KEN ULTSCHLAFER

RI 9078

Bureau of Mines Report of Investigations/1987

Low-Frequency Vibrations Produced by Surface Mine Blasting Over Abandoned Underground Mines

By David E. Siskind, Virgil J. Stachura,
and Michael J. Nutting

UNITED STATES DEPARTMENT OF THE INTERIOR

KEN ELTSCHLAGER

Report of Investigations 9078

Low-Frequency Vibrations Produced by Surface Mine Blasting Over Abandoned Underground Mines

By David E. Siskind, Virgil J. Stachura,
and Michael J. Nutting

UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

BUREAU OF MINES
Robert C. Horton, Director

Library of Congress Cataloging in Publication Data:

Siskind, D. E.
Low-frequency vibrations produced by surface mine blasting over abandoned underground mines.

(Report of investigations / United States Department of the Interior, Bureau of Mines ; 9078)

Bibliography; p. **57–58.**

Supt. of Docs. no.: I 28.23; 9078.

1. Blasting – Indiana – Blanford Region. 2. Dwellings – Indiana – Blanford Region – Vibration. 3. Blast effect. 4. Coal mines and mining – Indiana – Blanford Region. 5. Geology – Indiana – Blanford Region. I. Stachura, Virgil J. II. Nutting, Michael J. III. Title. IV. Series: Report of investigations (United States. Bureau of Mines) ; 9078.

TN23.U43 [TN279] 622 s [622'.334] 86-607927

CONTENTS

	Page
Abstract	1
Introduction	2
Acknowledgments	2
Experimental procedures	2
Data available	2
Data initially reported to OSM	3
Supplementary Peabody and DNR data	3
Bureau of Mines measurements	3
Additional available data	3
Sites	4
Surface	4
Subsurface	4
Blast designs	14
Production blasting, July 1984 to April 1985	14
Production and test blasts for Bureau of Mines, September 9-13, 1985	15
Results of findings	15
Vibration amplitudes and propagation plots	15
Production blast monitoring at residences	19
Bureau of Mines vibration tests	20
Comparisons between blast designs	21
Causes of high-vibration levels	22
Blast design as source function for vibration generation	22
Low attenuation of vibration	23
Frequency characteristics of vibration	23
General types	23
Impacts of low-frequency vibrations	24
Comparisons between casting blasts	28
Comparisons between blast designs	28
Comparisons between sites	28
Delay sequence and vibration frequency	28
Theoretical models	47
Underground openings	48
Level-loop surveys	48
Conclusions	57
References	57

ILLUSTRATIONS

1.	Peabody's Universal Mine and Blanford, IN	5
Shot and seismograph arrays for Bureau of Mines shots:		
2.	1-5	6
3.	6	7
4.	7	8
5.	Peabody Universal Mine near Blanford, IN	9
6.	Hollingsworth house	10
7.	Jackson house	10
8.	Massa house	11
9.	Polomski house	11
10.	Verhonik house	12
11.	Volk house	12

ILLUSTRATIONS--Continued

Page

12. Areas around Blanford undermined by abandoned coal mine workings..... 13
13. Old West Clinton No. 1 Mine, coalbed 5, beneath Blanford..... 14

Propagation plots of maximum particle velocity at--
14. Volk house..... 16
15. Polomski house..... 16
16. Hollingsworth house..... 16
17. Massa house..... 16
18. Jackson house..... 17
19. Verhonik house..... 17
20. Zell house..... 17
21. All seven houses..... 17

Propagation plots of Bureau of Mines tests:
22. All maximum velocity values..... 18
23. Regression-line summary..... 18
24. West array production blasts..... 18
25. North array production blasts..... 18
26. Single-charge blasts..... 19

27. Echelon blasts..... 19
28. Casting blasts..... 19

Ground vibration records:
29. Type A, low-frequency on all three components..... 24
30. Type B, low-frequency on transverse component..... 24
31. Type C, low-frequency on vertical and longitudinal components..... 25
32. Type D, low-frequency on vertical component..... 25

33. Echelon blasts: 42 ms between rows, 17 ms between holes in a row..... 30
34. Echelon blasts: 100 ms between rows, 17 ms between holes in a row..... 31
35. Echelon blasts: 200 ms between rows, 17 ms between holes in a row..... 32

36. Casting blasts: 200 ms between rows, 10 ms between holes in a row..... 33
37. Casting blasts: varying delays between rows..... 34

Vibration records from Bureau of Mines tests, production blast:
38. West array, longitudinal component, blast 3..... 36
39. West array, vertical component, blast 3..... 37
40. West array, transverse component, blast 3..... 38
41. North array, longitudinal component, blast 6..... 39
42. North array, vertical component, blast 6..... 40
43. North array, transverse component, blast 6..... 41

44. Initiation patterns for shot 3..... 42
45. Initiation patterns for shot 6..... 42

46. Vibration records from single charge: longitudinal component..... 43
47. Vibration records from single charge: vertical component..... 44
48. Vibration records from single charge: transverse component..... 45

49. Vibration spectra for production and single charge in near field..... 47
50. Vibration spectra for production and single charge in far field..... 47

ILLUSTRATIONS--Continued

Page

Study houses and level-loop surveys:
51. Ahlmeyer..... 49
52. Albrecht..... 50
53. E. Finger..... 51
54. O. Finger..... 52
55. Jovanovich..... 53
56. Marietta..... 54
57. Skorich..... 55
58. Zell..... 56

TABLES

1. Production blast designs used at Universal Mine, July 1984 through April 1985..... 3
2. Bureau of Mines vibration tests at Blanford, September 1985..... 20
3. Statistical comparisons of Universal Mine and previous vibration-propagation data..... 21
4. Analysis of charge weights for production blasts..... 22
5. Shot and site comparisons of vibration characteristics at residences monitored..... 26
6. Summary of two level-loop surveys of eight Blanford houses..... 57

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

dB	decibel	in/s	inch per second
ft	foot	(in/s)/in	inch per second per inch
$ft/lb^{1/2}$	foot per square-root pound (scaled distance)	µin/in	microinch per inch
ft/s	foot per second	ms	millisecond
Hz	hertz	s	second

LOW-FREQUENCY VIBRATIONS PRODUCED BY SURFACE MINE BLASTING OVER ABANDONED UNDERGROUND MINES

By David E. Siskind,[1] Virgil J. Stachura,[1] and Michael J. Nutting[1]

ABSTRACT

Bureau of Mines researchers assisted the U.S. Office of Surface Mining (OSM) by studying complaint-producing blasting vibrations resulting from an active surface mine operating over abandoned mine workings beneath the surface mine and the nearby town of Blanford, IN.

Bureau researchers analyzed over 500 blasting records collected by the Peabody Coal Co. and the Indiana Department of Natural Resources over a period of 9 months at seven Blanford residences. To characterize generated and propagated seismic waveforms, the Bureau set up two extended instrument arrays and monitored five production and two specially fired single-charge blasts.

Ground vibrations were of high amplitude and dominated by unusual and more structure response-producing low frequencies (4-8 Hz) than previous studies at other sites. These conditions resulted primarily from the geologic structure as the vibration propagating medium. Either the natural horizontal layering and/or the extensive horizontal room and pillar network underlying the region were trapping seismic energy and determining its character.

Blast designs were partly responsible, with high level casting and complex multidelayed blasts producing wave interaction and constructive reinforcement. The traditional 8-ms criteria for separating charge weights per delay appears insufficient for this low-frequency site.

[1]Geophysicist, Twin Cities Research Center, Bureau of Mines, Minneapolis, MN.

INTRODUCTION

The Bureau of Mines was asked by the Federal Office of Surface Mining (OSM) to examine surface mine blasting near the western Indiana town of Blanford. An abnormal number of complaints from this area alleged structural and cosmetic damage to homes in addition to a high level of annoyance. Available information indicated that the presence of extensive abandoned underground coal mine workings underlying the town and the nearby area to the south currently being surface mined by Peabody Coal Company might be related to these problems.

The Bureau conducted two studies for OSM and the Indiana Department of Natural Resources (DNR), working with the two agencies, Peabody Coal Company, and local citizens. The first study was an examination of seismograph records collected by OSM and DNR near seven of the Blanford homes (1).[2] A followup study was done by Bureau researchers with a greatly expanded scope (2). The latter study utilized vibrations from both single charges and production blasts. Researchers sought to determine the following:

1. Blast design influences on vibration amplitudes and frequencies.
2. Structural and geologic influences on vibration amplitudes and frequencies.
3. Site-specific influences on vibrations as received at the homes.
4. Other site-specific influences on the town structures such as settlement-induced strains and distortions.

An initial examination of State-collected blasting records revealed the presence of unusual low-frequency vibration waves of long duration. Previous work by the Bureau and others described observations of such waves from low-strength rock and soil layers (3). However, no studies are known that quantify such blasting waves in terms of measured structure and material properties.

This Bureau of Mines report includes and summarizes all data and analyses contained in the two reports to OSM. In addition, it includes the results of a 7-month followup resurvey of house settlement and/or subsidence and some additional analysis of vibration propagation and wave characteristics.

ACKNOWLEDGMENTS

This research was done at the request of James Gilley, Chief, Branch of Engineering Support, Eastern Technical Center of OSM, Pittsburgh, PA, and partly funded by OSM. Eric Gerst, Blasting Specialist, Indiana Department of Natural Resources, Jasonville, assisted in the data collection. The Peabody Coal fired all the blasts including the seven studied by the Bureau of Mines September 9-13, 1985. Peabody officials also provided many of the historical and current vibration records, blasting logs, and drillhole data. The Blanford Action Committee, a local homeowners group, provided useful suggestions.

EXPERIMENTAL PROCEDURES

DATA AVAILABLE

Four sets of data were used for this study: (1) records of blast vibrations and designs for the period May 15, 1984, to April 25, 1985, as discussed and analyzed in the Bureau of Mines May 15, 1985, report to OSM (1), (2) additional records and data subsequently obtained from Peabody Coal Co. and the DNR, (3) blast records the Bureau obtained by monitoring shots during the week of September 9-13, 1985, and (4) a resurvey of the levelness of eight Blanford houses. The first three items were discussed in detail in the Bureau's November 15, 1985,

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

report to OSM (2). At times, as many as six houses were simultaneously instrumented for vibrations by Peabody and the Indiana DNR.

Data Initially Reported to OSM

Available for the May 15, 1985, report to OSM were 432 vibration measurements obtained by Peabody and the DNR at seven different residences in and around Blanford from 235 production blasts during the period May 15, 1984, to April 25, 1985 (1). Blast design logs for all shots, regional maps, and drilling logs were provided by Peabody. A local resident's perception logs were also available. The DNR had seismographs installed in the Hollingsworth, Massa, Volk, and Zell houses during part of the study period. Peabody had seismographs in the Jackson, Massa, Polomski, and Verhonik houses.

Supplementary Peabody and DNR Data

Following analyses for the May 15 report, additional data were requested in anticipation of a followup study. These consisted of 30 three-component seismic records from Peabody to provide more comparisons between measuring sites and shots measured at each site. Previously, only single-component peak values from Peabody's blasting logs were available. Also obtained were 82 additional shot-to-recording distances for the DNR measurements to enhance the propagation plots.

Bureau of Mines Measurements

Using a 7-station array of 3-component seismographs, Bureau researchers collected 123 vibration records from 5 production blasts and 2 specially fired single-charge shots (table 1). These records were to be compared with coal mine blasting data previously reported by the Bureau (3). Measurements were made as close to the blast as 54 ft to identify the vibration source characteristics. For the same shots, measurements were also made at greater distances, up to 5,700 ft, to show how the vibrations changed character as they propagated. Single-charge blasts were made to identify the effects of the blast design. Of particular concern were the delays between individual charges and their effects on the wave characteristics, both close and at distances.

In addition to the vibration monitoring, Bureau researchers performed and repeated 7 months later level-loop surveys of eight Blanford houses to determine possible subsidence- or settlement-induced strains and distortions.

Additional Available Data

Besides the vibration data, blasting logs, and survey data, the following information was available for this study:

1. A regional map showing the surface mine layout as of April 1985, and the town and house locations.

TABLE 1. - Production blast designs used at Universal Mine, July 1984 through April 1985

Design type and delays,[1] ms	Number of decks	Charge weight per delay, lb	
		Typical	Exception or maximum
Echelon:			
17 by 42.....	1	1,500	2,258 maximum.
17 by 100.....	2-4	325	Exception: 625 on 4-22-85.
17 by 200.....	2-4	200- 400	Exception: 1,475 on 1-5-85
Casting: 8, 10, or 12.5 by 140 to 210.....	1	2,000	3,842 maximum.

[1]Delay between holes (e.g., 17 ms) and delay between rows (e.g., 42 ms).

2. Fifteen shallow drilling logs from Peabody used by that company to determine the overburden characteristics and the depth of the No. 6 coalbed.

3. Four specially drilled deep-hole logs from Peabody made for structural assessment around the Polomski house, which is being used as a continuously monitored test structure by the Peabody Coal Co.

4. Subjective perception logs of house vibrations from two homeowners. Alice Massa covered September 1984 to April 1985, and John Albrecht, March 1983 to September 1985.

5. Maps showing areas in and around Blanford underlain by previous underground mining, a small-scale map based on a U.S. Geological Survey (USGS) 7-1/2-min quadrangle and a large mining map of the No. 5 coalbed under the town.

SITES

Surface

The general mine layout and town of Blanford are shown in figure 1. Closer views of the town, the north end of the mine, and the instrument arrays used for the Bureau tests are shown in figures 2-4. Figure 5 shows the Universal Mine, where the No. 6 coalbed is being surface mined. The Volk and Polomski houses are next to each other as well as those of Zell and Massa. The Hollingsworth house is about 1,400 ft north of the Volk house. Jackson's house is the closest to the mine, being within about 1,000 ft when Peabody is blasting at the farthest north end of the pit. Verhonik is far east of the other sites. The remaining houses (Marietta, Skorich, Albrecht, O. Finger, E. Finger, Jovanovich, and Ahlmeyers) were not instrumented for vibrations although they were examined by level-loop surveys. Six of the seven houses instrumented for vibrations are shown in figures 6-11. The Zell house and all the others surveyed are shown in the section discussing level-loop surveys.

Subsurface

The geology of western Indiana is composed of sedimentary rocks, generally interbedded shales, limestones, and sandstones overlain by alluvium, sand, and gravel. Fifteen drilling logs were provided by Peabody for holes between the current mining and the town. Generally, the top zone is characterized as "sand and drift" and is 60 to 75 ft thick. Below this is coal, shale, or material classified as "coal and jack." Some topographic relief is provided by surface streams in the area. The logs do not include any information on voids or old underground workings. Presumably, the coal referred to is the No. 6 coalbed currently being surface mined at a depth of 50 to 100 ft.

Near Blanford, underground mining has occurred in the No. 6 coalbed and in deeper beds 5, 4, and 3 at depths of 85, 225, 325, and 395 ft, respectively. A total of four holes were drilled near the Polomski house to depths between 340 and 420 ft and, according to the driller and the downhole logs, no underground workings were encountered.

The extent of abandoned underground mines in the Blanford area is shown in figure 12. The No. 5 coalbed was mined beneath nearly all of present-day Blanford. A small amount of the deeper No. 4 coalbed was also mined. This area is approximately beneath the Massa, Zell, and Marietta houses. A detailed version of West Clinton No. 1, seam 5, is given in figure 13, a reproduction of a poor-quality original. Assuming surface features are accurate and correspond to their modern locations, and the underground map is complete, the study houses were located on this detailed map. According to this map, all the houses studied appear undermined except for a small area that includes the Volk and Polomski houses. The smaller scale map (fig. 12) was prepared as a summary by Indiana State officials and shows some differences, such as the unmined area being

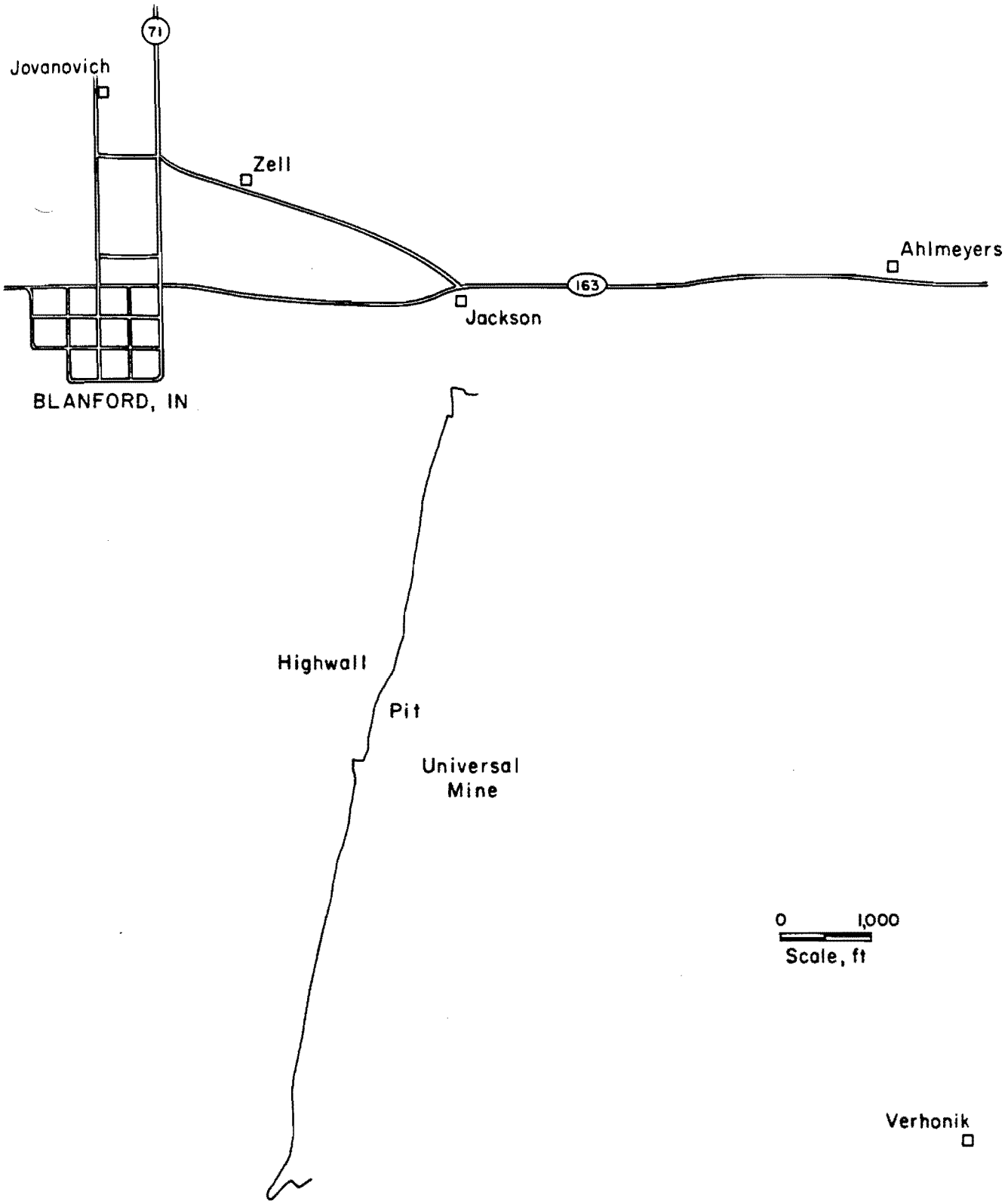
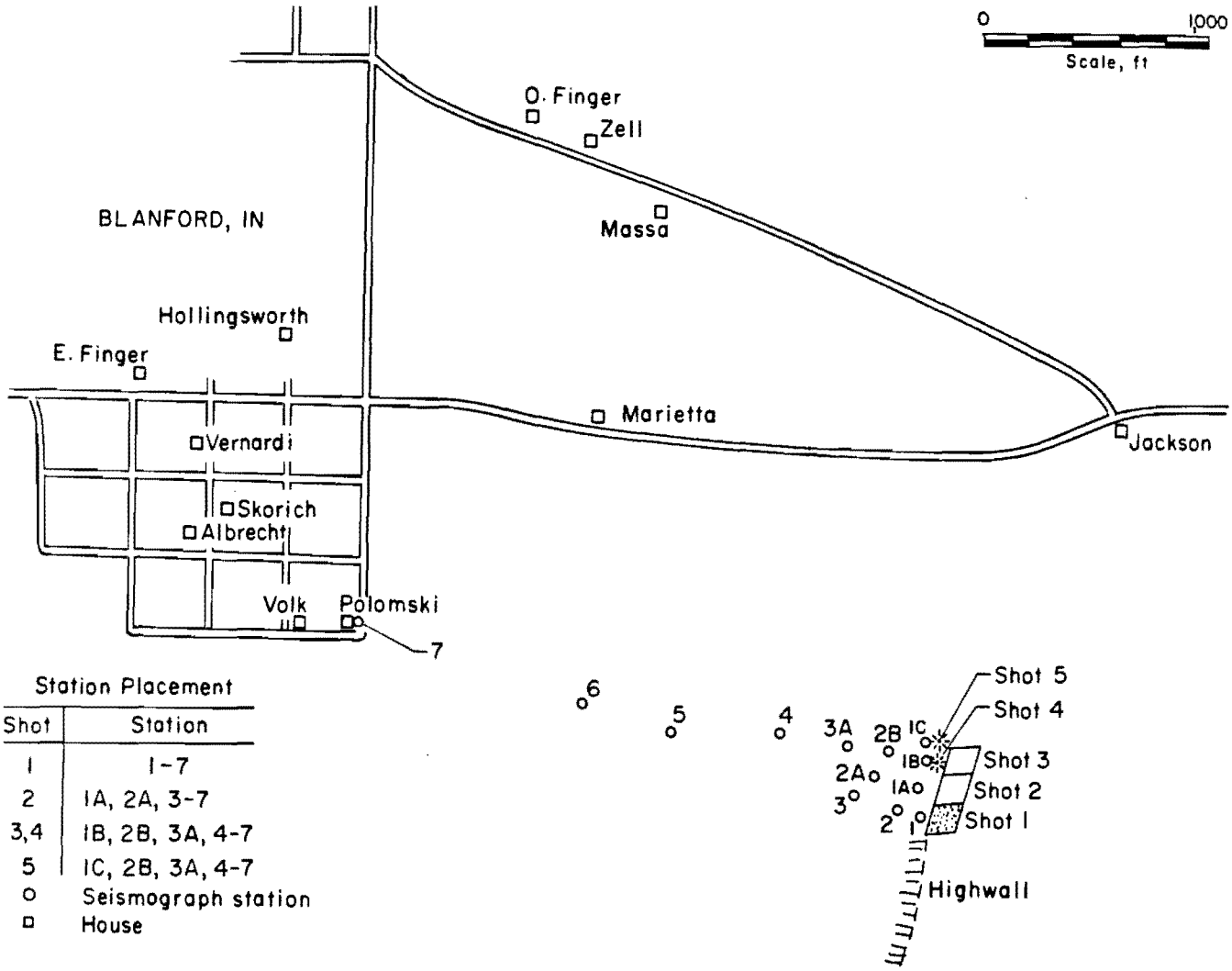


FIGURE 1.—Peabody's Universal Mine and Blanford, IN.



Station Placement

Shot	Station
1	1-7
2	1A, 2A, 3-7
3,4	1B, 2B, 3A, 4-7
5	1C, 2B, 3A, 4-7
o	Seismograph station
□	House

FIGURE 2.—Shot and seismograph array for Bureau shots 1-5.

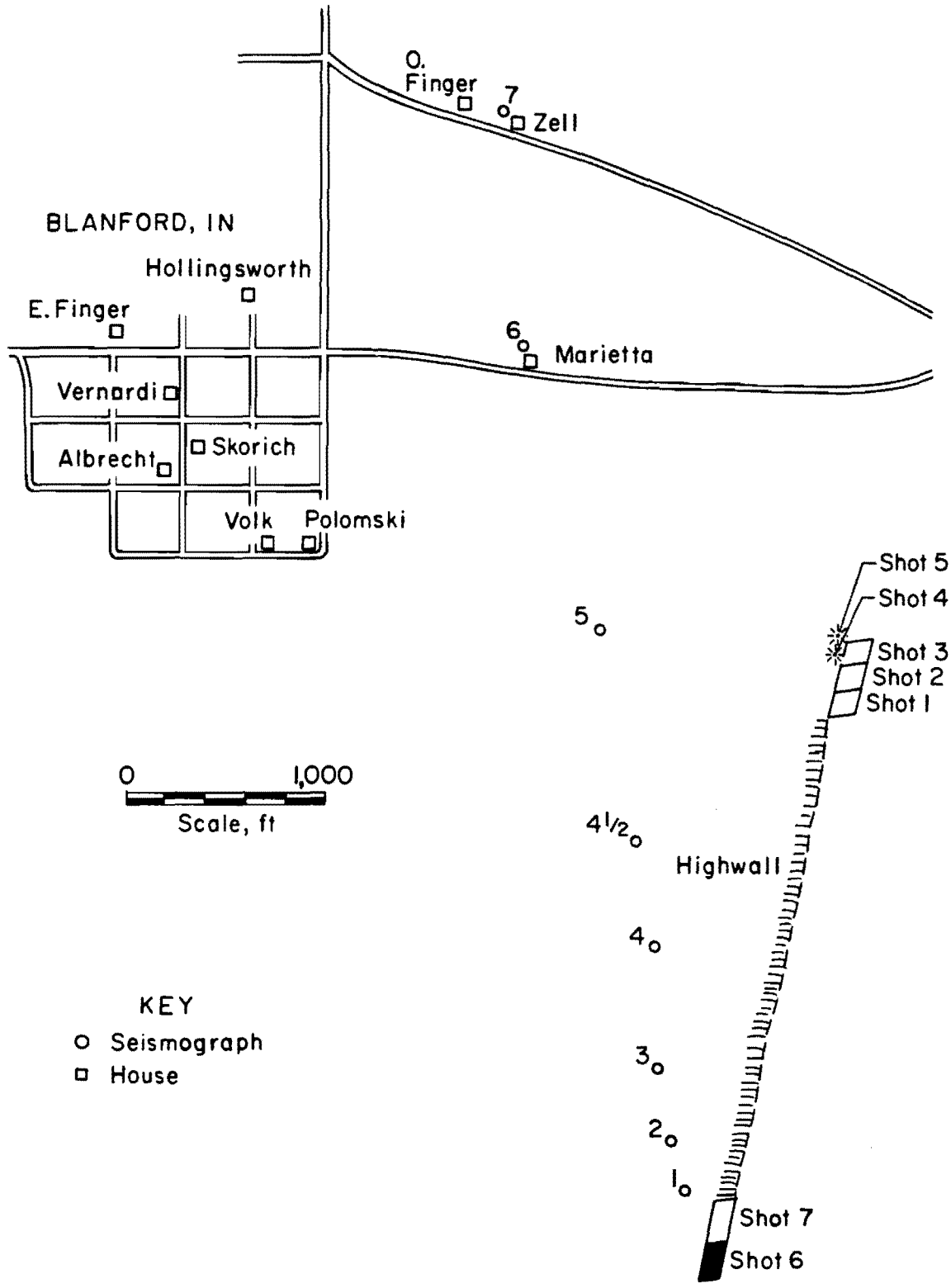


FIGURE 3.—Shot and seismograph array for Bureau shot 6.

