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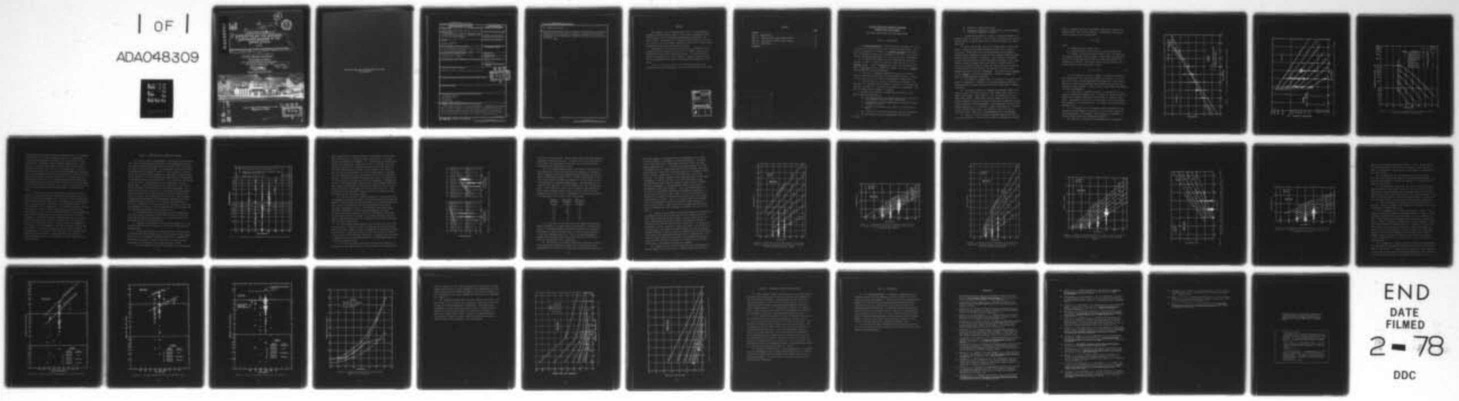

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# STATE-OF-THE-ART FOR ASSESSING EARTHQUAKE HAZARDS IN THE UNITED STATES.

## Report 7.

## SPECIFYING PEAK MOTIONS FOR DESIGN EARTHQUAKES

by

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The large dispersion of data for components of earthquake motion requires that the spread be appraised in design applications. Instrumental data also must be related to historic records of intensity. The near field and the far field contribute greatly to differences in peak motions. Site conditions, soil versus rock, affect duration. With these considerations, and with geological studies and the probability of recurrence, peak values can be

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specified from parameters of motions related to Modified Mercalli intensities. These peak values can be used for rescaling selected strong motion records or alternatively for the generation of synthetic seismograms. The procedure incorporates the wide variability in ground motions that have occurred during earthquakes.

# PREFACE

This report is part of ongoing work at the U. S. Army Engineer Waterways Experiment Station (WES) in Civil Works Investigation Study, "Methodologies for Selecting Design Earthquakes," sponsored by the Office, Chief of Engineers (OCE). General direction was by Mr. James P. Sale, Chief, Soils and Pavements Laboratory, and Mr. Don C. Banks, Chief, Engineering Geology and Rock Mechanics Division.

Preparation of the report was by Dr. Ellis L. Krinitzsky, Chief, Engineering Geology Research Facility, and Mr. Frank K. Chang of the Earthquake Engineering and Vibrations Division. The authors wish to express their appreciation to Mr. Stanley J. Johnson (retired) of WES for his encouragement and helpful advice during the preparation of this paper.

COL J. L. Cannon, CE, and Mr. F. R. Brown were Director and Technical Director, respectively, of WES during the period of this study.

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# STATE-OF-THE-ART FOR ASSESSING EARTHQUAKE HAZARDS IN THE UNITED STATES

## SPECIFYING PEAK MOTIONS FOR DESIGN EARTHQUAKES

## PART I: INTRODUCTION

1. A design earthquake is the ground motion estimated for the site of a structure and used as input for a dynamic response analysis. The motion is assigned on the basis of the maximum earthquake (the largest that is reasonably expected) and attenuated to the site. Given several sources for maximum earthquakes, there are several design earthquakes.

2. An important assumption is that earthquakes are produced by movement on faults. Faults are ubiquitous, hence movement will be on existing faults. A fault is active, when subject to present-day movement, or inactive, when not subject to movement. The fault is capable when movement will produce earthquakes.

3. The size of a maximum earthquake and the area in which it occurs is determined by geological and seismological studies. Attenuation from source to site is based on seismological interpretation.

4. The first step is a careful geological investigation. Its objective is to identify recent movement on faults, or to establish that none have occurred, and to interpret the prospect for earthquakes. All tools are used, from air imagery to trenches.

5. Widely used criteria for capable faults are those of the Nuclear Regulatory Commission:[1]

a. One datable movement in the past 35,000 years, and recurring movements during the past 500,000 years.

b. Instrumentally recorded macroseismic activity positively related to a fault.

c. Structural interrelation of a fault to a proven active fault.

d. Projection of an active fault under obscuring overburden.

6. The International Atomic Energy Agency[2] adds two other criteria:

a. Evidence of creep along a fault.

b. Topographic evidence of surface rupture, surface warping, or offset of geomorphic features.

7. In engineering practice, a fault is considered capable if it displaces surficial gravels, or cuts the base of alluvium or the base of glacial veneer, in regions where there are both earthquakes and competent rocks.

8. These criteria may fail in cases where there are fault movements in thick, unconsolidated sediments, such as occur in the U. S. Gulf Coast. Rather than faults, the displacements may be gigantic gravity slides, completely contained in soft sediments though the movements are many kilometres in dimension. Such movements are produced also by fluid extraction in partly consolidated sediments. Also, salt domes may produce growing, near-surface faults. Unless faults are rooted in competent crystalline rocks, the faults may move and fulfill the definitions for active faults, but they will not build up the stresses necessary to produce earthquakes. Thus, faults may be active, yet not capable of generating earthquakes. Geological judgment is needed in assessing these situations.

9. The length of a capable fault is a guide to the largest earthquake it can generate. Estimates of earthquake magnitude from fault length have been provided by Bonilla,[3] Bonilla and Buchanan,[4] Slemmons,[5] and others.

10. The greatest problem in judging the earthquake potential of faults in most of the United States is that capable faults may not be seen at the surface. Thus, they have to be interpreted by indirect means (Krinitzsky[6]). Magnetometer surveys, seismic profiles, stratigraphic analyses, patterns of subsurface structural deformation, seismic history, patterns of microearthquakes, focal mechanisms calculated from small earthquakes, etc., contribute to these interpretations. Activity can be specified within zones. The lengths of these zones can be related to fault length, then to maximum magnitudes of earthquakes.

11. There is a need to express earthquake magnitude in terms of epicentral intensity. The association permits instrumentally recorded

data to be applied over those considerable areas where there is only historic data in the form of intensity. Gutenberg and Richter[7] provided an equation that is widely used:

$$M = 1 + \frac{2}{3} I_o \qquad (1)$$

where

M = magnitude in the Richter scale

$I_o$ = Modified Mercalli (MM) intensity in the epicentral area

12. Figure 1 shows the Gutenberg Richter curve. Included are the currently available data for western United States from California Institute of Technology (CIT),[8] McEvilly, Bakun, and Casaday,[9] and Coffman and von Hake.[10] The present authors have interpreted a new equation based on the larger amount of data:

$$M = 2.1 + \frac{1}{2} I_o \qquad (2)$$

13. The spread of the data in Figure 1 reflects the subjectiveness, imprecision, and inherent variability of intensity. It is not practical to infer precise magnitudes from intensities. Mean curves, such as are shown, give magnitudes significantly less than have been observed at many locations. However, general relationships are possible for shallow earthquakes.

14. The effect of epicentral distance on the diminution of intensity is examined in Figures 2 and 3. Figure 2 is based on data from western United States, and Figure 3 from central and eastern United States. Attenuation in the West is on the order of four times greater than elsewhere in the United States. The division is along the Rocky Mountain front.

15. In Figures 2 and 3, the distance from an epicenter to the threshold of minor damage, at intensity V, can be crudely judged for various magnitudes of earthquakes. Other curves for attenuation of intensity with distance were published by Brazee.[11]

