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BLAST VIBRATION MEASUREMENTS AT FAR DISTANCES AND DESIGN INFLUENCES ON GROUND VIBRATIONS

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ABSTRACT

The Bureau of Mines was funded by the Office of Surface Mining (OSM) to determine how blast vibrations from a local surface coal mine were affecting homes in the towns of Daylight and McCutchanville, located in southwestern Indiana near Evansville. Although Daylight was about two miles from the blasting and McCutchanville four to five miles away, many residents claimed that blast vibrations were damaging their homes. At least one citizen felt that the vibrations worsened at the time the mine began cast blasting.

Ground vibrations and airblast were monitored at six selected homes in the area, with one house in each town instrumented to measure above ground structural response. Painstaking visual crack inspections were made in the homes immediately before and after most of the blasts and level-loop surveys of foundation alignments were done at the beginning and end of the monitoring period. Historical vibrations data collected during the ten months prior to the study were also included in the analysis. Peak vibration amplitudes recorded by the Bureau were typically very low and the study concluded that vibration amplitudes were far too small to be responsible for the structural and cosmetic cracks apparent in many of the homes. OSM is currently investigating the likelihood that damage has occurred because the homes were constructed on unsuitable soils.

Bureau researchers compared a limited amount of vibrations data from different blast designs and noticed that some variations in design factors may have influenced the amplitude and frequency characteristics of ground vibrations received in Daylight. By contrast, blast design alterations did not seem to affect the dominant frequencies of ground vibrations recorded in the more distant McCutchanville, which were consistently between 4 and 6 Hz. This is quite possibly the natural frequency range of the ground and suggests that geologic factors will eventually dominate blast vibration frequencies, an observation substantiated by other investigators.

INTRODUCTION

Overburden stripping blasts for surface coal mining involves large quantities of explosives. The mine under study, not untypical of the midwestern coal province, utilizes total blasts of up to several hundred-thousand pounds of explosives with quantities per delay period ranging widely from 200 to over 7000 lbs. Surface-mine blasts can therefore generate significant ground vibration and airblast noise. In populated areas, blast vibrations are a potential source of structural damage and human tolerance concerns.

Residents in the towns of Daylight and McCutchanville, Indiana, located in the southwestern part of the state near Evansville, have charged that vibrations from surface blasting at the Amax Ayrshire coal mine have damaged their homes. They claim that all damage has occurred or worsened since cast blasting was begun in March, 1988. The two towns are relatively far from the blasting; Daylight is about two miles from the blasting and McCutchanville four to five miles away (Figure 1). At these types of distances, blast vibrations are commonly not of concern because amplitudes have attenuated to very small levels far below regulatory limits.

In response to the citizen's concerns, the Federal Office of Surface Mining (OSM) organized a comprehensive investigation to study the problem. As part of the project, the OSM contracted the Bureau of Mines to record and analyze blast vibrations from the Ayrshire Mine and assess the structural impact to homes in Daylight and McCutchanville. Bureau personnel have extensive experience in studying the effects of blast vibrations on residential structures and have published several noted papers on their procedures and findings, many of which are cited in this text.

THE BUREAU OF MINES VIBRATIONS AND DAMAGE STUDY

From November 1, 1989 to January 3, 1990, ground vibrations and airblast from fifty-nine Ayrshire mine production blasts were monitored by the Bureau at six homes in the area. Figure 2 shows the location of the Bureau monitoring sites as well as other monitoring stations used for the study that were operated by the Ayrshire mine and the Indiana Department of Natural Resources (IDNR). The six homes were chosen from a long list of homes inspected by the OSM. Final selections were made because of preferable locations relative to the mine (e.g., a long wall facing the active highwall) and that the owners could provide unrestricted interior access for monitoring purposes. They were all of modern construction and had moderate levels of visually apparent damage that ranged from narrow cracks of less than 0.1 inch in the walls near door and window openings, to larger superstructure and foundation cracks on the order of a few tenths of an inch wide. Some other homes in the McCutchanville area had severe foundation damage including wide cracks on the floors and basement sections with displacements of nearly half an inch. In one case, a foundation block-wall was caved in.

Instrumentation

Dallas ST-4 self-triggering portable seismographs with airblast monitoring capabilities were used at all six Bureau monitoring sites. The ST-4 has an almost undistorted frequency response of 2 - 200 Hz for ground vibration recording (Stagg and Engler, 1980)

and a microphone response with less than 3 dB signal distortion down to 5 Hz. (The dB scale is logarithmic as opposed to the linear psi-scale. A change of 20 dB is equivalent to an order-of-magnitude difference, a factor of 10.) The three-component ground motion transducers were placed either outside the homes near the foundation, or inside at ground level on a foundation wall corner. The H~1 component of motion pointed in the direction of the mine. Airblast microphones were hung outside the homes from roof soffits - less than ideal, but deemed necessary to help protect from weather damage.
One home in each town, house 105 in Daylight and house 209 in McCutchanville, was also instrumented with a higher resolution recording system using accelerometer transducers and a low frequency "sonic boom" microphone with coupled charge amplifiers, all feeding into a broad-band 7-channel FM tape recorder. An MB velocity gauge was used to measure vertical ground motion at house 209. The transducers were orthogonally aligned to measure one vertical and two horizontal directions of motion. They were mounted at ground level on an inside foundation corner facing the mine and on the first-floor walls to include above-ground structural response. The sonic boom microphones were attached to the underside of the soffit overhang. These systems have linear frequency responses from 1 - 8000 Hz for ground vibration and structure response and from 0.1 - 16,000 Hz for airblast. For redundancy, a ST-4 self-triggering seismograph was used at each station.

