DAMAGE PRODUCED BY SMALL GROUND MOTIONS

By

Jack L. Alford*

INTRODUCTION

Motion of the ground results in vibration of structures. Such vibration is the same, in a qualitative sense, and is subject to the same physical laws, whether the source of the ground motion is natural (i.e., an earthquake) or man-made (i.e., from explosions, vehicular traffic, or the operation of heavy machinery). Quantitatively, the difference may be great since even the underground explosion of an atomic bomb involves an energy release into the ground which is equivalent to that of only a minor earthquake (1,2). Although the intensity of ground motion in the vicinity of man-made seismic disturbances is seldom great enough to cause loss of life or structural collapse, it may be sufficient to raise questions of property damage or nuisance. The frequency of such problems can be expected to increase in some proportion to the growth of urban population centers. It is of interest, therefore, to understand the effects of seismic disturbances in order that the possibilities of damage and nuisance can be balanced against the necessity for economical conduct of the disturbance-producing operations.

Most of the attention devoted to this problem has been concerned specifically with the effects of the use of commercial explosives. Few scientific investigations of the problem have been undertaken. Although many field observations have been made, these have seldom been comprehensive and the results are usually considered to be proprietary information. Nevertheless, impelled by economic pressure to use explosives at maximum effectiveness and limited by legal liability for the consequences of their actions, operating engineers have had to develop criteria for deciding what constitutes a "safe" seismic disturbance. The various criteria which have been developed may be classified in three groups, which are discussed in the following sections.

DIRECT CRITERION

The direct, or phenomenological, approach to the problem of blasting damage involves the correlation of blasting variables with reports of damage in neighboring structures for a number of blasts which is large enough to warrant generalization of the results. The important blasting variables are weight of explosive, distance from blast to neighboring structures, and geological conditions between the blast site and the structures. Damage reports, to be meaningful, should be based on careful inspections of the structures in question made before and after each blast by competent and unbiased observers. Several studies have been made which satisfy all or almost all of these requirements.

---

*Associate Professor of Engineering Harvey Mudd College, Claremont, California

Crandell (3) reports an investigation in which many structures were examined for evidence of damage caused by blasting operations. Although detailed data are not given for damage or for blasting conditions, the results lead to the threshold-of-damage relation shown in Figure 1. Each point on the line represents, for the given distance, a maximum charge of explosive above which damage is probable. The solid portion of the line indicates the range of blasting variables covered by the observations.

Damage to six buildings in a controlled series of blasting tests is documented by Edwards and Northwood (4). The threshold-of-damage line by means of which they describe their results is also shown in Figure 1.

For comparison, Figure 1 also includes points for two very large quarry blasts. In the first blast 373,000 pounds of explosive were fired approximately 1100 feet from a large mill building (5,6). In the second blast 1,347,000 pounds were fired approximately 1250 feet from the same mill building; complete information will be given in a forthcoming publication. The question of damage is difficult to assess since the mill building lacked the plaster which usually shows the first sign of minor damage. Even if it is assumed, however, that these two blasts represent conditions of incipient damage, it is apparent that many more data points are necessary to extend the existing damage criteria to such large charge weights.

By applying factors of safety to damage criteria, recommendations of maximum "safe" charge versus distance are derived. Figure 2 shows "safe" charge recommendations corresponding to the damage criteria of Figure 1. For comparison, Figure 2 also shows several other limit charge recommendations. Line 3 is the limit recommended by Langefors, Westerberg, and Kihlstrom (7); it is based on an extensive series of tests, all of which were fired in rock at distances of 100 feet or less. Line 2 is the limit proposed by Teichmann and Westwater (8) for clay soils; it is based on fewer instances of actual blasting damage than that of either Edwards and Northwood or Langefors et al. Line 5 represents the limit specified by the New Jersey Commissioner of Labor and Industry for blasting in "normal overburden." It is based on the field observations of the U. S. Bureau of Mines (9), in which only one instance of actual blasting damage was encountered.

Relations of the type shown in Figure 2 have the advantages of depending only on information which requires no instrumental observations, is known in advance of the blast, and is entirely within the control of the blaster. Such relations are widely used in practice because of their convenience. The lack of agreement among them is not surprising in view of the many detailed aspects of the blast and of the surrounding structures which are not taken into account. The limits recommended by Edwards and Northwood (for sand-clay and glacial till) and by Langefors et al (for rock) are not only the most conservative, but they have the most sound experimental basis. In the absence of local experience and where it is not feasible to make instrumental observations, they constitute the best available guide.

