BLASTING VIBRATIONS AFFECTED BY UNDERGROUND CAVITIES

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INTRODUCTION

In many areas of the eastern United States, especially in the Midwest, past mining activities have left large and extensive underground openings. Now, renewed mining is occurring in such areas in surface pits. Also, construction blasting often occurs in rock over such old openings. Within the last fifteen years, some attention has been given to the interaction between surface blasting and underground cavities; concern has been expressed about the possible changes in vibrations transmitted through areas underlain by old mine workings (Siskind, Stachura and Nutting 1987). Previous studies also had indicated that underground openings could influence transmission of surface mine blast vibrations (see, for example, Woodward-Clyde Consultants 1977). The principal concern is that underground openings under surface blasting may intensify low-frequency vibrations. If such intensification occurs, use of available equations to predict peak particle velocities and to design blasting patterns and select blasting parameters could lead to possibly damaging ground shaking.

In connection with an evaluation of the effects of blasting in surface coal workings in Southern Indiana, a large body of data was assembled on vibrations and blasting parameters in an area where underground mines existed under a portion of the currently active pits. Those data included information on charge weight per delay period, distance to recording seismographs, location of blast, peak particle velocity recorded at the seismographs, locations of seismographs, and locations of underground mines. These data were used in an analysis to evaluate possible changes in transmitted vibrations caused by underground cavities.

BACKGROUND INFORMATION

The area in which data were gathered is underlain by essentially flat-lying sedimentary rock strata of Pennsylvanian age. The strata immediately under the area of current mining consist of interbedded shale, limestone and sandstone that dip at a shallow angle generally to the west. Most of the coal beds being worked in the surface mines were in the Dugger Formation. The seams being worked were the VI coal and the VII coal, or the Lower Millersburg seam and the Upper Millersburg seam. Below these coal seams are irregular beds of shale containing limestone nodules, which in turn overlie the thin Universal Limestone. Below the Universal Limestone is a thick sequence of shales containing sandy zones, coal beds and thin limestones, called the Petersburg Formation. Coal bed V, associated with the Alum Cave Limestone, lies 60 to 140 feet below the surface, near the top of the Petersburg Formation; that coal was mined from 1910 to 1935 in one section of workings, and from 1947 to 1956 in another section. That seam is 5.5 to 6 feet thick.

The Dugger Formation is overlain by shales, sandstones and limestones of the Shelburn Formation. Unconsolidated soils including silty clays and silts overlie the sedimentary rock units, with sandy alluvial soils along streams; the soil deposits in the area are not thick. The terrain is characterized by low relief with generally shallow incisions by streams. Erosion has exposed progressively younger rock strata from east to west in the area. The surface topography reflects the underlying rock layering to only a subdued degree.

Information was obtained on blasting in four separate pits. One pit was located several thousand yards north of the other three pits, and from the locations of the old underground mines. Two large pits were located just north of a large area of underground mines; the southern arm of the western pit of this pair extended over a small area of underground mines. A fourth pit was quite small in comparison to the other three pits, and was located southwest from and very near the western pit of the paired central mines.

Information was obtained on blasting in these four pits between 1981 and 1992. Data available included comprehensive information on charge weight per delay, blasting patterns, and weather conditions during blasting. Additionally, several triggered seismographs were used to monitor blast vibrations at 29 different and varying locations around the mine pits. Seismographs were set to record data when particle velocity exceeded a trigger level, and the trigger levels varied from 0.05 inches per second (ips), to 0.08 ips, to 0.125 ips. A large number of blasts did not trigger any seismograph activity.

DATA ANALYSIS

Information on blasting activities was used to compile values of scaled distance for each blast, using distance to the nearest recording seismograph. Scaled distance is defined herein as the distance from the blast to the recording seismograph, D, divided by the square root of the maximum weight of explosives detonated per 8-millisecond delay period, W, in pounds. Scaled distance thus was calculated as $D/W^{1/2}$ for this analysis.

Most of the data on blasting vibrations presented in the recent past have been shown on graphs of peak particle velocity versus scaled distance. Plots customarily have been drawn on logarithmic scales for both abscissa and ordinate. Use of such plots has facilitated representation of results and statistical analysis of the data. Linear regression analysis typically has been used to develop straight correlation lines relating peak particle velocity to scaled distance. Similar plots and regression analyses were prepared in this study.