The vibration transducers were fixed and not realigned with the shot as the blasting progressed along the highwall. Previous research has indicted that precise transducer alignment is not critical for accurate vibration measurements at the low amplitudes and frequencies expected to be found (Siskind and Stagg, 1985). Accelerometer information was converted to particle velocity by the integrating mode of the charge amplifiers. The tape recording systems had to be operated manually, requiring close coordination with the mine to know within a minute or so when the shot was to be fired. Analog-to-digital data conversion and waveform analysis were completed with a Nicollet 4094 digital oscilloscope.

Visual Observations

Painstaking visual crack inspections were made in the homes immediately before and after most of the blasts. Specified areas on the inside foundation and superstructure walls and ceilings were checked and rechecked for changes in existing crack size and to determine if new cracks had formed. Over 1700 individual crack inspections were made during the two-month Bureau study. In addition, level-loop surveys of foundation alignments were performed at the beginning and end of the monitoring period.

Historical Vibrations Data

Also included in the analysis were peak ground vibration amplitude readings from over 120 blasts recorded at several different stations in the area from December, 1988 to early October, 1989, a ten month period just prior to the Bureau study (Figure 2). Associated peak amplitude airblast levels at some of the stations were available, but to a much lesser extent than the ground motion readings. This historical information, originally collected by the mine and IDNR, included many blasts that were at least as large, in terms of charge weight per delay period and total charge weight used, as those shot during the Bureau monitoring period.

Vibration Waveforms

Figure 3 shows the ground vibrations, airblast and structure response that were produced from a production blast at the Ayrshire mine and recorded by the Bureau at house 105 in Daylight. The home is a one-story ranch-type dwelling with a full concrete-block basement. The blast, referenced in Table 1 as shot #25, was detonated about 10,253 ft due west of the monitoring station. It incorporated a maximum charge weight per delay of 6,225 lbs resulting in square-root scaled-distance (SRSD) of 130 ft/lb~1/2. The vibrations from shot #25 were captured on the broad-band FM recording system are representative for the types of waveforms recorded during the project, although the measured peak particle-velocity amplitude of about 0.1 in/s was one of the largest observed during the study period.

Ground Vibrations

The orientation of the blast relative to the transducers gives an almost true orthogonal orientation helping to identify the characteristic seismic "phases". The arrivals of the principle body-wave phases are identified as "P" and "S" for primary and secondary waves, respectively. Body waves travel deepest and are usually of relatively small amplitude and high frequency as compared to the surface waves. The first arrival of the surface wave phases are indicated with an "R" for Rayleigh wave and an "L" for Love wave. Surface waves generated from blasting are formed by the interaction of seismic energy and the surface of the earth or other near-surface geologic features. They propagate more slowly than body waves and travel through the uppermost geologic layers.

Surface waves produced from blasting often contain the peak particle-velocity (PPV) phase - the part of the vibration waveform having the highest amplitude. The relatively flat-lying multi-layered sedimentary formations overlying the coal seams provide the necessary features for dominant surface-wave generation. The frequency of the PPV-phase, as referred to in this paper, is simply the reciprocal of the time period between successive peaks or troughs containing the peak amplitude portion (e.g., frequency, Hz = 1/period, s). The frequency of the PPV-phase for the vertical component of shot #25 is about 4 Hz, considered low frequency and not uncommon for the types of ground vibrations produced from blasting in the coal-bearing formations of southern Indiana (Siskind et al, 1989).

Structure Response

The horizontal corner response of the first floor superstructure shown in Figure 3 is very similar to the respective ground vibration but has slightly higher amplitude. The amplification is typical for one story structures such as house 105 and would tend to be larger if the structure were taller. Safe maximum blasting levels derived in RI 8507 (Siskind et al, 1980b) include the effects of superstructure amplification resulting from ground vibrations.

Airblast

As indicated by the vibration profiles, the airblast, with a peak amplitude of 117.5 dB, had no noticeable influence on the comer motion of the above-ground superstructure. The propagation velocity for airblast is about 1,100 ft/s, a small fraction of the propagation speed for ground vibrations. This accounts for the difference in arrival times between the ground vibrations and airblast. Even low amplitude airblast can be more noticeable than the associated ground vibration and casual observers, particularly indoors, often mistakenly identify airblast as ground vibration.

Peak-Level Vibrations Analysis

Ground vibration amplitudes recorded by the Bureau were very low. In Daylight, peak ground vibrations levels never exceeded 0.11 in/s, and in the more distant McCutchanville, the maximum observed peak ground vibration was 0.06 in/s. Frequencies of the PPV-phases ranged between 4 and 20 Hz in Daylight but were more narrowly constrained between 4 and 6 Hz in McCutchanville. Even at these relatively low frequencies, peak particle velocities were at least five times lower than the damage threshold established by Siskind et al (1980b) in RI 8507.

At comparable scaled distances, the peak particle velocities from the historical data were sometimes slightly higher than those measured from the Bureau recordings. The time histories for the historical information were not available, so PPV-phase frequencies could not be obtained, which are necessary for comparison to the damage threshold recommended in RI 8507 (Siskind et al, 1980b). But assuming that frequencies were similar to those that the Bureau measured, the historical vibration amplitudes were still well below levels that would be expected to initiate structural damage to homes in the area.

The maximum airblast measured by the Bureau had an amplitude of 121 dB and was recorded on a 5-Hz, ST-4 recorder at house 334 situated north of Daylight proper (Figure 2). (Airblast levels obtained on a 5-Hz system are about 8 dB lower than what would have been recorded on the linear, broad-band FM tape system.) The biggest airblast recorded in Daylight had a peak amplitude of 118 dB whereas the maximum airblast measured in McCutchanville had an amplitude of 114 dB, both being captured on the wide-band FM recording system. An airblast of 124 dB (5-Hz system) was measured by the IDNR at house 108, but an odd-looking time history suggested that the signal may have been an electronic apparition and not an actual event.

