data. A calculated value greater than the table value means that one line cannot be used to represent the data.
[2]Table values of F_1 are for a 95 percent confidence interval.

APPLICATION OF THE SCALED PROPAGATION EQUATION

This investigation has shown that the peak particle velocity of each component of ground motion can be related to distance and charge weight per delay interval by an equation of the form:

$$V = H_i \left(\frac{D}{W^{\frac{1}{2}}}\right)^{-\beta_i} \quad (10)$$

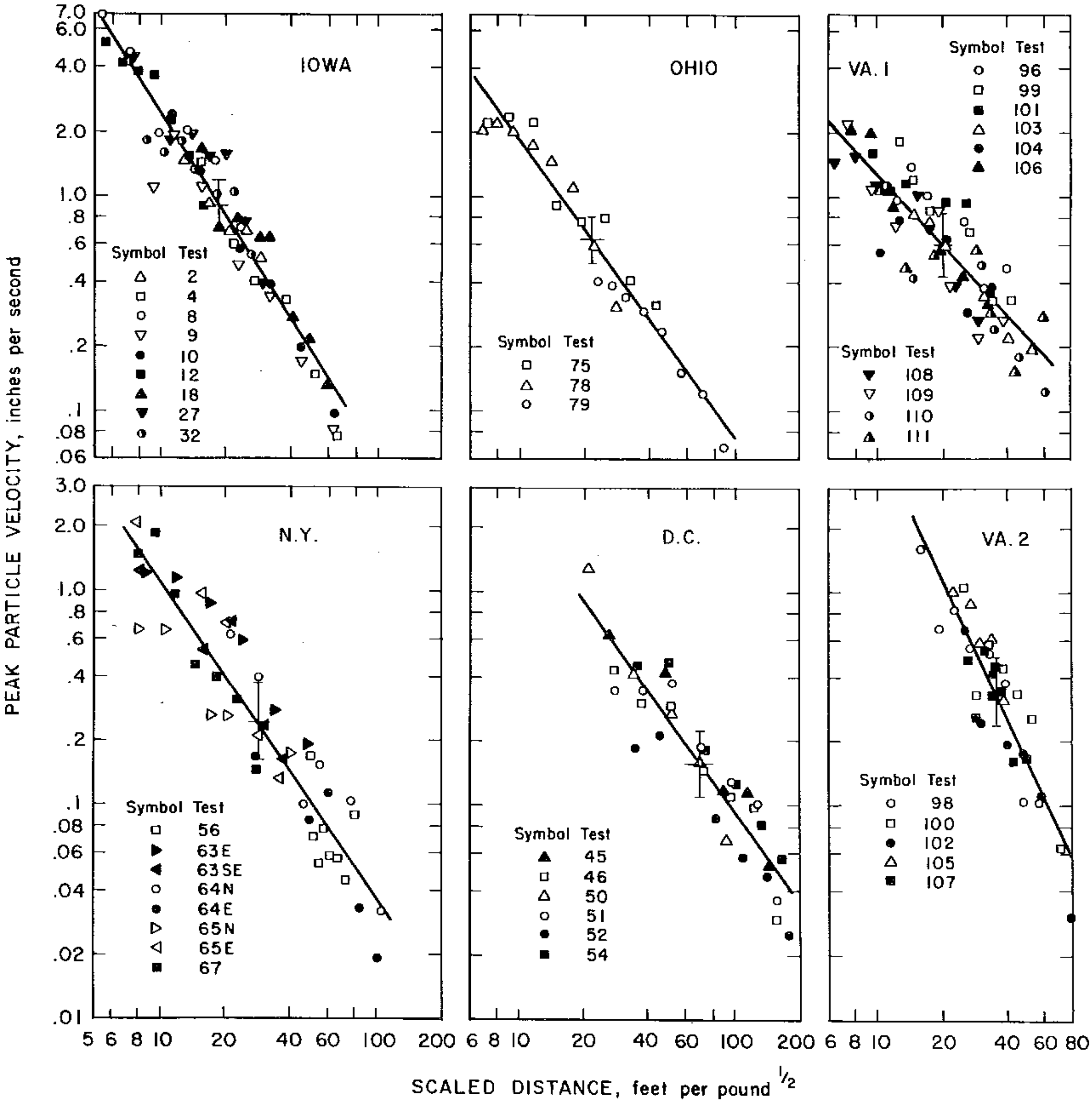

FIGURE 12. - Peak Particle Velocity Versus Scaled Distance, Radial Component.

