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CRITERIA FOR THE PROXIMITY OF SURFACE BLASTING TO UNDERGROUND COAL MINES*

by

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ABSTRACT

Where two coal seams, one above the other, are being mined simultaneously, and one by surface and the other by underground methods, it has become expedient to establish criteria for possible blasting damage to the underground mine similar to those established for damage to surface structures blasting in quarries and open pit mines. The criteria should also be applicable to surface blasting close to most types of underground excavations. The research project consisted of a literature search to establish a foundation for the research, a selection of two sites for experimentation, and the development of a research plan, field experimentation, analysis of results, and recommendation of criteria for safe charge weights and scaled distances.

INTRODUCTION

The increasing importance of coal as a major energy source is accompanied by the realization that a maximum recovery of deposits is necessary to supply the growing demand. Toward this end, interest has developed and in the simultaneous extraction of multiple seams by a combination of strip and underground mining. The United States Bureau of Mines in 1973 requested proposals to establish "Criteria for the Proximity of Surface Blasting to Underground Coal Mines" and subsequently awarded such a contract to the Rock Mechanics and Explosives Research Center, University of Missouri-Rolla. In addition to an initial literature and field survey, two underground mines active in the vicinity of open pit operations and located in different geologic environments were monitored.

TECHNOLOGICAL BACKGROUND

Early investigations of blasting damage of surface structures performed by the Bureau of Mines (Thoenen and Windes, 1937, 1938a, 1938b, and 1942) utilized criteria relating acceleration, frequency, charge size and distance. Later research by Duvall, et al, (1962) and Nicholls, et al, (1971) established a criterion of 2 in./sec particle velocity related to scaled eistances, the latter utilizing a 1/2 power scaling law:

$$v = K\left(\frac{R}{W^{1/2}}\right)^{-n} \qquad (1)$$

where R = distance, W = explosive weight, v = particle velocity, K = intercept, and n = decay exponent.

For concrete structures buried in soil, Lampson (1946) established scaling laws for relating peak pressure, impulse, particle velocity, acceleration, transient displacement, permanent displacement, damage-crack width, and radii of damage distances.

Most mathematical analyses of wave-cavity interaction (Baron, 1960) are for large explosions, utilizing a unit pressure step wave because pulse lengths are long relative to cavity sizes.

The Underground Explosion Test Program (Colorado School of Mines, 1948; ERA, 1952) experimentation by the Bureau of Mines (Duvall, et al, 1957) and military studies on tunnel demolition (Mason, et al, 1955; Clark, et al, 1958) provided valuable information for preliminary prediction of safe scaled distances for blasting over underground coal mines. Some of these and related investigations showed that a cube root law was applicable and some a square root law. Pulse lengths can be readily predicted for charge size and scaled distances, which can be employed to predict the possibility of failure by reflection slabbing. Decay with distance is a function of the geologic medium in which the waves travel. The closure of underground openings will occur only at very small scaled (cube root) distances varying from 1.85 to $2.00\ ft/lb^{1/3}$.

Studies of roof bolt behavior near operational underground blasts (Stehlik, 1964) showed that blasting caused some changes in tension on roof bolts and a square root law applied. Measurements in granite by Olson (1972) of particle velocities indicated that a cube root law applied in that geologic medium.

From these studies it was concluded that one of the better damage parameters is the peak particle velocity. Also a cube root law is more applicable in massive rock and a square root law in bedded rock. It was also postulated that the peak particle velocity for damage would be in the vicinity of 2 in./sec, depending upon the geologic structure, and the strength of roof, pillars, and floor of the mine.

The most pertinent data were plotted (Fig. 1) for the purpose of prediction of distances and weights of explosive relative to possible peak particle velocity. The "probable area for research" was based upon possible maximum and minimum weight of explosive charges employed in surface coal mining

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together with the probable scaled distance for a peak velocity of 2 in./sec.

GEOLOGY AND TEST SITE

The West Virginia test site was at the Ferguson Mine located in Nicholas County, West Virginia (Fig. 2). Local rock types belong to the Allegheny and Pottsville Series of Pennsylvanian age, with the upper Freeport sandstone exposed above the mine at an elevation of +2,490 feet. The coal is of the Clarion seam of Allegheny age although locally referred to as the Lower Kittanning or No. 5 Block and is 36-42 inches thick. At the test site the Lower Kittanning, however, lies approximately 20 feet above the Clarion. The underlying shales and sandstones belong predominately to the Pottsville Series of the Kanawha Group. Structurally, the various rocks are layer cake in nature with no faulting or folding present in the immediate experimental area. The mine adit lies at +2,080 feet. The immediate roof is shale and the overall top conditions are considered to be good by the miners. Roof support consists primarily of 20 ft by 20 ft coal pillars and roof bolts although timbers and headers are in place along the belt line and near the openings where temperature and humidity variations contribute to unstable roof conditions. Except under old workings near the mine opening the mine is dry.