The Bureau of Mines' recommended criteria for maximum safe airblast levels, from RI 8485 (Siskind et al, 1980a), is 134 dB for airblasts recorded on a linear system and 129 dB for a 5-Hz system. Research has indicated that, at or below these levels there is almost no probability for any airblast-induced damage to occur in residential-type structures. The vast majority of airblasts measured in the Daylight and McCutchanville area contained peak amplitudes (<110 dB) that were less than 20 percent of the recommended maximum safe airblast level, with the single highest amplitude recorded, 124 dB on a 5-Hz system, only about one-half of the recommended safe level.

Conclusions from the Damage Study

In its report to the OSM (Siskind et al, 1990), the Bureau concluded that blasting was probably not the cause of the structural damage apparent in the Daylight and McCutchanville communities. Amplitudes of the airblasts and ground vibrations studied were too low to be considered as potentially damaging. The visual crack inspections and level-loop surveys did not indicate that any additional damage was occurring as a result of blasting.

The Bureau could not appropriately study the vibration levels from March 1988 to December 1988, the time between the onset of damage complaints and the beginning of its own monitoring in Daylight and McCutchanville, because relevant information was not available. Also, the lack of airblast data in the historical records precludes a complete vibrations assessment during the 10-month period prior to the Bureau study. But considering the available data and the relatively large distances involved, it is highly unlikely that unrecorded vibration levels could have been so much greater than those studied to account for the observed damage. As an example, broken window glass is a preliminary indication that airblast levels are approaching or have exceeded maximum safe levels. Since widespread window glass failure was never reported there is no indication that any airblast had the potential to damage structures.

Soil conditions in the area were cited by the Bureau as a more probable cause for the observed structural damage than blast vibrations. The OSM is currently investigating the likelihood that homes in Daylight and McCutchanville were built on soils unsuitable to sustain proper support. Preliminary analysis has identified that expansive and/or highly erodible soils underlie many of the test homes. The characteristic humid climate of the region coupled with recent cycles of drought creates poor support conditions for these types of soils, suggesting another probable mechanism for structural damage. Level-loop survey results also supported the hypothesis of soil effects because all low elevations were consistent with down-slope slippage.

Nonetheless, the vibrations were still very noticeable to homeowners living two to five miles away from the blasting and responsible for citizens' fear that damage was occurring to their homes. Schomer and Averbuck (1989) have studied human response to transient noise and concluded that humans can be highly responsive to indoor rattling produced by low-level blast-type vibrations. A proper human response study was beyond the scope of the Bureau project, but such an investigation would help to quantify needed relationships between blast vibrations and community annoyance.

BLAST DESIGN INFLUENCE ON GROUND VIBRATIONS

Different blast designs, with variations in geometric layout, detonation-time sequencing and loading configuration, are often used in surface mining to accommodate specific production concerns and reduce vibrations. Controlling blast vibrations through shot design modification has been a topic of interest to researchers such as Anderson et al (1985), Wiss and Linehan (1978) and others.

The mine used several different blast designs during the Bureau monitoring; "conventional" and "box-cuts" with full-column and multi-decked loads, and cast-blast designs which the citizens felt produced the most damaging vibrations. Blast design analysis was not part of the OSM-sponsored project, but continued reviewof the vibrations data by Bureau and OSM researchers revealed interesting correlations between two particular casting patterns and the vibrations produced.

Cast-Blast Design

Figures 4 and 5 depict general schematics of the two types of cast blasts shot most often by the Ayrshire mine during the Bureau monitoring period. The total number of holes per shot ranged from about fifty to one hundred. Other variations were used, but not enough were monitored to provide useful comparisons. The casting shots had a front row with twice as many blastholes as subsequent rows so that the overburden material is thrown forward and away from the highwall. A relatively large explosive charge weight per delay period is often used to achieve satisfactory throw. This type of blast reduces overall mining costs by lessening the amount of materials handling, but the larger powder factor, sometimes using higher explosive charge weights, increases the risk for greater ground vibration and airblast levels.

The layout shown in Figure 4, denoted as design #261, is a center-initiated shot that fires in a row-by-row fashion. Blasthole sequencing forms an imaginary line parallel to the long highwall. The blasting pattern in Figure 5, labeled as design #271, is an end-initiated echelon design where the blasthole sequencing generally forms a line oblique to the long highwall. In addition to the obvious differences in geometric layout, design #271 uses a much higher percentage of longer between-hole delay periods. Design #271 has over 50 percent of its delays greater than 17 ms, whereas only 5 percent of design #261 delay periods are greater than 17 ms. This results in longer nominal between-hole and between-row time delays for design #271 as the shot is being fired.

Vibrations from the Two Cast Blast Designs

Table 1 lists the peak particle-velocity (PPV) amplitudes and corresponding frequencies obtained from monitoring blast designs #261 and #271. Shot-to-station distances and maximum charge weight used are also included. PPV values were calculated from full waveform vibrations recorded on the two FM recording systems installed in McCutchanville (house 209) and Daylight (house 105). The two horizontal components of motion were aligned in north-south and east-west directions, respectively. For several shots the vertical component at house 209 in McCutchanville failed to produce a resolvable waveform, so for these only the two horizontal components are considered. The shots were located at different points along the highwall but were generally confined to the northern half. Changes in scaled distance come from alterations in maximum charge weight and movement of the shot location relative to the fixed monitoring stations. The number of monitored cast blasts are limited, especially for design #261, so rigorous statistical analysis is not appropriate, but general observations can still be made as a prelude for further thought and discussion.

Corresponding peak airblast levels are listed in Table 1, but were not compared with blast design as were ground vibrations. The many variations in weather and air temperature made it difficult to develop relationships between airblast and the few cast blasts monitored.

