UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

CONSIDERATIONS IN SELECTING EARTHQUAKE MOTIONS FOR THE ENGINEERING DESIGN OF LARGE DAMS

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A DRAFT TECHNICAL REPORT OF SUBCOMMITTEE 3,
"EVALUATION OF SITE HAZARDS,"
A PART OF THE INTERAGENCY COMMITTEE ON SEISMIC SAFETY IN CONSTRUCTION

SUBCOMMITTEE CHAIRMAN - WALTER W. HAYS
U.S. GEOLOGICAL SURVEY
RESTON, VIRGINIA 22092

OPEN-FILE REPORT 83-636

Reston, Virginia

1983

PUBLICATIONS OF SUBCOMMITTEE 3
INTERAGENCY COMMITTEE ON
SEISMIC SAFETY IN CONSTRUCTION

M. G. Bonilla, 1982, Evaluation of Potential Surface Faulting and other Tectonic Deformation, U.S. Geological Survey Open-file Report 82-732.

John M. Ferritto, 1982, Evaluation of Earthquake-Induced Ground Failure, U.S. Geological Survey Open-file Report 82-880.

E. L. Krinitzsky and W. F. Marcuson III, 1983, Considerations in Selecting Earthquake Motions for the Engineering Design of Large Dams, U.S. Geological Survey Open-file Report 83-636.

FOREWORD

This draft technical report, "Considerations in Selecting Earthquake Motions for the Engineering Design of Large Dams" was developed within the Subcommittee for Evaluation of Site Hazards, a part of the Interagency Committee on Seismic Safety in Construction (ICSSC). This is the third report of the Subcommittee; the other two addressed surface faulting and earthquake-induced ground failure. The material for the report is based on procedures developed at the Waterways Experiment Station. Although these procedures are primarily for large dams, they may also be applicable for other facilities. The membership of the Subcommittee during the preparation of this report was:

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William H. Hakala	National Science Foundation
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The Subcommittee has recommended that this draft technical report be submitted to all concerned agencies with the request that they test its implementation through use in planning, design, contract administration, and quality control, either on a trial or real basis, during 1983 and 1984. Following the trial implementation, the Subcommittee plans to review the draft report, revise it as necessary, and then recommend its adoption by the Interagency Committee as a manual of standard practice for use in the design of large dams. Comment on this draft is welcomed and should be forwarded to the authors or Chairman:

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ABSTRACT

This report gives a synopsis of the various tools and techniques used in selecting earthquake ground motion parameters for large dams. It presents 18 charts giving newly developed relations for acceleration, velocity, and duration versus site earthquake intensity for near- and far-field hard and soft sites and earthquakes having magnitudes above and below 7. The material for this report is based on procedures developed at the Waterways Experiment Station. Although these procedures are suggested primarily for large dams, they may also be applicable for other facilities.

Because no standard procedure exists for selecting earthquake motions in engineering design of large dams, a number of precautions are presented to guide users. The selection of earthquake motions is dependent on which one of two types of engineering analyses are performed. A pseudostatic analysis uses a coefficient usually obtained from an appropriate contour map; whereas, a dynamic analysis uses either accelerograms assigned to a site or specified response spectra. Each type of analysis requires significantly different input motions. All selections of design motions must allow for the lack of representative strong motion records, especially near-field motions from earthquakes of magnitude 7 and greater, as well as an enormous spread in the available data. Limited data must be projected and its spread bracketed in order to fill in the gaps and to assure that there will be no surprises. Because each site may have differing special characteristics in its geology, seismic history, attenuation, recurrence, interpreted maximum events, etc., as integrated approach gives best results. Each part of the site investigation requires a number of decisions. In some cases, the decision to use a "least

work" approach may be suitable, simply assuming the worst of several possibilities and testing for it. Because there are no standard procedures to follow, multiple approaches are useful. For example, peak motions at a site may be obtained from several methods that involve magnitude of earthquake, distance from source, and corresponding motions; or, alternately, peak motions may be assigned from other correlations based on earthquake intensity. Various interpretations exist to account for duration, recurrence, effects of site conditions, etc. Comparison of the various interpretations can be very useful. Probabilities can be assigned; however, they can present very serious problems unless appropriate care is taken when data are extrapolated beyond their data base. In making deterministic judgments, probabilistic data can provide useful guidance in estimating the uncertainties of the decision.

