RI bureau of mines
report of investigations 5968

REVIEW OF CRITERIA FOR ESTIMATING DAMAGE TO RESIDENCES FROM BLASTING VIBRATIONS

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UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

1962

This publication has been cataloged as follows:

Duvall, Wilbur Irving, 1915-

Review of criteria for estimating damage to residences from blasting vibrations, by Wilbur I. Duvall and David E. Fogelson. [Washington] U. S. Dept. of the Interior, Bureau of Mines [1962]

19 p. illus., tables. 27 cm. (U. S. Bureau of Mines. Report of investigations, 5968)

Bibliography: p. 17-19

1. Blasting. I. Fogelson, David E joint author. II. Title. III. Title: Damage to residences from blasting vibrations. (Series)

TN23.U7 no. 5968 622.06173

U. S. Dept. of the Int. Library

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UNITED STATES DEPARTMENT OF THE INTERIOR
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by

Wilbur I. Duvall[2] and David E. Fogelson[3]

SUMMARY AND CONCLUSIONS

In a review of some 40 papers on damage to residential structures resulting from blasting, only 3 were found that present data on the observed amplitude and frequency of the vibration levels produced by blasting together with an observed degree of damage to a residential structure. The data from these three reports have been analyzed statistically to determine if one of the quantities, displacement, velocity, or acceleration, is more reliable than the others for estimating the degree of damage to a residential structure. From this analysis the conclusion is drawn that a given degree of damage to a structure is most closely related to the magnitude of the particle velocity of the wave motion passing thru the earth at the structure location. On the average, only minor damage is observed for peak particle velocities of 5.4 inches per second, and major damage is observed for peak particle velocities of 7.6 inches per second. When the spread of the data is taken into consideration, the following statement can be made: Wave motions that have a peak particle velocity in excess of 2 inches per second have a fair probability of producing some damage to structures, whereas wave motions that have a peak velocity less than 2 inches per second have a very low probability of causing any damage. Therefore, the recommendation is made that vibration levels in the vicinity of residential structures should be maintained below a peak particle velocity of 2 inches per second. The above criterion for safe blasting is considered to hold over a wide variety of soil and rock conditions because the original data were obtained for a wide range of soil and rock conditions and on various types of residential structures.

INTRODUCTION

Ever since explosives were discovered and developed for mining purposes, there has existed the problem of what effects the air and ground vibrations resulting from blasting have on structures of various types. This problem is

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especially acute for surface operations such as open-pit mines, quarries, and construction projects that are in the proximity of residential districts. If nuclear explosions are ever developed and used for mining purposes, the vibration problem will also become acute for underground mining operations.

Because the general public is directly involved in the blasting vibration problem, it has been of major concern to local, State, and Federal governments as well as to mining and construction companies, explosive manufacturers, insurance companies, and scientific investigators. Consequently, many investigations have been conducted, both in this country and abroad on the effects of air and ground vibrations on residential and other structures. One of the first such studies in this country was made in 1927 by Rockwell (37, 38).[4] From his instrumented studies he concluded that quarry blasting would not produce damage to residential structures that were more than 200 to 300 feet from a quarry. He also pointed out the need for measuring the vibrations from quarry blasting in order to establish the level of vibration as a function of charge size and distance.

During the period from 1935 to 1942, the Bureau of Mines conducted an extensive investigation on the problem of seismic effects of quarry blasting (40-47). This work, summarized in Bulletin 442 (46), was the first major effort at establishing damage criteria for residential structures. Damage criterion as used in this report is defined as the magnitude of one or more quantities associated with the vibration impinging on, or experienced by, a structure which when exceeded results in some degree of failure within the structure. The criteria of damage given in Bulletin 442 were based upon the acceleration experienced by the structure. Vibration levels below 0.1 g. were labeled no damage; between 0.1 and 1.0 g., caution; and above 1.0 g. damage.

The next major contribution to the study of damage to structures was by F. J. Crandell in 1949 (3). His criteria of damage were based upon vibration levels in the ground at the location of the structure. Vibration levels were specified in terms of energy ratio, which he defined as the acceleration squared divided by the frequency squared, where the acceleration was expressed in units of feet per second squared and the frequency in units of cycles per second. Energy ratios below 3 were labeled safe; between 3 and 6, caution; and above 6, danger.

Between 1949 and 1960 interest in the problem of seismic vibrations from blasting and their effects upon structures continued to increase as is shown by the many publications released during this time (1, 2, 4, 13, 15, 17, 19, 20-25). Many investigators were also active in other countries (6-10, 26-28, 39). In addition, the study of the effects of nuclear devices resulted in the publication of several books and articles containing important information on damage (11-12). During this period several states and organizations adopted different damage criteria. For example, New Jersey and Massachusetts specified an energy ratio of 1 as the allowable limit, while Pennsylvania adopted a displacement of 0.03 of an inch as a safe blasting limit. A damage criterion based on an energy ratio of 1 was also specified by the U.S. Corps of Engineers and the New York State Power Authority. From 1949 to the present there was

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[4] Underlined numbers in parenthesis refer to references in the bibliography at the end of this report.

also considerable interest in trying to correlate vibration levels and damage resulting from earthquakes with vibration levels and damage resulting from blasting (29-32). More recent investigations have made use of frequency spectrum analysis as a method of predicting damage to structures (14, 16, 33).

In 1957 an article by Langefors, Kihlstrom, and Westerberg established still another set of damage criteria (18). These damage criteria were based on velocity of motion of the ground at the house location; four levels of damage were designated: (1) 2.8 inches per second, no noticeable damage; (2) 4.3 inches per second, fine cracks and fall of plaster; (3) 6.3 inches per second, cracking; (4) 9.1 inches per second, serious cracking.

