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# Comparative Study of Blasting Vibrations From Indiana Surface Coal Mines

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BUREAU OF MINES

UNITED STATES DEPARTMENT OF THE INTERIOR

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## UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

| | | | |
|---|---|---|---|
| ft | foot | in/s | inch per second |
| $ft/lb^{1/2}$ | foot per square-root pound (scaled distance) | lb | pound |
| | | ms | millisecond |
| ft/s | foot per second | pct | percent |
| Hz | Hertz | s | second |
| in | inch | st | short ton |

# COMPARATIVE STUDY OF BLASTING VIBRATIONS FROM INDIANA SURFACE COAL MINES

By David E. Siskind,[1] Steven V. Crum,[2] Rolfe E. Otterness,[3] and John W. Kopp[4]

## ABSTRACT

The Bureau of Mines performed a comparative study of nine sites at eight surface coal mines to determine if the presence of near-surface underground abandoned workings resulted in the generation of adverse long-duration, low-frequency blast vibrations. Six of the nine sites had underlying workings, and two had thick layers of low-velocity unconsolidated surface material.

Extended seismic arrays were used to identify the vibration characteristics within a few tens of feet of the blasts and also as modified by the propagating media at distances over 1 mile. Production blasts and specially fired single-charge blasts allowed the determination of natural ground frequency and the influence of initiation delay timing.

Vibration amplitudes from the production blasts at all sites exceeded historical norms, particularly at the greater distances. This contrasts with the near-normal results from single-charge blasts. Apparently, between-hole time delays were insufficient to separate vibrations from adjacent charges for the low-frequency waves present. Single-charge tests showed that the propagating media produced low-frequency, ground-roll-type surface waves at nearly all sites. Large blasts at such sites could produce an unacceptable risk of vibration-induced cracks in nearby structures.

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# INTRODUCTION

The Bureau of Mines maintains a strong research program in mine blasting technology. During the past decade, researchers at the Bureau's Twin Cities Research Center conducted a variety of studies on the environmental aspects of blasting, such as ground vibrations and the damage that may result to nearby structures. These studies allowed the Bureau to provide guidelines on blasting practices that minimize damage to surrounding structures. Because of this background, the Bureau was asked by the Office of Surface Mining Reclamation and Enforcement (OSMRE) to examine surface mine blasting over abandoned underground workings to identify the influence of such conditions on vibration characteristics and damage risk to surface structures. The Bureau agreed to conduct the study because of the opportunity to broaden the scope of its blasting guidelines.

The risk of damage was to be assessed by comparisons between the generated vibrations and safe blasting criteria established by earlier Bureau research. An earlier Bureau study of one such site at Blanford, IN, found abnormally high vibration amplitudes, long durations, and low frequencies (*1*).[5] This site was underlain by extensive coal mine workings about 200 ft beneath both the active mining and the town of Blanford, and the situation caused a large number of citizen complaints.

The purpose of the present study was to determine if the unusual vibrations were specific to this one site or also occurred elsewhere in the region. Where such vibrations were found to occur at other surface coal mines, researchers examined common blast designs and ground structural elements in order to identify the causes. Specifically, mining activities over and nearby old workings were examined, and through the technique of comparing production and single-charge blasts, the influences of blast design were also studied. One of the study sites had no underlying workings. However, it did have a history of low-frequency vibration and was characterized by a thick surface layer of low-velocity, unconsolidated material behind the highwall (*2*).

Vibration waves are strongly influenced by the media through which they are propagating, as described in the detailed report on the Blanford site (*1*). Specifically of concern are surface waves, which are produced at material interfaces. Because surface wave amplitudes decrease with distance (R) from a source at a rate of $1/R^{1/2}$, instead of 1/R as is the case with body waves near surfaces, surface waves typically become the dominant part of the vibration record at large distances. The difference in geometric spreading results from the concentration of surface wave energy near an interface or within a layer. Unlike body waves, surface waves are restricted to two rather than three dimensions. They are characterized as low-frequency, long-duration, and simple in appearance. They are sometimes pure or nearly pure sinusoidal waves of many cycles.

The Blanford report (Bureau RI 9078) describes the two basic surface waves:

> Rayleigh waves are vertically polarized with retrograde eliptical particle motions. They should have significant motion in the longitudinal and vertical directions. The generation of these waves requires only a single free surface (the ground-air interface or any sharp acoustic contrasting layer at depth).
>
> Love waves are horizontally polarized shear waves. They should be strong only in the transverse component of ground motion. Generation of Love waves requires a layer with the top and bottom boundaries having good reflecting properties. Extensive underground voids could provide such a reflecting surface, as could any low-velocity layer (*1*).

In addition to these surface waves, additional low-frequency, long-duration waves can occur in regions with good reflectors. These multiple reflecting waves are a form of trapped energy and decrease in frequency with time (*3*). One good example of such a region is a low-velocity surface layer over a solid competent rock. With a 5:1 ratio of acoustic impedance (product of density and acoustic velocity), reflection amplitudes will be about two-thirds of the incident wave amplitude. An even better reflector would be a horizontal void, which can give total reflection.

Several studies have been done on the influences of low-velocity surface layers on earthquake vibration wave characteristics. Murphy (*4*) found that displacement amplitudes were higher in soil than in rock in the proportion of their respective acoustic impedances. This is consistent with and results from a corresponding decrease of vibration frequency in soil compared with rock. He also found that the amplitudes were frequency dependent and peaked between 2 and 8 Hz. Johnson (*5*) examined waves in 115-ft-thick alluvium and found vibration amplitudes near the surface of 1.5 to 4.3 times those in bedrock. Johnson's radial-component vibration consisted of a 6.5-Hz direct wave with a strong surface wave tail of 2.3 Hz.

King (*6*) studied earthquake motions across a sediment-filled valley, finding waves of 3 to 7 Hz in valley sediments of 115- to 197-ft thickness. His impedance contrast was 5.8, suggesting efficient wave reflections. A similar analysis by Bard (*7*) described Love waves in the valley sediment with amplitude proportional to sediment thickness.

The above studies list frequencies that are consistent with two mathematical models that describe the generation of surface waves. The Gupta model (*8*) is for shear waves, dominant on longitudinal and transverse components, and the O'Brien model (*9*) is for compressional waves, dominant on longitudinal and vertical components. The velocities $V_1$ and $V_2$ represent the low- and high-propagation velocity layers, respectively, for both models. Presumably, the high-velocity layer is beneath the low-velocity layer for both versions. The models require a low-velocity surface layer with a strong velocity contrast between it and the underlying layer. Both models reduce to the same equation when $V_2 >> V_1$. 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 thickness of the low-velocity layer. The theoretical section of this report applies the model to the nine Indiana sites.

The importance of vibration frequency for structural response and damage risk is discussed in detail in Bureau RI 8507 (*10*). This 1980 report contains frequency-dependent safe blasting criteria that convert from particle velocity to displacement as frequencies drop below 4 Hz. In other words, low frequencies produce increased risk from excessive strain (a differential displacement) unless velocities are accordingly reduced.

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[5] Italic numbers in parentheses refer to items in the list of references preceding the appendix at the end of this report.

The question for OSMRE is whether more protection against vibration is needed where such low frequencies are present and whether this is an isolated situation or common to a class of structural or blast design conditions. Where warranted, adjustments could be made in regulatory levels or methods of assessment to provide the desired and appropriate amount of protection against blasting vibration.

The previous Bureau work identified one problem site. This report describes and compares the previously studied site with eight other surface coal mine sites in western and southwestern Indiana where low-frequency vibration waves were suspected.

This research was done at the request of James E. Gilley, chief, Branch of Engineering Support, Eastern Technical Center of OSMRE Pittsburgh, PA, and was partly funded by OSMRE through Interagency Agreement J5160070. During most of the study period, Louis L. McGee served as the OSMRE technical project officer.

## ACKNOWLEDGMENTS

Eric Gerst, blasting specialist, Indiana Department of Natural Resources (DNR), Jasonville, provided suggestions for candidate sites and additional vibration data from DNR files for sites not available for direct Bureau of Mines monitoring. Essential cooperation was supplied by six Indiana mines.

## EXPERIMENTAL PROCEDURES

### SITE LOCATIONS

Blast vibration data were collected from nine surface coal mine sites in western and southwestern Indiana, three near Terre Haute and six near Evansville (fig. 1). All the sites were characterized as occasionally having vibration problems. Near-surface abandoned coal mine workings existed beneath six of the mines. Several sites, including the nonundermined ones, were known to have thick, unconsolidated, low-velocity surface deposits. The northernmost sites (1, 2, and 7) were also in regions of thick glacial till deposits, which were not thought to be present farther south.

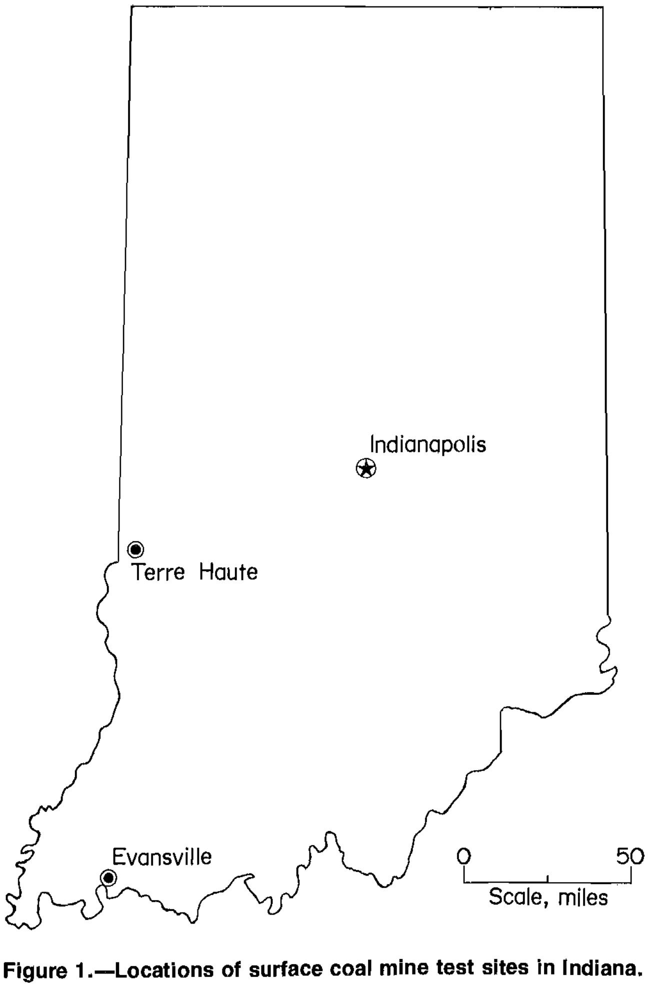

Figure 1.—Locations of surface coal mine test sites in Indiana.

### PROPAGATION ARRAYS

Seismograph stations were placed in linear arrays in the directions that the mine operators indicated were of primary concern. In each case, the array was on the highwall behind the face, although not necessarily perpendicular to it. The closest station was a four-channel FM recorder capable of measuring over 10 in/s peak particle velocity. The remaining four to seven stations were self-triggered four-channel seismographs recording vibrations up to 4 in/s full scale. The closest stations were within 35 ft of the blast. They were intended to record signals characteristic of the source functions (blasts in this case). At these close distances, vibrations are essentially unaltered by the propagating media. The far stations, up to over a mile distant, recorded vibrations with characteristics strongly influenced by the propagating media. Attenuation, dispersion, multiple path reflections, and surface wave generation had greatly changed the far-field vibrations.

Of the nine sites studied, six were available for Bureau testing, which consisted of widely spaced instrument arrays and a suite of test blasts. The other sites were studied through the collection of Indiana DNR records, company blasting logs, and other available information. The propagation array data cover a wide range of distances and were used to form statistical propagation curves. By contrast, the DNR data were collected at nearby structures and are highly bunched. Therefore, the DNR data could only be generally compared with the historical mean (defined as the "maximum horizontal" line [6] from RI 8507 (*10*), figure 10, surface coal mine summary).

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[6] The maximum horizontal line is the least squares regression of the maximum of the radial (longitudinal) and transverse components for each coal mine blast monitored. Each of the 172 blasts is represented by one peak particle velocity value.

## SINGLE-CHARGE BLASTS

The use of single charges is a powerful potential tool for studying both site and blast design influences on vibration characteristics (*11-12*). Single charges are simple impulsive sources lasting about a millisecond. They quickly spread out to about 100 ms duration through the borehole-crushing and rock-fracturing processes. The production blast, in principle, is assumed to be a linear superposition (addition) of time-delayed single charges with amplitudes of certain frequencies determined or at least influenced by the delay intervals between charges.

Production blasts at surface coal mines are usually multihole, multirow, and sometimes also multideck blasts with as many as several hundred individual charges. Such vibration sources are difficult to analyze. Production blasts must be more than a simple addition of single charges because of nonlinear effects and differences in charge environment (top deck compared with bottom, row delay versus within-row delay, etc.). Seismic phases such as compressional and shear wave arrivals are difficult if not impossible to identify for production blasts. However, collecting both single-charge and production vibration data at the same sites is the best currently available method to identify the relative influences of the blast timing interval and propagating medium on the resulting wave characteristics.

Recent work by the West Germans has shown that even single charges are not simple or unique at a given site. One study by Hinzen, as yet unpublished, describes how shallow blasts produced a vibration that was nearly all surface wave at a distance of 262 ft. A deeper blast at the same distance produced a waveform of greater complexity, with significant body wave energy of considerably higher frequency. Part of this effect could be from the longer explosive column and consequently larger charge weight. This observation is highly relevant to the question of wave generation as a function of blast designs that use decking, with deep decks possibly behaving differently than shallow decks.

Earlier research by Kisslinger (*13*) also documented a source-depth influence on Rayleigh wave generation. He described how a depth of burial of 17.4 ft reduced the vertical-component displacement by 40 pct compared with a shallow 2.7 ft burial and reduced the radial-component displacement even more.

Because of production problems, not all the mines studied were able to provide ideal single-charge blasts. One mine (site 3) was willing to fire a single hole but wanted four individually delayed decks. Another mine used two decks per hole but with the same delay in each deck (sites 4 and 5). This mine also fired single-hole charges, which researchers counted as equivalent to a single charge. None of the three sites studied through data acquired from the Indiana DNR has single-charge vibration measurements.

## TEST SITES

### Site 1

This is the Blanford, IN, site with the nearby Peabody Coal Co. Universal Mine described in detail in RI 9078 (*1*). Figure 2 shows the town, mine, and seismic array used for the first five blasts monitored. The other two production blasts

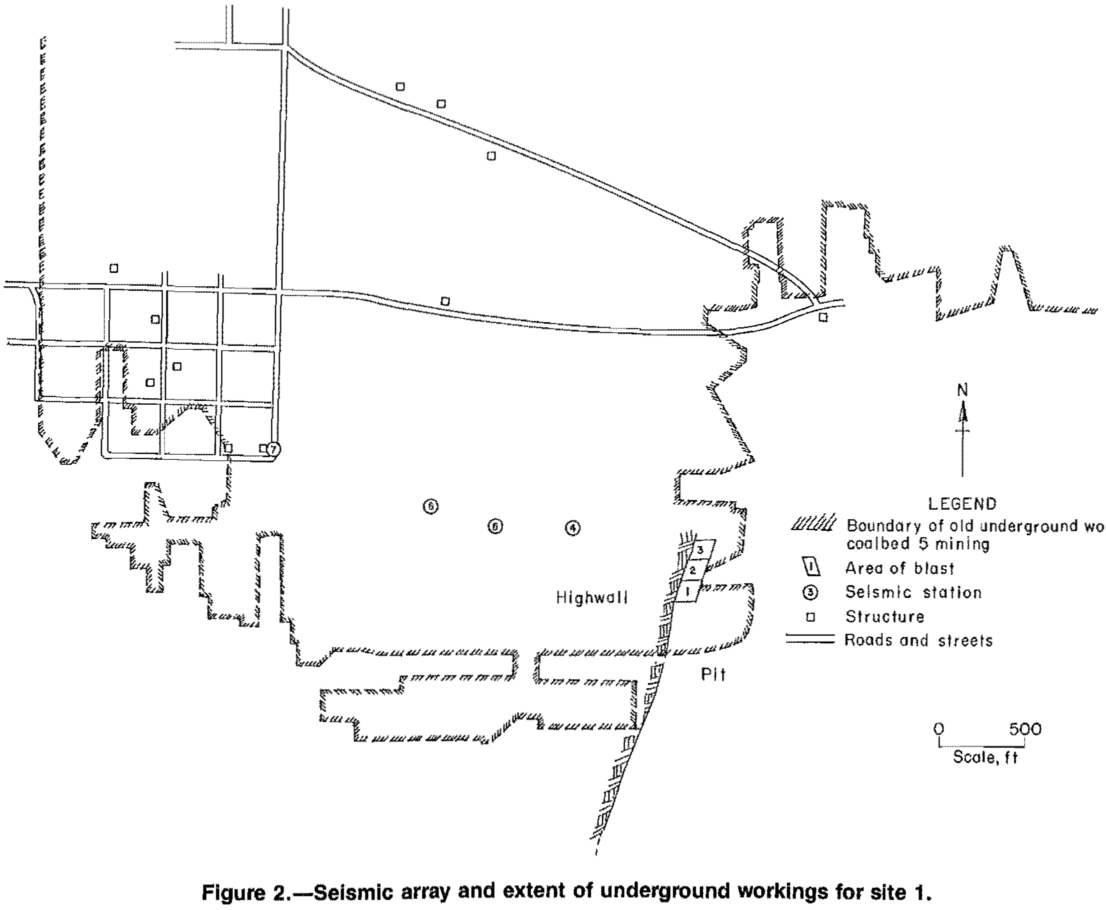

**Figure 2.—Seismic array and extent of underground workings for site 1.**

used a northern array. At the time of the Bureau tests, the mine was using an echelon 17- by 100-ms blast design. (This pattern has 17 ms between holes in a row and 100 ms between rows.) Several other blast designs had previously been in use.

Most significant at this site are the extensive abandoned underground workings in the No. 5 coalbed located about 225 ft below the surface and last mined about 1931. Portions of the No. 4 coalbed located at a depth of about 325 ft beneath the east side of Blanford were also mined. Current surface mining is in the No. 6 coalbed at a depth at about 85 ft. Drilling logs at this site characterize the upper 60 to 75 ft as "sand and drift." For this site as well as most of the others, the closest monitoring station locations are not shown. They were moved between shots to maintain a straight alignment.

## Site 2

This site is near Blanford and still thought to be in the glacial till zone (figs. 3–4). A small residential community is located to the northwest of the active pit. Members of this community are complaining of noticeable ground vibrations from surface mine blasting of the No. 3 coalbed at the mine. According to maps provided by the mining company, the town is completely underlain by abandoned underground mine workings in the same No. 3 coal at depths of 110 to 150 ft.

The placement of the vibration monitoring stations for the Bureau's shot 6 are also shown in figure 3. The farthest two stations were placed next to occupied private homes. Station 1 was set at the base of a 10-ft clay (soil and loess) layer for all the monitored shots.

Four drill logs were provided by the mining company along the line of seismic stations nearly out to station 5. From these, a generalized geologic cross section was prepared (fig. 4). The subsurface geology associated with the coal mine can be characterized as a series of flat-lying horizontal beds of varying rock types. A thin veneer of soil (less than 10 ft and already removed in the figure 4 section) overlies an approximately 10-ft-thick layer of clay. Beneath the clay lies 10 to 20 ft of sand, gravel, and drift, which may have been deposited by ancient glacial activity. This is underlain by a competent shale layer, about 20 ft thick. Beneath the shale is a 40- to 50-ft layer of massive light-gray rock composed of high percentages (30 to 50 pct) of sand and clay, which some drilling logs identify as a sandstone while others call it a sandy shale. Figure 4 labels this zone "sandy shale". Directly below, at a depth of about 100 ft, is the 5-ft-thick No. 3 coalbed. An underlying secondary coal seam is observed to begin between wells 1 and 2, separated from the main seam by layers of fire clay and shale. The deepest recorded stratum is described in the drilling logs as "sandy shale."

After the experimental program and data analysis for this study were completed, this mine supplied additional structural information that could be of use in the event of a followup study. The maximum thickness of surface soil and loess is 10 ft. Beneath these deposits, the unconsolidated section consists of a network of glacial "buried valley-fill" deposits and

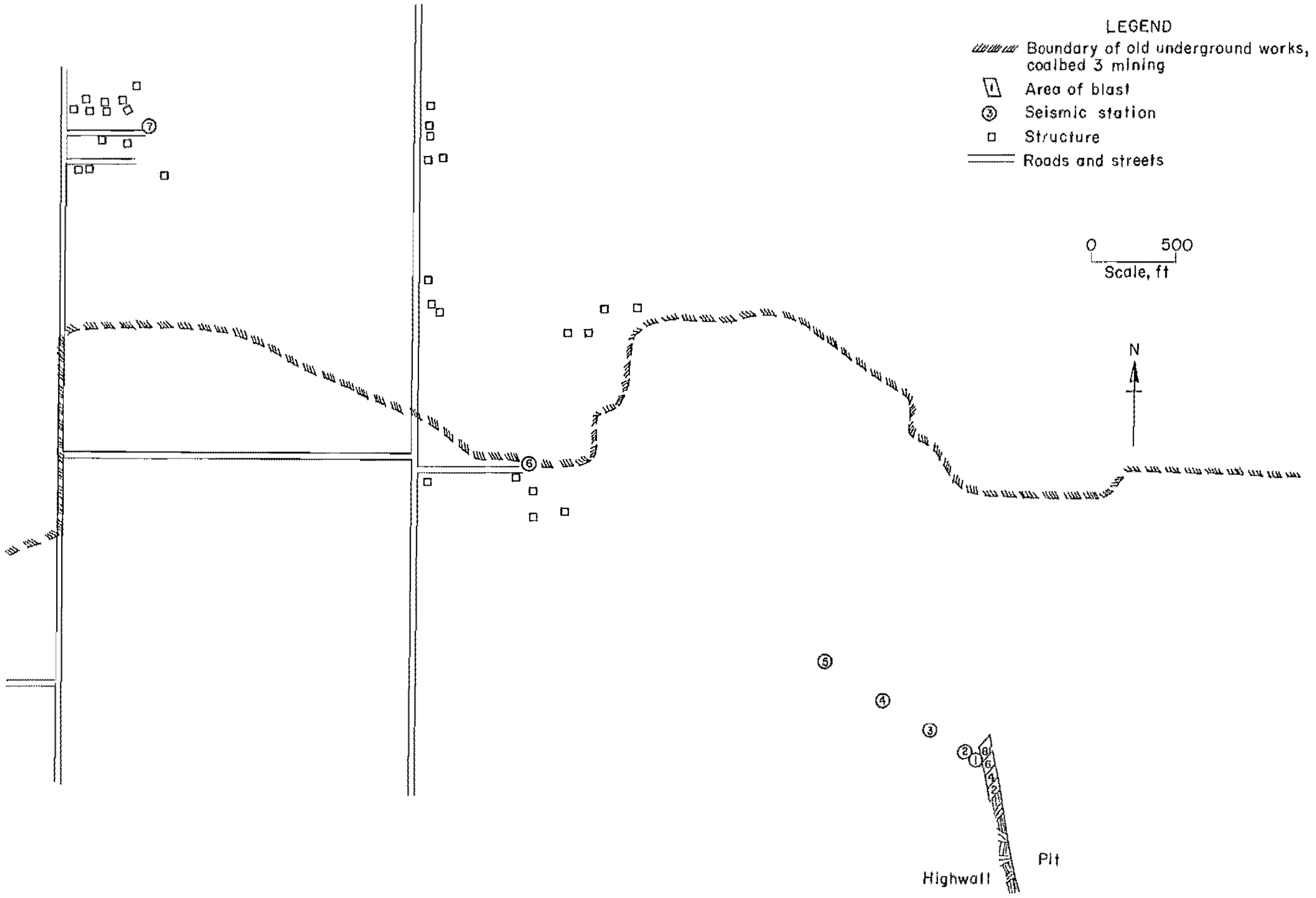

Figure 3.—Seismic array and extent of underground workings for site 2.