16. The rate of recurrence of earthquakes can be estimated. A

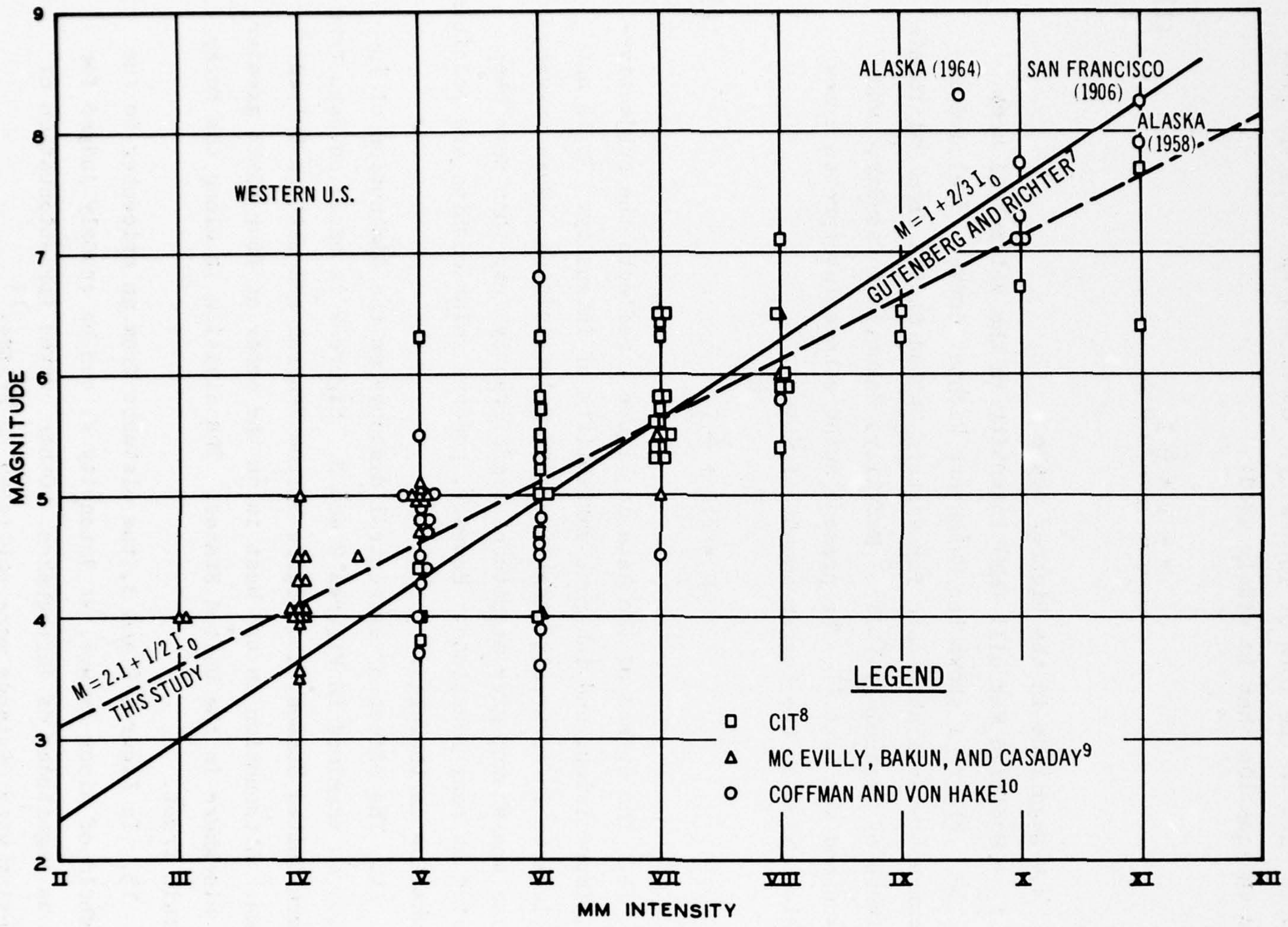


Figure 1. Relation between earthquake magnitude and intensity

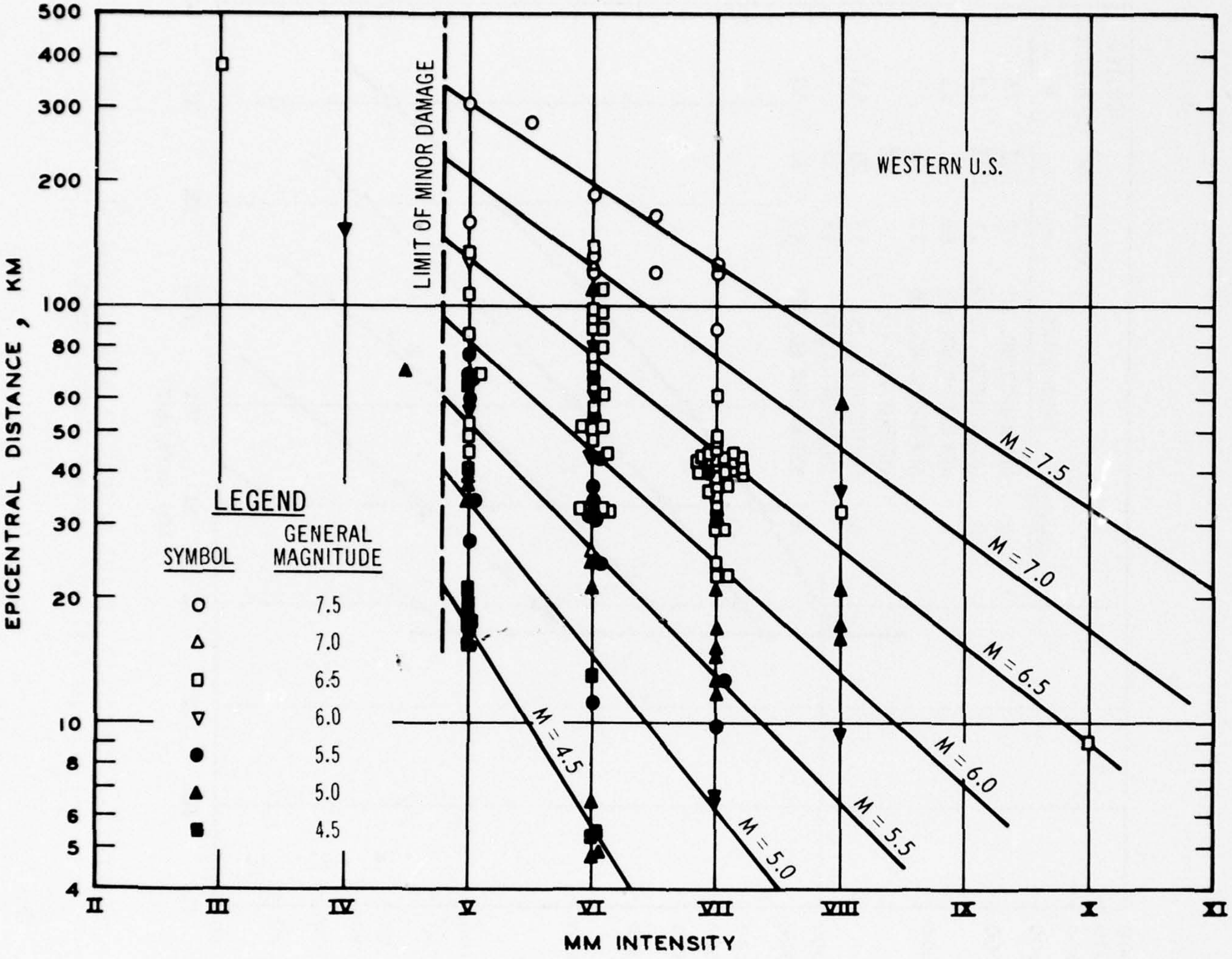


Figure 2. Intensity versus magnitude and epicentral distance, western United States

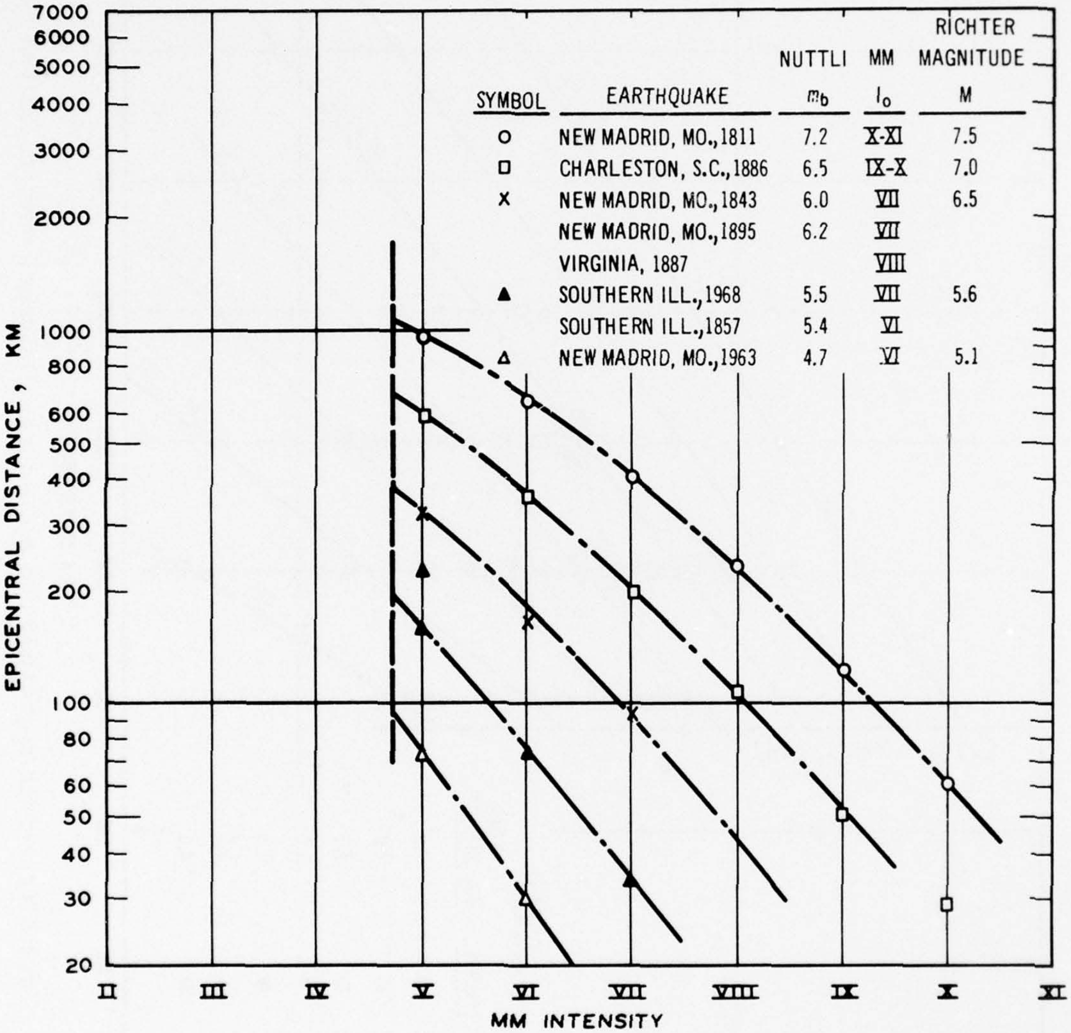


Figure 3. Intensity versus magnitude and epicentral distance, central and eastern United States

seismological method, which involves a linear projection of the numbers of events per year of various maximum intensities of earthquakes, is illustrated by Algermissen[12] and Brazee[11] for various zones of the United States. Algermissen shows a maximum magnitude event of MM intensity XI in the New Madrid area of central United States with an interpreted recurrence rate of once in a thousand years. Cornell[13] and others have been involved in estimating the probability of specific levels of earthquakes for any given location within a zone and for peak motions such as acceleration with attenuations to any specified site. Algermissen and Perkins,[14] as an example, have used these approaches to map acceleration values over the United States with a 90 percent probability of not being exceeded in 50 years. Their acceleration values are those of Schnabel and Seed[15] with modifications for eastern United States.

