# Delay timing and geological influences on low-frequency vibrations from blasting at nine Indiana surface coal mines

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# Delay timing and geological influences on low-frequency vibrations from blasting at nine Indiana surface coal mines

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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 one mile. Production and specially fired single-charge blasts allowed the determination of natural ground frequency and also the influence of the 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 relatively low-frequency waves present. This suggests that the widely-used design criteria of 8 ms minimum delay separation may not be sufficiently long for sites with abnormal low frequencies. Both undermined and sites with thick unconsolidated overburden produced low-frequency surface waves.

## 1 INTRODUCTION

The Bureau of Mines was asked by the Office of Surface Mining Reclamation and Enforcement (OSMRE) to examine surface coal mine blasting to determine the prevalence of serious low-frequency vibrations and the relative roles of geologic structure and blast delay intervals in producing such vibrations. An earlier Bureau study for OSM of one such site at Blanford, Indiana, which was extensively undermined by old workings, found abnormally high vibration amplitudes, long durations, and low-frequencies (Siskind 1987). This paper summarizes a comprehensive follow-up study to the Blanford work where results from Blanford were combined with data from eight other Indiana surface coal mine sites suspected to have low-frequency vibration problems (Siskind 1989). Where low frequencies were found, 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. One of the sites had no underlying workings. However, a previous study did find low-frequency vibration on a thick surface layer of low velocity unconsolidated material behind the highwall (Kopp 1986).

Surface waves are seismic waves generated by discontinuities and surfaces in the propagating media, including the ground-air interface. Because these waves tend to be restricted to two-dimensional spreading, they attenuate less with distance than body waves. Therefore they are often the dominate vibration components at long distances. They arrive late in the record (slow relative velocity), are polarized (appear on specific vibration motion components), and often appear as nearly pure sinusoidal, long-lasting wave trains (generation mechanisms favor specific vibration frequencies) (Siskind 1989).

Of particular interest in this study is the generation of surface waves by good reflecting boundaries. Examples of such boundaries are 1) a sharp interface between a surface soil or other low-velocity deposit and the underlying competent rock and 2) extensive horizontal mined-out zones serving to exclude and reflect seismic energy. Studies have been done on the influences of low-velocity surface layers on earthquake vibration wave characteristics (Sheriff 1982, Murphy 1971, Johnson 1981, King 1984, Bard 1985). These studies measured vibrations on top of the upper layer of low-velocity and found increased vibration amplitudes, low frequencies, and long wave durations. Frequencies observed were consistent with simple generation models based on the layer thickness and upper layer velocity (Gupta 1961, O'Brien 1957). These models assume horizontal layering and a strong velocity contrast, that is, the seismic velocity of the lower layer is much greater than that of the upper layer ($V_1$). 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 the report applies this model to the nine Indiana sites.

The importance of vibration frequency for structural response and damage risk is discussed in detail in Bureau of Mines RI 8507 (Siskind 1980). 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.

The question for OSM is to determine if stricter controls are 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.

## 2 EXPERIMENTAL PROCEDURES

Blast vibration data were collected from nine surface coal mine sites, three near Terre Haute in west-central Indiana and six near Evansville in southern Indiana. 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 non-undermined ones, were known to have thick, unconsolidated, and low-velocity surface deposits. The northernmost sites were also in regions of thick glacial till deposits which were not thought to be present farther south. Table 1 summarizes site conditions with more details provided in the full study report (Siskind 1989).

### 2.1 Propagation arrays

Seismographic stations were placed in linear arrays in the directions that the mine operators indicated were of primary concern. In each case, the 7-station array was on the highwall behind the face, although not necessarily perpendicular to it. The closest stations were within 35 feet of a blasthole and the farthest up to about 8,000 feet. Very close-in measurements were intended to record signals characteristic of the sources while distant stations recorded vibrations assumed to be influenced by the propagating media. These influences include the effects of attenuation, dispersion, multiple path reflections, and surface wave generation.

Of the nine sites studied, numbers one through six were available for Bureau testing which consisted of widely spaced instrument arrays and a suite of test blasts. The other three 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 in distance. Therefore, the DNR data could only be generally compared with the historical mean.

### 2.2 Single-charge blasts as a study tool

The use of single charges is a powerful potential tool for studying both site and blast design influences on vibration characteristics (Anderson

1982, 1983). 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 a 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, back rows compared to front rows, 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.

### 2.3 Single-charge blast for Bureau monitoring

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 used 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. None of the three sites studied through data acquired from the Indiana DNR has single-charge vibration measurements.

Table 1. Test sites for Indiana vibration study, all surface coal.

| Site No | Location | Undermined Existent | Undermined Depth(s), ft | Surface LV layers Nature | Surface LV layers Thickness, ft | Monitoring distances, ft | Maximum charge wt per delay, lb |
|---------|----------|---------------------|-------------------------|--------------------------|----------------------------------|--------------------------|----------------------------------|
| 1 | Near Terre Haute | Yes | 225 Extensive 325 | Sand and drift | 60-75 | 54-5,700 | 250 |
| 2 | Near Terre Haute | Yes | 110-150 | Soil and loess Sand, gravel and drift | 10 10-20 | 70-8,100 | 2,000 |
| 3 | Near Evansville | Yes | 240 | Sandy clay, sandy muck and gravel | 50-70 | 140-4,600 | 165 |
| 4 | Near Evansville | Yes | 90 | NA | -- | 35-3,800 | 102 |
| 5 | Near Evansville | Yes | 90 | Lacustrine | NA | 110-2,100 | 102 |
| 6 | Near Evansville | No | -- | Loess and soil Lacustrine silt and clay | 20 60 | 110-6,050 | 1,350 |
| 7 | Near Terre Haute | Yes | 140-192 268 350 | NA | -- | 2,300-7,000 | 1,400 |
| 8 | Near Evansville | No | -- | Soil | 10 | 600-4,000 | 350 |
| 9 | Near Evansville | No | -- | NA | -- | 1,800-9,000 | 2,500 |

NA Data not available.