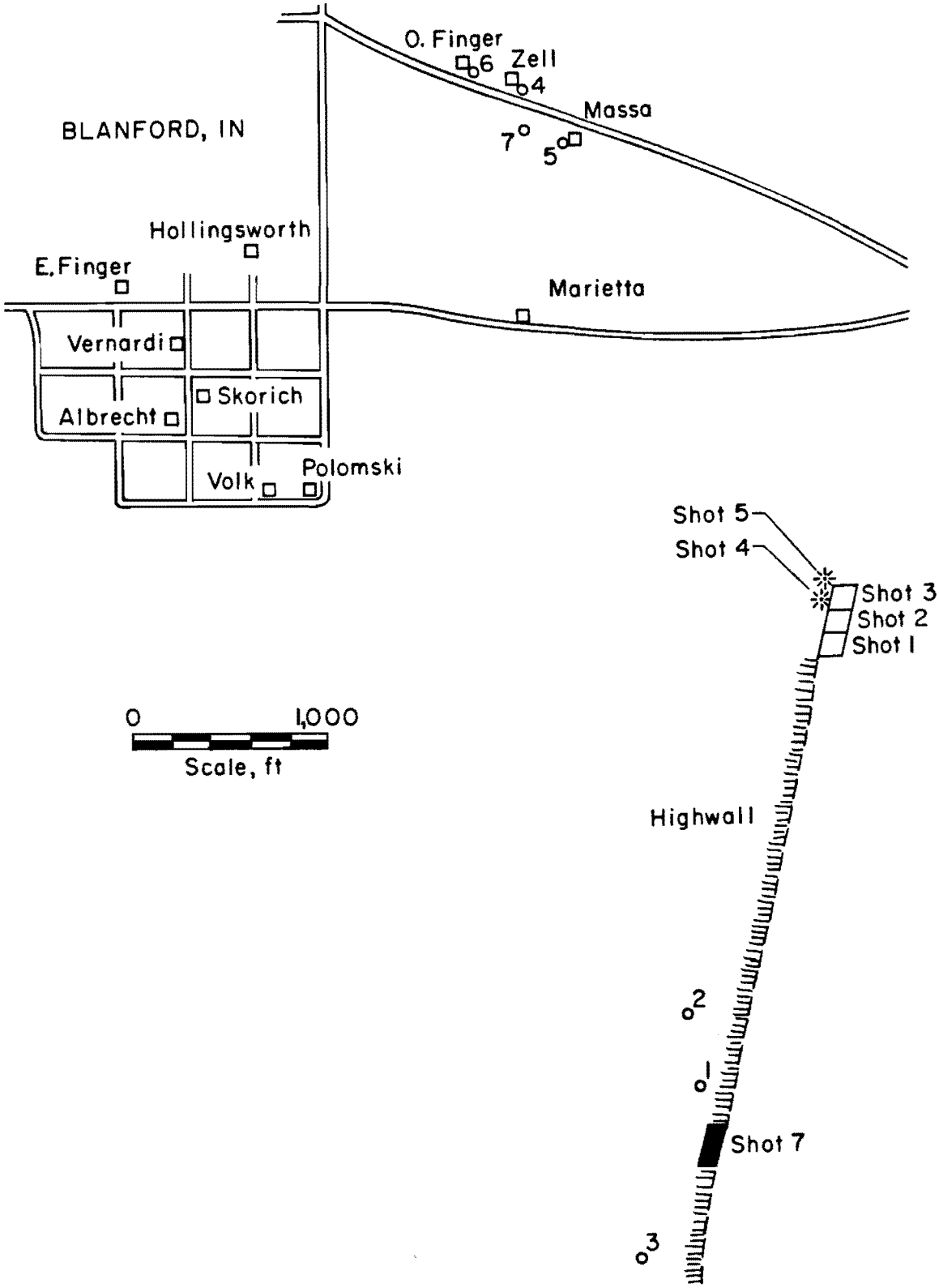


FIGURE 4.—Shot and seismograph array for Bureau shot 7.

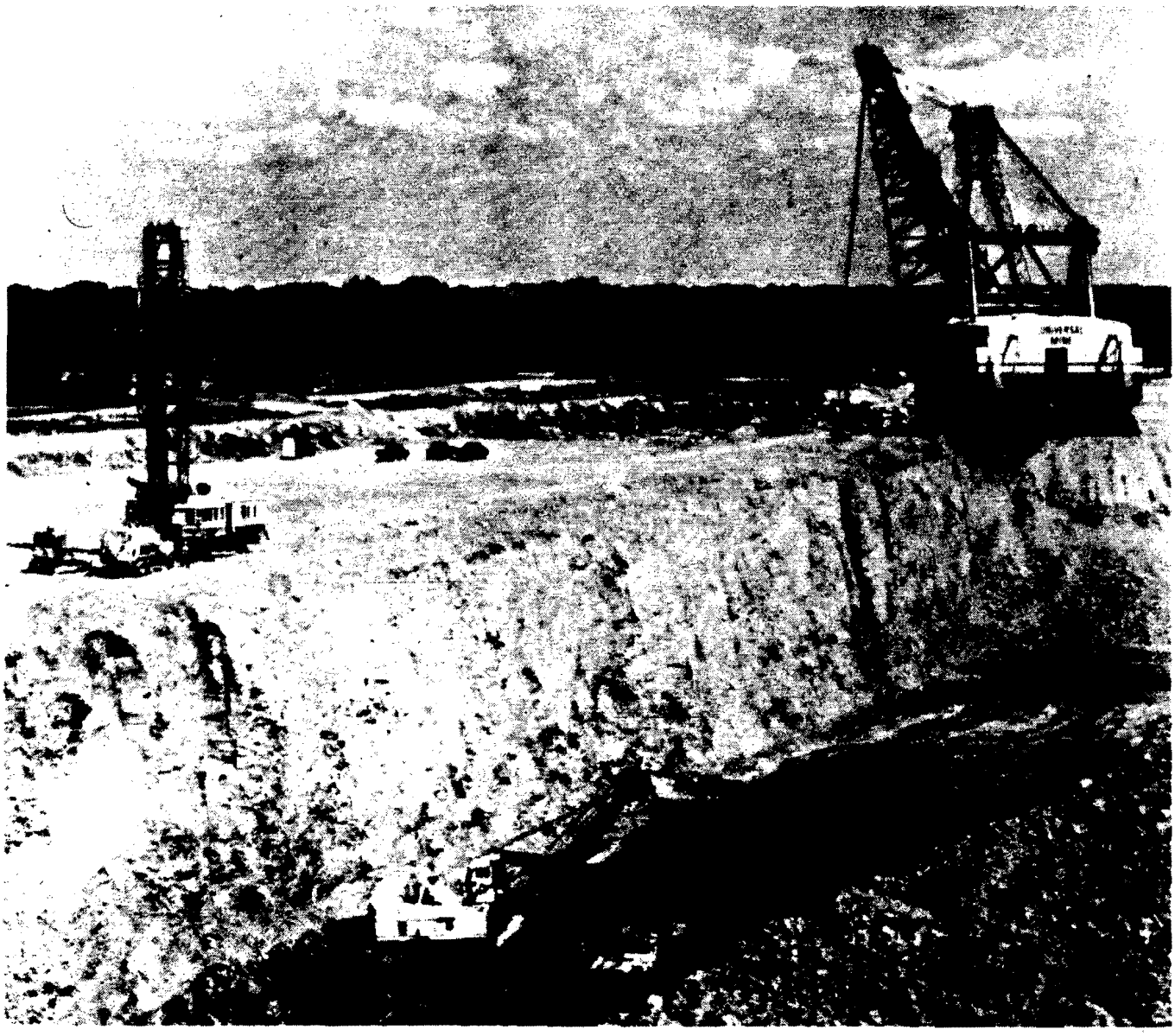


FIGURE 5.—Peabody's Universal Mine near Blanford, IN. Town is beyond trees.

FIGURE 6.—Hollingsworth house.

FIGURE 7.—Jackson house.

FIGURE 8.—Massa house.

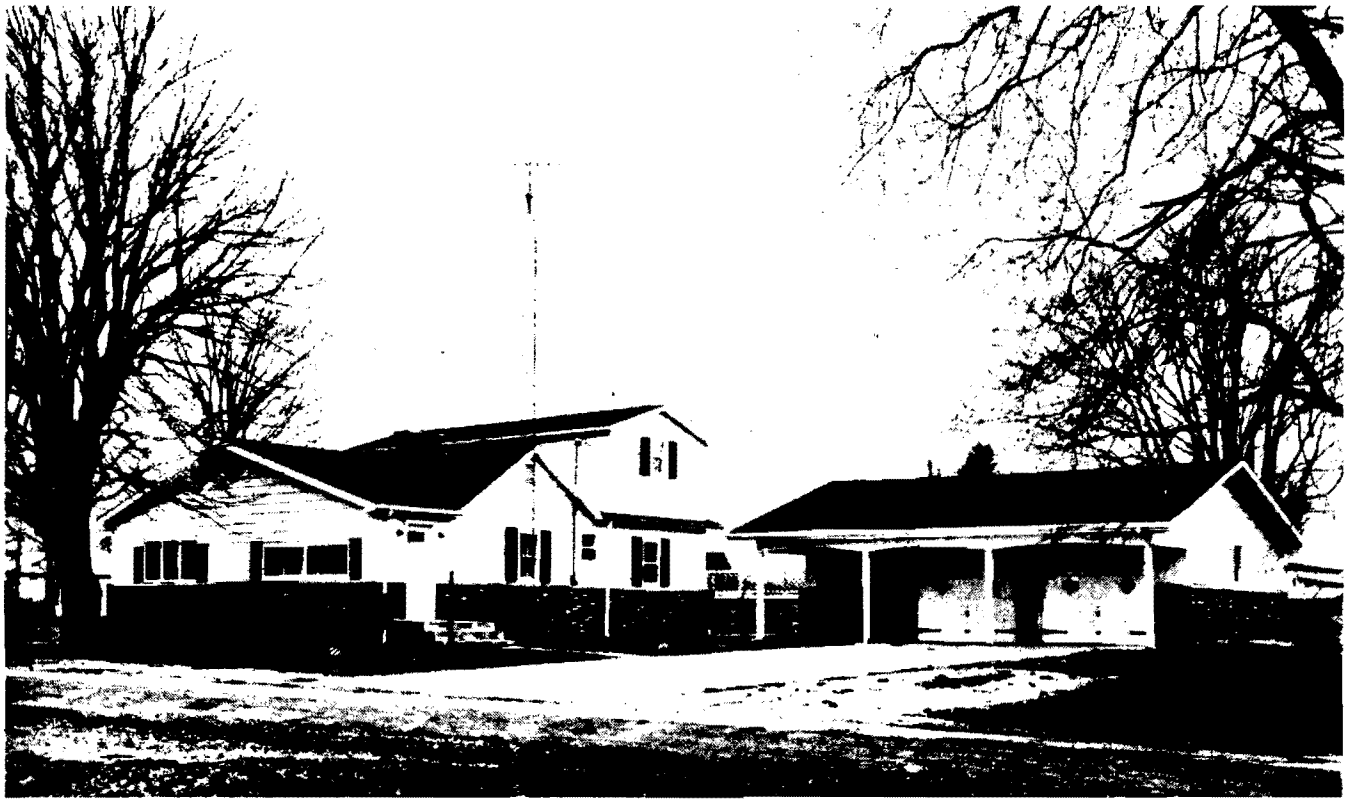


FIGURE 9.—Polomski house.

FIGURE 10.—Verhonik house.

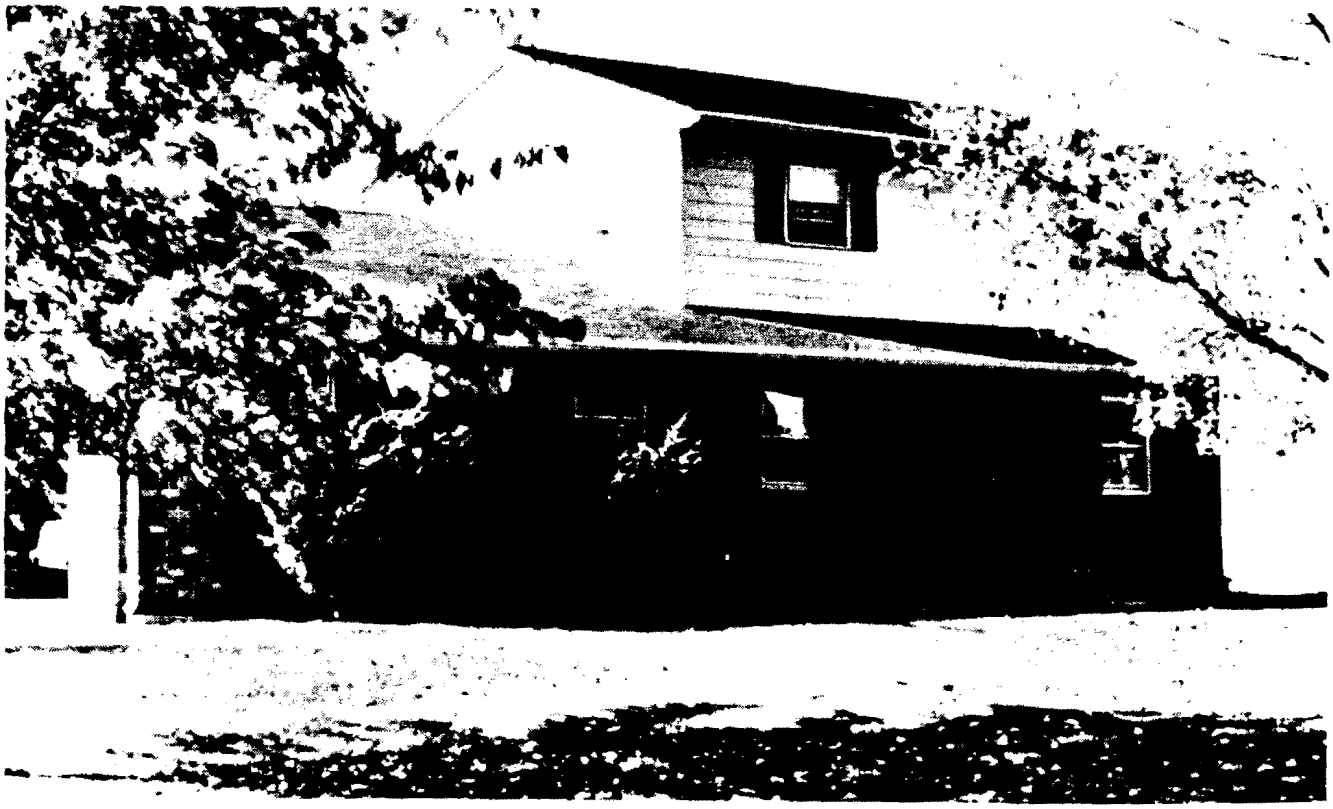


FIGURE 11.—Volk house.

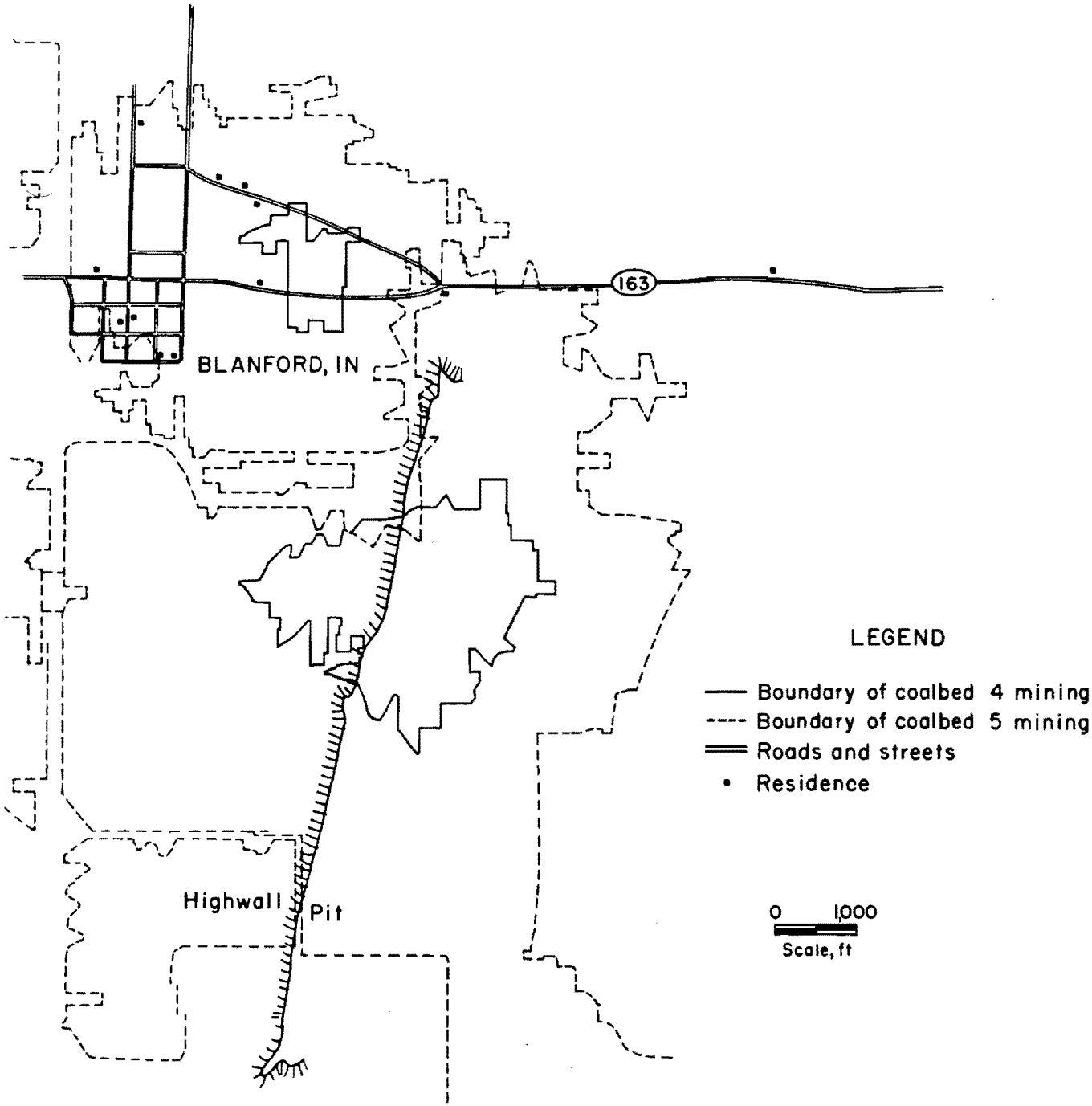


FIGURE 12.—Areas around Blanford undermined by abandoned mine workings.

slightly to the west of the Polomski house.

Some other geologic features are of possible significance, particularly for comparisons of vibration characteristics at houses in different parts of town. The ground surface between the current blasting and the Verhonik house was disturbed and is now entirely mine spoil. At the north end of the pit, between the mine and the town, is a large area with no coal; it is filled with sandy, gravely till or other similar unconsolidated material. The No. 6 bed is missing in this region. Also, old surface mine spoils exist due north of the pit, between the mine and the northeast side of town (fig. 1). These unconsolidated and possibly

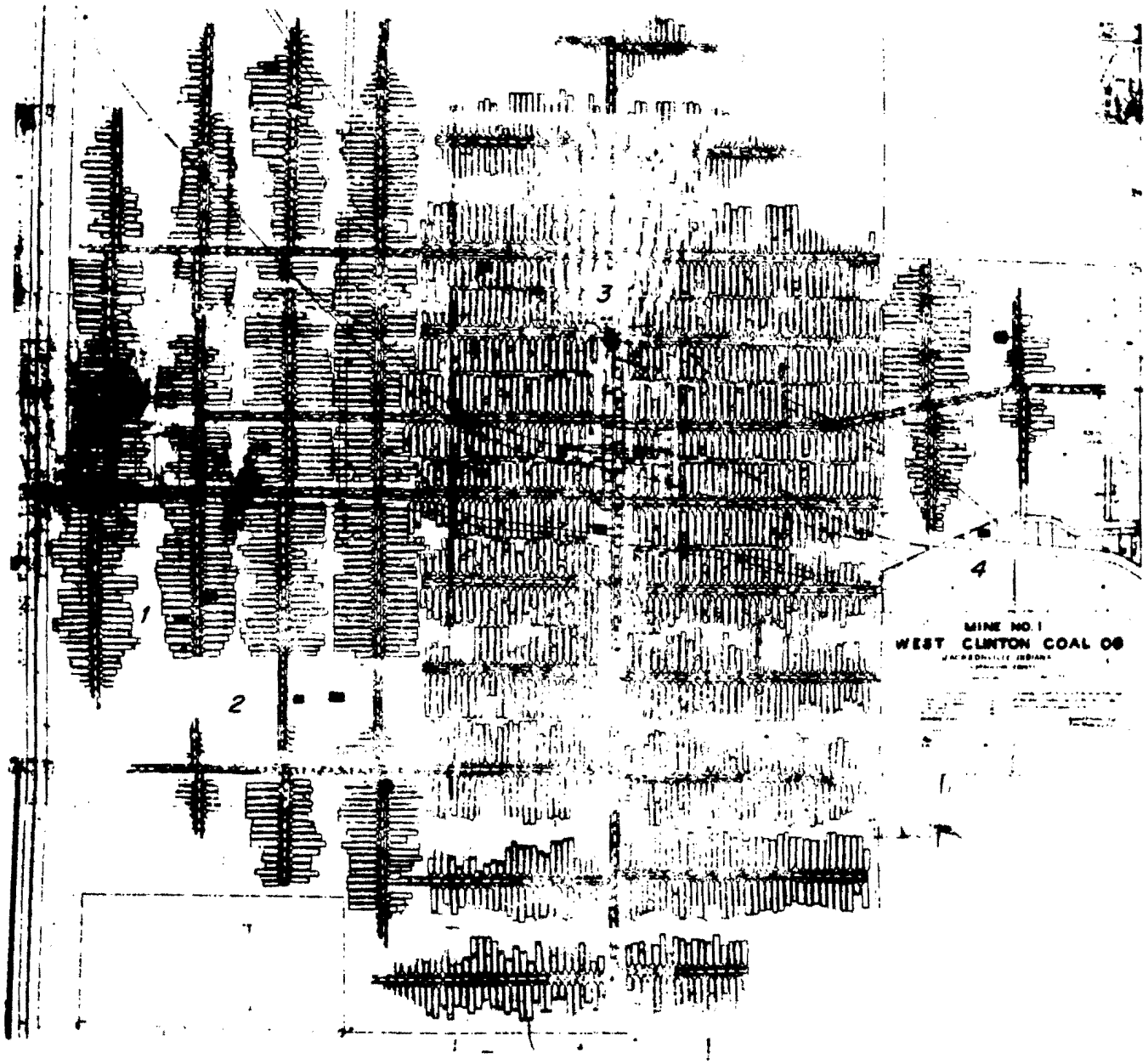


FIGURE 13.—Old West Clinton No. 1 Mine, coalbed 5, beneath Blanford. Houses: 1, Albrecht and Skorich; 2, Volk and Polomski; 3, O. Finger, Zell, and Massa; and 4, Jackson.

saturated materials could significantly influence the vibration character and contribute to the generation of low-frequency vibrations.

More work is needed to clearly identify the influences of the old workings. Most important is knowledge of which houses are located over abandoned workings and the existence of significant voids along the propagation path of the blast vibrations. Also needed are depths to the underground workings for use in the theoretical models that predict surface wave frequencies. It is unlikely that old maps alone will provide sufficient detail for surface feature correlation.

BLAST DESIGNS

Production Blasting, July 1984 to April 1985

Peabody used four basic blast designs during the 10-month period covered by the

vibration data at their Universal Mine (table 1). Three of these were echelon arrays with different between-row and between-hole delays, along with a few minor variations. Charges were full-column or multiply decked with up to four independently delayed charges per hole. Nonel[3] and Hercudet initiation systems were used. The other major blasting method was casting, with short delays of 8, 10, or 12-1/2 ms between holes in a row parallel to the pit highwall. The time between rows for casting was much greater than for echelon blasts, at about 200 ms to allow good relief and rock throw.

Previous research suggests that vibration frequencies are related to delay intervals (4-5). This is most likely for close-in hard rock situations where the propagating medium does not have a dominating influence on the wave characteristics. Similarly, delay intervals may affect maximum peak partical velocity values. Wave interference for blasts is complicated and unpredictable, having as many as 200 independently delayed charges. Because relief (time and space provided for rock moveout) is thought to be a minor influence on vibrations, the number and depth of decks were not expected to be major factors for vibrations (8). Blast casting might also be a minor influence with the increased relief partly balancing larger charges (up to 3,000 lb per delay). Despite these expectations and speculations, no definitive study has been published comparing the influences of decking and casting on vibration levels and wave character. Blanford residents characterized the period that includes the blast casting as "very bad" or "worst"; however, rather than casting as such, the large charge weights per delay (typically 2,000 lb per delay) could have been responsible.

Table 1 summarizes the major blast designs used at the Universal Mine between July 1984 and April 1985. Casting was limited to the period October 22, 1984, to March 1, 1985, and used the largest charge weights. After March 1, 1985, blasts utilized the 17- by 100-ms echelon pattern, which was the method in use in September 1985 when the Bureau of Mines obtained its field data.

Production and Test Blasts for Bureau of Mines September 9-13, 1985

The mine fired seven shots during the Bureau of Mines study period. Three were production shots at the far north end of the pit (fig. 2). The next two were single-charge shots in the same highwall area with a bottom-of-the-hole load at the same charge weight per delay as the production blasts. The last two were again standard 17- by 100-ms echelon production blasts except they were 2,800 ft south along the highwall (figs. 3-4).

RESULTS OF FINDINGS

VIBRATION AMPLITUDES AND PROPAGATION PLOTS

Propagation plots of measured blast vibrations were prepared for site and shot comparisons as well as for comparison with measurements made at other surface coal mines. Scaled distances employed the charge weights per delay as specified in Peabody's blasting logs. There is a significant chance that individual charges, thought to be independent, are interacting constructively because of the complexity of the multihole, multidecked blasts, cap inaccuracy, and the site conditions. This problem is addressed later in the report.