Surface mining exists approximately three-quarters of a mile east of the Ferguson mine and the stripped coal seam is the No. 5 block which is considered possibly to compromise both the Middle and Lower Kittanning and the Clarion. The coal underlies approximately 45-60 feet of overburden which requires blasting. Exploratory drilling after the site selection indicated the target coal seam was not as extensive as first believed and consequently, the strip advance terminated within three thousand feet of the underground site. For this reason five additional shots were fired over the instrument sites.

RESEARCH PLAN

The premise upon which the research was based is that damage criteria should be measured by instrumentation which is either available off the shelf or easily and inexpensively fabricated. Further, installation and monitoring should be performed by non-research personnel with a minimum of specialized equipment. Peak particle velocities were to be measured and considered as one independent variable proportional to damage measurements. Safety, economics, and production governed the hole patterns, charge weights, delays and location of charges in the surface mine, and it was therefore not anticipated that any severe damage such as roof falls or rib collapses would occur. Damage criteria were defined to include changes in roof load and horizontal strain, opening convergence, observable fracture formation or extension, and spallation of the top and ribs. Temperature and humidity variations were also monitored, and the information obtained used in rectifying the recorded data.

INSTRUMENTATION

Eleven instrument stations were located along a segment of the intake portion of the mine. Various combinations of three component moving coil geophones, roof bolt pads, horizontal roof strain indicators (HORSI), convergence pins and thermometers were installed as shown by Figs. 3 and 4 and Table I. Surface blast charge size and location and the resulting ground movement and damage were monitored for approximately six months. Included in the charges were five shots having zero delays, charge weights ranging from 1000 to 2800 lbs, and distances from 0 to 1200 feet from the instrument stations. Typical velocity wave forms are as shown by Figs. 5 through 7.

VISUAL DAMAGE ASSESSMENT

On the day preceding each shot the instrument stations were examined for fractures and loose spall which were identified by paint and the instruments were read. On the day following each shot the presence of new fractures or spall was noted as were changes in measured roof conditions and convergence. Only those three shots located directly over the mine resulted in spall or fracture formations and this was relatively minor (Figs. 8, 9 and 10).

DATA ANALYSIS

The method of analysis is similar to that performed by Olson, et al (1970). Particle velocity V is assumed to be related to distance R and charge weight W by the expression

$$V = K(R/W^{b})^{-n} \tag{2}$$

generalized as

$$V = CL^{-n} \tag{3}$$

and linearized by the logarithmic transformation

$$\log V = \log C - n \log L. \tag{4}$$

The data for each location and charge was analyzed using this relationship and only that shot data possessing negative slopes and with a coefficient of multiple determination $\hat{R}^2 > 0.95$.

The analysis was then repeated for the retained data after scaling the distances by both the square and cube root of the charge weight per delay (Figs. 11 through 16 and Table II).

For the roof, rib, and bottom composite velocities, square root scaling is only slightly better than that of the cube provided the largest $\hat{R}^2$ values are the sole criterion. However, except for the rib, $\hat{R}^2$ differences are less than a tenth of a percent while, including the rib, agreement is within four percent. It is significant to note that if individual velocities are considered, the largest $\hat{R}^2$ value occurs when cube root scaling is used for the vertical roof component which exceeds the square root value by more than eight percent. The same is true to a lesser extent for the floor data. A linear multiregression model was assumed of the form:

$$Y = B_0 + \hat{\beta}_1 x_1 + \hat{\beta}_2 x_2 + \hat{\beta}_3 x_3 + \hat{\beta}_4 x_4 \tag{5}$$

where Y is the dependent variable which was considered in turn as the horizontal roof strain, roof bolt load and the roof convergence values. The independent variables (x_1, x_2, x_3, and x_4) were the temperature, humidity, roof velocity and floor velocity, respectively. The Statistical Analysis System program (Barr, et al, 1976) was used for the analysis. A significance level of entry of 0.5000 and a significance level of stay of 0.1000 were utilized and significant independent variables determined by the forward selection procedure.

Because the model assumed did not include distance as an independent variable, the number of velocity values utilized was increased from the four of the linear analysis to thirteen. This was necessary to avoid a forced perfect fit imposed by the four degrees of freedom. The resulting regression coefficient (Table III) are grouped by dependent variables rather than by station. Although the model assumed is of the simplest form, the resulting coefficients and R^2 values indicate its usefulness in determining trends and relative importance of independent variables. The following discussion pertains to those twenty-seven of a total of fifty-three responses having an $\bar{R}^2 > 0.500$. This value is arbitrarily chosen as an indication of an acceptable fit.

FLOOR PARTICLE VELOCITY $\hat{\beta}_4$

This parameter is considered to be insignificant because of all the responses only one, that of C4 at Station 5, indicates a dependence upon floor velocity. This is not unexpected, however, as almost all load and strain instrumentation was located in the roof.