where V = peak particle velocity, in/sec,

D = distance, feet,

W = charge weight per delay, lbs,

and H_1, β_1 = parameters for a particular site.

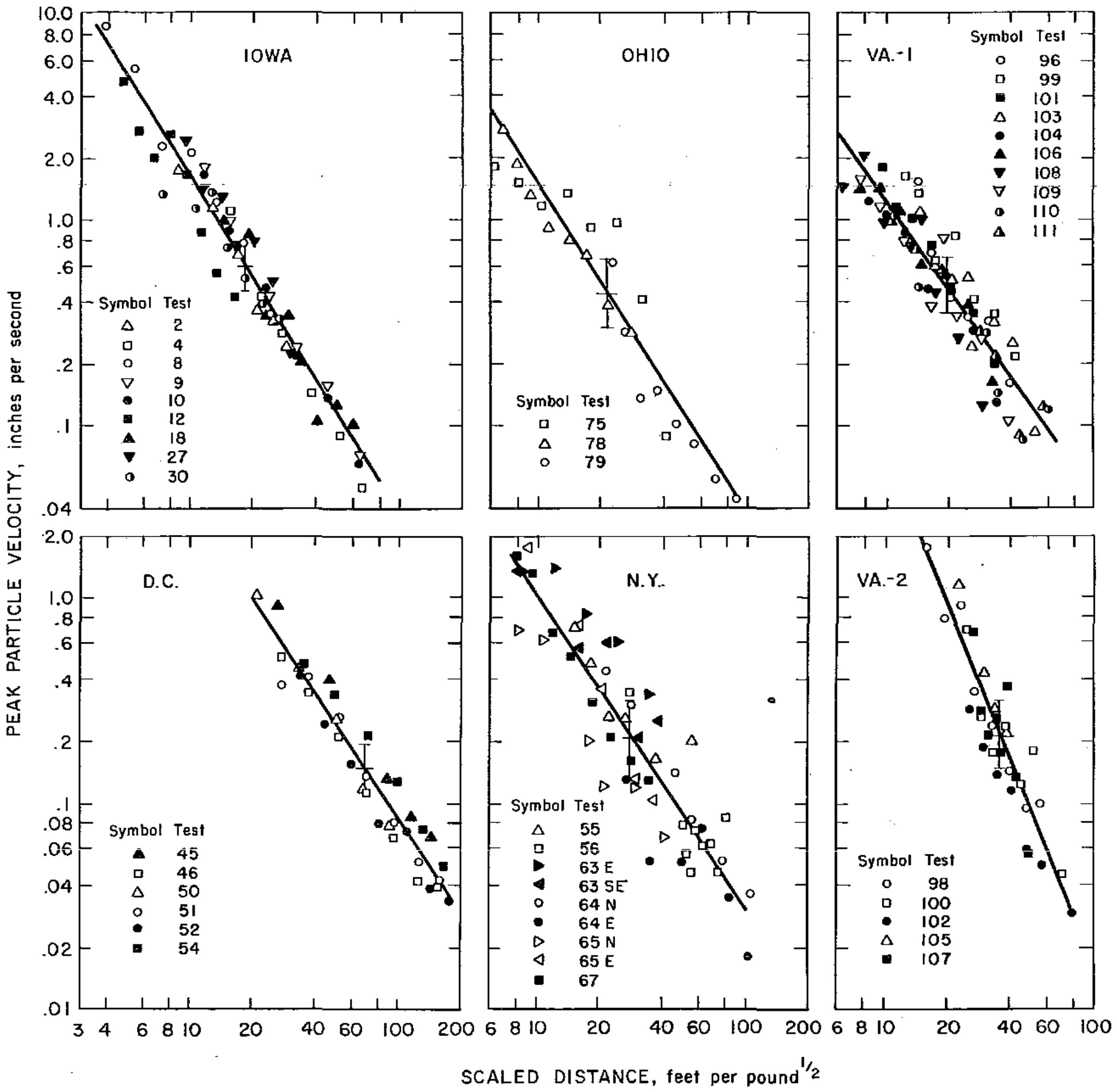

FIGURE 13. - Peak Particle Velocity Versus Scaled Distance, Vertical Component.

Equation 10 shows that, when particle velocity is plotted on log-log coordinates as a function of scaled distance, $D/W^{\frac{1}{2}}$, straight lines having a slope of β_i can be placed through the data from each site and component. Figure 15 shows the straight lines that were placed through the data from the six sites included in this report. Each component of particle velocity is shown separately.

Even though a wide variety of blasting conditions were encountered, the total spread in all of the data, represented by the straight lines in figure