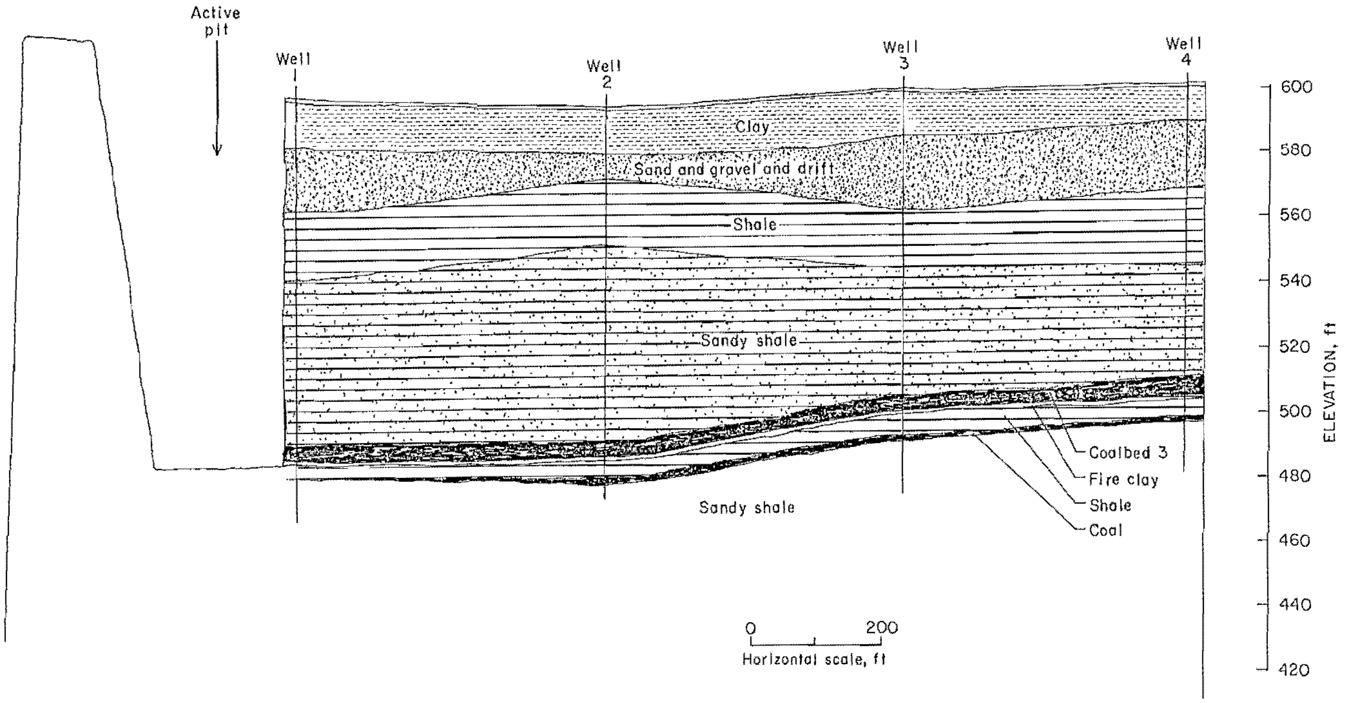

**Figure 4.—Generalized cross section from mining company drill logs along the seismic array between the highwall and monitoring station 5, for site 2, looking southwest.**

ground moraine deposits. Ground moraine glacial till lies between pre-glacial valleys, has a thickness up to 20 ft, and contains minor sand lenses. Some of these lenses have entrapped ground water. In some locations, the glacial drift (till and sand-gravel) extends to and even through the coal, acting as a coal cutout.

The bedrock is also not as simple as depicted in figure 4. It contains lenticular sandstones of considerable laterial extent and up to 60 ft thick and also thin limestone marker beds (less than 1 ft thick), which could influence vibration wave characteristics.

## Site 3

Site 3 is also on the edge of a small community, but near Evansville. The active surface mine itself is not undermined. However, the nearby community is, and the propagation-monitoring array extends just into this region (fig. 5). Current surface mining is in the No. 7 coalbed, and the abandoned underground workings are in the No. 5 coal, with a depth of about 240 ft.

Three drill logs were obtained by the operator near seismic station 4. They describe a layer of surface material as "sandy clay," "sandy muck," and "gravel," 50 to 70 ft thick. Beneath this, the rock being blasted appears very solid, competent, and massive. All monitoring stations were on top of the sandy layers except the one closest to the blast.

For this site, the face orientation was such that the seismic array was not behind it, but at an angle off the front (fig. 5). A massive, full-height buffer from previous blasts was left in front of the face, causing seismic energy to take a path down and around the buffer and/or across the piled-up muck. Slightly lower vibration amplitudes were consequently expected.

## Site 4

This site is also near Evansville on the edge of a community that is in part undermined by abandoned workings (fig. 6). With blasting at the pit's northernmost extent, the array was placed directly behind the face and toward the east. The farthest three monitoring stations were over the abandoned 90-ft-deep No. 5 workings. Current surface mining is also in the No. 5 coal at depths of 30 to 125 ft.

## Site 5

This is the same mining operation as site 4. Because the mine operator suspected a different vibration situation when blasting in the south and central part of the pit, a different seismic station array direction was used (fig. 7).

Lacustrine deposits exist in the area of monitoring stations 2 and 3 and were suspected to influence the vibrations. In addition, stations 5 and 5B were over the old workings.

## Site 6

This Evansville area site is not undermined; however, unconsolidated surface deposits of about 20-ft thickness are known to exist and possibly produce low-frequency vibrations (*2*). Beneath the windblown loess soil layer are lacustrine silt and clay deposits with inclusions of sand and gravel. Figures 8 and 9 show the seismic station array layout and a sectional view nearly exactly along the seismic station array line. The active surface mining is in the No. 6 coal at a depth of about 100 ft.

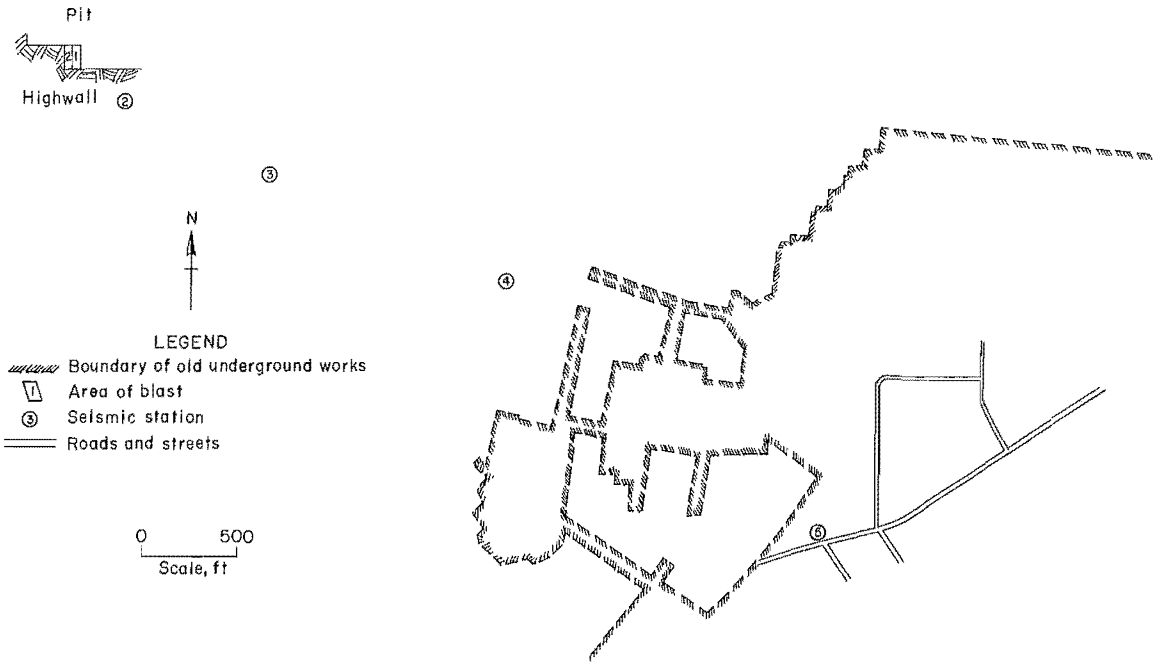

Figure 5.—Seismic array and extent of underground workings for site 3.

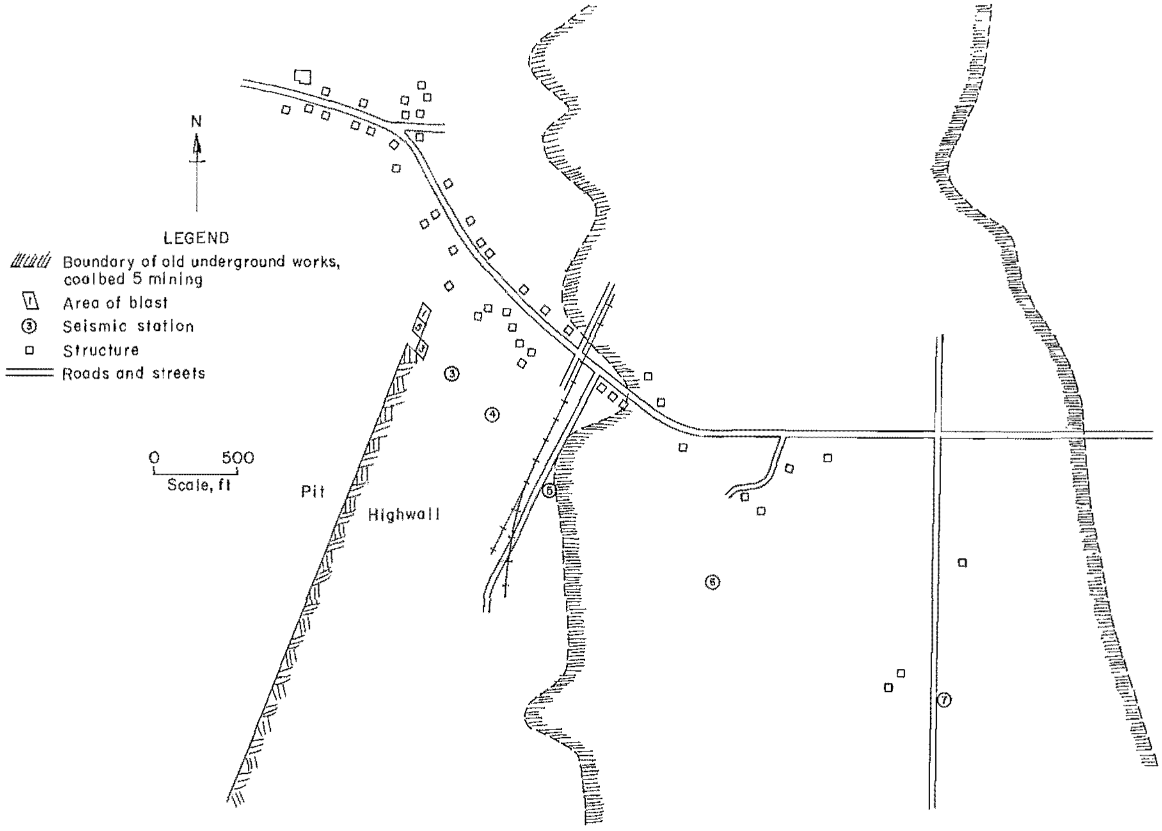

Figure 6.—Seismic array and extent of underground workings for site 4.

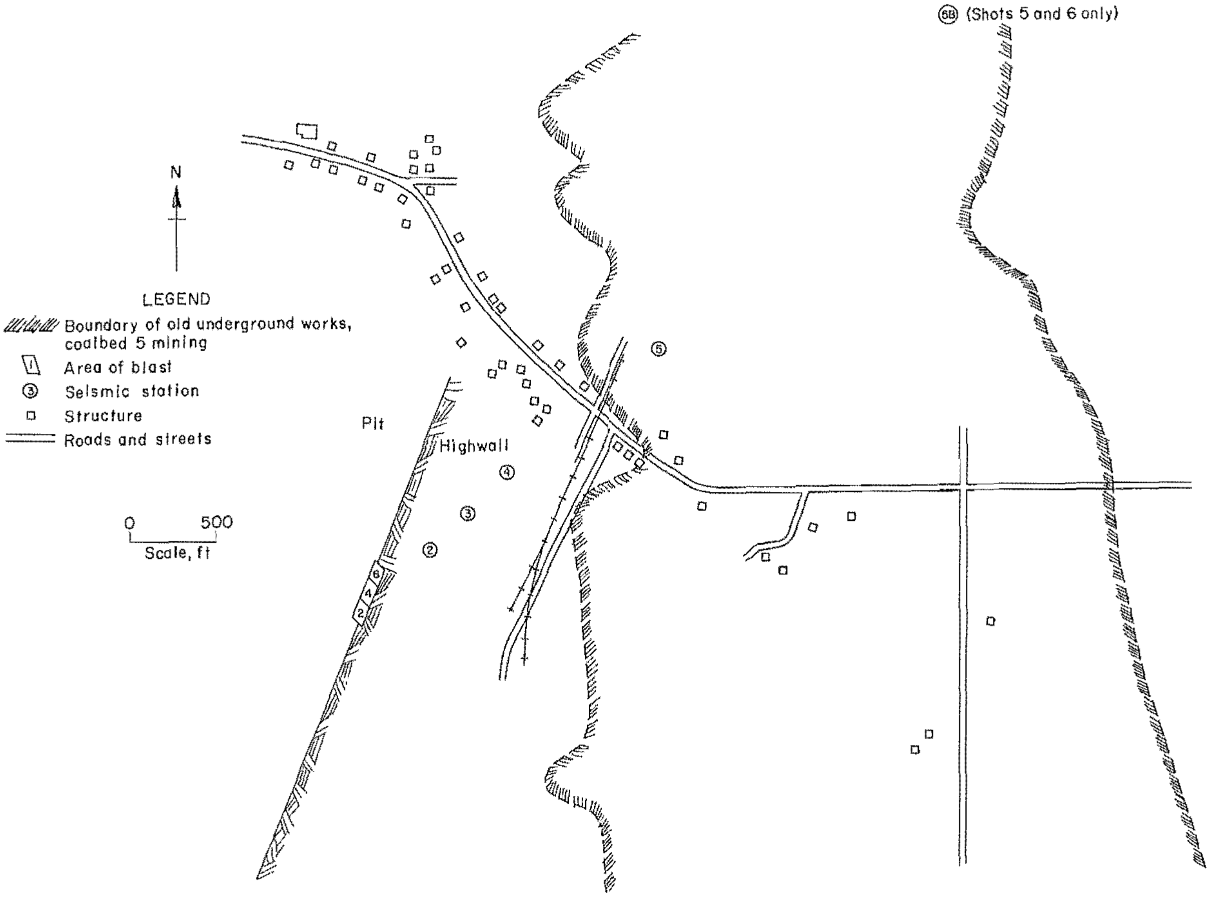

Figure 7.—Seismic array and extent of underground workings for site 5.

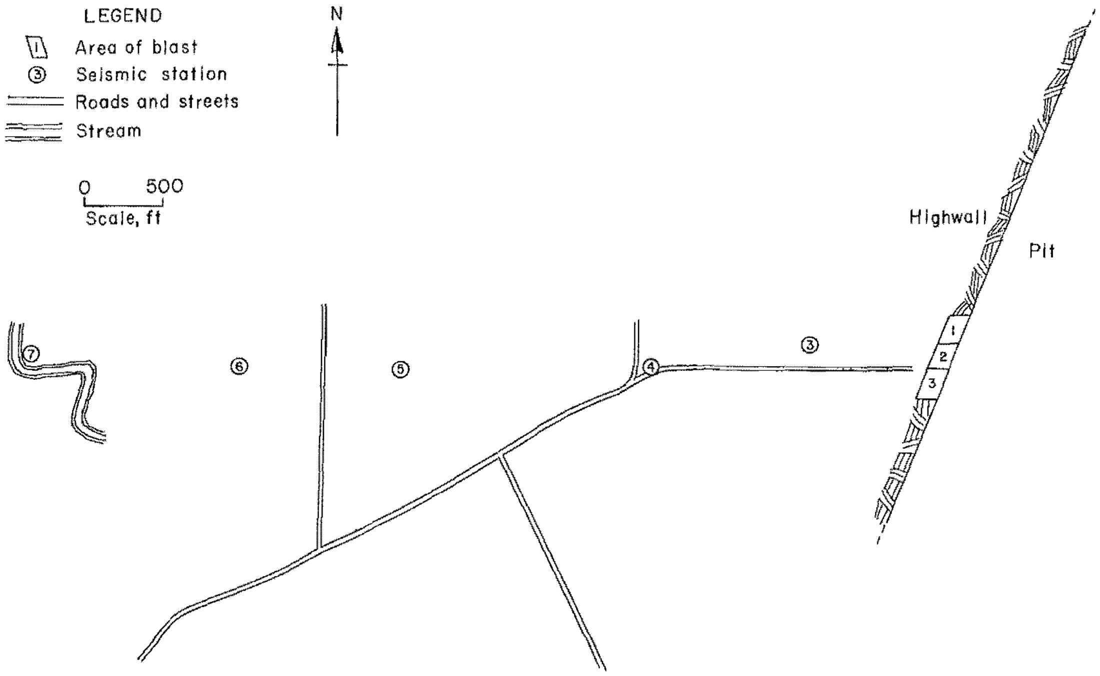

Figure 8.—Seismic array for site 6.

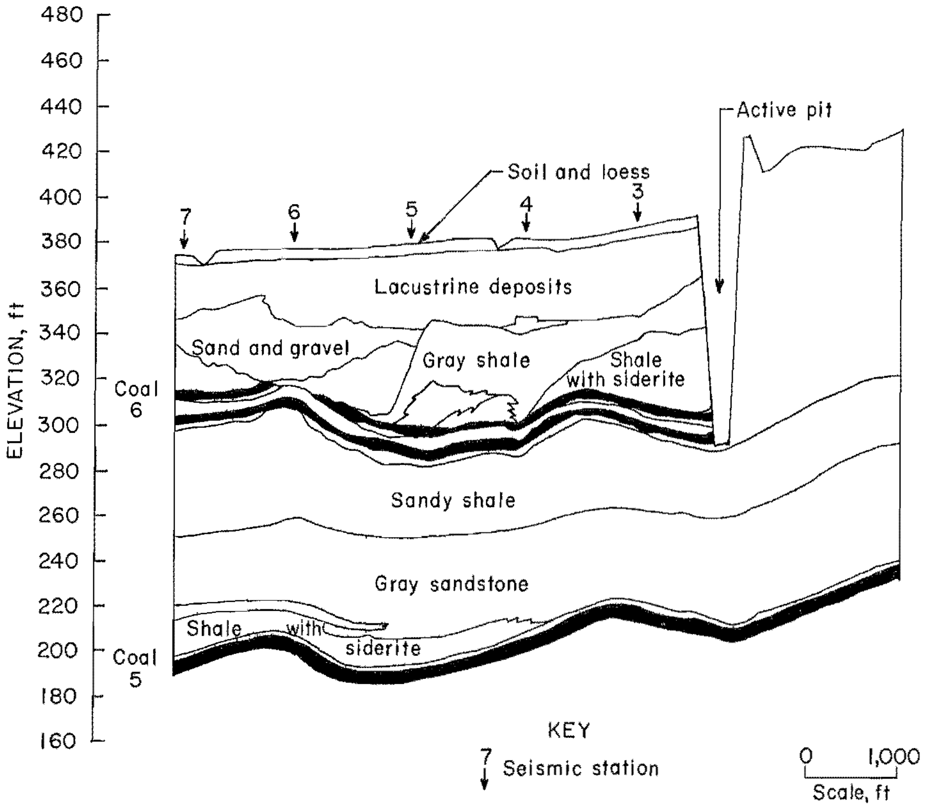

**Figure 9.—Sectional view of site 6 showing locations of seismic stations and active pit, looking south.**

## Site 7

This site is a northerly one, near Terre Haute, with a community of new homes on a series of hills above a river valley. Thirty-eight sets of records were available for study, 20 collected at one home by the company and 18 at two others by the Indiana DNR. Analysis was limited by the narrow range of distances and the small number of blasts per blast design. Since 4 designs were represented by only 20 blasts, not enough replications existed for good analysis of the blast designs.

Current surface mining at this site is in the No. 6 coal. The area is also extensively undermined by old workings in three other coalbeds. The active pit and one of the closer monitored structures are undermined at coalbed No. 4 at a depth of 268 ft. Beneath the farthest structure (at 5,200 to 6,800 ft) are old workings in the Nos. 3, 4, and 5 coalbeds. Depths to coalbeds 3 and 5 are given as 350 ft and 140 to 192 ft, respectively. Total mined coal from the shallow No. 5 coalbed was 8 million st during the period 1917-36.

## Site 8

This Evansville area site is not undermined. All blasting records are from DNR monitoring conducted at one residence. Distances from the active surface mine ranged from 600 to 4,000 ft, with charge weights adjusted accordingly. During the 4-month period represented by the data available, the company tried 15 variations of hole, row, and deck delays in an effort to control vibrations. Because only a few values were available for some of the designs (as few as two vibration amplitudes), a reliable and definitive comparison could not be made for this study. The influence of blast design could be studied at a future date, provided the mine is willing to cooperate.

A drill hole near the monitored structure found 10 ft of soil, 40 to 45 ft of a shale rider, and a few feet of parting. The active mining is in the No. 7 coal at a depth of about 70 ft.

## Site 9

This site is near site 8 and is also not undermined. However, old spoils lay between the blasts and the monitoring sites, and the area has old surface workings visible as long, water-filled pits. Four structures were monitored by the DNR and the mining company; however, only two to four blast records per structure were available for the 2-month period. Blasts were relatively simple, consisting of two to three rows and full column charges. An interesting variation here is the angle drilling (18° toward the toe), to assist in the casting action. When blasting within 1,300 ft of structures, this mine does not cast-blast. No detailed information was available on blast design, pit size, or orientation.

# TEST BLASTS

Data for this study consist primarily of vibration records collected by five- to seven-station seismic arrays from both production and single-charge blasts. Sites 1 through 6 were studied with Bureau seismic arrays. In addition, the Indiana DNR was able to supply vibration data for three sites that were not available for Bureau monitoring. These additional sites were therefore not analyzed by the single-charge methods.

The actual test blasts monitored are listed in table 1. Seismic array distances listed are distances out to the stations that actually recorded useful data. For instance, the array for site 4, shot 2, had stations beyond 659 ft, but the vibration levels were too low to trigger the seismographs.

Site 1 data were supplemented by a large amount of data collected by the company and Indiana DNR. Although not ideal for generation and propagation analyses, the State and company data provided insight on the general vibration levels from the four blast designs used during the 1-year period spanned by the monitoring program and also local measurement site differences. This research was previously described in detail in RI 9078 (*1*).