## 2.4 Production blast designs

Table 2 lists the production blast designs analyzed in this comparative study, sites one through six by the Bureau and seven to nine by the DNR. 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 which resembled Nonel and is called LVST (Low Velocity Signal Transmission). It is claimed to be more accurate.

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

| Site | Design type and delays, ms | Number of decks | Hole diameter, 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,[4]42[3] | 4 | 6-3/4 | 165 | 17 | 16.5 |
| 4 | Echelon,[4] 25 by 42 | 2 | 6-3/4 | 102 | 14 | 14 |
| 5 | ..do....,......... | 2 | 6-3/4 | 102 | 14 | 14 |
| 6 | Echelon,[4] 17 by100 | 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 |

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

## 3. RESULTS OF FINDINGS

### 3.1 Vibration amplitudes and propaation plots

Square-root-scaled propagation plots were prepared for each of the sites studied. Two examples are shown by Figures 1 and 2. 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. For most of the six sites monitored, these amplitude differences are greater at farther distances. This suggests that the delays from the production blast are only long enough to
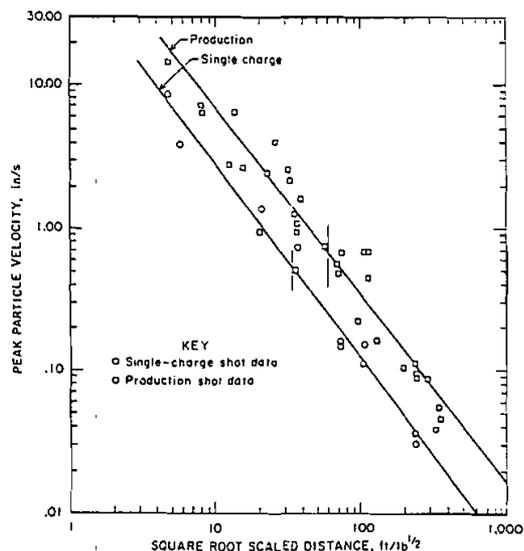
Figure 1. Propagation plots of production and single-charge blasts from site 1.
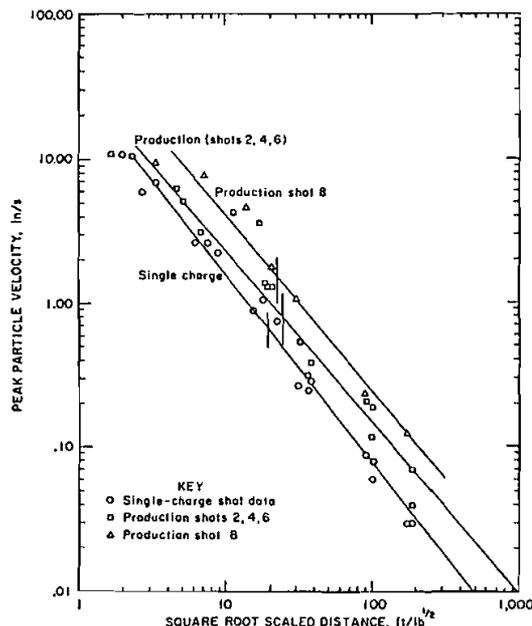
Figure 2. Propagation plots of production and single-charge blasts from site 2.

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.

### 3.2 Vibration amplitude comparisons between sites

Least squares regressions of mean velocities for the various sites are compared in Figures 3 for single charges and Figure 4 for production blasts. Standard deviation bars are omitted here for clarity. Except for site 5, the single-charge (or single-hole) values 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 non-undetermined 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, shown in Figure 4, 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 (Figures 5-7). 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
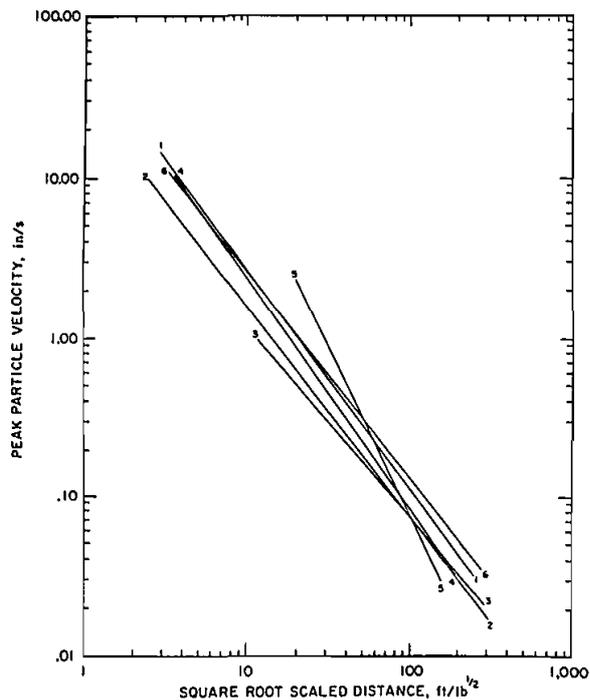
Figure 3. Propagation plot regressions for single-hole or single-charge blasts for six Indiana coal mines monitored by the Bureau of Mines.