Particle-Velocity Analysis

Figures 6 displays largest single-component PPV versus scaled distance and Figure 7 again shows largest single-component PPV but now plotted against the related frequency. Largest single-component PPV values were used for simplicity and to be consistent with the damage threshold analysis incorporated by Siskind et al (1980b) in RI 8507. There, damage levels were directly related to the largest single-component PPV and related PPV-phase frequencies. For those components listing two frequencies in Table 1, the largest value was plotted.

Slightly different PPV amplitudes produced from the two cast-blast designs were observed in Daylight but became more similar in McCutchanville. For scaled distances less than about 300 ft/lb~1/2, /2, which corresponds mainly to the Daylight station, design #271 produced slightly lower PPV values, as seen in Figure 6. But at scaled distances greater than about 400 ft/lb~1/2, indicative of the McCutchanville station, the single data point from design #261 grouped more closely with the peak amplitudes from design #271.

Similarly, PPV-phase frequencies in Daylight differed between the two blast designs, but became more uniform in McCutchanville. Figure 7 shows that frequencies of the largest-single component PPV-phase from design #261 were consistently between 4 - 6 Hz at both stations. Design #271 generated noticeably higher vibration frequencies at the Daylight station, with maximum single component PPV-phase frequencies from 6 18 Hz. Although 4 - 6 Hz values were measured from several of the other, smaller amplitude components of motion, design #271 generally seemed to produced an overall trend toward higher PPV-phase frequencies than did ground vibrations from design #261. Conversely, all PPV-phase frequencies measured in McCutchanville were between 4 - 6 Hz for both designs #261 and #271.

Significance of the Findings

Although the differences in ground vibration from the two cast blast designs are not very dramatic, the observations may have relative significance. The trend to lower peak particle-velocities and higher PPV-phase frequencies, as found in Daylight from design #271, could translate into fewer citizen's complaints. The low amplitude PPVs near 0.1 in/s approximate the threshold limitations of human perceptibility. Decreases by only a few percent, could, in theory, appreciably lower the potential for human annoyance (Siskind et al, 1980b, Figure 61). Low amplitude vibrations with PPV-phase frequencies greater than 12 Hz would lessen whole-structure response and also possibly reduce complaints. Whole structure response, or "racking", tends to produce creaking, rattling and "groaning" noises in homes, sounds that can increase the fear that damage may be occurring.

What factors were most responsible for the changes in vibrations character found in Daylight? Too many differences exist between designs #261 and #271 and too few shots were monitored to draw definite conclusions. But, a previous study by Wiss et al (1978) recommended the use of delay intervals of 17 ms or more as an effective means to minimize ground vibrations. Therefore, the longer-period delays used in design #271 may have had a significant influence in producing the somewhat lower amplitude, higher frequency vibrations.

A full evaluation of the effects of blast design on wave character was beyond the scope of the OSM-funded project which concentrated on structural impacts. However, such a study would determine if the vibration changes produced from the two blast designs would be significant for reducing human perceptibility and lessening the number of complaints.

PPV-phase frequencies measured in McCutchanville were almost always constrained between 4 - 6 Hz, seemingly unaffected by design variations of the cast blasts or other blasts monitored by the Bureau. Judging from these observations, the frequency range of 4 - 6 Hz is probably indicative of the natural frequency of the ground in this area. Comparison of ground vibrations from single-charge and production blasts made by Siskind et al (1989) suggests that as distance from the shot increases, the particular influence of blast design is filtered out by transmission through the ground. The characteristic frequencies of the ground will tend to dominate the waveform since they propagate most efficiently.

Recommendations for Further Study on Blast Design Influence

Additional research is needed to more completely study blast design effects on vibrations at relatively far distances. A statistically significant number of controlled blasting experiments are necessary where detonation sequencing is accurately monitored and design parameters are only slightly altered. More monitoring sites should also be incorporated with stations configured in logarithmically-spaced linear arrays to observe propagation effects. If a limited number of units are available, a systematic, non-linear distribution of seismographs can be incorporated to measure directional influences on blast vibrations. The important blast design parameters to study would be explosive charge weight, shot-hole pattern, shot orientation relative to observer, delay timing, accuracy of drilling and loading, actual hole firing times and also site geology. In addition, studies of human response to transient blast-type vibrations are required to help establish vibrations control guidelines in annoyance situations.

SUMMARY

In a project sponsored by the Office of Surface Mining (OSM), the Bureau of Mines monitored blast vibrations in the towns of Daylight and McCutchanville, Indiana. Citizens were complaining that blast vibrations from a surface coal mine were damaging their homes even though the active mine was about two miles from Daylight and four to five miles from McCutchanville.

The Bureau investigation determined that the observed blast vibration levels were too low to cause structural damage and that blasting was probably not responsible for existing damage. The OSM is currently investigating the likelihood that the damage resulted from construction on unsuitable soils.

Ground vibrations produced from two different types of cast blasts were compared. It was found that one design produced somewhat lower amplitude and higher frequency vibrations in Daylight, suggesting that blast design modifications could be used to control ground vibrations at relatively far distances. In McCutchanville, located about twice as far from the mine, differences in blast design did not appear to have any significant influence on PPV-phase frequencies.