## Single-Charge Blasts

Not all the mines studied were able to provide ideal single-charge blasts because of fears that such blasts could cause later production problems. Sites 1, 2, and 6 fired bottom-load single charges with weights equal to production blast charge weights per delay. Sites 4 and 5 fired a single hole with two separated charges (decks). As with production blasts at this mine, both decks were initiated with the same delay and were therefore added together for charge weight per delay calculations.

The site 3 mine uses four decks for its production blasts. While unwilling to fire a single charge, the operator was able to lengthen the deck delays to assist the researchers in the time separation of the individual charges. Instead of delays of 125, 150, 175, and 200 ms, this site's single-hole shot had delays of 25, 125, 250, and 350 ms, giving at least 100 ms between charges.

## Production Blasts

Table 2 lists the production blast designs analyzed in this comparative study. All blasts were the mine's normal designs, in use at the time, and not modified for vibration control. As far as Bureau researchers could determine, all used standard pyrotechnic delays with their inherent inaccuracies. One production blast at site 6 employed an experimental system that resembles Nonel [7] and is called LVST (low-velocity signal transmission). It is claimed to be more accurate.

**Table 1.—Blasts monitored at Indiana test sites**

| Site | Shot | Distance of seismic array, ft | Blast type[1] | Maximum charge weight, lb | |
|---|---|---|---|---|---|
| | | | | Per hole | Per delay |
| 1 | 1 | 54–2,693 | PR | 450 | 125 |
| | 2 | 92–2,675 | PR | 450 | 125 |
| | 3 | 90–2,640 | PR | 450 | 125 |
| | 4 | 65–2,615 | SC | 125 | 125 |
| | 5 | 54–2,620 | SC | 125 | 125 |
| | 6 | 200–5,710 | PR | 950 | 250 |
| | 7 | 200–5,400 | PR | 950 | 250 |
| 2 | 1 | 86–8,095 | SC | 1,800 | 1,800 |
| | 2 | 56–8,065 | PR | 1,800 | 1,800 |
| | 3 | 115–8,039 | SC | 1,800 | 1,800 |
| | 4 | 70–7,994 | PR | 1,800 | 1,800 |
| | [2]5 | 125–7,955 | SC | 1,800 | 1,800 |
| | 6 | 103–7,882 | PR | 2,000 | 2,000 |
| | 7 | 150–7,842 | SC | 2,000 | 2,000 |
| | 8 | 150–7,769 | PR | 2,000 | 2,000 |
| 3 | 1 | 152–4,600 | PR | 660 | 165 |
| | 2 | 183–2,597 | SH | 660 | 165 |
| | 3 | 141–4,620 | PR | 660 | 165 |
| 4 | 1 | 49–3,850 | PR | 102 | 102 |
| | 2 | 75– 659 | SC | 102 | 102 |
| | 3 | 40–3,800 | PR | 102 | 102 |
| | 4 | 70–1,260 | SC | 102 | 102 |
| | 5 | 35–1,225 | PR | 102 | 102 |
| 5 | 1 | 297–1,223 | SH | 102 | 102 |
| | 2 | 182–2,256 | PR | 102 | 102 |
| | 3 | 271–1,105 | SH | 102 | 102 |
| | 4 | 129–2,108 | PR | 102 | 102 |
| | 5 | 261– 954 | SH | 102 | 102 |
| | 6 | 114–1,952 | PR | 102 | 102 |
| 6 | 1 | 107–6,050 | SC | 1,350 | 1,350 |
| | 2 | 114–5,950 | PR | 2,150 | 1,350 |
| | [3]3 | 118–5,875 | PR | 2,400 | 1,350 |
| | 4 | 122–5,800 | PR | 2,500 | 1,350 |

[1] PR = production; SC = single charge; SH = single hole.
[2] Misfire.
[3] LVST (low-velocity signal transmission) initiation system.

**Table 2.—Production blast designs at Indiana surface coal mines**

| Site | Design type and delays, ms | Number of decks | Hole diam, in | Typical charge weights per delay, lb | Burden, ft | Spacing, ft |
|---|---|---|---|---|---|---|
| 1 | Echelon,[1] 17 by 100 | 4 | 12-1/4 | 125 | 25 | 30 |
| 2 | Rows parallel to face, 25 between holes.[2] | 1 | 10-5/8 | 2,000 | 36 | 36 |
| 3 | Echelon,[3] 42 | 4 | 6-3/4 | 165 | 17 | 16.5 |
| 4 | Echelon,[1] 25 by 42 | [4]2 | 6-3/4 | 102 | 14 | 14 |
| 5 | . .do[1] | [4]2 | 6-3/4 | 102 | 14 | 14 |
| 6 | Echelon,[1] 17 by 100 | 2 | 12-1/4 | 1,350 | 32 | 32 |
| 7 | Varied | Varied | 9-7/8 | 150–1,400 | 20–22 | 25 |
| 8 | Echelon and cast | Varied | 10-5/8 | 100– 350 | NA | NA |
| 9 | Casting | 1 | 12-1/4 | 1,000–2,500 | NA | NA |

NA Not available.
[1] Echelon design: 1st number is delay interval between holes in a row and 2d number is delay between rows.
[2] Between-row delays were 64 ms for 3 blasts and about 150 ms for 1. Rows were short, with 5 or fewer holes each.
[3] 42 ms between holes in a row and between the last hole in a previous row and the 1st hole in the next row.
[4] Both decks had the same 200-ms delays.

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[7] Reference to specific products does not imply endorsement by the Bureau of Mines.

# RESULTS OF FINDINGS

## VIBRATION AMPLITUDES AND PROPAGATION PLOTS

Square-root-scaled propagation plots were prepared for each of the sites studied (fig. 10). Each plot has separate least squares regression lines and standard deviation bars for measured peak particle velocities for the single-charge and production vibration data. Generally, the production blasts produced vibration amplitudes two to three times those from the single charges despite the same charge weights per 8-ms delay interval:

| | |
|---|---|
| Site 1 ... | 2.5–3 times |
| Site 2 ... | 2–3.5 times |
| Site 3 ... | 3–4 times |
| Site 4 ... | 1.7–3 times |
| Site 5 ... | 1–3 times |
| Site 6 ... | 1–2.3 times |

These amplitude differences are greater at farther distances, suggesting that the delays from the production blasts are only long enough to influence and reduce vibration (through time-delay-produced phase interference) for the closest measurements. As suggested in the site 1 study (RI 9078), the long-period surface-type waves observed at far distances are not subject to destructive wave interference because their periods are far longer than the 8- and 9-ms minimum intervals used between charges. Hence, higher than normal vibrations are observed at far distances. The influence of blast design on vibration frequency is discussed later in this report.

### Site Comparisons

Least squares regressions of mean velocities for the various sites are compared in figure 11. Standard deviation bars are omitted here for clarity. Except for site 5, the single-charge (or single-hole) values (fig. 11*A*) group fairly well throughout the distance range. Values for sites 1, 4, and 6 are virtually identical close in and diverge slightly at large distances. The two sites with highest velocities are the undermined site 1 (Blanford) and the nonundermined site 6, with the thick lacustrine surface deposits. The site 5 plot has a much greater slope, with unusually high values close in and very high attenuation, giving the lowest values at large distances.

Production blast comparisons (fig. 11*B*) have less variability than found for single charges, and all the data could probably be represented by a single propagation line. The Blanford values, site 1, are the highest at all distances; however, the total spread of means for all sites is less than ± 40 pct. This result must be surprising and discouraging to those who believe that blast designs can be used to significantly reduce or control average vibration amplitudes. A wide variation of delays, decks, and charge weights are represented by these six sites.

Three additional coal mine sites were studied by using State DNR- and company-collected vibration records (figs. 12–16). These measurements were collected at nearby homes and not with widely spaced propagation arrays. Because of the resulting data clustering, no attempts were made to fit least squares propagation lines. For comparisons of relative amplitudes, the mean regression line is shown for production blasts at site 3, being the approximate middle line in figure 11*B*, production blast summary.

Site 7 amplitudes cluster around the site 3 mean; however, the full-column casting blasts are noticeably lower in amplitude than both the decked casting blasts and the few echelon values in the comparison plot (fig. 12). This is consistent with observations at the Universal Mine (*1*), where increased blast design complexity used to lower charge weights per delay did not necessarily produce corresponding lower vibration amplitudes.

All echelon blasts for site 7 are shown in figure 13*A*. They are generally higher than the site 3 mean and about the same at all three measuring locations. Casting blasts are plotted in figure 13*B*. Evident is the high variability of amplitudes for both the nearest and farthest monitoring locations.

Site 8 amplitudes are given in figure 14. Most are on the high side. A single value for a 42- by 100-ms echelon blast stands well below the site 3 mean at close distances. However, two measurements, at large scaled distances of about 200 $ft/lb^{1/2}$, group with the other blast designs. An expanded version of these data is shown in figure 15.

Site 9 amplitudes are given in figure 16. Amplitudes from closer monitoring are below the site 3 comparison mean; however, distant monitoring gives values right on the line. From this small amount of amplitude data, this site appears not to have a vibration problem.

### Comparisons With Historical Vibrations

Vibration values for both single charges and production blasts are plotted in figure 17 for comparison with the historical mean and envelopes from RI 8507 (*10*). The mean line represents the surface coal mine summary from RI 8507, figure 10, "maximum horizontal," and is not the mean for the data points shown. Similarly, the envelopes are upper and lower limits from the same RI 8507 figure. The maximum horizontal was usually the radial component of motion.

Single-charge data fit within the envelopes with one minor exception. Many are on or below the RI 8507 mean, particularly close in. Production data, by contrast, are mostly above the RI 8507 mean, particularly at farther distances. Many measurements exceed the historical maximum envelope. Additional comparisons for various blast designs are given in the site 1 study, based on the large amount of data collected by the mine and State DNR (*1*). In that previous study, the maximum envelope was approximated by a line representing two standard deviations ($2\sigma$) above the mean.

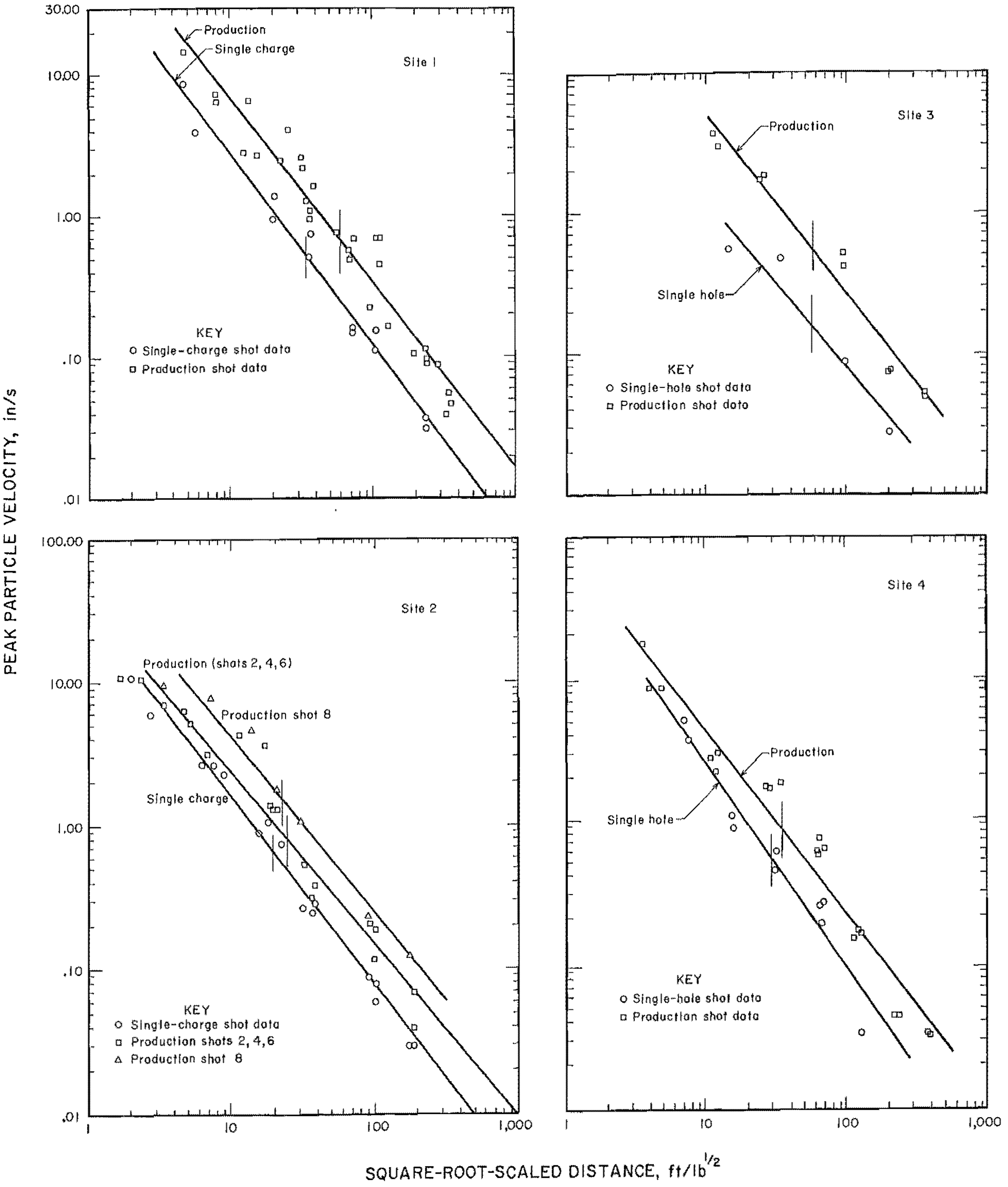


**Figure 10.—Propagation plots of production, single-charge, and single-hole blasts.**

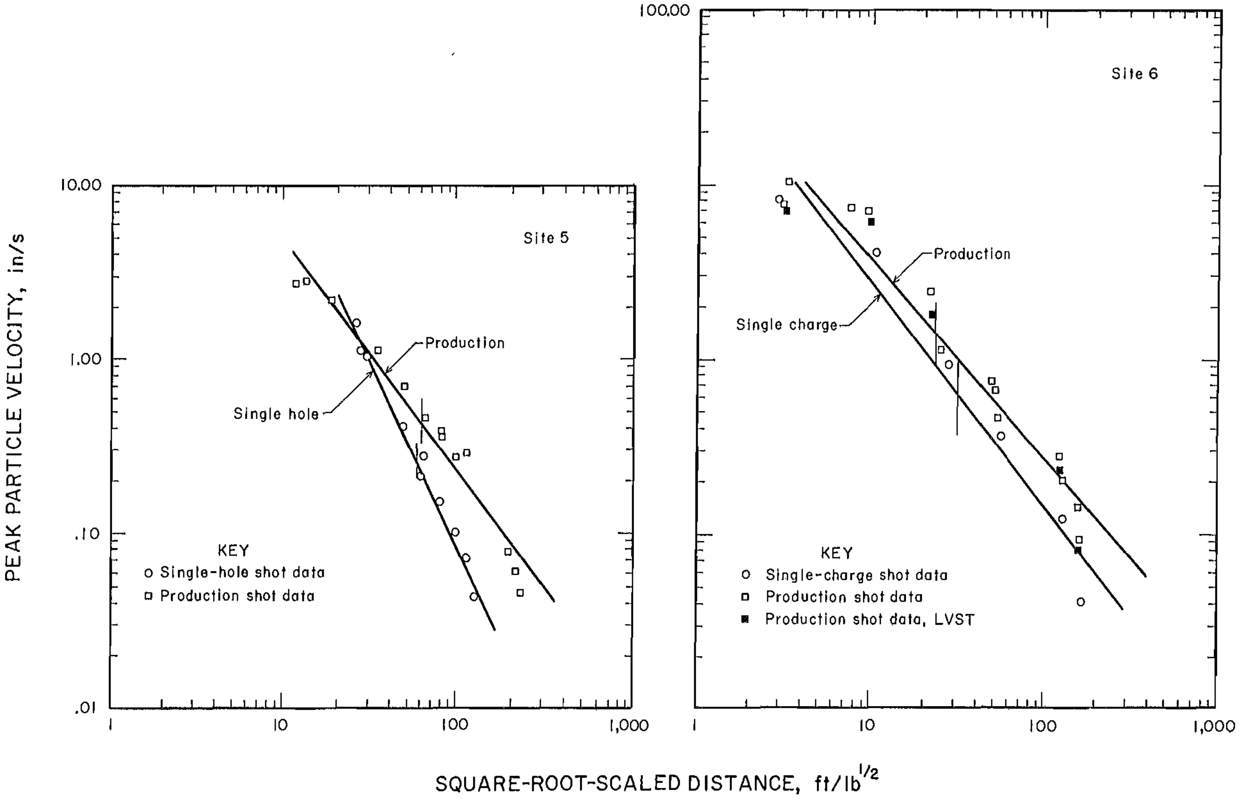


Figure 10.—Propagation plots of production, single-charge, and single-hole blasts—Continued.

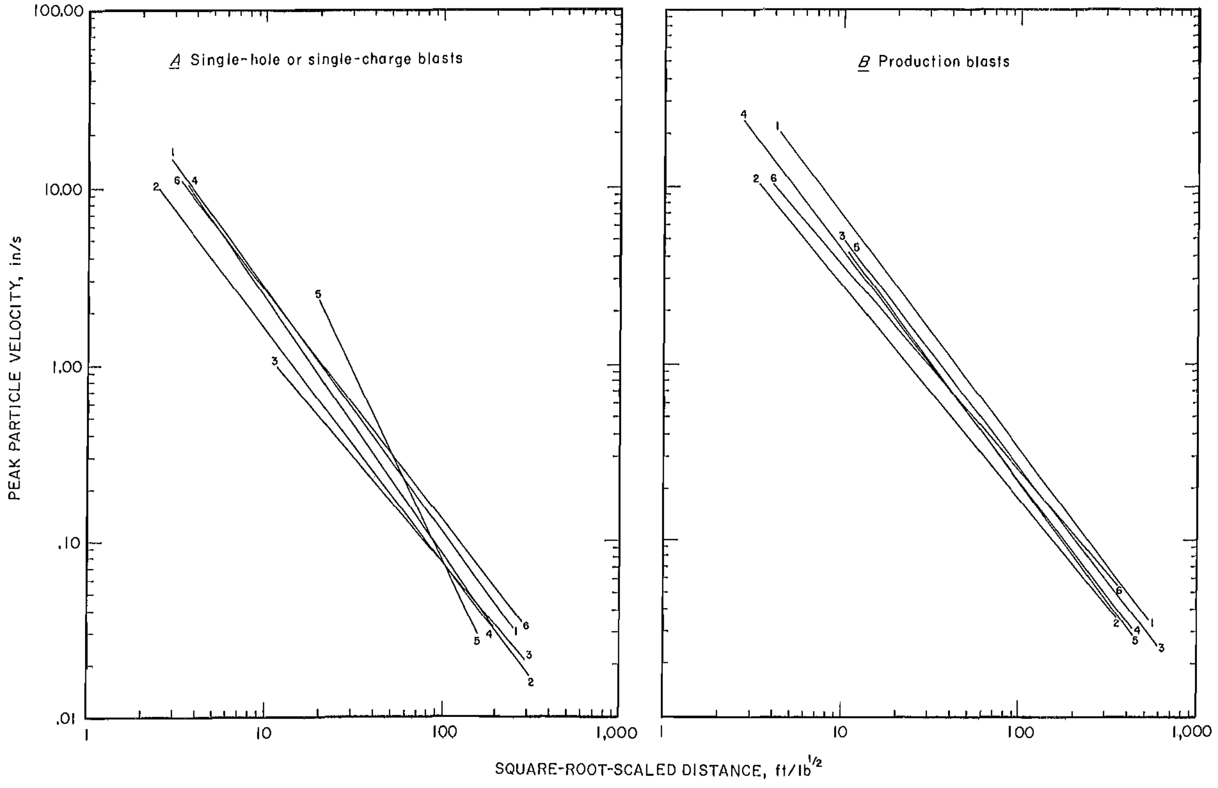


Figure 11.—Propagation plot regressions for single-hole, single-charge, and production blasts for six Indiana coal mines monitored by the Bureau of Mines.

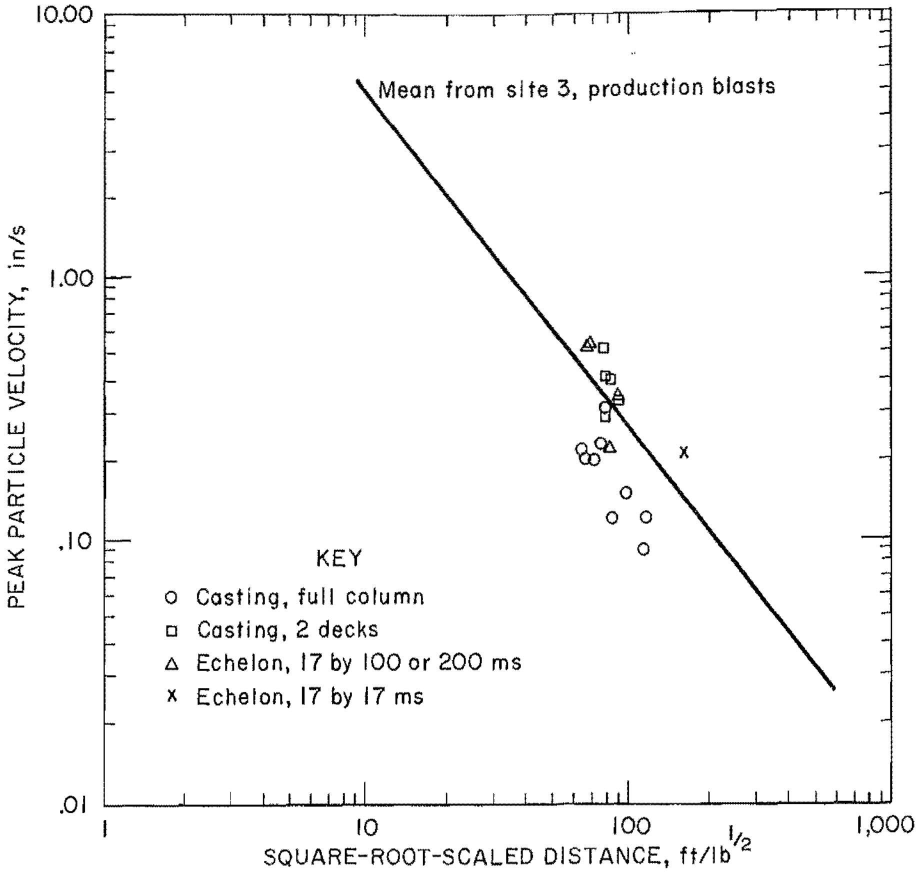


Figure 12.—Vibration amplitudes for site 7 at closest structure and for four blast designs.