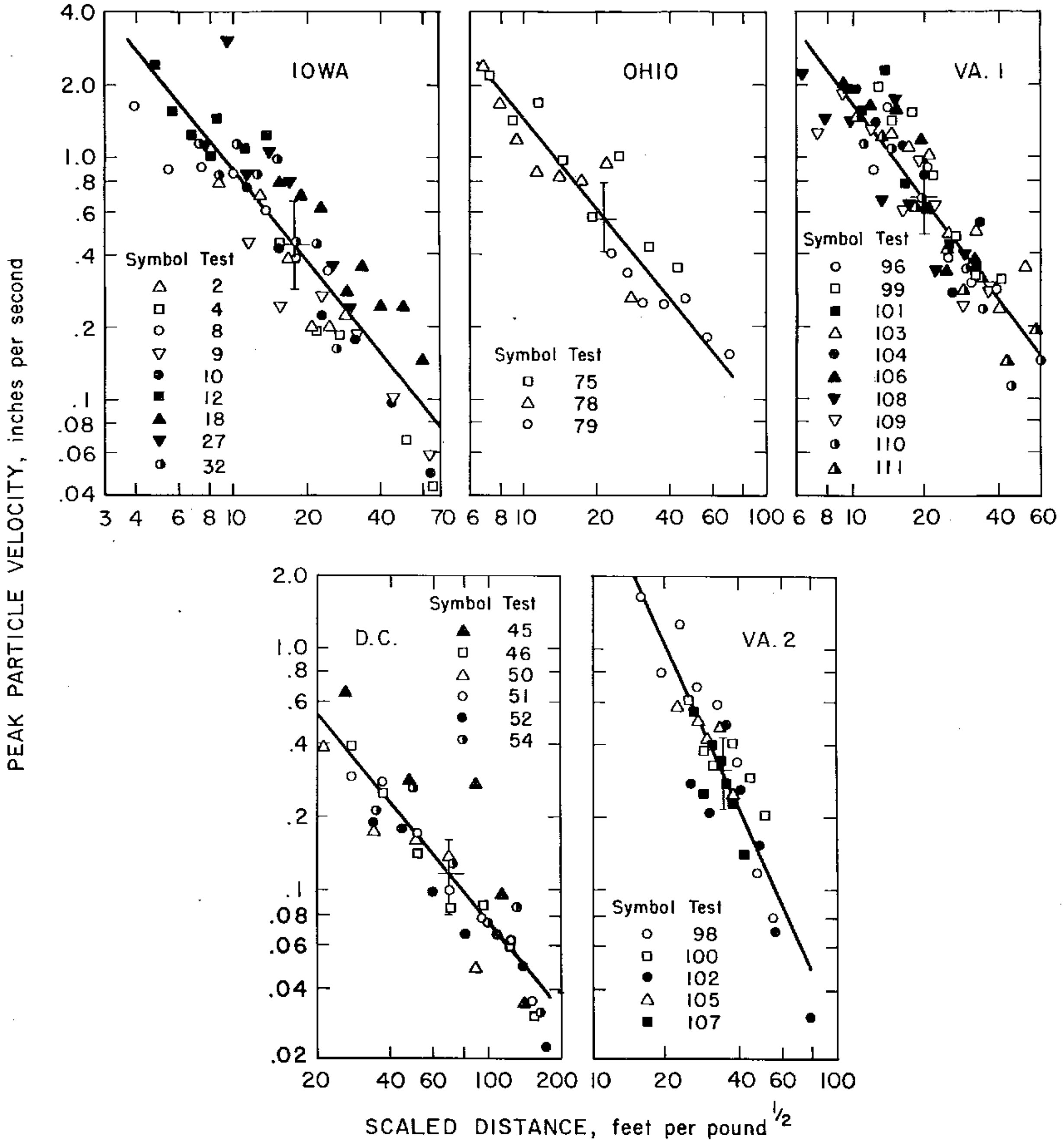

FIGURE 14. - Peak Particle Velocity Versus Scaled Distance, Transverse Component.

15, is relatively small (±a factor of 2). Therefore, an average slope through all these data can be used for making a first approximation of the particle velocity that is produced from a blast at any site.