17. The major, once-in-a-thousand-years earthquake in the New Madrid area, when located by a probabilistic method, will not be site specific and may occur anywhere within the area. When the probabilities consider both the random distribution of earthquakes plus their attenuations to any given site, a much lower rate of recurrence may be indicated, possibly once in 10,000 years. All probability analyses for such long periods of time are strained because they are projected from a short historic record, in this case only 165 years. General probability maps can be deficient because of the lack or uneveness of geologic information. Nonetheless, probability analyses can serve a very valuable function if they are related to economic risk. The dependence should be on the intended life of a structure and the consequences of its failure. If the consequences of failure are severe, as with a dam in an urban area, one should design for the worst event regardless of its probability of recurrence. Where failure has only economic consequences and an owner wishes to accept some risk in the interest of reduced construction cost, it is appropriate to accept some less conservative design.

## PART II: SPECIFICATION OF PEAK GROUND MOTIONS

18. Figure 4 shows a correspondence of MM intensity with acceleration. The data from western United States were supplemented by worldwide data from Ambraseys,[16] see Johnson and Heller,[17] that fall outside the limits of United States data. The supplemental data are mostly for low intensities, particularly III and IV. Also included is a notable record for the Stone Canyon earthquake of 4 September 1972 during which an acceleration of 0.7 g was recorded at Melendy Ranch for the magnitude 4.7 earthquake (Morrill and Matthiesen[18]). The acceleration was revised to 0.61 g at CIT. The location was in close proximity to the San Andreas fault. The record confirms opinions that, near a fault trace, high accelerations can be generated by very small earthquakes. The velocity was 24 cm/sec, a value that is associated with major damage, though this was not the case here because the motion lasted only one fifth of a second. The displacement was only 0.3 cm. Other evidence of high-ground accelerations from low-magnitude earthquakes has been reported recently by Leivas et al.[19] They note an acceleration of 0.56 g for a magnitude 3.4 event near Oroville, California. The severest earthquake in Figure 4 is the San Fernando event of 9 February 1971 with the highest acceleration ever recorded, 1.25 g.

19. The Melendy Ranch record illustrates the unsuitability of using either peak acceleration or peak velocity alone as a basis for evaluating the effects of earthquakes or as a controlling basis for generating motions for dynamic analyses.

20. Equally, the dispersion of data noted in Figure 4 is so considerable that mean values or averages of the data are unsuitable for design purposes.

21. Curves based on mean or average values for intensity versus acceleration have been prepared by more than 40 people. The principal curves are those of Neumann,[20] Gutenberg and Richter,[7] Hershberger,[21] and Medvedev, Sponheuer, and Kárnik (Barosh[22]). All have the same shortcoming of not providing for the huge dispersion of data.

22. Coulter, Waldron, and Devine[23] published a set of boundaries

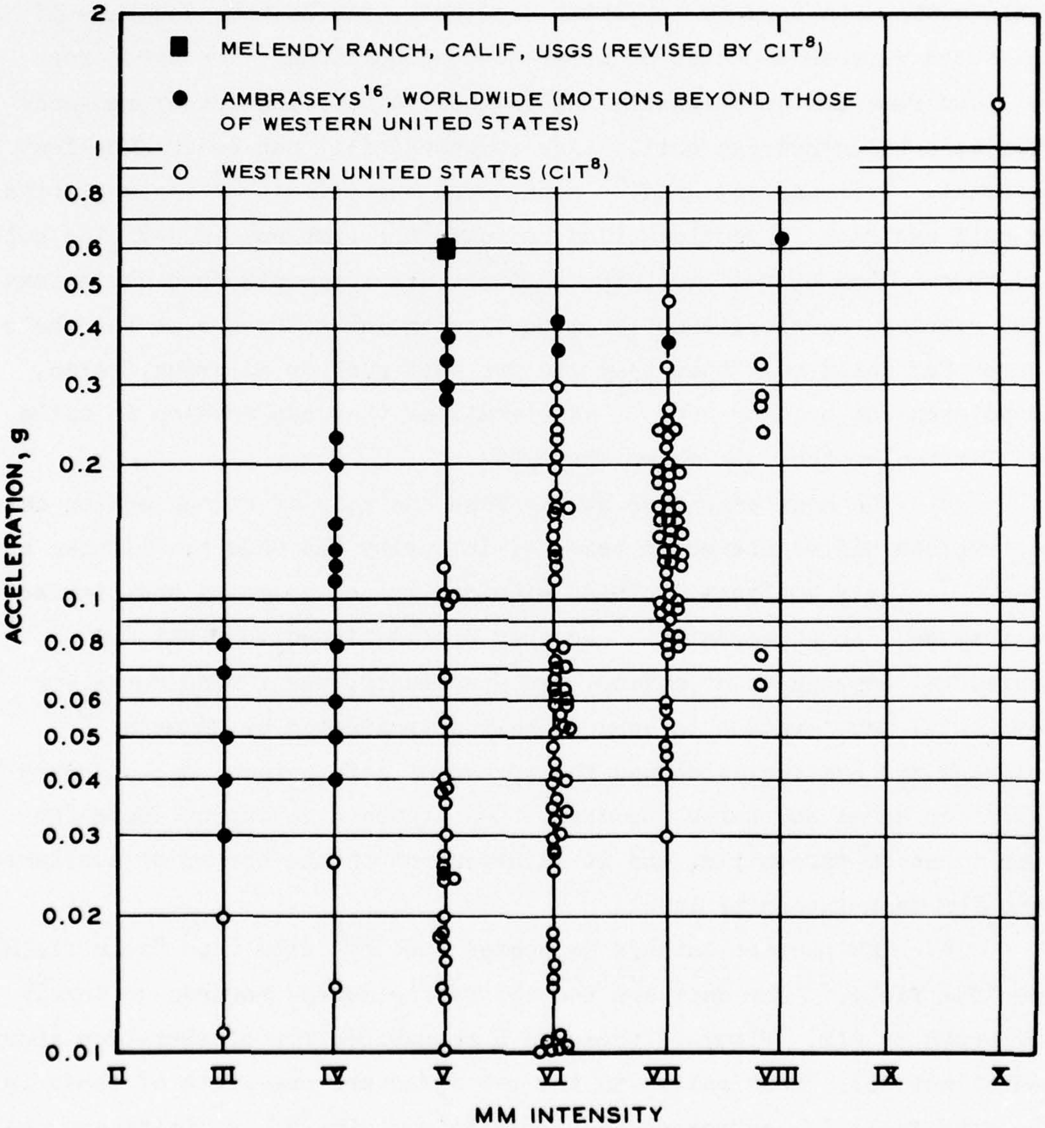


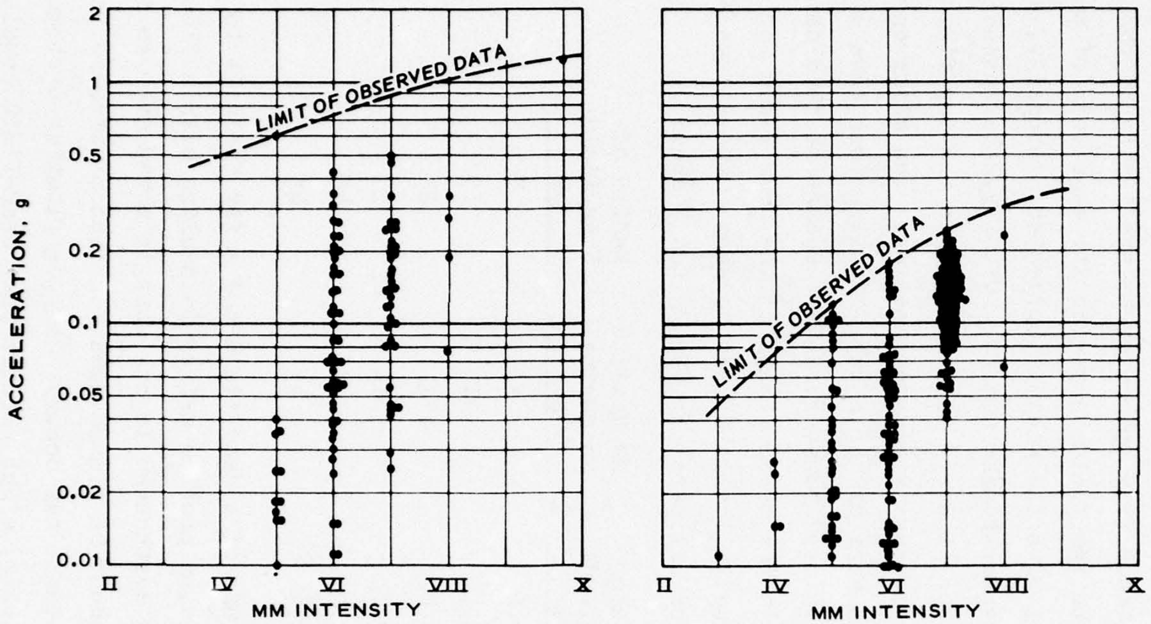
Figure 4. Correspondence of worldwide MM intensity and acceleration

which assume that for a given intensity the acceleration will increase from (a) bedrock to (b) average foundation conditions to (c) below-average soil material and man-made fill. They exclude all high accelerations at low intensities. They give no method of analysis and do not include the data used to establish the zones, nor do they indicate if the zones represent median or upper bound conditions. The zones for soil and rock are questionable, as is their classification of man-made fill as a below-average soil, since compacted fill can be an excellent material. Trifunac and Brady[24] considered the effects of variabilities in soil and rock on accelerations and also the problems in defining soil and rock. They showed that, though there are large standard deviations that overlap, accelerations for a particular intensity are on the whole larger for solid rock than they are for soft rock or alluvium. Also, as pointed out by Ambraseys,[16] accelerations that can develop in soils are limited by the soil shear strength.