Early in 1959 Edwards and Northwood published an article (5) that described their vibration studies in connection with the St. Lawrence Project in Canada. In this report they concluded that either velocity or acceleration could be used as an index of damage for the two soil types studied, but that velocity was the most generally applicable quantity. They proposed that vibration levels below 2 inches per second be considered safe; between 2 and 4 inches per second, caution; and above 4 inches per second, damage.

Because of the ever increasing demand for additional information on vibration problems resulting from blasting, the continual controversy over damage criteria, and the new developments in the technology of blasting rock, the Bureau of Mines decided to restudy the problem of vibrations from quarry blasting and their effects upon structures. A meeting of representatives from the Bureau of Mines, the quarry industry, insurance companies, seismologists, and vibration consultants was held at College Park, Maryland, early in 1959. At this meeting the purpose and objectives of the Bureau of Mines long-range vibration program were discussed and formulated. A complete statement of the objectives and an outline of the Bureau of Mines program has been published (34). In addition, a progress report was recently presented to the quarry industry (35).

One of the objectives of the present investigation is the development of reliable vibration-damage criteria for structures of various types. Considering that four or five different sets of damage criteria exist today for residential structures, that the papers in which these damage criteria are discussed are not readily available, and that any new data forthcoming from the present Bureau of Mines investigation will not be available for several years, it seemed advisable to make an evaluation study of the published experimental data pertaining to damage. The purpose of this evaluation study is to determine if the published data relating measured vibration amplitudes and frequencies to damage can be pooled to establish one set of reliable damage criteria. If the data cannot be pooled, then this study should indicate the direction of further investigation so that reliable damage criteria can be established.

Of the publications listed in the bibliography, only three contain published data on the amplitude and frequency of the vibration level associated with a given damage evaluation of the structures (5, 18, 46). The data from these three investigations are the subject of study in this report. First, the data are analyzed separately by statistical methods to determine if one of

the quantities, displacement, velocity, or acceleration, is more reliable in estimating damage to residential structures than the others. Second, the collective data are analyzed statistically to determine if pooling of the data can be used to increase the accuracy of the estimation of damage. Third, a level of vibration is selected that can be used as a criterion for safe blasting operations.

INVESTIGATIONS BY THE BUREAU OF MINES

The Bureau of Mines studied the seismic effects of quarry blasting over a period of 7 years from 1935 to 1942. Vibration amplitudes were recorded for many quarry blasts, but no evidence of structural damage was discovered except for a few special test shots. Because of this lack of data on actual damage and the difficulty of finding structures that could be tested to the damage point, the Bureau decided to make an intensive study of mechanically-induced house vibrations and to correlate these results with vibrations from quarry blasting.

A total of 14 buildings ranging from one to three stories in height were tested. These structures were frame, brick, or stone masonry in construction. No reinforced concrete or steel buildings were tested.

Vibration amplitudes were measured by variable capacitance seismometers of the displacement recording type. Both horizontal and vertical seismometers were developed by the Bureau so that all three components of motion could be recorded. The outputs of 12 seismometers were recorded simultaneously by using a 12-channel oscillograph.

House vibrations were produced by quarry blasting and by a mechanical shaker. The shaker was an electrically driven unbalanced-rotor type, capable of 1,000 pounds force with a maximum frequency of 40 c.p.s.

By placing the shaker in a particular location in the building, usually in a doorway, it was possible to shake the structure as a unit. These vibrations were recorded by seismometers placed on all three floor levels. Vibrations from quarry blasting were recorded at the same seismometer positions, but an additional seismometer was placed on the ground outside the building.

These studies provided a basis for correlating the mechanical vibrations with those from blasting. The authors concluded that the shaker tests agreed closely with the quarry blasts except for the duration of the motion and the wave shape. However, no damage was observed for the quarry vibrations, and it was impossible to shake the house as a unit until the damage occurred, as very large amplitudes were required. Therefore, it was necessary to study the effect of vibrations on the individual floor and ceiling panels.

In this method the shaker was mounted in the center of the panel, and the frequency and amplitude of vibration were increased until damage occurred. The vibration amplitudes were recorded by placing vertical seismometers at different positions on the floor. It was believed that the motion of the floor panel would be essentially the same as that produced when the house moved as a unit.

In 6 of the 14 buildings tested, 160 shaker tests were made of 16 ceiling panels about the damage point, as defined by the failure of plaster. Figure 1 shows a plot of the data. Amplitudes ranged from 1 to 500 mils and frequencies from 4 to 40 c.p.s.

The data are divided into three classification as follows:

1. Major damage (fall of plaster, serious cracking).

2. Minor damage (fine plaster cracks, opening of old cracks).

3. No damage.

Straight lines have been drawn through the major and minor damage data as determined by least squares analysis. The results are summarized in table 1.

TABLE 1. - Regression analysis, Bureau of Mines data

Type of damage	Observations	Slope	Error in slope	Standard deviation about regression, percent
Major...............	34	-1.22	±0.25	69
Minor...............	26	-2.00	±0.31	96

In Bulletin 442 the authors proposed a damage index of 1 g. which was not based on a statistical analysis of the data. If only the slope of the minor damage data is considered, their conclusion appears reasonable, as the data should plot with a slope of -2 on log-log graph paper if the damage depends on the magnitude of acceleration. The slope of the major damage data is nearer to -1 than -2, indicating that the damage may depend on the velocity rather than the acceleration.