In a previous report (3) a peak particle velocity of 2 in/sec for any one of three mutually perpendicular components of the ground vibrations near a residential structure was established as a tentative safe blasting criterion.

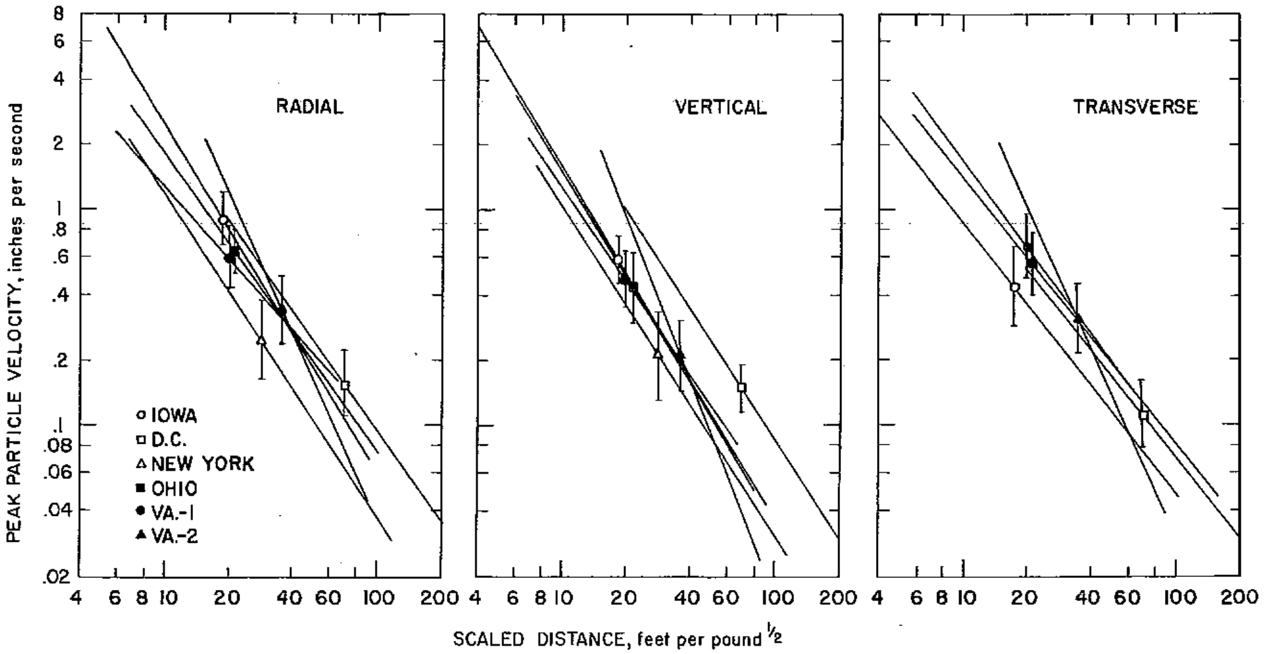

FIGURE 15. - Peak Particle Velocity Versus Scaled Distance, Combined Data.