23. The most extensive statistical analysis of strong motion data for western United States in terms of intensity was made by Trifunac and Brady.[24] Their analyses included examinations of velocity and displacement as well as acceleration, and they distinguished vertical and horizontal components of motion. Interestingly, their mean curve for horizontal acceleration is very closely approximated by Neumann.[20] Trifunac and Brady also showed the spread of data between one standard deviation above and below the mean. One standard deviation above the mean is an 86 percentile, and it is dependent on the spread of available data for each intensity level.

24. The present authors separated the CIT[8] data into "near field" and "far field." The data are the 187 strong motion records uniformly processed by CIT. Figure 5 presents a comparison for acceleration (horizontal motion). Peak values in the far field are one-fifth of those in the near field for corresponding intensities. The upper limits are those of observed data, projected where there are no corresponding values for a particular intensity level.

25. In the near field, complicated reflection and refraction of waves occur in the subsurface with resonant effects and a large range in



a. NEAR FIELD

b. FAR FIELD

Figure 5. Intensity versus acceleration in the near and far fields

the scale of ground motions. Intense ground motions and high-frequency components of motion are present. In the far field, the wave patterns are orderly; the oscillations in wave forms are more muted and more predictable; and frequencies are lower.

26. The distance from epicenter to the limits of the near field and beginning of the far field vary with the magnitude of the earthquake, consequently with the maximum epicentral intensity, and with the region in which the earthquake occurs. Usually, the intensity in the near field attenuates linearly and rapidly; in the far field, the rate of attenuation for intensity becomes smaller. The differences in attenuations west and east of the Rocky Mountain front have already been noted. Field conditions, however, do not change at this demarcation. The following tabulation shows limits of the near field for various magnitude and intensity levels of earthquakes. The values are believed to be applicable for all parts of the United States.

| Richter Magnitude m | MM Maximum Intensity $I_o$ | Radius of Near Field km |
|---|---|---|
| 5.0 | VI | 5 |
| 5.5 | VII | 15 |
| 6.0 | VIII | 25 |
| 6.5 | IX | 35 |
| 7.0 | X | 40 |
| 7.5 | XI | 45 |

27. If the use of a near field and a far field is to be recommended for analysis, a problem arises in dealing with a floating earthquake. A floating earthquake is one that is moved over an inclusive area because it cannot be pinned down for lack of precise information on where the earthquake may occur. Thus, a floating earthquake, if handled conservatively, might require that near-field conditions be extended unrealistically over a large area.

28. The problem in the western United States may not be serious. Recent geologic and seismologic studies and opinions conclude that earthquakes can be related to existing faults and that the formation of

new faults capable of causing destructive earthquakes is not a possibility that should be considered in design (Krinitzsky[6]). Uncertainties in the association of earthquakes with faults affect only small events, magnitudes 4 or 5. Long faults, which are necessary for large earthquakes, would not remain undetected if careful geologic investigations were made. While this is generally the case in the western United States, there are uncertainties in the concept east of the Rocky Mountains. For example, causative faults responsible for the New Madrid earthquakes of 1811 and 1812 have not yet been identified, though microearthquake studies using the regional seismic array in southeast Missouri are beginning to reveal possible trends of active faults (cf Herrmann, Fisher, and Zollweg[25]). Thus, this shortcoming may be the result of insufficient geologic and seismologic investigations rather than a limitation in the concept. If this is accepted, the importance of critically considering the extent and quality of geologic investigations is evident. Thus, it is possible that careful geologic studies can eliminate the need for floating earthquakes except for events that are small. Small events have such small near-field areas that the likelihood of their occurring at a specific site is of a low order.

29. Figures 6 and 7 present the relation between MM intensity and acceleration in the near field and the far field, respectively; Figures 8 and 9, intensity versus velocity in the near field and the far field, respectively; and Figures 10 and 11, displacement versus MM intensity in the near and the far field, respectively. The motions are horizontal. Vertical components of motion are taken to be two-thirds of the horizontal. The spread of data was divided into equal ten percent increments between 50 percent, taken at the median line, and 100 percent, taken along a line that approximates the limit of observed data. The curves for these increments are suitable for obtaining peak motions at levels selected either at the maximum or at lesser levels determined by decisions on the seismic risk that is acceptable.

30. Figures 6-11 also show the mean-plus-one standard deviation for the respective intensity levels. Figure 6 shows that mean plus $\sigma$

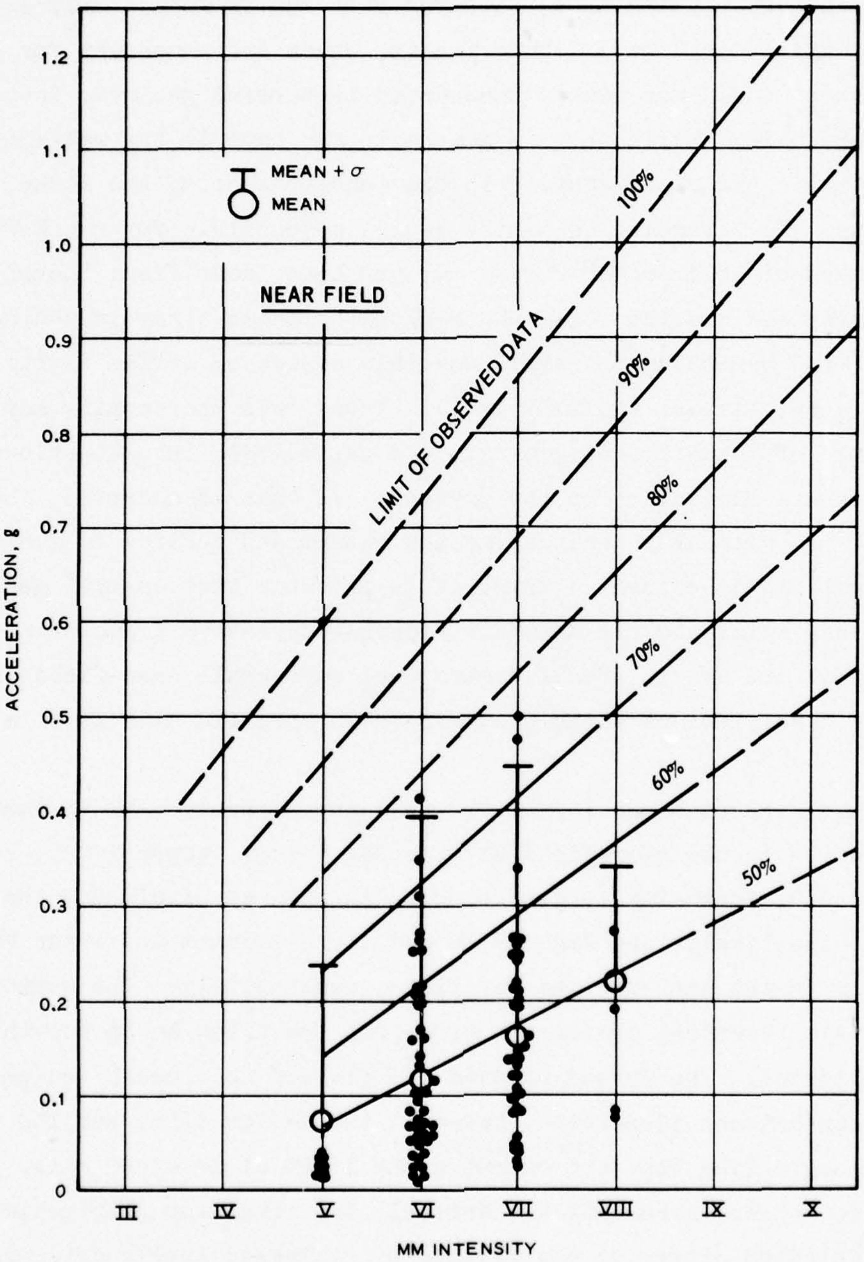


Figure 6. Acceleration versus MM intensity in the near field (10 percent increments between the mean (50%) and the limit of observed data (100%)

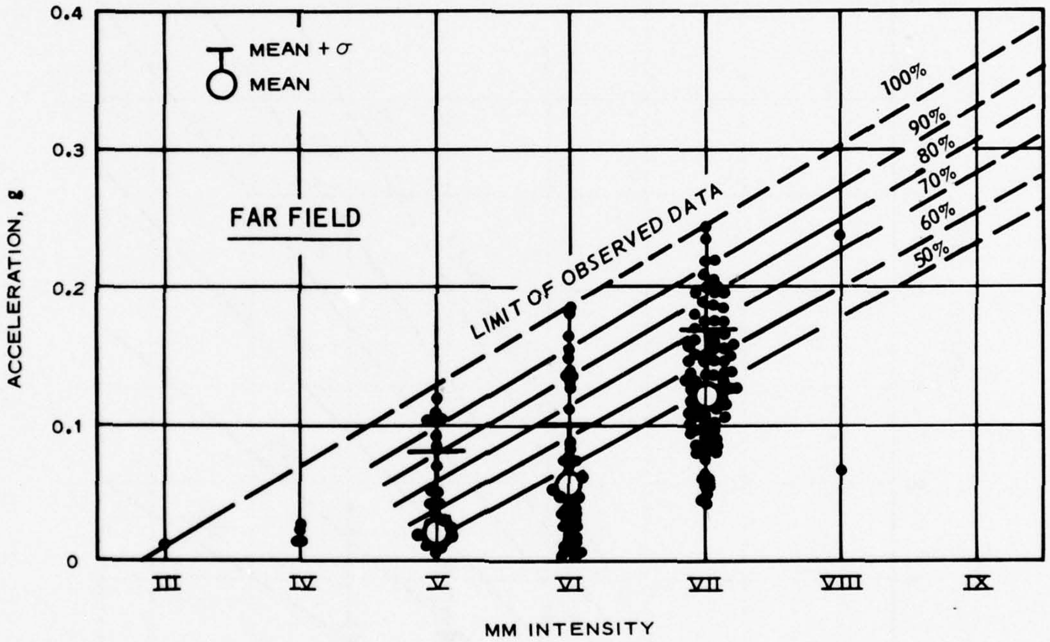


Figure 7. Acceleration versus MM intensity in the far field (10 percent increments between the mean (50%) and the limit of observed data (100%))