The selection of a design ground motion for large dams is based in the end on subjective judgments which should depend, to an important extent, on the consequences of failure. Usually, use of a design value of ground motion representing a mean plus one standard deviation of possible variation in the mean of the data puts one in a conservative position. If failure presents no hazard to life, lower values of design ground motion may be justified, providing there are cost benefits and the risk is acceptable to the owner. Where a large hazard to life exists (i.e., a dam above an urbanized area) one may wish to use values of design ground motion that approximate the very worst case. The selection of a design ground motion must be appropriate for its particular set of circumstances.

1. INTRODUCTION

The selection of earthquake ground motions in engineering design of large dams is dependent on the engineering analysis to be performed. Essentially, two categories of analyses are used: pseudostatic and dynamic.

1.1 Pseudostatic Analysis - A pseudostatic analysis treats the earthquake loading as an inertial force that is applied statically to a structure, or to a structural component, at the center of mass. The analysis determines the ability of the structure to sustain that additional load. The magnitude of this inertial force is determined as the product of the structural mass and a seismic coefficient. Ideally, the seismic coefficient is a ratio of the acceleration for an appropriate spectral content and response in a structure to that of the ground. Each coefficient has to be determined for a particular type of structure. Historically, seismic coefficients have been chosen by structural engineers on the basis of experience and judgment. Sometimes the coefficients are modified by factors that represent changes in local foundation conditions or differences in a structure.

To obtain a seismic coefficient, one may use a map created for this purpose. Such a map depicts a geographic area, ranging from a continent to a city, contoured or zoned to provide appropriate coefficients for each part of the area. Sometimes a coefficient is spoken of as if it were a value of acceleration; however, in no case can it be related directly to acceleration recorded by a strong-motion instrument.

Where a pseudostatic analysis is to be done, usually no geologic or seismologic investigation is needed, except possibly to verify that pseudostatic analysis is appropriate. Only in exceptional cases, where there is a question of differential ground displacement along a fault at a site, is a detailed geologic examination likely to be warranted.

1.2 Dynamic Analysis - A dynamic analysis tests a structure by applying a cyclical load approximating that of an earthquake. As a reasonable approximation, the shaking may be applied as a wave traveling vertically from bedrock through soil and into a structure. The objective is to test for possible structural damage, evaluating factors such as failure in concrete from excessive peak stresses, the buildup of strain in soils beyond acceptable limits, and, in the case of saturated granular soils, the possibility of failure by liquefaction.

Two general approaches are used in dynamic analyses. Each approach determines the way earthquake motions are specified and used.

One approach begins with acceleration values which may be modified by factors for given structural components and then entered directly into standard curves for smoothed response spectra. Accelerations may be taken from maps of geographic areas containing acceleration contours, such as those by Algermissen and others (1976, 1982). The applicability and usefulness of such maps should be judged on an individual basis. A notable set of maps for the design of noncritical structures was made by the Applied Technology Council (1978) for the United States. These maps present: (1) contours of horizontal acceleration in terms of 90 percent probability of not being exceeded in an exposure time of 50 years (an annual probability of 0.002); (2) effective peak accelerations suitable for entering smoothed response spectra; and (3) an effective peak velocity-related acceleration coefficient.

The second approach begins by selecting and scaling accelerograms considered to be appropriate for a site. Values are specified for peak horizontal acceleration, velocity, and displacement, and a value for the duration of strong shaking is assigned. The motion must be identified as representing the ground surface, rock outcrop, or a bedrock surface.

The first category is non-site-specific and can be used for expedient analysis of elastic structures. The second is site-specific and is usually used when nonlinear effects are important. An example of a non-site-specific approach is that of the Nuclear Regulatory Guide 1.60. It was produced by combining the spectral components from a selected group of 37 earthquake records. Accelerograms, if needed, can be produced by fitting them to the smooth response spectra. In the alternative approach, when beginning with accelerograms, smooth response spectra can be produced as needed.