A statistical test of these data has been made to determine which quantity (displacement, velocity, or acceleration) correlates best with the observed damage. The following hypotheses were tested:

1. The major and minor damage data have slopes of 0 (displacement).

2. The major and minor damage data have slopes of -1 (velocity).

3. The major and minor damage data have slopes of -2 (acceleration).

Table 2 summarizes these tests. For the major damage data the hypothesis that the slope is -1 is accepted, and the hypothesis that the slope is 0 or -2 is rejected at the 1-percent significance level. For the minor damage data, however, the hypothesis that the slope is -2 must be accepted, and the hypotheses that the slope is 0 or -1 are rejected.

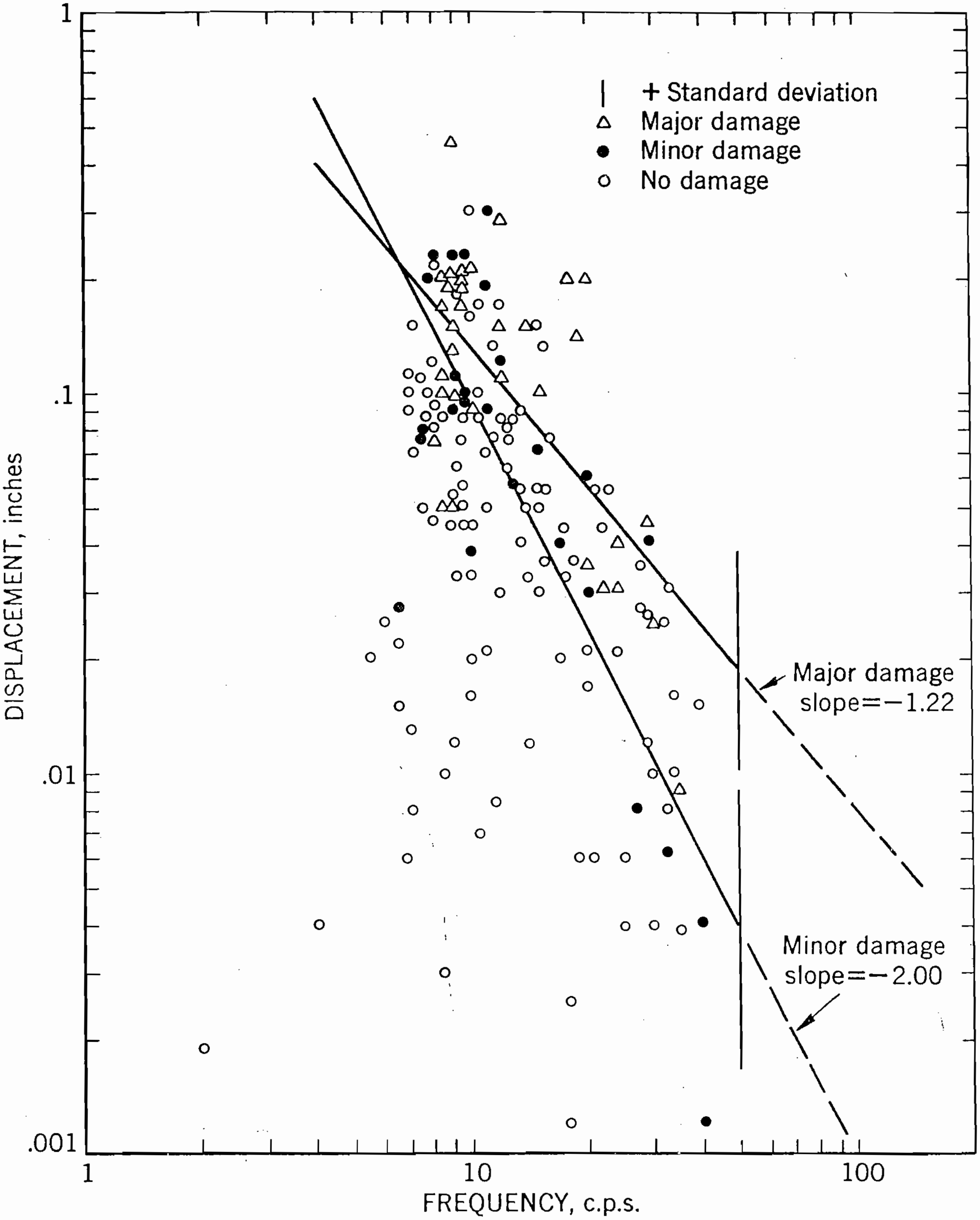

FIGURE 1. - Displacement Versus Frequency for Observed Damage, Bureau of Mines.

TABLE 2. - t Test, Bureau of Mines data

Type of damage	Observations	Slope Hypothesis	t	$t_{.01}$	Reject hypothesis?
Major................	34	0	-4.88	2.71	Yes.
Minor................	26	0	-6.45	2.80	Yes.
Major................	34	-1	.88	2.71	No.
Minor................	26	-1	-3.23	2.80	Yes.
Major................	34	-2	3.12	2.71	Yes.
Minor................	26	-2	0	2.80	No.

These tests show that the Bureau of Mines data give contradictory results because the data indicate that major damage occurs if the level of vibration exceeds a given value of particle velocity and that minor damage occurs if the level of vibration exceeds a given value of particle acceleration. Additional evidence must be found to clarify these conclusions.

INVESTIGATIONS BY LANGEFORS, KIHLSTROM, AND WESTERBERG

In 1957 a report (18) by Langefors, Kihlstrom, and Westerberg was published which described extensive studies of the relationship between damage and ground vibrations from short-range blasting. The data were obtained during a large reconstruction project in Stockholm which required the use of explosives near buildings. As the buildings rested on rock, the size of the blast was important since the amplitude of the vibrations would attenuate very little before reaching the structures. However, larger blasts were desirable, as this would improve the economy of the operation. Therefore, larger shots were decided upon, with the risk of some minor damage that could be repaired. This procedure enabled the investigators to record and analyze a large amount of data on damage to buildings from blasting. A Cambridge vibrograph (a mass-spring system that is proportional to displacement above five cycles and records on celluloid strips) was used to measure the vibrations from the blasting. The instrument was usually placed on the rock close to the building and was clamped to the rock whenever the accelerations were greater than 1 g., thus preventing the base of the instrument from leaving the surface at high accelerations. Initial tests indicated that the level of vibration in the horizontal direction was of the same general magnitude as that in the vertical direction. Thus, later tests included only the measurement of vertical vibrations.