The plots in figure 15 together with the safe blasting criterion can be used to obtain a first approximation for the maximum safe charge size per delay that can be used at any given distance from a residential structure. For example, in figure 15 the value of 2 in/sec is obtained for scaled distances ranging from about 5 to 20 $ft/lb^{\frac{1}{2}}$, depending upon site and component. The data in figure 15 represent only 6 sites, and may not be a good sample of all sites. Thus a scaled distance greater than 20 should be selected if no instrumentation is available to check the site. By increasing the scaled distance, the probability of finding a site that gives vibration levels greater than 2 in/sec is reduced. For example, at a scaled distance of 50 $ft/lb^{\frac{1}{2}}$ the maximum peak particle velocity that has been observed is about 0.4 in/sec. This value of particle velocity is 1/5 of the safe blasting criterion and should represent for any site a relatively safe scaled distance.

The use of scaled distances of less than 50 $ft/lb^{\frac{1}{2}}$ is not recommended unless the propagation law parameters H_i and β_i in equation 10 for the given site are determined by measuring the ground vibrations from at least three blasts. At some quarries there is a large variation in the propagation law parameters H_i and β_i with direction from the blast area. Therefore, measurements of ground vibration should be made in each direction in which the vibration level is of concern, if scaled distances of less than 50 $ft/lb^{\frac{1}{2}}$ are to be used.

Once the safe minimum scaled distance has been determined, the maximum safe charge weight per delay for any blast can be determined by use of the relationship

$$W_s = \left(\frac{D}{D_s}\right)^2, \qquad (11)$$

where W_s = maximum safe charge weight per delay in lbs,

D = distance in feet,

and D_s = minimum safe scaled distance allowable in $ft/lb^{\frac{1}{2}}$.

For example, if a safe scaled distance of 50 $ft/lb^{\frac{1}{2}}$ is selected and the point of interest is 1,000 feet from the blast area the maximum safe charge weight per delay is

$$W_s = \left(\frac{1{,}000}{50}\right)^2 ,$$

or

$$W_s = 400 \text{ pounds}.$$

Table 15 gives some representative charge weight-distance relationships that have scaled distances of 50 $ft/lb^{\frac{1}{2}}$.

TABLE 15. - Representative charge weight-distance relationships for scaled distance of 50 $ft/lb^{\frac{1}{2}}$

Distance, feet:	Charge weight, pounds
100	4
300	36
500	100
700	196
1,000	400
1,500	900
2,000	1,600
3,000	3,600
5,000	10,000

CONCLUSIONS

Analysis of vibration data from 39 blasts at quarries in Iowa, Ohio, New York, Washington, D. C., and Virginia have shown statistically that the radial, vertical, or transverse component of the peak particle velocity can be expressed by a scaled propagation equation of the form

$$V = H\left(\frac{D}{W^{\frac{1}{2}}}\right)^{-\beta} ,$$

where V = peak particle velocity (radial, vertical, transverse),

D = distance from gage to blast area,

W = charge weight per delay interval,

H = particle velocity intercept at unity scaled distance, and β = slope of particle velocity-scaled distance data on a log-log plot (β is constant for each component at a site, but may vary from site to site).

For a given distance, D, a scaled distance, $D/W^{\frac{1}{2}}$, of 50 can be used to determine the maximum charge weight per delay without the use of seismic instrumentation. If larger charge weights per delay are needed, vibration measurements should be made to determine if the safe vibrations level will be exceeded.

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