TOP PARTICLE VELOCITY $\hat{\beta}_3$

This coefficient was significant in fourteen of the accepted fits. Of these, four negative values were associated with roof convergence. If the $\bar{R}^2$ value is ignored, twenty-two responses are function of $\hat{\beta}_3$ with seventeen located between Stations 1 and 4. It is significant to note however that these stations occupy the portions of the mine not overlain by old workings. Thus, the observed velocity values are neither influenced by changes of acoustic impedence resulting from a rock air or rock water interface in the old workings nor a scattering of the seismic energy resulting from a collapse of the overlying mine structure.

HUMIDITY $\hat{\beta}_2$

Variations in humidity were in general confined to those stations near the opening and under the old workings where water was a problem. However, analysis does not indicate that this is important. As the wet portions also correspond to those heavily timbered, a compensating effect may exist.

TEMPERATURE COEFFICIENT $\hat{\beta}_1$

Temperature was found to be significant in twenty-nine responses of which eighteen are considered good by the $\bar{R}^2$ criterion.

HORIZONTAL ROOF STRAIN INDICATORS (HORSI'S)

The instrumentation of the mine included the installation of one pair each of resin and anchor rock bolts between which HORSI's were affixed. These were aligned parallel to one another and to compare relative responses. The multi-regression analysis utilized data from twenty-eight HORSI's, fourteen each of the two installation types. Of the total, thirteen have $\bar{R}^2$ values greater than 0.500 and of these, nine are associated with mechanical anchor installations. This suggests this type of installation is more sensitive to the model parameters than is the resin.

ROOF BOLT LOAD PADS

Of the nine roof bolt load pads monitored only three responses had $\bar{R}^2$ values greater than 0.500. Although this suggests that both the assumed model and associated regression expressions are poor, it is of interest to note that with the exception of Stations 3 and 11, velocity is not a significant variable and the dominant coefficient at all stations is the constant term $\hat{\beta}_0$. Furthermore, each $\hat{\beta}_0$ differs from the maximum input pad value by less than one unit or scale division. Thus, changes in the bolt load do not vary more than ±250 pounds throughout the test period. An implication of this is that over the range of charge weights, distances, temperature and humidity of the experiments, permanent changes in the roof load were less than the accuracy of the measurements.

CONVERGENCE

Two convergence measurements were made at each station. These are designated C2 and C4 and represent top to bottom values as measured from anchors located two and four feet into the roof, respectively. The dominant coefficient as with the pad responses was the constant $\hat{\beta}_0$ term. The temperature coefficient $\hat{\beta}$ was statistically significant for twelve of the twenty responses of which ten were negative. Furthermore, six of the seven significant particle velocity coefficients $\hat{\beta}_3$ were also negative. The dominance of the negative $\hat{\beta}_1$ and $\hat{\beta}_3$ values is consistent with the assumptions that (1) an increase in temperature expands the rock bolt and the surrounding rock mass and introduces bottom heave, and (2) an increase in particle velocity is accompanied by an increase in bolt movement, top sag, formation of spall or any combination. Both decrease convergence values. As with the pad results, however, the large $\hat{\beta}_0$ coefficients indicate the contributions of the dependent variables assumed are extremely small and that convergence measurements remain constant. This further indicates that the surface shots induced little changes in the mine condition. Furthermore, difference between the C2 and C4 readings are insignificant. Figs. 17, 18, and 19 illustrate these two conclusions. The pairs of curves are essentially parallel and constant with the few variations attributed to errors in instrument (dial gage) readings rather than actual changes in the top to bottom separation.

SUMMARY AND CONCLUSIONS

Peak particle velocities of seismic waves generated near the surface but recorded underground are related to scaled distances by the equation

$$V = K\left(\frac{R}{W^b}\right)^{-n} \qquad (6)$$

Statistically a b value of 0.5 is only slightly better than 0.3333 for expressing the roof, rib and bottom total peak velocity. However, cube root scaling is best for predicting the vertical roof component and because the roof condition is of major importance this value should be used.

Only minor damage of the form of localized thin spall and possible collapse of portions of previously fractured coal ribs resulted from those shots having associated peak particle velocities in excess of 2 in./sec. The absence of major damage or changes in the mine condition is verified by a linear multi-regression analysis which relates damage criteria parameters to peak particle velocities, temperature and humidity. Although the independent variables were found to be statistically significant and the sign of the associated coefficients of the proper value, the dominant coefficients are the constants.