Blasting parameter information was collected for more than 4,700 blasts, but a large number of those blasts did not trigger a recording seismograph. However, seismograph records were available for 1,450 blasts. Data from those blasts were used with seismograph records and information on distance from blast to seismograph to develop a general relation between peak particle velocity and scaled distance for blasting at all four pits.

Then, the 1,450 records were divided into blasts where underground mines were unlikely to have affected the vibrations, and blasts where vibrations probably were modified by the presence of underground cavities. The division between the two categories of blast was made by drawing a line between blast location and seismograph location, and determining whether any undergound mines were located under that line, which crudely represented the path of transmission of vibrations.

Next, since the mine to the north of the underground mines was located far from the underground cavities, data from that mine were excluded from further analysis. Also, the blasting in the small pit to the southwest of the main area was omitted from further analysis because the parameters of those blasts were significantly different from the values for the production blasts in the large pits. The final analysis included data from only the two centrally-paired pits.

Results of the Analysis

A very large degree of scatter was evident in the data for all four pits. A best-fit correlation equation was developed from those data as

$$\text{Peak Particle Velocity, ips} = 3.016\,(\text{Scaled Distance})^{-0.568} \qquad (1)$$

When the data from the four pits were separated into the two categories (vibrations passed over underground mines, and vibrations did not pass over underground mines), the 230 data pairs for the blasts probably affected by underground mines produced the graph shown in **Figure 1**. For those data, the best-fit correlation line is represented by Equation 2, below:

$$\text{Peak Particle Velocity, ips} = 0.313\,(\text{Scaled Distance})^{-0.135} \qquad (2)$$

In contrast, the data from 1,220 blasts in which the line between blast and seismograph did not pass over underground cavities produced the graph shown in **Figure 2,** and the best-fit correlation line given by Equation 3:

$$\text{Peak Particle Velocity, ips} = 4.416\,(\text{Scaled Distance})^{-0.642} \qquad (3)$$

Undoubtedly, the presence of underground mines located near but not under the line between the blast location and the seismograph location may have affected the transmission of vibrations from the second category of blasts. However, the intent in this study was to see if there were any obvious differences in recorded vibration intensity between blasts where effects of underground mines were most probable and other blasts where effects were much less likely. Effects on vibration transmission were considered to be most likely for those blasts in which old mines lay under the straight transmission path between blast and seismograph.

FIG. 1. Peak Particle Velocity versus Scaled Distance
All Pits, Underground Mines Under Transmission Path

