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THE DEVELOPMENT OF RATIONAL DAMAGE CRITERIA FOR LOW-RISE STRUCTURES SUBJECTED TO BLASTING VIBRATIONS

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ABSTRACT

There is considerable evidence that more rational damage criteria need to be generated with regard to low-rise structures subjected to blasting vibrations. There is not sufficient basis for specifying a maximum ground particle velocity damage criterion, such as 2 inches/second, and such specifications have proven to be unacceptable in a number of recent cases. A peak ground velocity guideline does not currently take into account a number of significant parameters, including the predominant frequencies of the ground motion excitation and the structure being excited. Although a number of states have adopted, or are adopting, maximum particle velocity criteria, such criteria have been ruled inadequate in certain legal decisions affecting blasting operations. The development of more rational damage criteria is thus of significant importance.

More refined procedures have been utilized in determining the damage potential associated with the ground motions resulting from underground nuclear detonations, and efforts are continuing in that area. A recent applied research effort (Medearis, 1976) involved the structural response and damage predictions for nuclear gas stimulation Project Rio Blanco. One instrumented residential structure (Medearis, 1975) only 6 miles from the detonation sustained a maximum ground particle velocity of 3 inches/second with no damage. Of interest was the fact the maximum velocity recorded on the house roof was on the order of 9 inches/second, i.e., about three times as great. Such amplification is obviously of importance in assessing damage potential. It thus follows that structural damage criteria should include considerations of the response of structures, as well as the response of the ground.

The ground motions produced by nuclear explosions are somewhat different from those produced by commercial blasting, but the basic structural dynamics solution principles are the same. Very little analysis has been done with regard to determining the dynamic characteristics of blasting ground motions, however. A significant part of this research effort involved the determination of these characteristics for a sizeable number of actual blasting records using appropriate theoretical and computer analyses.

The dynamics of low-rise residential-type structures are also relatively unknown. Such structures are typically characterized as having fundamental frequencies in the rather broad range of 5-30 Hz. Such a range clearly needs to be narrowed for response predictions. Pertinent parameters such as the height of the structure, type of construction, etc. need to be considered. Modern micro-vibration techniques (Medearis, 1976) were utilized in the investigation of a reasonably large number of existing low-rise structures. The frequency and damping characteristics were then determined using the micro-vibration records.

The dynamic characteristics of blasting ground motions and low-rise structures were then utilized in conjunction with available, reliable data defining actual threshold damage to develop a rational damage criteria. These criteria are based on appropriate statistical models of the sizeable amount of data obtained during the course of the investigation. They thus have considerable basis, both experimental and theoretical. No previous research effort known to the authors has such a basis, thus the results should be of significant value in predicting, and preventing, damage due to blasting vibrations. Application of these criteria to specific cases is desirable to further refine the data base.

ANALYSIS--HOUSE DYNAMIC CHARACTERISTICS

A total of 63 residences were subjected to micro-vibration testing and analysis in order to assess their dynamic characteristics. The vibrations were induced by slamming doors or by bumping appropriate structural components, the resulting motions being recorded using sensitive seismic units. A number of readings were taken along the major axes of the house in each case, with the seismometer(s) placed on floors inside the house, or/and on the roof.

Measurements were taken on residences in four states so as to include a variety of construction types. Specifically, micro-vibrations were recorded on 40 houses in Colorado, 11 in Illinois, 7 in California, and 5 in New Mexico. The house ages ranged from less than one year to ninety-six years. Pertinent descriptive data were tabulated and each house categorized with respect to height, 27 being classed as 1-story, 8 as 1½-story, and 26 as 2-story. Two units were eliminated as being of untypical construction. The construction types included masonry bearing wall, wood frame, and wood frame with masonry or stucco veneer. All but two of the houses had crawl spaces, partial basements, or full basements.

In general, there were no observable tendencies of fundamental frequency to vary directly with age or location, although taller houses have lower frequencies and older houses often tend to be taller. Thus, for example, the house sample from Illinois was found to have a relatively low average frequency, but that is clearly due to the height of the houses tested rather than local construction techniques. There appeared to be no correlation of frequency with plan dimension, possibly because houses are usually partitioned into somewhat square rooms regardless of the exterior dimensions.