INDIRECT CRITERIA

Many attempts have been made to relate damage to some property of the ground motion produced by blasting. Such criteria depend upon measurements of the ground motion and are therefore not as convenient in practice as a simple weight-distance relation. They have the advantage that they do not depend upon the characteristics of the structures in the vicinity of the blasting, which may be too numerous for detailed consideration. Among the criteria which have been proposed are the maximum values of the displacement, the velocity, and the acceleration of the ground motion. Such criteria, like the direct criterion, depend for their validity upon the observations of actual blasting damage which support them.

It has been found (4, 8, 9) that the relation between damage and ground displacement or acceleration is dependent on the frequency of the ground motion, large displacements being tolerable at low frequencies and relatively large accelerations being tolerable at higher frequencies. This frequency dependence can be eliminated, to a good approximation, if comparisons are based on maximum ground velocity. Crandell's results (3), although expressed in terms of an "energy ratio," are equivalent to a critical ground velocity of 4.7 inches per second, above which damage is predicted. Edwards and Northwood (4) propose a critical velocity of 4.5 inches per second on the basis of their measurements. Damage was experienced above 110 millimeters per second (4.3 inches per second) in the work of Langefors et al (7). Such unanimity is remakable in view of the many uncertainties remaining in the problem.

Allowing a margin of safety, Edwards and Northwood recommend an operating limit on ground velocity of 2 inches per second. The New Jersey regulation requires that the allowable ground displacement be reduced with increasing frequency of ground vibration according to Table 1. It is interesting to note that this has the effect of limiting the maximum ground velocity (calculated on the assumption of simple harmonic motion) to 2 inches per second.

TABLE 1

FREQUENCY-AMPLITUDE RELATIONS

Frequency of ground motion, CPS	Maximum amplitude of ground motion, inches
Up to 10	Not more than 0.0305
20	0.0153
30	0.0102
40	0.0076
50	0.0061
60	0.0051

BUILDING RESPONSE CRITERION

The preceding sections indicate the extent to which investigators are agreed concerning the seismic effects of blasting operations. Despite recent contributions, however, a considerable degree of uncertainty remains and it is therefore necessary to use large factors of safety to control the risk of damage. Can this uncertainty be reduced, with a corresponding increase in the efficiency of blasting operations?

The accumulation of competent damage reports will lead, in time, to improvement of the existing criteria and many apparent conflicts will be resolved. Meanwhile, understanding of the damage problem could be increased by consideration of the relation between damage and the structural properties of buildings. Although it may be neither practicable nor desirable to control blasting by predicting the dynamic stresses in particular buildings, it is now feasible to analyze the response of typical structures to a wide variety of ground motions. This process of analysis, called the response spectrum technique, has been described by Hudson (10). By performing many such analyses and interpreting the results in a statistical manner, as has been done in the similar problem of earthquake damage (11,12), it will be possible to draw general conclusions concerning the structural effects of blasting. This knowledge, in turn, would permit more exact interpretation of blasting damage observations.

Consider, for example, the response spectrum shown in Figure 3; it represents the response of a series of idealized structures to the ground acceleration which was recorded in the basement of a large mill building at the Corona, California quarry blast of July 1952 (5). Using this spectrum and the fundamental vibration period of the building, calculated from structural plans, it was possible to predict the vibration of the building which was measured independently at the time of the blast (6). This example demonstrates that, if the ground acceleration caused by a blast is known, the response spectrum is a significant means for summarizing the structural effects of the blast. It also shows that the response spectrum is more directly useful than the recorded ground motion itself.

The importance of such information to the further evolution of damage criteria can be demonstrated by means of a hypothetical example. Suppose that two mill buildings of similar design and construction, instead of one, had been subjected to the ground motion of the 1952 Corona quarry blast. Suppose also that one of these buildings, like the actual structure, had a fundamental vibration period of 0.35 second and that the second building had a fundamental period of 0.25 second. Examination of Figure 3 shows that the vibration response of the second building (and hence the dynamic stresses) would have been from two to four times as great as that of the first building, depending upon the degree of structural damping appropriate to the design. Under these circumstances it is probable that one building would be damaged and that the other would not. It is clear that a damage criterion based on the performance of the longer-period building would be hazardous for the shorter-period building. Conversely, a damage criterion based on the performance of the shorter-period building might be unnecessarily conservative for buildings of longer period.