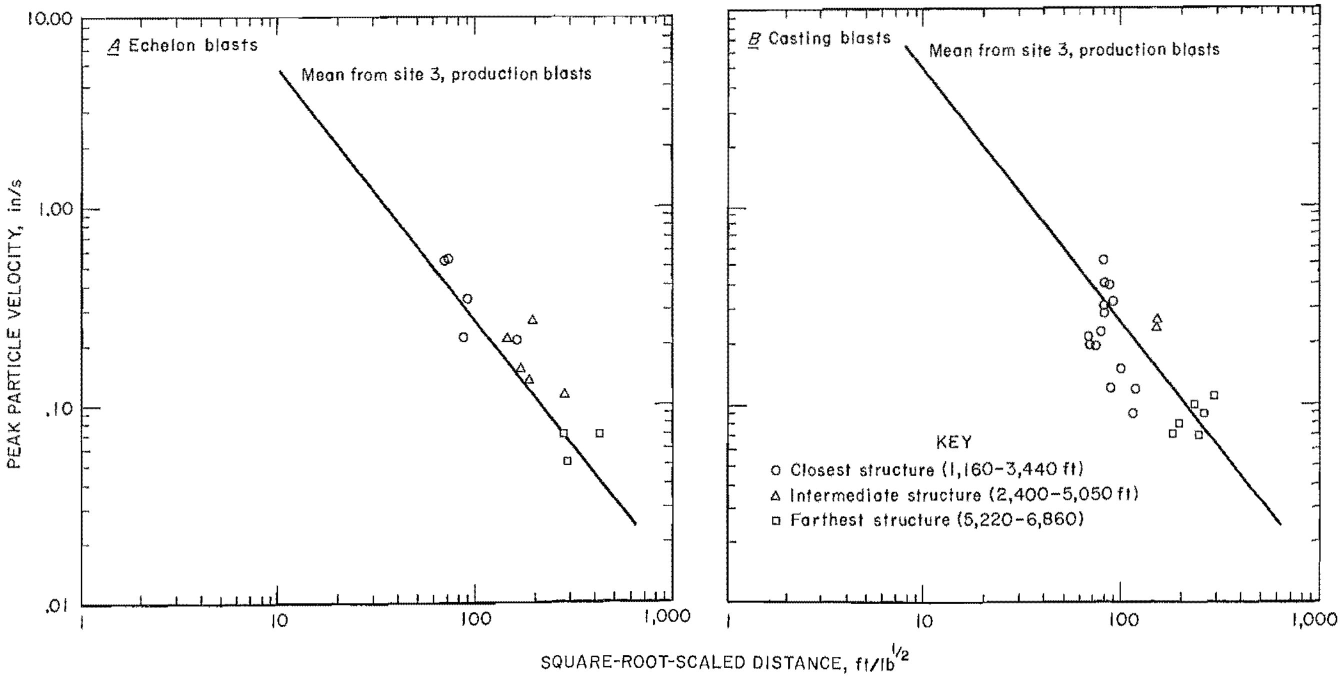


Figure 13.—Vibration amplitudes for site 7 for echelon and casting blasts.

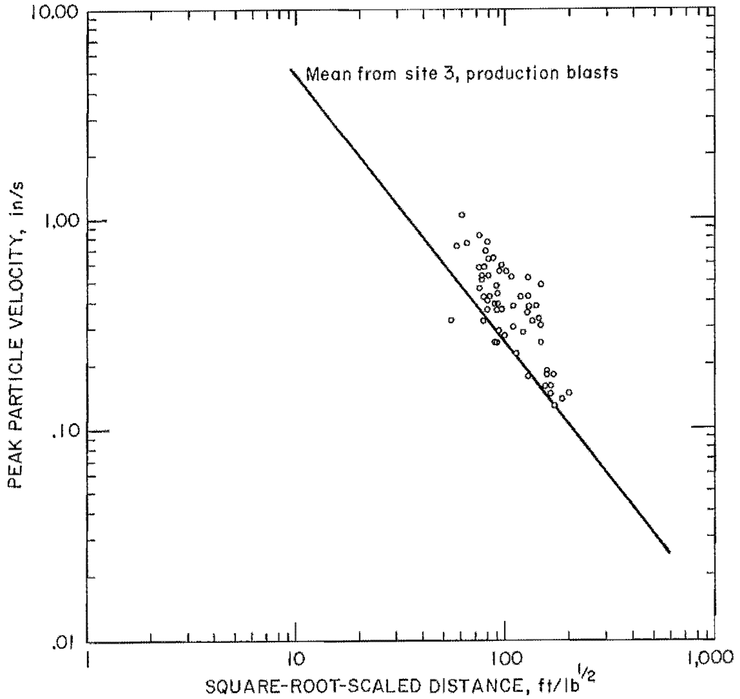


Figure 14.—Vibration amplitudes for site 8.

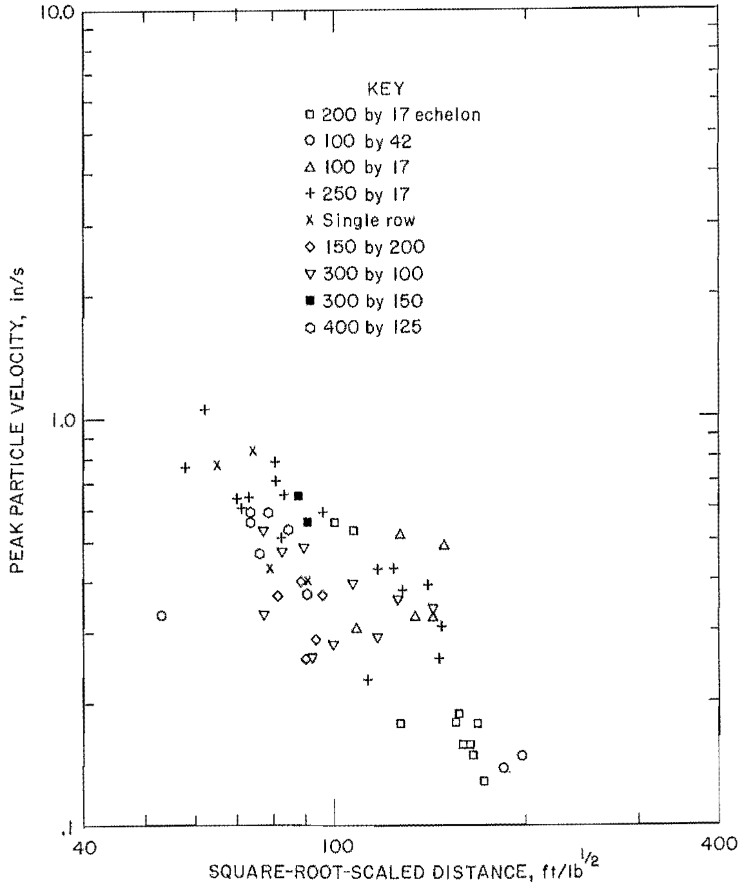


Figure 15.—Vibration amplitudes for site 8 showing blast design influences.

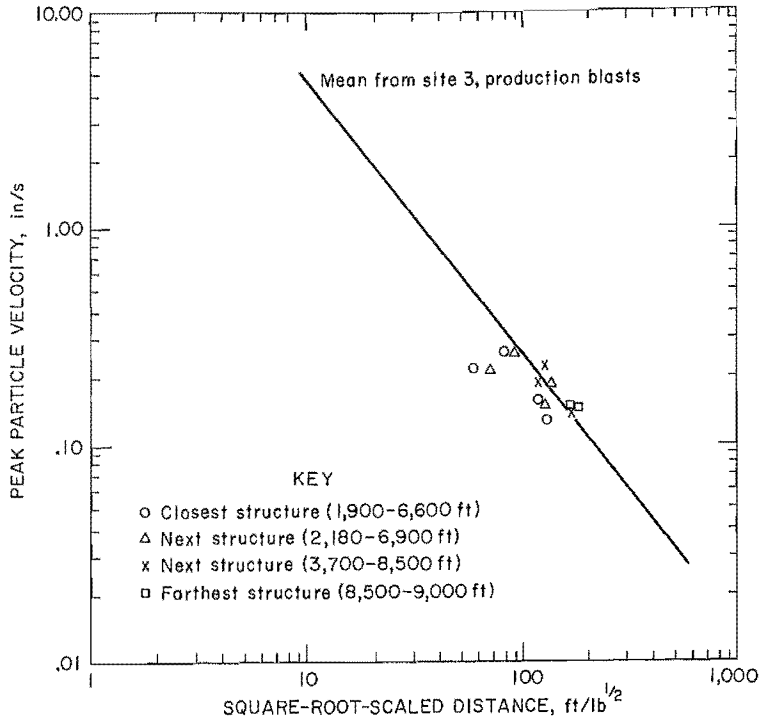


**Figure 16.—Vibration amplitudes for site 9.**

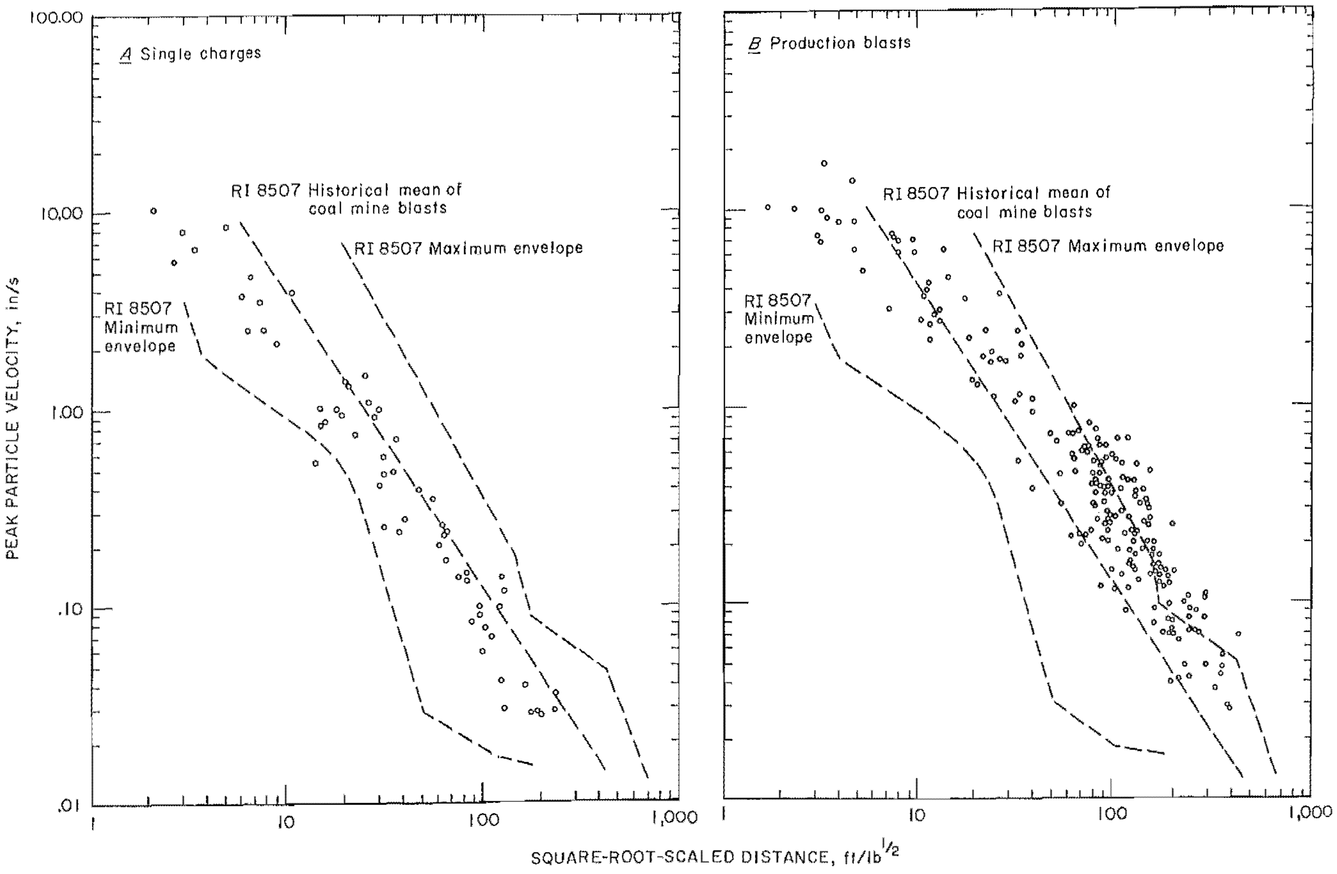


**Figure 17.—Measured vibrations from single charges and production blasts and comparisons with RI 8507 (*10*) coal mine mean and data envelopes.**

# VIBRATION FREQUENCIES

## Summary Observations

A total of 657 vibration time history records were collected by the Bureau from 33 blasts at six surface coal mine sites in Indiana. These were supplemented by 398 DNR-collected records at three additional mines. Figures 18–23 show sets of vibration traces for a significant component of motion for each site, for both one single-charge (or single-hole) (*A*) and one production blast (*B*). Such sets of records show the character of the vibration waves as they are generated and as they change as they propagate to large distances. Comparisons between the single charges and production blasts show, in theory, differences produced by the blast design. Specifically, the production blast can be approximated by a superposition of the time-delayed single charges and should have frequencies characteristic of the single charge, the ground's natural frequency, and the delays between charges or groups of charges. Unfortunately, combinations of deck, row, and hole delays, with their inherent inaccuracies, combined with geometric factors (travel path differences), give records of great complexity, which differ from those predicted by superposition.

The frequency characteristics of the vibration records are summarized in table 3. Low frequencies (vibrations of 6 to 10 Hz) occur at most sites for both single charges and production blasts. At many sites (1, 2, 3, and 6), very low frequencies (VLF) of 3 to 5 Hz occur at larger distances of about 2,000 ft but are generally of low amplitudes at such distances, less than 0.1 in/s peak particle velocity. Low frequencies appearing at long distances sometimes decay to insignificance at even greater distances, such as for production blasts at sites 3 and 4. All sites studied except site 8 favor the generation of low or very low frequencies. Because the sites do not behave the same with regard to low frequency and distance, it is likely that more than one mechanism of low-frequency generation is present.

Sites 1, 2, 3, and 6, and possibly 7 and 9, produce very long duration vibrations of 6 or more seconds at far distances, beyond about 1,000 ft. These are well beyond source durations. Figure 24 shows some of the longest duration records collected, for site 6 single-charge and production blasts at relatively far distances of about 6,000 ft. These are nearly single frequency and appear as beat oscillations. Because of the late arrivals and long durations, these low-frequency vibrations cannot be direct-arriving surface waves but are likely trapped waves taking very long effective travel paths through multiple reflections. Apparently, the mechanism trapping the waves and generating the low frequencies, e.g., a surface layer of low propagation velocity, also provides a long effective travel time. A low-velocity layer would also have a high energy absorption leading to eventual loss of vibration amplitude for these low-frequency waves. Such a loss of specific low frequencies was noted to occur at sites 3 and 4. The phenomena of trapped waves is discussed later in this report in the section "Theoretical Prediction Models."

Site 6 has a vibration anomaly that appears to be related to the low-velocity surface layer thickness. Figure 25 shows three components of motion for each of two recording stations for the same production blast at this site. Station 4 was over thin low-velocity surface deposits, and 5 was at the location where the deposits thickened. The sectional profile in figure 9 shows the station locations and material descriptions. Initially, station 5 data were not included in the analysis because the abnormal longitudinal-component (radial) amplitude appeared to be instrumental failure. Hence, amplitudes from this station are not included in the propagation plots, figures 10–11 and 17, nor are traces included in figure 23.

Although the overranging of station 5's longitudinal component makes the exact vibration amplitude uncertain, there is no doubt that this vibration is somehow enhanced so that its amplitude does not decrease relative to the much closer station 4. In other words, transverse and vertical components are half the amplitude at the farther station, as expected for normal wave amplitude decay. By contrast, the longitudinal component at station 5 is nearly three-fourths the particle velocity at recording station 4 at about twice the distance and also continues for a longer duration. Because of waveform clipping, it could even be of larger peak amplitude than the closer station. The exact mechanism of wave generation at this transition zone is beyond the scope of this study. However, the thicker low-velocity layer appears to contribute to the anomalous wave amplitudes in addition to the enhancement of low frequencies. The thicker surface layer would enhance low-frequency ground motion (see "Theoretical Prediction Models" later in this report). Therefore, the high-amplitude, low-frequency ground motion may be directly related to the thicker low-velocity layer under station 5.

Vibration characteristics for the nine study sites are graphically shown by special propagation plots with measurements broken down into three frequency bands between 3 and 20 Hz (fig. 26). The technique employed was to directly measure wave periods for the easily visible dominant low-frequency components (frequency = 1/period). Typically, the records had high-frequency beginnings (>10 and sometimes >20 Hz) followed by low-frequency tails, which were often of lesser amplitude (not the peak particle velocity). Note that figure 26 plots particle velocity against distance, not scaled distance. Consequently, the vibration amplitude differences between the sites are partly the result of the different charge sizes (see tables 1 and 2).

## Table 3.—Frequency characteristics of Indiana coal mine blast vibrations

| Site | Single charges |  | Production blasts |  |
|---|---|---|---|---|
|  | Near field | Far field | Near field | Far field |
| 1 | 12–20 Hz at 50–60 ft | 5–6 Hz at distances >800 ft.<br>Amplitude of ~0.15 in/s.<br>Duration of 1.5 s at 1,200 ft. | 9–10 Hz at 54–90 ft | 4–6 Hz at distances >1,200 ft as principal or significant frequency.<br>Amplitudes of 0.10 in/s or less.<br>Durations up to 6 s. |
| 2 | 10 Hz within 300 ft | 7 Hz at distance of 800 ft.<br>Amplitudes of 0.9–1.3 in/s.<br>5 Hz at 4,000 ft but of low amplitude, <0.04 in/s. | 8–9 Hz at 200–300 ft | 7 Hz at distances of 800 ft.<br>Amplitudes of up to 2 in/s.<br>5 Hz at large distances (>4,000 ft) with amplitudes of 0.10 in/s. |
| 3 | 8–10 Hz at 424 ft.<br>Duration of 0.37 s.[1] | 6 Hz at 1,250 and 2,600 ft.<br>Secondary frequency of 3.2–3.4 Hz at amplitude of 0.015 in/s. | 11 Hz at 323 ft | 3–4 Hz at 2,500 ft at 0.04 in/s, about 1/2 the amplitude of higher frequency components.<br>3–4 Hz decays to insignificance at 4,600 ft.<br>Durations of 6–7 s at 2,500 ft. |
| 4 | 20 Hz at 70 ft.<br>7–8 Hz emerging at 150 ft but of about 1/3 amplitude, at 0.2 in/s. | 10–12 Hz at 700 ft.<br>Amplitude of 0.2 in/s. | Secondary frequency of 7–8 Hz at a distance of 150 ft.<br>Amplitude of 0.40 in/s. | 8 Hz at distances of 800–1,200 ft.<br>Amplitudes of 0.10 in/s or less, about 1/2 the amplitudes of higher frequency components.<br>8 Hz decays to insignificance at about 2,300 ft.<br>Durations of 2 s. |
| 5 | 13–14 Hz at 260 ft | 7–10 Hz beyond about 1,000 ft.<br>Amplitudes of about 0.2 in/s, about 1/3 amplitude of higher frequency components. | Secondary frequency of 6–12 Hz at closer stations (<800 ft).<br>Amplitude up to 0.5 in/s. | 6–7 Hz at 2,100 ft at about 0.06 in/s.<br>10 Hz at 2,256 ft for 1 blast, 0.04 in/s.<br>Durations of 2 s. |
| 6 | 3.5–4 Hz at 388 ft at 2 in/s.<br>Amplitude is about 1/2 of higher frequency. | 6 Hz at about 3,600 ft, dominant component.<br>Amplitudes of about 0.2 in/s, 10 Hz also present. | 10 Hz on all records, dominant component. | 10 Hz on all records.<br>3.7–5 Hz at distances beyond about 800 ft and dominating records at 2,000 ft, 0.3 in/s.<br>Durations over 6 s. |
| 7 | NA | NA | NA | 4–6 Hz at intermediate distances of 2,500–3,000 ft.<br>Amplitudes of 0.11–0.27 in/s.<br>3–4 Hz at distances of 6,300–6,900, amplitudes less than 0.11 in/s.<br>Durations up to 5 s. |
| 8 | NA | NA | NA | Above 12 Hz for all blasts at distances from 580–3,900 ft.<br>Durations up to 5 s. |
| 9 | NA | NA | NA | 4–5 Hz at large distances of 3,400–7,000 ft.<br>Amplitudes of 0.15–0.26 in/s.<br>Durations up to 5 s. |

NA Not available.

[1] 3 deck delay intervals total 0.325 s.