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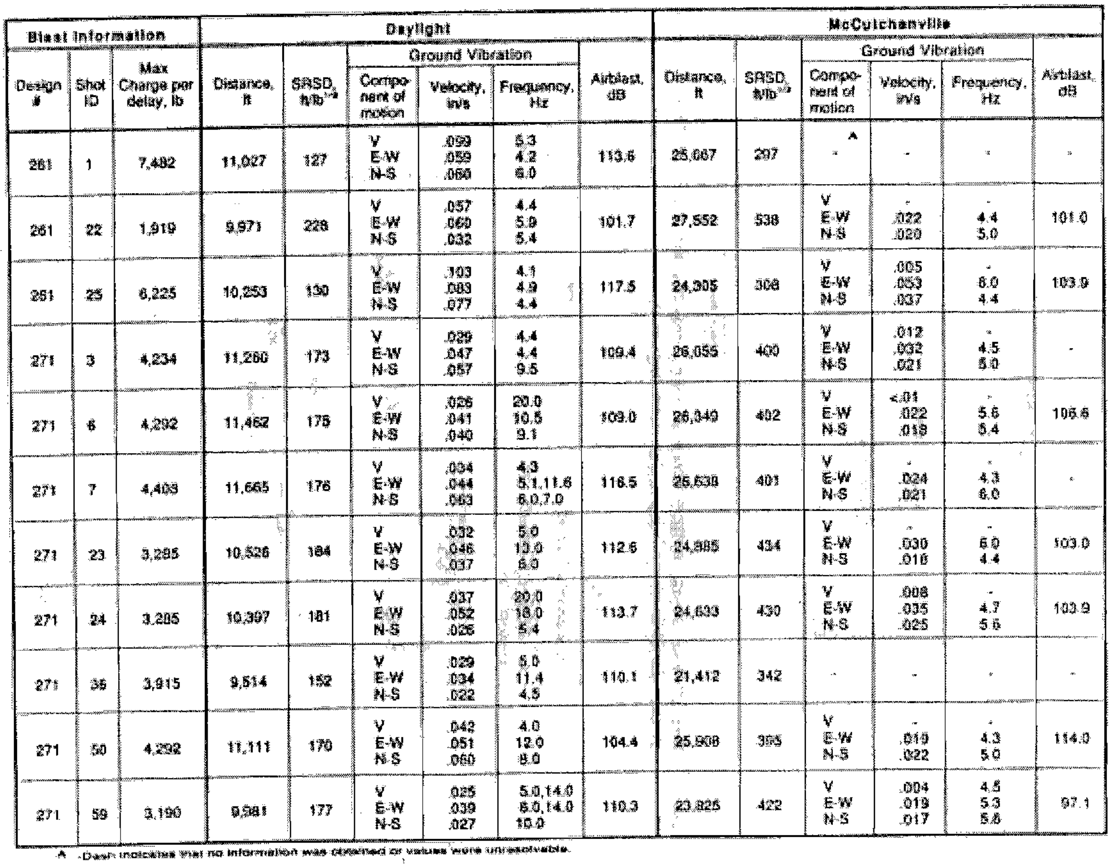
Table 1. Blast parameters and vibration amplitudes



Blast Information			Daylight						McCutchanville					
					Ground Vibration						Ground Vibration			
Design #	Shot ID	Max Charge per delay, lb	Distance, ft	SRSD, ft/lb$^{1/2}$	Component of motion	Velocity, in/s	Frequency, Hz	Airblast, dB	Distance, ft	SRSD, ft/lb$^{1/2}$	Component of motion	Velocity, in/s	Frequency, Hz	Airblast, dB
261	1	7,482	11,027	127	V E-W N-S	.099 .059 .060	5.3 4.2 6.0	113.6	25,067	297	-[A]	-	-	-
261	22	1,919	9,971	228	V E-W N-S	.057 .060 .032	4.4 5.9 5.4	101.7	27,552	538	V E-W N-S	- .022 .020	- 4.4 5.0	101.0
261	25	6,225	10,253	130	V E-W N-S	.103 .083 .077	4.1 4.9 4.4	117.5	24,305	308	V E-W N-S	.005 .053 .037	- 6.0 4.4	103.9
271	3	4,234	11,260	173	V E-W N-S	.029 .047 .057	4.4 4.4 9.5	109.4	26,055	400	V E-W N-S	.012 .032 .021	- 4.5 5.0	-
271	6	4,292	11,462	175	V E-W N-S	.026 .041 .040	20.0 10.5 9.1	109.0	26,340	402	V E-W N-S	<.01 .022 .019	- 5.6 5.4	106.6
271	7	4,403	11,665	176	V E-W N-S	.034 .044 .063	4.3 5.1,11.6 6.0,7.0	116.5	25,630	401	V E-W N-S	- .024 .021	- 4.3 6.0	-
271	23	3,285	10,526	184	V E-W N-S	.032 .046 .037	5.0 13.0 6.0	112.6	24,885	434	V E-W N-S	- .030 .010	- 6.0 4.4	103.0
271	24	3,285	10,397	181	V E-W N-S	.037 .052 .026	20.0 18.0 5.4	113.7	24,633	430	V E-W N-S	.008 .035 .025	- 4.7 5.6	103.9
271	36	3,915	9,514	152	V E-W N-S	.029 .034 .022	5.0 11.4 4.5	110.1	21,412	342	-	-	-	-
271	50	4,292	11,111	170	V E-W N-S	.042 .051 .060	4.0 12.0 8.0	104.4	25,908	395	V E-W N-S	- .019 .022	- 4.3 5.0	114.0
271	59	3,190	9,581	177	V E-W N-S	.025 .039 .027	5.0,14.0 6.0,14.0 10.0	110.3	23,825	422	V E-W N-S	.004 .019 .017	4.5 5.3 5.6	97.1

[A] Dash indicates that no information was obtained or values were unresolvable.