More than a hundred tests were conducted, and the results were analyzed. Vertical ground displacements varied from 0.02 to 2 mils; frequencies, from 50 to 500 c.p.s. The authors concluded that velocity was the best criterion of damage and proposed the following: (1) 2.8 inches per second, no noticeable damage; (2) 4.3 inches per second, fine cracks and fall of plaster; (3) 6.3 inches per second, cracking; (4) 9.1 inches per second, serious cracking.

Figure 2 shows a plot of these data where cracking and serious cracking are labeled major damage, fine cracking and fall of plaster are labeled minor damage, and no noticeable damage is labeled no damage.

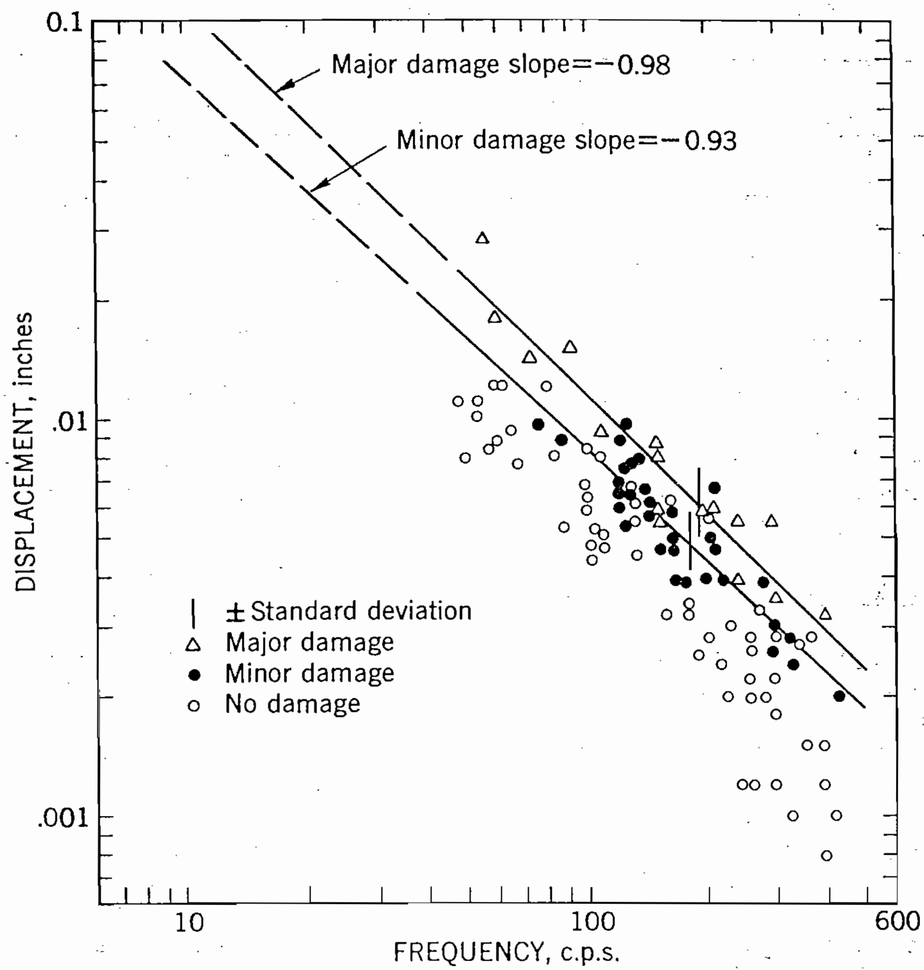

FIGURE 2. - Displacement Versus Frequency for Observed Damage, Langefors.

Least square lines have been drawn through the major and minor damage data, and the results of the least squares analysis are summarized in table 3.

As in the case of the Bureau of Mines data, statistical tests of the slopes have been made to determine if the degree of damage is determined by constant displacement, velocity, or acceleration. Table 4 shows the results of the statistical tests. The hypothesis that both the major and minor damage data have slopes of -1 cannot be rejected at the 1-percent significance level, but the hypotheses that the slopes are 0 or -2 can be rejected. Thus, the data show that both major and minor damage correlate with a given level of particle velocity.

TABLE 3. - Regression analysis, Langefors data

Type of damage	Observations	Slope	Error in slope	Standard deviation about regression, percent
Major.............	16	-0.98	±0.09	21
Minor.............	32	- .93	± .08	18

TABLE 4. - t Test, Langefors data

Type of damage	Observations	Slope hypothesis	t	$t_{.01}$	Reject hypothesis?
Major.............	16	0	-10.9	2.98	Yes.
Minor.............	32	0	-11.9	2.75	Yes.
Major.............	16	-1	.22	2.98	No.
Minor.............	32	-1	.63	2.75	No.
Major.............	16	-2	11.3	2.98	Yes.
Minor.............	32	-2	13.4	2.75	Yes.

INVESTIGATIONS BY EDWARDS AND NORTHWOOD

A recent report (5) by Edwards and Northwood describes a series of controlled blasting tests on six buildings located along the St. Lawrence Seaway. The construction of power facilities necessitated the destruction of several residential structures. Six buildings were selected for damage tests. Three of the buildings were situated in a wet, silty, clay soil, and the others in a well consolidated glacial till. The houses had either frame or brick superstructures and all had basements of heavy stone masonry.