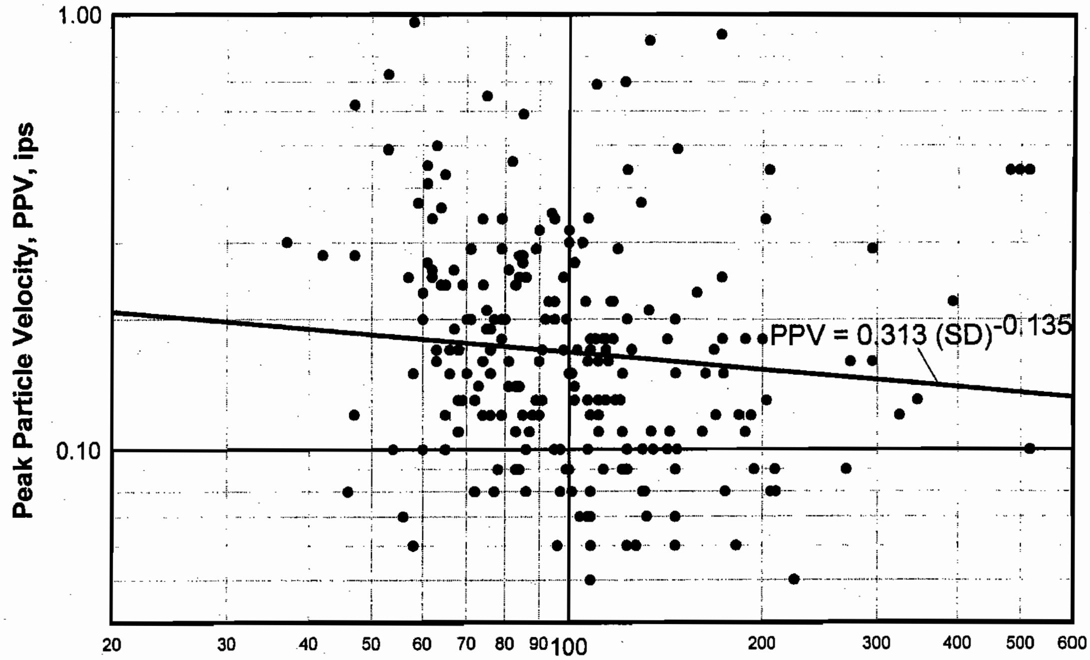
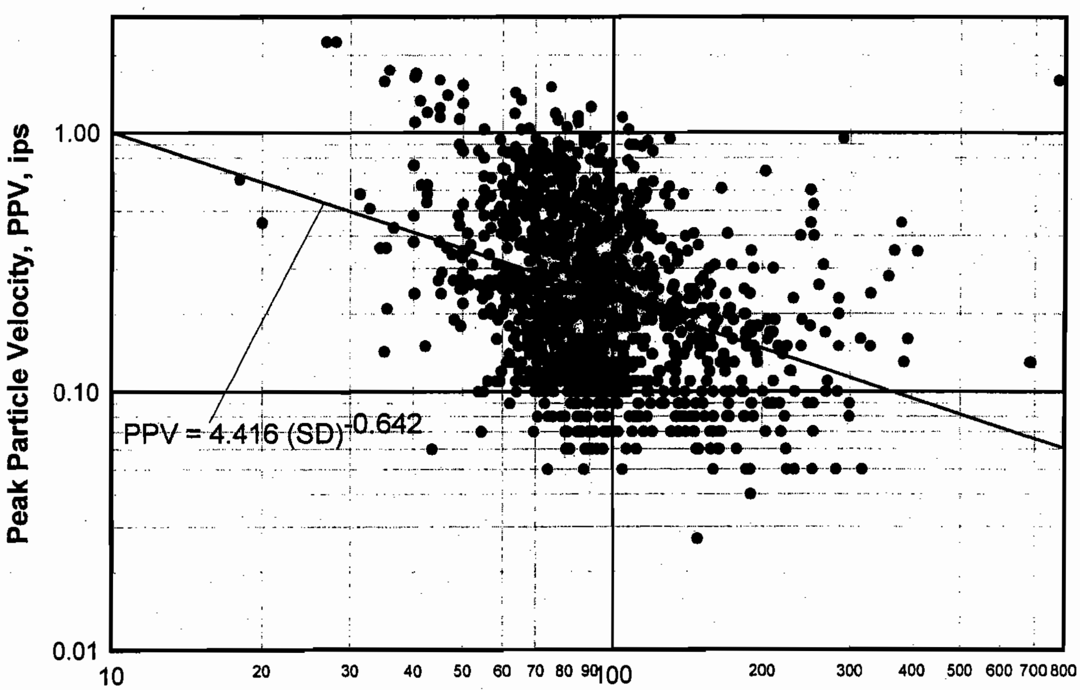


FIG. 2. Peak Particle Velocity versus Scaled Distance
All Pits, No Underground Mines Under Transmission Path



Scaled Distance, SD, feet per square root of pounds

FIG. 3. Peak Particle Velocity versus Scaled Distance, Central Mines, Underground Mines Under Transmission Path