The 15 propagation plots in figures 14-28 represent various combinations of sites, blast arrays, and special test blasts. For easy comparisons, most of the plots include propagation summary lines derived from a Bureau report (3) that includes a summary of surface coal mines (figure 10 of reference 3). The lines represent the mean least-squares regression of the maximum peak particle velocity; that is, for each shot that

[3]Reference to specific equipment is made for identification and does not imply endorsemejt by the Bureau of Mines.

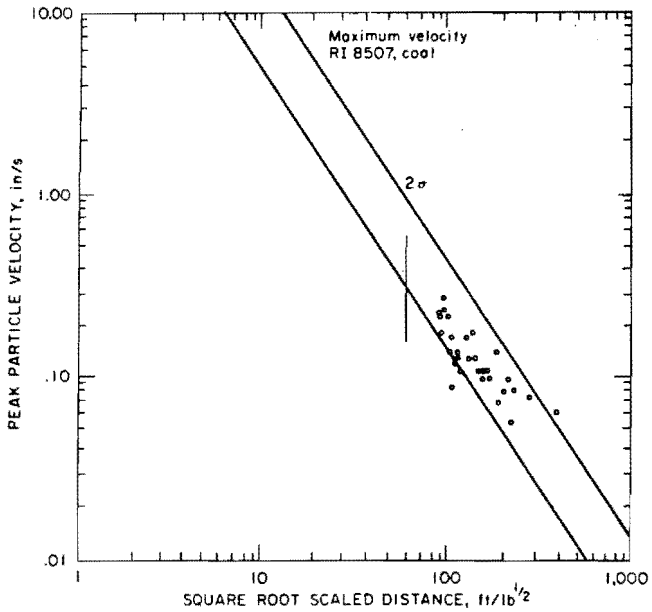


FIGURE 14.—Propagation plot of maximum particle velocity, Volk house, and surface coal mine blasting data (3).

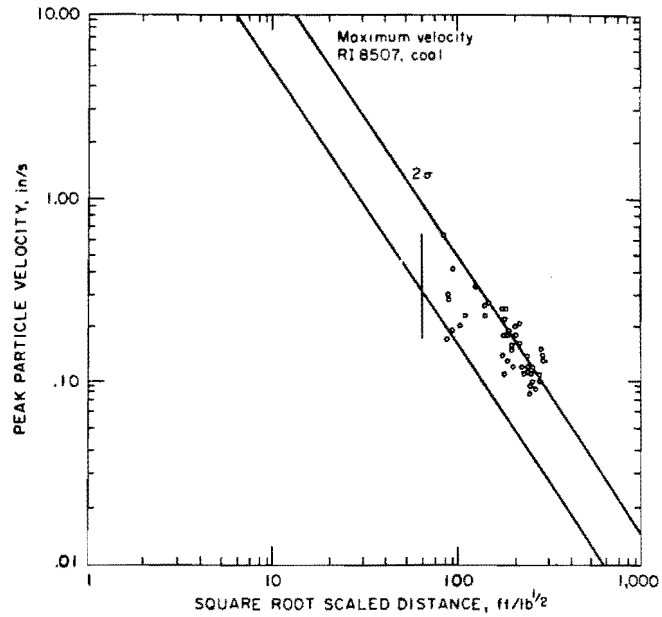


FIGURE 15.—Propagation plot of maximum particle velocity, Polomski house, and surface coal mine blasting data (3).

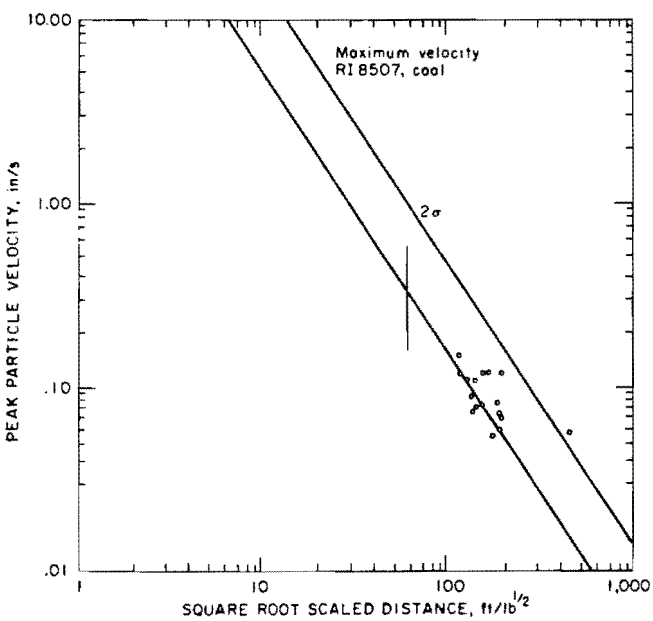


FIGURE 16.—Propagation plot of maximum particle velocity, Hollingsworth house, and surface coal mine blasting data (3).

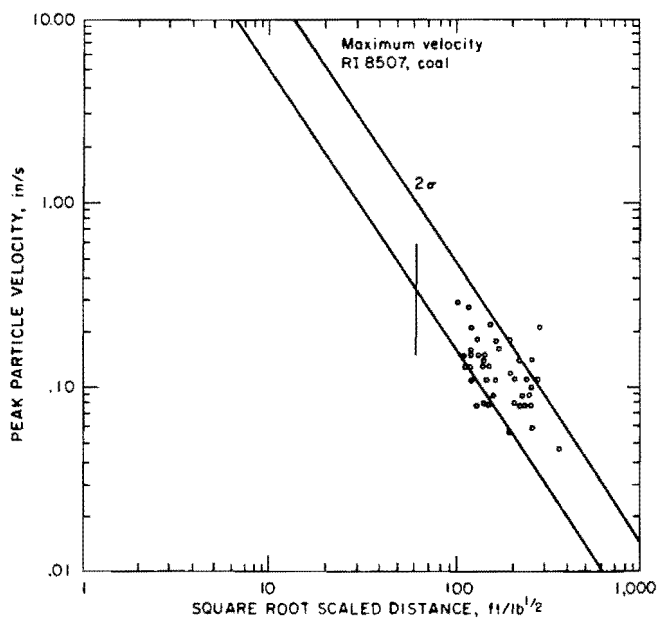


FIGURE 17.—Propagation plot of maximum particle velocity, Massa house, and surface coal mine blasting data (3).

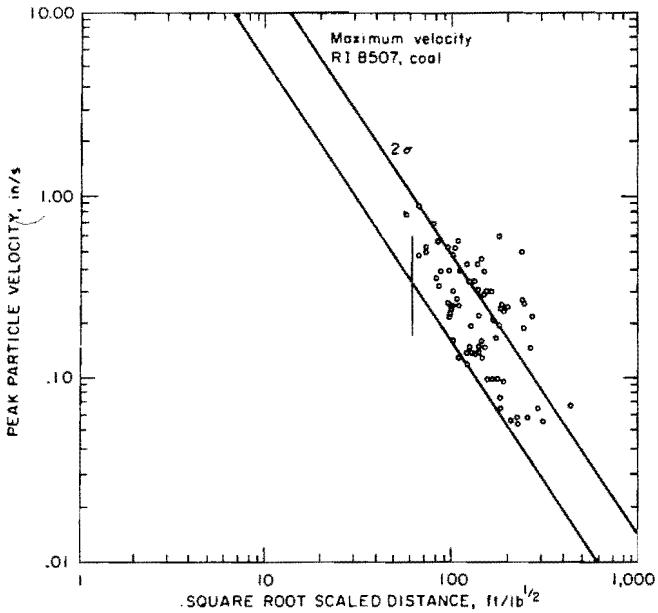


FIGURE 18.—Propagation plot of maximum particle velocity, Jackson house, and surface coal mine blasting data (3).

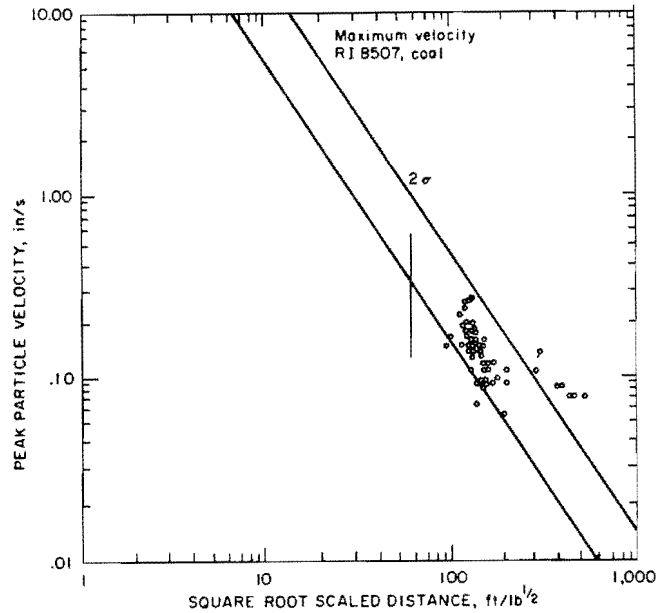


FIGURE 19.—Propagation plot of maximum particle velocity, Verhonik house, and surface coal mine blasting data (3).

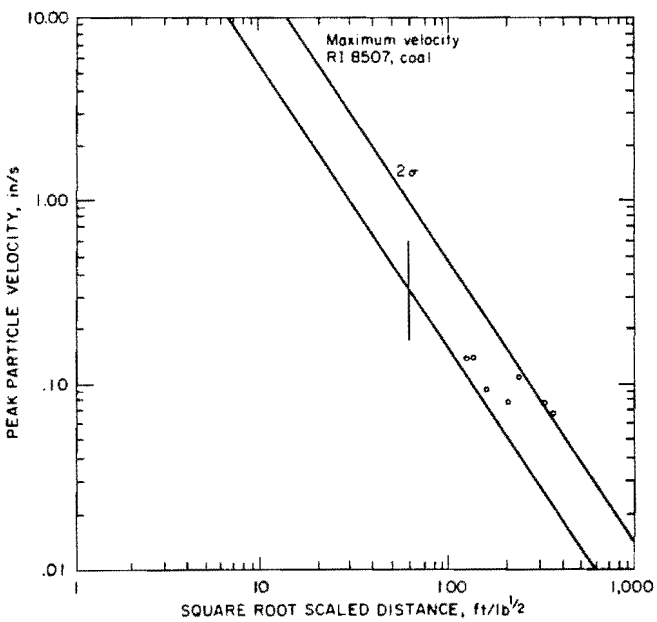


FIGURE 20.—Propagation plot of maximum particle velocity, Zell home, and surface coal mine blasting data from RI 8507 (3).

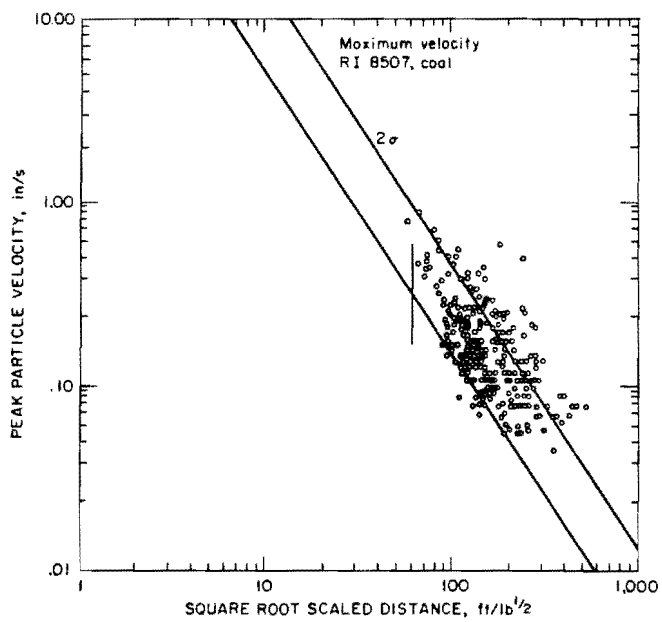


FIGURE 21.—Propagation plot of maximum particle velocity, all seven homes, and surface coal mine blasting data (3).

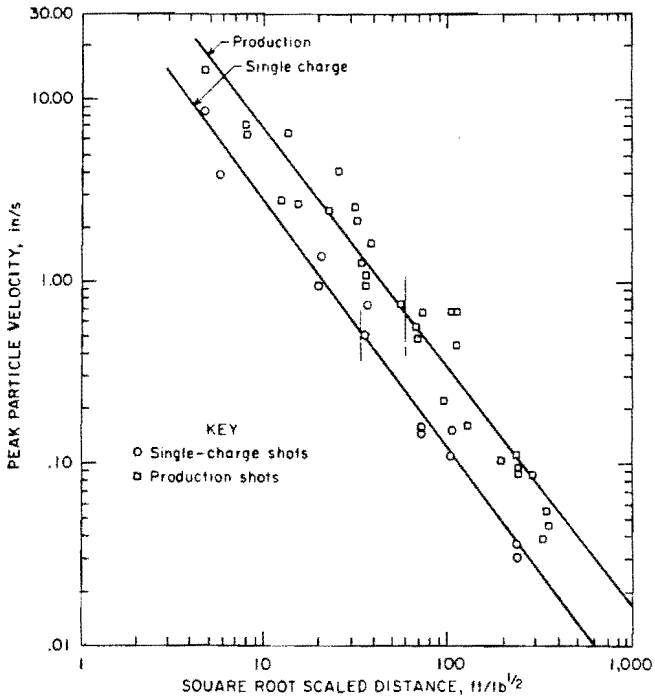


FIGURE 22.—Propagation plots of Bureau tests, all maximum velocity values.

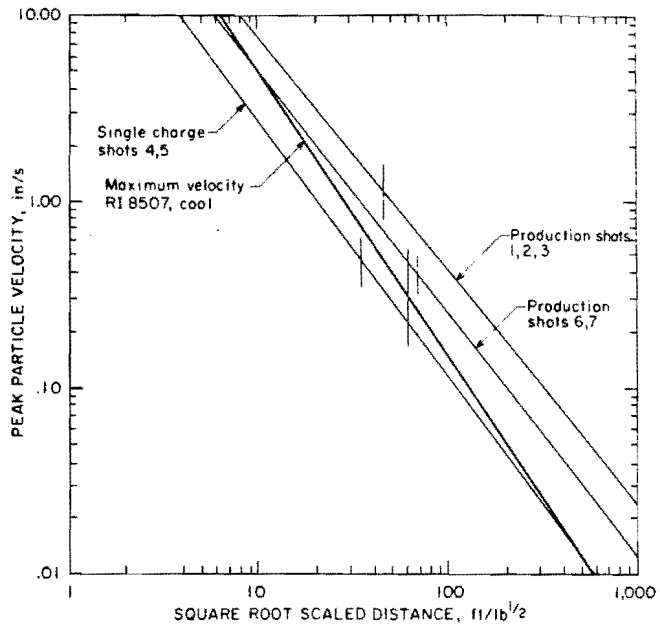


FIGURE 23.—Propagation plots of Bureau tests, regression-line summary.

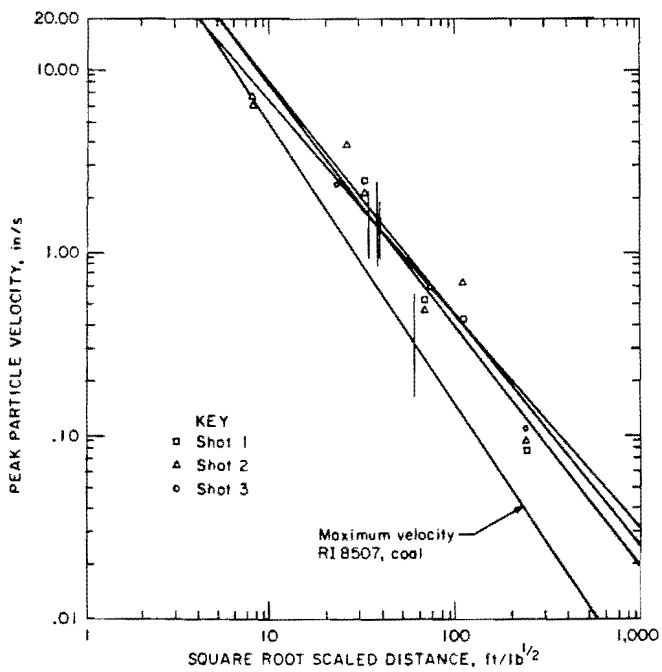


FIGURE 24.—Propagation plots of Bureau tests, west array production blasts.

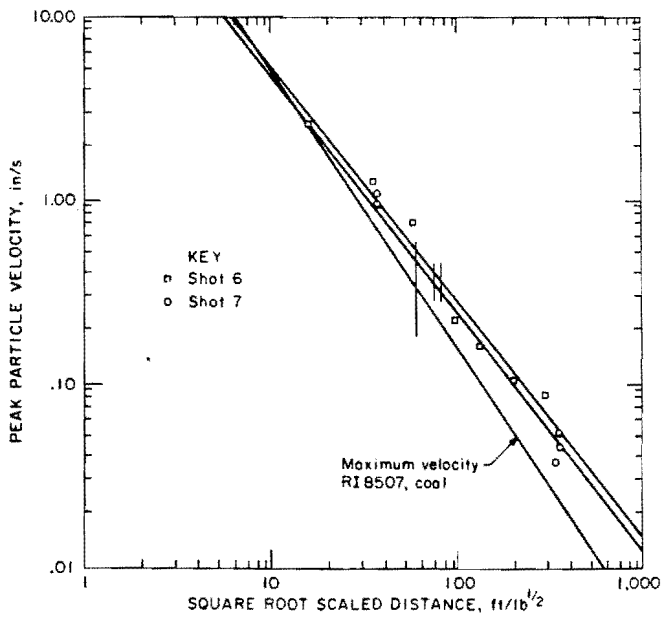


FIGURE 25.—Propagation plots of Bureau tests, north array production blasts.

produced three component values, radial ("longitudinal"), vertical, and transverse, only the single maximum of the three was plotted. All the Blanford data were treated in a similar manner unless the individual motion components are specified. This simplified the appearance of the plots and also conforms to the regulatory practice of evaluating the highest of the three components.

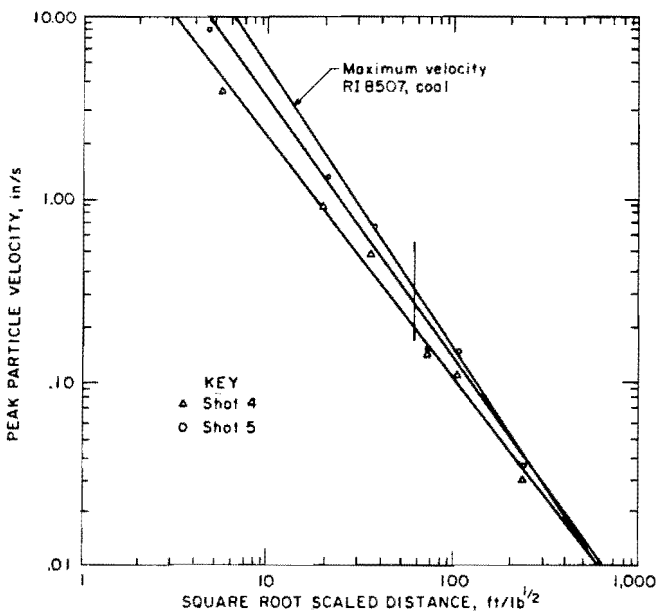


FIGURE 26.—Propagation plots of Bureau tests, single-charge blasts.

The propagation plots also have a line for two standard deviations above the mean. This line approximates the envelope that enclosed the highest vibrations measured from blasting in surface coal mines as summarized in the Bureau report (3).

Production Blast Monitoring at Residences

Vibrations measured at each of seven Blanford houses by Peabody and the Indiana DNR are given in figures 14-20. The majority of values exceed the mean propagation plot shown in the Bureau report (3). Furthermore, many exceed the maximum-value envelope. Only the Hollingsworth house appears nearly "normal" or typical of measurements made elsewhere. Three explanations are possible:

1. Abnormally efficient propagation, which should show up as an unusually flat slope in the propagation line.
2. Scaled distance values in error because of a failure in the 8-ms criterion for determining charge-weight-per-day values.
3. Cap scatter. (This study did not include determination of actual initiation times.)

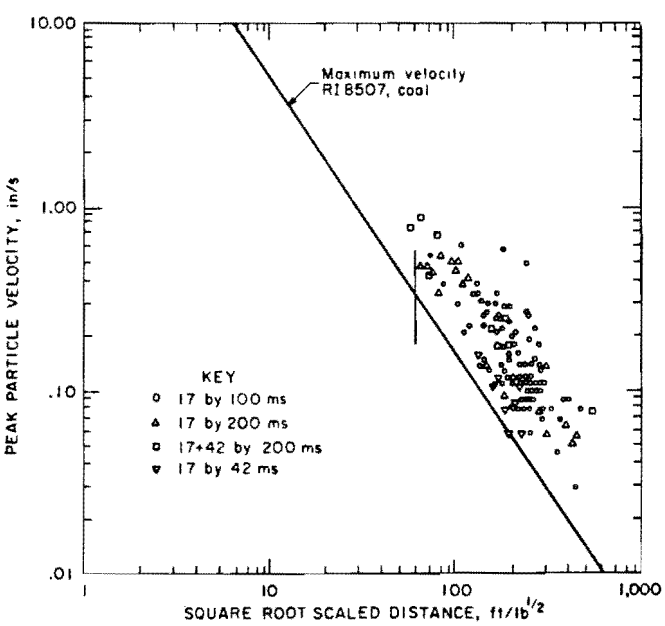


FIGURE 27.—Propagation plots of echelon blasts.

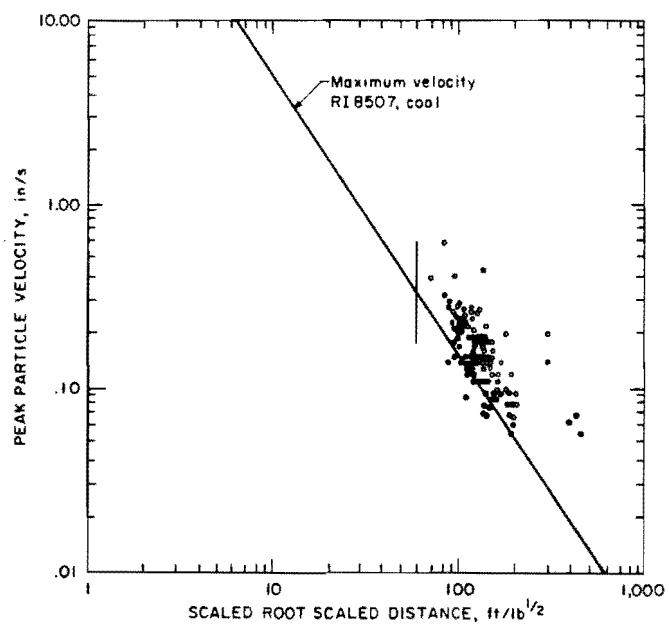


FIGURE 28.—Propagation plots of casting blasts.

Because the measurements shown in figures 14-20 were collected to assess damage risk and not propagation, they cluster within narrow scaled distance ranges and do not permit reliable determinations of propagation equations. Vibrations from all the seven homes are summarized in figure 21. Predictions of vibrations in Blanford using normally defined charge weights and scaled distances are not similar to other surface coal mines studied previously. This result prompted the experiment designed by the Bureau of Mines and is discussed in the next section.

Bureau of Mines Vibration Tests

The Bureau measured blasting vibrations at Peabody's Universal Mine from five production and two single-charge blasts, using wide-spaced seismic propagation arrays (figs. 2-4). Table 2 summarizes these tests.

Figure 22 compares the production and single-charge shots. The two mean regression lines are almost parallel, indicating similar amplitude attenuation with distance. However, the intercepts are dissimilar, as would be expected with the differences in the blast sources. The intercept value, k, for each propagation line is the vibration level projected at a scaled distance of unity.

$$V = k\ (D/W^{1/2})^{a},$$

where v is the velocity amplitude, D is the distance, W is the charge weight, and a is the regression line slope.

In figure 23, production shots 6 and 7 were separated from shots 1, 2, and 3, since they were in different locations in the pit and had different burdens, spacings, hole depths, and seismograph array geometries. The regression lines are again nearly parallel, indicating similar attenuation. The intercepts are not the same, indicating differences in the blasts.

The three regression lines of the Universal Mine data (single-charge and production shots) have similar slopes, but all are flatter than in previous studies. This suggests less attenuation of vibration amplitudes with distance than does the data for other surface coal mines described in the Bureau report (3).

A statistical analysis of data comparisons is given in table 3. The only data that can be statistically pooled with previous coal mine data are the single-charge shots 4 and 5. The groups that failed the F1 tests are statistically different and cannot be represented by one regression line. This suggests that the vibrations from the production shots are outside the older data previously considered representative of surface coal mine blasting (3). The F2 test determines if the same slopes can used for the various data groups.

TABLE 2. - Bureau of Mines vibration tests at Blanford, September 1985

Shot	Distance to seismic station, ft[1]	Array orientation	Blast design			
			Pattern[2]	Hole depth, ft	Maximum charge weights, lb	
					Per hole	Per deck
1...	54-2,693	East-West..	Echelon.....	54	450	125
2...	92-2,675	...do.....	...do.....	54	450	125
3...	90-2,640	...do.....	...do.....	50	450	125
4...	65-2,615	...do.....	Single charge	50	125	125
5...	54-2,620	...do.....	...do.....	50	125	125
6...	290-5,710	North-South	Echelon.....	83-85	950	250
7...	200-5,400	...do.....	...do.....	82-85	950	250

[1]All shots had 7 stations except shot 6, which had an additional seismograph on load from the DNR.

[2]Echelons used 17 ms between holes in a row and 100 ms between rows. All production blasts used 4 decks.

TABLE 3. - Statistical comparisons of Universal Mine and previous vibration-propagation data

Data group	F1 test	F2 test
Universal Mine shots:		
1-3.....	Failed.....	Failed.
6-7.....	...do.....	Passed.
1-3 and 6-7.....	...do.....	Borderline fail.
Single-charge shots 4-5[1].....	Passed.....	NAp.

NAp Not applicable.

[1]Data from single-charge shots 4 and 5 can be statistically pooled with previous Bureau data (3); other shots cannot be pooled.

In the F2 test, only the pooled data from shots 6 and 7 passed, probably because most of the points fell within one standard deviation of the previous Bureau data (3). When Universal shots 6 and 7 are pooled with 1, 2, and 3, enough data points fall outside one standard deviation of the Bureau data that they borderline fail as a group. Nevertheless, all the production shots fall on the high side of the data range.