Charges, buried at depths of 15 to 30 feet, were detonated progressively closer to the buildings until damage occurred. A minimum charge to structure distance of 50 feet was maintained to assure that the soil between the charge and the structure was undisturbed.

Vibration amplitudes were measured with accelerometers, velocity gages, and displacement seismographs. The accelerometers and velocity gages were placed inside the buildings, and the seismograph was placed on the ground outside. Some difficulty was experienced with the velocity gages; therefore, the major sources of the data were the accelerometers and the seismographs.

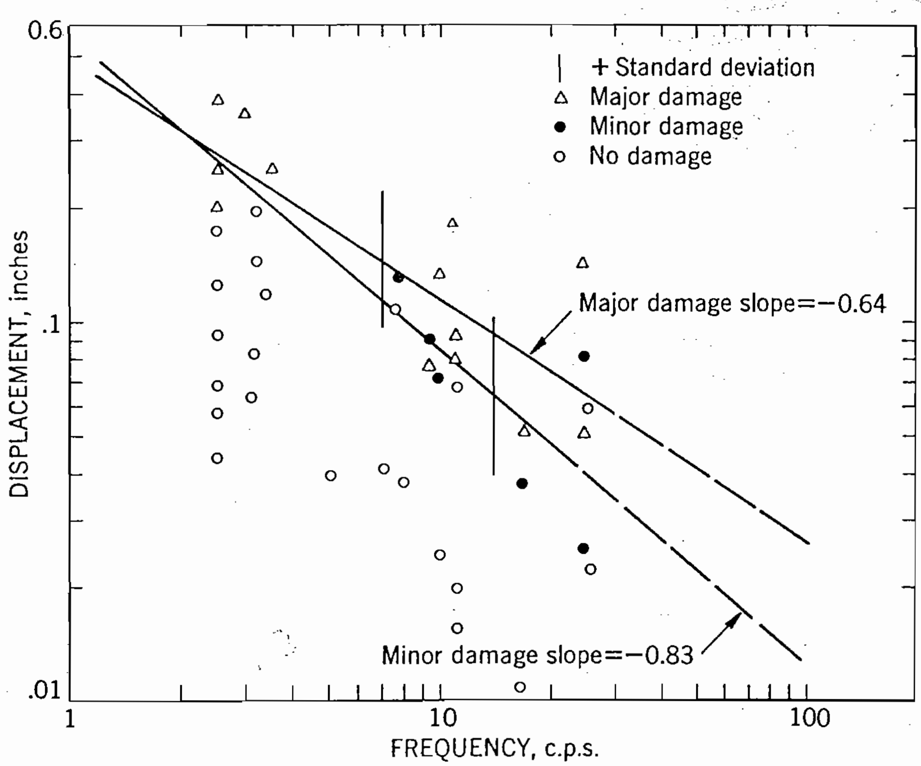

FIGURE 3. - Displacement Versus Frequency for Observed Damage, Edwards and Northwood.

Because the ground amplitudes from damaging shots were too large for the seismographs when placed near the structure, they were normally located farther from the blast than the house. Small calibration shots were used to compare displacements at the structure with those at the monitoring point. The seismographs were anchored to the surface by chains and turnbuckles to prevent their movement when the acceleration levels were greater than 1 g.

Figure 3 shows a plot of frequency versus displacement for the type of damage observed. Both horizontal and vertical displacements are included. As in the other plots, these data have been grouped into major, minor, and no damage classifications. Major damage corresponds to large cracks and fall of plaster. Minor damage corresponds to fine plaster cracks and the opening of old cracks. Displacements ranged from 10 to 350 mils; frequencies, from 3 to 30 c.p.s.

The least squares analysis is summarized in table 5.

TABLE 5. - Regression analysis, Edwards and Northwood data

Type of damage	Observations	Slope	Error in slope	Standard deviation about regression, percent
Major.............	13	-0.64	±0.14	43
Minor.............	6	-0.83	±0.41	49

Statistical tests regarding the slope of the regression line have been performed on these data also. The hypothesis that the slope for the major damage data is -1 has to be accepted, and the hypotheses that the slope is either 0 or -2 must be rejected at the 1-percent significance level. For the minor damage data, the statistical tests are inconclusive, as the spread in the data is so large that all three slopes (0, -1, or -2) are possible. The results of these statistical tests are summarized in table 6.

TABLE 6. - t Test, Edwards and Northwood data

Type of damage	Observations	Slope hypothesis	t	$t_{.01}$	Reject hypothesis?
Major............	13	0	-4.57	3.11	Yes.
Minor............	6	0	-2.02	4.60	No.
Major............	13	-1	2.57	3.11	No.
Minor............	6	-1	0.41	4.60	No.
Major............	13	-2	9.71	3.11	Yes.
Minor............	6	-2	2.85	4.60	No.

