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Low frequency blast vibrations from Indiana surface coal mines

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1 INTRODUCTION

The Bureau of Mines was asked by the Office of Surface Mining (OSM) 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 et al. (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 et al. (1989). Where low frequencies were found, researchers examined common blast designs and ground structural elements in order to identify the causes.

Of particular interest in this study is the generation of surface waves by good reflecting boundaries. Such as sharp interface between a surface soil and underlying competent rock and 2) extensive horizontal mined-out zones serving to exclude and reflect seismic energy. Studies done on the influences of low-velocity surface layers on earthquake vibration waves have found increased vibration amplitudes, low frequencies, and long wave durations. They 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 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 et al. (1980), including the additional concern for frequencies below 10 Hz.

2 TEST SITES

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-surfaced 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.

3 MONITORING PROCEDURES

Seismic stations were placed in linear arrays at distances from the blast sites of 10 to 2500 meters. The nearest stations were intended to record data characteristic of the vibration sources. The far station data had characteristics greatly influenced by the propagation media. Of the nine test sites, the first six were studied with linear propagation arrays. The remaining three were studied through measurements collected by the mine itself or the State (Indiana DNR). The latter group consisted of data with little distance spread, being mainly regulatory compliance measurements.

In addition to production blasts, most mines were willing to provide single-charge blasts. These simple and short-duration single-charge blasts are impulsive sources lasting about a millisecond and provide the means to determine the influences of the propagating media on the vibration character. Production blasts are, in principle, linear superpositions (additions) of time-delayed single charges with amplitudes of certain frequencies determined or at least influenced by delay intervals between charges and/or groups of charges (e.g., rows).

Production blasts were multihole, multirow and sometimes miltidecked blasts with as many as several hundred individual charges. For this study, hole diameters ranged from 17 to 31 cm, charge weights per 8-ms delay from 46 to 1140 kg, and included both echelon and blast casting designs. Siskind et al. (1989) describes the sites and also the problems of analyzing such complex vibration sources.

4 MEASURED VIBRATION AMPLITUDES

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 form 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 suggest that the delays from the production blast 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.

Comparisons between sites are shown in figures 3 and 4. Site 1 has consistently higher vibrations, being both extensively undermined at a shallow depth and having thick glacial till surface deposits. 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 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. These measurements were collected at nearby homes and not with widely spaced propagation arrays.

The propagation plots showed little influence of blast design except that the full column cast designs produced lower vibrations than the decked echelon blasts on a charge weight per delay basis. The reader is referred to Siskind et al., (1989) for more detail on comparisons between sites and blast designs, and also for comparisons between these mainly low frequency blasts and an historical summary for surface coal mines. In summary, researchers found that single charges grouped around the historical coal mine mean; however, many of the production blasts exceeded predictions based on the historical summary in Siskind et al. (1980), figure 10. The postulated reason for the high production blast vibrations is the very low frequencies at several of the sites studied and the resulting inability of an 8-ms minimum time separation to provide destructive wave interference.

5 VIBRATION FREQUENCIES

Bureau researchers examined 1055 vibration records for frequency and found that many of the sites (1,2,3, and 6) had very low frequencies of 3-5 Hz at distances beyond 600 M. Fortunately, typical particle velocity amplitudes at these distances were low at 0.1 in/s. There generally were no differences in frequency character between single charges and production blasts. For both types of blasts, low frequencies of 7-8 Hz appeared at less than 100 m and, in one case, a strong 3.5 Hz only slightly farther (site 6). One site had no frequencies below 12 Hz (site 8) and one (site 6) had a significant low frequency amplitude enhancement at a monitoring location where the unconsolidated surface deposits suddenly increased in thickness.

Figures 5 and 6 are examples of vibration records collected, representing the radial component of a single charge and production blast, respectively. For this example, as for most shots studied, the blast design appeared to have little effect on vibration frequency but an unknown and possible large influence on amplitude.

6 BLAST DESIGN INFLUENCES ON VIBRATION AMPLITUDES AND FREQUENCIES

Aside from the simple factors of charge size and distance, the most important and promising design factor for controlling blast effects is initiation delay timing. The basic approach for analysis of blast delays is to compute detonation times and present them on one or more time axes showing relative flows of energy. Most significant are times of unusual bunching of initiations and systematic repeated gaps (periodicities) in the time records. For practically, 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. Figures 7 and 8 show two examples.

There is hope that blast vibration amplitudes can be influenced by blast designs, particularly delays between charges or groups of charges. This study is ambiguous on this point, finding some evidence both for and against. There is no question that the production blasts produced higher vibrations than single charges although both had the same charge weight per 8-ms delay. This violates the long-standing definition of "independent charges" developed by Duvall et al. (1963), probably because of lower frequencies here than in Duvall's study. All production blasts studied (with one minor exception) used, commercial pyrotechnic delays with their standard scatter of delay times around nominal values. Precision initiators have an as-yet undefined potential to provide increased control of vibration characteristics.