Figures 24 to 26 compare the individual production and single-hole shots with the previous results (3). The single-charge shot measurements were mostly within 1 standard deviation of the historical surface coal data. Production shots 6 and 7 were within one standard deviation except at a scaled distance of greater than 300 ft/lb$^{1/2}$ where they become higher than the historical data. The production shots 1, 2, and 3, were mostly outside one standard deviation. The north end of the pit produced the highest vibration level for multidelay shots with possible causes being the effects of shot geometry (discussed later) and/or differences in actual ground structure.

A difference of vibration amplitudes was noted for the two array directions. Higher vibration levels were recorded with the east-west array from production shots 1, 2, and 3 than with the north-south array from production shots 6 and 7. In figure 23, the vibration amplitudes are plotted versus scaled distance for comparison purposes. Although shots 6 and 7 consisted of more shot holes, which were 30 ft deeper and contained more pounds of explosives, the higher vibration levels resulting from shots 1, 2, and 3 are probably a result of the acute angle between the array and the firing orientation of the shots. The array to the west was at an angle of only 28° with respect to the firing orientation of shots 1, 2, and 3, while the array to the north was at an angle of 98° to shots 6 and 7 (figs. 2-4). A similar increase in vibration amplitudes with decreasing angle between the instrument array and firing orientation was previously observed by Kopp (9) and Wiss (8). They reported that the lowest vibration amplitudes are observed in the opposite direction of initiation (180°), and the greatest amplitudes (two to six times larger) are observed in the direction of initiation (0°). Amplitudes from shots 1, 2, and 3 are more than 1-1/2 times larger than those from shots 6 and 7.

Comparisons Between Blast Designs

The vibration levels from the four echelon designs and blast casting are plotted in figures 27 and 28. These figures also show the regression line and standard deviation representing surface coal data from the Bureau report (3). All five of the Universal Mine production blast designs yielded higher vibrations than would be expected based on the Bureau results. The lowest vibrations were from the 17- by 42-ms echelon and casting designs. More data would be needed to verify the 17- by 42-ms echelon with only 11 data points. It is worth noting that the 17- by 42-ms echelon and blast casting designs used full explosive columns,

and the other echelon blasts used two to four decks (charges) per hole. The complex multideck shots are associated with the highest vibration levels. However, it is not known if this is caused by the number of closely spaced delays or by some other factor of decking such as insufficient lower deck relief.

Causes of High-Vibration Levels

The propagation plots reveal the influences of blast design and propagation media on vibrations.

Blast Design as Source Function for Vibration Generation

Comparisons between the single-hole blasts and the production blasts at the same charge weight per delay strongly suggest that the >8-ms-delay separation method for computing charge weights per delay is failing at this site. In other words, the vibrations as measured were not excessive compared with damage levels, but they were high in comparison to their scaled distances. Two results support this supposition:

1. The single-charge shots agree with the summary data from previous research on surface coal mine blasting and can be statistically pooled with them. By contrast, the five production shots studied were higher by factors of 2 for shots 6 and 7, and 3.3 for shots 1 to 3.
2. The relatively simple full-column shots produce less vibration for a given scaled distance than the multidecked shots.

Note that scaled distances are based on charge weights per delay for delay separations exceeding 8 ms. This long-accepted criterion is based on research by Duvall published in 1963 (1). Some blasters violate this rule if the charges are spatially separated. However, this also introduces geometric factors such as the propagation time across the array and the apparent or observed timing, which is location-specific.

More recent research by Wiss (8) specifically examined area surface coal mines with softer rock and larger holes and blasts than Duvall's research in a limestone aggregate quarry. Wiss recommended 17-ms separation for defining charge weights per delay for this type of blasting. Because the mechanism for preventing individual charge vibration interactions is destructive wave interaction rather than wave packet energy separation, it is expected to be related to vibration frequency. Hence, what works at high frequency in hard massive limestone (Duvall) may not at lower frequencies typical of coal mine overburden (Wiss) nor at Blanford with its very low-frequency (4-10 Hz) blast vibration. Table 4 lists the number of charges for various Universal Mine production blast designs going off within three different time intervals, including 60 ms, which would place the two 8-Hz waves 180° out of phase.

Recalling the vibration amplitude differences between the single charges and production shots of 2.0 to 3.3 times, and the square-root charge-weight factor for scaling, this is consistent with 4 to 10 charges interacting or with charge weights per delay of 4 to 10 times higher than expected. With this adjustment, the data from the Universal Mine are consistent in vibartion amplitudes with other mines studied by the Bureau.

TABLE 4. - Analysis of charge weights for production blasts

(Maximum number of charges per time interval)

Design type and delays, ms	8 ms	17 ms	60 ms
Echelon:			
17 by 42.....	2	3	7
17 by 100.....	2	3	9
17 by 200.....	2	3	7
Casting:			
Short array.....	1	2	5
Long array.....	3	6	13

Low Attenuation of Vibration

The low values for the propagation equation slopes represent low attenuations of blast vibrations at Blanford (figs. 23-26). This is true for the single hole and the production shots, strongly suggesting that this factor is not related to blast design and, in particular, not to interactions between charges. The reasons for this are somewhat conjectural. The low attenuation and the generation of strong dominant surface waves hint at geologic and/or structural influences, trapping energy near the surface or favoring the generation of large-amplitude surface waves. These surface waves normally do attenuate less with distance than do body waves usually experienced.

FREQUENCY CHARACTERISTICS OF VIBRATION

General Types

Man of the blasting vibrations measured at Blanford are characterized as having very prominent low frequencies following the initial arrivals by about 1 s. These appear very much like surface waves with clear sinusoidal vibrations having frequencies of 3 to 4 Hz. Total vibration durations exceed 3 s in many cases. The prominent low frequencies and the extended vibration durations are untypical of the many blasting vibrations measured elsewhere in Indiana and other States in previous studies by the Bureau of Mines (3, 6-7).

Two basic surface waves exist:

1. Rayleigh waves are vertically polarized with retrograde elliptical particle motions. They should have significant motion in the longitudinal and vertical directions, and little in the transverse. The generation of these waves requires only a single free surface (the ground-air interface or any sharp acoustic contrasting layer at depth).

2. Love waves are horizontally polarized shear waves. They should be strong only in transverse. Generation of Love waves require a layer with top and bottom boundaries having good reflecting properties. Extensive underground voids could provide such a reflecting surface, as could any low-velocity layer.

To facilitate comparisons between shots and sites, vibration records were characterized by type according to the amounts of low-frequency (3-5 Hz) present in the three components of motion:

Type A. - All components have significant, clear and/or dominant low frequency of about 4 Hz.

Type B. - Only transverse components have clear and prominent low frequency.

Type C. - Longitudinal and vertical components have prominent low frequency. Transverse has only high frequency (>10 Hz) or is complex in form.

Type D. - Only vertical components have clear and prominent low frequency.

Figures 29 through 32 show examples of the above types of vibrations for a single production shot on January 25, 1985, measured at four sites. These are typical of the 522 company and State vibration records analyzed although some appeared intermediate in type and not as clear. Furthermore, the relationship among the four types is also not clear. It is likely that a type D develops into type C and then type A as the wave propagates farther along in a medium favorable for its development. Type B could also be an "early A" or the local effect of a strong subsurface reflector.

For comparison purposes, all shots for which time histories were available were analyzed for amounts of very low frequency (VLF). Table 5 lists the available comparisons that have been expanded from the earlier reports prepared for OSM (1-2). All the original vibration data used for the analyses in table 5 are from the DNR and the Peabody Coal Co. Most of

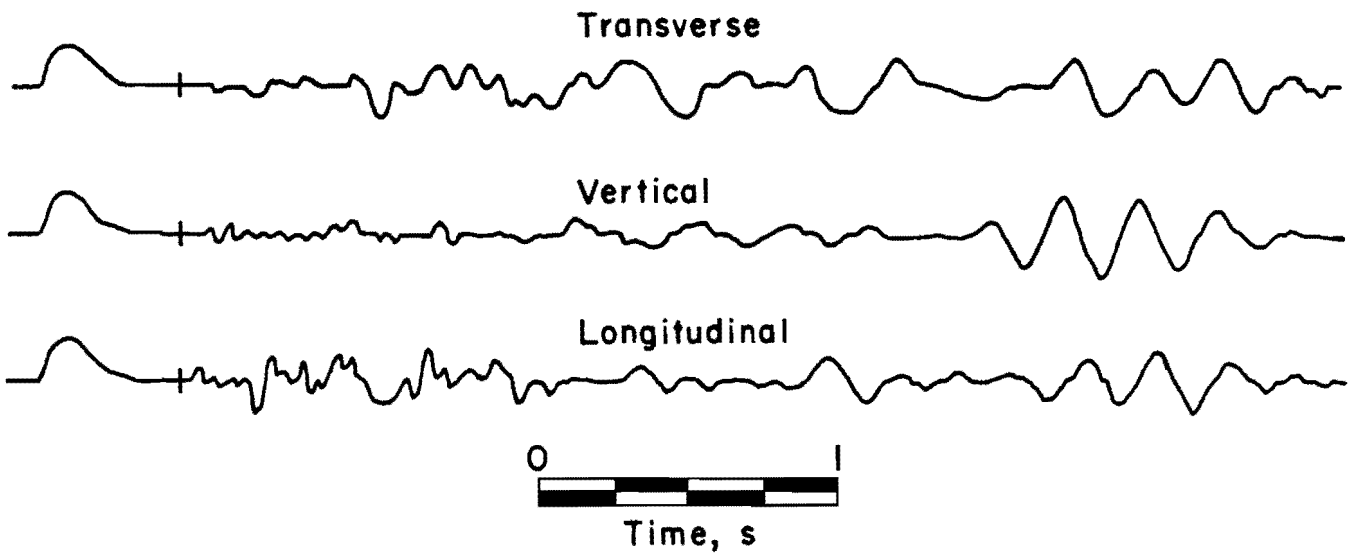


FIGURE 29.—Ground vibration record, type A, low frequency on all three components.

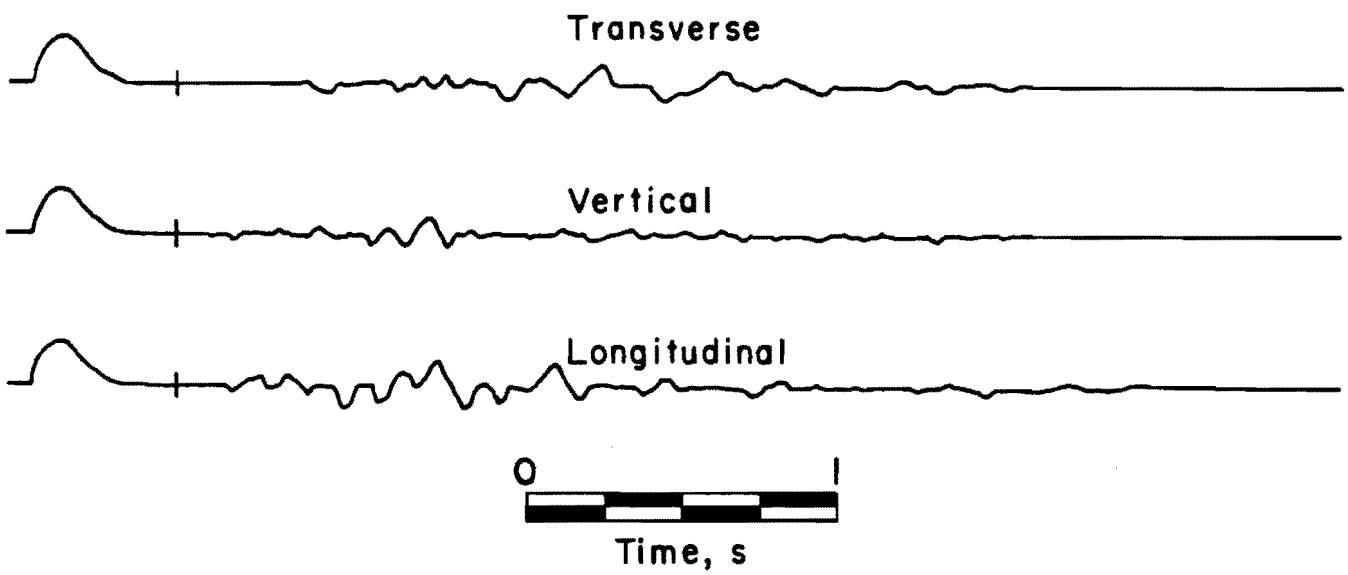


FIGURE 30.—Ground vibration record, type B, low frequency on transverse component.

the shots were blast casting where many of the subject homes had been monitored simultaneously. The few echelon shots that provided good comparisons suggest that blast designs do influence vibration character as measured at the homes.

Impacts of Low-Frequency Vibrations

Comparisons of Blanford site amplitudes and frequencies with Bureau of Mines blasting vibration criteria (3, appendix B) show that many values are near the frequency realm where displacement rather than velocity limiting is appropriate (3). Although none of the vibration amplitudes exceed the Bureau's criteria, they are close to the inflection point where frequency becomes critical and where displacements must be limited to insure that excessive structural strains are not produced (3). These waves will

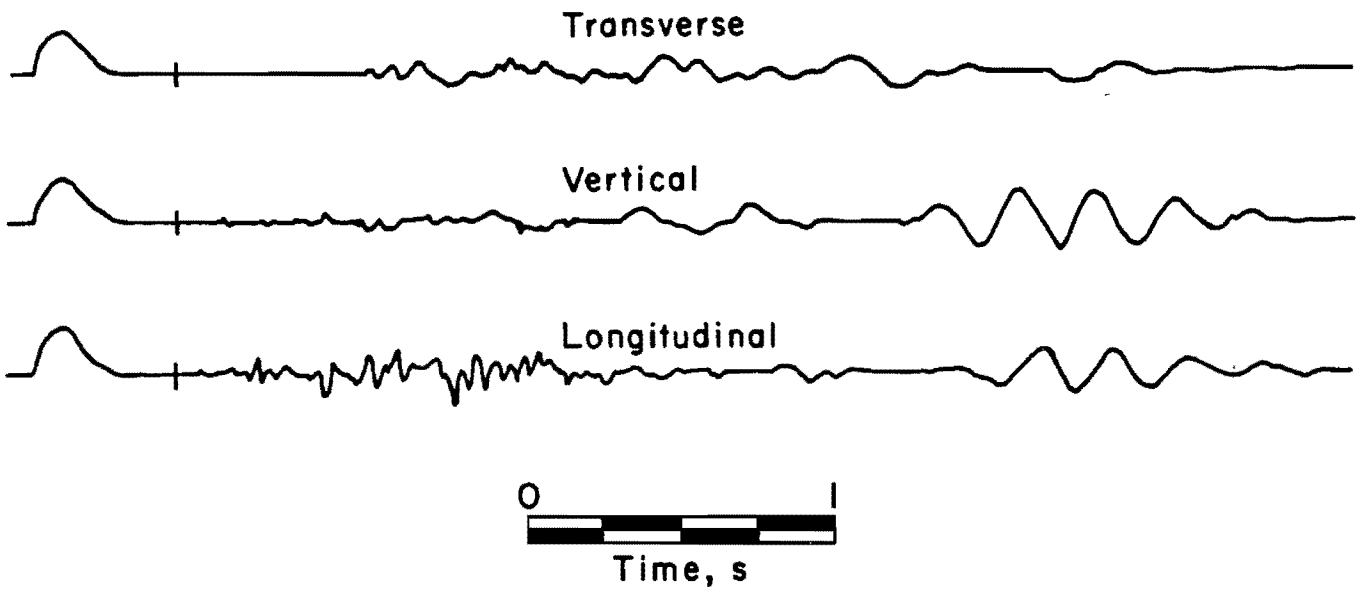


FIGURE 31.—Ground vibration record, type C, low frequency on vertical and longitudinal, components.

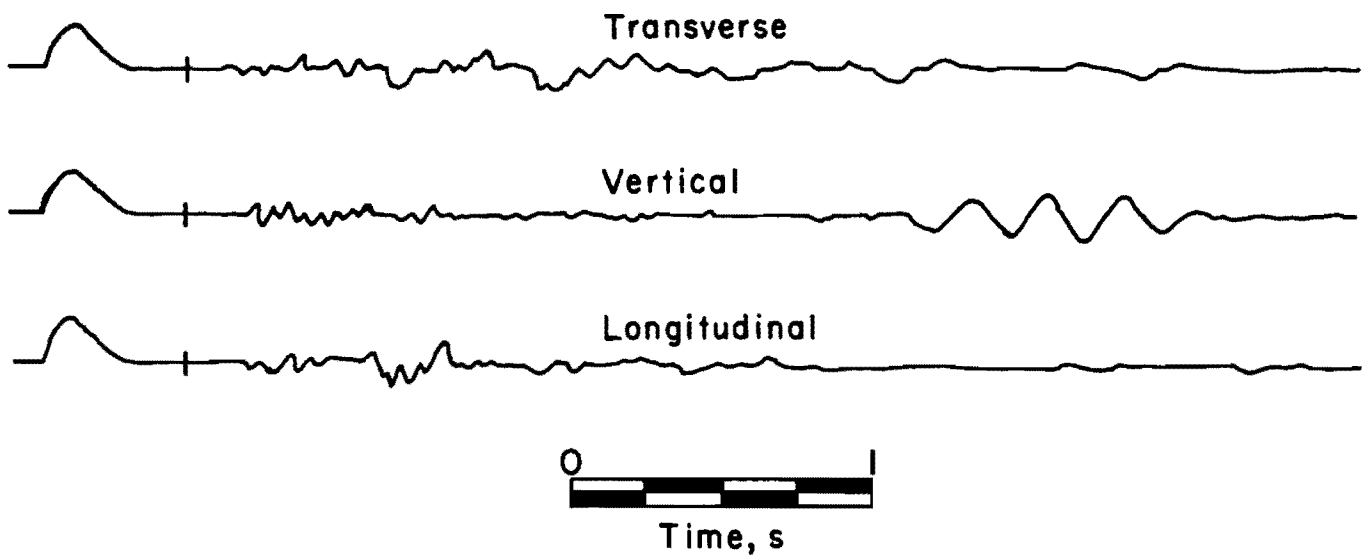


FIGURE 32.—Ground vibration record, type D, low frequency on vertical component.

produce significant vibration structural response, and, combined with their long duration, they are likely to produce significant psychological reactions from those affected. Low-rise structures are particularly responsive to frequencies in the range of 4 to 12 Hz. Because of significant levels of displacement and strain, frequencies below 4 Hz are even more undesirable (3). Note that the OSM regulations reflect, but are somewhat higher (less restrictive) than those identified in the Bureau's field investigations. It is worth noting that none of the Blanford vibration levels observed in this study were high enough to produce a significant probability of structural damage based on known practice and experience.

TABLE 5. - Shot and site comparisons of vibration characteristics at residences monitored

Date	Massa	Volk	Hollings-worth	Zell	Polomski	Jackson	Verhonik
ECHELON BLASTS, 17 ms BETWEEN HOLES IN A ROW							
42 ms between rows:							
12-18-84.....		HF					
12-19-84.....		~C					
12-22-84.....						HF	
12-28-84.....		~D				HF	
12-31-84.....							
1- 4-85.....		~D				HF	
1- 9-85.....		~C				HF	
100 ms between rows:							
3- 2-85.....						HF	
3- 2-85.....						HF	
3- 2-85.....	HF				HF	HF	
3-14-85.....						~8 Hz	
3-16-85.....						~8 Hz	
3-18-85.....						HF	
3-21-85.....						HF	
3-25-85.....						HF	
3-26-85.....						HF	
9-10-86.....	HF				HF	~10 Hz	
9-10-86.....	8 Hz				HF	~10 Hz	
9-10-86.....	HF				~5 Hz	~14 Hz	
9-12-86.....					HF	~9 Hz	
9-13-86.....	HF						
200 ms between rows:							
7- 2-84.....						B	
7- 3-84.....						B	
7- 6-84.....						~A	
7- 7-84.....						A	
7- 7-84.....						A	
7-11-84.....						B	
7-11-84.....						B	
7-11-84.....						B	
7-13-84.....						~B	
7-14-84.....						~B	
7-28-84.....						A or C	
1- 5-85.....		HF					
1-12-85.....		C					
3- 5-85.....						HF	
3- 6-85.....	HF				~A	HF	
3- 7-85.....						HF	
3- 9-85.....						HF	

See explanatory notes at end of table.

TABLE 5. - Shot and site comparisons of vibration characteristics at residences monitored--Continued

Date	Massa	Volk	Hollings-worth	Zell	Polomski	Jackson	Verhonik
CASTING BLASTS							
200 ms between rows:							
8- 9-84.....				A			
8-13-84.....				B, A			
10-30-84.....						D	
11- 5-84.....						~D	
11- 7-84.....						C	B
11-10-84.....	A					C or A	B
11-15-84.....	A						B
11-17-84.....	A					C	
11-19-84.....	A					C or A	B
11-23-84.....		A				C	
11-24-84.....						C	
11-26-84.....						C	
12- 1-84.....	~A	A	A				
12- 4-84.....		A					
12- 6-84.....	C or A	C	A				B
12- 8-84.....							B
12-10-84.....	~A	~B	A				B[1]
12-12-84.....		~A	A				B[1]
12-15-84.....		~D					B[1]
12-17-84.....		~A	A				
1-12-85.....		~C					B
1-14-85.....			A			C or D	B
1-17-85.....	A	C	A				~B
1-21-85.....		A	A				B
1-25-85.....	A	A or C	A			D	B
1-28-85.....	A	A	A			~D	B
1-31-85.....	A	~C	C			D or C	B
2- 2-85.....	A	A	A		A		B
2- 6-85.....		A	A		A	D	B
2- 9-85.....		A	D		A	D	B
2-14-85.....		~A			~A		~B[1]
2-16-85.....	A or C	~A					~B[1]
2-19-85.....	C	A			A or C		~B[1]
2-21-85.....	C				C	C	
3- 1-85.....						HF	

A All components had very low frequencies of about 4 Hz.
B Only transverse comonent had very low frequencies of about 4 Hz.
C Longitudinal and vertical components had very low frequencies of about 4 Hz.
D Only vertical component had very low frequencies of about 4 Hz.
HF Higher frequency, no clear components below about 10 Hz.
[1]Vertical component appeared to be defective; may have been A type.

NOTE.--No entry means no records available.

Comparisons Between Casting Blasts

These are obtained by reading vertically in table 5. Seven sites had usable shot comparison data:

Volk. - Most records are type A, but some of the more distant measurements are type C. No clear distance correlation exists. The transverse component is very small in most type C events and varies greatly in frequency and amplitude.

Polomski. - This house is next to the Volk house. Again, most records are type A. However, the type C cases are the closer-in shots. The two type C's are somewhat unclear, and could be irregular type A's.

Hollingsworth. - All are type A except the closest shot, which has only a clear low-frequency vertical, or type D characteristic. This house is farther from the blasting than are the Volk and Polomski houses, but it is in the same part of town (fig. 2).

Massa. - Most are type A. The two closest are type C, but some of the type A's are borderline type C's. Several were too small in amplitude to analyze reliably.

Zell. - The Zell house is within 100 ft of Massa's and would be expected to have similar vibrations. Unfortunately, none of the blasts were monitored simultaneously at the two houses. The two shots measured at Zell's are type B, although the May 15 blast has some emerging low frequency in the longitudinal component.

Jackson. - These records were mixed, two C's and two D's. The two type D's were farther; however, the whole distance range was not wide, being 4,859 to 6,371 ft.

Verhonik. - Virtually all were type B. Some have a little low frequency in the longitudinal components, as was the case at the Zell house. The Verhonik house was not located near any of the others, but is east of the mine.

Concluding this comparison, there does not appear to be much change at a given site from shot-to-shot for these mostly casting blasts. This is despite the varying shot locations on the highwall, which produced different vibration travel paths. Each site is mainly self-consistent except for a possible distance effect that is not clear from the currently available data.

Comparisons Between Blast Designs

Many of the seismograph records collected by Peabody and the DNR were not processed for time histories. From the records that were made available as time histories, a summary analysis suggests that the echelon blasts, particularly those with shorter between-row times, produce less of the more serious low frequencies below 5 Hz (table 5). The influences of blast designs on vibration frequency were examined by specific Bureau tests, which will be discussed in the section on delay sequencing.

Comparisons Between Sites

Vibration types measured at various homes can be compared by reading horizontally in table 5. Distance from the blast appears to be a possible factor. Site differences do appear real because of their consistency; however, variations between shots do not. Neighbors had similar vibrations of similar character where comparisons were possible. Only the Zell and Verhonik measurements indicated type B vibrations (Love waves?). More measurements at Zell's would have provided additional comparisons, including similarities and differences with his neighbor, Massa.

Delay Sequence and Vibration Frequency

The four basic blast designs at the Universal Mine were discussed previously, three being echelons with different between-row delays and blast casting (table 1). It has been long suspected, and recent research is suggesting, that blast delays may influence the frequency of the generated vibrations (4-5). Still unclear are the influences of the propagation medium when it is structurally complex and dispersive (has frequency-dependent attenuation separating low and high frequencies at large distances). Most surface coal mines represent complex

situations with soil top layers, beds of soft rock of varying thicknesses and properties, and lenses or areas of non-rock, such as sand, alluvium, and lacustrine deposits. These low-strength, low-velocity materials strongly influence seismic waves, attenuating high frequencies and enhancing low ones.

Production Blasting, July 1984 to April 1985

Time sequence examples of the four types of blasts are shown in figures 33-37. All calculations are based on nominal or designed initiation times. Included are initiation system travel times down the holes and between holes and rows based on Nonel as-labeled and Hercudet at 8,000 ft/s. Burdens, spacings, designed delay sequences, and depths are from Peabody's blasting logs. Not included are the geometric effects of the observer's location relative to the orientation of the shot pattern.

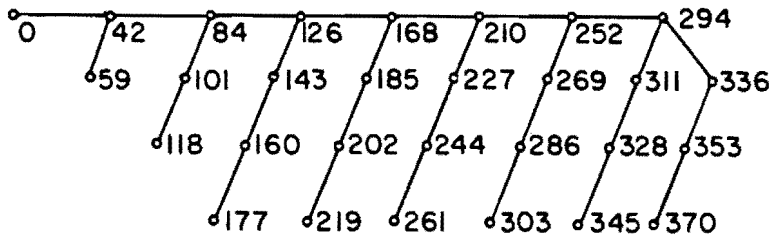
The shot layout is not a point source, and the wave propagation velocity is not infinite. Therefore, true separation times between charges at different distances would require slight adjustments for propagation times across the array and amounting to a few milliseconds (e.g., 3 ms for two charges with a 30-ft distance difference and a propagation velocity of 10,000 ft/s). Because of this effect, shots that have two or more individually delayed charges that fire at nearly the same time may not appear to do so to observers at certain locations. Conversely, other time separations may be shortened because of this doppler-shift effect.