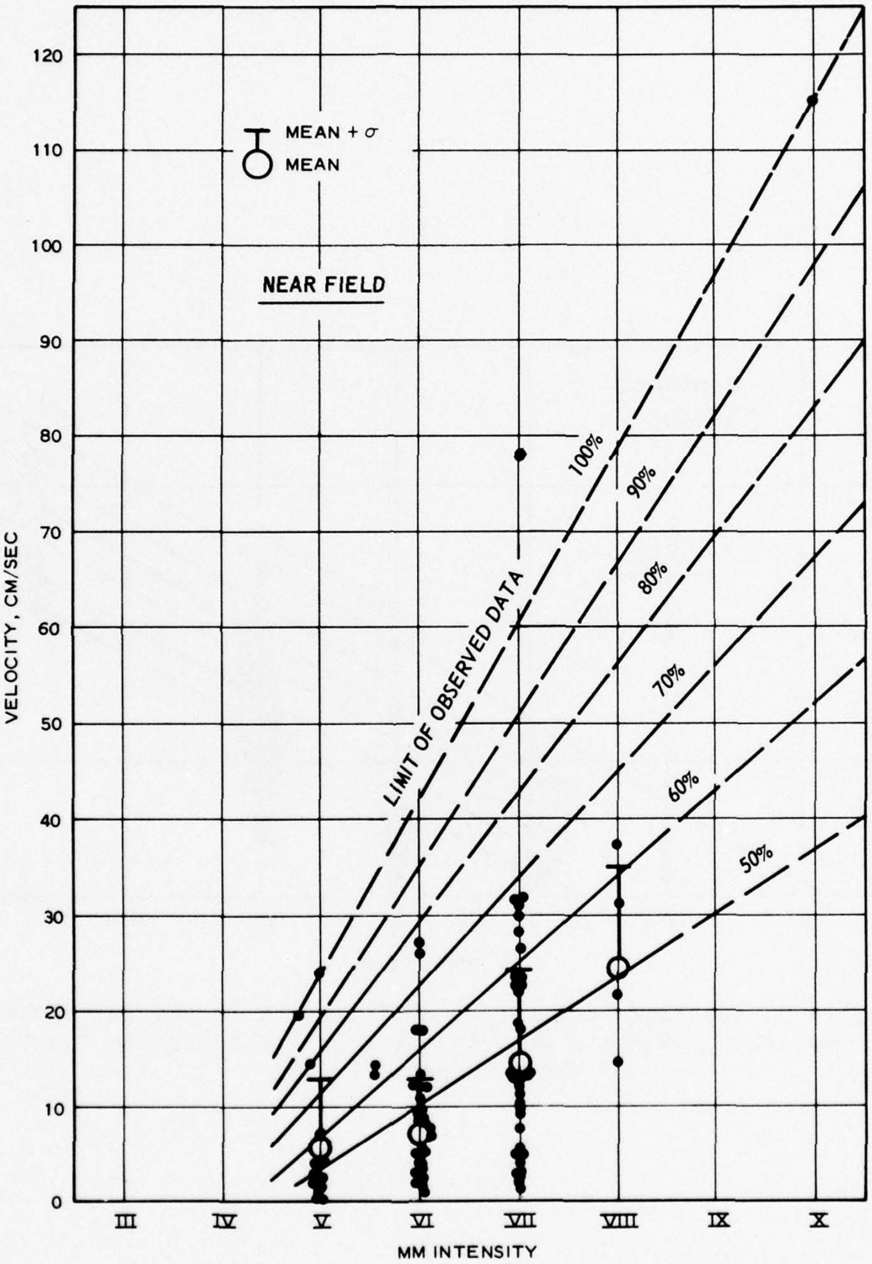


Figure 8. Velocity versus MM intensity in the near field (10 percent increments between the mean (50%) and the limit of observed data (100%))

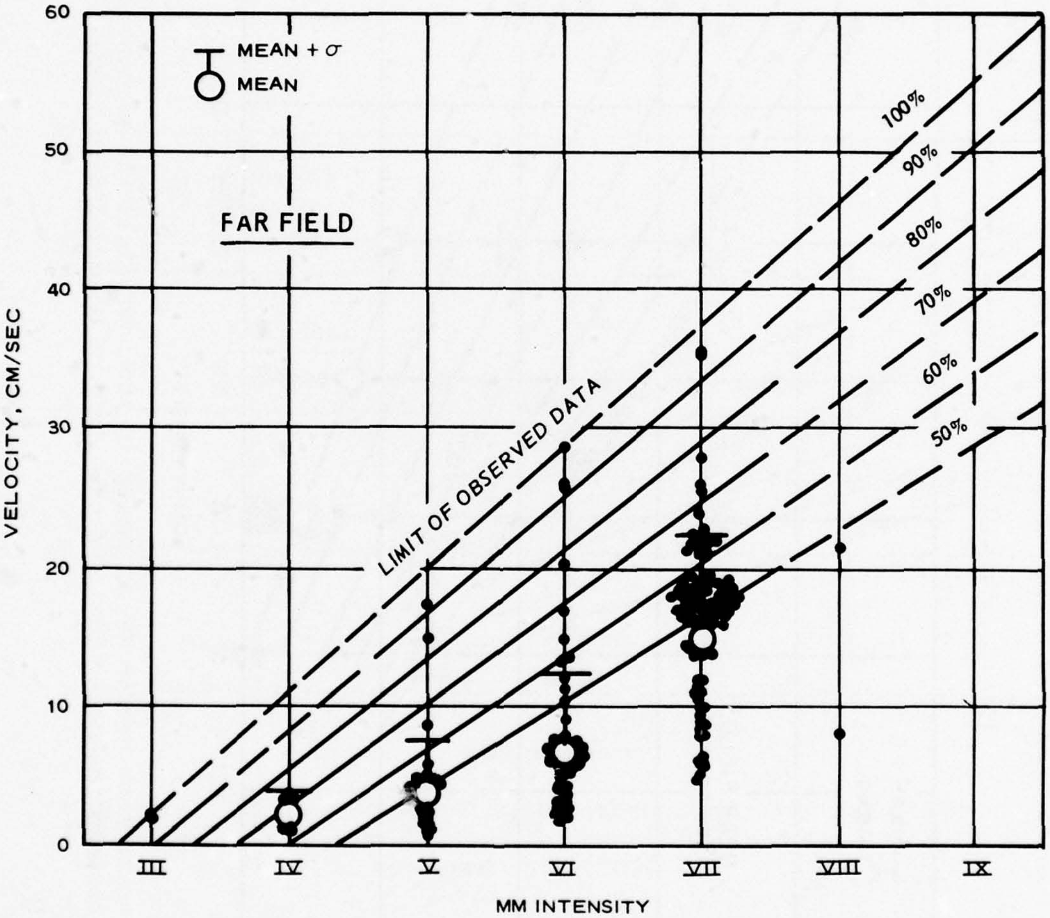


Figure 9. Velocity versus MM intensity in the far field (10 percent increments between the mean (50%) and the limit of observed data (100%))

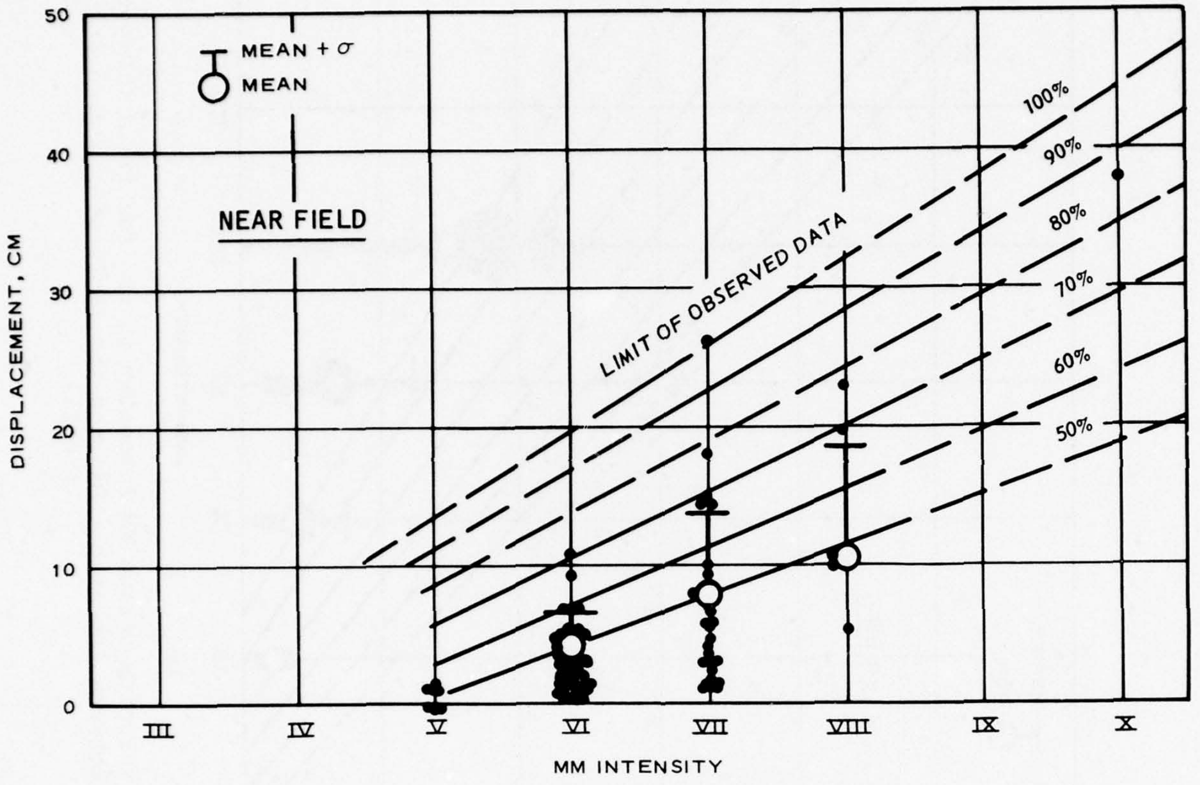


Figure 10. Displacement versus MM intensity in the near field (10 percent increments between the mean (50%) and the limit of observed data (100%))