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FIGURE CAPTIONS

1. Distance vs. charge weight showing damage zone - UET tests.
2. Map of West Virginia showing the location of Tioga, West Virginia.
3. Typical instrument cluster in the timbered portion of the mine.
4. Typical instrument cluster in the nontimbered portion of the mine.
5. Typical roof geophone wave forms - Station No. 1.
6. Typical roof geophone wave forms - Station No. 10.
7. Typical floor geophone wave forms - Station No. 10.
8. Scale resulting from blasting.
9. Scale resulting from blasting. Note prominent separation in the center of the paint stripe.
10. Coal rib showing fractures resulting from blasting.
11. Square root scaled distances vs. total peak roof particle velocity.
12. Cube root scaled distance vs. total peak roof particle velocity.
13. Square root scaled distance vs. total peak floor particle velocity.
14. Cube root scaled distance vs. total peak floor particle velocity.
15. Square root scaled distance vs. total peak rib particle velocity.
16. Cube root scaled distance vs. total peak rib particle velocity.
17. Comparison of two and four foot convergence measurements - Station 1A.
18. Comparison of two and four foot convergence measurements - Station 5.
19. Comparison of two and four foot convergence measurements - Station 9.

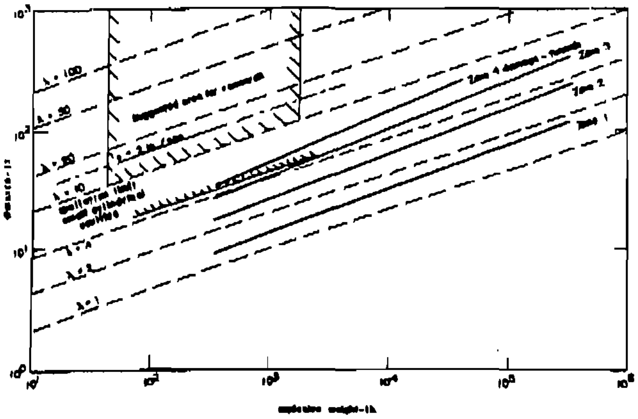


Figure 1

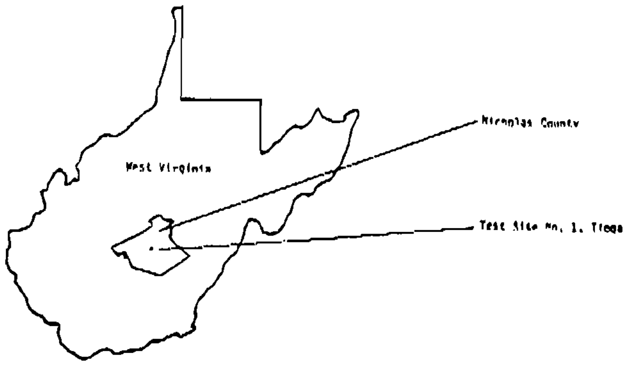
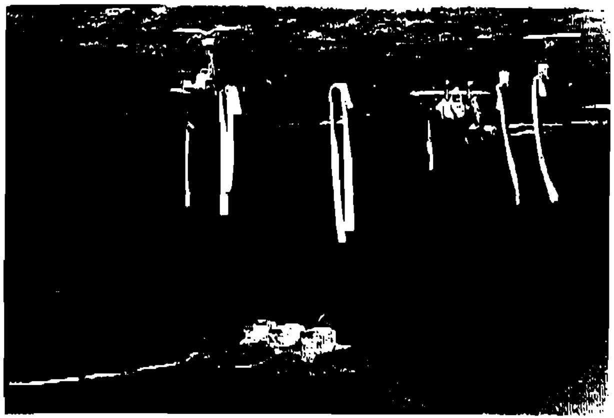


Figure 2

Figure 3



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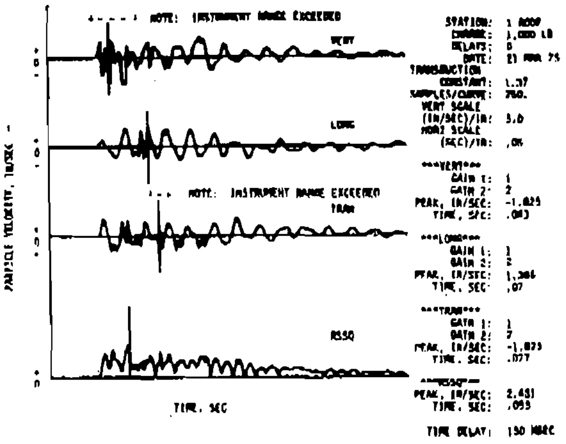

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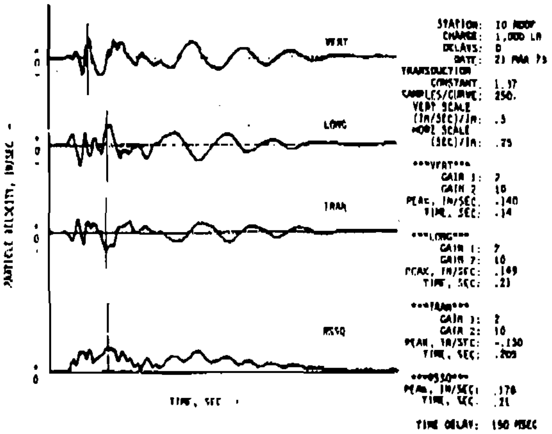