1. Echelon blast, 17 by 42 ms. - Figure 33 shows the time sequence by rows, which overlap in time. No serious low-frequency periodicities exist, and energy flow is very uniform. The time history corresponding to this particular blast is typical of the 10 available for this blast design. It is dominated by an irregular-shaped wave pattern of 125-ms periodicity (8 Hz). None of the shots had significant amounts of VLF.

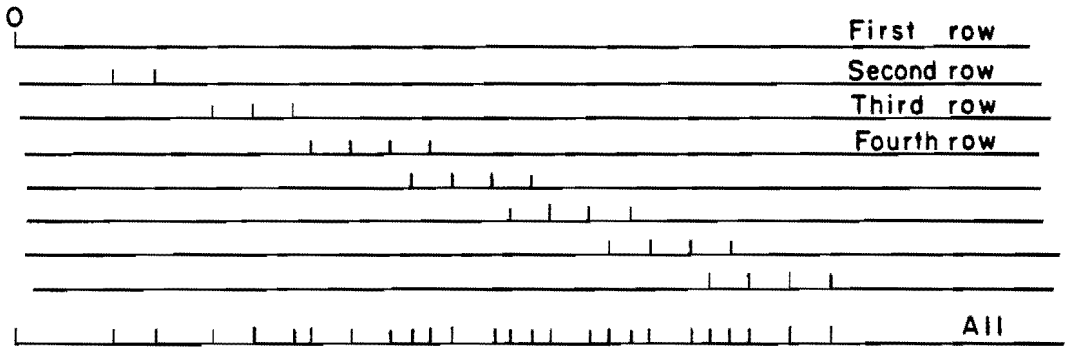
2. Echelon blast, 17 by 100 ms. - Echelon blasts using the pattern shown in figure 34 had two to four decks and a very uniform energy flow like the 17 by 42 pattern. The 100-ms between-row periodicity (10 Hz) is close to the apparent ground natural frequency as shown by the single hole blasts discussed in the next section. All vibration records were either similar to the Jackson example shown (7 to 10 Hz) or of higher frequency. Only the Volk house had any significant VLF (table 5). The duration of the vibration record is longer than the record from the 17 by 42 ms echelon blast. This is consistent with, and resulting at least in part from, the over two times longer duration of the blast initiation sequence: 1,010 ms (for the echelon with 100 ms between rows) and 370 ms (for the echelon with 42 ms between rows).

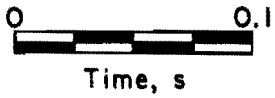
3. Echelon blast, 200 by 17 ms. - As shown in figure 35, the between-row delays are now long enough to separate the row events as isolated bursts of energy. In the case of the particular blast, these "bursts" continue for the incredibly long time of 4-1/2 s. A row periodicity of 204 ms is created by this blast design, equivalent to about 5 Hz. The vibration time histories have a clear periodicity of about 110 ms (~9 Hz), particularly the first-arriving longitudinal component. However, a large amplitude periodicity of about 5 Hz is also visible and strongest on the transverse, consistent with the row periodicity. This is a case where the blast design appears to be influencing the vibration frequency at a large distance.

4. Casting, short blasthole array. - Figure 36 shows a simple array design with a full-column charge (no decking). The time sequence is again a series of bursts at about 200-ms periodicity corresponding to the between-row delays. The vibration record has abundant dominating VLF, this one being a type A. Many of these shots produced VLF; however, they included the complete variety of types A through D, at the seven sites. Possibly, filling in the empty periods in the time sequence might prevent the on-and-off

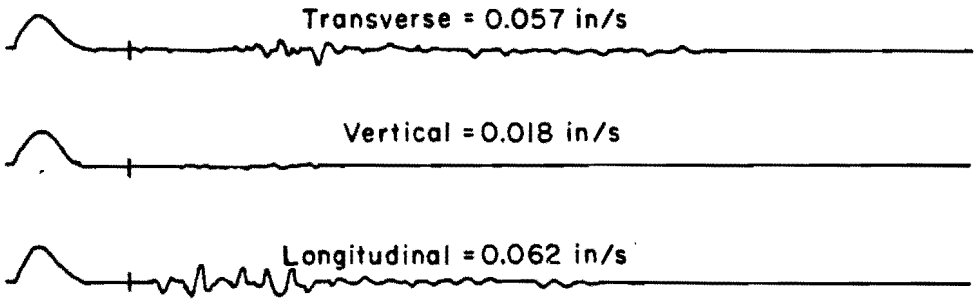


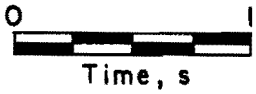
PATTERN LAYOUT, NONEL SYSTEM, TIME IN MILLISECONDS





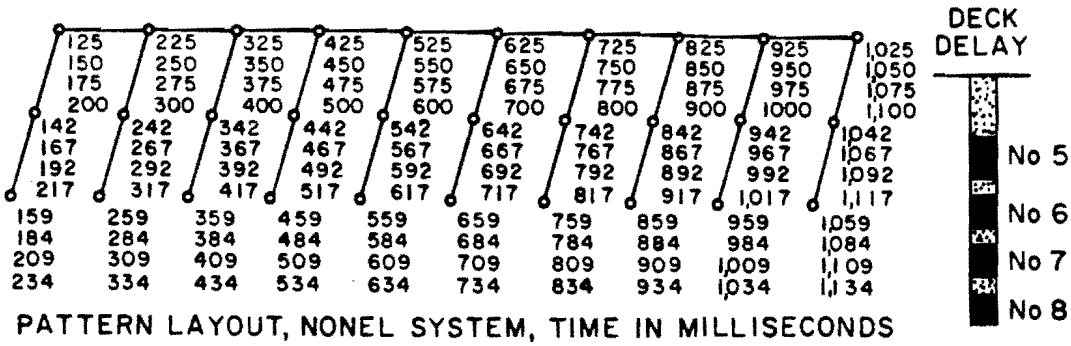
SEQUENCE OF CHARGES

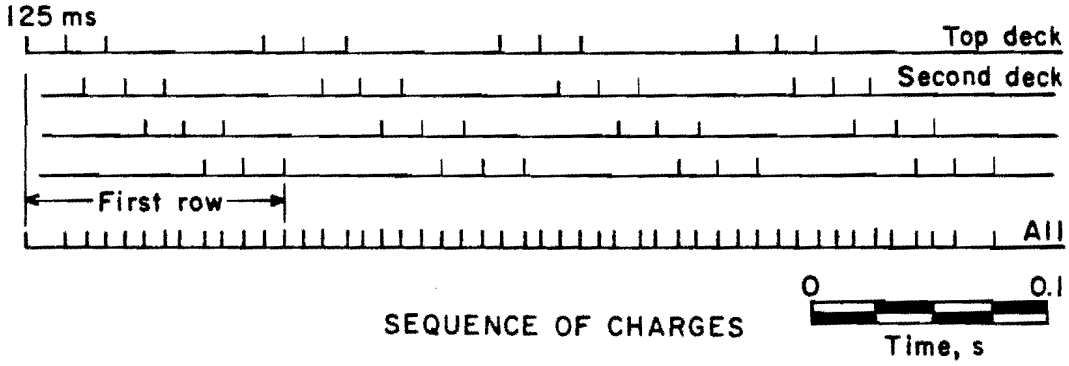




VIBRATION RECORDS, JACKSON HOUSE AT 8,510 FT

FIGURE 33.—Echelon blast, 42 ms between rows, 17 ms between holes in a row, January 9, 1985.





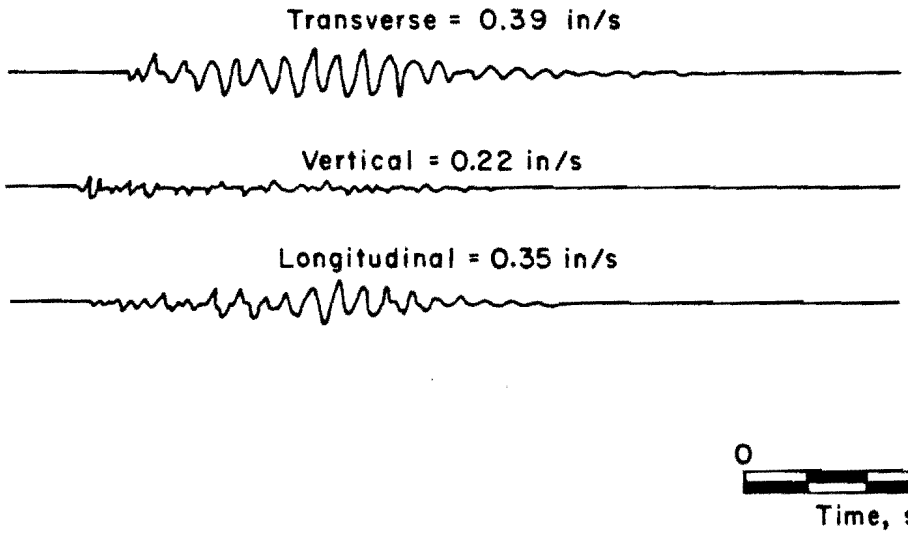


FIGURE 34.—Echelon blast, 100 ms between rows, 17 ms between holes in a row, March 14, 1985.

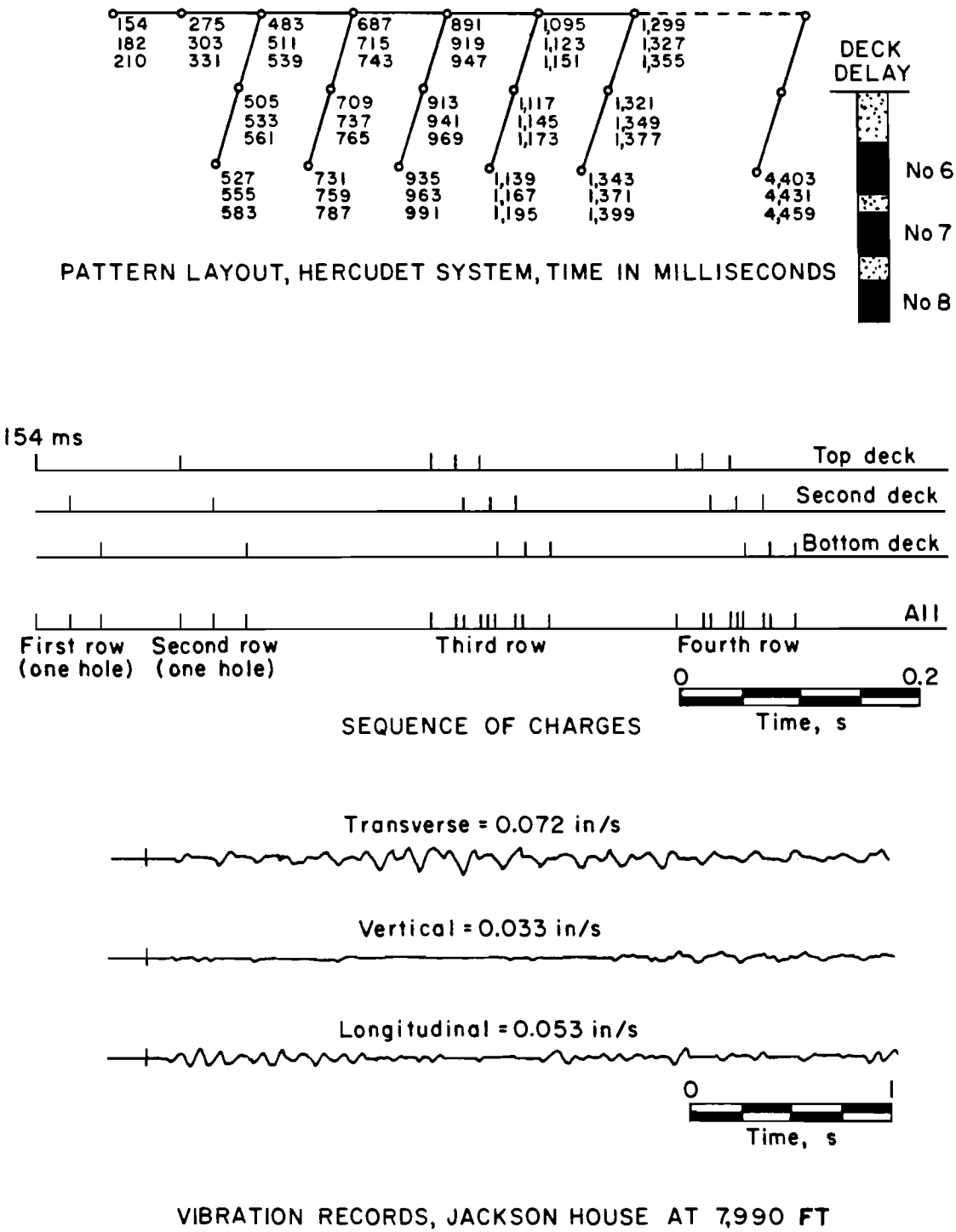
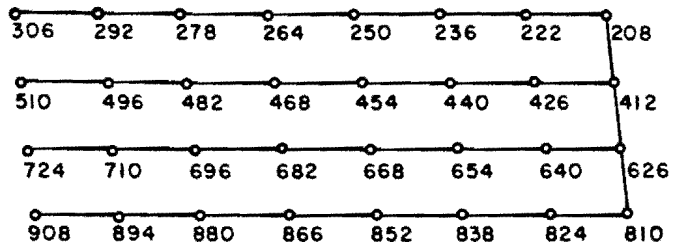
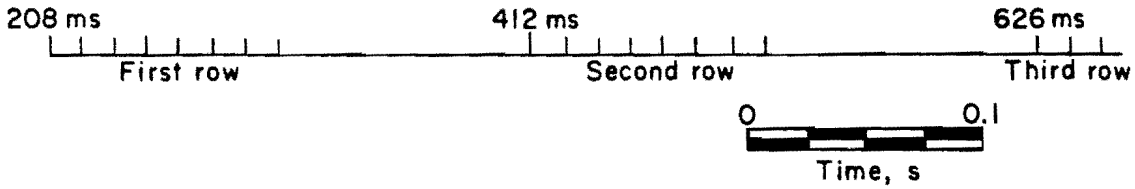


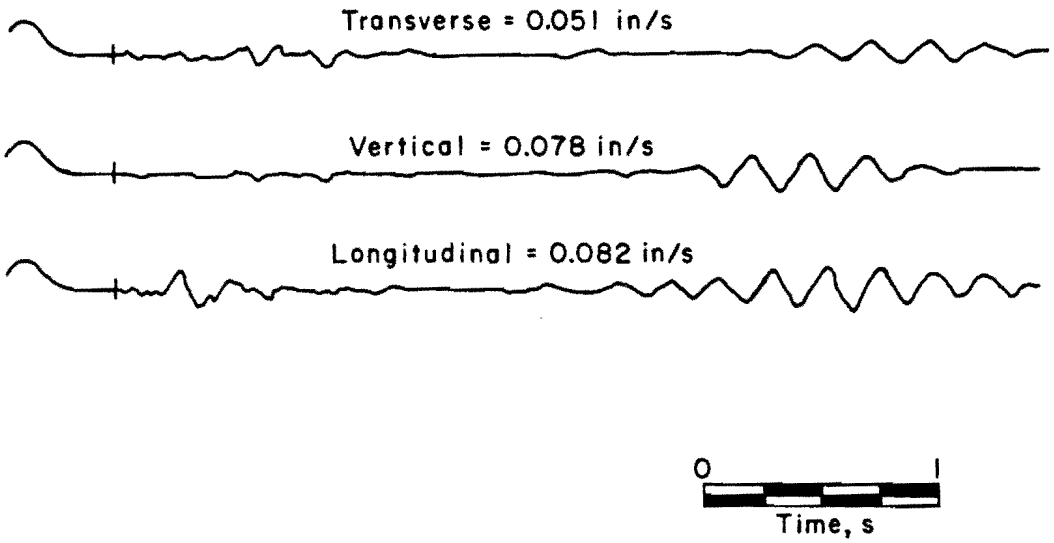
FIGURE 35.—Echelon blast, 200 ms between rows, 17 ms between holes in a row, January 12, 1985.



PATTERN LAYOUT, HERCUDET SYSTEM, TIME IN MILLISECONDS

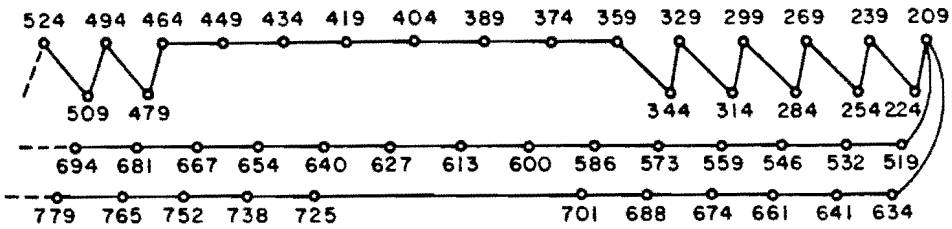


SEQUENCE OF CHARGES

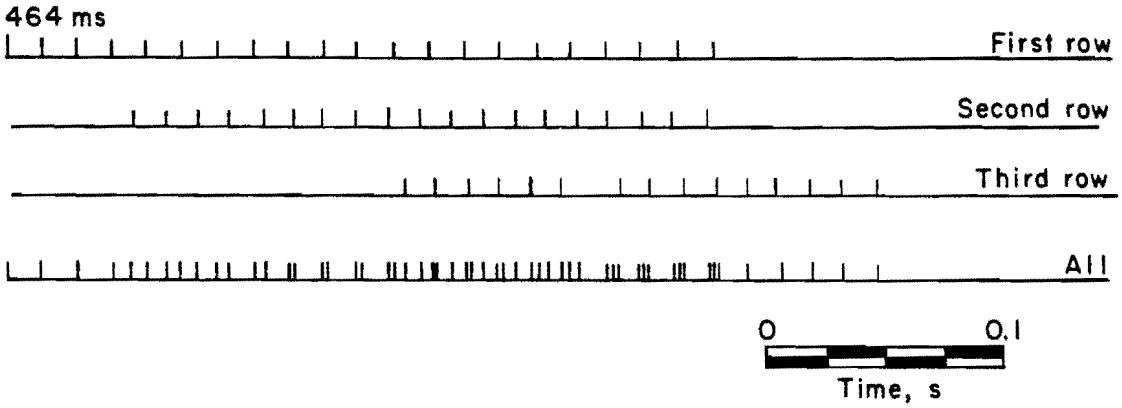


VIBRATION RECORDS, HOLLINGSWORTH HOUSE AT 7,520 FT

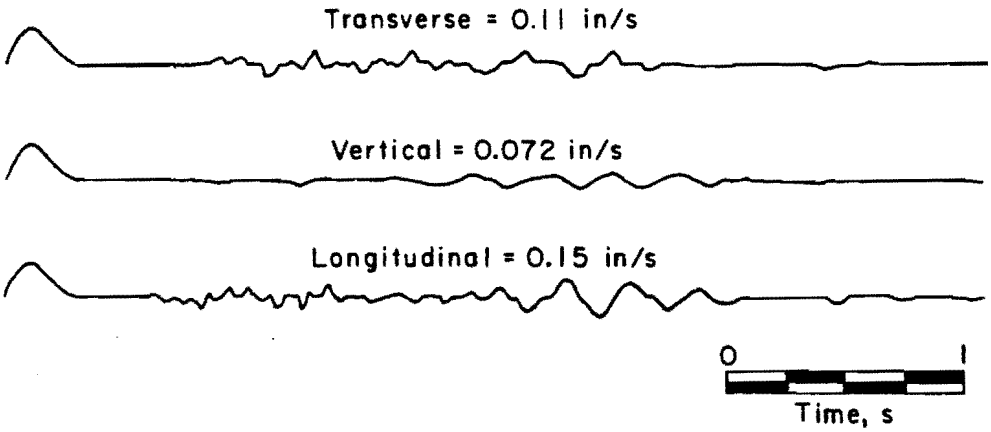
FIGURE 36.—Casting blast, 200 ms between rows, 10 ms between holes in a row, January 21, 1985.



PATTERN LAYOUT, HERCUDET SYSTEM, TIME IN MILLISECONDS



SEQUENCE OF CHARGES



VIBRATION RECORDS, MASSA HOUSE AT 4,960 FT

FIGURE 37.—Casting blast, varying delays between rows, 10 ms between holes in a row, February 16, 1985.

effect, which produces the unwanted periodicity. Fortunately, the vibration amplitudes are not high for these shots. A peak particle velocity above 0.5 in/s at these frequencies would be at the limit of the Bureau's safe-level criterion for cosmetic cracking for all residences.

5. Casting, long blasthole array. - As shown in figure 37, many of the casting blasts were more complex than the short blasthole array described previously. Some had more holes per row, which eliminated the quiet periods and, depending on the exact timing, produced a complex blast sequencing such as this one. Because of the zig-zag front row pattern used on many of the blasts, more time is allowed between this and the next row. In fact, for over half the total initiation time, only the front row holes have fired. Note that figure 37 starts with the 18th front-row hole at 464 ms. The row periodicity is not as uniform as that of the previous example (the short casting shot). This blast had 300 ms between rows 1 and 2 and 115 ms between rows 2 and 3. The measurements at the Massa house contain strong VLF, but the waveform is not nearly as clear or clean as that of the previous casting shot. Other records for this shot also had VLF; however, they were dominated by a 110-ms periodicity (9 Hz).

Bureau of Mines Measurements of Production and Single-Charge Blasts, September 1985

Vibration Characteristics. - To investigate the influence of shot design and geology on the generation and propagation of ground vibrations, two instrument arrays were set up. One array extended approximately 2,640 ft in a westerly direction from shots 1 to 5 to the Polomski house. The second array extended approximately 5,600 ft in a northerly direction from shots 6 and 7 to the Zell house. Note that shot 7 used a cluster of stations and not a true linear array. Figures 2 to 4 show the locations of the two arrays and of the seven shots. Table 1 summarizes the seven test blasts.

Production Shots. - Figures 38 to 43 show the ground vibration recordings for production shot 3 for the west instrument array and shot 6 for the north array for the longitudinal, vertical, and transverse components of motion. Ideally, the closest station should best reflect the source; i.e., the shot design, and minimize the effects of geology on the propagating waveform. Figures 44 and 45 show the blasthole patterns for shots 3 and 6, respectively. Included are the detonation times for each of the four decks per shot hole. The nearest recording for shot 3 was at 90 ft and shows that the ground motion lasted approximately 350 ms longer than the time between detonation of the first and the last hole. A similar observation was made for shot 6. The fact that the ground vibrations away from the shot last longer than the shot itself is due to the arrival of multiple reflected and refracted phases and the response of the medium to these phases.

A comparison of the nearest recordings made for each shot reveals obvious differences in the character of the two waveforms, which can be mostly attributed to the difference in the two shot designs. Shot 6 contained a sequence of delayed explosive charges lasting 1.49 s, and shot 3 lasted 1.01 s. The longer sequence of shot 6 is seen in the longer duration of recorded ground vibrations at the nearest station. The longitudinal component record for shot 6 shows that vibration amplitudes gradually increased to a maximum for several cycles and then decayed gradually. An analysis of the sequence of delays for this shot determined that at the beginning and end of the shot, only single decks were detonated, but in between, multiple decks were detonating at nearly the same time and thus generating the maximum amplitudes. The record of the longitudinal component for shot 3 shows lower vibration amplitudes in the first half and at the very end, with larger, impulsive phases in the third quarter. Although the sequence is uniform with interaction of multiple decks occurring throughout, the packet of large amplitudes roughly correlates with the detonation times for the back two rows, which are more confined than are the three front rows.

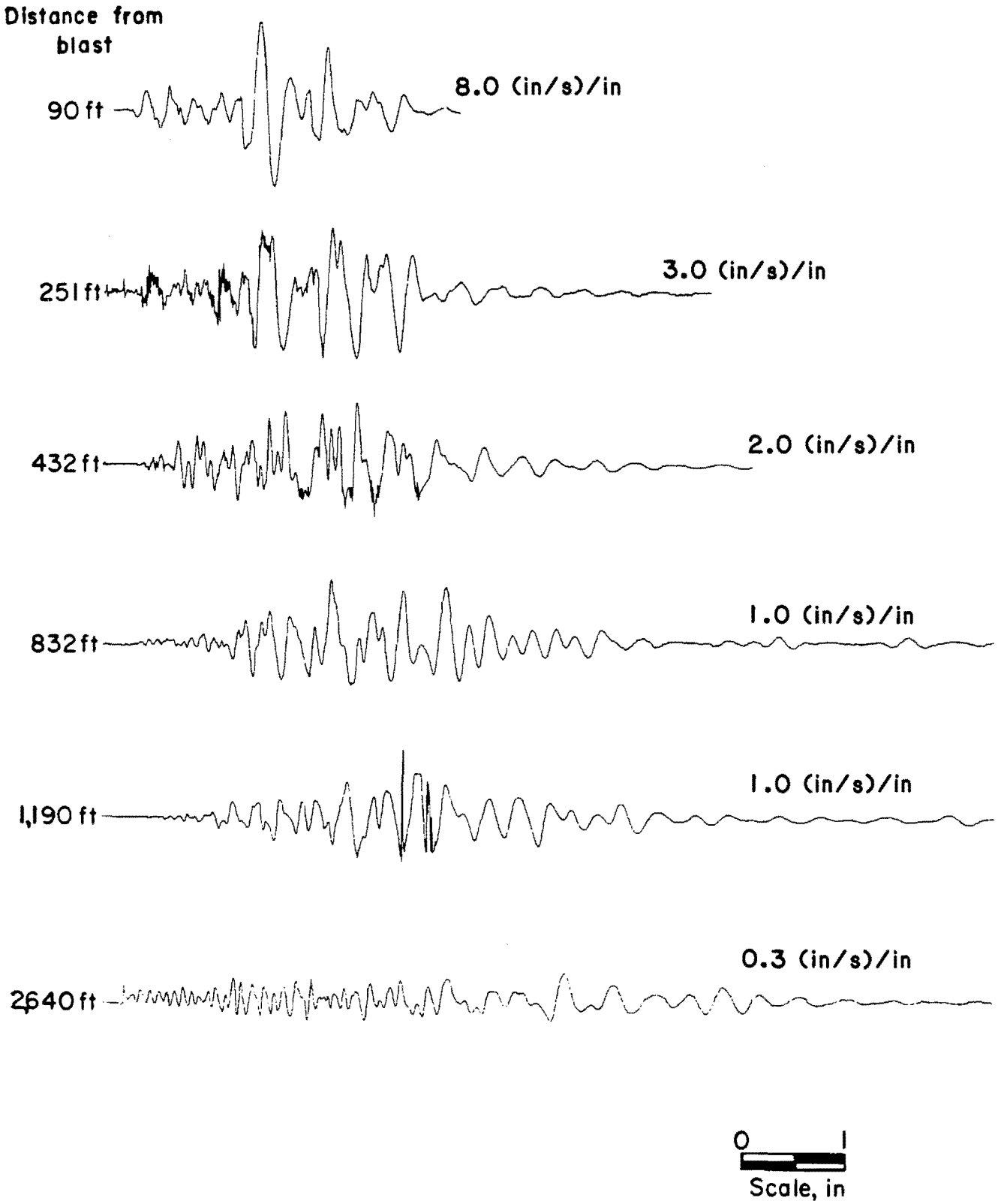


FIGURE 38.—Vibration records from west array, production blast 3, longitudinal. Horizontal scale is 500 ms/in.