Figure 5. Vibration amplitudes for site 7 at closest structure and for four blast designs.

squares lines. For comparison of relative amplitudes, the mean regression line is shown for production blasts at site 3, being the approximate middle line in Figure 4, 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 Figure 5. This is consistent with observations at the Universal Mine (Siskind 1987), where increased blast design complexity used to
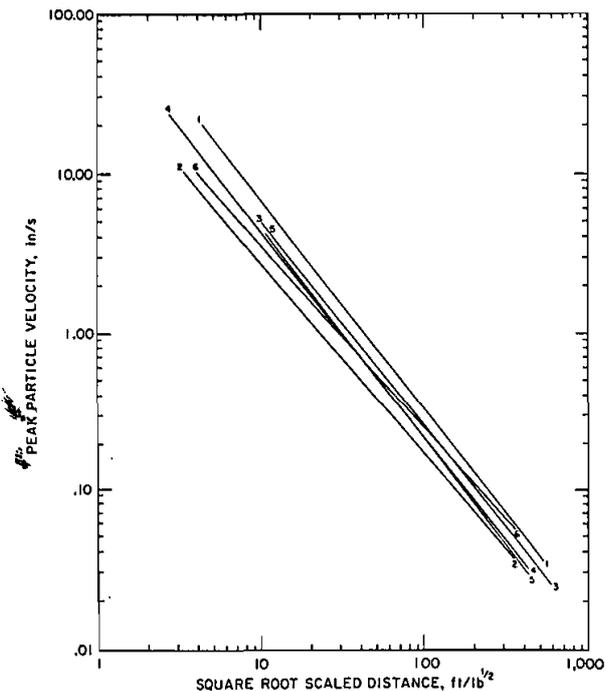
lower charge weights per delay did not necessarily produce corresponding lower vibration amplitudes.

Site 8 amplitudes are given in Figure 6. 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 7.

The small amount of site 9 data suggests that this site has no abnormal vibration amplitudes.



Figure 4. Propagation plot regressions for production blasts for six Indiana coal mines monitored by the Bureau of Mines.



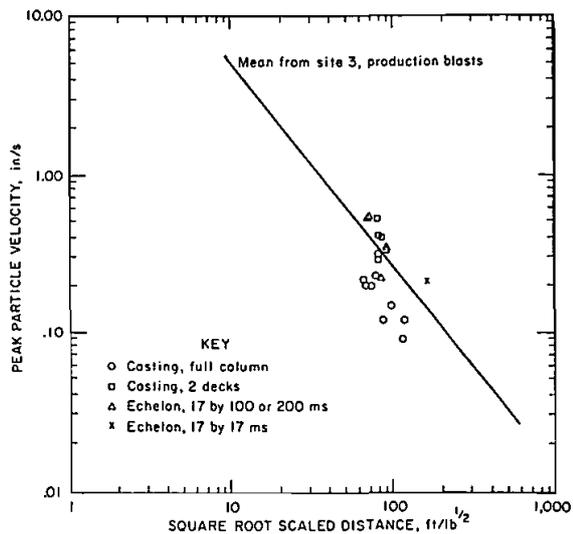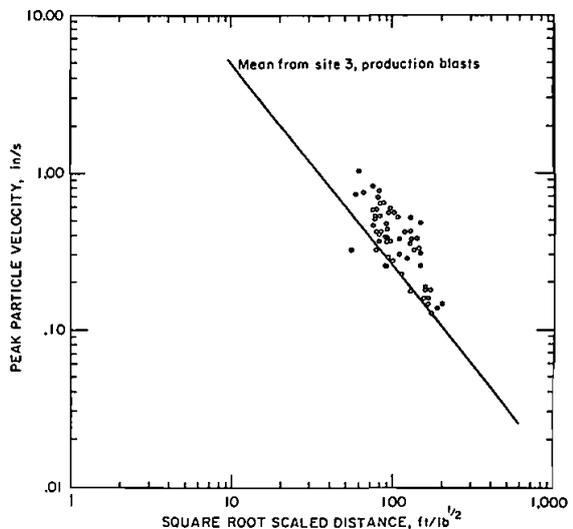Figure 6. Vibration amplitudes for site 8.