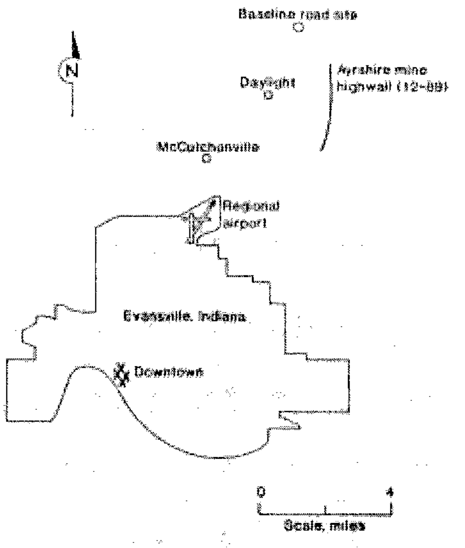
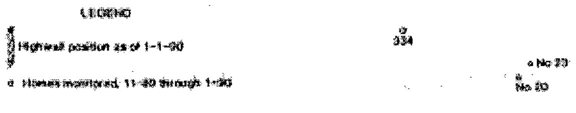
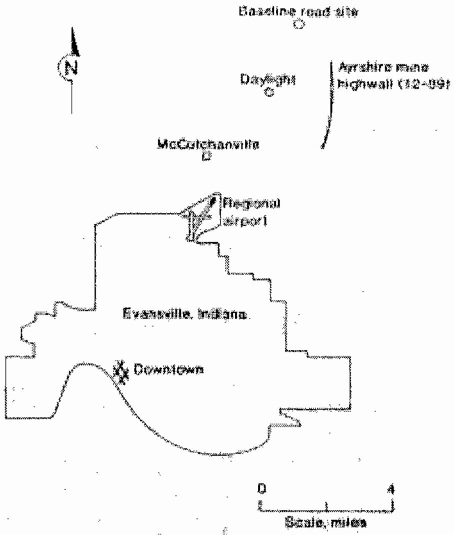


Figure 1. Map of Evansville, Indiana area showing relative locations of Daylight and McCutchanville to the Ayrshire mine highwall.





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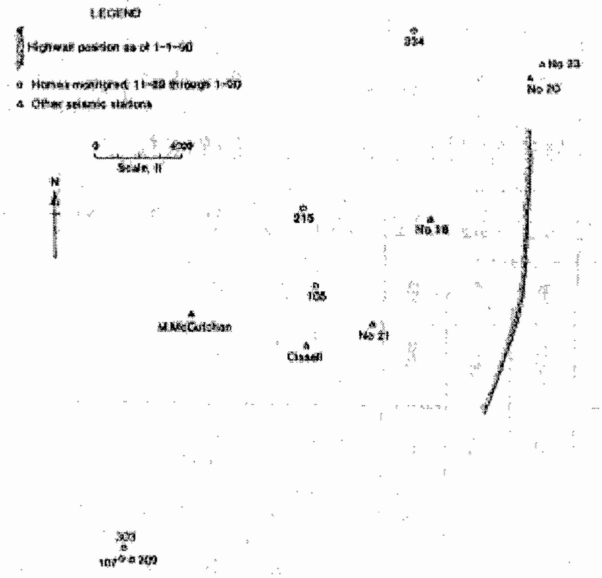
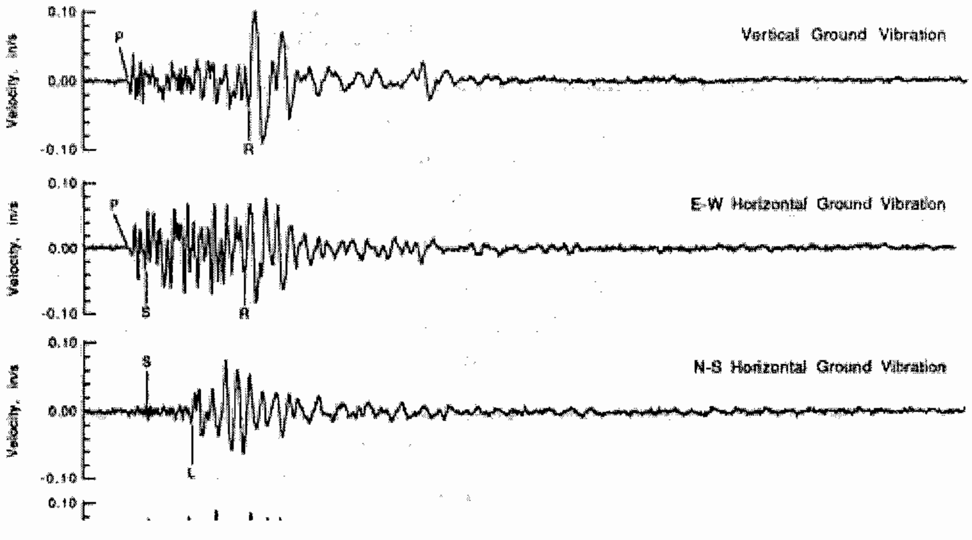


Figure 2. Locations of instrumented homes and additional vibrations monitoring stations used in the Bureau of Mines study.