2. SPECIFYING GROUND MOTIONS

The literature contains many pertinent references to the subjects discussed in this section. Therefore, the treatment will be brief. The reader can refer to earlier publications of Subcommittee 3 for suggestions dealing with surface faulting (Bonilla, 1982) and earthquake-induced ground failure (Ferritto, 1982).

Ground motions specified for design should be based on the following relationships:

a. The presence or absence of identifiable active faults capable of producing earthquakes.

b. The estimated maximum magnitudes for these earthquakes.

c. The frequency of occurrence of earthquakes of various magnitudes.

d. The boundaries for zones of seismic activity in which maximum earthquakes are assigned and floated throughout the zones.

e. The types of faulting that produce these earthquakes and the character of surface displacement.

f. The peak motions (particle acceleration, velocity, displacement), as well as duration and predominant period that are associated with these events.

g. The attenuation of these motions from source to site.

h. The effects of site characteristics (soil, rock, topography, water table, etc.) on the resultant motions.

i. As an alternative to b and g, spectral estimates may be derived directly.

In this way ground motion paramters are selected that are appropriate for any given site. Such investigations are usually greatly involved and costly. Thus, these procedures are usually followed when major engineering works, such as dams or nuclear power plants, are being considered or where safety-related aspects of a structure are critical for special reasons.

2.1 Geologic Studies

Geologic and seismological studies produce the best results when conducted in an integrated manner. Here, they are discussed separately. Included in geological studies are interpretations of plate tectonics and satellite imagery. These types of studies are nearly always too grand to provide specific date that are of importance in evaluating a site. Thus, they can be treated briefly, with very little investment in time or money. Their benefit is that they enable one to give a fuller account of the geologic setting. Airphoto interpretation and overflights are more meaningful. Their objective is to help locate faults and to judge whether the faults are active or inactive. Slemmons and Glass (1978) provide a useful summary of guidance for the utilization of imagery. Generally, no fault can be accepted from imagery or overflights until it is located on the ground or "ground-truthed."

A fault that is shown to be active must also be determined to be capable, that is capable of generating earthquakes.

The larger the capable fault, the greater the potential earthquake. Thus, relationships have been developed between dimensions of faults and magnitude of earthquakes. Dimensions include length of fault rupture, displacement during movement of the fault, whether the movement is on a primary fault or a branch fault or an accessory fault. Compilations have also included the types of faults, whether strike-slip, thrust or normal, and estimates of seismic moment. The latter may be calculated from the area of a fault plane involved in movement, the permanent displacement and the rigidity of the rock. the moment may also be evaluted from the spectral displacement amplitude of long period surface waves.

A useful summary relating faults to earthquake magnitude is provided by Slemmons (1977). Use of the data is ultimately a matter of responsible judgment on the part of the investigator.

2.2 Seismic History

Historic earthquakes should be tabulated and plotted geographically along with the geology. The area studied should be large enough to identify any geotectonic patterns that may be relevant to a site. The tabulation of historic earthquake events, though they are obtained from authoritative sources, should be examined critically. The epicentral intensity of earthquakes are sometimes overstated. Epicenters may also be shifted on the basis of reinterpreting the available data. If the site is important, the historic records should be examined and the interpretations should be checked. The records include newspaper accounts, diaries, early scientific and historical works, etc. A certain caution is in order: no earthquake should be related to a fault unless there is evidence that the fault actually moved during that earthquake.

The seismic history can be used, in combination with seismicity analyses and geologic studies to assess capable faults and to identify earthquake zones. The earthquake zone is an inclusive area over which an earthquake of a determined maximum magnitude, the floating earthquake, may occur anywhere. It is a seismotectonic zone and it need not coincide with tectonic provinces.

2.3 Determining Peak Motions

There is no standard procedure for assigning the peak ground motions appropriate for a site. No matter what procedures are used, one must consider certain basic problems:

a. The paucity of strong motion records for large earthquakes.

b. The limited data near causative faults.

c. The spread in the available data.

The two principal approaches are described below.

2.3.1 Motions Based on Earthquake Intensity

Intensity can be used reliably in earthquake assessment. The intensity scales allow for differences in types of construction and resulting damage. In postearthquake investigations, investigators generally arrive at the same value of intensity for any given site. For most of the United States and the world, no historic data are available except intensities.