## 3.3 Vibration amplitude comparisons with historic data

Vibration values for both single charges and production blasts are plotted in Figures 8 and 9 for comparisons with the historical mean and envelopes from RI 8507 (Siskind 1980). The mean line in Figures 8 and 9 represents the surface coal mines summary from RI 8507, Figure 10, "maximum horizontal," and are not the means 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.
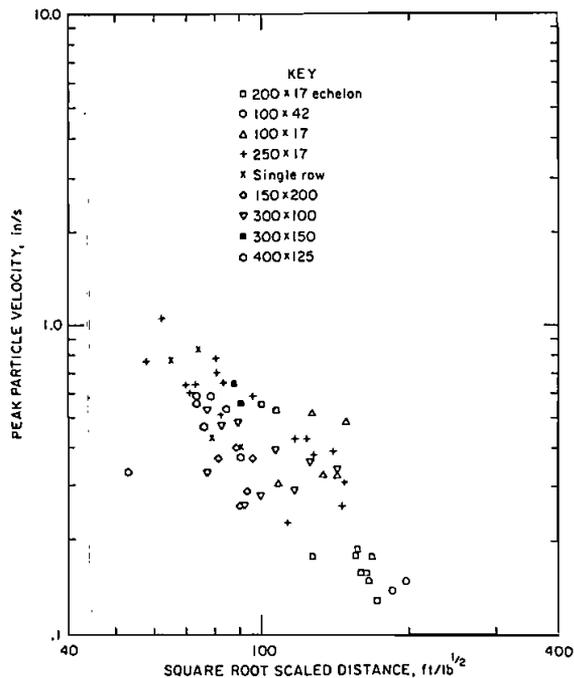
Figure 7. Vibration amplitudes for site 8 showing blast design influences.

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 (Siskind 1987). In that previous study, the maximum envelope was approximated by a line representing two standard deviations (2σ) above the mean.
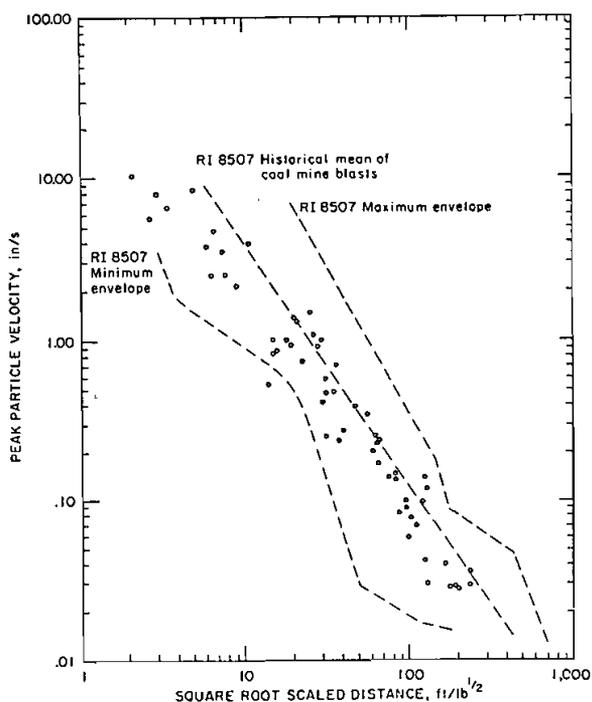


Figure 8. Measured vibrations from single charges and comparisons to RI 8507 coal mine mean and data envelopes.
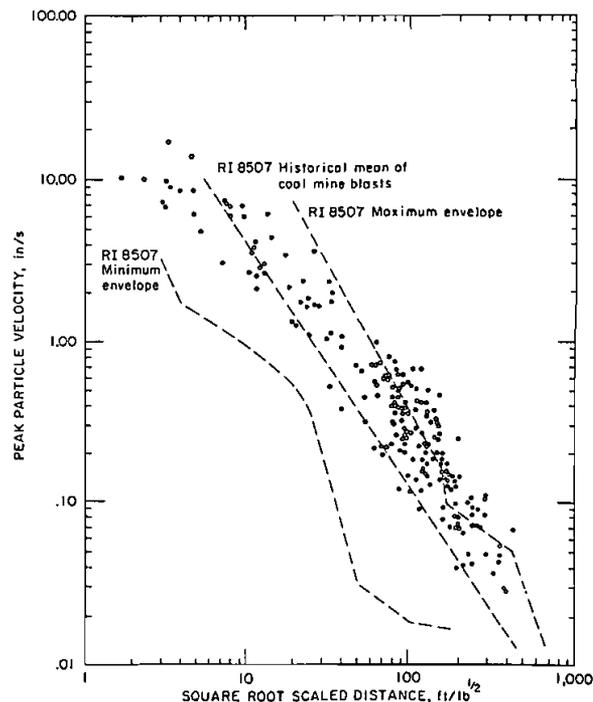


Figure 9. Measured vibrations from production blasts and comparisons to RI 8507 coal mine and data envelopes.