DISCUSSION AND ANALYSIS

Major Damage Data

The statistical tests performed on each of the three groups of major damaged data have shown that the hypothesis that the slope is -1 must be

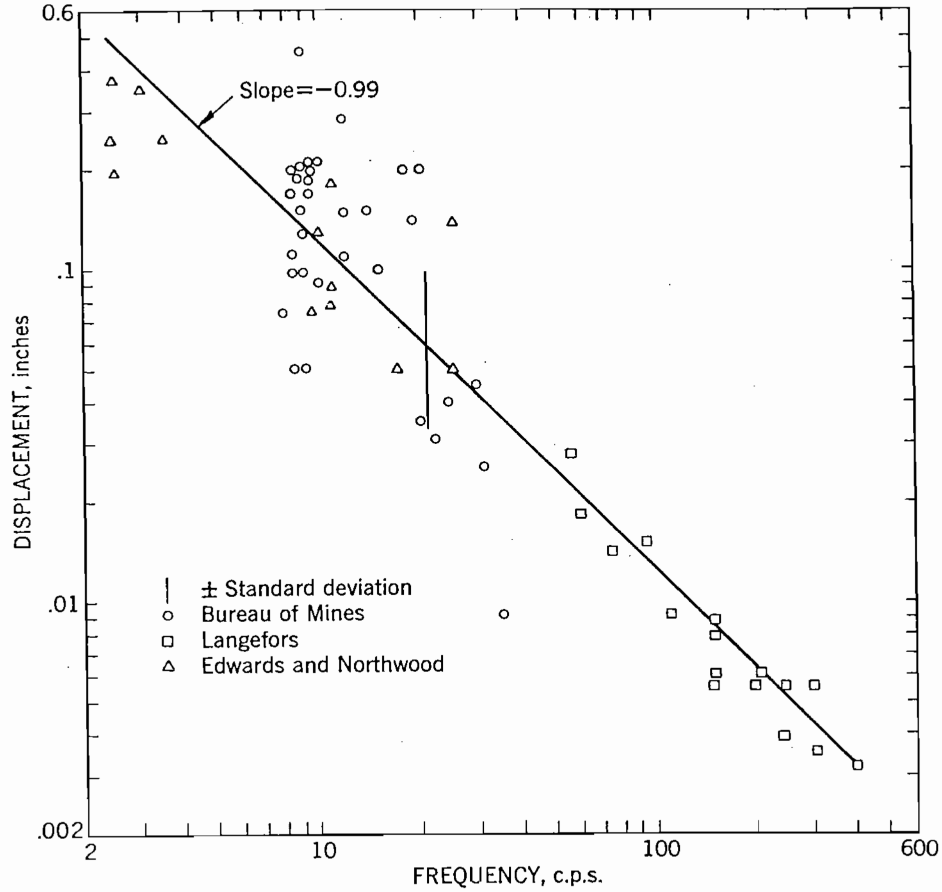

FIGURE 4. - Displacement Versus Frequency for Major Damage.

accepted and that the hypotheses that the slope is either 0 or -2 must be rejected at the 1-percent significance level. Thus, the conclusion that the three groups of data have a common slope of -1 is statistically acceptable. A slope of -1 for a plot of amplitude versus frequency on log-log coordinates corresponds to a constant particle velocity. The next step is to determine if the three groups of data are estimating that major damage occurs at the same magnitude of particle velocity.

One method of determining if several groups of data are estimating a common regression coefficient and a common intercept is to perform an analysis of variance tests (36). In this method, the data from the three groups are pooled and a grand regression line through all the data is obtained as shown in figure 4. The variances about regression are calculated and used to test certain hypotheses. Table 7 summarizes the results of this analysis for the major damage data. The hypothesis that a grand regression line can be used to represent all the data can be accepted at the 1-percent significance level. The slope of the grand regression line is -0.99 ± .05, and the standard deviation about the grand regression line is 56 percent.

Statistical tests have been performed to determine if the slope of the grand regression line for the major damage data is 0, -1, or -2. Table 8 summarizes these results. The hypothesis of a slope of 0 or -2 must be rejected at the 5-percent significance level, but the hypothesis of a slope of -1 cannot be rejected at the 5-percent significance level. Therefore, the grand regression line corresponds to a constant particle velocity. The magnitude of this velocity, if a line with a slope of -1 is drawn through the average point of the data, is 7.6 inches per second. This velocity is shown as a dashed line in figure 6.

TABLE 7. - Analysis of variance, major damage data

Group	Sum of squares about regression	Degrees of freedom	Mean square
Bureau of Mines................	2.4853	32	
Langefors......................	.1109	14	
Edwards and Northwood..........	.3539	11	
Total about individual regression lines.............	2.9501	57	0.05176
Total about grand regression line........................	3.3249	61	
Difference.....................	.3748	4	.09370
$F = \frac{.09370}{.05176} = 1.81$	$F_{(.01)(4,57)} = 3.67$		Accept hypothesis

TABLE 8. - t Test, major damage data

Observations	Slope hypothesis	t	$t_{.05}$	Reject hypothesis?
63........................	0	-19.8	2.00	Yes.
63........................	-1	.20	2.00	No.
63........................	-2	20.2	2.00	Yes.

Minor Damage Data

The minor damage data are inconclusive at the 1-percent significance level. Statistical analysis of the Langefors data shows that a slope of -1 can be accepted, but that slopes of 0 and -2 must be rejected. For the Bureau of Mines data the hypothesis of a slope of -2 can be accepted, but slopes of 0 and -1 must be rejected. The Edwards and Northwood data show poor correlation, as none of the hypotheses can be rejected.

Because the minor damage results are inconclusive, it is worthwhile to re-examine the regression line analysis and the data plots. The Bureau of Mines data and the Edwards and Northwood data have the largest errors in the slopes and the largest standard deviations about the regression lines. This implies that these data are not very reliable. For example, the Bureau of Mines minor damage points have a standard deviation about the regression line of 96 percent. If one data point (frequency, 40 c.p.s.; displacement, 0.012 inch) is omitted from the analysis, the slope changes from -2.00 to -1.69, and a t test shows that the data may have either a slope of -1 or -2 at the 1-percent significance level.

However, it still may be possible to pool the minor damage data and to put one grand regression line through all the data. If the data can be pooled, the error in the slope of the grand regression line should be less than the errors in the slopes of the individual regression lines because of the wider frequency range when the data are pooled.