Single-charge blasts reveal the ground's natural frequency at a site. 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. 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 of sequences of charges, are shown in Figures 5 and 6 for two 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. With spatial separations between holes not considered.

Both of the energy-flow examples shown in figures 7 and 8 show row-induced periodicies, 200 ms for the casting blast and a less obvious 100 ms for the echelon design. For both designs, more holes in the rows could eliminate the gaps.

7 PREDICTIVE MODEL FOR LOW FREQUENCY GENERATION

The simple predictive models of Gupta and O'Brien were given in the Introduction. Two cases are represented by the mining sites studied here, 1) a low velocity surface layer and 2) an extensive mined-out area serving to exclude and reflect seismic energy. The first example corresponds to a wavelength $\lambda = 4H$ and the second $\lambda = 2H$.

Applications to the Indiana situation require the assumptions of propagation velocities in the low-velocity layer. The one attempt to measure them with blasting seismographs was unsuccessful. Based on published studies, typical compressional and shear wave velocities of 1463 and 549 m/s were assumed. Table 2 summarizes observed and predicted frequencies based on these velocities frequencies based on these velocities and various layer thicknesses, with quite a few plausible matches.

8 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.

Blast designs based on controlling delay times had only a limited influence on average vibration amplitudes at distances greater than a few hundred feet for short delay periods with standard accuracies. 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 10Hz. 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 trapped surface waves. 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.

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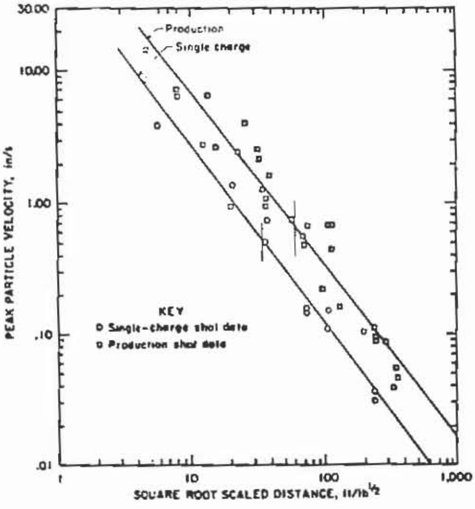

Figure 1. Propagation plots for site 1.

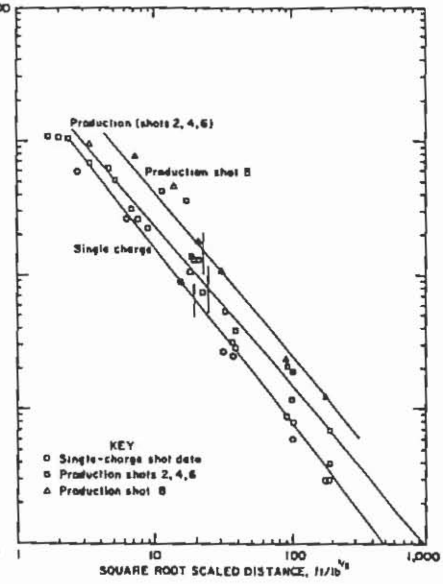

Figure 2. Propagation plots for site 2.

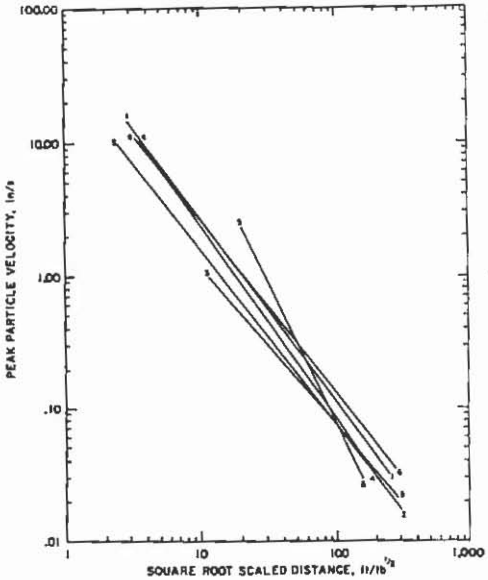

Figure 3. Propagation regressions for single charges at six Indiana surface coal mines.

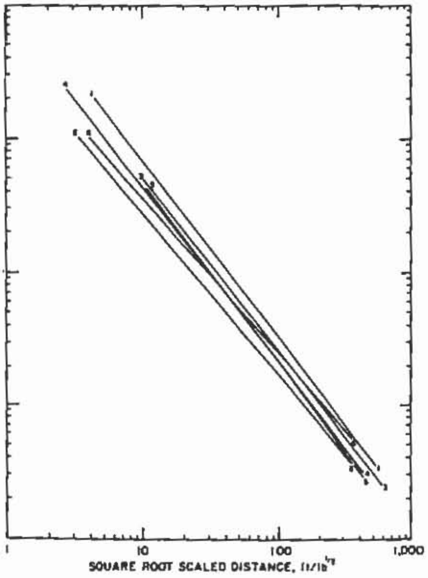

Figure 4. Propagation regressions for production blasts at six Indiana surface coal mines.