Intensities can be attenuated from a source to a site by any of a number of intensity-attenuation charts. Krinitzsky and Chang (1977) show a comparison for intensity attenuation in the Western United States and Eastern United States. Attenuation differs greatly in these two geographic areas.
The range in acceleration for Modified Mercalli (MM) Intensities obtained from representative worldwide data is several orders of magnitude. Also there is a deficiency of data for MM VIII and greater. It is obvious from the dispersion of the values for acceleration that curves based on the mean or average do not reflect the spread in the data. However, such curves have been widely used for design.

Krinitzsky and Chang (1977) presented charts that show an important difference in peak motions for the near field and far field. In the near field there is much focussing of waves from their source and there is reflection and refraction. Also, there may be a buildup of motions from resonance effects as well as cancellation of motions. In the near field, the spectrum is richer in high-frequency components of motion. Thus, in the near field, there is a large spread in the peak motions for any given intensity. In the far field, the motions are less diverse; they are more orderly and predictable and their peaks are also more subdued.

Boundaries between near field and far field differ in terms of the size of the earthquake. The can be estimated in a general way as shown in Table 1.

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Table 1

Limits of Near Field

Richter Magnitude	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

****

In 1977, Krinitzsky and Chang devised sets of curves for near field and far field accelerations, velocities, and displacements. These curves showed the dispersion of the data, and values for the mean, the mean plus one standard deviation (σ), or 84th percentile, and the trend of peak observed values. Krinitzsky and Chang updated the graphs for accelerations, velocities, and durations by incorporating about 600 strong-motion records, including most of the data available from large earthquakes ($M_S \geq 7.0$), and many from very soft soil sites in Japan. A definition of soft for Figures 1 to 18 is a bounding shear wave velocity of 2500 ft/sec. Eighteen of the updated Krinitzsky-Chang curves are listed in Table 2 and are included in this report as Figures 1 to 18. These curves have not been published elsewhere.

* * *

Table 2

Figure number for Krinitzsky-Chang Curves

	Near Field		Far Field			
	All Eqks		$M \leq 6.9$		$M \geq 7.0$	
Site:	Hard	Soft	Hard	Soft	Hard	Soft
Accel:	1	4	7	10	13	16
Vel:	2	5	8	11	14	17
Dur:	3	6	9	12	15	18

NOTE: Soft denotes a bounding shear-wave velocity of 2500 ft/sec.

* * *

By using these curves, peak motion values may be obtained that are relatable to the spread in the data and are projected where data is sparse. Two <u>cautions:</u>

(1) The large motions at MM IX and X for near field, hard site acceleration and velocity are derived from very limited data.

(2) The curves need not necessarily project still higher for MM XI, at least not based on the trends that are shown. Upper limits, or a cutoff, must prevail somewhere.

Use of a mean plus σ puts one in a conservative position for a major structure for which failure is not tolerable. If there is no hazard to life and there is a cost-risk benefit from a lesser design, lesser values can be taken. If a structure is near a major fault or is in an area with a high danger to life, such as a dam above an urban area, then it may be desirable to select "worst case" motions. These decisions are to a large extent subjective, depending on the needs of the project and the experience and judgment of the investigator.

2.3.2 Motions Based on Magnitude and Distance

The now classic work that established present-day levels of peak motions for earthquakes in relation to magnitude and distance is that of Page and others (1972) for the Trans-Alaska Pipeline System. They utilized the strong-motion records recorded from the San Fernando earthquake of February 9, 1971, in which accelerations greater than 1 g were recorded. However, a note of caution is in order whern using the table of motions that Page and others specified for various magnitudes of earthquakes; they are for a frequency range of 1 to 9 Hz suitable for the pipeline. They filtered the Pacoima record to eliminate high-frequency components of motion removing about 25 percent of the range in acceleration. Also, their specified motions are for the worst-case situations where the pipeline is directly over active faults. Thus, the tabulated values of Page and others need to be assessed carefully for use in engineering design situations other than pipelines.

Donovan (1973) showed acceleration values with distance for worldwide earthquakes and for the San Fernando earthquake. The spreads are shown by the mean, mean plus σ and mean plus 2σ. The total spread of the worldwide data is several orders of magnitude.