## 3.4 Vibration frequency comparisons between sites

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 sites. Figures 10 and 11 show sets of vibration traces for a significant component of motion for one site, for both one single-charge and one production blast. 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 both 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 feet 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 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.
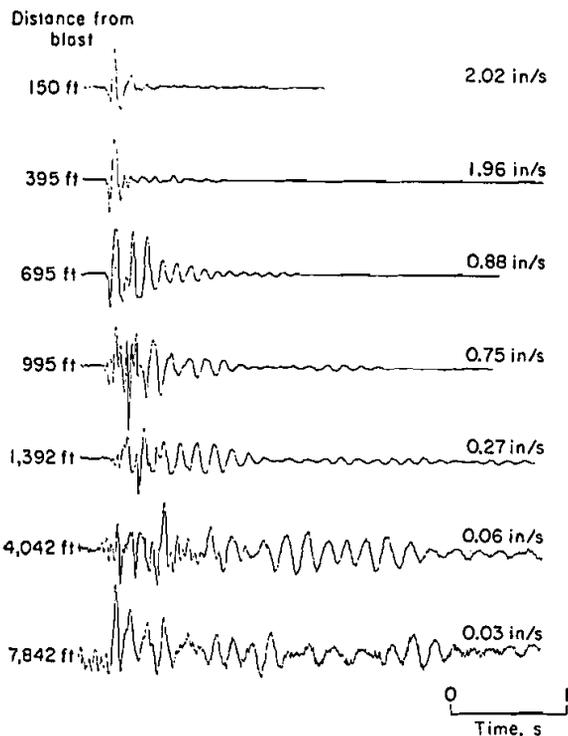
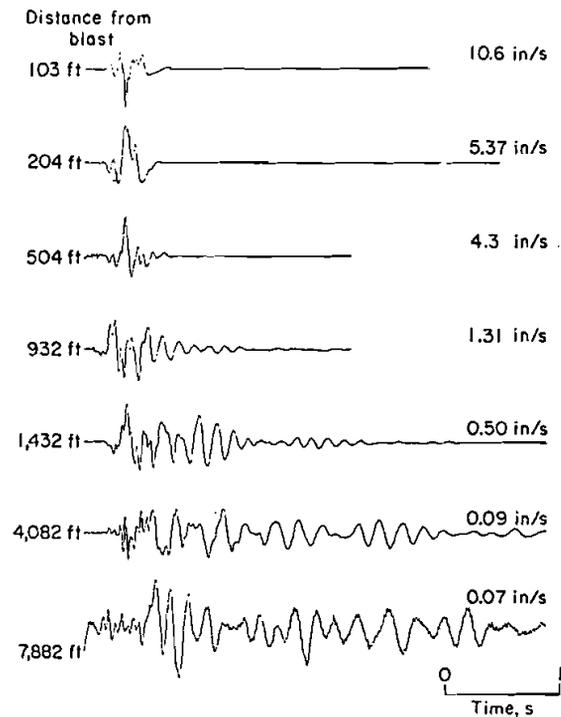Figure 10. Single-charge vibration records, radial, site 2, shot 7.



Figure 11. Production blast vibration records, radial, site 2, shot 6.

Table 3. Frequency characteristics of Indiana coal mine blast vibrations.
(Frequency in Hz, distances in ft, and particle velocities in in/s.)

| 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. Amplitude of ~ 0.15 in/s. 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. Amplitudes of 0.10 in/s or less. Durations up to 6 s. |
| 2 | 10 Hz within 300 ft. | 7 Hz at distance of 800 ft. Amplitudes of 0.9-1.3 in/s. 5 Hz at 4,000 ft but of low amplitude, less than 0.04 in/s. | 8-9 Hz at 200-300 ft. | 7 Hz at distances of 800 ft. Amplitudes of up to 2 in/s. 5 Hz at large distances (>4,000 ft) with amplitudes of 0.10 in/s. |
| 3 | 8-10 Hz at 424 ft. Duration of 0.37 s. (Note: Three deck delay intervals total 0.215 s.) | 6 Hz at 1,250 and 2,600 ft. 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. This is about half the amplitude of higher frequency components. 3-4 Hz decays to insignificance at 4,600 ft. Durations of 6-7 s at 2,500 ft. |
| 4 | 20 Hz at 70 ft. 7-8 Hz emerging at 150 ft but of about one-third amplitude, at 0.2 in/s. | 10-12 Hz at 700 ft. Amplitude of 0.2 in/s. | Secondary frequency of 7-8 Hz at a distance of 150 ft. Amplitude of 0.40 in/s. | 8 Hz at distances of 800-1,200 ft. Amplitudes of 0.10 in/s or less, or about half the amplitudes of higher frequency components. 8 Hz decays to insignificance at about 2,300 ft. Durations of 2 s. |
| 5 | 13-14 Hz at 260 ft. | 7-10 Hz beyond about 1,000 ft. Amplitudes of about 0.2 in/s. This is about 1/3 amplitude of higher frequency components. | Secondary frequency of 12 Hz at closer stations (<800 ft). Amplitude up to 0.5 in/s. | 6-7 Hz at 2,100 ft at about .06 in/s. 10 Hz at 2,256 ft for one blast, 0.04 in/s. Durations of 2 s. |
| 6 | 3.5-4 Hz at 388 ft at 2 in/s. Amplitude is about half of higher frequency. | 6 Hz at about 3,600 ft, dominant component. Amplitudes of about 0.2 in/s 10 Hz also present. | 10 Hz on all records, dominant component. | 10 Hz on all records. 3.7-5 Hz at distances beyond about 800 ft and dominating records at 2,000 ft, 0.3 in/s. Durations over 6 s. |
| 7 | NA | NA | NA | 4-6 Hz at intermediate distances of 2,500-3,000 ft. Amplitudes of 0.11-0.27 in/s. 3-4 Hz at distances of 6,300-6,900, amplitudes less than 0.11 in/s. Durations up to 5 s. |
| 8 | NA | NA | NA | Above 12 Hz for all blasts at distances from 580-3,900 ft. Durations of 5 s. |
| 9 | NA | NA | NA | 4-5 Hz at large distances of 3,400-7,000 ft. Amplitudes of 0.15-0.26 in/s. Durations up to 5 s. |

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 feet. These times are well beyond source durations. Figure 12 shows some of the longest duration records collected for a site 6 production blast at a relatively far distance of about 6,000 feet. These records 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 relatively 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

Site 6 has a vibration anomily that appears to be related to the low-velocity surface layer thickness. Figure 13 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. Initially, station 5 data were not included in the analyses 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 3 and 4.