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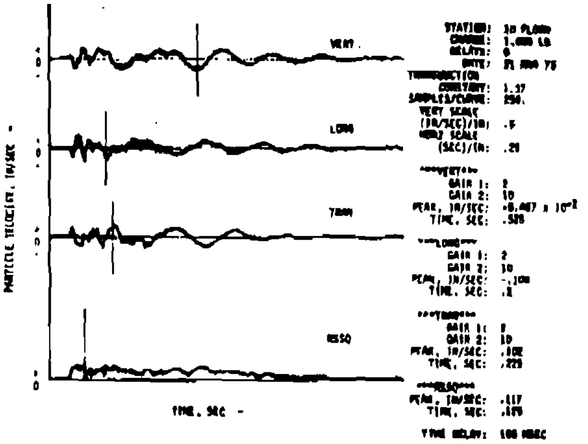

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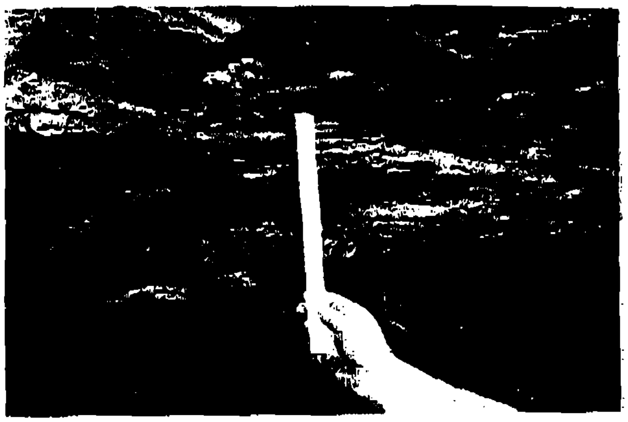

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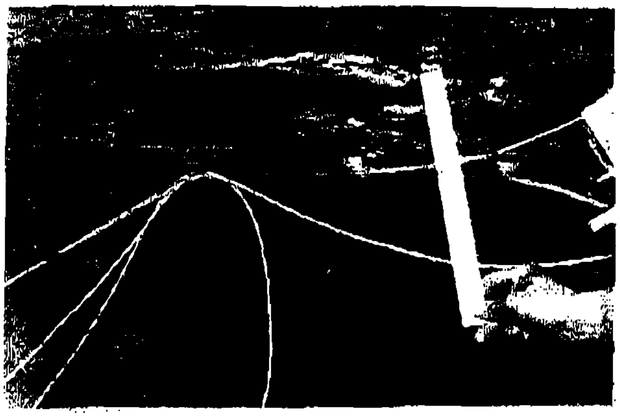

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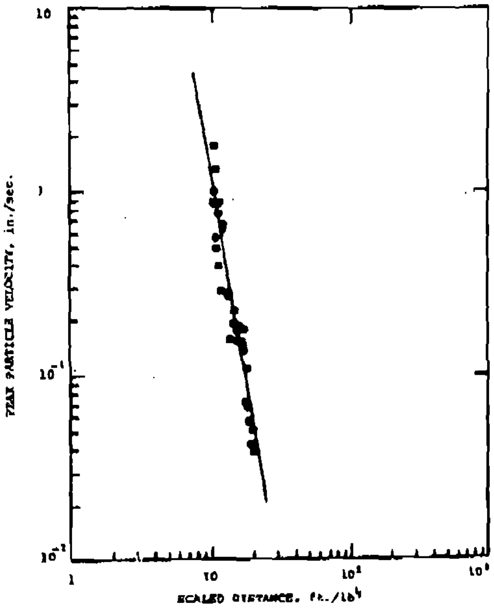

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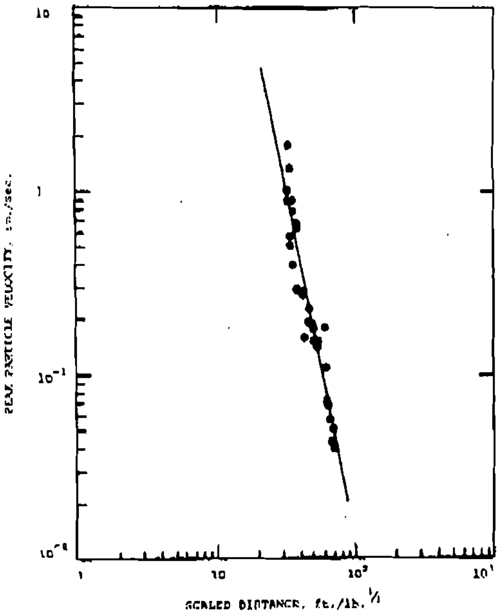