It was determined that fundamental frequencies were normally distributed about their means for the three divisions of houses by story height. A linear regression was performed relating frequency in Hz to height to the roof peak in feet, with the intercept, a, and the slope, b, being determined in the least-squares sense. The best fit line for all houses, as well as lines of plus or minus one standard deviation, are plotted in Figure 1. The structure frequencies ranged from 4-18 Hz.

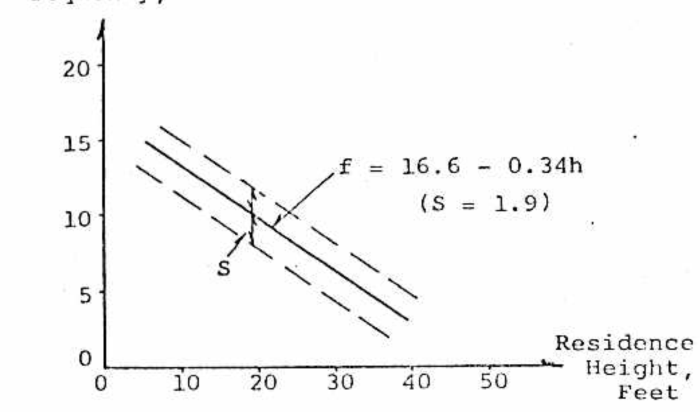

Figure 1. Frequency vs. Height-All Houses

Damping values for the houses showed no clear tendency to vary with location, age, dimension, or frequency. A lognormal distribution was found to give a satisfactory fit to the observed data. The median damping value was found to be 5.2%. House damping values, in general, would be greater for motions of a magnitude that might cause damage.

ANALYSIS--GROUND MOTION DYNAMIC CHARACTERISTICS

Vibra-Tech Engineers, Inc., of Hazleton, Pa., provided recordings of 74 commercial blasts occurring in the eastern United States over the period of 1974-1975. Of these blasts, 44 were associated with quarry operations, 11 with strip mining, 10 with pipeline or sewer work, 6 with general construction, and 3 with road construction. The detonations typically originated in firm rock and were monitored on soil near a residence or other structure.

Three orthogonal components of velocity - vertical, radial, and transverse - plus the sound of the blast were recorded on cassette tapes with Vibra-Tech Mark II four channel electronic recorders. The cassette tapes were played back on a Dallas Instruments TR-4A reproducer, and digital records of the velocity produced utilizing analog-to-digital equipment. The resulting digital records were of 4.8 seconds duration with 1000 points per second. Digital acceleration records were generated from the velocity records using the same time interval and a duration on the order of one second.

The peak amplitudes of velocity and acceleration were then curve fit to the form

$$\dot{x},\ddot{x} = a\,L^{b}\,W^{c} \qquad (1)$$

where $\dot{x}$, $\ddot{x}$ are the peak ground velocity in inches/second and the peak ground acceleration in g's, respectively, L is the distance from the detonation in feet, W is the maximum weight in pounds of explosive per delay, and a, b, and c are arbitrary constants determined by regression analysis in the log domain. The resulting expression predicts the median of a peak amplitude which is lognormally distributed at any given charge and distance. It was found that peak ground acceleration attenuates more rapidly with distance and is more widely dispersed than peak ground velocity. The predicted median and standard error of estimate velocities are plotted in Figure 2.