Similar conclusions result if one considers the behavior of two other hypothetical structures, both having a fundamental period of 0.25 second but differing markedly in their damping properties. An all-welded, steel structure might have a fraction of critical damping as low as 0.02; whereas a reinforced concrete building with hollow-tile filler walls would have approximately 0.15 of critical damping (13). Again it is clear that the differences in structural properties would significantly influence the interpretation of any resulting damage.

RECOMMENDATIONS FOR FURTHER INVESTIGATION

For the reasons outlined in the preceding paragraphs, it is desirable that future investigation of the blasting damage problem include the collection of information on the shape and magnitude of response spectra as related to weight of explosive charge, distance, and type of ground. To this end it will be necessary that measurements of ground acceleration be added to the instrumental observations now commonly made. Acceleration measurements might very well replace measurements of displacement and velocity since ground velocity can be determined by integration of the acceleration record and since displacement is not required in order to determine structural effects.

The usefulness of such information will be increased if the work of various investigators has some common basis. For this purpose the following recommendations are offered.

(a) Blasting data. Complete information is needed on number of holes fired, type and quantity of explosive per hole, and whether breakage is free or confined. If delays are used, it should be possible to determine the actual charge fire at each instant.

(b) Distance and type of ground. Distance from blast point to measurement point should be measured, and presented by means of a map showing the relation between blast and neighboring structures. Description of soil conditions should be given in standard geological terms and supported by geological data.

(c) Damage observations. Nearby structures should be inspected in detail before and after the blast, by persons qualified in structural mechanics. Existing damage should be marked and recorded, by photographic means if possible, for objective comparison with the results of post-blast inspection. A general description of each structure should be given, together with any available information on the dynamic properties of the structures.

(d) Instrumentation. Complete acceleration-time histories of three components of ground motion should be recorded: one vertical and two horizontal at right angles to each other. When measuring on free ground, one horizontal component should be oriented toward the blast. When measuring at the base of a structure, the horizontal components should be aligned with the principal axes of the structure. Care should be taken that the accelerometers are tightly coupled to the ground or foundation in order that true ground acceleration be sensed. The accelerometers and the recording system should be free from dynamic errors in the range from zero to 100 cycles per second. Instrument characteristics and calibration data should be included in the results.

REFERENCES

1. "The Effects of Atomic Weapons," U.S. Government Printing Office, Washington, D.C., 1950

2. Carder, D.S., and W.K. Cloud. "Surface Motion from Large Underground Explosions," Journal of Geophysical Research, vol. 64, no. 10, p. 1471, October 1959.

3. Crandell, F.J. "Ground Vibration Due to Blasting and Its Effect upon Structures," Journal of Boston Society of Civil Engineers, vol. 36, p. 222, April 1949.

4. Edwards, A.T., and T.D. Northwood. "Experimental Blasting Strudies on Structures," The Engineering Journal (Canada), to be published.

5. Hudson, D.E., J.L. Alford, and G.W. Housner. "Measured Response of a Structure to an Explosive-Generated Ground Shock," Bulletin of the Seismological Society of America, vol. 44, no. 3, p. 513, July 1954.

6. Hudson, D.E., and G.W. Housner. "Structural Vibrations Produced by Ground Motion," Transactions American Society of Civil Engineers, vol. 122, p. 705, 1957.

7. Langefors, U., H. Westerberg, and B. Kihlstrom. "Ground Vibrations in Blasting," Water Power, p. 335, September 1958; p. 390, October 1958; p. 421, November 1958.

8. Teichmann, G.A. and R. Westwater. "Blasting and Associated Vibrations," Engineering, vol. 183, no. 4, p. 460, April 1957.

9. Thoenen, J.R. and S.L. Windes. "Seismic Effects of Quarry Blasting," U.S. Bureau of Mines Bulletin 442, Washington, D.C., 1942.

10. Hudson, D.E. "Response Spectrum Techniques in Engineering Seismology," Proceedings First World Conference on Earthquake Engineering, Berkeley, 1956.

11. Housner, G.W., R.R. Martel and J.L. Alford. "Spectrum Analysis of Strong-Motion Earthquakes," Bulletin of the Seismological Society of America, vol. 43, no. 2, p. 97, April 1953.