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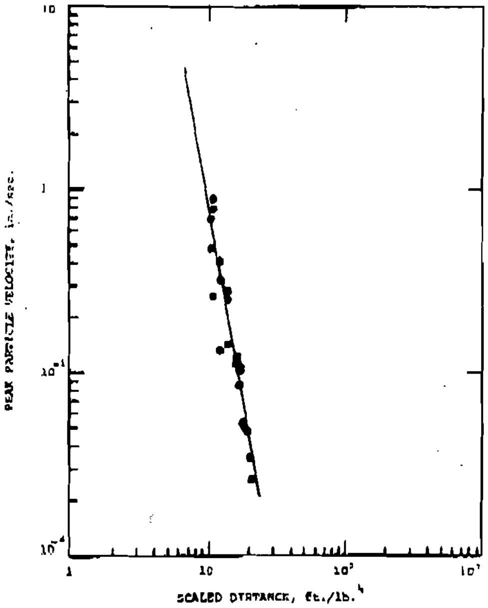

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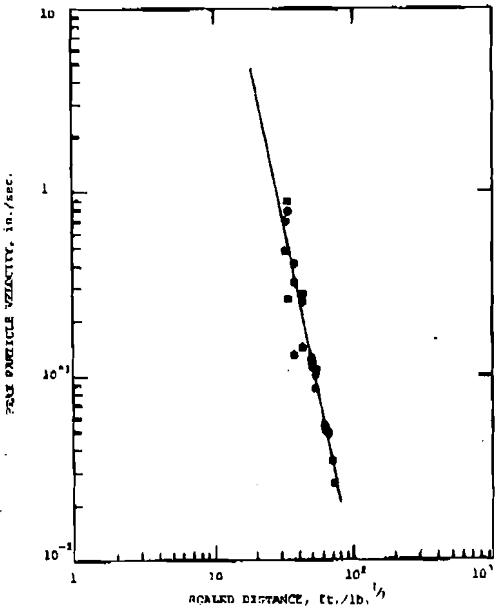

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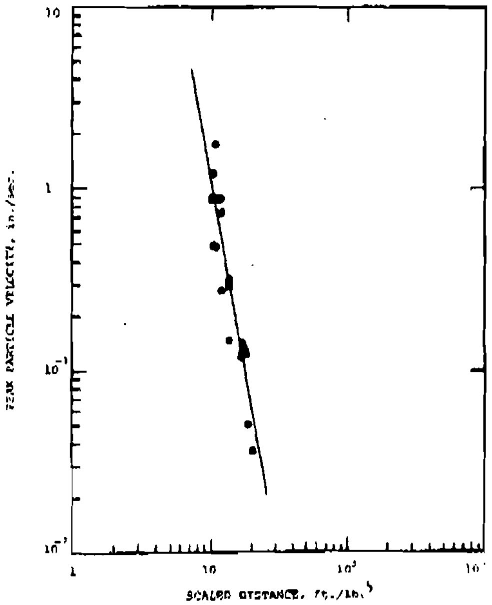

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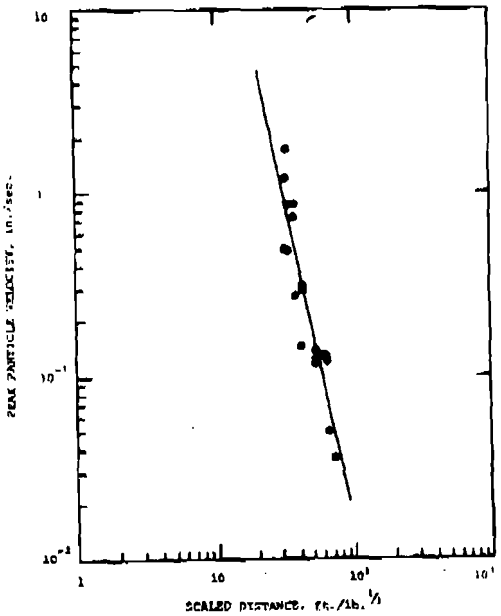

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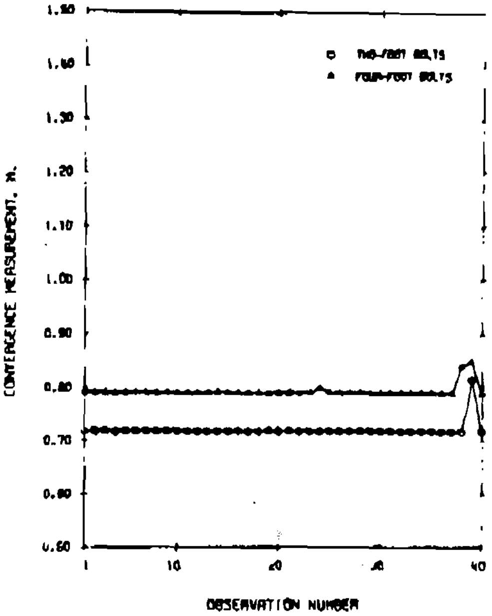