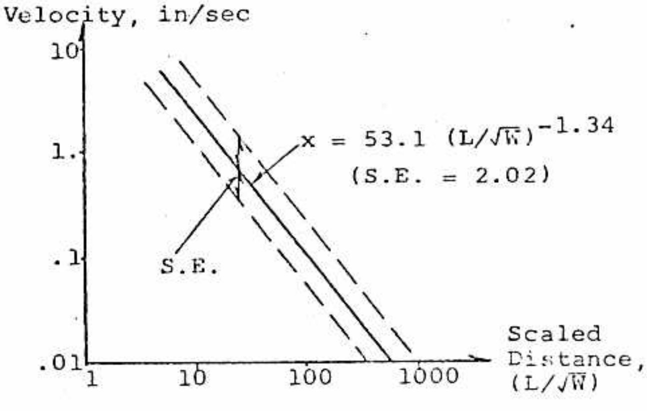

Figure 2. Peak Radial Ground Velocities

The next step in the blast recording analyses involved the development of response spectra for the records. A response spectrum may be defined as the curve represented by the locus of the maximum response values (displacement, velocity, or acceleration) of a single degree-of-freedom system, with or without damping, when subjected to a transient ground motion forcing function, as determined for various values of the system natural frequency. From the residential and other damping studies (Medearis, 1964 and 1966), it was concluded that 5% damped spectra are relevant for residential structures, and conservative at damage-inducing levels of ground motion. Pseudo spectral relative velocity (PSRV) was utilized in this research effort, rather than true spectral relative velocity (TSRV). Peak values of PSRV and TSRV are normally quite similar in magnitude, and PSRV are easily related to system spectral relative displacement and absolute acceleration. Specifically, the spectral relative displacement is obtained by dividing the pseudo relative velocity by the system circular frequency; the pseudo spectral absolute acceleration is obtained by multiplying the pseudo relative velocity by the system circular frequency. The mean and one standard deviation curves of the 5% damped pseudo relative velocity are plotted in Figure 3, along with the maximum spectral values. Peak response occurs at about 40 Hz, although response is fairly constant from 20 to 50 Hz.

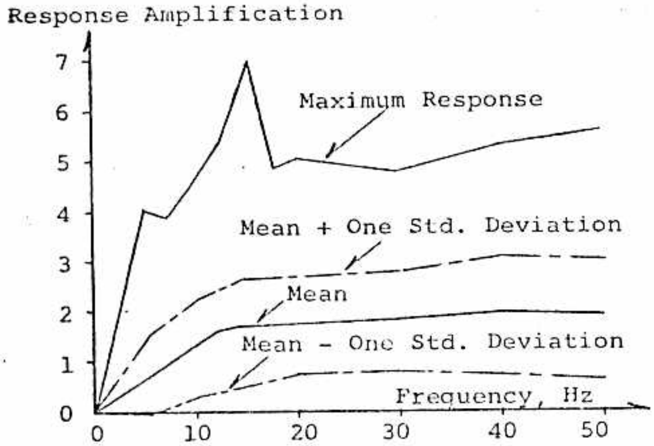

Figure 3. Blasting Operation PSRV-5% Damping

In order to evaluate the variation of the spectra with charge and distance, the 5% damped pseudo relative velocity response to radial ground motion was curve fit to the form of Eq. 1, where $\dot{x}$ is now the response at a specific frequency. PSRV values were evaluated for sample cases with a charge of 1000 lbs and distances of 50', 500', and 5000'. They were then normalized by dividing by the predicted median value of radial ground velocity, the results being given in Figure 4. These curves indicate there is considerable variation of response with distance for frequencies of 20 Hz or less, i.e., the frequency range common to residences, as previously discussed. This clearly indicates that neither peak ground velocity or peak ground acceleration are optimum predictors of damage to residences.

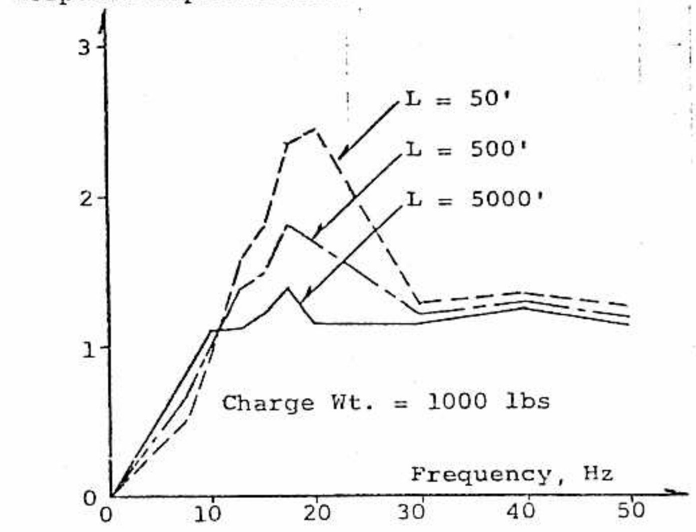

Figure 4. PSRV Variation With Distance

The residential structure results were then used to determine probable residence response. Histograms of 5% damped pseudo relative velocity response were obtained for each story height utilizing frequencies weighted according to the distributions for the different categories and summing the resulting responses. These responses were then normalized by dividing by the median peak radial ground velocity, a typical histogram being given in Figure 5. This histogram may be interpreted as the distribution of residential response to a unit peak ground velocity. It may be noted the distribution is approximately lognormal. All of the