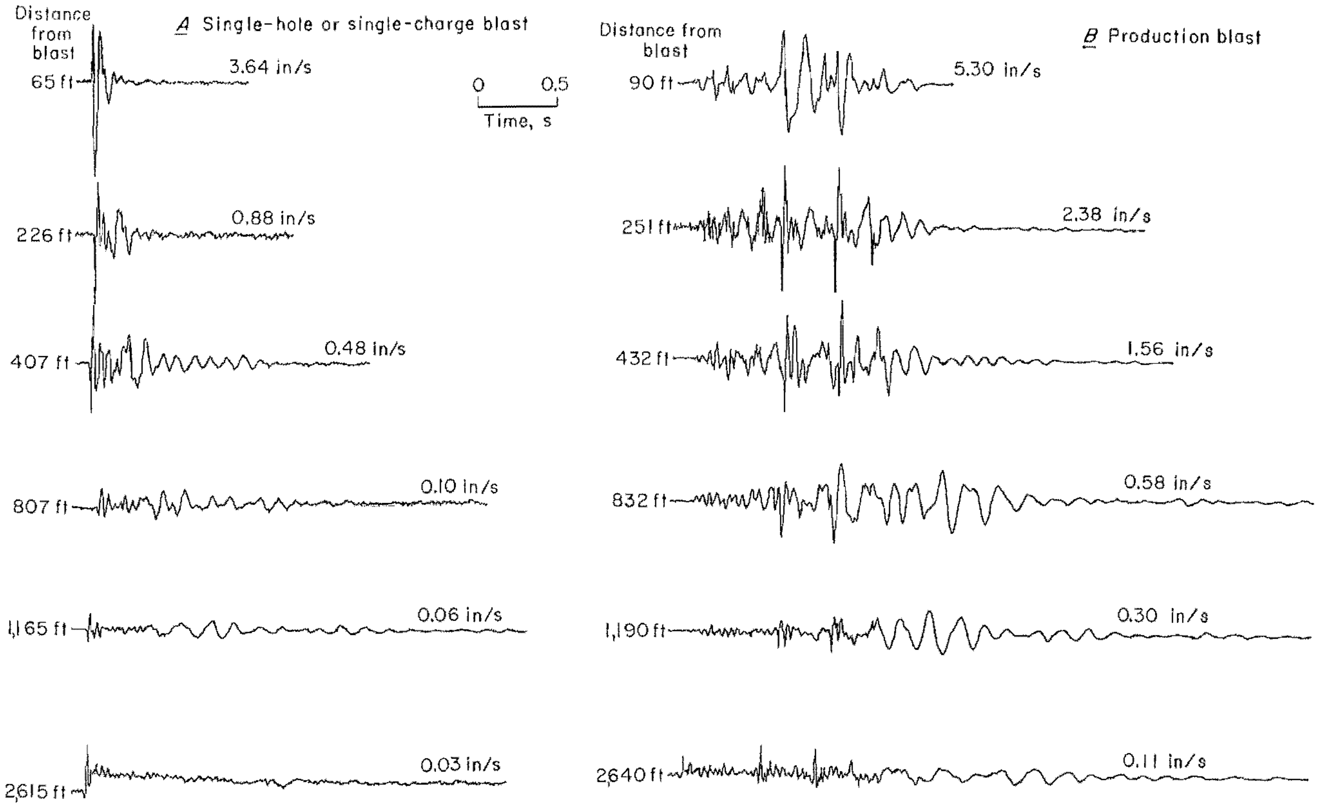


**Figure 18.—Vibration records, vertical, site 1 (*A*, shot 4; *B*, shot 3).**

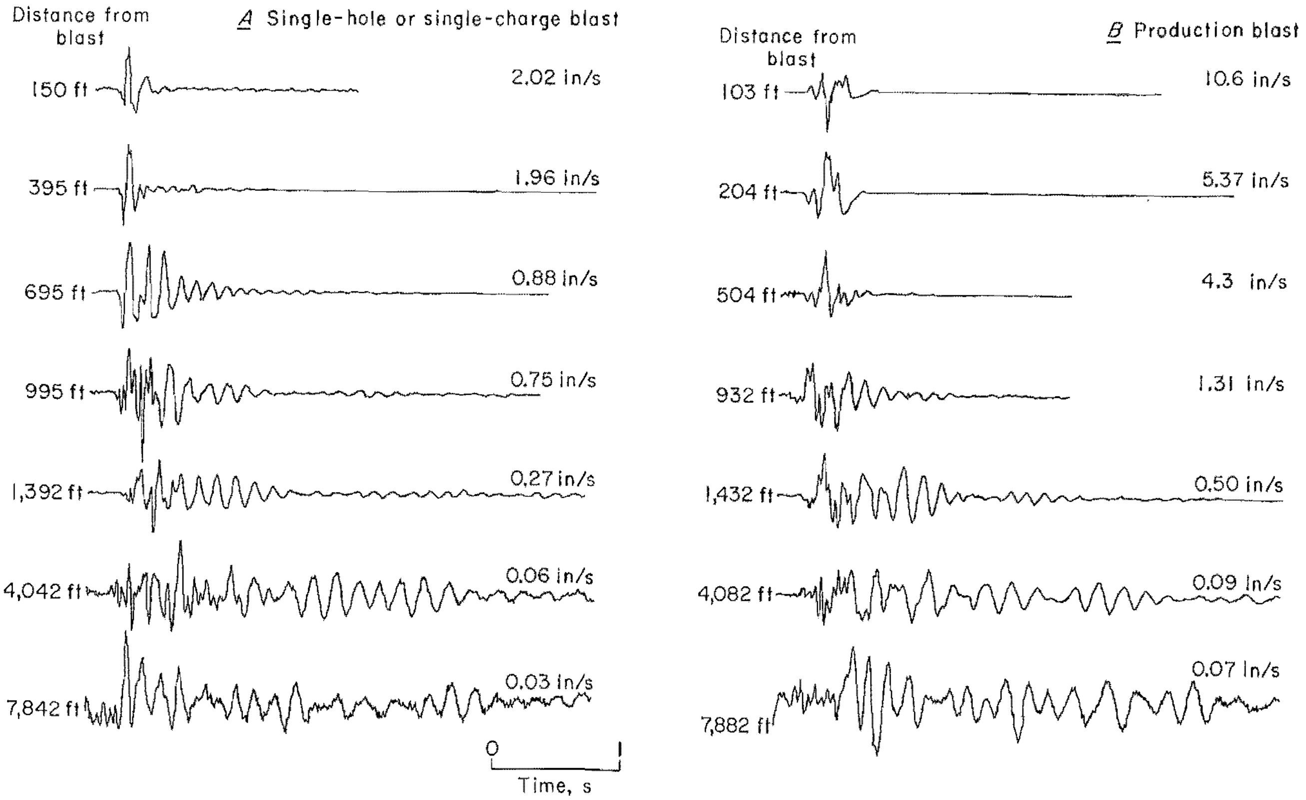


**Figure 19.—Vibration records, radial, site 2 (*A*, shot 7; *B*, shot 6).**

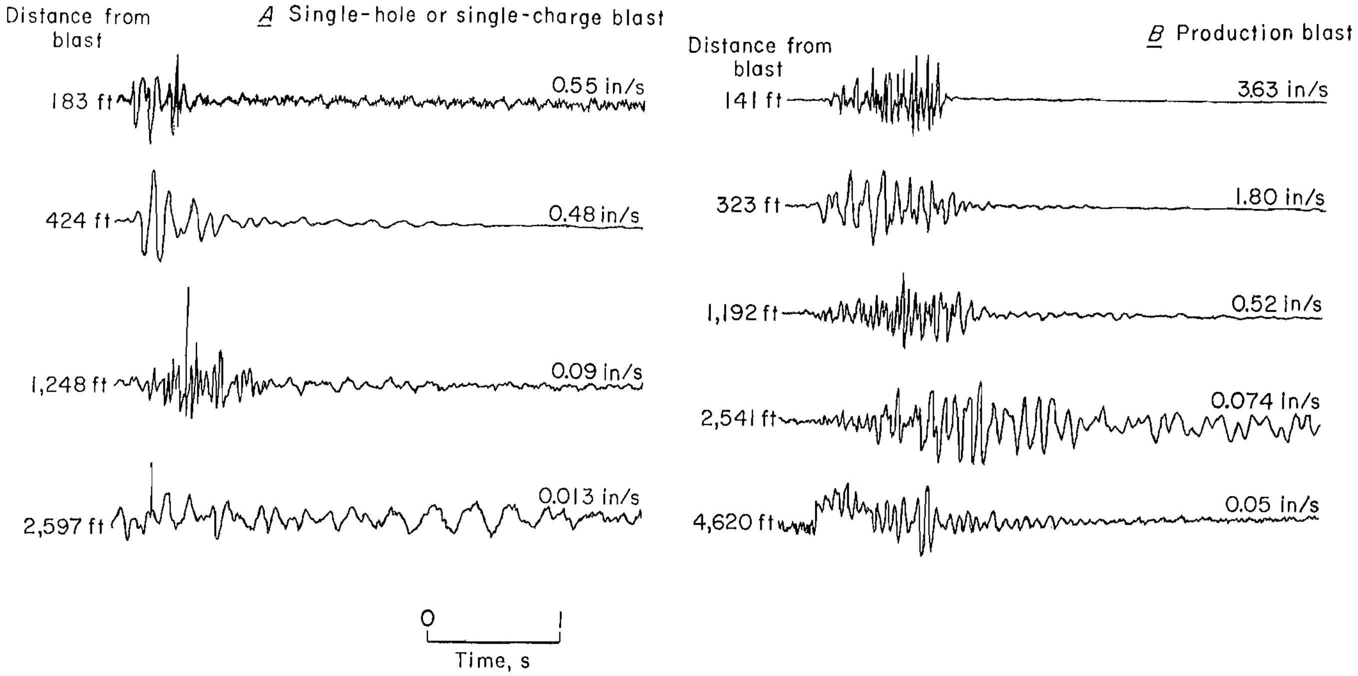


Figure 20.—Vibration records, radial, site 3 (*A*, shot 2; *B*, shot 3).

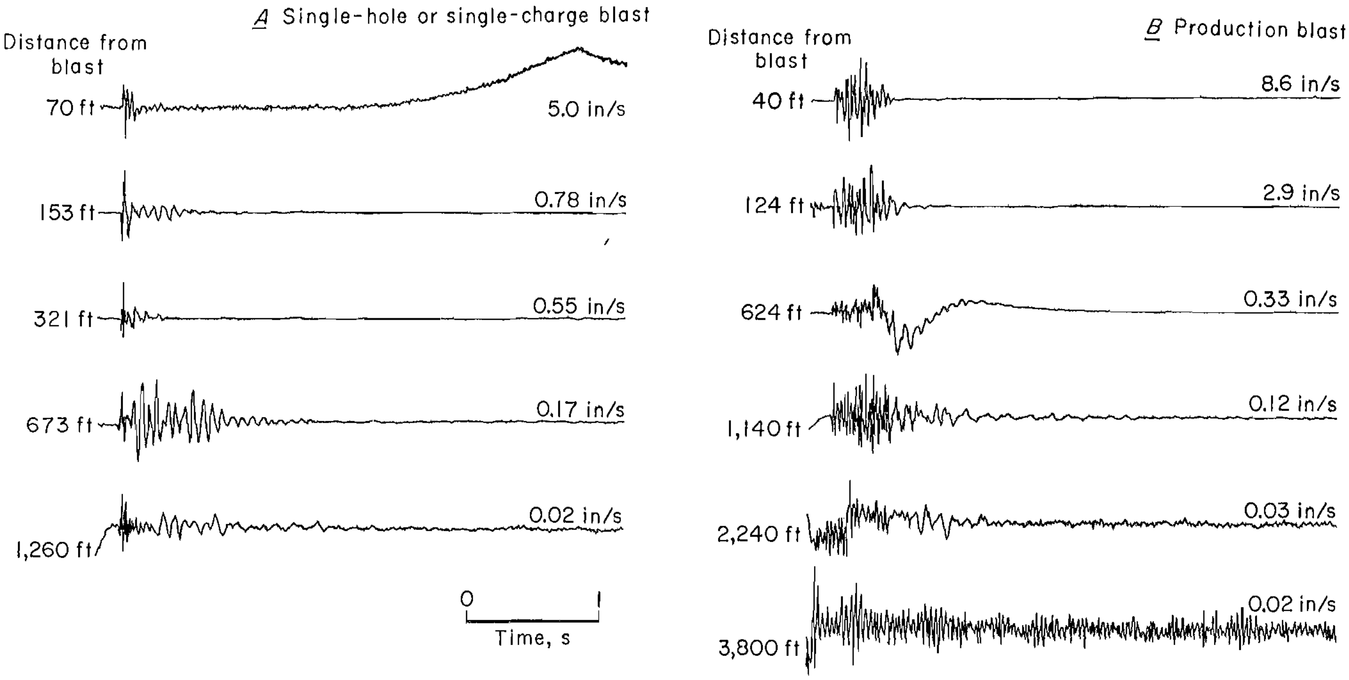


Figure 21.—Vibration records, vertical, site 4 (*A*, shot 4; *B*, shot 3).