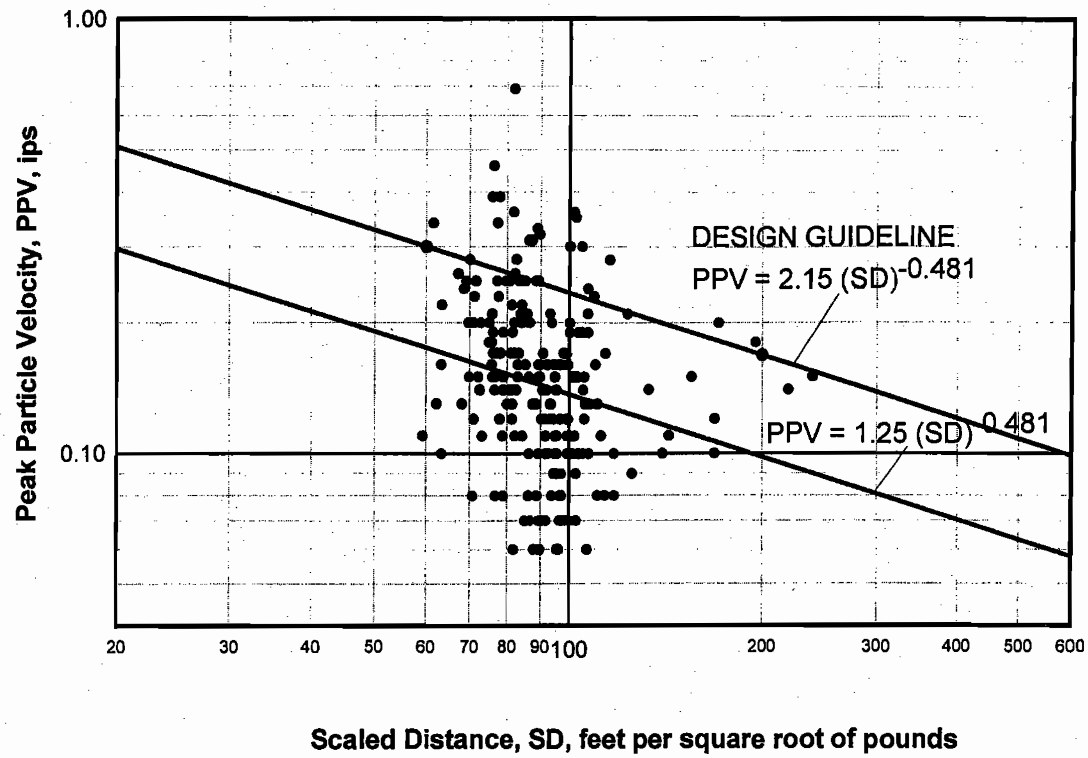
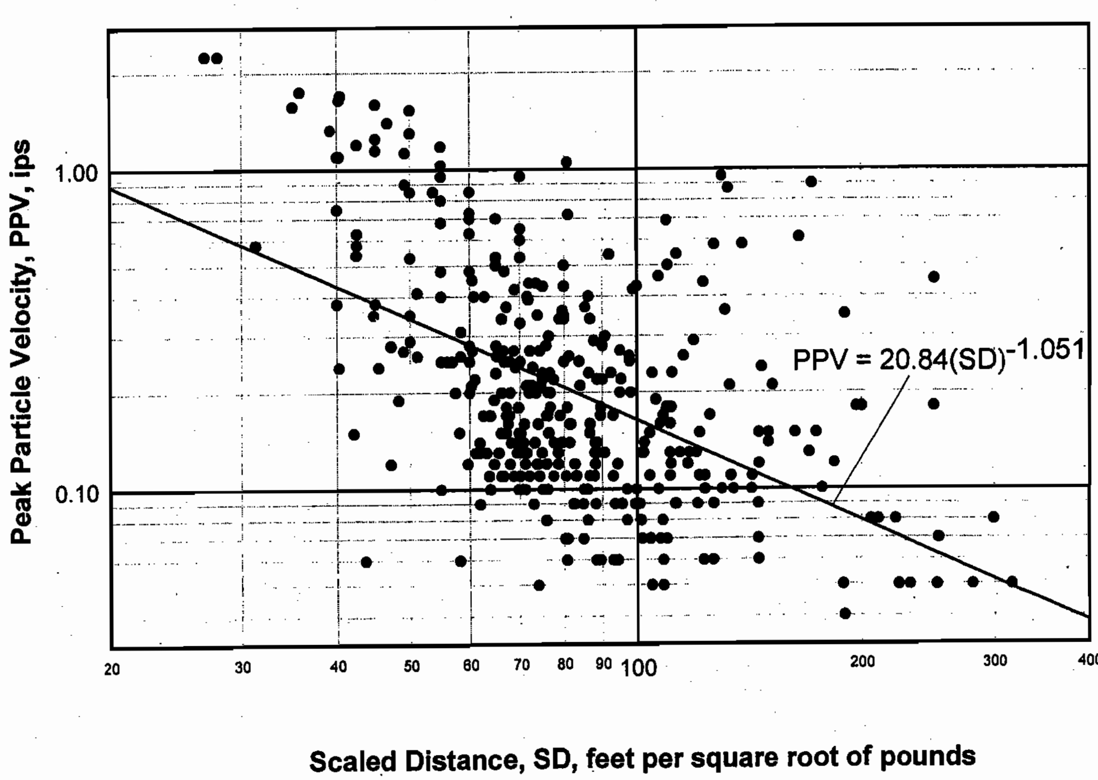