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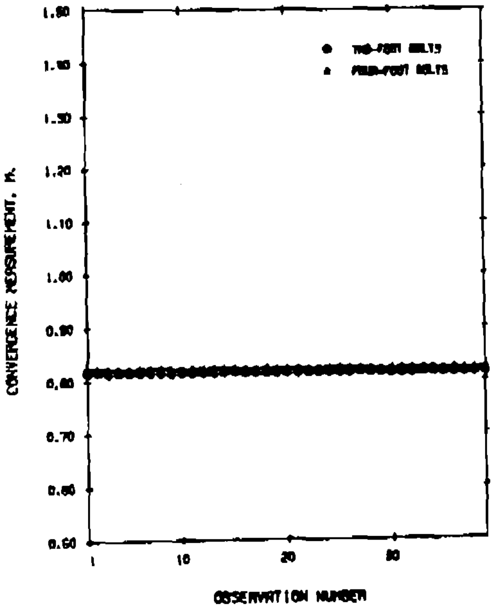

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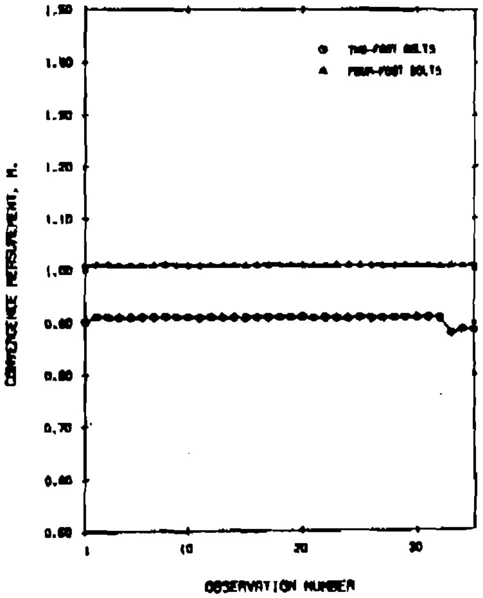

Figure 19

TABLE I. INSTRUMENTS AT EACH STATION

Station Number	Top	Geophones Bottom	Rib	Pad No.	2C	4C	TTH No.	TRH No.	LTH No.	LRH No.	WMS
1	X	X	X	-			3	4	5	6	X
1a	-	-	-	27	X	X	8	9	-	-	
2	-	-	-	16	X	X	10	11	12	13	
3	X	X	X	51	X	X	14	15	-	-	X
4	X	-	-	19	X	X	16	17	-	-	
5a	-	-	-	-	-	-	18	19	20	21	X
5	X	X	X	14	X	X	22	23	-	-	
6	-	-	-	15	X	X	24	25	-	-	X
7	X	X	X	17	X	X	26	27	-	-	X
8	X	-	-	8	X	X	-	-	-	-	X
9	X	X	-	50	X	X	28	29	-	-	
10	X	X	X	20	-	-	30	31	-	-	
11					X	X	32	33	-	-	X

2C	Two foot roof bolt and floor hook for convergence determination
4C	Four foot roof bolt and floor hook for convergence determination
TTH	Transverse oriented HORSI mounted on torqued roof bolts
TRH	Transverse oriented HORSI mounted on resin roof bolts
LTH	Longitudinal oriented HORSI mounted on torqued roof bolts
LRH	Longitudinal oriented HORSI mounted on resin roof bolts
X	Present
-	Absent or non-functional

TABLE II. PROPAGATION EQUATION CONSTANTS AND REGRESSION STATISTICS

Velocity	Site Constant		Scaling Exponent b	Standard Error of Estimate	Square of Multiple Correlation Coefficient, R^2, %
	K	-n			
			Roof		
Vertical	24,241.90	-4.27	1/2	0.1957	81.83
Radial	24,241.90	-4.27	1/2	0.1957	81.83
Transverse	12,456.47	-4.09	1/2	0.2149	77.27
Composite	69,114.46	-4.53	1/2	0.1593	88.64
Vertical	651,770.05	-3.79	1/3	0.1442	90.21
Radial	312,193.17	-3.63	1/3	0.1901	82.87
Transverse	148,330.41	-3.50	1/3	0.2195	76.28
Composite	1,029,667.00	-3.85	1/3	0.1598	88.57
			Rib		
Vertical	28,010.70	-4.27	1/2	0.1873	85.23
Radial	2,916.01	-3.52	1/2	0.2625	63.72
Transverse	7,053.99	-3.89	1/2	0.2337	74.97
Composite	26,489.85	-4.19	1/2	0.2039	82.43
Vertical	341.937.16	-3.61	1/3	0.1982	83.44
Radial	13,358.09	-2.83	1/3	0.2729	60.79
Transverse	87,117.54	-3.35	1/3	0.2354	74.60
Composite	281,124.89	-3.52	1/3	0.2197	79.60
			Floor		
Vertical	16,841.53	-4.25	1/2	0.1603	87.71
Radial	771.97	-3.24	1/2	0.2650	58.89
Transverse	2,669.09	-3.63	1/2	0.1908	79.85
Composite	10,333.56	-3.99	1/2	0.1586	86.84
Vertical	275,493.34	-3.68	1/3	0.1513	89.04
Radial	4,718.64	-2.72	1/3	0.2702	57.36
Transverse	22,921.45	-3.09	1/3	0.1988	78.12
Composite	117,934.29	-3.40	1/3	0.1628	86.13