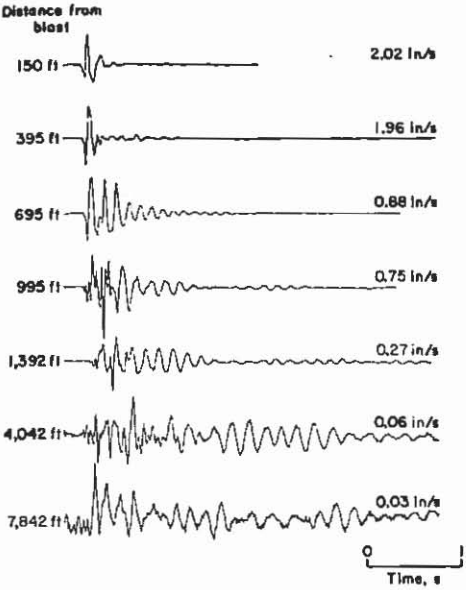

Figure 5. Single-charge vibration records for site 2, shot 7.

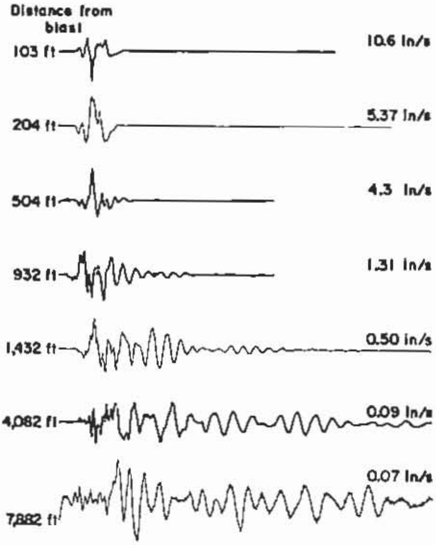

Figure 6. Production blast vibration records for site 2, shot 6.

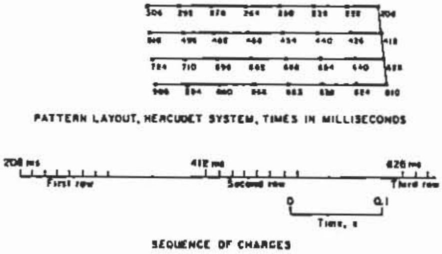

Figure 7. Blast hole array and charges sequences for casting blast at site 1: approximately 200 ms between rows.

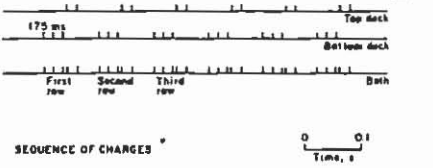

Figure 8. Blast hole array and charge sequences for echelon blast at site 6: 100 ms between rows and 17 ms between holes in a row.

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

Site No	Location	Undermined		Surface LV layers		Monitoring distances, m	Maximum charge wt per delay, kg
		Existent	Depth(s), m	Nature	Thickness, m		
1	Near Terre Haute	Yes	69 Extensive 100	Sand and drift	18-23	16-1740	114
2	Near Terre Haute	Yes	34-46	Soil and loess Sand, gravel and drift	3 3-6.1	21-2500	910
3	Near Evansville	Yes	73	Sandy clay, sandy muck and gravel	15-21	43-1400	75
4	Near Evansville	Yes	27	NA	--	10.7-1160	46
5	Near Evansville	Yes	27	Lacustrine	NA	34-640	46
6	Near Evansville	No	--	Loess and soil Lacustrine silt and clay	6.1 18.3	34-1850	614
7	Near Terre Haute	Yes	43-59 82 107	NA	--	700-2150	636
8	Near Evansville	No	--	Soil	3	180-1200	159
9	Near Evansville	No	--	NA	--	550-2750	1136

NA Data not available

Table 2. 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, m	Low velocity layer		Layer over void		Thickness m	Low velocity layer		Layer over void	
			P	S	P	S		P	S	P	S
1	4-8	20	18	6.8	36	13.6	69	5.3	2	10.6	4
2	5-7	9	40	15	80	30	30	12	4.5	24	9
3	3-4	18	20	7.5	40	15	73	5	1.9	10	3.8
4	6-8	6	60	23	120	45	-30	-12	-4.5	-24	-9
5	10	6	60	23	120	45	-30	-12	-4.5	-24	-9
6	3.7-5	3	120	45	240	90	18	20	7.5	40	15
7	4-6	NA$_p$	NA$_p$	NA$_p$	NA$_p$	NA$_p$	82	4.4	1.7	8.8	3.3
8	>12	3	120	45	240	90	15	24	9	48	18
9	4-5	--	--	--	--	--	--	--	--	--	--

P Compressional wave with velocity of 1460 m/s
S Shear wave with velocity of 550 m/s
NA$_p$ Not applicable (no near-surface layers are present).

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