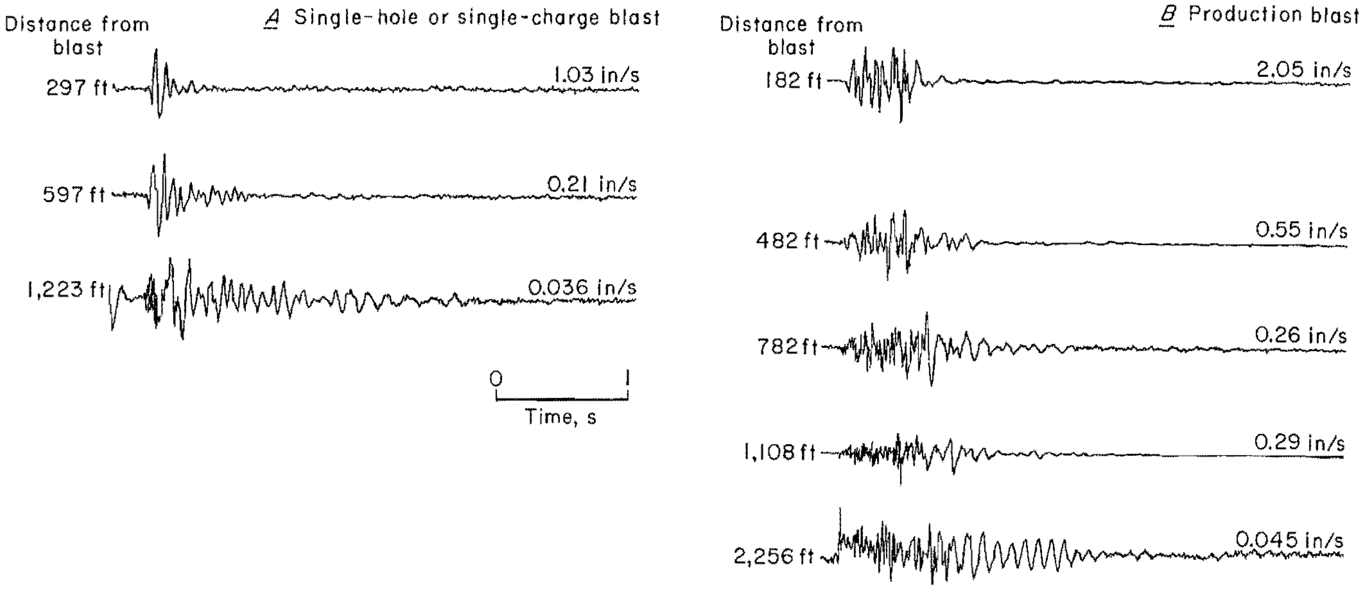


**Figure 22.—Vibration records, radial, site 5 (*A*, shot 1; *B*, shot 2).**

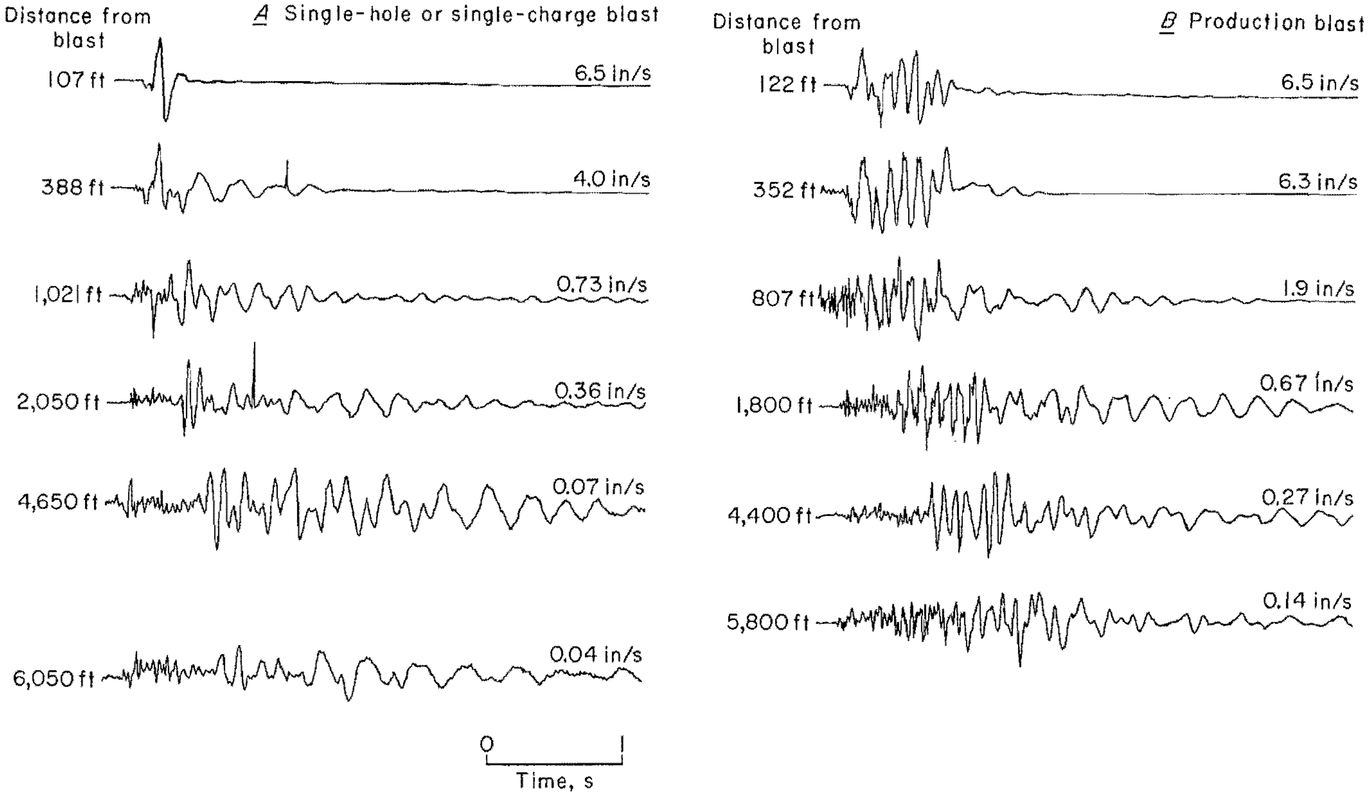


**Figure 23.—Vibration records, radial, site 6 (*A*, shot 1; *B*, shot 4).**

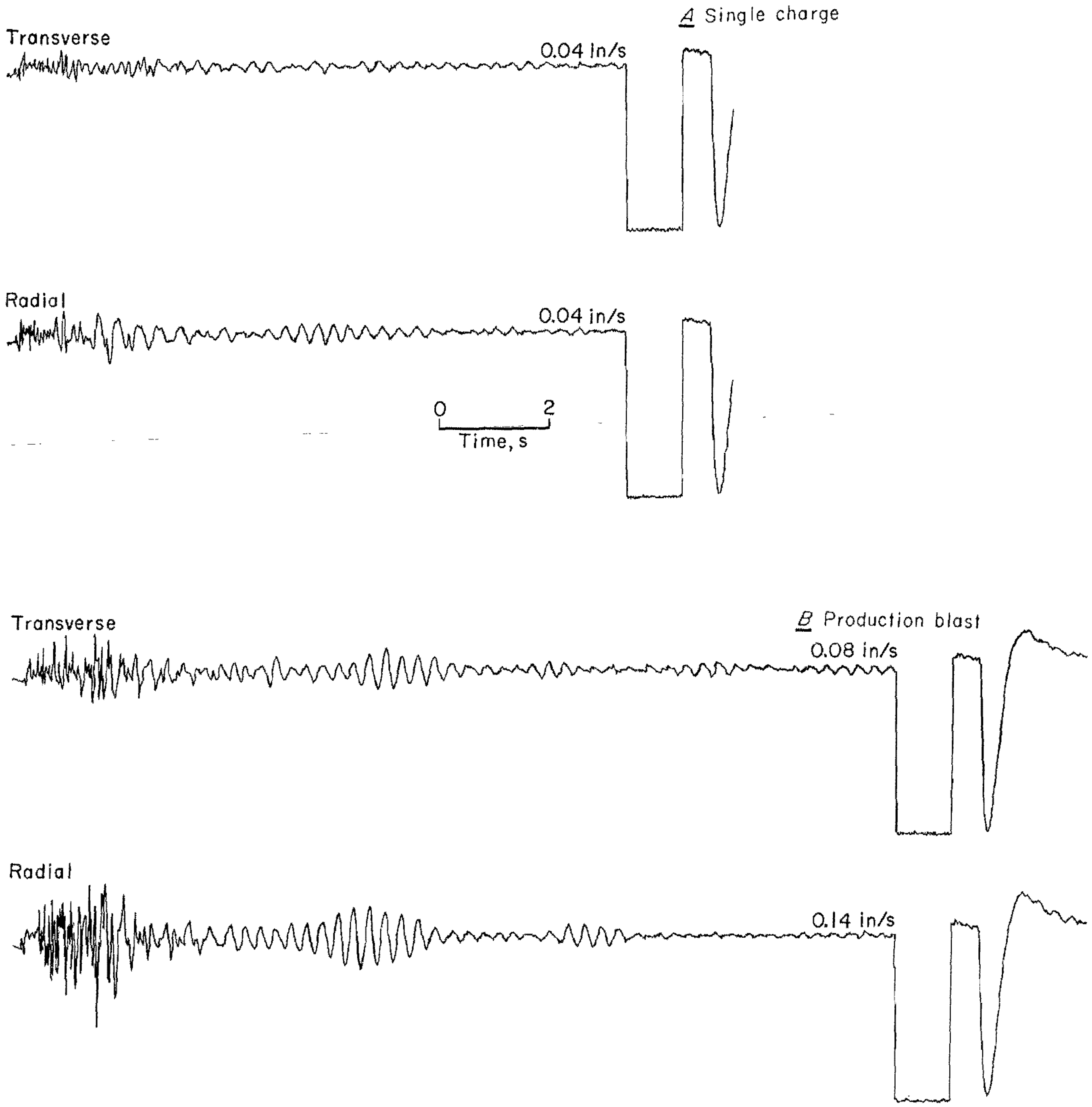


**Figure 24.—Long-duration vibrations for site 6 (*A*, shot 1, 6,050 ft; *B*, shot 4, 5,800 ft).**

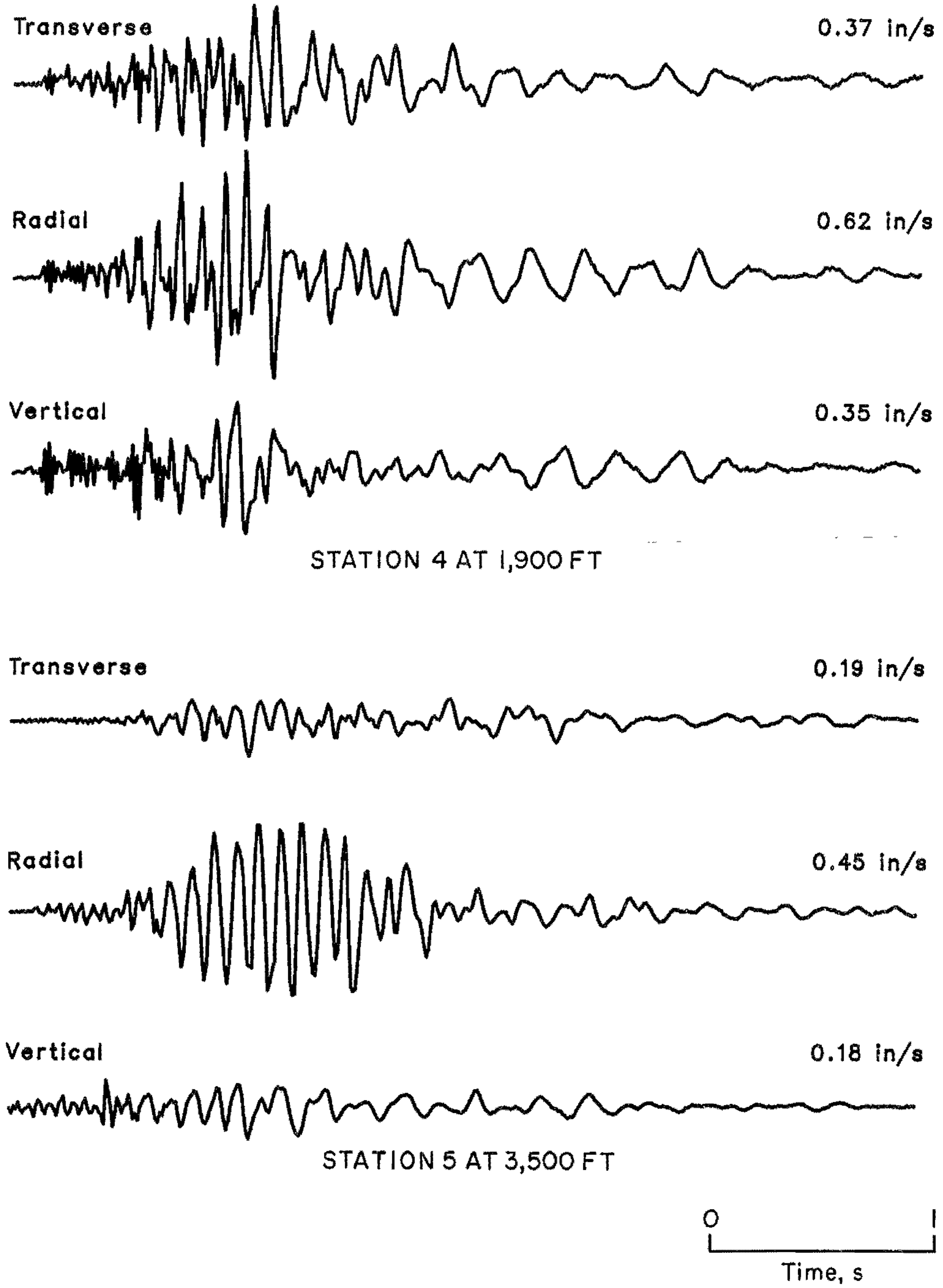


**Figure 25.—Three-component vibration traces for two adjacent stations for production blast 3 at site 6.**

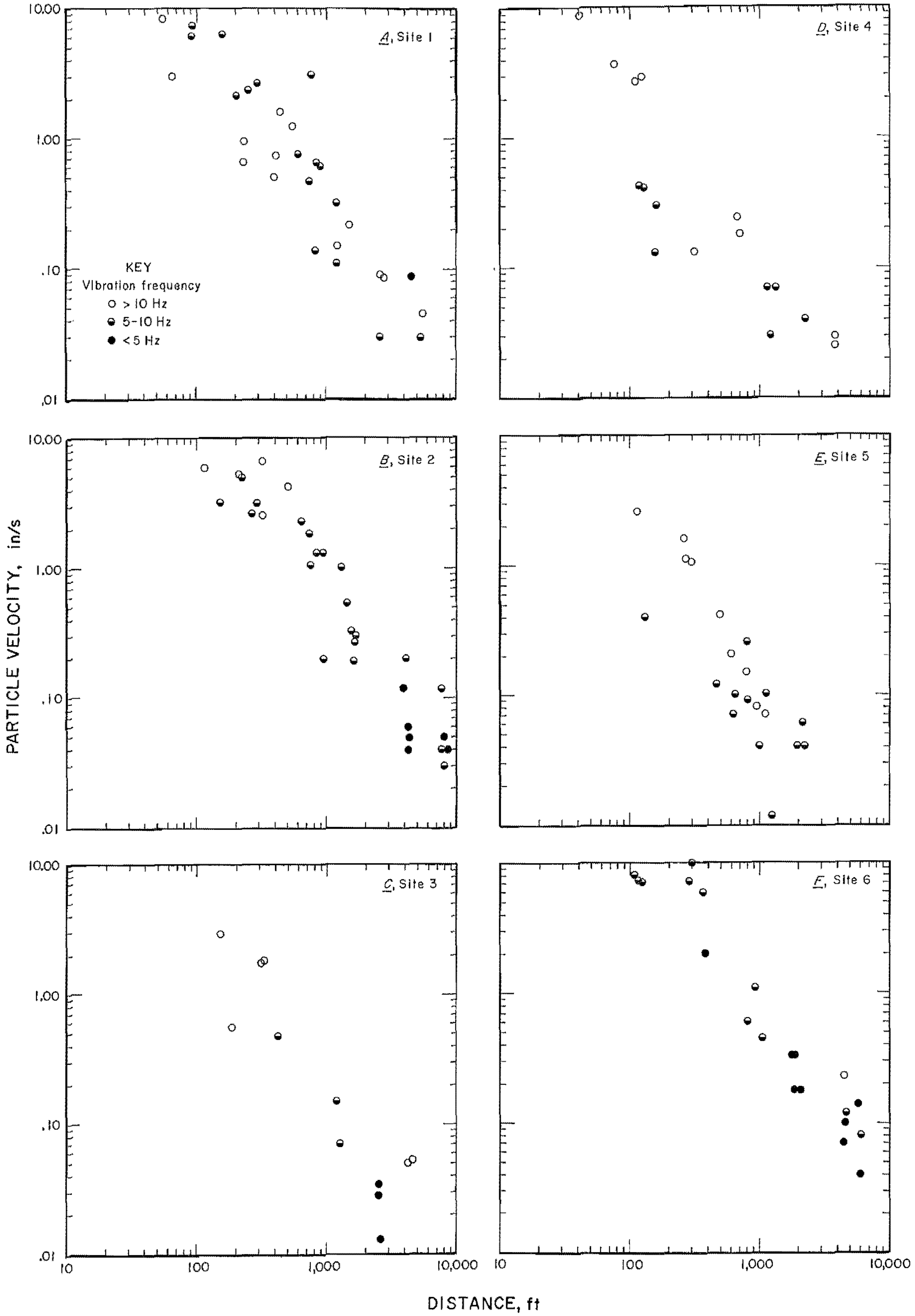


Figure 26.—Propagation plots of low-frequency components of blast vibrations.

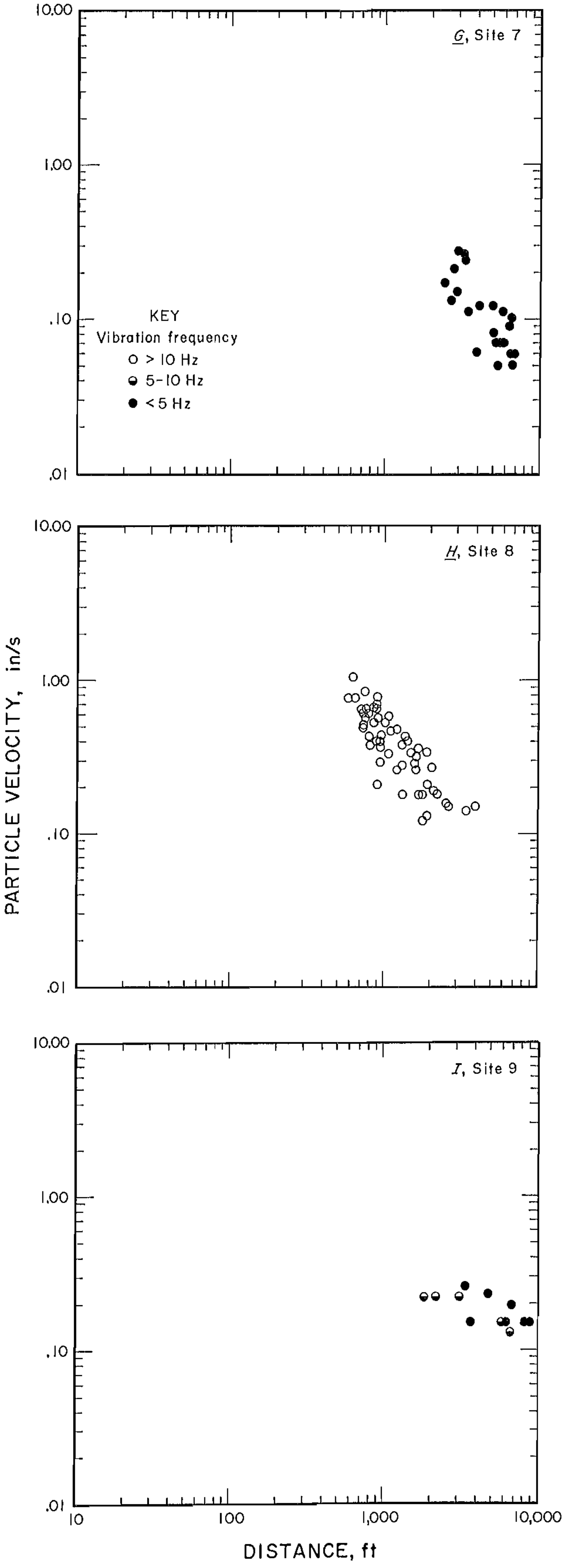


**Figure 26.—Propagation plots of low-frequency components of blast vibrations—Continued.**

## Vibration Characteristics by Site

### Site 1

Site 1 produced low frequencies of 5 to 10 Hz at distances 90 ft and greater; however, Bureau measurements found only one record below 5 Hz, which was at a low amplitude of about 0.09 in/s (fig. 26*A*). The earlier study of this site described the common occurrence of such VLF down to 4 Hz in Indiana DNR- and company-collected records of cast blasting (*1*). An interesting characteristic of this site is its variability. For instance, at 4,000 to 5,000 ft, VLF (<5 Hz), low frequency (5 to 10 Hz), and higher frequency (>10 Hz) all occur for different blasts of the same design. This variability could be caused by the sporadic occurrence of the Universal Limestone Member with a thickness of up to 11 ft.

### Site 2

Site 2 vibrations occur as both low frequency (7 Hz) and VLF (5 Hz), as listed in table 3 and shown in figures 19 and 26*B*. The 7-Hz dominant occurs at intermediate distances of 500 to 1,500 ft from the blast area. The amplitudes are high at 0.5 to 2.0 in/s (fig. 19), which could be a problem if private residences were located that close. Other blast designs at this site may give different results as hinted by the section on blast design later in this report. This site also produces 5-Hz vibrations at greater distances corresponding to the undermined zone beyond about 4,000 ft (fig. 3). The low amplitude of these long-distance vibrations, 0.10 in/s, renders them harmless to structures, although still easily noticeable.

### Sites 3 and 4

Sites 3 and 4 both have low frequencies at intermediate distances and an apparent absence of such waves at greater distances, such as beyond 3,800 ft (figs. 26*C–D*). Some VLF is found at site 3 at a distance of 2,600 ft. At 3 Hz, it is among the lowest frequencies observed. Amplitudes are even lower than those found at sites 1 and 2, at around 0.04 in/s.

Site 4 has no VLF; however, it has strong 8-Hz waves beginning to emerge at close distances of 150 ft, which remain significant out to about 2,300 ft. At no distance does the 8-Hz component have an amplitude more than about half the higher frequency peak.

### Site 5

Site 5 is the same mining operation as site 4. Blasting is in a different part of the pit, and the array directions differ (figs. 6–7). The vibration characteristics also look different, with slightly lower frequencies for site 5 for both single charges and production blasts. As with site 4, no VLF is observed. Again, the amplitudes of the low-frequency components are small, being less than 0.5 in/s close in (120 ft) and 0.10 in/s beyond 1,000 ft (fig. 26*E*).

### Site 6

Site 6 has VLF and sufficient amplitude to be of concern if homes were within a few hundred feet. A vibration of 0.75 in/s below 4 Hz exceeds Bureau criteria for cracking interior walls in homes, as published in RI 8507, appendix B (*10*). Figure 26*F* shows borderline low frequencies of 10 Hz at all distances beyond about 100 ft, an isolated VLF record at 380 ft, and much VLF (3.7 to 5 Hz) at and beyond 2,000 ft.

Additional measurements at this site would be worthwhile, particularly with different blast designs and some replications of single charges.

### Site 7

Site 7 data were supplied by the DNR and consist only of far-field vibrations from production blasts. All data exhibit VLF, with some of the records being of moderate amplitudes, nearly 0.30 in/s (fig. 26*G*). This highly undermined site would be ideal for a full-scale study involving propagation arrays and single-charge comparisons. However, the DNR has stated that mining activity has been terminated with the exhaustion of local coal resources.

### Site 8

Site 8 differs from the other eight sites by having neither low-frequency nor VLF vibrations at the distances monitored, 600 to 4,000 ft (fig. 26*H*). Durations are also shorter than at other sites, being less than 3 s. Blast vibrations do not appear to be a problem at this site except possibly for the amplitudes, which are high considering the small charge weights (e.g., compare amplitudes with those for sites 4 and 5).

### Site 9

Site 9, although not undermined, produced both low frequencies and VLF (fig. 26*I*). As with site 7, these are also of considerable amplitude and a cause for caution at distances as far as 3,000 ft. Far more data are needed for this site; this study had only two to four measurements at each of three homes monitored. Also, as with site 7, a propagation array is needed to identify the generation characteristics and influences of distance.

## Safe Blasting Criteria

Figure 26 can be used to estimate safe blasting distances based on the Bureau criteria in RI 8507 (*10*) and the occurrence of low frequencies. The wide range of distances determined this way is strongly influenced by charge size variations, which range from 102 to 2,500 lb per delay for the nine sites. Based on an envelope of velocity versus distance for all vibrations below 10 Hz, and maximum particle velocities of 0.5 and 0.75 in/s, approximate minimal distances have been calculated (table 4). The table 4 distances are based on only a few production blasts at some of the sites and are, therefore, intended to guide concern and not be applied as regulatory limits. At the same time, they illustrate a potentially useful approach for low-frequency sites.

An alternative analysis was done using calculated displacements based on the assumption that the waves can be represented by simple harmonic vibrations. Figure 27 shows displacement values for the measured blast vibrations below 10 Hz.

**Table 4.—Distances of concern for residential structures when low frequencies (<10 Hz) are dominant**

| Site | Charge weight per delay, lb | Minimum distances, ft | | |
|---|---|---|---|---|
| | | Velocity criterion | | Displacement criterion: 0.03 in |
| | | 0.5 in/s | 0.75 in/s | |
| 1 | 125 | 1,000 | 800 | 550 |
| 2 | 2,000 | 1,500 | 1,300 | 1,200 |
| 3 | 165 | 430 | 270 | 290 |
| 4 | 102 | 120 | NP | 100 |
| 5 | 102 | 100 | NP | 200 |
| 6 | 1,350 | 1,500 | 1,100 | 1,300 |
| 7 | 150–1,400 | NP | NP | NP |
| 8 | 100– 350 | None | None | 730 |
| 9 | 1,000–2,500 | NP | NP | NP |

NP Not predictable with data available.

Envelopes of maximum values are shown for all sites except 7 and 9, where data were limited in range. Based on RI 8507, appendix B (*10*), a maximum safe displacement of 0.03 in gives an additional set of minimum safe distances (table 4). These are in fair-to-good agreement with those based on velocity.

Some sites could not be fully analyzed for frequency versus distance because of lack of a sufficient range variation in monitoring. Site 7 data (fig. 26*G*) are all VLF in character, with all measurements made at far distances. A very rough estimate of minimal distance would be 1,500 ft, assuming a data slope similar to that of the other sites. Site 9 minimal distance is less than 1,500 ft but not well defined by the limited range of measurement distances. A similar analysis for a maximum vibration of 1.0 in/s would give lower minimal distances.

# BLAST DELAYS AND ENERGY FLOW

A useful tool for studying the influences of blast delays on vibration characteristics is through energy flow diagrams based on actual initiation times, if available, or nominal times otherwise. Figures 28–34 show blasthole array designs and time records of charge sequences by rows, holes in a row, and decks for each site instrumented by the Bureau.

## Blast Design and Vibration Amplitude

Vibration amplitudes for the various sites were given earlier in this report, with some evidence of blast design influence on vibration amplitudes at a single site and the variation of differences between single charges and production blasts in comparing all sites (fig. 10). By contrast, other evidence suggests that there is minimal influence. Examples are the tight grouping of all production blasts (fig. 11*B*) and the

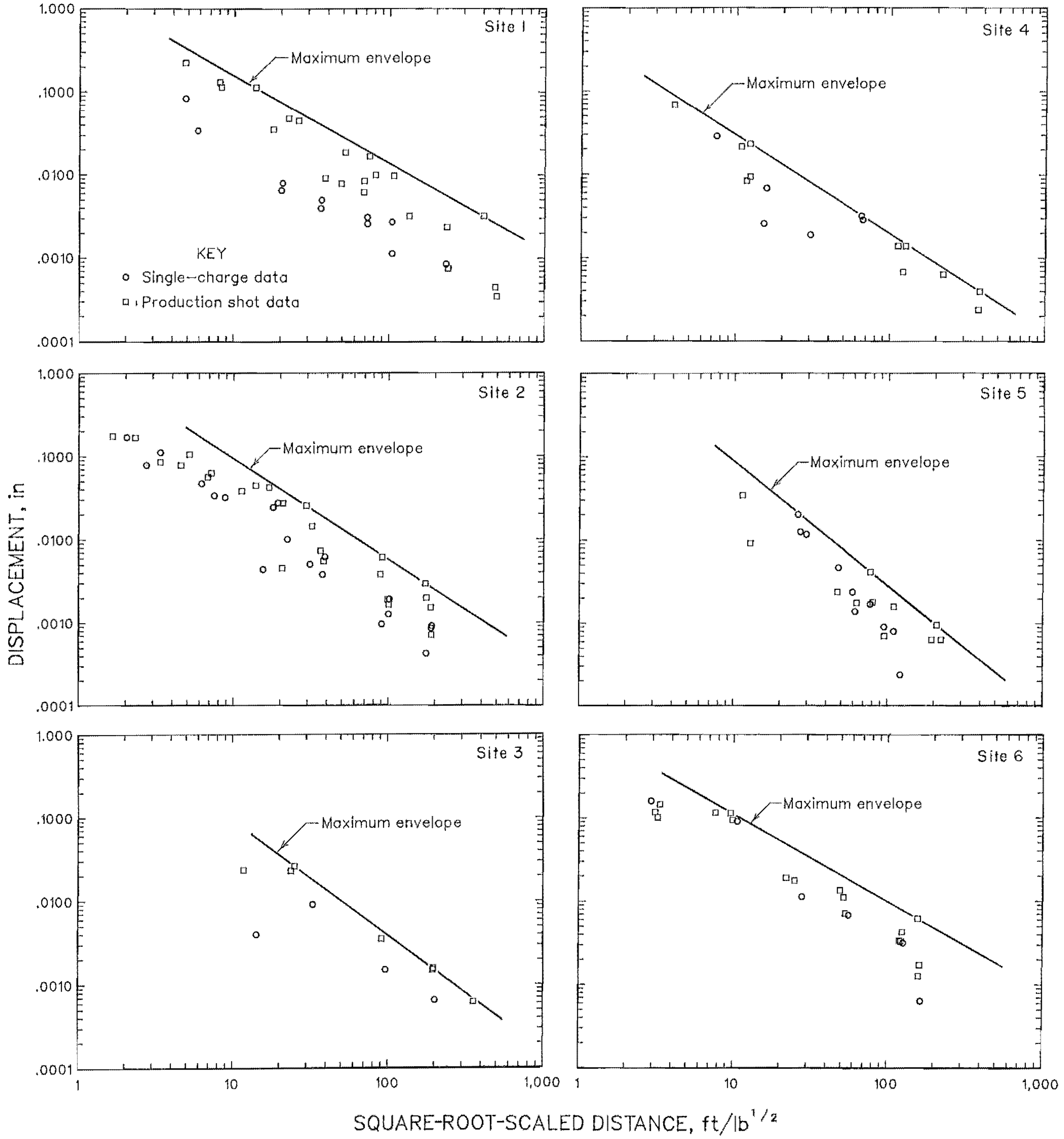


Figure 27.—Propagation plots for displacements for low-frequency vibrations.

many designs employed at single sites (figs. 12, 15). More data will be needed to quantify exactly how much vibration amplitudes can be controlled by initiation sequencing. However, the industry is attempting to influence vibration frequency, and success has occurred in some cases with the shifting of peak amplitudes toward higher frequencies.

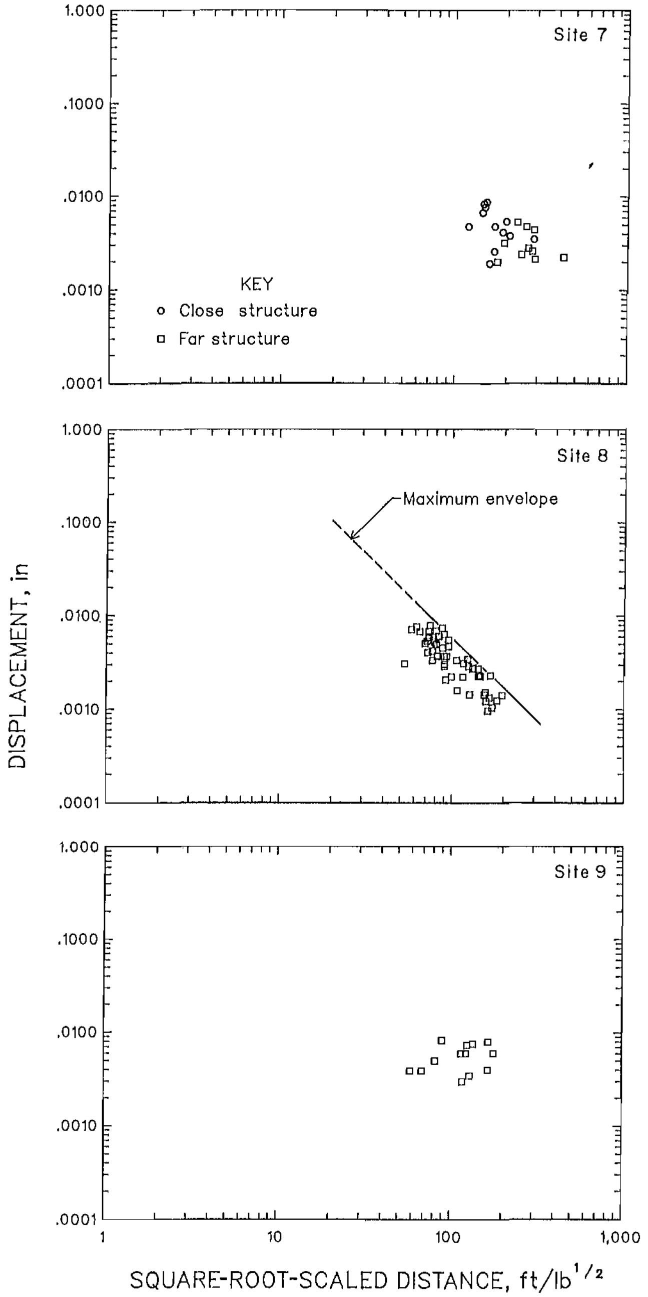


**Figure 27.—Propagation plots for displacements for low-frequency vibrations—Continued.**

## Blast Design and Vibration Frequency

For analysis of blast initiation, the basic approach is to compute all detonation times and present them on one or more time axes showing a relative dependent flow of energy. Most significant are times of unusual bunching of initiations and systematic repeated gaps (periodicities) in the time records. For practicality, nominal delay times are used, corrected for any needed intervals for the initiation system to travel to the individual charges. Actual initiation times are preferable but rarely available.

Single-charge blasts reveal the ground's natural frequency at a site. Table 3 lists these frequencies. This natural frequency is expected to also be present in records of production blasts. In addition, delay periodicities, in theory, can enhance this frequency's amplitude and also introduce other higher frequencies. Unwanted frequencies can be reduced by delaying at half the period of the unwanted vibration. For example, a 7-Hz vibration has a period of 143 ms. Two 7-Hz waves with a 72-ms delay between them should have considerable destructive interference. Alternatively, energy grouping of shorter delays at 72-ms intervals may have similar effects. Such techniques are still under study and may work only in simple situations of propagation path and blast design.

Energy flows, as indicated by the time delays for sequences of all charges, are shown in figures 28–34 for the six sites studied by the Bureau propagation arrays. All times are nominal and assume detonations occur as designed. Also, for all seven analyses, the observer location is arbitrary. This means that spatial separations between holes are not considered. Actual or effective delays are also influenced by travel times across the array pattern. A 25-ms hole separation between two holes could be shortened or lengthened by up to 4 ms depending on separation distance and velocity. When blasts are being designed to minimize effects at a particular monitoring location, actual times can be calculated for that site.

### Site 1

Site 1 (fig. 28) shows a very uniform energy flow with charges having 8- and 9-ms separations throughout and no gaps. For receivers in the direction of initiation, these time intervals will shorten by about 3 ms. They will lengthen by about that amount in the opposite direction, which happens to be toward the pit. Unless there is an effect from the 100-ms between-row delay, this pattern should not enhance the 5- to 6-Hz natural frequency characteristic of this site. This design plus several others are described in the earlier report, RI 9078 (*1*). In this study of site 1 and the previous detailed one, only a hint was found that blast delays can influence the low-frequency vibrations. This is because only one blast design was in use during the time the array was in place and comparisons could not be made.

A casting blast from the earlier site 1 study (*1*) is shown in figure 29. Because of the relatively low number of holes in a row and resulting gaps in the time record, the row periodicity of about 200 ms shows up in the energy flow. The vibration records have a dominating 4-Hz periodicity as a late arrival, approximately corresponding to the between-row periodicity. However, without simultaneous close-in measurements and comparison of single-charge shots in the same area of the pit, it is not possible to determine if the observed low frequency is directly related to the delay interval.