12. Housner, G.W. "Spectrum Intensities of Strong Motion Earthquakes," Proceedings Symposium on Earthquake and Blast Effects on Structures, Los Angeles, 1952.

13. Alford, J.L. and G.W. Housner. "A Dynamic Test of a Four-Story Reinforced Concrete Building," Bulletin of the Seismological Society of America, vol. 43, no. 1, p. 7, January 1953.

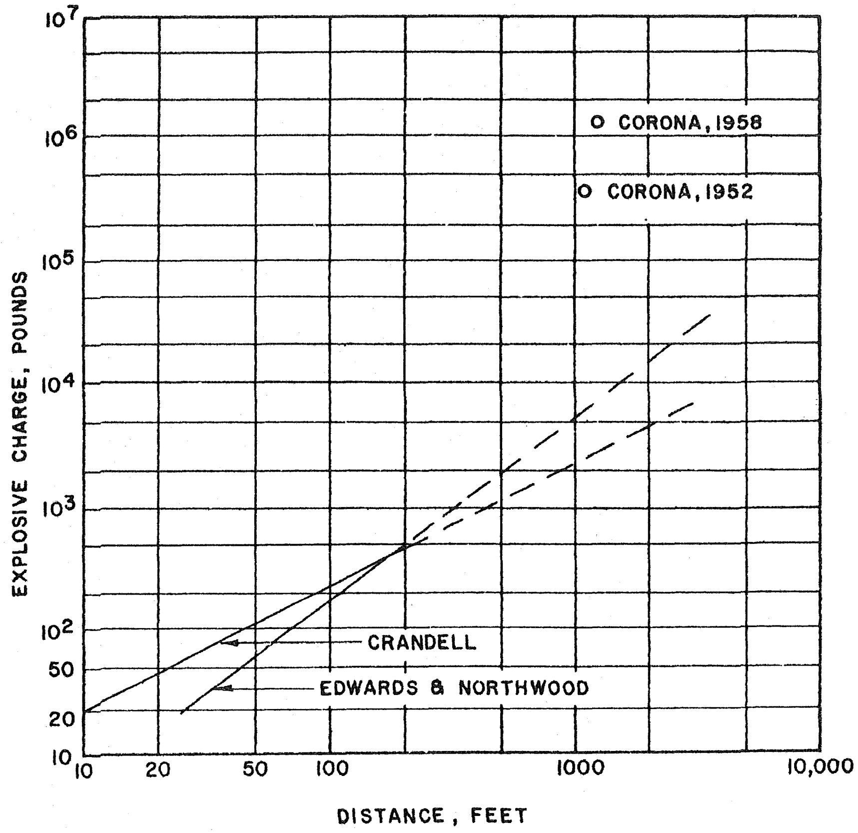

Figure 1. Comparison of predicted damage lines with data from two large quarry blasts.

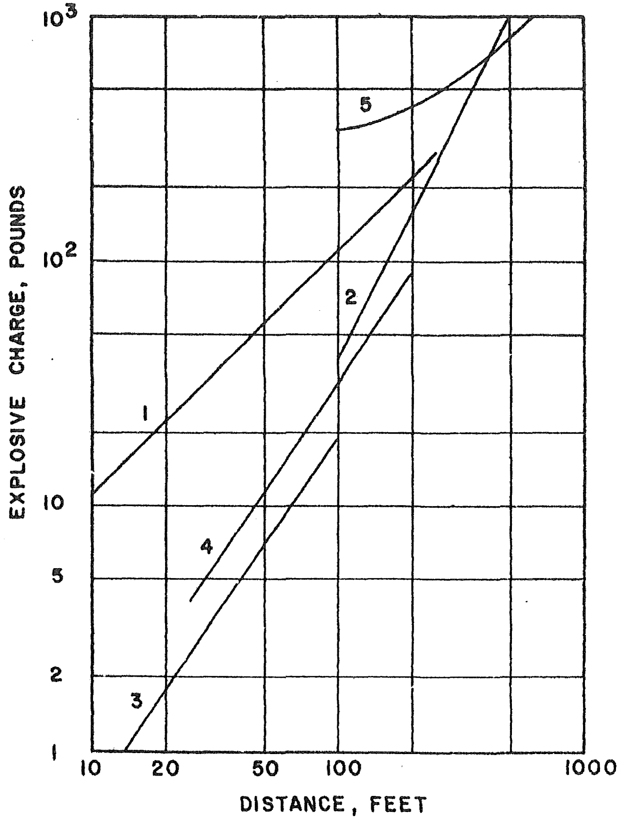

Figure 2. Comparison of limiting charge versus distance relations recommended by: 1) Crandell; 2) Teichmann & Westwater (clay); 3) Langefors et al. (rock); 4) Edwards & Northwood; 5) New Jersey regulation.