The results of an analysis of variance of the minor damage data are given in table 9. All the minor damage data are included in this analysis except the single point of the Bureau of Mines data which is greater than 4 standard deviations from the grand regression line. The hypothesis of a grand regression line through all the minor damage data can be accepted at the 1-percent significance level.

TABLE 9. - Analysis of variance, minor damage data

Group	Sum of squares about regression	Degrees of freedom	Mean squares
Bureau of Mines...............	2.5691	23	
Langefors.....................	.1741	30	
Edwards and Northwood.........	.1699	4	
Total about individual regression lines............	2.9131	57	0.05111
Total about grand regression line.............	3.4631	61	
Difference....................	.5500	4	.1375
$F = \frac{.1375}{.05111} = 2.69$	$F_{(.01)(4,57)} = 3.67$		Accept hypothesis

The slope of the grand regression line is -1.02 ± 0.05, and the standard deviation about the grand regression line is 58 percent. Figure 5 is a plot of the minor damage data with the grand regression line.

Table 10 gives the results of the t tests made on the slope of the grand regression line for the minor damage data. The hypothesis of a slope of -1 cannot be rejected at the 5-percent significance level. Thus, the slope of the grand regression line of the minor damage data also corresponds to a constant velocity. If a line with a slope of -1 is drawn through the average point of the data the velocity indicated by the line is 5.4 inches per second. Figure 6 shows this velocity as a dashed line.

TABLE 10. - t Test, minor damage data

Observations	Slope hypothesis	t	$t_{.05}$	Reject hypothesis?
63........................	0	-20.4	2.00	Yes.
63........................	-1	-.40	2.00	No.
63........................	-2	19.6	2.00	Yes.

RECOMMENDED DAMAGE CRITERION

Analysis of the major and minor damage data have shown that the Bureau of Mines, Langefors, and Edwards and Northwood data can be pooled and that the slopes of the grand regression lines correspond to constant particle velocity.

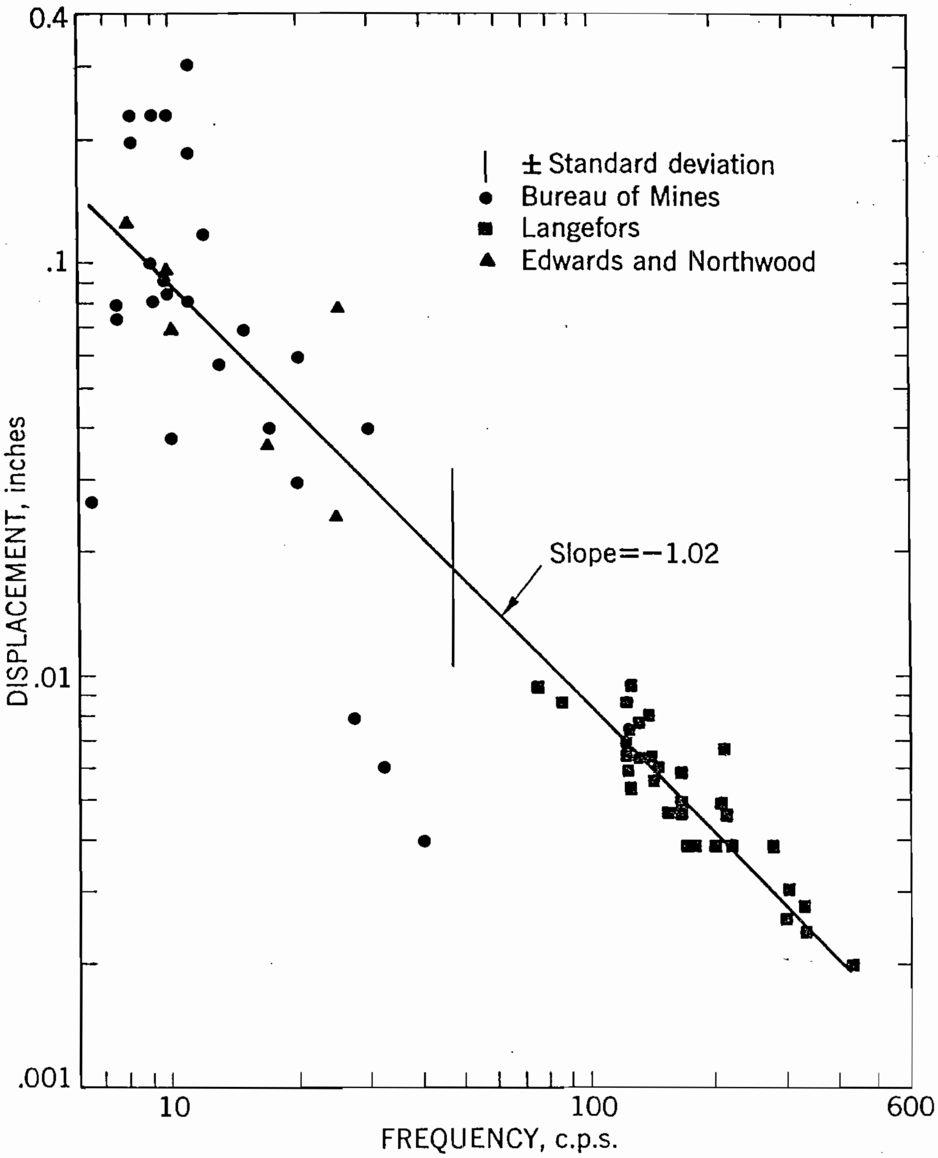

FIGURE 5. - Displacement Versus Frequency for Minor Damage.

This result is significant because the data were obtained by different investigators using different instrumentation and a wide variety of house structures on different types of foundation material. Thus, a criterion of damage, based on velocity, should be applicable to a variety of physical conditions.