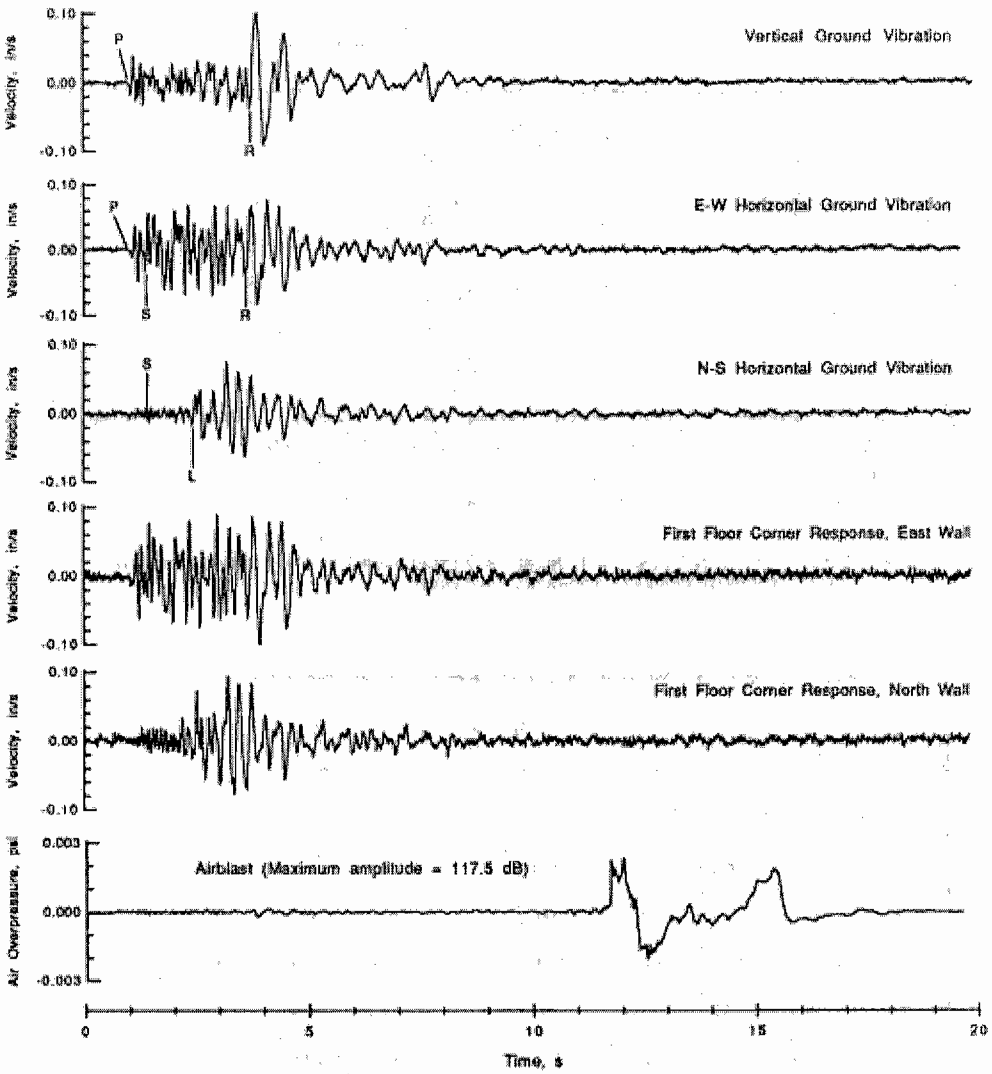


Figure 3. Complete set of blast vibrations recorded from shot #25 at house 105 in Daylight. The blast was 10,253 ft due east of the monitoring site and incorporated a maximum charge weight per delay of 6,225 lbs. Seismic phase arrivals: "P" = P-wave, "S" = S-wave, "R" = Rayleigh wave and "L" = Love wave.

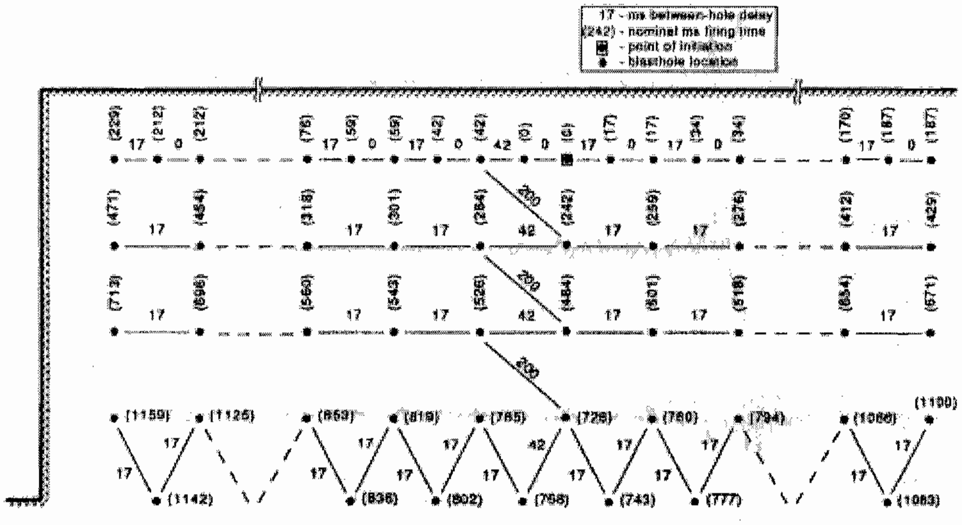


Figure 4. Schematic for blast design #271. Numbers in parenthesis indicate nominal sequential firing time relative to the between-hole delays used.

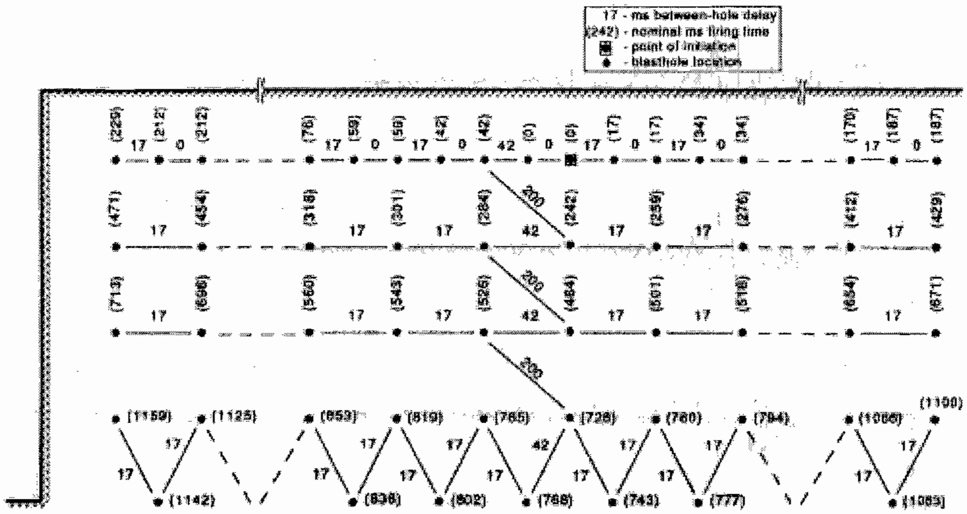


Figure 4. Schematic for blast design #271. Numbers in parenthesis indicate nominal sequential firing time relative to the between-hole delays used.