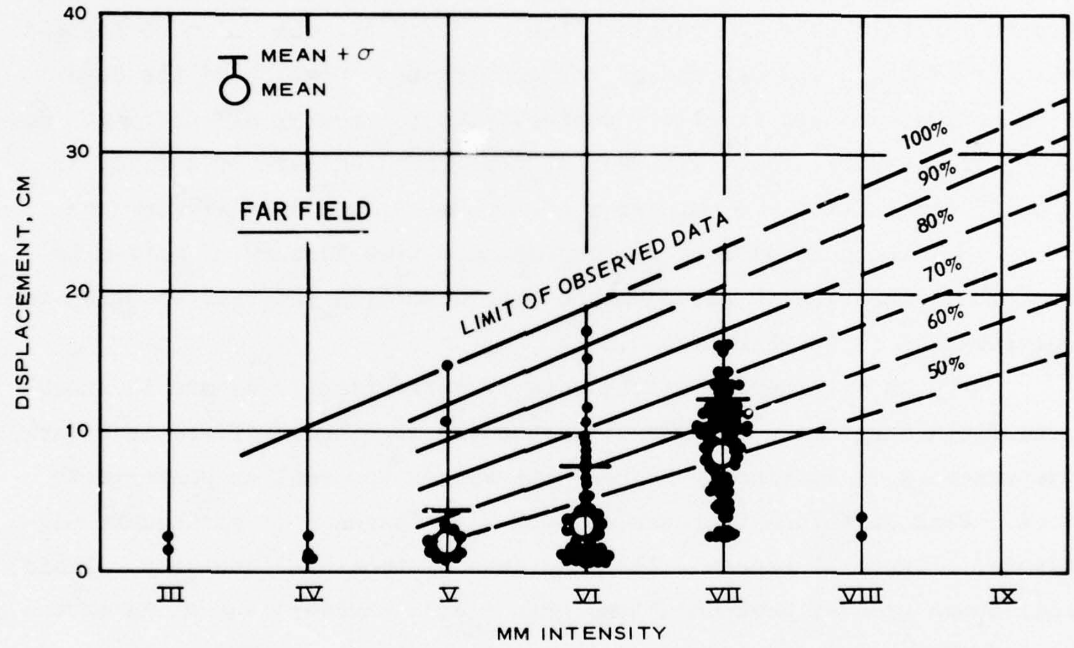


Figure 11. Displacement versus MM intensity in the far field (10 percent increments between the mean (50%) and the limit of observed data (100%))

drops as the intensity increases from MM VII to VIII. The drop-off is not from lesser motions but simply from a decrease in the quantity of data. The projection of the 10 percent lines attempts to compensate for this lack of data.

31. No distinction was made between data from soil and rock since the values overlap too greatly to provide useful comparison. Figures 6-11 are intended to provide peak components of ground motion on bedrock at the surface.

32. The mean-plus-$\sigma$ values show that the data points are concentrated far below the 100 percent line. In effect, the 70 to 80 percent band brackets an upper boundary for the greatest portion of the data. Peak motions at this level are conservative for nearly all designs. However, if a capable fault was seen at the ground surface of a site, then the 100 percent motion, or even a higher value, would be appropriate.

33. The next element in developing a time history of motion is duration. Duration is taken as the bracketed time interval in which the acceleration is greater than 0.05 g.

34. An examination of the data is appropriate. Figure 12 shows near-field durations in terms of earthquake magnitude. There is a large dispersion with distinctly higher peak values for soil as compared to rock. Peak durations increase steeply with increase of earthquake magnitude. Figure 13 presents the same data by local MM intensity. Again, soil shows greater peak durations than rock. However, the slope of the peak duration for rock does not increase as steeply with greater intensity as it does for magnitude. The discrepancy results from incompleteness of data and the inexactness that is inherent in intensity. However, Figure 13 provides conservative upper limits for duration to be used with MM intensities in the near field. Figure 14 shows far-field durations.

35. A comparison is shown in Figure 15 of duration and magnitude for near-field soil and rock with durations developed in recent work by Page et al.[26] and Bolt.[27] Essentially, the durations in rock developed in this study are the same as the durations proposed by Bolt. The durations for soil are the same as those proposed by Page et al. The