### Site 2

Site 2 arrays and sequences of charges are shown for two shots, 6 in figure 30 and 8 in figure 31. Shot 6 is typical of the earlier production blasts, shots 2 and 4, all containing relatively few holes on a distorted echelon with 64- by 25-ms intervals. Shot 8 was fired by rows in head-to-tail sequencing, resulting in an approximate row interval of 150 ms. Because of the short rows, the sequencing shows gaps of the same interval, 150 ms. This delay period corresponds to about 6.7 Hz.

Although shot 8 did produce higher peak vibration amplitudes than other site 2 production blasts (fig. 10), it did not result in a noticeably increased amount of low frequencies in most of the records. For instance, at close distances, all blasts produced waves with significant 8- to 10-Hz energy. At 900 ft, shot 6 was rich with 7.7-Hz energy while shot 8 had reduced amplitudes at 7 and 9 Hz. At far distances, shots 6 and 8 had the same amounts of low frequency, with amplitudes of 0.10 in/s at 5 Hz at 4,000 ft.

### Site 3

Site 3 design produced an energy flow with gaps of 42 ms, similar to the between-row delay intervals (fig. 32). This relatively short period appears unrelated to the observed 11-Hz (90-ms period) vibration at 323 ft (fig. 20) or the 3 to 4 Hz appearing at larger distances of 2,500 ft.

### Sites 4 and 5

Sites 4 and 5 are the same mining operation and used the same blast design (fig. 33). The pattern starts with widely spaced time intervals, which become a regular sequence of 8- and 9-ms spaced blasts. No obvious periodicities exist that would serve to reinforce the sites' 7- to 10-Hz natural frequency as tabulated under "single charges" in table 3. Site 5 records are somewhat lower in frequency than site 4 records close in and significantly different at 2,300 ft. The low-frequency part of the vibration record for site 5 at 2,256 ft lasts far longer than the barely visible counterpart for site 4 (at 2,240 ft). These differences are the result of different propagating media for the two array directions or different angles between the seismic array and direction of initiation in the array pattern (see maps, figures 6 and 7). The effect of the angle between the seismic array and the direction of blast initiation was observed in two previous studies (*1-2*). Site 5 had the seismic array nearly in line with the direction of initiation in the blast round.

### Site 6

Site 6 uses the same 100- by 17-ms echelon design as site 1 except for the absence of extra back rows and the use of two decks instead of four. Here is an example of how a delay group periodicity could be contributing to the problem. Figure 34 shows row periodicities of 100 ms in the energy flow. A significant and corresponding 10-Hz component was observed on all production blast records (table 3). The 10-Hz component was also observed in the single-charge blast although the duration was considerably shorter (fig. 23). Of most concern at this site is the 4-Hz wave-train tail appearing at surprisingly close distances of 300 ft and of relatively large amplitude at far distances (fig. 23). This VLF is undoubtedly a site phenomenon and not the result of a blast design.

### Sites 7 to 9

Limited analyses could be done of blast designs versus frequencies for sites 7 and 9 in the absence of complete blast design information, single-charge data, and close-in measurements. Site 7 used both echelon and cast blasting, with virtually all blasts producing VLF. Echelon blasts had either 100 or 200 ms between rows, with one 17-ms exception. Delays between holes in a row were 17 ms except for two shots combining 17 and 100 ms within rows. The 4 and 5 Hz observed for these blasts do not appear related to delays. By contrast, the casting blasts utilized mostly 170 to 200 ms between rows plus 17 ms down the rows. This is close to the observed periods of 167 to 250 ms (4 to 6 Hz). However, as the same VLF resulted from both types of blasts, echelon and casting, the low frequencies are likely site phenomena and unrelated to design delays.

Site 8 produced no low frequencies for any of the 15 blast designs used. All designs were variations of echelons and single rows.

Site 9 used one design, casting with 100 ms between rows and 9 ms between holes in a row. Depending on the number of holes in a row, this could produce gaps at 100-ms intervals. Many of the blasts at 1,900 to 2,200 ft did produce vibrations of about 8 and 9 Hz, fairly close to 10 Hz corresponding to the 100 ms row delay. However, most important for this site is the strong 4 to 5 Hz that appeared at farther distances of 3,400 to 7,000 ft. As with site 7, the observed VLF is probably site and not design related.

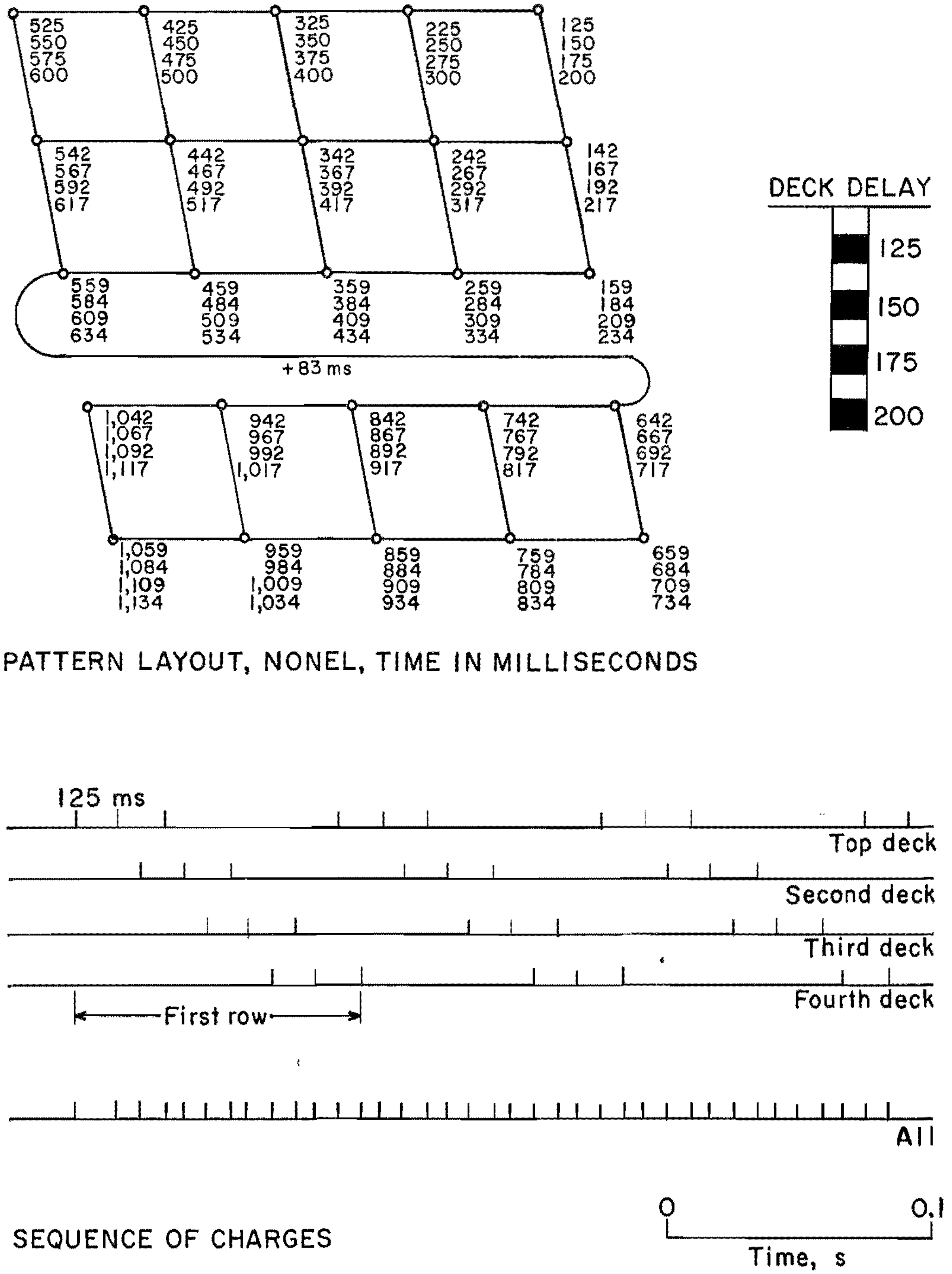
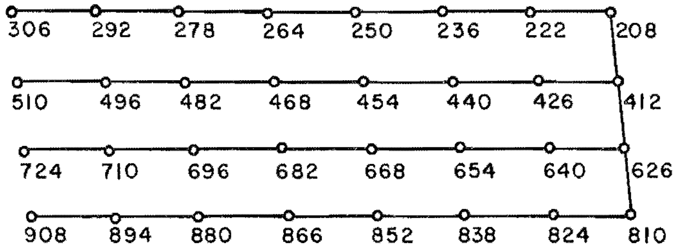
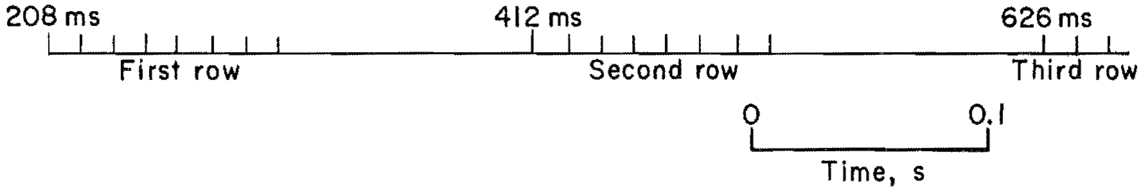


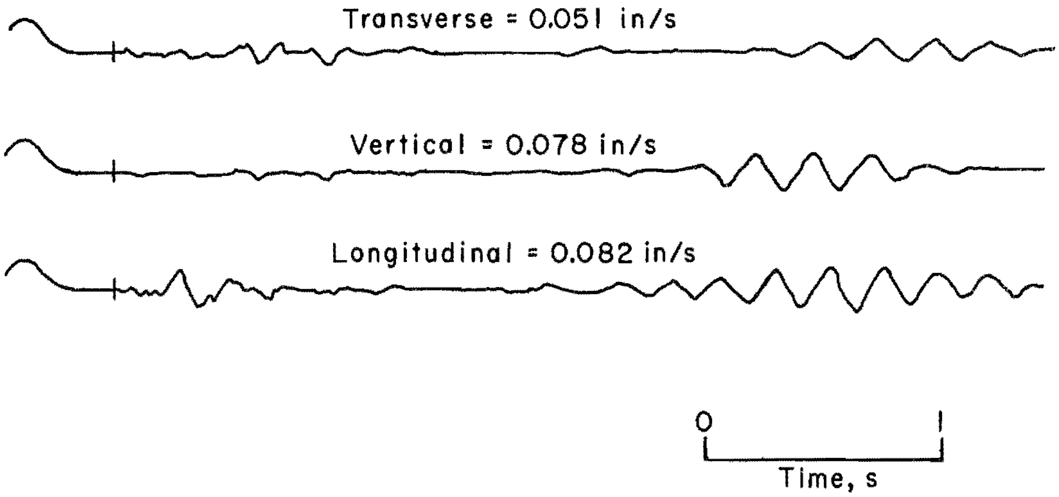
**Figure 28.—Production blast at site 1: echelon with 100 ms between rows and 17 ms between holes in a row, with additional back rows.**



PATTERN LAYOUT, HERCUDET SYSTEM, TIMES IN MILLISECONDS

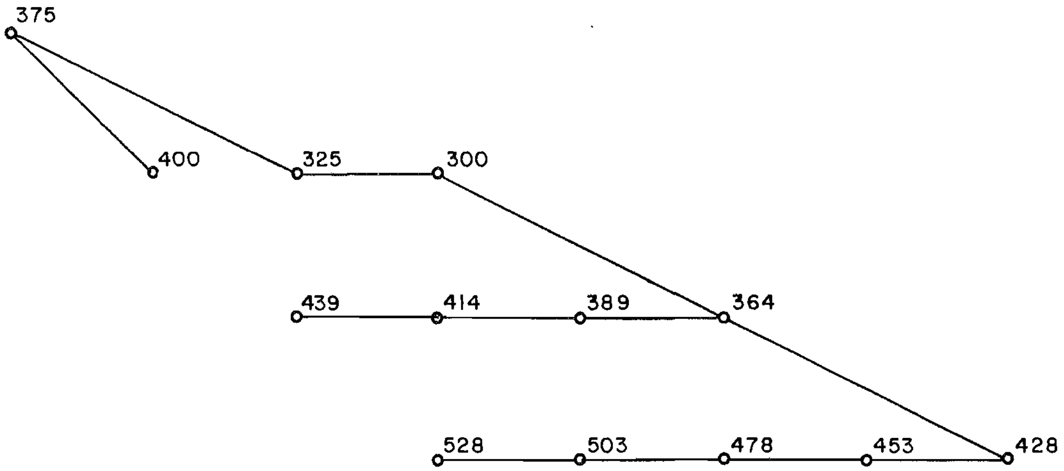


SEQUENCE OF CHARGES

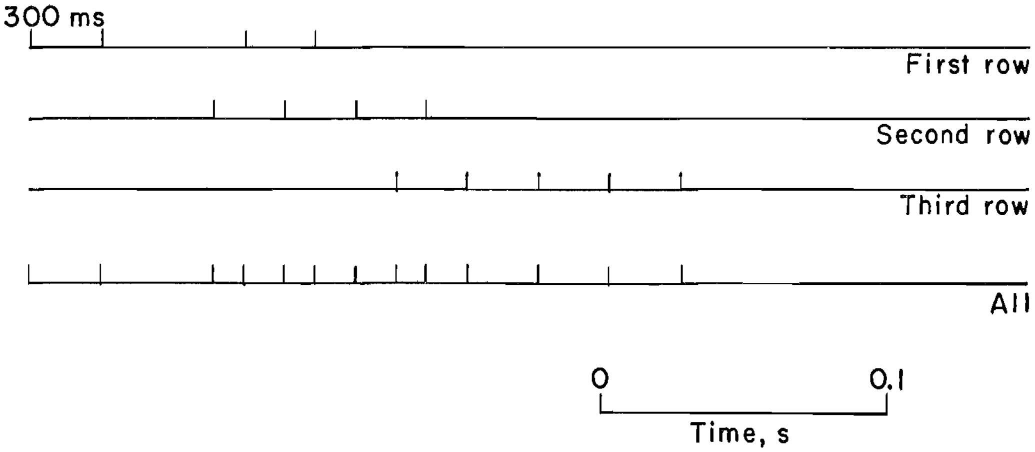


VIBRATION RECORDS, HOLLINGSWORTH HOUSE, 7,520 FT

**Figure 29.—Blasthole array, sequence of charges, and measured vibration time histories for casting blast at site 1.**

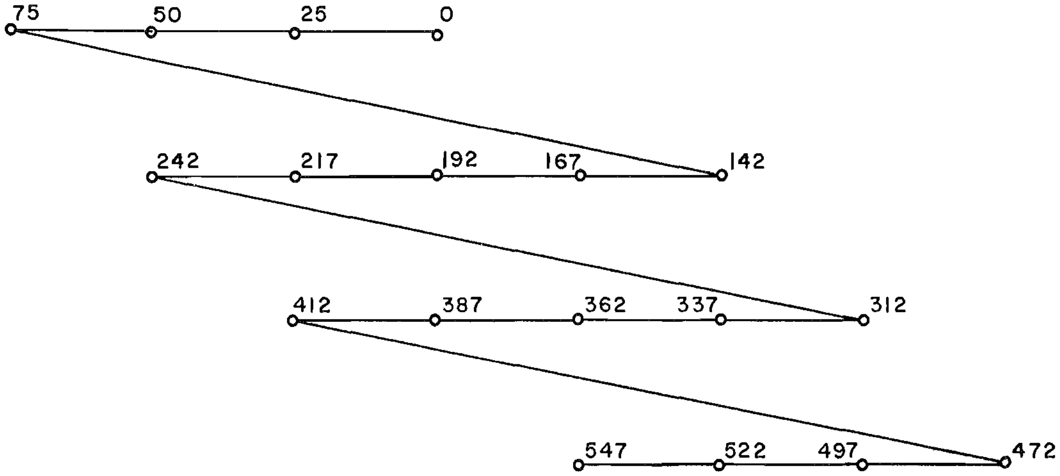


PATTERN LAYOUT, NONEL SYSTEM, TIME IN MILLISECONDS

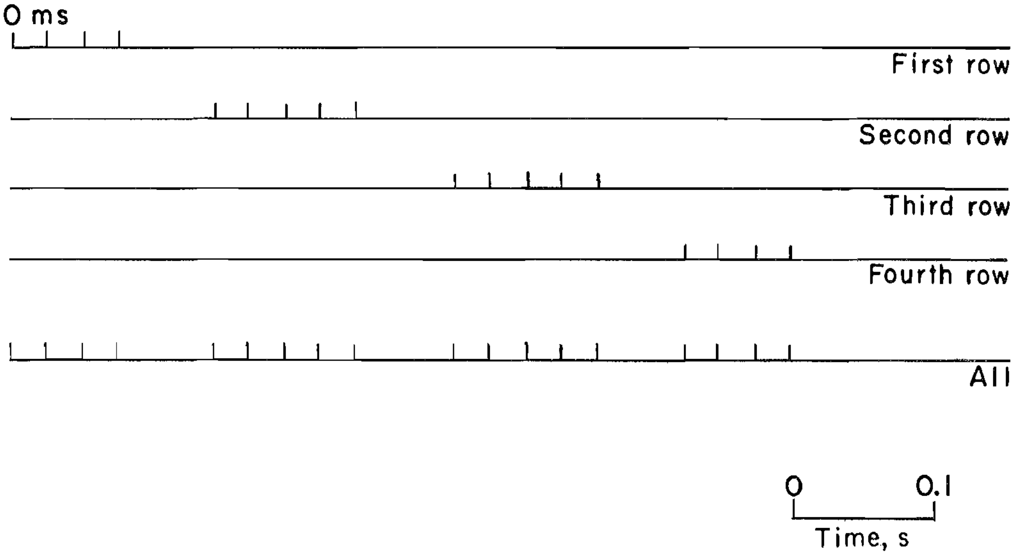


SEQUENCE OF CHARGES

**Figure 30.—Production blast at site 2: rows by sequence with 64 ms between rows and 25 ms between holes in row (shot 6).**



PATTERN LAYOUT, NONEL SYSTEM, TIME IN MILLISECONDS



SEQUENCE OF CHARGES

**Figure 31.—Production blast at site 2: rows by sequence with about 150 ms between rows and 25 ms between holes in row (shot 8).**

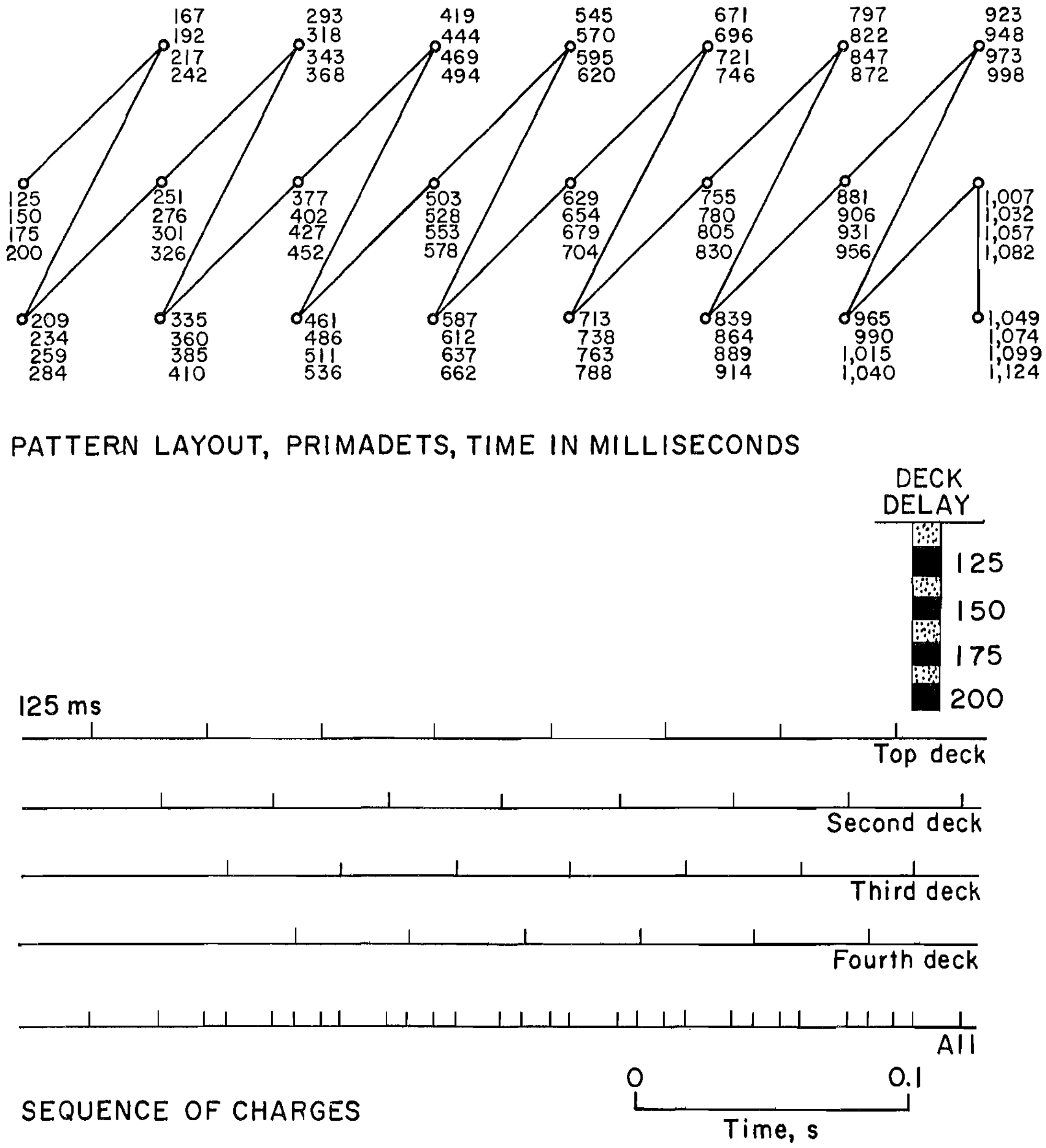


Figure 32.—Production blast at site 3: echelon with 42 ms between rows and also between holes in a row.