FIG. 4. Peak Particle Velocity versus Scaled Distance, Central Mines, No Underground Mines Under Transmission Path



Because the north pit was located far from the underground mines, and the blasts in the small southwestern pit were not characteristic of production blasts in the other three pits, data from the two central pits only were used to develop the two graphs shown in **Figures 3 and 4**. Figure 3 shows results for 215 blasts in which the transmission path between blast and seismograph lay directly over an underground cavity. Regression analysis of the data shown in Figure 3 yielded the best-fit correlation line represented by Equation 4:

Peak Particle Velocity, ips =
$$1.25\ (\text{Scaled Distance})^{-0.481} \qquad (4)$$

Data were available from 364 blasts in the two central pits, in which the transmission path from blast to seismograph did not cross an underground mine opening. Analysis of those data yielded the graph shown in Figure 4, and produced a best-fit correlation line given by Equation 5:

Peak Particle Velocity, ips =
$$20.84\ (\text{Scaled Distance})^{-1.051} \qquad (5)$$

In Figure 3, a design guideline for conservative prediction of vibrations from blasting over underground openings has been developed by constructing a line at the same slope as the best-fit correlation line, and positioned to include 90 percent of all the data points. That line is represented by Equation 6:

Peak Particle Velocity, ips =
$$2.15\ (\text{Scaled Distance})^{-0.481} \qquad (6)$$

The results of these analyses indicate that significant effects on vibration transmission can be expected when underground mines lie below surface workings where blasting is being done.

SIGNIFICANCE OF RESULTS

The results of the various analyses of data from the surface mine blasts evaluated in this study can be put into better perspective by a **simple example.** The various cases that were analyzed are listed below with the equations that were generated from each analysis.

Case 1 - Data from all four pits, all blasts that triggered seismographs: Eqn. 1

Case 2 - Data from all four pits, transmission path crossed over underground mines: Eqn. 2

Case 3 - Data from all four pits, transmission path did not cross over underground mines: Eqn. 3

Case 4 - Data from two central pits only, transmission path crossed over underground mines: Eqn. 4

Case 5 - Data from two central pits only, transmission path did not cross over underground mines: Eqn. 5

The conservative prediction equation derived from Case 4 is Eqn. 6.

For several values of scaled distance, peak particle velocity in inches per second can be predicted from each of these equations, as shown in Table 1. Comparison of the predicted values shows the variability among the results of the four analyses.

Obviously, there is a very significant difference between the predicted particle velocities comparing the situation where the transmission path did not cross underground mines and the situation where the transmission path did cross old underground openings (compare Case 2 with Case 3, and Case 4 with Case 5).

The values given by the prediction equation developed from all the data (Case 1) also differed significantly from all the values predicted from the analyses of each of the other situations (Cases 2 through 5).

It is noteworthy also that exclusion of data from just 15 blasts caused a significant difference in results between Case 2 and Case 4, both cases in which the vibration transmission path crossed over underground cavities. The 15 blasts that were omitted in Case 4 were blasts detonated in the north pit at a very large distance from the underground mine openings. The significant variation between the regression analysis results for Case 2 (including the north pit blasts) and those for Case 4 (no north pit blasts) indicates that the effects of underground openings may be most important on low-frequency vibrations in cases where large scaled distances are involved.