Algermissen and Perkins (1976) adjusted the Schnabel and Seed (1973) curves using attenuations for Central United States developed by Nuttli so that the Schnabel and Seed curves for acceleration could be used for any part of the United States. These curves, however, present problems in accommodating the range acceleration values. Also, guidance for specifying other critical ground motion parameters such as velocity, displacement, and duration is lacking.

Nuttli and Herrmann (1978) provided useful curves for Central United States giving acceleration and velocity for magnitude and distance from source. A few <u>cautions</u> are in order:

1. Because of a lack of data, most of the curves are simply interpreted.

2. The indicated levels of motions, especially close to the source, do not show what is likely to be a large dispersion in the data.

3. The curves do not depict exactly peak values or means or mean plus σ; they are not specified in these terms and probably depict various parameters over the graph.

4. No distinction is made between soil and rock, again because of a lack of data.

An important set of relationships between acceleration and velocity, magnitude and distance, and rock versus soil was developed by Joyner and Boore (1981). Their values are expressed as mean (50 percentile) and mean plus σ (84th percentile). The motions are very high for sites close to the sources for large earthquakes ($M = 7.0, 7.5$). The curves for these large earthquakes are not based on observed data but on the patterns set by the 1979 Imperial Valley earthquake, of $M = 6.5$, for which there are excellent instrumental records. Two notes of caution:

1) It is not clear that near a fault the peak motions for $M = 6.5$ will continue to increase in the proportions shown for larger magnitudes.

2) The attenuations with distance are suitable for the Western United States, but are not suitable for other areas such as east of the Rocky Mountains.

Seed and Idriss (1983) provided an updated version of the Schnabel and Seed curves. The new curves were determined from a selected group of records and by reducing the values of the Pacoima record. These curves depict mean values for rock site. The values may be increased by a factor of 1.4 to 1.5 to attain a mean plus σ. Also, the values may be reduced, according to another set of curves, to correlate with sites underlain by soils. The accelerations go to almost nothing at about 160 km, even for the largest magnitudes. A note of caution: Other data would indicate higher values at distance. For example, accelerations of more than 0.2 g were recorded during earthquakes at 150 to 280 km from their source: Hososhima-S of April 1, 1968, Aomori-S of May 16, 1968, and Muroran-S of May 16, 1968.

Seed and Idriss (1983) compared attenuation curves for the Western United States and Eastern United States and showed a reasonable agreement in slopes between 10 and about 80 kms from a source. Although it is not explicitly stated, the suggestion is that the attenuations in both parts of the United States are similar. They are similar because the comparison is for a distance of about 80 km where geometric spreading is the dominant cause of attenuation. At greater distances, the western and eastern attenuation effects become notably different.

Under some circumstances, a precise knowledge of a capable fault, and its mechanics of rupture, can be used in two ways to refine the motions that are selected: (1) by obtaining analogous strong motion records for scaling; and (2) by modifying peak motions to accord with the geometry of wave focusing of the fault rupture (see Bolt, 1981, and Singh, 1981). More recently, Bolt (personal communication) advises that, because of the complexities, directivity factors cannot be recommended at this time for design.

2.4 Duration

Several investigators have proposed methods of measuring the duration of strong motion shaking. An important method is based on an integration of the acceleration record, defining duration in terms of the inflection of the curve at the beginning and the end of shaking. (See Arias, 1970; VanMarcke, 1979).

Probably, the method most widely used in engineering design is that of Bolt (1973), called bracketed duration. It is the inclusive time in which the acceleration level equals or exceeds some selected amplitude threshold such as 0.05 g, or 0.10 g. Comparisons of bracketed durations for soil and for rock by Krinitzsky and Chang (1977), of Page and others (1972), and Bolt (1973) show reasonable agreement. A significant difference, roughly a hundred percent, in duration is indicated between soil and rock sites.

A note of caution should be made. Duration will always provide the greatest uncertainty in specifying earthquake motions. Very simply, a large earthquake may actually result from ruptures on several fault planes. These motions are fused together in their effects at any one site so that a record gives the appearance of one earthquake rather than the sum of several. For example, the Caucete, Argentina, earthquake of 1979 had a magnitude of 7.1 and a bracketed duration ($> .05$ g) of 48 seconds at a distance of 70 km. Caucete may be three earthquakes. With more data, even more extreme variances in duration should be expected.