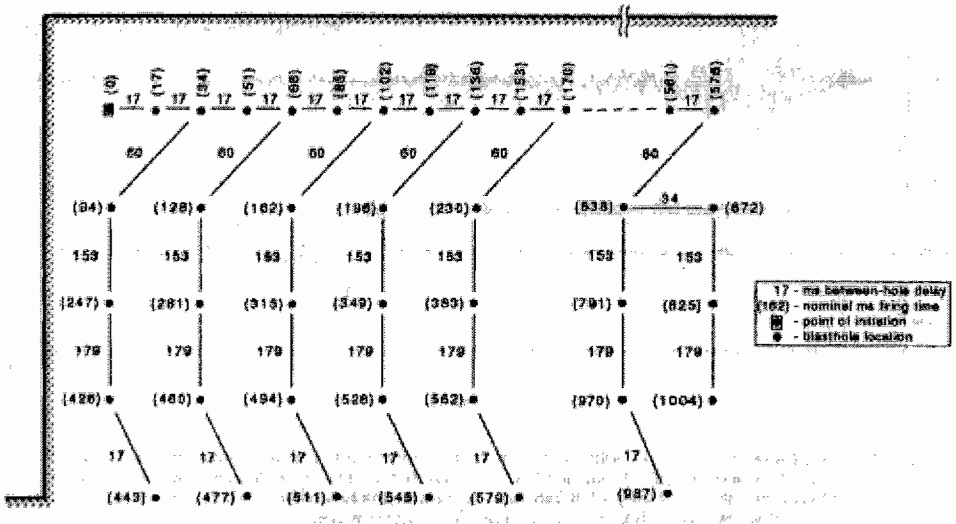
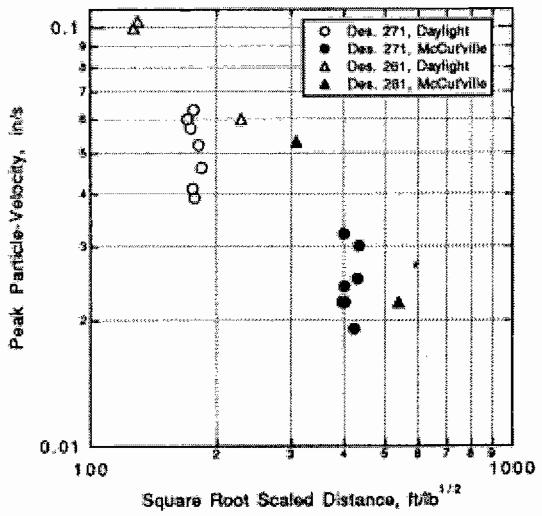


Figure 5. Schematic for blast design #261. Numbers in parenthesis indicate nominal sequential firing time relative to the between-hole delays used.



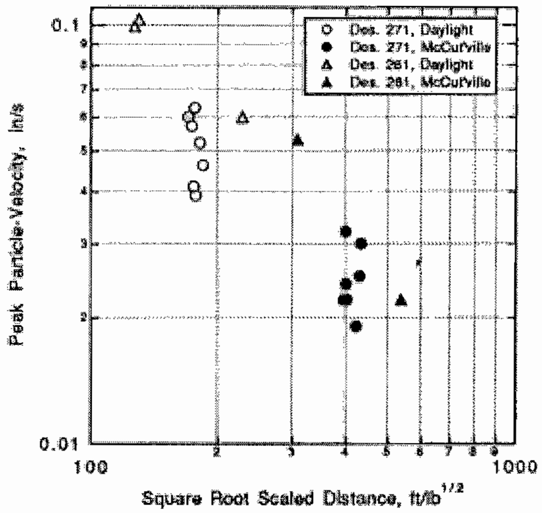


Figure 6. Maximum single component peak particle-velocity amplitudes measured from designs #261 and #271 versus scaled distance.

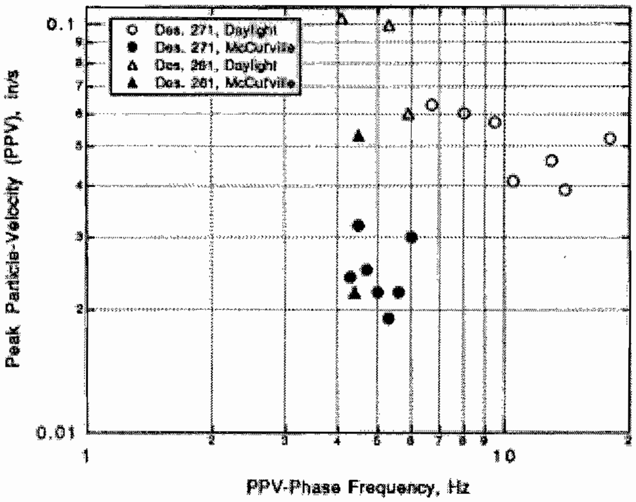


Figure 7. Maximum single component peak particle-velocity amplitudes measured from designs #261 and #271 versus associated frequency.