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 the same particle velocity as 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.

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 (Figures 14 and 15 show two examples). The technique employed was to directly measure wave periods for the easily visible
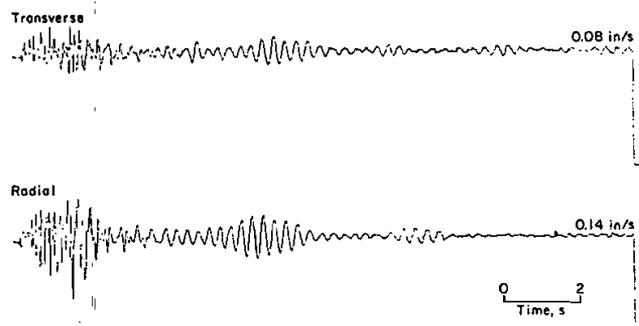
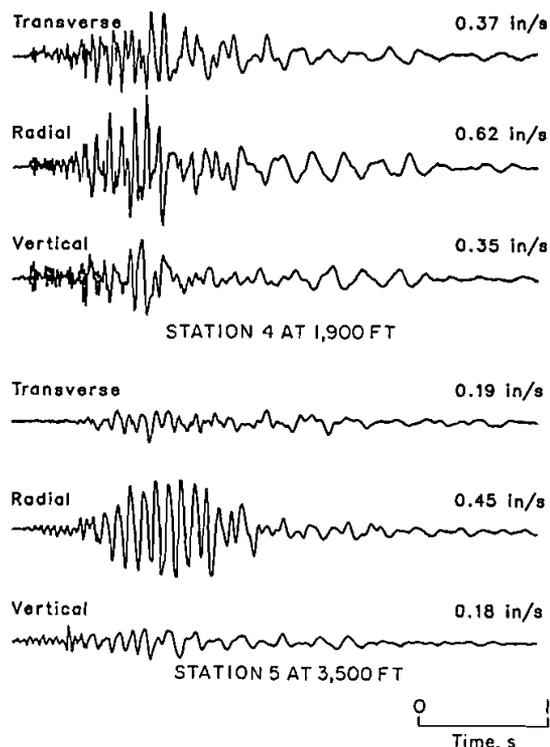STATION 4 AT 1,900 FT

STATION 5 AT 3,500 FT

Time, s

Figure 13. Three-component vibration traces for two adjacent stations for production blast 3 at site 6.

dominant low-frequency components (frequency = 1/period). Typically, the records had high-frequency beginnings (>20 Hz) followed by low-frequency tails which were often of lesser amplitude (not the peak particle velocity). Note that Figures 14 and 15 plot particle velocity against distance, not scaled distance. Consequently, the vibration amplitude differences between the sites are partly the result of the different charge sizes (Tables 1 and 2).

Figure 12. Production blast record for site 6, shot 4 at a distance of 5,800 ft.
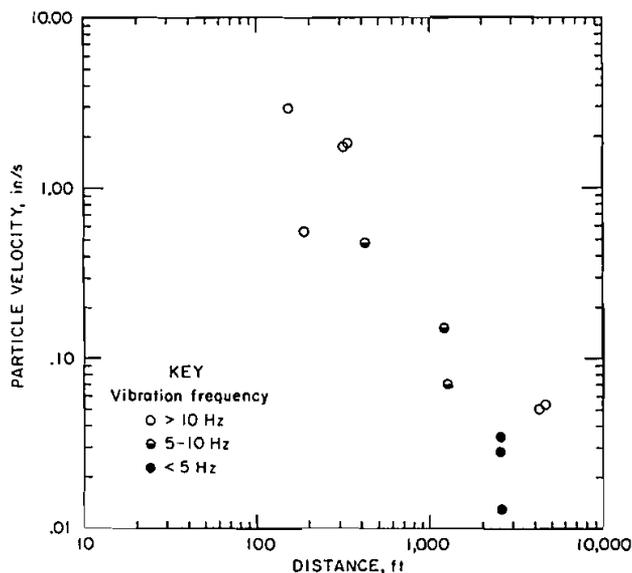
Figure 14. Propagation plot of low-frequency components of blast vibrations for site 3.
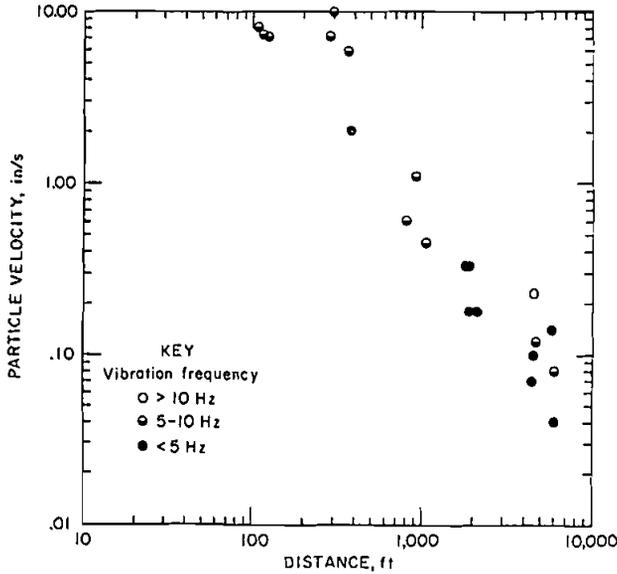
Figure 15. Propagation plot of low-frequency components of blast vibrations for site 6.