2.5 Spectral Properties

The spectral composition of strong motion records are likely to be affected by site conditions and by distance from earthquake source. The appropriate spectral composition for design can be obtained by selecting records for scaling from earthquakes that are as analogous as possible to the specified type of faulting, magnitude, distance from source, attenuation and site conditions. Synthetic accelerograms are likely to generate appropriate spectra, but these spectra may be somewhat conservative as they may contain spectral components that most natural events do not have.

Seed and others (1976) presented a statistical analysis of shapes of response spectra showing differences for soil and rock sites in the Western United States. Chang and Krinitzsky (1977) presented predominant period characteristics that are related to magnitude and distance together with local geological conditions.

Chang (1981) developed non-site-specific spectra based on geology of the sites and expressed in terms of power density. He found close relationships among peak acceleration, duration, and root mean square (rms) accelerations.

Anderson and Trifunac (1978) describe "uniform risk functionals" that have the same probability of exceedance at each frequency, when the regional seismicity is completely evaluated. The uniform risk functional does not necessarily reflect the shaking from any single earthquake, but will provide an inclusive coverage of the motions to be expected at a site.

Site-specific earthquake ground motions can be developed without first obtaining peak values for acceleration, velocity, etc. The site response spectrum and the duration can be estimated as a first step. With the spectrum defined, historical accelerograms, scaled or unscaled, or artificial accelerograms can be selected according to how their spectra for various values of damping match the prescribed site response. Response spectra generated for rock can be modified for the soil column at a site by performing a one- or two-dimensional wave propagation or finite element analysis using computer programs such as SHAKE, QUAD4, LUSH, etc.

2.6 Scaling of Accelerograms

Chang (1978) provided a catalogue of earthquakes of Western United States arranged by fault type, magnitude, soil and rock, epicentral distance and peak acceleration, velocity, and displacement. Tabulations also listed the duration, predominant period, and focal depth. This source, or the selection of representative earthquakes listed by Hays (1980) in his Table 16 to show appropriate earthquakes for soil and rock sites, may be used to select appropriate strong motion records to use either as they are or for scaling. VanMarcke (1979) indicated that scaling should be restricted to a factor of two or less in order to avoid distortion of the spectral properties of the records. The time scale should not be altered unless there are definite spectral values that are desired. The time scale can be repeated or deleted in portions of the record in order to obtain the desired duration.

The peak accelerations of scaled accelerograms are not suitable for use as acceleration values for entering smoothed response spectra such as those of the Nuclear Regulatory Guide 1.60. VanMarcke (1979) proposed a methodology for developing site-specific design response spectra based on use of appropriate accelerograms recorded from past earthquakes.

3. UNCERTAINTY IN SPECIFIED MOTIONS

The variance in data may be accommodated by bracketing its spread and selecting safe, encompassing parameters. One may project values into areas of a chart where there are no data. One may use data from one geographic region in another. The objective is to utilize available data and rational projections of data in such a way that, should earthquakes occur, there will be no surprises. Thus, the spread in the data and the uncertainties in the extrapolation of data must be accommodated in a reasonably safe manner. Less certain are some of the problems associated with requirements in the methods of analysis and with the use of probabilities. However, in making deterministic judgments, probabilistic data can provide useful data in estimating the uncertainties of the decision.

3.1 Method of Analysis

In section 1, it was pointed out that there are two general approaches for engineering analysis; pseudostatic and dynamic. The dynamic analyses may be either site-specific or non-site-specific. Each type of analysis requires its own input motions. The input motions specified for these differing analyses are not always the same, even for identical sites. For example, a site may require a coeffieient of 0.1 for a pseudostatic analysis, 0.42 g for the acceleration peak in a time history and 0.25 g to enter smoothed response spectra of NRC Guide 1.60. As a caution, it is important to note that a lesser or greater number does not mean that one is more or less conservative than the other. In fact, the reverse may be the case. At present, the relation between input motion requirements is a gray area in which satisfactory equivalents have not been entirely worked out. A guide for producing acceleration values appropriate to smoothed response spectra from accelerograms is provided by VanMarcke (1979).