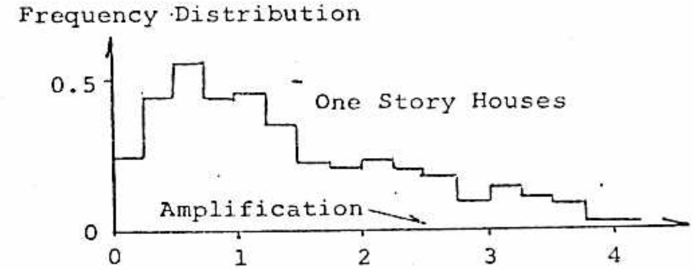

Figure 5. Normalized 5% Damped PSRV Histogram

previously noted concepts were then incorporated to obtain the predicted median response of the various house groups in the form of Eq. 1.

Several aspects of the response spectra generation should be noted. Good statistical convergence was attained using about 30 records although all records were utilized for certainty. No significant difference in amplification was found between results for components in the three orthogonal directions. It should be kept in mind the results presented are values for blasts in rock, the associated ground motions being recorded on soil. Soil tends to have natural frequencies similar to those of residencies, while the natural frequencies of rock tend to be higher, i.e., greater than 20 Hz. It should thus be expected that spectra for blast vibrations transmitted through rock would exhibit peaks at higher frequencies, and have small amplitudes in the residential frequency range than the spectra presented. It is probable the reverse might result if the detonation were, for some reason, in soil. It must be remembered the cited results are primarily applicable to vibrations in soil result- from detonations in rock.

THRESHOLD DAMAGE CORRELATION AND CRITERIA

Intuitively, structural damage due to blasting ground motions must be related to the response of the structure as a result of its unique vibratory characteristics. This concept is somewhat verified by tests wherein blasts close to a structure resulted in localized damage to components emphasizing high frequency response, such as basement walls, while blasts farther away caused damage to the superstructure. This may be at least partially explained by the increase in spectral response amplification with distance in the range of frequencies of most residences. This variation of response with distance in the range of residential frequencies, i.e., with increasing response below 10 Hz and decreasing response between 10 and 30 Hz, cannot be accounted for by any damage criteria based solely on peak ground motion. Consideration of these points indicated that correlation of predicted spectral response with threshold structural damage merited careful consideration.

Past studies, however, have tended to correlate peak ground motion parameters with damage thresholds. A review of these studies was thus carried out initially. The best sources of data were deemed to be Swedish (Langefors, Westerberg, and Kihlstrom, 1958) and Canadian (Edwards and Northwood, 1960, and Northwood, Crawford, and Edwards, 1963) studies. These data suffered from certain limitations, the primary one being a lack of thorough damage correlation for one-story residences. Analyses were performed to obtain a general idea of damage thresholds for low-rise structures. For the range of applicability of the tests, the probability of damage at particle velocities less than the commonly specified 2 inches/second was found to be on the order of 2%. It should be noted this probability value has significance only if peak particle velocity is statistically the most valid damage predictor. These results thus raised questions with regard to several studies that have indicated significant damage at peak particle velocities almost an order of magnitude less than 2 in/sec. However, analyses of these studies revealed, in general, either questionable damage assessment techniques, questionable or incorrect statistical analyses, or both. Virtually none had utilized pre-and post-shot observations of damage, relying primarily on damage claims or complaints, generalizations, etc. It is unfortunate that much of the nuclear detonation damage data is deemed to be somewhat unreliable because of the lack of scientific basis for establishing credible damage (Hammon and Hammon, 1968). Damage has frequently been acknowledged solely on the basis of post-shot investigations, a relatively unreliable procedure in most cases. Also, ground motions for all locations within an entire town or area have been based (in some cases, necessarily) on a single record. It is also known, from actual experience, that a number of claims have been settled on the basis of public relations, potential legal costs, etc. There is some rationale for such settlements, especially with small claims. Unfortunately, the claims have subsequently been cited as legitimate damage, resulting in invalid statistics. Only data from pre- and post-shot blasting damage observations were thus considered in the prediction effort. More data of this kind need to be taken.