## 3.5 Safe vibration criteria for low-frequency cases

Analyses such as shown in Figures 14 and 15 can be used to estimate safe blasting distances based on the Bureau criteria in RI 8507 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 pound per delay for the nine sites. Based on an envelope of velocity versus distance for all vibrations below 10 Hz, and maximum safe particle velocities of 0.5 and 0.75 in/s, approximate minimal distances have been calculated (Table 4). These 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 (Siskind 1989).

## 3.6 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 16-18 show blasthole array designs and time records of charge sequences by rows, holes in a row, and decks for three of the sites instrumented by the Bureau.

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

| Site | Charge weight per delay, lb | Minimum distance, ft | | |
| | | Velocity criterion, in/s | | Displacement criterion |
| | | 0.5 | 0.75 | 0.03 in |
| --- | --- | --- | --- | --- |
| 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.



PATTERN LAYOUT, HERCUDET SYSTEM, TIMES IN MILLISECONDS

SEQUENCE OF CHARGES

Transverse = 0.051 in/s

Vertical = 0.078 in/s
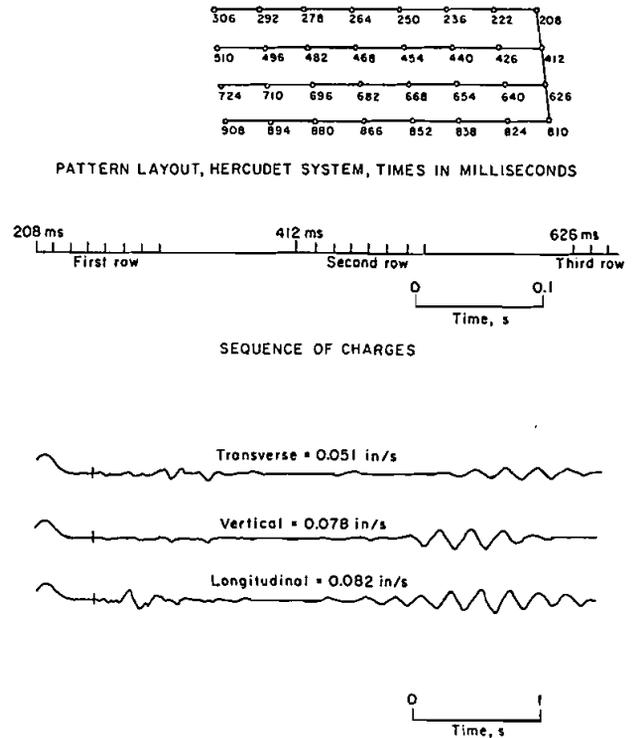
Longitudinal = 0.082 in/s

Time, s

VIBRATION RECORDS, HOLLINGSWORTH HOUSE 7,520 FT

Figure 16. Blasthole array, sequency of charges and measured vibration time histories for casting blast at site 1.



PATTERN LAYOUT, NONEL SYSTEM, TIME IN MS

First row

Second row

Third row

Fourth row

Fifth row, etc

All

SEQUENCE OF CHARGES

Time, s

Figure 17. Production blast at sites 4 and 5: echelon with 42 ms between rows and 25 ms between holes in a row.

## 3.7 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 (Figure 1), and the variation of differences between single charges and production blasts in comparing all sites (Figures 1 and 2). By contrast, other evidence suggests that there is

minimal influence. Examples are the tight grouping of all production blasts (Figures 4), and the many designs employed at single sites (Figures 5 and 7). 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.



PATTERN LAYOUT, NONEL SYSTEM, TIME IN MILLISECONDS

DECK DELAY

SEQUENCE OF CHARGES
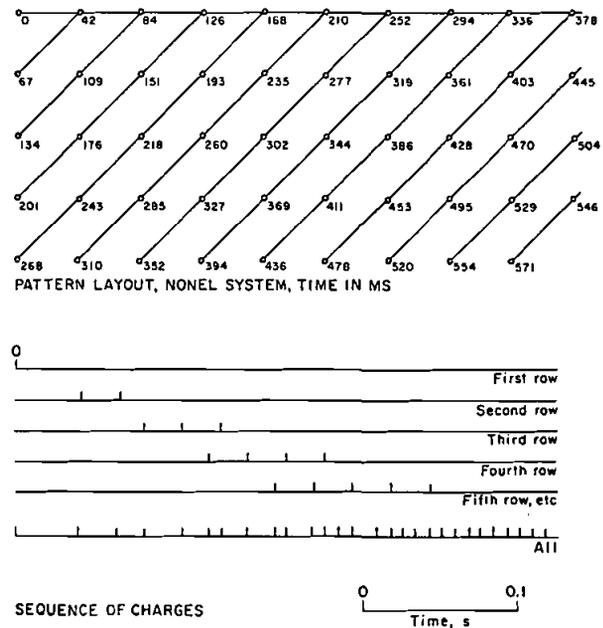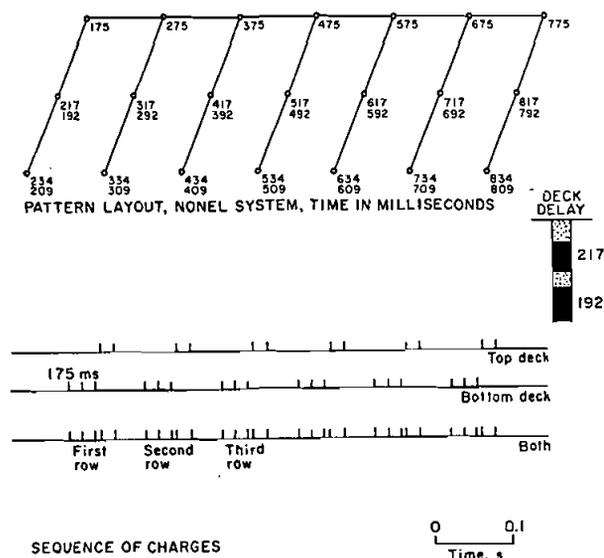
Figure 18. Production blast at site 6: echelon with 100 ms between rows and 17 ms between holes in a row.