The values predicted for a scaled distance of 200, for Cases 1, 2 and 3 are very similar (different only in the third decimal place). Those values illustrate how **an analysis of limited data from a narrow range of scaled distance could mislead an investigator into concluding that little effect was exerted by underground mines on the transmitted vibrations.**

TABLE 1

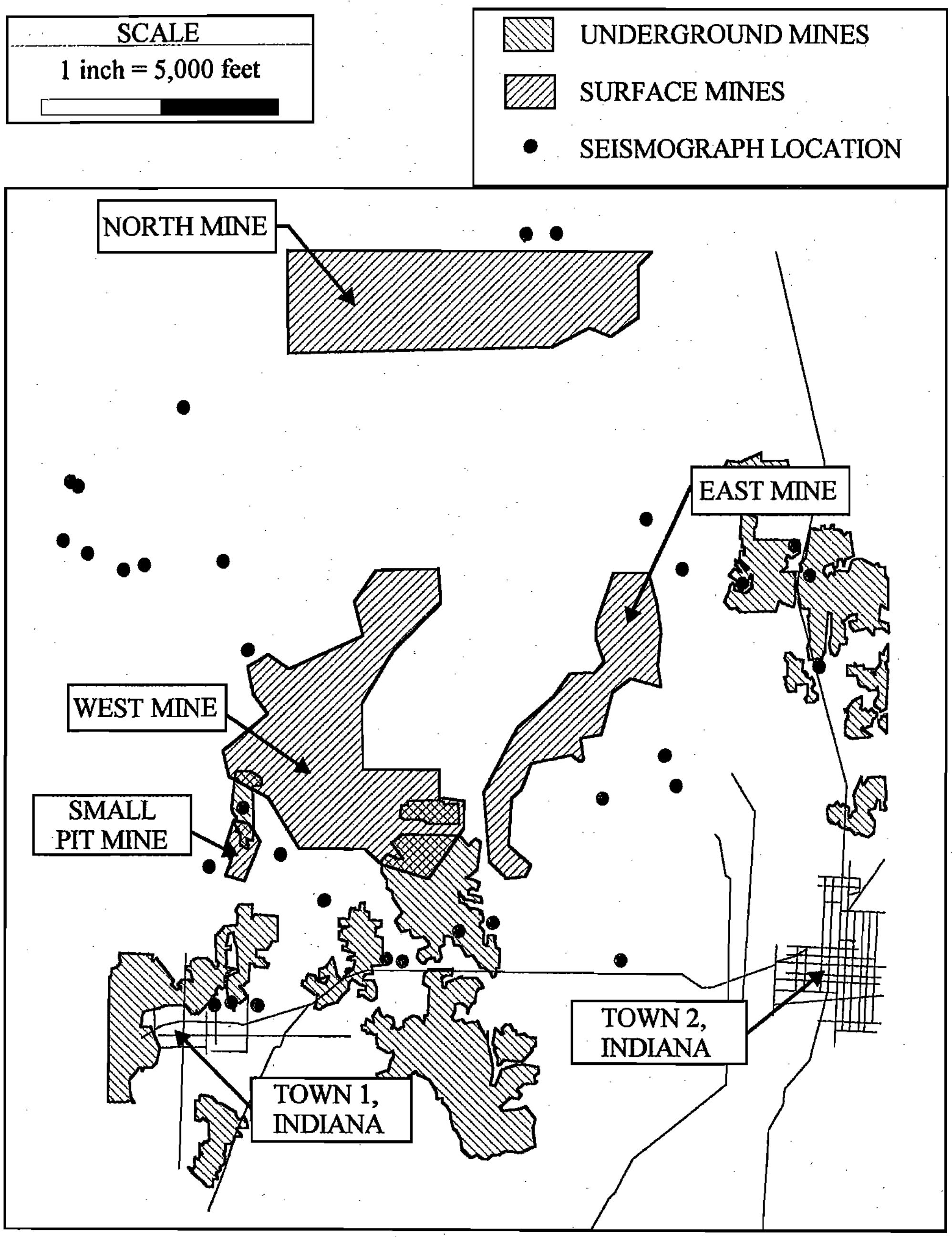
Scaled Distance	Predicted Peak Particle Velocity, inches per second					
SD	Case 1	Case 2	Case 3	Case 4	Case 5	Eqn. 6
10	0.82	0.23	1.01	0.41	1.85	0.71
100	0.22	0.17	0.23	0.14	0.16	0.23
200	0.15	0.15	0.15	0.10	0.08	0.17
500	0.09	0.135	0.08	0.06	0.03	0.11
1000	0.06	0.12	0.05	0.045	0.015	0.08