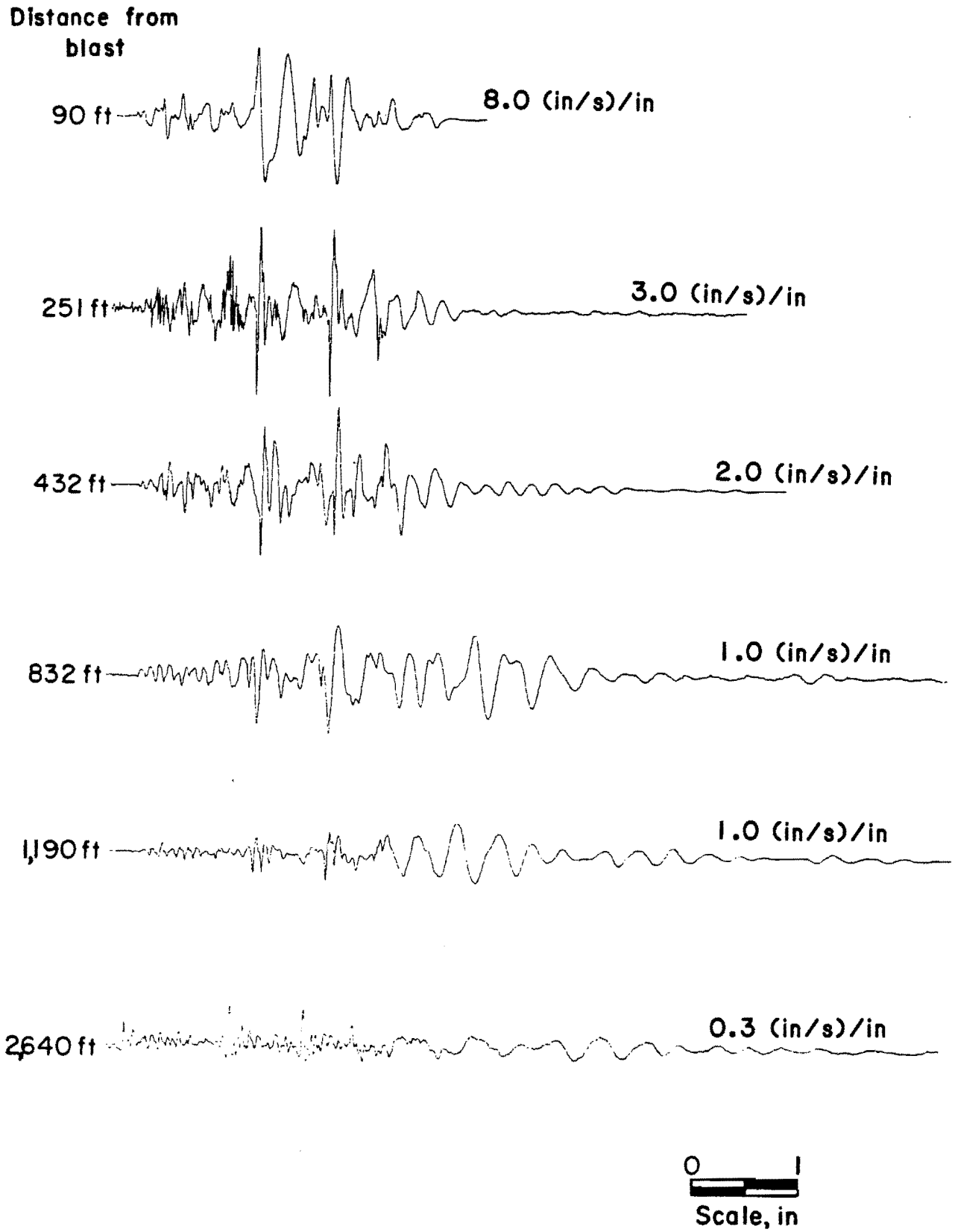


FIGURE 39.—Vibration records from west array, production blast 3, vertical. Horizontal scale is 500 ms/in.

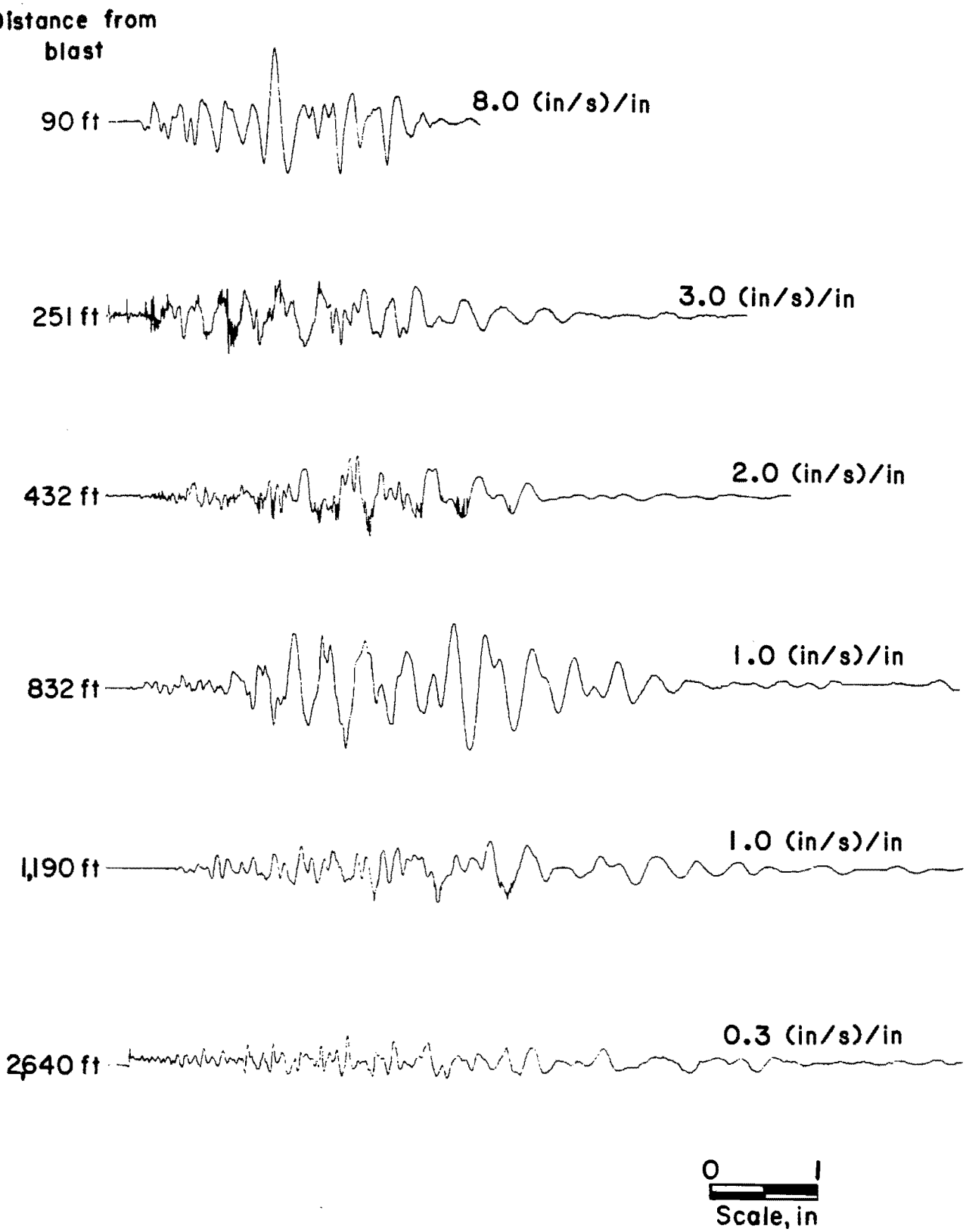


FIGURE 40.—Vibration records from west array, production blast 3, transverse. Horizontal scale is 500 ms/in.

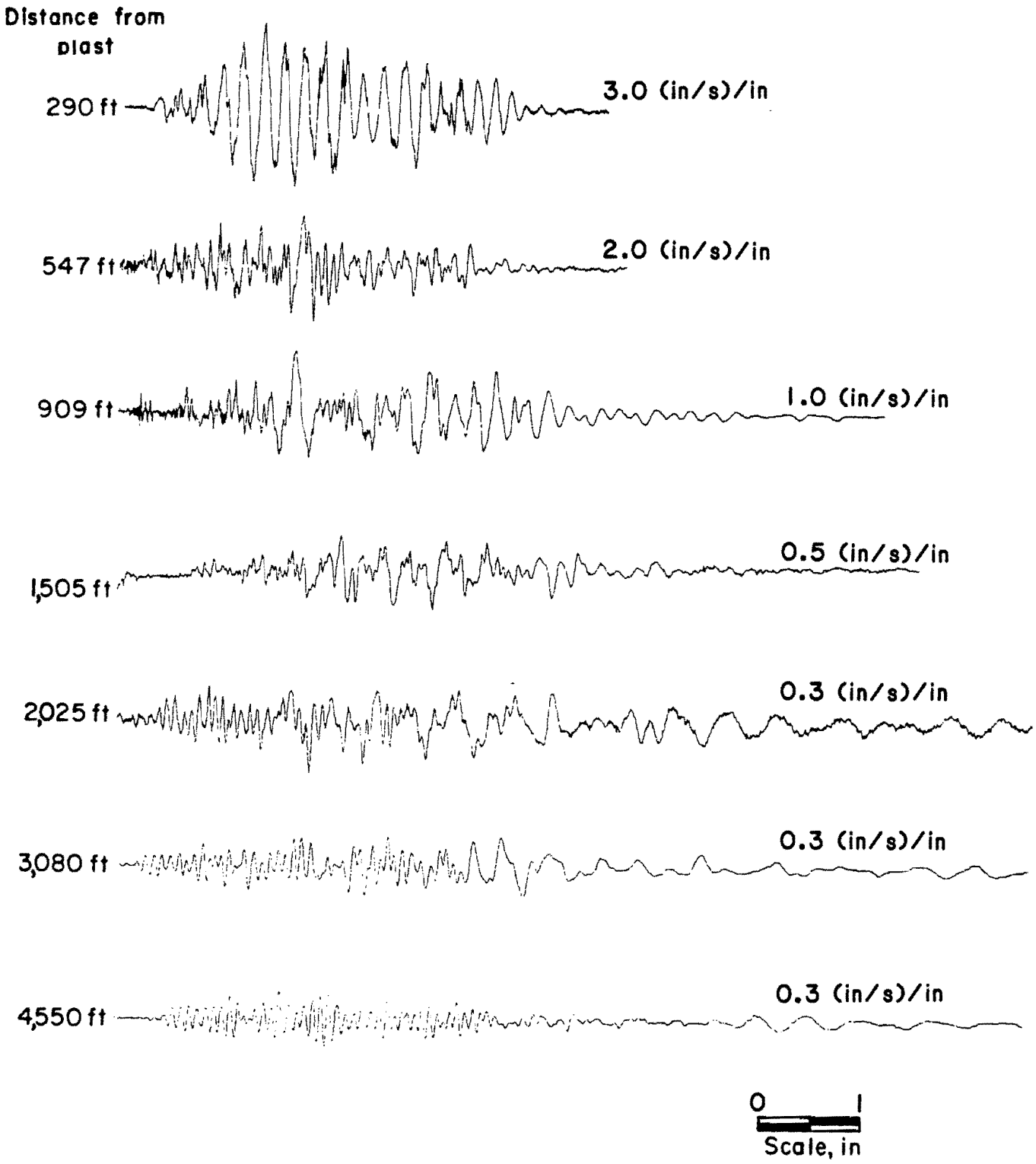


FIGURE 41.—Vibration records from north array, production blast 6, longitudinal. Horizontal scale is 500 ms/in.

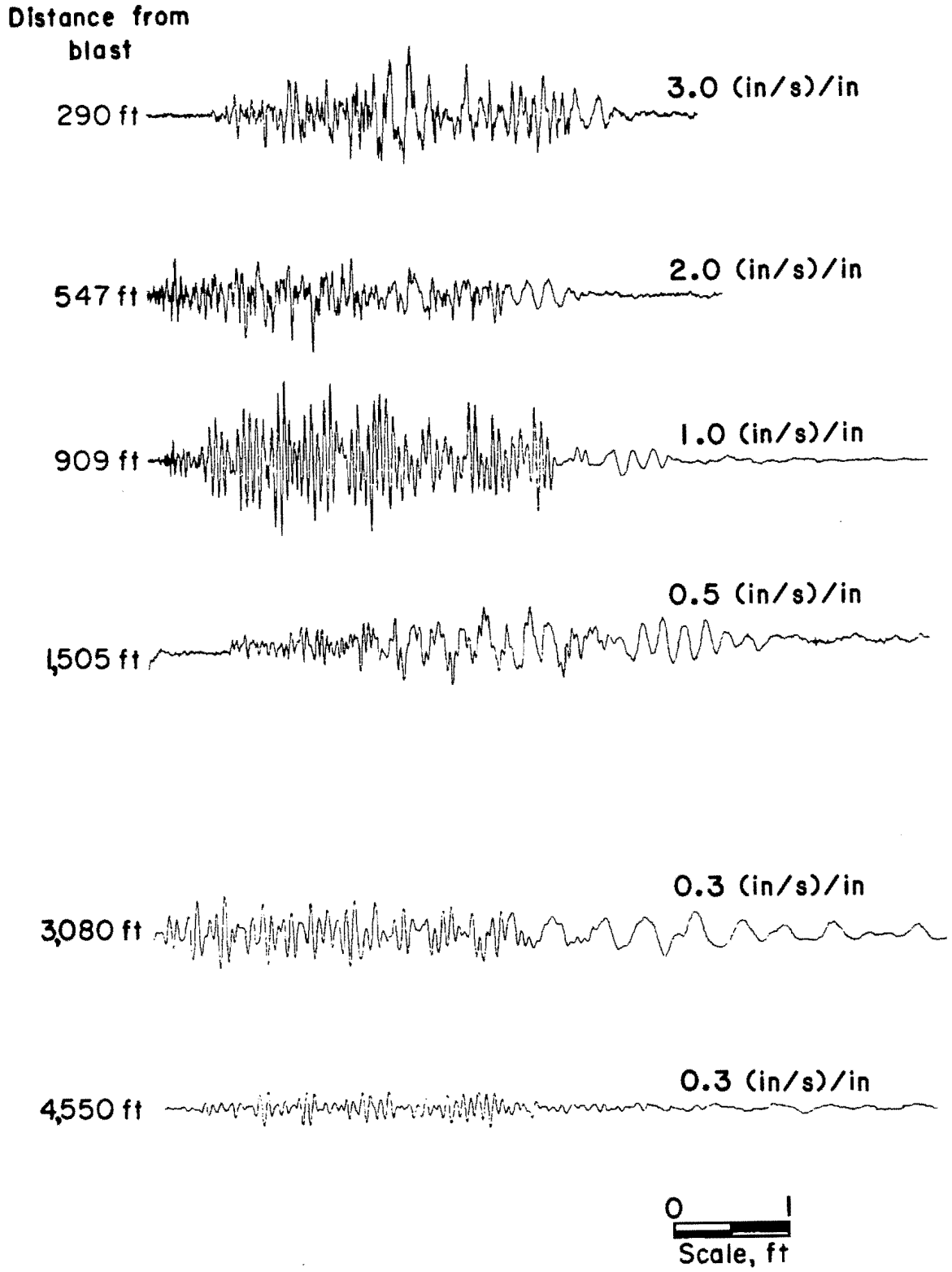


FIGURE 42.—Vibration records from north array, production blast 6, vertical. Horizontal scale is 500 ms/in.

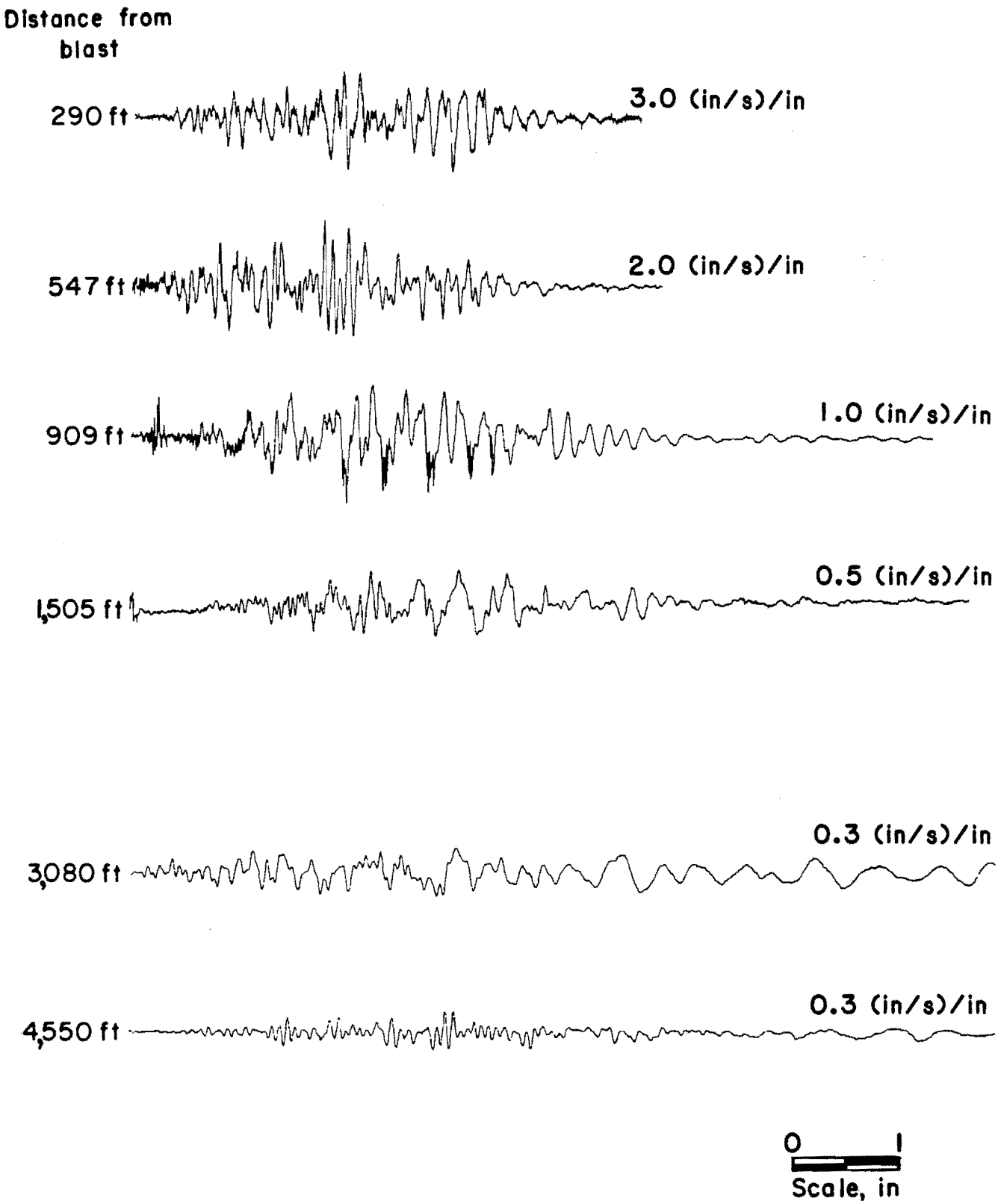


FIGURE 43.—Vibration records from north array, production blast 6, transverse. Horizontal scale is 500 ms/in.

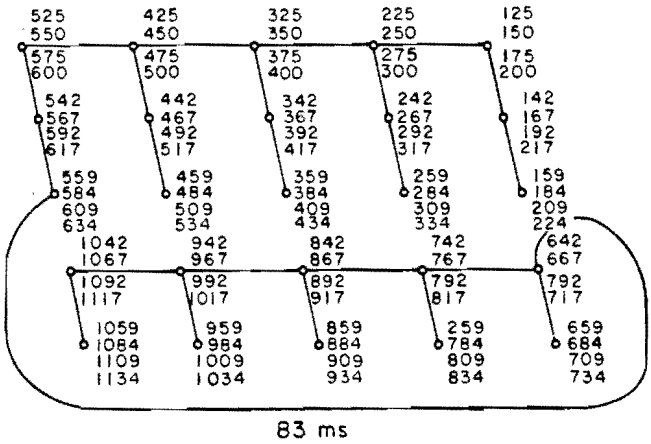


FIGURE 44.—Initiation pattern for shot 3.

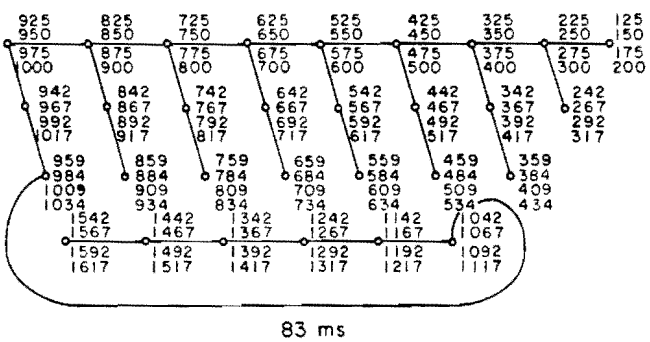


FIGURE 45.—Initiation pattern for shot 6.

Shot 6 contained only one back row, and appeared not to be an important factor in generating ground vibrations.

As mentioned previously, an analysis of shot 6 determined that it was designed to barely meet the questionable 8-ms criterion. The time delay between rows (100 ms) likely contributed to the predominant 10-Hz component observed in the recordings. Since most residential structures have a natural frequency between 4 and 12 Hz, a shot should be designed to minimize generation of frequencies within this range.

The nearest recordings tend to be strongly influenced by the shot design and less so by the geology. As the waves travel across the array, they become more complicated through the influences of the subsurface geology and disturbed travel path. Also, phases are separated in time near the shot and allow waveform characteristics to be easily discernible. However, they interfere with one another constructively and destructively at larger distances from multiple reflections, refractions, and wave modifications such as dispersion. For instance, the longitudinal component recording of a shot at 547 ft changed character considerably compared with the recording at 290 ft. Although the duration of the two are approximately the same, the shot design effects observed for the near station record have become more difficult to identify. The interference of phases has created a waveform of varied impulses and frequencies that no longer resemble the harmonic motion recorded at the near station.

The durations of the ground vibrations at the far stations are two to three times those at the near stations and are caused primarily by low-frequency surface waves. These surface waves are first noticeable near 400 ft, but they do not have large amplitudes relative to the earlier arriving, higher frequency body waves until about 1,000 ft for the westerly array (shot 3) and 2,000 ft for the northerly array (shot 6). The significance of this is not fully understood, but it is likely to have been caused by the geology (propagating medium) and possibly aggavated by shot size or delays. These surface waves are predominant at the larger distances and have frequency of 5 to 10 Hz, which are near the response frequencies of residential structures. These surface waves can produce excessive structural displacements and strains.

Single-Charge Shots. - Two single-charge shots (4 and 5) were detonated to obtain a more simplified source than a production shot consisting of a sequence of delayed explosive charges. The shots were recorded by the instrument array to the west (the same as for production shots 1-3) in order to study the effects of blast design on influencing the generation of vibrations and to observe changes in the character of vibrations as they propagate.

The ground vibrations from shot 4 were recorded as they propagated across the instrument array and are shown in figures 46 to 48. The single-hole shot consisted of 125 lb of ANFO in a 12-1/4-in-diam

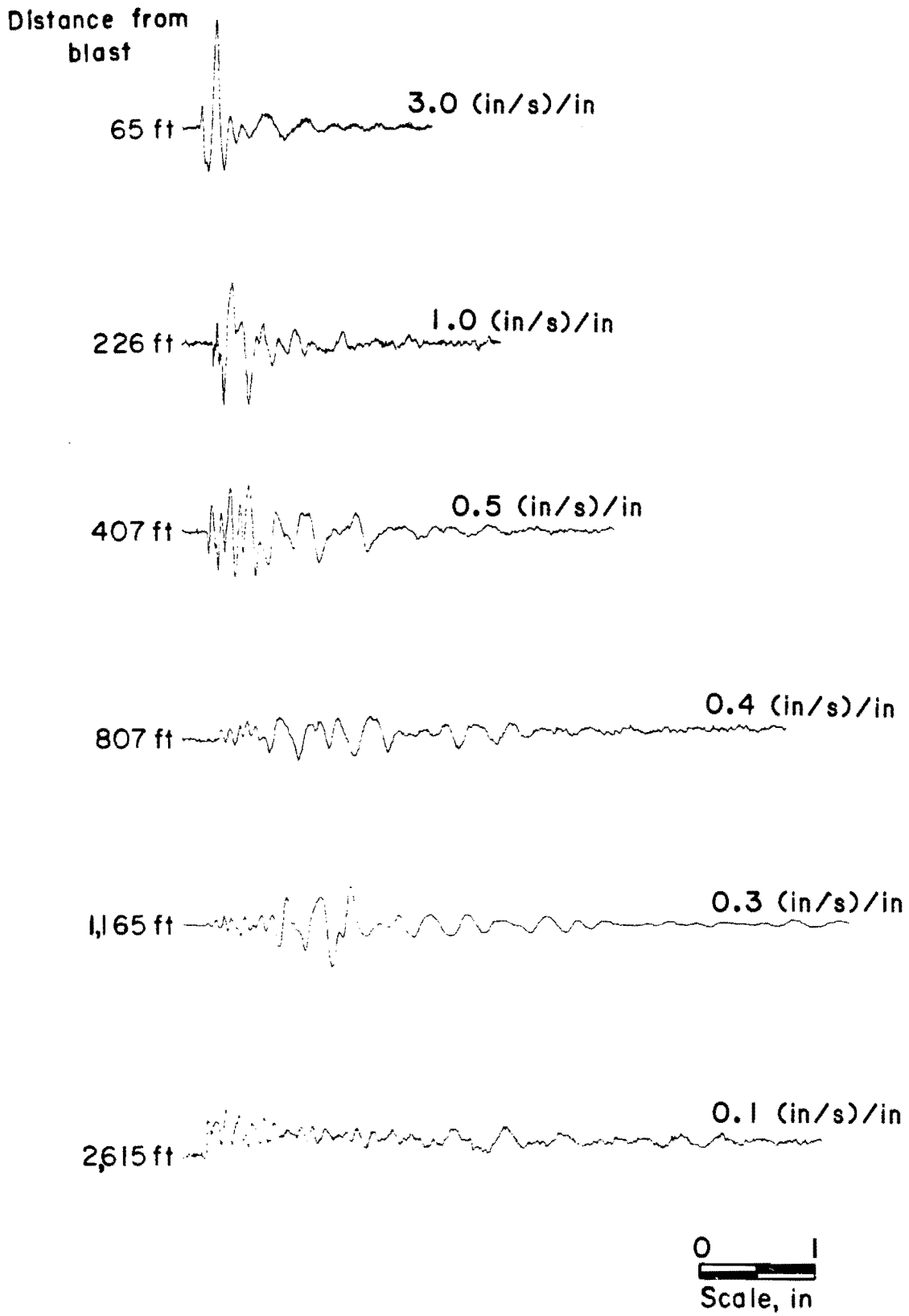


FIGURE 46.—Vibration records from single charge (shot 4), longitudinal component. Horizontal scale is 500 ms/in.