## 3.8 Blast design and vibration frequency

For analysis of blast initiation, the basic approach is to compute 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 can enhance this frequency's amplitude and also introduce other higher frequencies. Unwanted frequencies can be reduced, in theory, 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 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 charges, are shown in Figures 16-18 for three of the six sites studied by the Bureau propagation arrays. These are representative results. All times are nominal and assume detonations occur as designed. Also, for all 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 time 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 location.

A casting blast from the earlier site 1 study (Siskind 1987) shown in Figure 16. 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.

Sites 4 and 5 are the same mining operation and used the same blast design (Figure 17). 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 feet. The low frequency part of the vibration record for site 5 at 2,256 feet lasts far longer than the barely visible counterpart for site 4 (at 2,240 feet). 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.

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 18 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. Of most concern at this site is the 4-Hz wave-train tail appearing at surprisingly close distances of 300 feet and of relatively large amplitude at far distances. This VLF is undoubtedly a site phenonenon and not the result of blast design.

The reader is directed to the complete report (Siskind 1989) for additional blast design and site analyses.

## 4. THEORETICAL MODELS OF SURFACE WAVE GENERATION

### 4.1 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 (Siskind 1987) 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 impedence, 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. Examples for these two cases are (1) a thick layer of soil over competent rock and (2) a near-surface rock layer over a worked-out zone or one of extensive 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.

The low-velocity surface layer case was already mentioned in the Introduction section and applies to both shear waves (Gupta 1961) and compressional waves (O'Brien 1957) by using appropriate propagation velocities. The complete report describes model assumptions and details of derivation (Siskind 1989). Also, already mentioned, experimental studies of earthquake surface waves found low-frequencies consistent with the simple generation model. Kisslinger studied explosion-produced Rayleigh waves of 4-Hz in experiments involving a 50-fold range of charge sizes (Kisslinger 1963). These waves were attributed to a 210-ft thick low-velocity surface layer.

The second case is an extensively mined-out horizontal zone beneath the active blasting. In the absence of a refracting boundary, the resulting standing wave would appear to have a wavelength of 2H where H is the layer thickness based on a Simme reflection. This is one-half that of the low-velocity layer case.

## 4.2 Application of models to Indiana sites

Actual applications of the theoretical models require known or assumed wave propagation velocities. Only at site 2 was an attempt made to measure a velocity and the resulting 9,450 ft/s is likely a refractor and not the direct wave in the surface layer. Therefore, values were assumed based on the already-mentioned previous works of others. Using compressional and shear wave velocities of 4,800 and 1,800 ft/s respectively, and depths reported of surface layers and old workings, model frequencies were computed to compare to measured vibrations (Table 5).

Table 5 has quite a few plausible matches between computed and observed vibration frequencies. For example, site 1 records had extensive 8-Hz characteristics, even when measured close in. This is consistent with a shear (S) wave in the 66-feet near-surface sand and drift layer and also possibly a compressional (P) wave in a 225-ft thick layer over a void. The later, occasionally appearing 4 Hz is consistent with trapped S-wave above the old workings at about 225 feet.

Low frequencies at site 2 could be attributed to a S-wave in a 100-ft thick low-velocity layer. This depth corresponds to the active coalbed above which

is shale and sandstone with high sand and clay content, or an S-wave in a low-velocity 100-ft thick surface layer.

The only near match for site 6 frequency is an S-wave in the low-velocity surface layer consisting of 60 feet of lacustrine and sand and gravel. Note 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.

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 generation mechanisms keep this from being a simple analysis. This is an area where further work would likely be beneficial; however, actual propagation velocities are needed.

## 5 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 and the complications of local geology. However, thick low-velocity surface layers and extensive underground workings at shallow depths of 100 to 400 feet 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 too short 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 generation at the frequency of the

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

| Site | Measured low frequency, Hz | Predicted low frequencies from theoretical models for a given layer thickness, Hz | | | | | | | | | |
| | | Near-surface layer | | | | | Deep layers or old workings | | | | |
| | | Thickness, ft | Low velocity layer | | Layer over void | | Thickness, ft | 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 |
| 9 | 4-5 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |

P   Compressional wave with velocity of 4,800 ft/s.
S   Shear wave with velocity of 1,800 ft/s.
NAp   Not applicable (no near-surface layers are present).

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 primarily a site characteristic and that standard pyrotechnique 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. Another approach would be fewer decks per hole with larger delay intervals.

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 for vibration abatement.

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