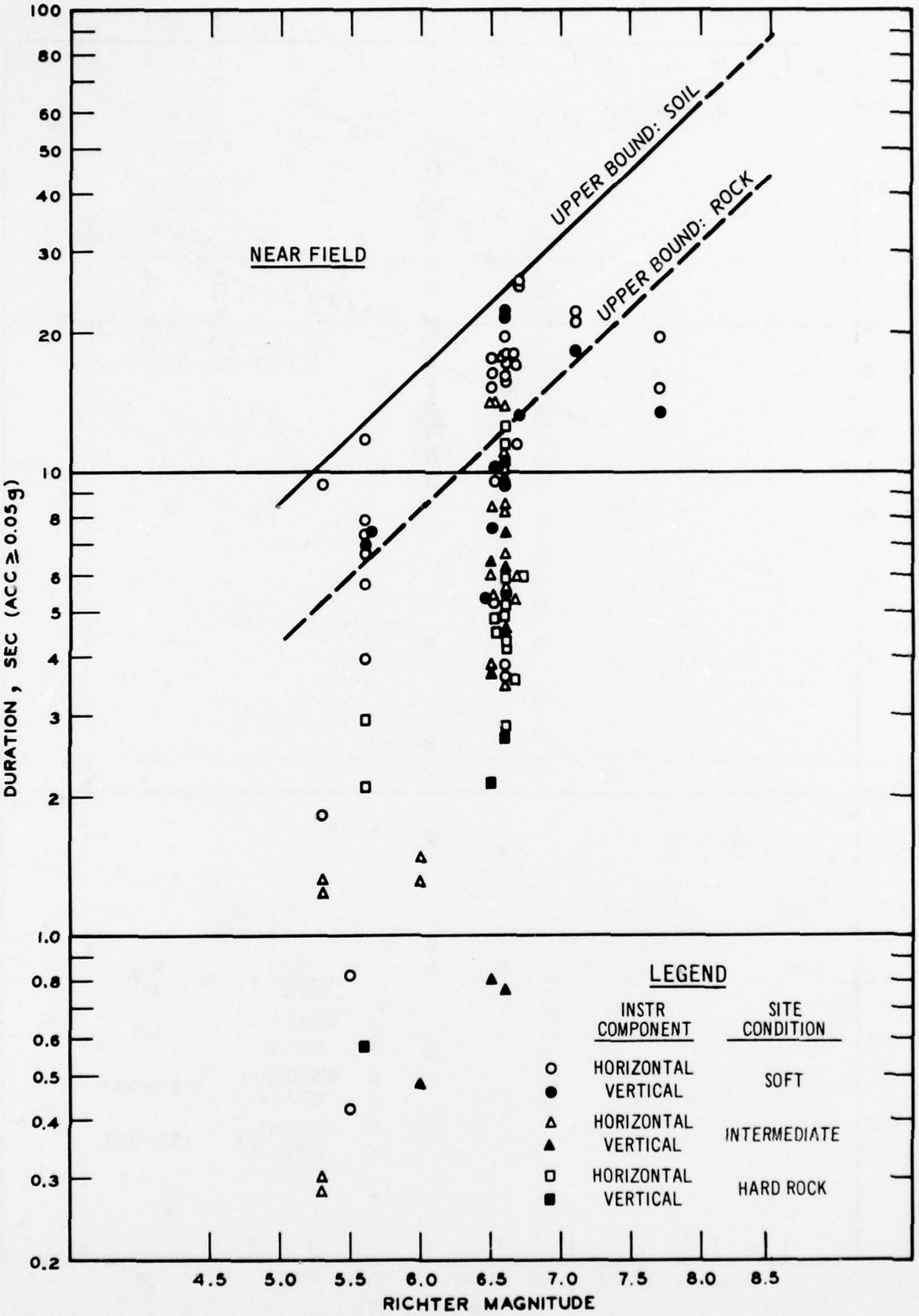


Figure 12. Duration versus Richter magnitude in the near field

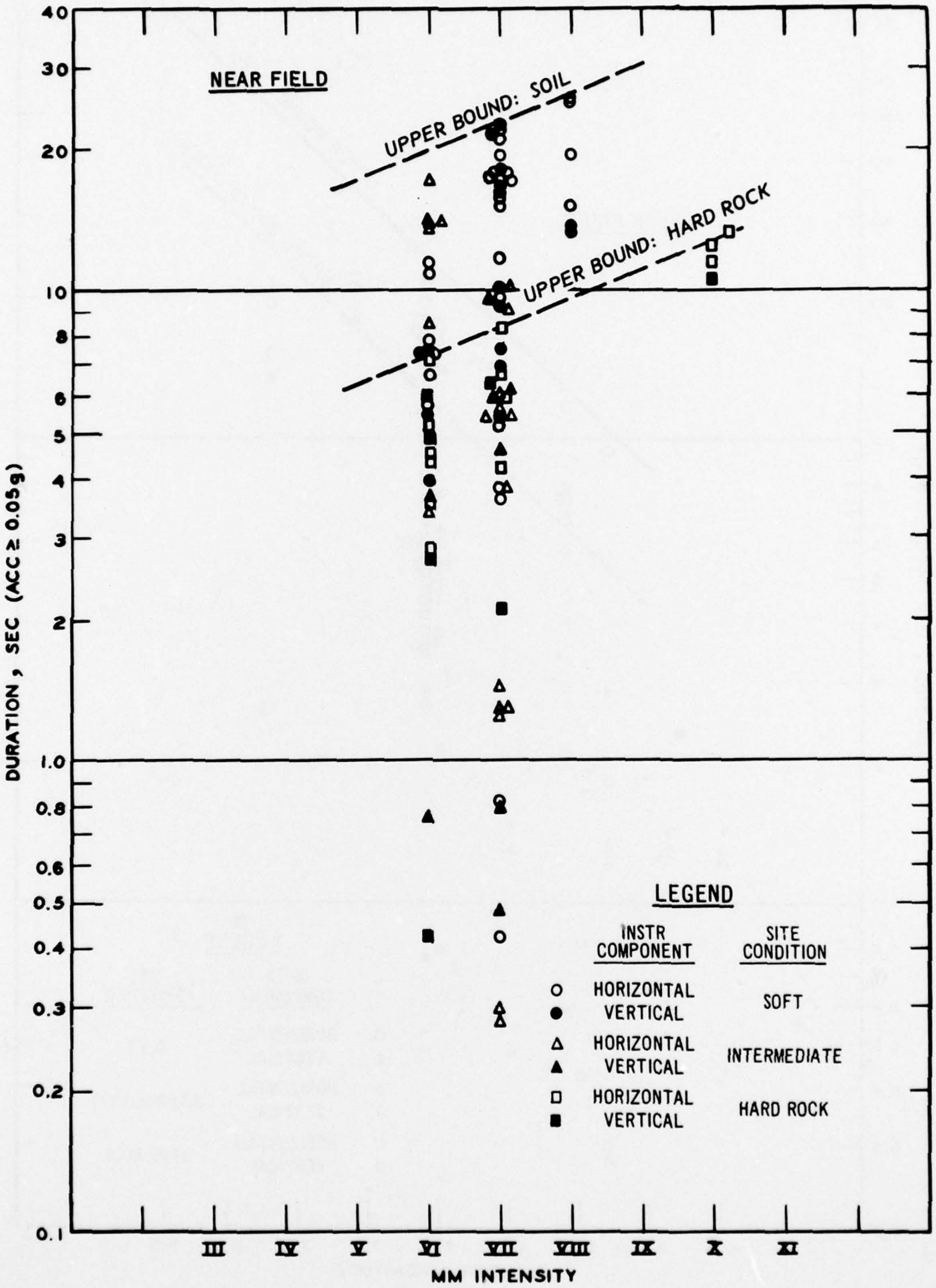


Figure 13. Duration versus MM intensity in the near field

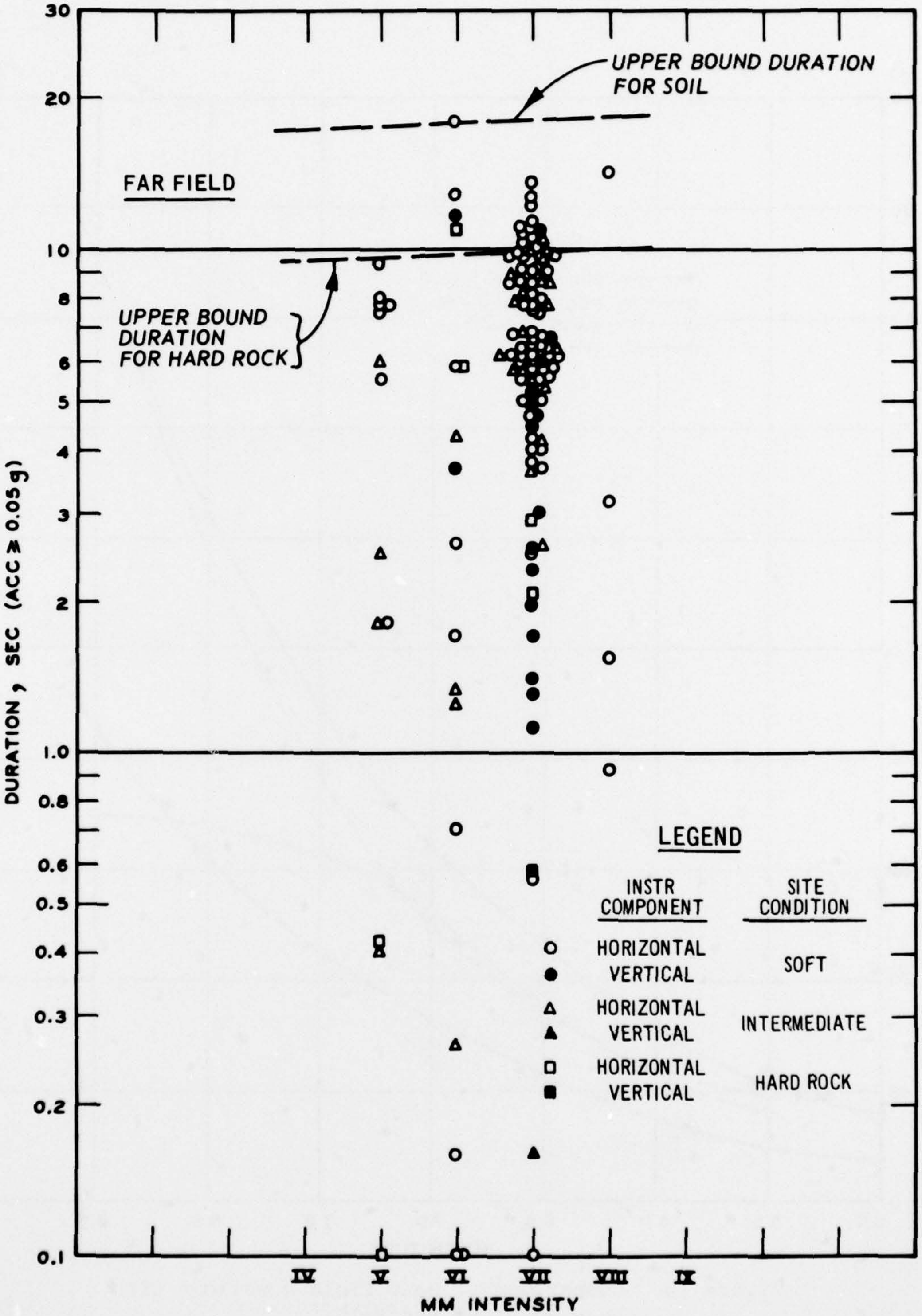


Figure 14. Duration versus MM intensity in the far field

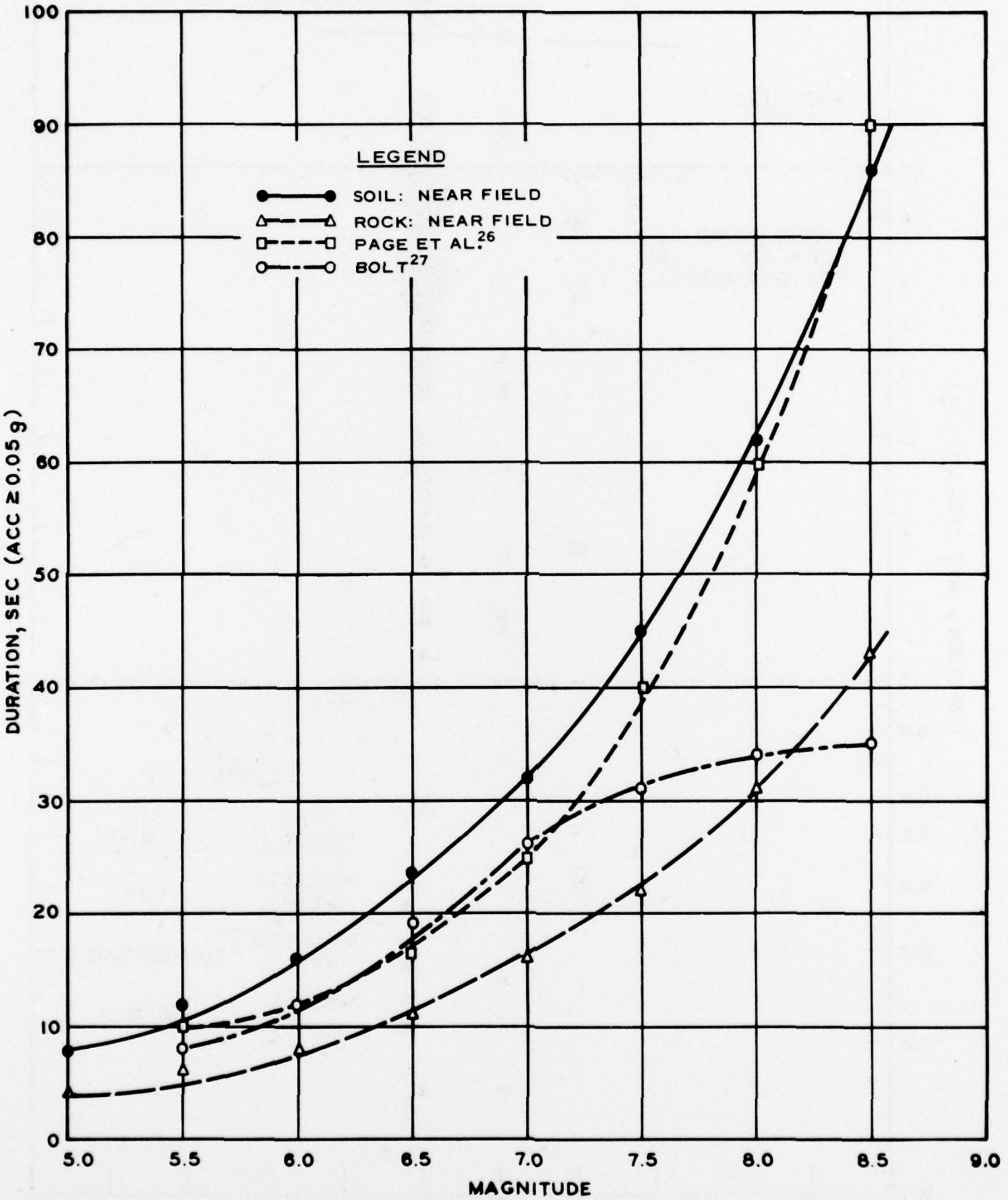


Figure 15. Comparison of near field durations with Page et al.[26] and Bolt[27]

values of Page et al. are in part calculated from assumptions of fault lengths and velocity of rupture propagation with confirmations by "felt" reports during the 1964 Alaska earthquake. Their durations appear to be too conservative for rock when compared with projections from available data (Figure 12).