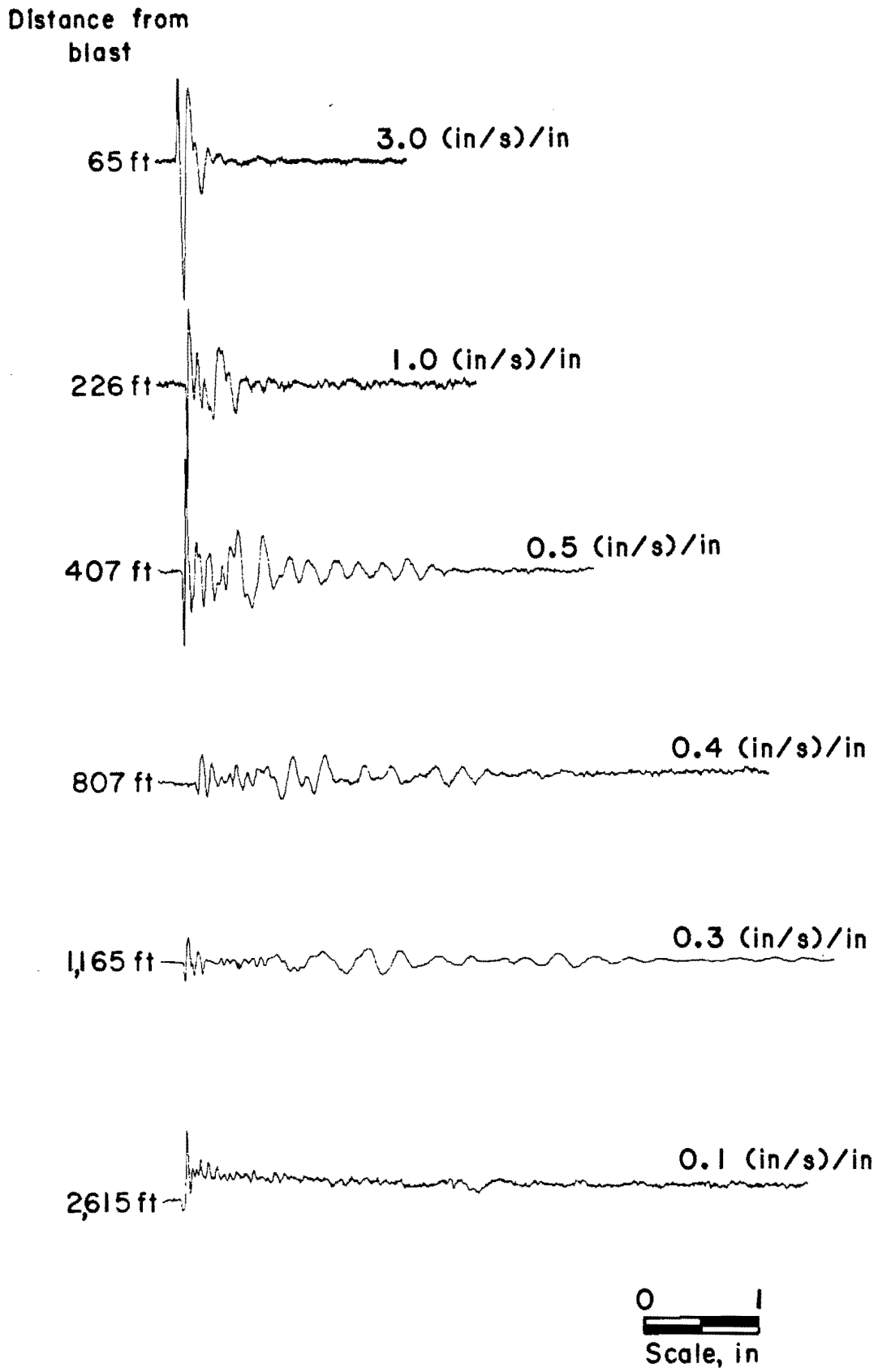


FIGURE 47.—Vibration records from single charge (shot 4), vertical component. Horizontal scale is 500 ms/in.

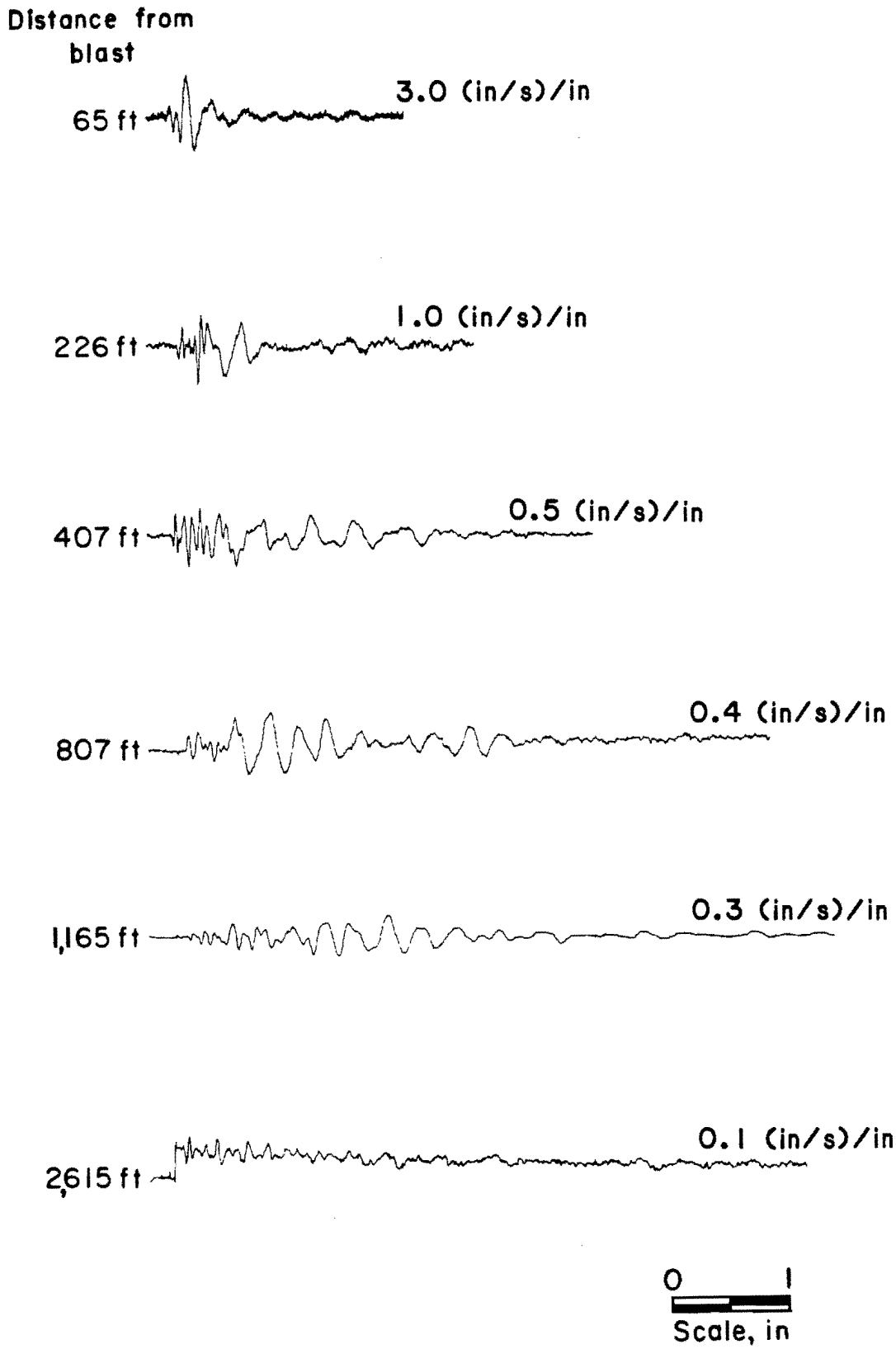


FIGURE 48.—Vibration records from single charge (shot 4), transverse component. Horizontal scale is 500 ms/in.

hole at a depth of 50 ft. The 3-ft column of explosive took approximately 0.3 ms to detonate. The nearest recording station was only 65 ft from the shot hole and shows that the ground vibrations had already been strongly affected by the medium through which they propagated. The single-charge source has been transformed into a complicated signal lasting over 500 ms with predominant motion or vibration in the beginning of the signal occurring for 150 ms.

It is interesting to note the change in character of the signal from the near instrument station to the far. The character of the waveforms out to approximately 400 ft can be described by relatively high-amplitude, high-frequency vibrations in the early part of the signal, which are associated with the arrival of reflected and refracted body waves, both P (compression) and S (shear). The complexity of these waves is best illustrated by comparing the longitudinal component of waveforms recorded at 65 and 407 ft. Although it is not possible to identify individual phases at the farther station, it is obvious that the predominant single pulse observed at 65 ft has become several pulses at 407 ft. If the propagation medium were infinitely homogeneous, then a wave recorded across the array would be very similar in character and change only in amplitude and frequency. However, the medium generally comprises several different materials (e.g., soil, weathered rock, shale, sandstone, coal, and voids from mining). Each material provides a separate transmission path, and each structure and compositional interface gives rise to new phases as a wave propagates across the many boundaries. These phases eventually arrive at a recording station and comprise the waveform.

The higher velocity body waves are followed by lower velocity, lower frequency surface waves. As their name implies, the surface waves are a result of a boundary in the propagating medium, e.g., the air-ground or rock-rock interfaces, and are actually composed of P and S waves which constructively interfere during propagation. Since high frequencies attenuate more rapidly than do low frequencies, the recordings made at large distances (e.g., between 800 and 2,600 ft) reveal the predominance of the later-arriving surface waves, which are responsible for the relatively larger low-frequency vibrations at the larger distances. Surface waves are of concern to the mining and blasting industry because their frequency is often near the natural frequencies of residential structures (2).

Blast Design and Geologic Influence. - A comparison of ground vibrations recorded by the west instrument array for production shot 3 and single-charge shot 4 reveal some similarities. As previously mentioned, vibration amplitudes attenuated at the same rate. This suggests that the production shot with a sequence of over 100 delays lasting about 1.0 s is not exciting the subsurface structure and causing some kind of ground resonance.

Further proof is found in the duration of surface waves measured at the stations between 400 and 1,200 ft (figs. 38-40, 46-48). The duration of ground motion associated with the surface waves for the production shot is the same for the single-charge shots at these stations. (Amplitudes are greater for shot 3 because multiple decks were detonated close enough in time to interfere.)

Two stations were chosen to examine the frequency content of the ground vibrations for production and single-charge shots. At the near station, the distances to the production and single-charge shots were 90 and 65 ft, respectively; at the far station, the distances to the production and single-charge shots were 1,190 and 1,165, respectively. The frequency spectra for the longitudinal components at the near station are similar and shown in figure 49: Predominant frequencies for the production shot were between 5 to 10 Hz and for the single-charge shot between 5 to 15 Hz. The frequency spectra for the far station (fig. 50) compare even more favorably, with a predominant frequency near 6 Hz. Overall, there is a very good correlation between spectra for the production shot and the single-charge shot, which supports the theory that the subsurface geology controls the frequency content of a

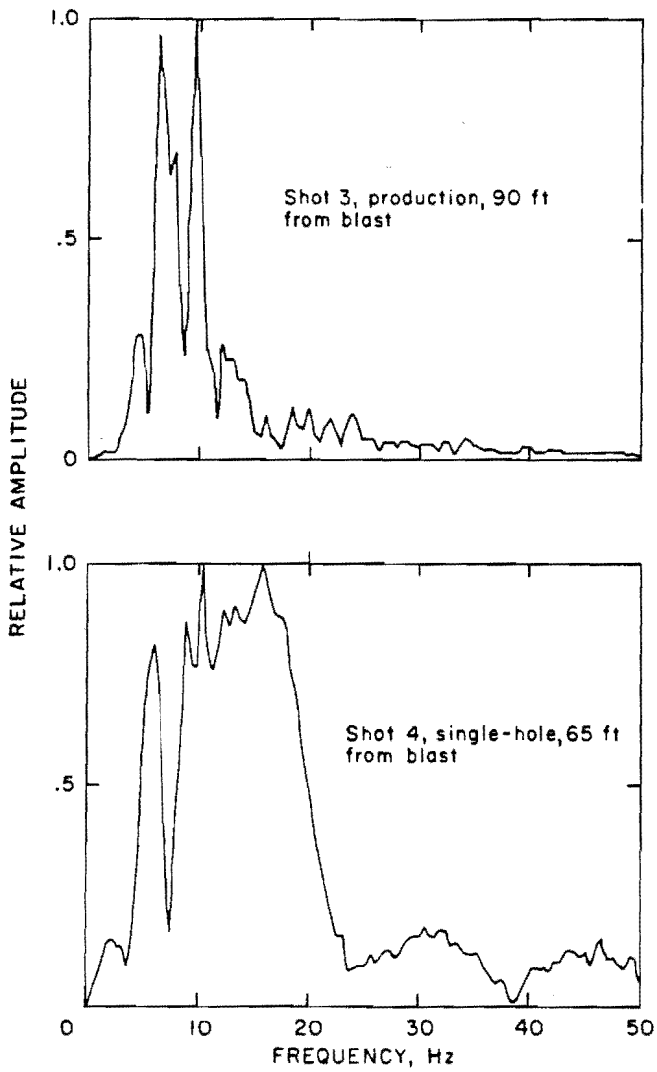


FIGURE 49.—Vibration spectra for production and single charge in near field.

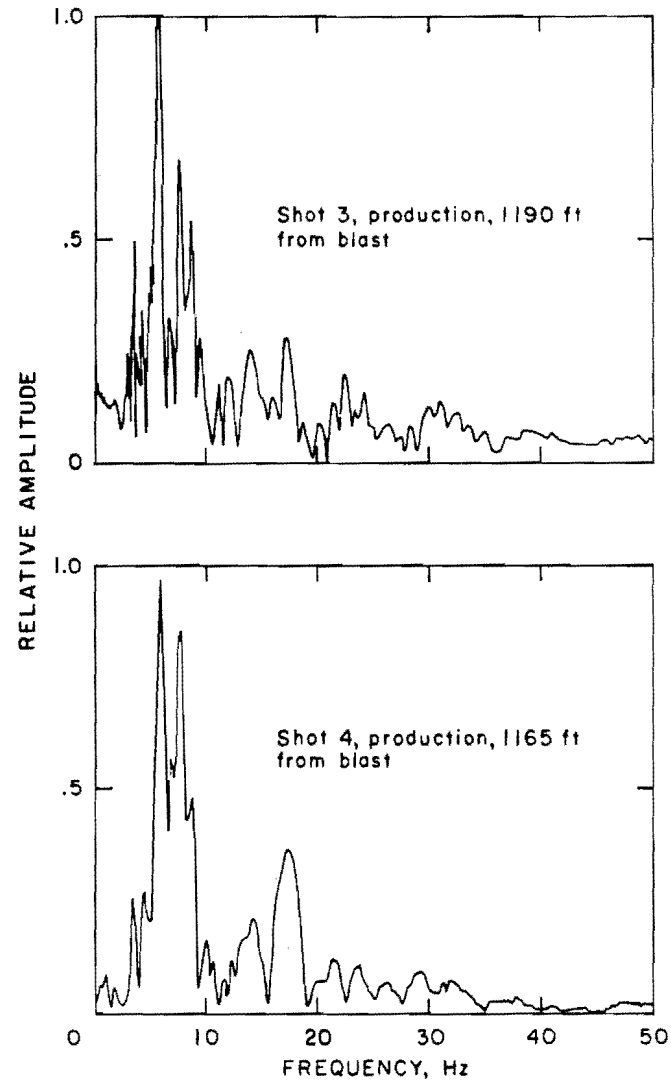


FIGURE 50.—Vibration spectra for production and single charge in far field.

signal. However, it does appear that the delay interval period of 100 ms may have affected the spectral content for the near recording.

Theoretical Models

Two mathematical models exist for describing surface-wave generation. The Gupta model (10-11) for shear waves, dominant on longitudinal and transverse, and the O'Brien model (12) for compressional waves, dominant on longitudinal and vertical. Both models use the same equation, which is simple when $V_2 >> V_1$. The V_1 and V_2 represent the velocities in the low- and high-propagation-velocity layers for both models, Gupta's shear wave model and O'Brien's compression wave model. Presumably, the high-velocity layer is beneath the low-velocity layer for both versions. The model requires a low-velocity surface layer with a strong velocity contrast between it and the underlying layer. The simplified relationship is

$$T = \frac{4h}{V_1},$$

where T is the surface-wave period, or the inverse of the frequency ($T = 1/f$), and h is the low velocity layer thickness.

For example, using the Volk house 11-25-85 record, calculation of velocity and thickness (depth) are possible. The surface wave arrives 1.6 s later than the direct arrival. Bureau researchers measured propagation velocity at the mine of about 10,000 ft/s for the first arrival. The surface wave period is 0.26 s or 4 Hz. Using the 1.6-s difference in travel time, the low-velocity layer has a velocity of about 2,700 ft/s. From the O'Brien equation, a layer thickness of 175 ft is indicated. It is difficult to believe that there is a near-surface layer this thick with an average propagation velocity of 2,700 ft/s. Although unlikely, it is possible if the zone is highly fractured or low-strength rock. The Gupta model presumably requires the shear wave propagation velocity, which was not measured. More work is needed, including measurements of propagation velocity and subsurface structure characteristics.

UNDERGROUND OPENINGS

This is an entirely different case than the O'Brien model discussed above. Instead of a low-velocity layer over an underlying high velocity, this is case of voids, probably flooded, which act as a low-velocity or exclusion layer. They are reflectors rather than refractors. Because of the various surface-wave characteristics observed in Blanford, more than one generation mechanism may be at work.

Summarizing the influences on vibration frequency, the propagating medium appears to have a dominating influence at large distances, greater than about 400 ft, based on the Bureau's single-hole and production blasting comparisons. Closer measurements at this site found vibration records resembling the blast sequencing. However, review of the five examples of blast designs (figs. 33-37) suggests that design periodicities can show up in records obtained at large distances. The natural ground frequency of 8 to 10 Hz can be excited as can the 4- to 5-Hz surface waves. More work is needed on surface-wave generation mechanisms and correlation with underground structures.

LEVEL-LOOP SURVEYS

Surveys were made of eight houses in Blanford using an automatic level to determine if differential settlement or subsidence occurred. An automatic level is a transit-type device that measures relative elevations. Surveys that employ such devices usually involve measuring all sides of a structure (or "closing the loop") to assure accuracy of the data obtained.

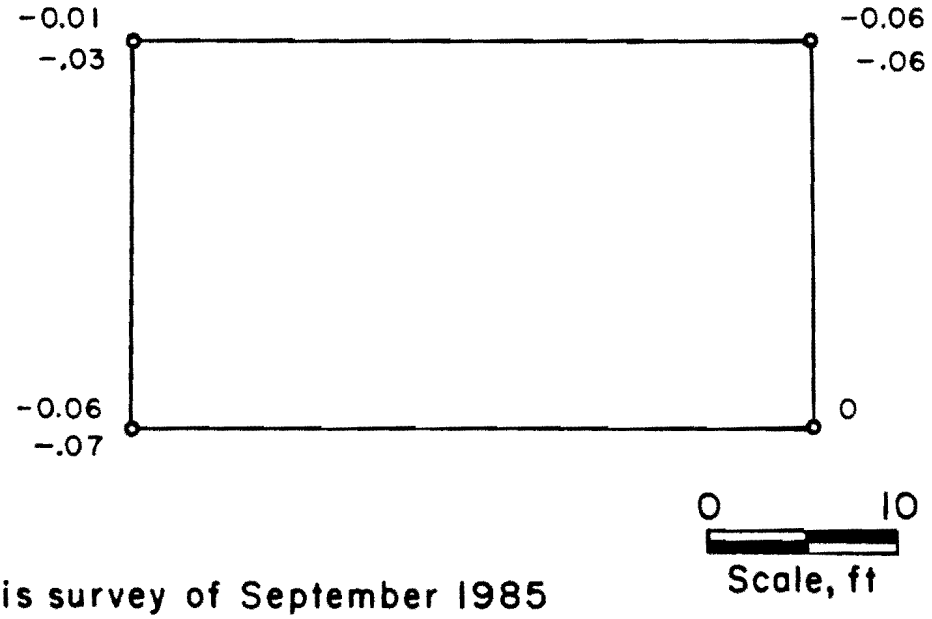
The first survey was made at the time of the vibration tests, September 1985. A resurvey was made 7 months later, April 1986, to test for long-term changes. An identifiable survey horizon was chosen, such as the foundation or a brick or block mortar joint. Relative elevations were determined; however, this does not directly indicate that a structure is under strain. Measured deviations could be due to differential settlement, or the structures could have built slightly out of level and free of true strain, not having moved at all. Unless the builder can guarantee a certain level tolerance, the only way to identify ongoing vertical movement is by periodic resurvey, with reference to a base station or control point.

Figures 51 through 58 show the eight houses and survey results. Table 6 summarizes the results. Note that several of the structures had "deformations" (assuming the houses were originally level) of more than 1 part in 300.

Boscardin (13) cites the following defection ratio criteria in terms of angular distortions:

Structural damage.....	1:150
Cracking of panel and load-bearing walls.....	1:300
Noncracking case.....	1:500

These are relatively high values. If they represent true distortion, they provide an explanation for wall cracks and other types of minor damage. Periodic surveys are recommended, particularly where other evidence of subsidence exists, such as sink holes. No constant or



Top number is survey of September 1985
Bottom number is survey of April 1986
All elevations are in feet

FIGURE 51.—Ahlmeyer house and level-loop surveys.