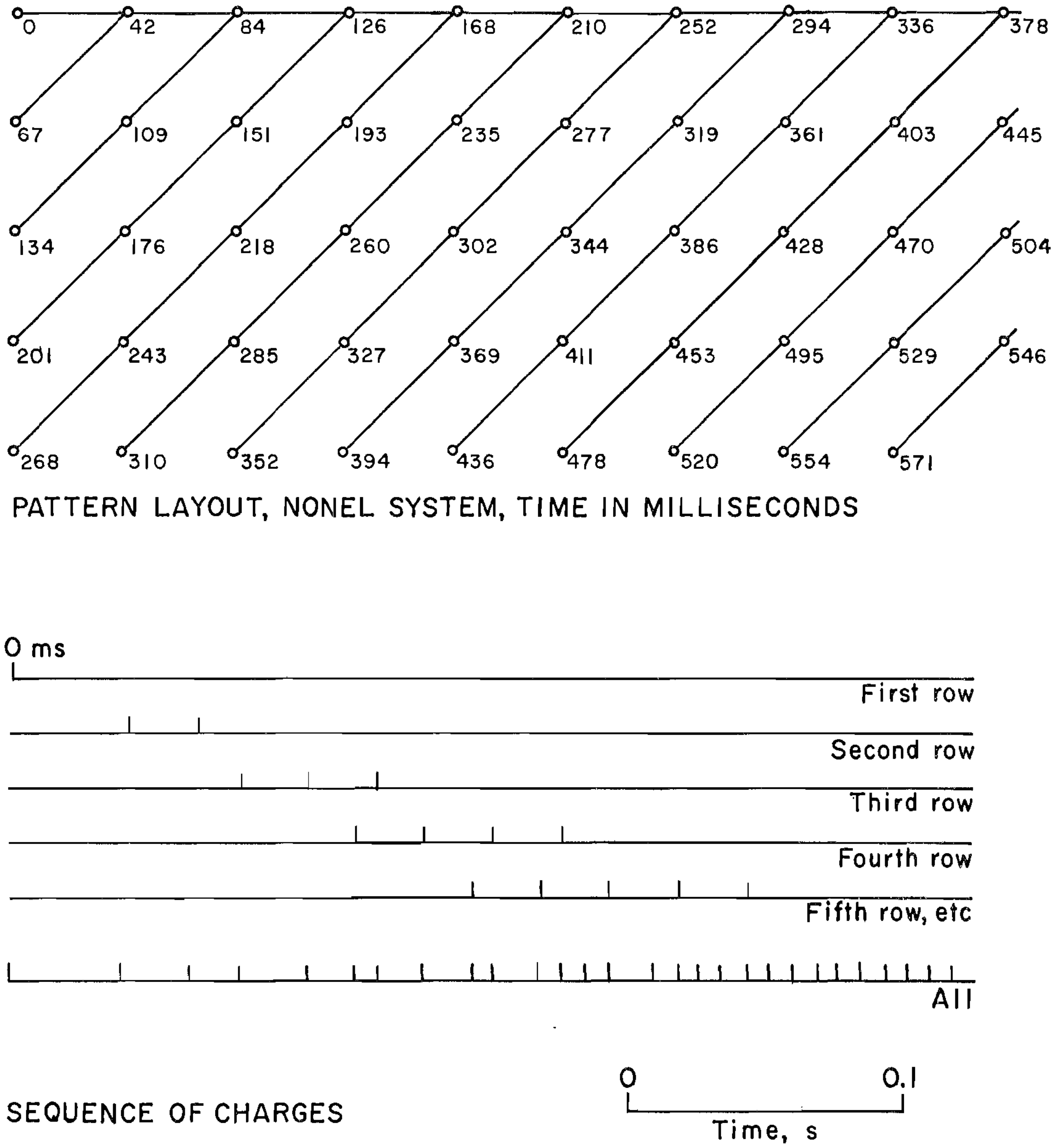
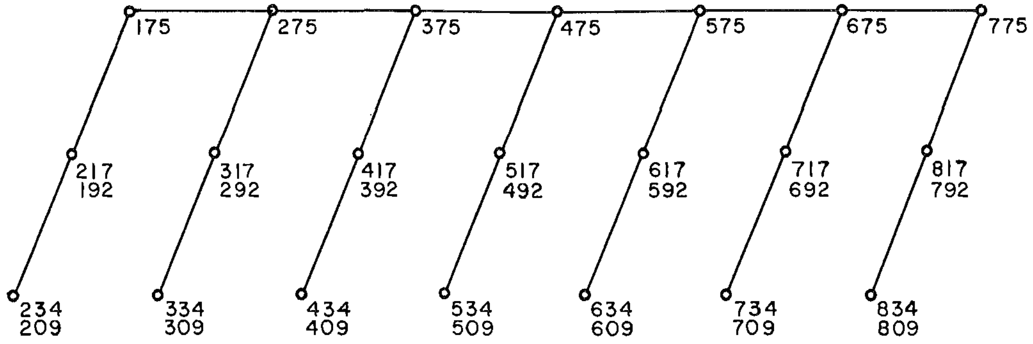
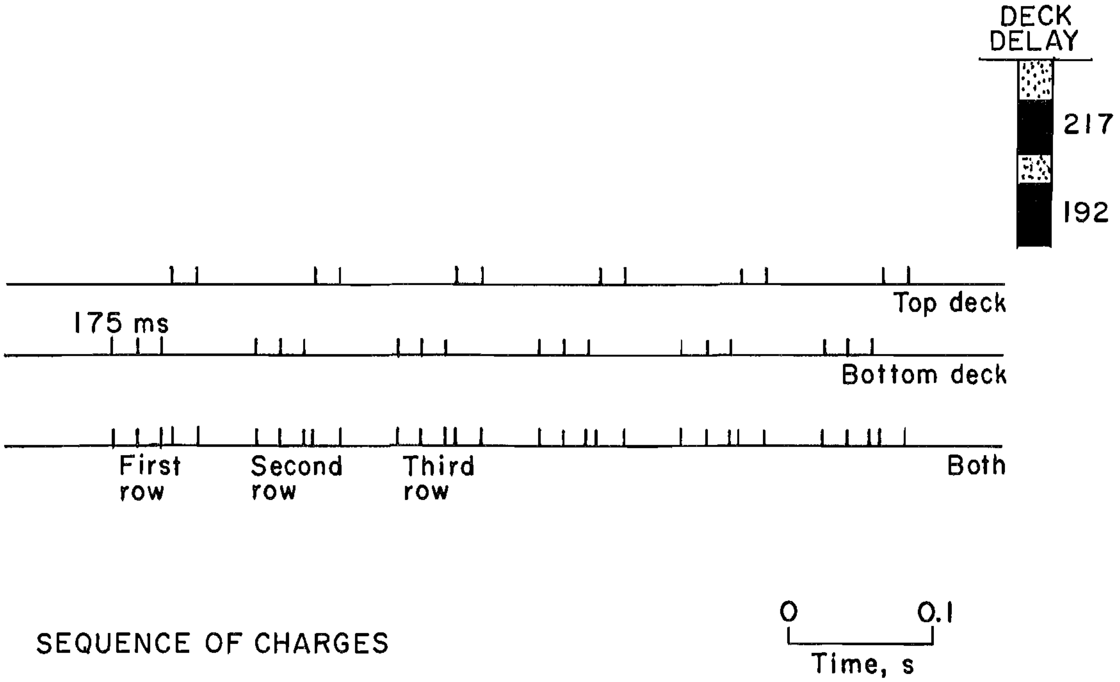


**Figure 33.—Production blast at site 4 and 5: echelon with 42 ms between rows and 25 ms between holes in a row.**



PATTERN LAYOUT, NONEL SYSTEM, TIME IN MILLISECONDS



SEQUENCE OF CHARGES

**Figure 34.—Production blast at site 6: echelon with 100 ms between rows and 17 ms between holes in a row.**

# THEORETICAL PREDICTION MODELS

Review of seismology literature revealed that the mechanism of surface wave generation is not as simple as presented in the Blanford site study (*1*) and mentioned previously in the introduction. Two general cases exist: (1) a low-velocity layer over one of higher velocity (more accurately, the contrast is one of material impedance, which is the product of velocity and density) and (2) a propagation layer bounded by two zones of low velocity. Note that "velocity" here refers to seismic wave propagation velocities, which range from about 1,000 to 20,000 ft/s depending on the material and the type of wave. Examples for these two cases are (1) a thick layer of surface soil over competent rock and (2) a rock layer over a worked-out zone or an extensive zone of collapse, respectively. In reality, existing geologic structures are not precisely known for any of the sites. Even if known, they would not exactly match the relatively simple model parameters such as infinite layers and half spaces, flat interfaces, homogeneous and isotropic materials, etc. Consequently, it is possible to apply these models only in a general and very approximate analysis of the Indiana sites until additional subsurface data become available.

## LOW-VELOCITY SURFACE LAYER

This is the much-studied case in which multiple-reflected refractions produce a low-frequency wave with characteristics related to layer thickness and velocity. Gupta (*8*) addresses Love wave generation involving shear wave reflections at a refraction boundary occurring in phase for discrete wave frequencies. Gupta's relationship is based on the travel distance for the multiple reflections being multiples of the wave length:

$$\frac{2H\sec\theta}{V_1} - \frac{2H\tan\theta}{V_2} = nT - \frac{T}{2},$$

where H is the layer thickness, $V_1$ and $V_2$ are the upper and lower layer shear wave velocities, T is the vibration period, and $V_2 > V_1$. The critical refraction angle ($\theta$) is given as

$$\theta = \sin^{-1}\frac{V_1}{V_2}.$$

The period (T) is equal to 1/f, and n is a positive integer (fig. 35). This relationship can be simplified if $V_2 >> V_1$ and n = 1 for the fundamental or lowest frequency:

$$T = \frac{4H}{V_1}.$$

This is the same as the wave length $\lambda = 4H$.

O'Brien (*9*) derived a similar model for compressional waves. Instead of being shear wave velocities, $V_1$ and $V_2$ are the compressional wave velocities, and if $V_2 >> V_1$, the same simple relationship of $\lambda = 4H$ results.

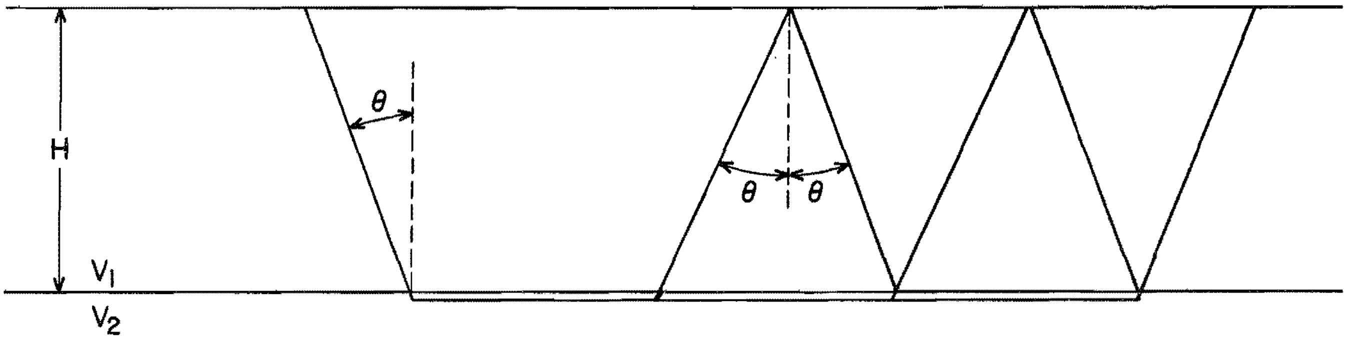


Figure 35.—Surface wave generation model for low-velocity layer.

Several studies of vibrations in low-velocity surface layers have allowed comparisons with the prediction models. Gupta (*8*) found strong 8-Hz waves generated in a 25-ft-thick surface soil layer with a very low shear wave velocity, $V_1$, of 700 ft/s. The underlying rock velocity, $V_2$, was 7,000 ft/s. Johnson (*5*) measured earthquakes on a 115-ft-thick alluvium layer over shale and found a strong 2.3-Hz wave. With Johnson's observed shear wave velocities of 980 and 2,950 ft/s, respectively, in the two materials, the Gupta model predicts 2.14 Hz. This is an excellent agreement.

King (*6*) observed seismic waves on a sediment-filled valley using two profiles and found dominant compression (P) and shear (S) wave low frequencies in good agreement with the simple predictive models. In 200-ft sediments, he found dominant frequencies of about 4 and 3 Hz. The Gupta and O'Brien models predict 5.25 and 3.25 Hz, based on King's compression wave velocity ($V_p$) of 4,130 ft/s and shear wave velocity ($V_s$) of 2,560 ft/s. Another set of measurements in 115-ft-thick sediment found 7- and 4.5-Hz waves. At this site, $V_p$ was 3,510 ft/s and $V_s$ was 2,100 ft/s. These give predicted frequencies of 7.6 and 4.6 Hz, again in good agreement.

Kisslinger (*13*) studied Rayleigh surface waves from buried explosive detonations. At one site, he found that the vibration characteristics were predominantly determined by the surface layering, which consisted of about 210 ft of silts, clays, and gravels over sandstone and shale. This dominant influence of geology was surprising for a study with a 50-fold range of charge sizes. He observed 4-Hz Rayleigh waves at this site, giving a layer velocity of 3,360 ft/s using the O'Brien model. He also noted that the lack of dispersion is an indication that the layering is having an important influence on wave generation. The result is a low-frequency wave of single and constant frequency and long duration and appearing on close-in measurements at distances within about $\lambda/2$.

## SURFACE LAYER OVER A VOID

This is a case of an extensively mined-out horizontal zone at a depth H. Coal mine workings of any significant age could very well be a collapsed zone rather than a void. If so, they would represent a low-velocity medium but with smaller impedance contrast and an irregular interface. These old mine zones would also likely be water filled.

Unlike the Gupta and O'Brien models, this model does not contain a refractor wave, and interference must be between the direct-arriving wave and various multiple reflections. A standing wave in such a layer would appear to have a wave length $\lambda = 2H$, or half that given in the Gupta and O'Brien models. Exactly how this could appear as a reinforced wave at long distances is beyond the scope of this research but certainly worthy of study where conventional wave generation models fail to explain observed vibration characteristics.

## MODEL APPLICATIONS TO INDIANA SITES

Bureau researchers measured wave propagation velocity at site 2 for use in the prediction models. Unfortunately, there is no way to tell which layer corresponds to the measured velocity of 9,450 ft/s, although this value is certainly too high for the near-surface clay, sand, gravel, and drift. In retrospect, a vertical seismic profile or a more detailed refraction survey is required for such studies.

Propagation velocities of unconsolidated surface layers have been measured by various researchers and found to vary with water saturation, compositions, and depths. Kisslinger (*13*) found a dry $V_p$ of 1,510 ft/s for clay-loess. For saturated materials, $V_p$ ranged from about 3,500 to 6,200 ft/s, assuming that King's data also pertained to saturated media (*5-6*). Values for $V_s$ ranged from 1,000 to 2,600 ft/s. Table 5 lists observed and predicted frequencies for the Indiana sites using assumed $V_p$ and $V_s$ values for near-surface layers of 4,800 and 1,800 ft/s, respectively.

Unless the assumed velocities are too high, it appears that the near-surface layers cannot be responsible for the observed low frequencies in the vibration records. Most of the sites are consistent with trapped waves in the deeper layers. The following analyses are from comparisons of observed vibrations and table 5 model predictions. Because they are based on estimated propagation velocities, these conclusions must remain tentative.

In addition and possibly very significant, the sites' structures as described previously in this report could be unrealistic oversimplifications. As found for site 2, the various soil and rock layers can, and probably do, depart from the simple models of constant thickness and horizontal beds. Unfortunately, the prediction models are not yet available for application to such real and individual cases.

Site 1 records had extensive 8-Hz characteristics, even when measured close in. This is consistent with an S-wave in the 66-ft near-surface sand and drift layer and also possibly a P-wave in a 225-ft-thick layer over a void. The later, occasionally appearing 4 Hz is consistent with a trapped S-wave above the old workings at about 225 ft.

Site 2 frequency is consistent with an S-wave in a low-velocity layer of 100-ft thickness. This depth corresponds to the active coalbed, above which is shale and sandstone with high sand and clay content.

Site 3 frequency, with its 3- to 4-Hz waves, is consistent with either a P-wave in a deep low-velocity layer or an S-wave is a layer over a void. Note that the old workings are only beneath one seismograph at the far end of the array (fig.5).

Site 4 frequency is approximately consistent with an S-wave over a void at a depth of 100 ft, with existing low frequencies of 6 to 8 Hz. Site 5, the same mining operation as site 4, has a different array direction and fewer measurements over the deep mined-out seam. Here, predicted vibration frequencies approximate measured ones for two possible cases, P-waves in a low-velocity surface layer and S-waves over a void, with a layer thickness of 100 ft in both cases and a frequency close to 10 Hz.

The only near match for site 6 frequency is an S-wave in the low-velocity surface layer consisting of 60 ft of lacustrine and sand and gravel. Note from figure 9 that the sand and gravel layer is beneath only part of the propagation path. The lacustrine alone is only about 30 ft thick. This site has no old deep workings.

Site 7 could have either a P-wave in a thick low-velocity layer or an S-wave over a void at 270 ft. As this site is extensively undermined, the latter case appears more likely.

Site 8 frequency is consistent with S-waves in the 50-ft surface layer. The layering is described as 10 ft of soil and 40 to 45 ft of a shale rider. Depending on the physical properties of the shale, the assumed S-wave velocity of 1,800 ft/s may not be reasonable. The prediction must therefore remain tentative at the site, which appears, in any case, not to produce VLF.

No geologic information was available for site 9, so no predictions were made. As this is a low-frequency site, it is a viable candidate for future work, although not thought to be undermined.

The individual vibration wave components of motion should reveal much about the kind of waves generated. However, the geologic complexity and multiple wave paths and

Table 5.—Comparisons of measured vibration frequencies and those predicted from simple generation models

| Site [1] | Measured low frequency, Hz | Near-surface layer | | | | | Deep layers or old workings | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Thickness, ft | Predicted low frequency, Hz | | | | Thickness, ft | Predicted low frequency, Hz | | | |
| | | | Low-velocity layer | | Layer over void | | | Low-velocity layer | | Layer over void | |
| | | | P | S | P | S | | P | S | P | S |
| 1 | 4–8 | 66 | 18 | 6.8 | 36 | 13.6 | 225 | 5.3 | 2 | 10.6 | 4 |
| 2 | 5–7 | 30 | 40 | 15 | 80 | 30 | 100 | 12 | 4.5 | 24 | 9 |
| 3 | 3–4 | 60 | 20 | 7.5 | 40 | 15 | 240 | 5 | 1.88 | 10 | 3.8 |
| 4 | 6–8 | 20 | 60 | 23 | 120 | 45 | ~100 | ~12 | ~4.5 | ~24 | ~9 |
| 5 | 10 | 20 | 60 | 23 | 120 | 45 | ~100 | ~12 | ~4.5 | ~24 | ~9 |
| 6 | 3.7–5 | 10 | 120 | 45 | 240 | 90 | 60 | 20 | 7.5 | 40 | 15 |
| 7 | 4–6 | NAp | NAp | NAp | NAp | NAp | 270 | 4.4 | 1.67 | 8.8 | 3.3 |
| 8 | >12 | 10 | 120 | 45 | 240 | 90 | 50 | 24 | 9 | 48 | 18 |

NAp Not applicable.
P Compressional wave with velocity of 4,800 ft/s.
S Shear wave with velocity of 1,800 ft/s.
[1] No predictions made for site 9.

generation mechanisms keep this from being a simple analysis. Sites 1 and 7 are totally undermined and have records which sometimes, but not always, have VLF on radial and transverse components of motion but not on vertical. Often, the transverse component represents the lowest frequency, consistent with trapped S-waves. Site 6, not undermined, has VLF on all components. Site 8, also not undermined, has low frequency that occasionally appears only on the vertical component. Sites 3, 4, and 5 mostly have low-frequency components. Apparently the existence of one adverse generation mechanism does not preclude others at the same site. Generally, it is advisable to address the lowest frequency components first, or alternatively in the frequency range below 10 Hz, those producing the strongest displacements.

# CONCLUSIONS

Near-surface underground coal mine workings produced long-duration, low-frequency, surface-type seismic waves through a multiple-reflection trapping mechanism. In addition, one site without underlying workings also produced low-frequency waves by reflections in a thick low-velocity surface layer, consistent with similar observations made by earthquake researchers at other locations.

In general, the geologic structure is primarily responsible for the blast vibration characteristics, greatly influencing vibration frequency and having an indirect influence on peak vibration amplitudes through low-frequency wave interference. Apparently, it is not possible to make an accurate prediction of vibration frequency because of multiple generation mechanisms. However, thick low-velocity surface layers and extensive underground workings at shallow depths of 100 to 400 ft are potentially serious problems for both vibration amplitudes and frequencies.

Blast designs based on controlling delay times between charges will have only a limited influence on average vibration amplitudes at distances greater than a few hundred feet, for short delay periods with standard accuracies. More accurate delay initiators have promise as a way to influence vibration frequencies.

The 8-ms minimum time separation for independent charges appears insufficiently long for low-frequency sites and should not be used in cases of vibrations with dominant frequencies below about 10 Hz. Charge weights per delay should be estimated from delays within the time interval T/2, where T is the wave period (1/f). When available, precise delays should be tested to determine if special intervals can be used to reduce wave generation at the frequency of the trapped surface waves. Single-charge tests and the use of a wide variety of blast designs at some sites suggested that the vibration frequencies were a site characteristic and that standard pyrotechnic delays, with high amounts of statistical scatter, had little or no noticeable influence on vibration frequency.

Based on charge weights per 8-ms delay, decking appeared to be ineffective in reducing vibration amplitudes and actually produced higher vibrations at a given scaled distance for both echelon and casting designs than did full-column loads. One possible approach to reducing surface wave generation could be differential deck loads, a longer column of explosive at depth and a shorter column near the surface, recalling the studies that found relatively strong surface wave generation from shallow charges.

Specific problem sites should be studied for generation mechanisms by conducting vertical seismic profiles and/or detailed refraction surveys. The use of reliable propagation velocities may allow the development and analysis of generation models that could assess the effectiveness of blast designs meant for vibration abatement.

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# APPENDIX.—GLOSSARY OF SEISMIC TERMS

*Components of motion.*—Particle motion as measured in three orthogonal planes, usually longitudinal, vertical, and transverse. The longitudinal is often labeled "radial" because it is radially aligned with the source-receiver direction.

*Frequency.*—Periodicity of a wave expressed in cycles per second or hertz. Very low frequency (VLF) is defined in this report as a predominant frequency of less than 5 Hz. The reciprocal of frequency (f) is wave period (T) or time for a complete cycle ($f = 1/T$).

*Particle velocity.*—Measure of motion of a wave at any given measuring point or its energy at that place of measurement, caused by the passing of a seismic wave. Particle velocities decay with distance through absorption and geometric spreading and are relatively independent of material properties.

*Propagation velocity.*—Velocity of wave travel. Strongly dependent on material properties, ranging as low as or even lower than the velocity of sound in air at 1,080 ft/s to over 20,000 ft/s in strong solids.

1. $V_1$, $V_2$ are propagation velocities in layers 1 and 2, respectively.

2. $V_p$, $V_s$ are propagation velocities of compression waves (P) and shear waves (S), respectively.

*Seismic waves.*—Acoustic waves traveling in solid or liquid material at propagation velocities dependent on wave type and material properties. Common types of seismic waves are as follows:

1. P-wave: Compressional wave (P stands for primary). P-waves have the highest propagation velocity, and particle motion is in the direction of travel. For a shallow and close-in source, the particle motion is longitudinal.

2. S-wave: Shear wave (S stands for secondary). S-waves are slower than P-waves, typically about 0.6 times the P velocity. Particle motion is perpendicular to direction of travel and can be vertically and/or horizontally polarized. For shallow, close-in sources, a vertically polarized S-wave will be strongest on the vertical component of motion and a horizontally polarized S-wave will be strongest on the transverse.

3. Rayleigh wave: A surface wave with retrograde eliptical particle motion. Strongest on vertical and longitudinal components. Propagation velocity slightly lower than that of S-waves. Generation of Rayleigh waves requires a single interface, and particle motion amplitudes decrease rapidly with increasing distances from that interface.

4. Love wave: A surface wave with horizontally polarized particle motion. Strongest on transverse component. Requires a material layer or two interfaces. An example is a low-velocity soil layer over rock, with the soil-air boundary serving as the second interface.

5. Body waves: A general term for P- and S-waves as opposed to surface waves. Body waves generally travel and spread out in three dimensions.

6. Surface waves: Waves produced by the interaction of body waves and structural interfaces. They are strongest near the interfaces and decrease rapidly with distance from these interfaces. As an example, the Rayleigh wave is produced at the ground-air surface.

7. Direct wave: A seismic wave that takes a direct path from the source to receiver, without any reflections or refractions.

*Wavelength* ($\lambda$).—Periodicity of a wave expressed in distance. The product of wavelength and frequency is the propagation velocity.

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