No previous research effort has apparently correlated damage with the actual fundamental frequencies of residences. Also, past damage investigations have tended to give only minimal descriptions of the houses tested. It was possible to estimate the frequencies of seven tested houses (Edwards and Northwood, 1960, and Wiss, 1972), however, using their heights, number of stories, and the previously developed frequency-height relationships. Two orthogonal ground motion components, radial and vertical, had been measured for each of the tests. Eleven different tests were considered, and the results organized into several data sets for statistical analysis. In several cases, some judgment was necessary in estimating pertinent parameters at the threshold damage level, since the testing did not always closely define the point of incipient damage.

Predicted response and ground motion parameters were computed for each test using the previously developed relationships based on charge, distance, and residence estimated frequency. Statistical studies and comparisons were then made between various damage prediction alternatives. The statistical dispersion of damage prediction using predicted PSRV was found to be less, in terms of both standard error of estimate and coefficient of variation, than predicted PSAA, predicted and measured peak ground velocity, and predicted and measured peak ground acceleration. In particular, spectral absolute acceleration was found to be less precise, partially because of the effects of high frequency components. Statistical correlation of predicted spectral relative displacement was found to be good, but data for damage-inducing displacements are both sparse and variable. Pseudo spectral response velocity (PSRV) is thus deemed to be the best predictor of damage due to blasting vibrations.

Lognormal distributions were found to fit the PSRV data quite well. These models, developed using control band techniques, represent a basis for estimating the probability of threshold damage at a given predicted pseudo relative velocity response. For a predicted PSRV of 1.5 inches/second, the probabilities of damage for the data sets analyzed ranged from 0+ % to 1.0%. The log-normal distributions of predicted PSRV were previously developed for the various house groups. The distribution of damage, given predicted PSRV, was then statistically combined with the distribution of predicted PSRV for a given charge and distance limit to obtain probabilities of damage. The distribution most carefully investigated was that corresponding to a limit of charge and distance such that the one standard error of estimate response is equal to 1.5 inches/second, i.e., the probability of predicted PSRV less than 1.5 in/sec is 84.1%. By combining the two probabilistic distributions, the upper bound probability of damage was found to be about 3.8%. This value is deemed to be quite conservative since it reflects both the scatter in response for given blast parameters and the variation of damage with response. Further, that figure is considered to be a reasonable risk to assume for conventional blasting, and any associated damage should be very minor in nature. It should be noted that if the actual measured, or computed, PSRV values were 1.5 in/sec or less, the damage probability is estimated at no more than 1%. It is thus recommended that charge and distance be limited such that the standard error of estimate, single degree-of-freedom, pseudo relative velocity response is less than 1.5 inches/second.

Curves relating minimum required distance to charge per delay for the suggested 1.5 in/sec standard error PSRV limit are plotted in Figure 6 for the various house groups.