TABLE 2

Scaled Distance	Predicted Peak Particle Velocity, inches per second					
SD	Eqn. 7	Eqn. 8	Eqn. 9	Case 2	Case 4	Eqn. 6
10	1.42	3.59	5.93	0.23	0.41	0.71
100	0.15	0.11	0.31	0.17	0.14	0.23
200	0.08	0.04	0.13	0.15	0.10	0.17
500	0.03	0.009	0.04	0.135	0.06	0.11
1000	0.016	0.003	0.016	0.12	0.045	0.08

COMPARISON TO PUBLISHED PREDICTION EQUATIONS

A number of equations have been developed from regression analyses of data from other locations around the United States, and have been published



in the technical literature. For example, Woodward-Clyde Consultants (1977) developed a prediction equation based on data generated from blasting in surface mines over old underground workings in Eastern Kentucky:

Peak Particle Velocity, ips =
$$13.6\ (\text{Scaled Distance})^{-0.98} \qquad (7)$$

A more general USBM study of the impacts of surface coal mining (Siskind et al. 1980) produced the following prediction equation:
Peak Particle Velocity, ips =
$$133\ (\text{Scaled Distance})^{-1.5} \qquad (8)$$

Finally, in a special study in 1987 of vibrations produced by surface mining in Southern Indiana over old underground workings (Siskind, Stachura and Nutting, 1987), the USBM produced the prediction equation given as Eqn. 9:

Peak Particle Velocity, ips =
$$113\ (\text{Scaled Distance})^{-1.28} \qquad (9)$$

Values of peak particle velocity predicted by use of Equations 7, 8 and 9 can be compared to values generated from Equations 2 and 4, for vibrations which passed over old underground workings, and to values predicted using the conservative design guideline based on Case 4, Equation 6, as shown in **Table 2.**

Examination of the predicted values of peak particle velocity shown in Table 2 shows clearly that **the published equations predict much higher vibration intensities at very low values of scaled distance; blasting at such scaled distances is not likely to happen.** At moderate values of scaled distance between about 100 and 200, Equations 7 and 8 predict values somewhat similar to those predicted from the results of this study (Cases 2 and 4). **At high values of scaled distance, Equations 7 and 8 predict peak particle velocities much lower than those predicted from the results of this study.**

Equation 9 predicts values that are higher than those predicted from the results of this study at low to moderate scaled distance, but are much lower than values based on Cases 2 and 4, at large scaled distance. It is interesting to note that Eqn. 7 was developed from a study of blasting over old underground mines in Kentucky and Eqn. 9 was developed from a similar study of blasting over underground mines in Southern Indiana not far from the area examined in this study.

CONCLUSIONS

1. The results of the analyses done in this study clearly show that **underground cavities below surface blasting activities can have a very significant effect on the transmission of vibrations from such surface blasting.** For blasts where vibrations were likely to have been affected by underground openings, the vibrations recorded at high values of scaled distance for the blasts analyzed in this research were much more intense that the vibrations recorded in previous studies, as shown by regression analysis of the available data. This finding clearly indicates that additional research is warranted on the effects of underground cavities on the transmission of vibrations from surface mining.

2. Comparison of results for Cases 2 and 4 described herein, shows that **even a small number of blast events can change the results of regression analyses significantly if the parameters for those blast events were very different from the conditions under which most of the vibrations were recorded.** The 15 blasts included for the Case 2 analysis but excluded from the Case 4 analysis were much farther from the underground openings than the blasts in the Case 4 situation.

3. In evaluating the results of these analyses, the conservative nature of the investigation must not be ignored. Although results from 1,450 blasts were analyzed in this study, **more than 3,200 blasts were excluded from the analysis because seismographs were not triggered by the vibrations produced from those blasts. This consideration suggests that analysis of data from all 4,700 blasts, if such analysis had been possible, would have generated regression equations that would predict much lower peak particle velocities at high values of scaled distance.**

4. **The results obtained from these analyses suggest that conservative design of blasting activities should include consideration of the data shown in Figure 3 and represented by Equation 4. Safe design could be based on the guideline shown in Figure 3 and represented by Equation 6, in the absence of more definitive research findings.**

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