Other investigators have proposed several damage criteria that use particle velocity to define the limits of three zones of damage. These zones are usually called the no damage zone, the caution zone, and the damage zone. Because the data in this investigation do not have homogeneous variance when pooled, the limits of the damaged zones are difficult to determine statistically. Therefore, only two zones are recommended, a safe zone and a damage zone.

Figure 6 shows the major and minor damage data with constant velocity lines of 7.6 inches per second and 5.4 inches per second drawn through their average points. On the basis of these data a velocity of 2.0 inches per second appears reasonable as a separation between the safe zone and the damage zone. All the major damage points and 94 percent of the minor damage points lie above this line. The only data points lying below the 2-inch-per-second line are from the Bureau of Mines minor damage data, which have the largest standard deviation about the regression line. Furthermore, the Bureau of Mines data were obtained inside the structures, which may have increased

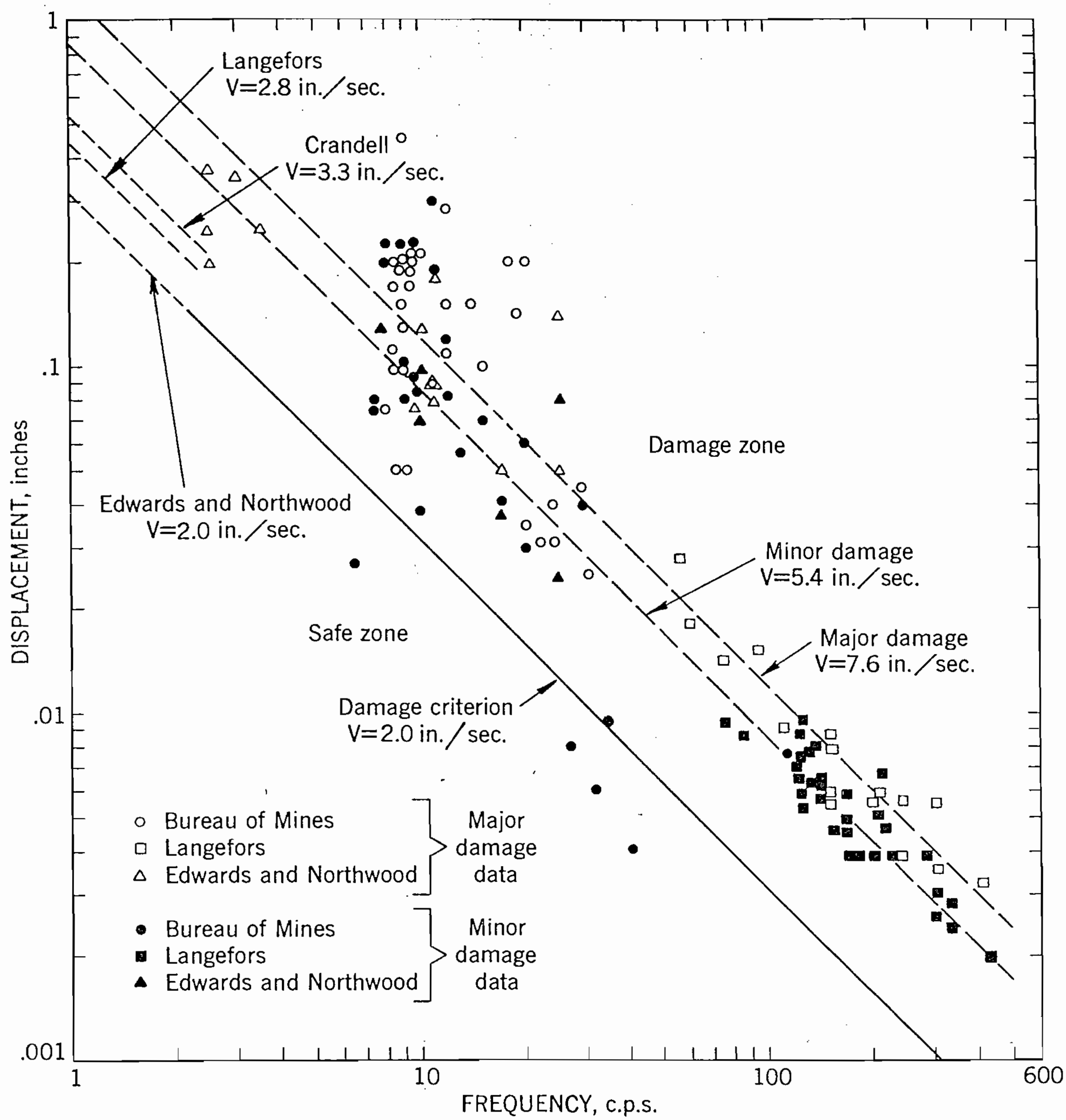

FIGURE 6. - Recommended Damage Criterion.

the spread in the data, whereas the other data were obtained on the ground near the structure. Therefore, if measurements are taken on the ground, a particle velocity of 2 inches per second appears to be a reasonable value for the separation between the safe zone and the damage zone.

The criterion of 2 inches per second may be compared with similar criteria suggested by the investigators cited in the introduction. Crandell's energy ratio of 3 corresponds to a velocity of 3.3 inches per second. Langefors proposed a velocity of 2.8 inches per second; Edwards and Northwood, a velocity of 2.0 inches per second. These criteria are shown as dashed lines in figure 6.

As the particle velocity is more closely associated with structural damage than either displacement or acceleration, and as the determination of peak particle velocity from records of displacement or acceleration versus time is often difficult, the suggestion is made that consideration should be given to the measurement of particle velocity versus time rather than displacement or acceleration.

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