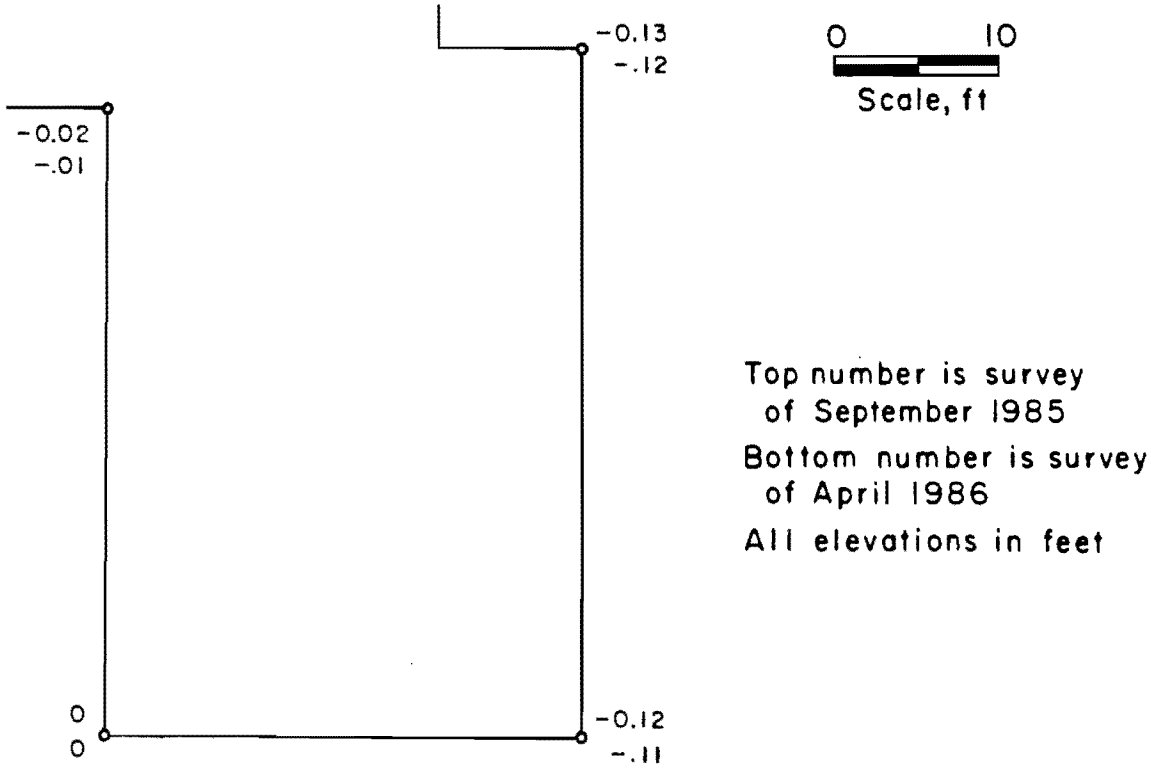
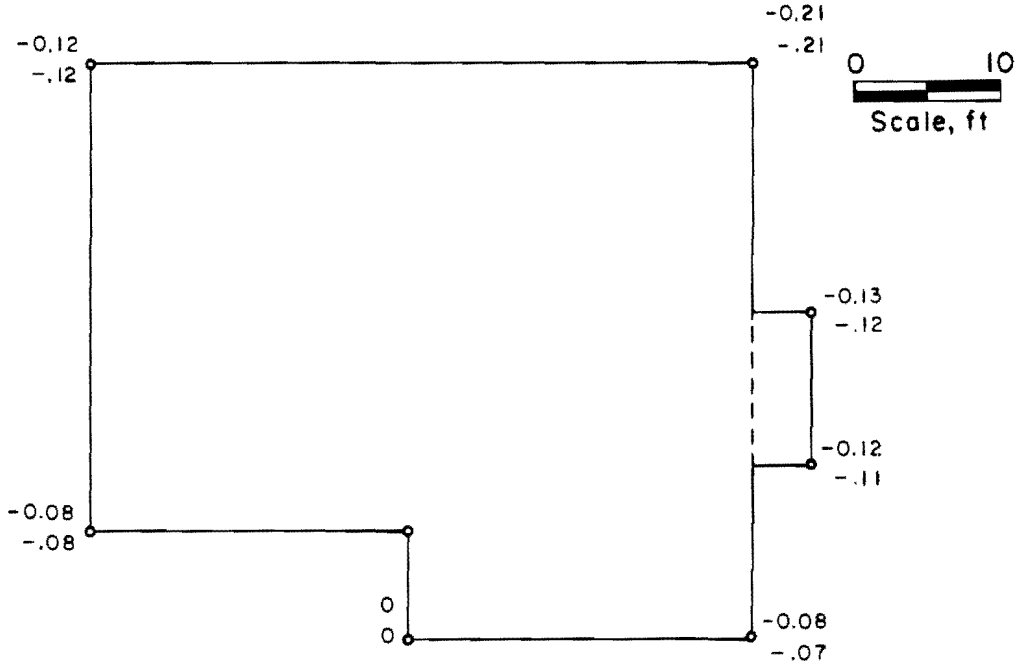
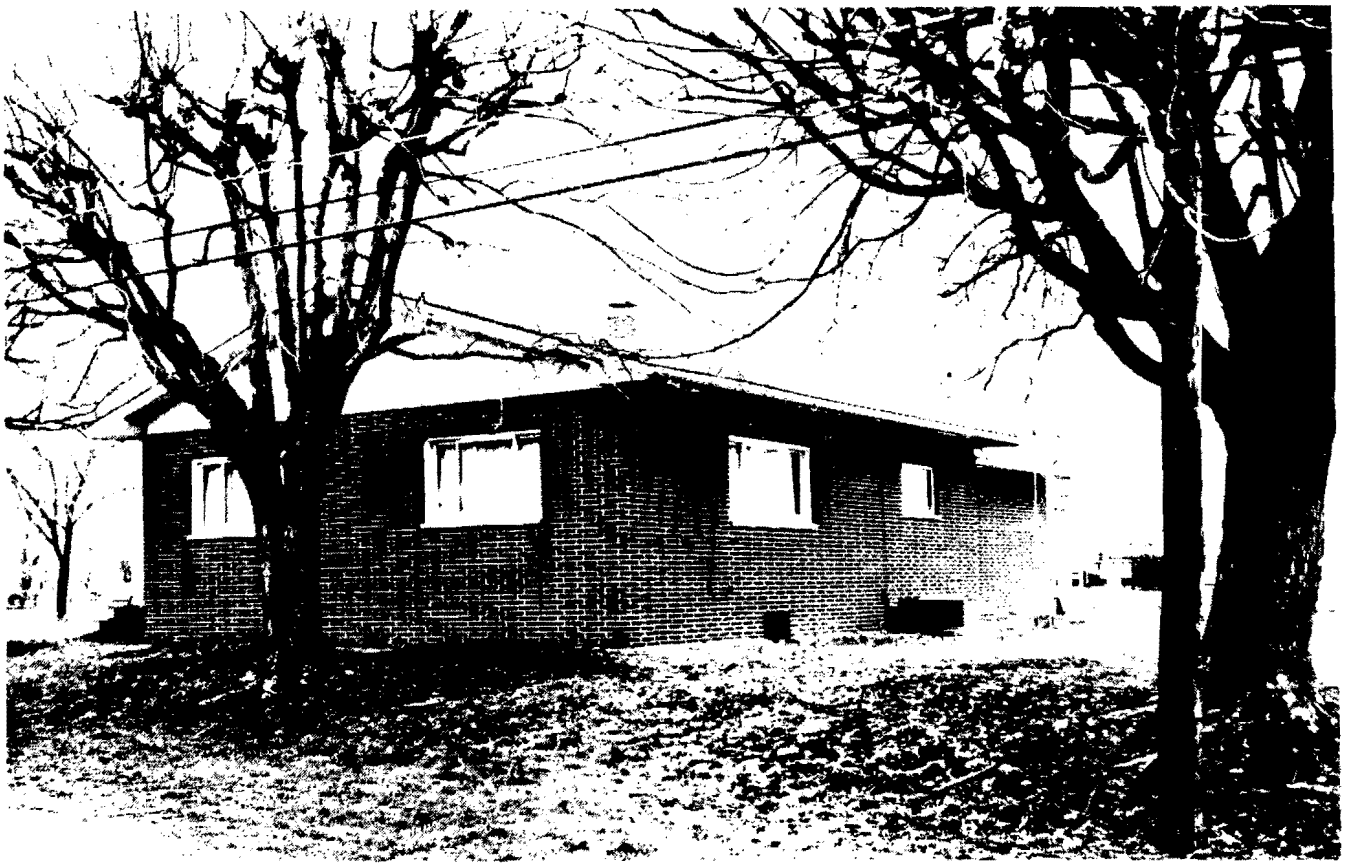


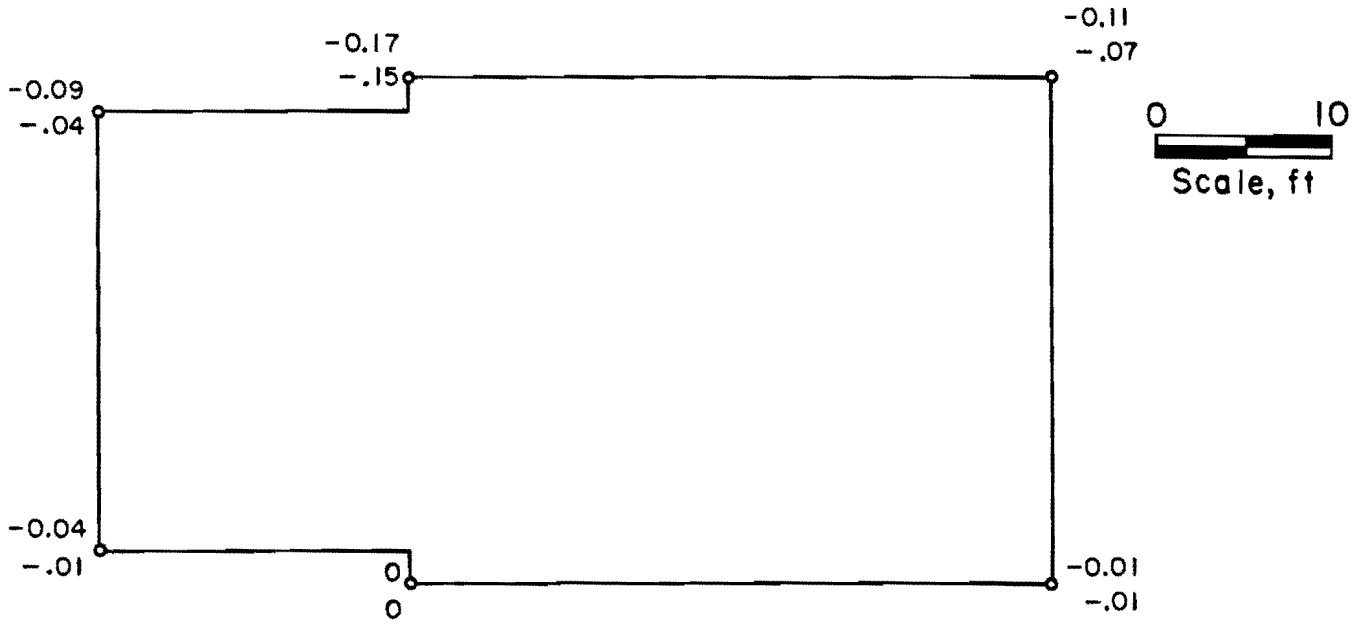
FIGURE 52.—Albrecht house and level-loop surveys.



Top number is survey of September 1985
Bottom number is survey April 1986
All elevations are in feet

FIGURE 53.—E. Finger house and level-loop surveys.





Top number is survey of September 1985
Bottom number is survey April 1986
All elevations are in feet

FIGURE 54.—O. Finger house and level-loop surveys.

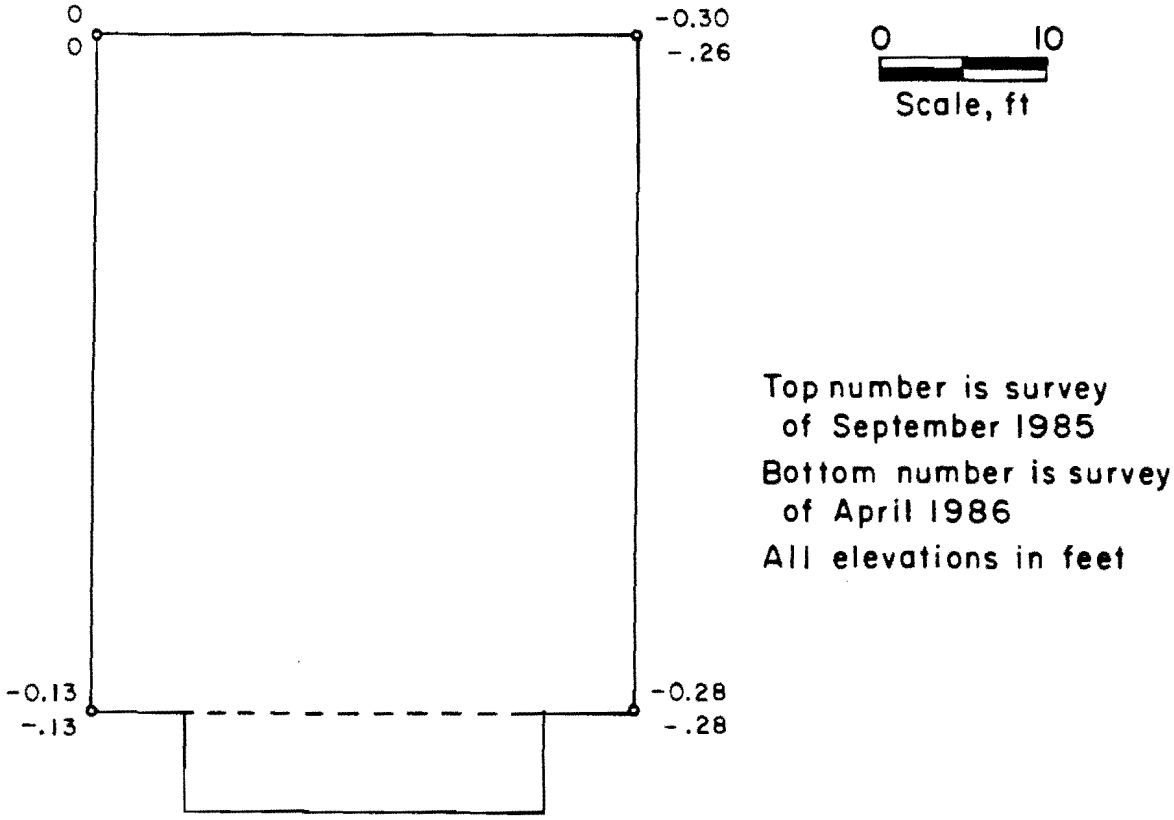


FIGURE 55.—Jovanovich house and level-loop surveys.

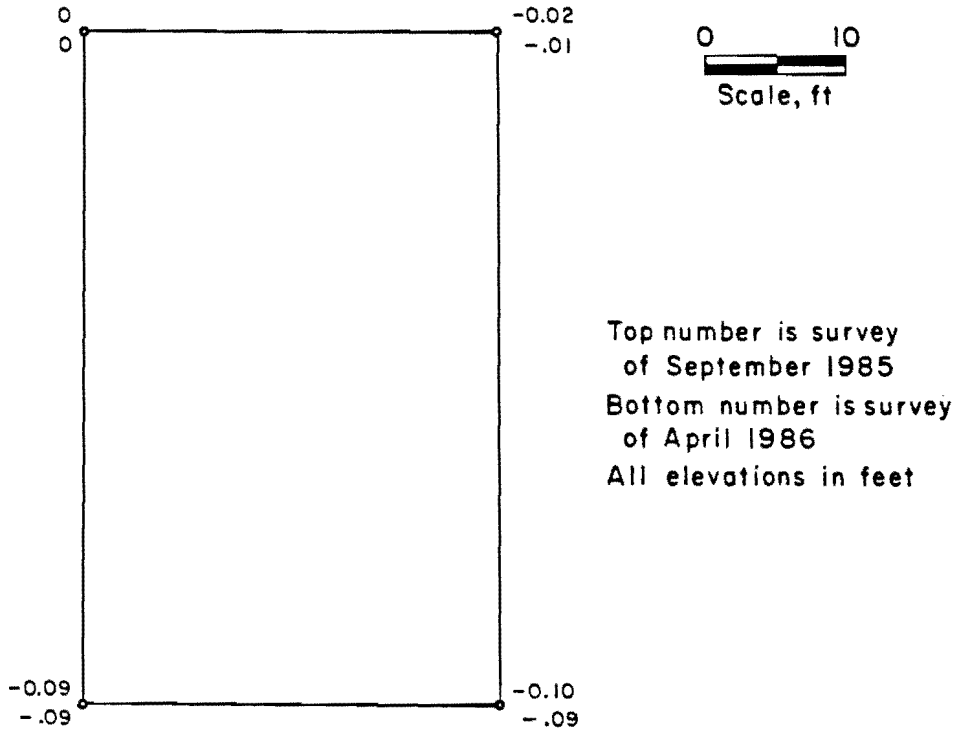
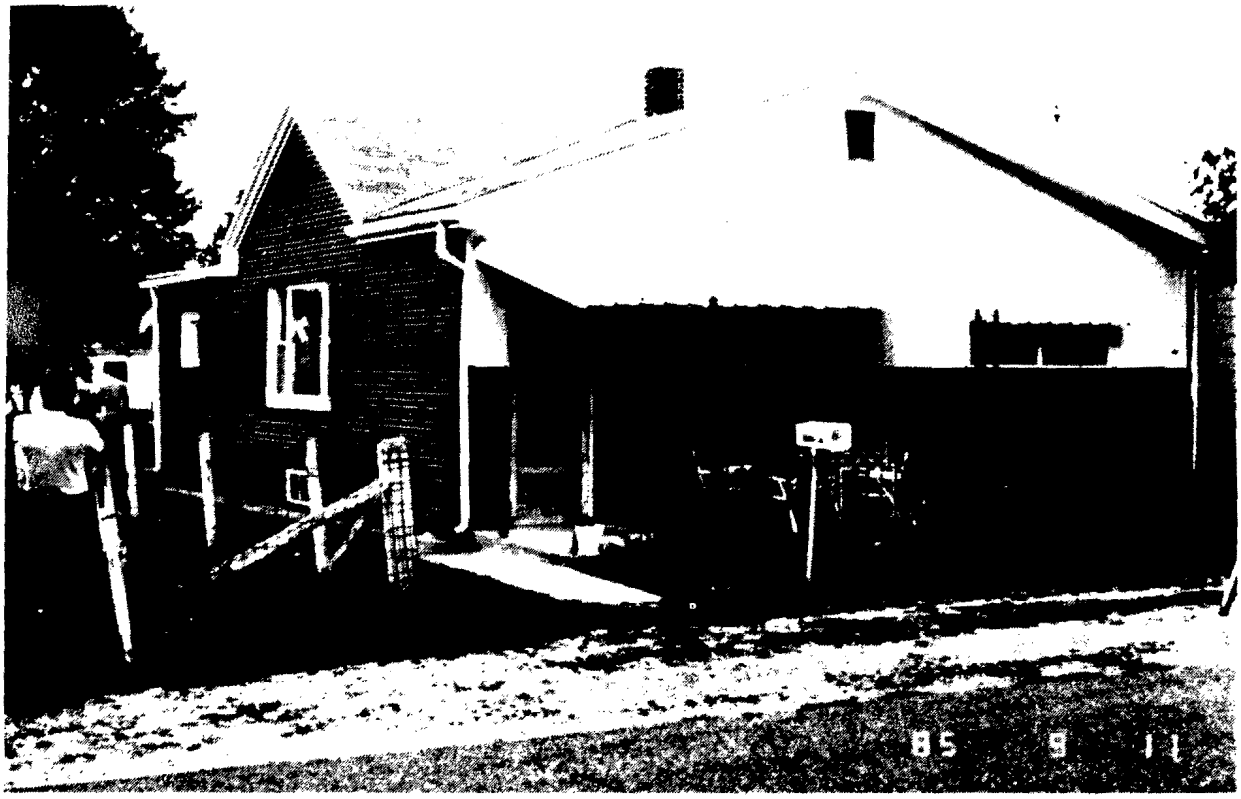


FIGURE 56.—Marietta house and level-loop surveys.



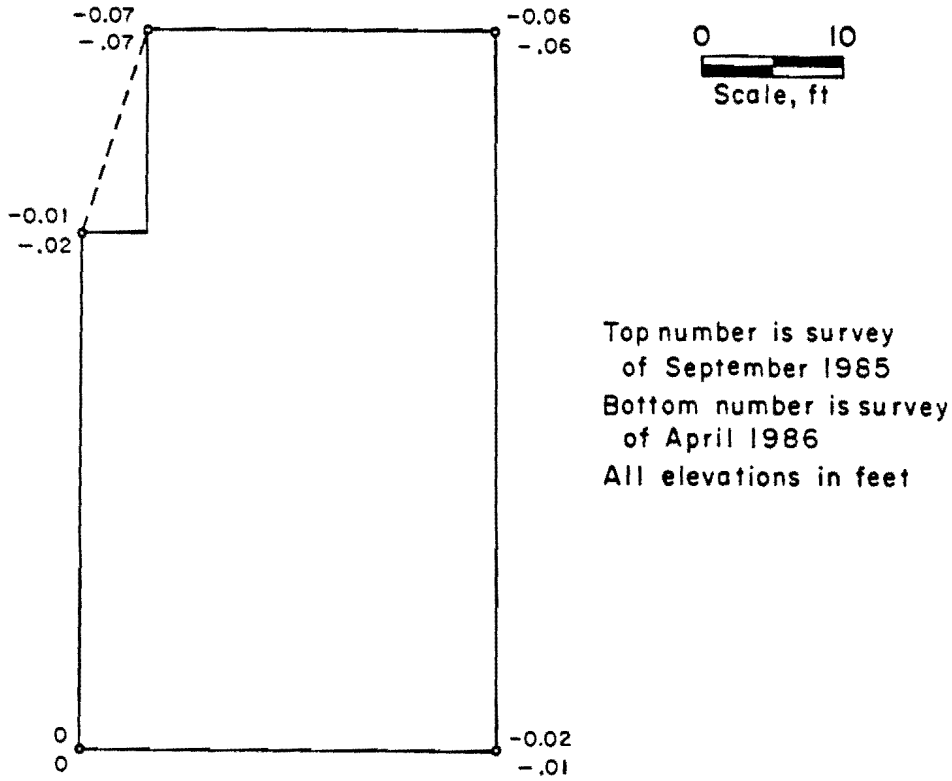


FIGURE 57.—Skorich house and level-loop surveys.

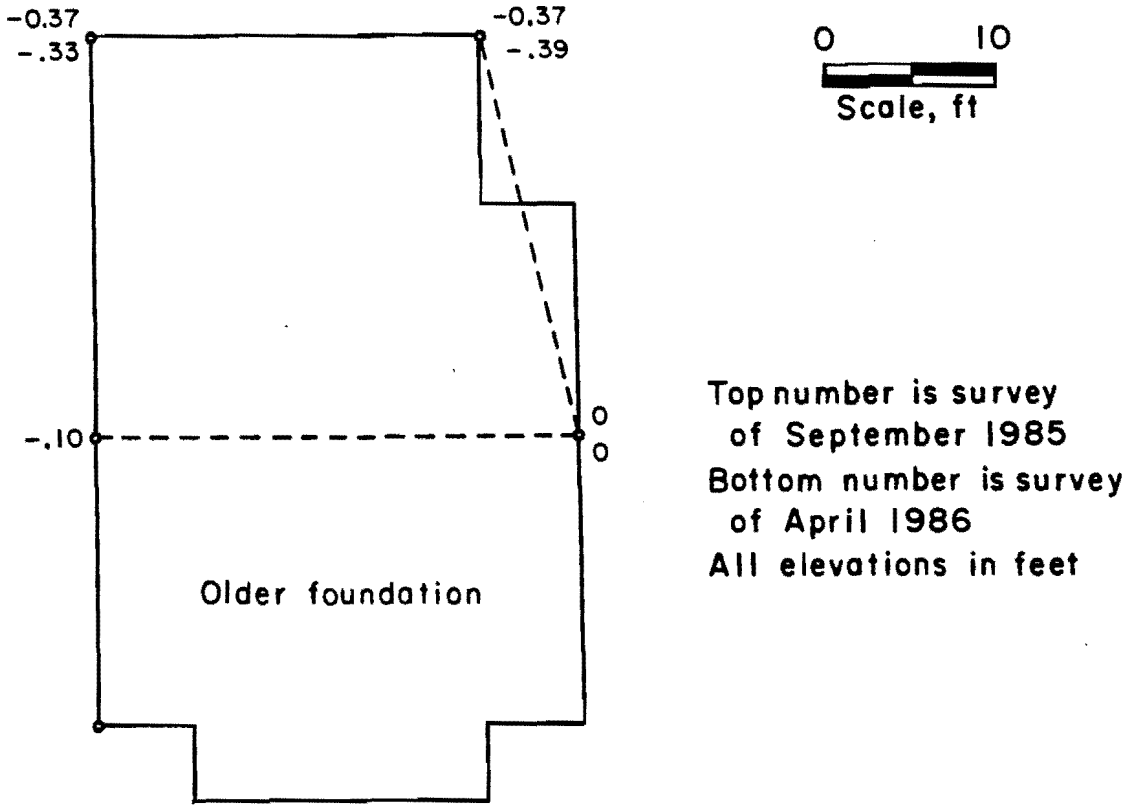


FIGURE 58.—Zell house and level-loop surveys.

TABLE 6. - Summary of two level-loop surveys of eight Blanford houses

House	Maximum elevation differences,[1] ft		Maximum angular distortion[2]	
	Sept. 1985	Apr. 1986	Sept. 1985	Apr. 1986
Ahlmeyers.....	0.06	0.07	1:340	1:340
Albrecht.....	.12	.11	1:250	1:260
Finger, E.....	.08	.07	1:300	1:340
Finger, O.....	.09	.11	1:200	1:164
Jovanovich.....	.30	.26	1:108	1:125
Marietta.....	.09	.09	1:560	1:533
Skorich.....	.06	.05	1:250	1:300
Zell.....	.37	.39	1:65	1:65

[1]Accuracy is ±0.01 ft.
[2]1:340 = distortion of 1 part in 340, etc.

significant trend was noted by the repeat survey 7 months after the initial one. In fact, the houses had slightly smaller differences in elevations.

CONCLUSIONS

The propagating medium appears responsible for the adverse vibration impacts in Blanford through three mechanisms: Mechanism 1 favors generation of low frequency surface waves of several types with frequencies between 4 and 10 Hz; mechanism 2 has the appearance of reduced vibration attenuation (higher amplitudes) with distance compared with those of other coal mine blasts; and mechanism 3 produces interactions between delayed charges beyond what would be expected from the blasts as designed because of constructive wave interference for these long-period waves.

The widely adopted 8-ms charge-separation criterion appears not to apply for this low-frequency site because the wavelengths are simply too long to constructively cancel out. This was also previously suspected in a 1979 study of large-scale surface coal mine blasting (8). Vibration frequency characteristics also appear to reflect periodicities in the blast design timing, particularly close to the shot. For example, delays between rows of 200 ms will favor the generation of 5-Hz waves if the energy is produced in discrete pulses of 5 per second.

Although further study of the subsurface conditions is needed in order to identify their influences, the observed surface waves are consistent with a strongly reflecting subsurface interface at a depth of about 175 ft, or about the depth of the extensively mined No. 5 coalbed. This agrees with theoretical models that predict low-frequency waves from strongly reflecting near-surface horizontal layers.

REFERENCES

1. Siskind, D. E. (BuMines). Assessment of Blasting Vibrations From Surface Mine Blasting in Peabody's Universal Mine, Blanford, IN. Off. Surf. Min., May 15, 1985, 28 pp.

2. Siskind, D. E., V. J. Stachura, and M. J. Nutting (BuMines). The Generation of Low-Frequency Long-Duration Vibrations From Surface Mine Blasting at Blanford, IN. Off. Surf. Min., Nov. 15, 1985, 98 pp.

3. Siskind, D. E., M. S. Stagg, J. W. Kopp, and C. H. Dowding. Structure Response and Damage Produced by Ground

Vibration From Surface Mine Blasting. BuMines RI 8507, 1980, 74 pp.

4. Anderson, D. A., S. R. Winzer, and A. P. Ritter. Blast Design for Optimizing Fragmentation While Controlling Frequency of Ground Vibration. Paper in Proc. Eighth Annual Conference on Explosives and Blasting Technique (New Orleans, LA, Jan. 31-Feb. 4, 1982). Soc. Explos. Eng., 1982, pp. 69-89.

5. _____. Synthetic Delay Versus Frequency Plots for Predicting Ground Vibration From Blasting. Paper in Proc. Third Int. Conf. on Computer-Aided Seismic Analysis and Discrimination (Washington, DC, June 16-17, 1983). Catholic Univ. 1983, pp. 70-74.

6. Stagg, M. S., and A. J. Engler. Ground Vibration Measurement and Seismograph Calibration. BuMines RI 8506, 1980, 62 pp.

7. Duvall, W. I., C. F. Johnson, A. V. C. Meyer, and J. F. Devine. Vibrations From Instantaneous and Millisecond-Delayed Quarry Blasts. BuMines RI 6151, 1963, 34 pp.

8. Wiss, J. F., and P. Linehan. Control of Vibration and Blast Noise From Surface Coal Mining (contract J255022, Wiss, Janney, Elstner and Associates, Inc.). Volume 2. BuMines OFR 103(2)-79, 1978, 280 pp.; NTIS PB 299 888.

9. Kopp, J. W., and D. E. Siskind. Effects of Millisecond Delay Intervals on Vibrations and Airblast Generation From Surface Mine Blasting. BuMines RI 9026, 1986, 44 pp.

10. Bollinger, G. A. Blast Vibration Analysis. So. IL Univ. Press, Carbondale, IL, 1971, 129 pp.

11. Gupta, I. N. Resonant Oscillations of the Overburden Excited by Seismic Waves. Earthquake Notes, v. 32, Mar.-June, 1961, pp. 5-11.

12. O'Brien, P. N. S. Multiply Reflected Refractions in a Shallow Layer. Geophy. Prospect., v. 5, 1957, pp. 371-380.

13. Boscardin, M. D. Building Response to Excitation-Induced Ground Movements. Ph.D. Thesis, Univ. IL at Urbana-Champaign, Urbana, IL, 1980, 279 pp.

U.S GOVERNMENT PRINTING OFFICE 1987 605-017 60045

INT.-BU.OF MINES,PGH.,PA. 28486