36. Bracketed duration falls off with distance from source. Figures 16 and 17, for soil and rock, respectively, show the drop-off with distance for various magnitudes of earthquakes. Where motions are attenuated to a site, these curves may be used as a general guide for durations in western United States, but they are not suitable for central and eastern United States. However, the magnitude-duration relationship in Figure 12 and the intensity-duration relationship in Figure 13 may be used everywhere in the United States.

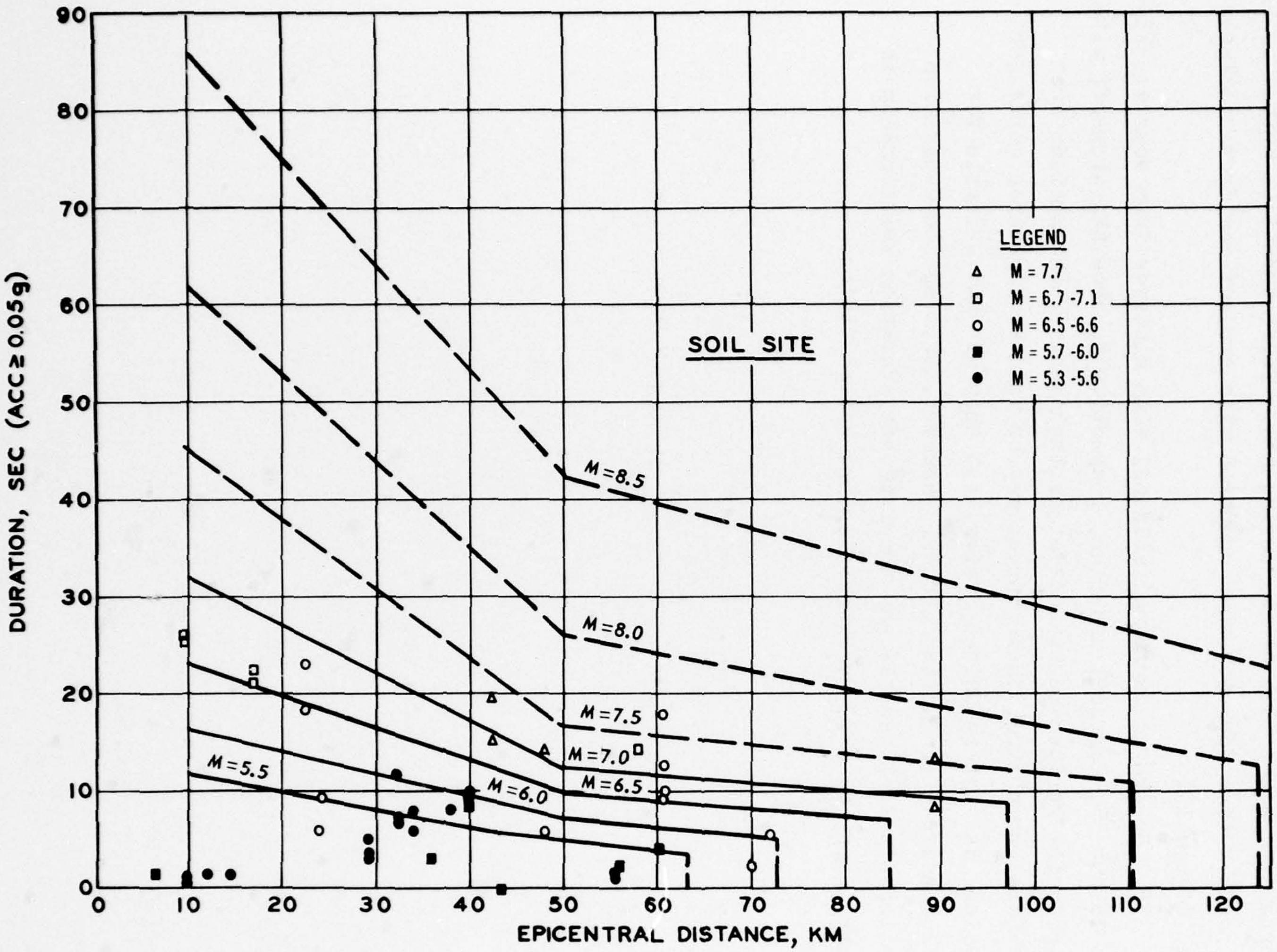


Figure 16. Duration versus epicentral distance and magnitude for soil

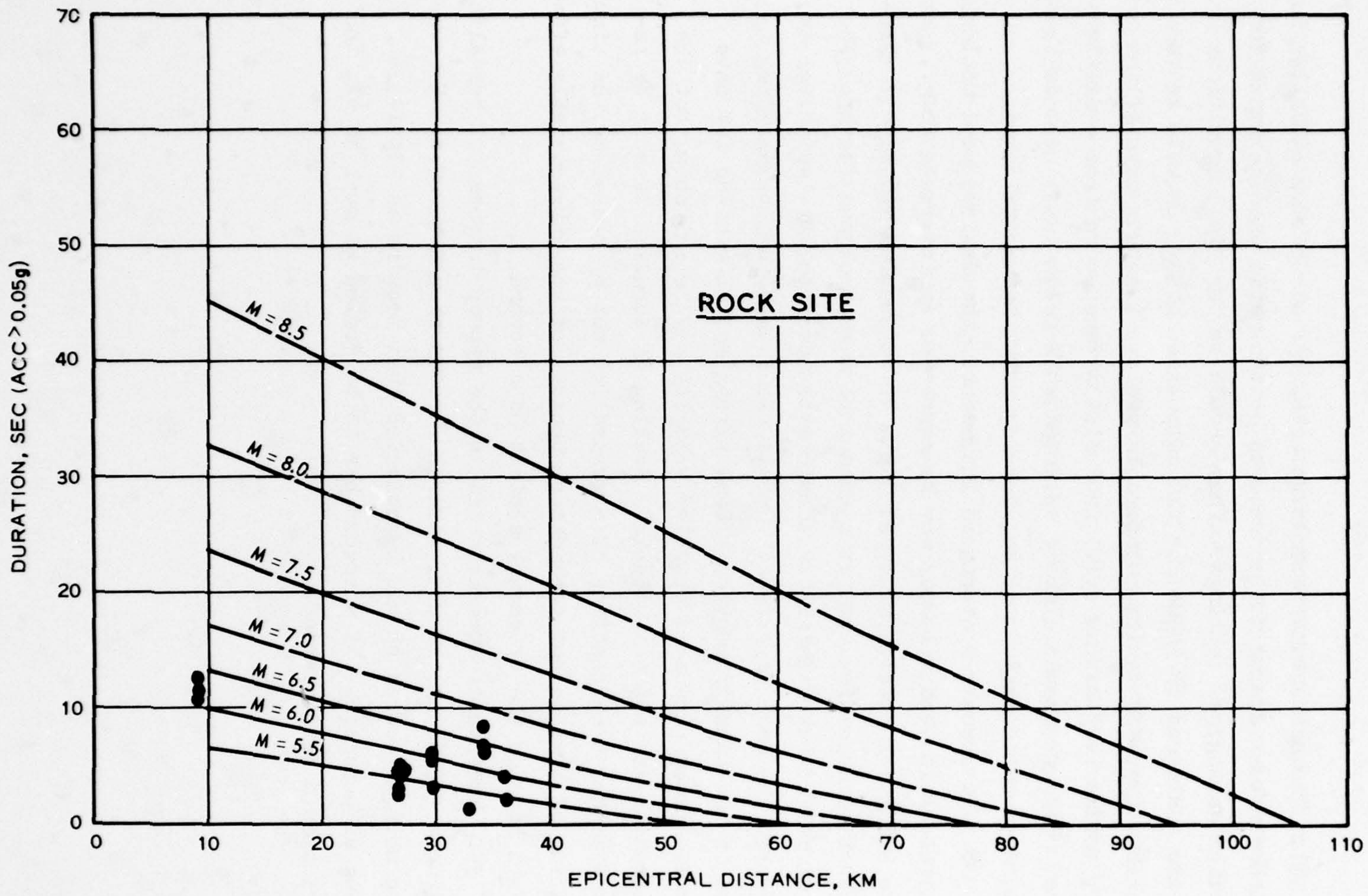


Figure 17. Duration versus epicentral distance and magnitude for rock

## PART III: RESCALING OF STRONG MOTION RECORDS

37. The earthquake records selected for use or for rescaling may be either actual strong motion records or synthetic ones designed for specified geological settings. They should be for field conditions that are analogous to those for the site under study, as well as for comparable types of faults, comparable geology (whether crystalline rocks, sedimentary basin, etc.), and similar distances from causative faults. Records should also be selected with predominant periods that may correspond to periods of engineering works being evaluated.

38. To rescale a strong motion record, the desired peak motions for acceleration and velocity may be expressed as intervals (e.g., 0.4 to 0.5 g for acceleration and 30 to 45 cm/sec for velocity). Displacement is specified, but it need not be a controlling factor. The scaling may be based on either acceleration or velocity, whichever is considered the most important. One is used; the other values are scaled in the same proportion. Some strong motion records may have to be discarded because a rescaled velocity may be suitable, but the acceleration may not be suitable. Scaling of duration is done by repeating or deleting portions of a record but not by rescaling the time. Rescaling of time is not recommended because of the unpredictable effect it would have on the frequency content of a record.

39. Because of uncertainties in the appropriateness of rescaling any single earthquake record, several records should be used. However, strong motion records should be selected that require as little rescaling as possible. If a record has to be scaled as much as 4X, the record should be discarded.

# PART IV: CONCLUSIONS

40. The maximum earthquake or earthquakes interpreted for an important project should be based on a review of seismic history and careful geological investigation. Peak motions for these maximum earthquakes can be specified from relationships between MM intensity and acceleration, velocity, displacement, and duration developed from available strong motion records. An important distinction exists between the near field and the far field. Durations are greatly affected by the presence of soil or rock at a site. Lower values may be justified for cost-risk advantages based on the recurrence rates for earthquakes. Peak motions may then be used to rescale selected existing records or for the generation of appropriate synthetic ones.

41. The procedure shows the designer what information actually exists and incorporates the wide variability in ground motions that have occurred during earthquakes.

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