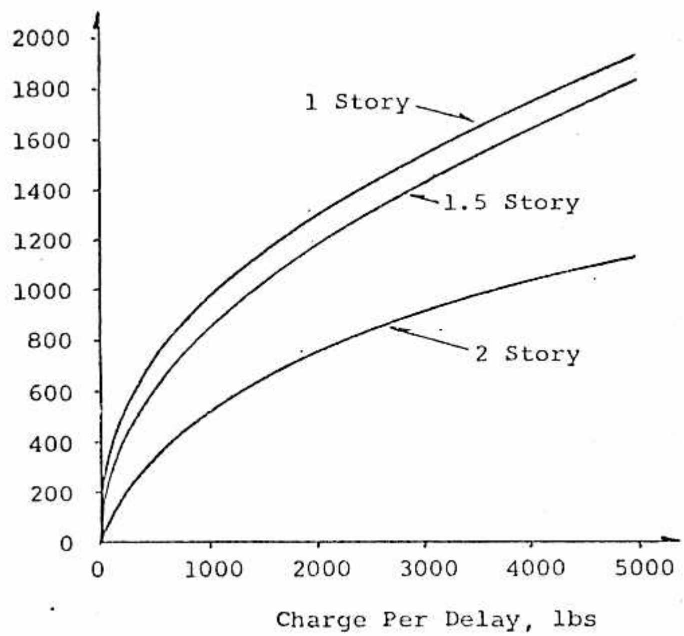

Figure 6. Distance vs. Charge, 1.5 in/sec PSRV

It is also possible to estimate the predicted one standard error of estimate peak ground velocities for the various limiting charges and distances using previously described relationships. Curves depicting these velocities for the various house groups vs. distance are given in Figure 7. It will be noted the recommended velocities are somewhat less than the commonly cited 2 in/sec for distances greater than about 500 ft., and the allowable values decrease with distance.

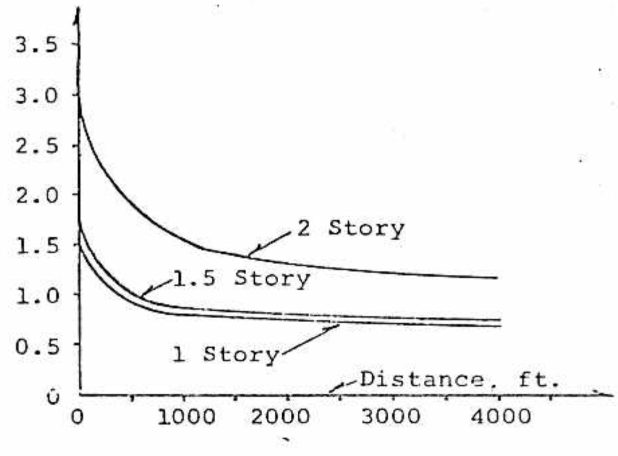

Figure 7. Limit Peak Velocity vs. Distance

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

There are a number of items that should be pointed out in regard to this damage criteria study. First, the primary objective has been to generate relevant information with regard to damage threshold criteria. It has not been concerned with the criteria for structural failure. A vast majority of complaints associated with blasting ground motions (conventional or nuclear) involve relatively minor items such as hairline cracks in masonry walls, stucco, gypsum wallboard, and plaster, occasional breakage of window glass, etc., and not failure, or even potential failure, of the primary structure. It follows the elastic range is of primary importance, and that inelastic action need not be considered.

Second, this study is only concerned with the effects of conventional blasting on residential structures. As such, it has concentrated on determining the characteristics of blasting ground motions and residential structures. Contrary to popular belief, very little response data are available for either. Of significance is the fact that results obtained for residential design and construction in quite different parts of the United States were found to be quite similar. There will be, of course, certain exceptions, but these should represent a distinct minority for a given situation.

Third, this study has not devoted major consideration to the possibility of fatigue damage to structures as a result of blasting vibrations. It is well known that component fatigue damage potential is related to the component loading level. Research test results obtained by a number of investigators (for example, Medearis, 1964 and 1966) for cyclic loading of typical, full-scale, residential structural components, including walls, indicate little probability of such damage occuring. Residential structural components are usually lightly loaded in relation to their capacities. For example, the walls tested in the cited studies all sustained more than 3 times their design loadings without failure. The increase in component stress levels due to blasting vibrations should be relatively nominal by comparison. Further, non-structural components, such as gypsum wallboard, should only incur dynamic stresses. As indicated, such stresses are typically well below component yield and ultimate strengths and, as such, should not precipitate damaging effects due to the cyclic blasting vibration loadings.

A rational basis for precluding damage has been derived, subject to the limits of available data. That basis incorporates the dynamic characteristics of residential structures and blasting ground motions. The associated criteria are somewhat more restrictive than current practice with regard to one-story residences, and somewhat less restrictive with respect to two-story residences. It is anticipated the results will be of significant value, but it should be noted that additional research in this area is desirable.

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