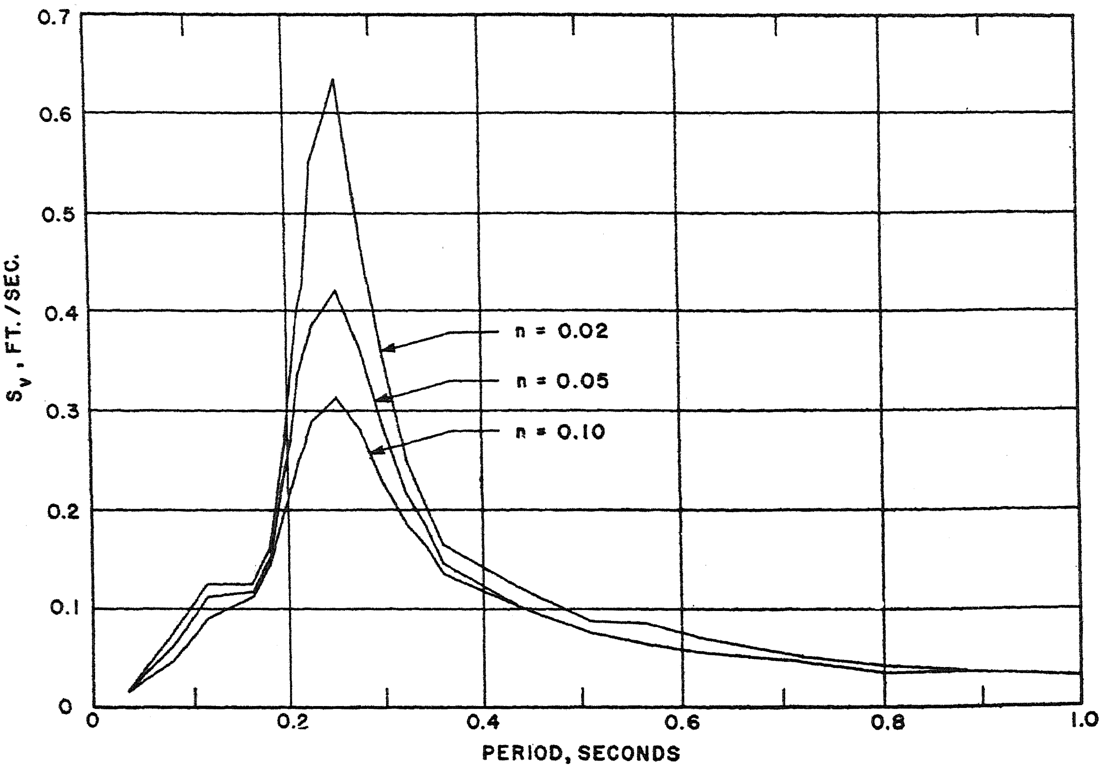

Figure 3. Velocity response spectrum for horizontal component, N31W, Corona, California, 26 July 1952. Charge weight: 373,000 pounds. Distance: 1100 feet.

DISCUSSION

F. W. Evans, British General Electric Co. of Japan Ltd., Japan:

I was very interested to see that Prof. Alford makes reference to the work of Teichman and Westwater and that he shows their curve for the limiting explosure charge and distance.

On a large unclear power station site in Scotland I had occasion to make use of the figures and formulae they give in their paper.

We had to satisfy the Atomic Energy Authority that reacter foundations under construction would not be subjected to vibration amplitudes above a certain value, by adjacent blasting for other works. By using their formula, the factors (to determine the probable amplitude of vibration) are:-

The weight of explosure charge
The distance
And a constant which depends on the ground nature (in this case rock).

We were able to lay down limiting weights of explosure charge to be used at various distances from the structures to be safeguarded.

Smaller charges than those permitted were first fired and the amplitudes of vibration they produced were checked with a vibragraph. The results agreed quite closely with those derived from the formula.

J. L. Alford:

I thanked Mr. Evans for his comment and asked if it were possible to obtain the data for the blasts to which he referred.