TABLE III. MULTIPLE LINEAR REGRESSION COEFFICIENTS

Station	Response	$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	$\hat{\beta}_3$	$\hat{\beta}_4$	R_2 percent	C.V. percent
1	LRH	0.02963	0.00032	--	--	--	33.63	3.80
1	LTH	0.01906	0.00081	--	0.00184	--	70.53	9.50
2	LRH	0.04519	--	--	0.00280	--	27.48	5.31
2	LTH	0.04277	--	--	0.00585	--	16.12	16.10
1	TRH	0.00831	--	0.00021	0.00185	--	65.83	7.00
1	TTH	0.07851	0.00044	--	0.00165	--	79.72	1.56
1A	TRH	0.03844	--	0.00020	--	--	17.15	5.49
1A	TTH	0.04585	--	0.00021	0.00225	--	58.05	3.61
2	TRH	0.05836	0.00060	--	--	--	30.43	3.94
2	TTH	0.04947	--	--	0.00495	--	77.44	2.82
3	TRH	0.04593	--	--	0.00489	--	59.38	4.59
3	TTH	0.00795	--	0.00009	0.00192	--	82.87	3.62
4	TRH	0.00988	--	--	0.00995	--	69.95	32.36
4	TTH	0.01295	--	--	0.00226	--	42.56	10.33
5A	TRH	0.03640	--	-0.00021	--	--	24.28	12.72
5A	TTH	0.02691	0.00024	--	--	--	51.49	3.09
5	TRH	0.06927	0.00050	--	--	--	50.21	2.59
5	TTH	--	--	--	--	--	--	--
6	TRH	0.07184	--	--	-0.00166	--	12.13	2.30
6	TTH	0.03591	-0.00015	--	--	--	76.38	0.97
7	TRH	--	--	--	--	--	--	--
7	TTH	0.05617	0.00028	--	--	--	64.09	1.70
1A	C2	0.71808	-0.00004	--	--	--	35.48	0.02
1A	C4	0.83617	0.00462	-0.00101	--	--	60.75	1.25
2	C2	0.83817	--	--	-0.00045	--	37.39	0.04
2	C4	0.86267	--	--	--	-0.00039	46.81	0.02
3	C2	0.72773	-0.00003	--	-0.00035	--	84.84	0.02
3	C4	0.84367	--	--	-0.00053	--	80.14	0.02
4	C2	0.92942	-0.00006	--	--	--	50.51	0.02
4	C4	0.94159	--	--	-0.00029	--	42.74	0.02
5	C2	0.81366	-0.00005	--	-0.00033	--	93.43	0.01
5	C4	0.81963	-0.00010	0.00003	--	--	88.46	0.02
6	C2	0.78217	-0.00006	0.00002	--	--	68.52	0.03
6	C4	0.89583	0.00039	-0.00020	--	--	80.47	0.13
7	C2	--	--	--	--	--	--	--
7	C4	0.92659	-0.00008	--	--	--	76.33	0.02
8	C2	0.80719	--	0.00004	--	--	37.99	0.05
8	C4	1.03327	-0.00003	--	--	-0.00118	73.42	0.02
9	C2	0.93903	-0.00007	--	--	--	4.31	0.18
9	C4	1.02313	-0.00009	--	--	--	8.38	1.42
11	C2	0.88789	--	--	-2.52117	--	47.73	45.74
11	C4	1.00945	--	--	0.00473	--	79.27	0.03
1A	PAD	2.97736	0.02311	--	--	--	25.31	3.40
2	PAD	3.59442	0.03047	--	--	--	21.51	4.16
9	TRH	0.05193	0.00035	--	--	--	3.49	16.61
9	TTH	0.02423	--	0.00032	--	--	4.53	26.13
10	TRH	-0.01315	-0.00141	0.00057	--	--	16.20	75.81
10	TTH	--	--	--	--	--	--	--
11	TRH	0.01998	--	0.00014	--	--	28.23	9.10
11	TTH	0.05694	--	--	0.01466	--	76.30	1.65
3	PAD	5.00395	0.03031	--	0.15851	--	78.62	1.75
4	PAD	4.02682	0.04774	--	--	--	46.70	4.39
5	PAD	--	--	--	--	--	--	--
6	PAD	5.74271	0.03334	-0.01222	--	--	81.00	1.71
7	PAD	5.25613	--	-0.00517	--	--	12.40	2.50
8	PAD	5.51615	0.01478	0.00555	--	--	58.88	1.27
9	PAD	--	--	--	--	--	--	--
10	PAD	3.97641	0.01542	--	--	--	15.14	4.21
11	PAD	3.65310	--	--	-1.64729	--	36.99	7.20