3.2 Deterministic versus Probabilistic Characterization

A deterministic characterization of peak motions is a statement of the appropriate values that may be used in an analysis for a site. These values are obtained from a combination of empirical knowledge, theoretical computation, conceptualization, and professional judgment.

Probabilistic characterization recognizes two facts: (1) that no structure is absolutely safe, and (2) no motion is absolutely the maximum. Therefore, it is argued, a probabilistic analysis is needed to estimate the recurrence of whatever motions are assigned, and by projection, to estimate the levels of larger motions and how often such motions will occur. The motions may get to be very severe when they are projected over long periods of time, up to thousands of years. (Projection to return periods of 10,000 years from a historic seismic record of only 150 to 350 years is not uncommon.) The reasoning is that the recurrence of such very severe events is extremely low.

An argument can always be made that something worse can happen. Can a meteor smash into a dam and demolish it? Yes, it can. Can it happen coincidentally when the reservoir is at its highest? Yes, that can happen too. What then is the probability? It is not always possible to assign a physically meaningful number to the likelihood of such a compound event. The number would have such an enormous range of error that generating it may be indistinguishable from pure fiction. Therefore, great care must be taken when using probabilities in assessing seismic risk, especially when projections are made that greatly exceed the time represented by the seismicity data base.

Recurrence of larger and larger earthquakes is equated with an increase for peak motions, notably acceleration. A difficulty is that the recurrence rate may not relate to peak motions in satisfactory way. The motions include a large number of variables: near field versus far field, spectral content, dispersion of the data, gaps in the data, saturation of peak motions, focusing of seismic waves, effects of site conditions, geological influences, etc. Probabilistic analyses applied when there are so many variables may produce misleading results. Probabilistic analyses, as with other mathematical treatments, is an idealization of a complex problem for which there are multiple inputs and subjective decisions. Properly, the results should be tempered with the knowledge and judgment that is the basis for one's physical understanding of the problem. When treated accordingly, probabilistic data can provide useful guidance, particularly if they are used in conjunction with noncritical elements of design or for time intervals that are within the seismicity data base. For insurance purposes, probabilities are useful because of their short-term projections which keep estimates close to the data base. Yegian (1979) provides a review of methods for probabilistic analysis. A theoretical review of errors in probabilistic analysis, especially those that occur in large projections beyond the data base, is given by Veneziano (1982).

For a large structure, such as a dam or a nuclear power plant, where the design must be safe, the major decisions are based on deterministic analyses. However, deterministic decisionmaking does not necessarily ensure a safe design.

4. CONCLUSIONS

Because no standard procedure exists for selecting earthquake motions in the engineering design of large dams, certain cautions are necessary. Many decision levels exist, varying from project to project. It is prudent to review one's results and check them through several approaches and, if necessary, to allow for a consensus. Because the state-of-the-art has developed rapidly, one should integrate geologic and seismological studies, taking into account new methods and additions to the data base. The safest general approach is to base one's selection of design ground motions on a large catalogue of observed data considered appropriate for the situation, projecting the trends in the data when the data are insufficient and bracketing the values in such a way that there will be as few surprises as possible should an earthquake occur. The peak motions should be adjusted so that they are appropriate for the pseudostatic or dynamic analyses in which they are used.

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6. ACKNOWLEDGEMENTS

The Krinitzsky and Chang curves (Figures 1-18) were reviewed by Bruce A. Bolt, University of California, and Otto W. Nuttli, St. Louis University. The authors greatly appreciate their guidance. The text of this paper was reviewed by Paul R. Fisher, Ken Kelly, Lucian Guthrie, and Paul F. Mlakar of the Corps of Enginers, Walter W. Hays and Manuel G. Bonilla of the U.S. Geological Survey, Leon Reiter of the Nuclear Regulatory Commission, John M. Ferritto of the Naval Civil Engineering Laboratory, James F. Lander and Jerry Coffman of the National Oceanic and Atmospheric Administration, and Martin W. McCann, Jr., of Jack R. Benjamin & Associates. To all of them the authors are deeply grateful.

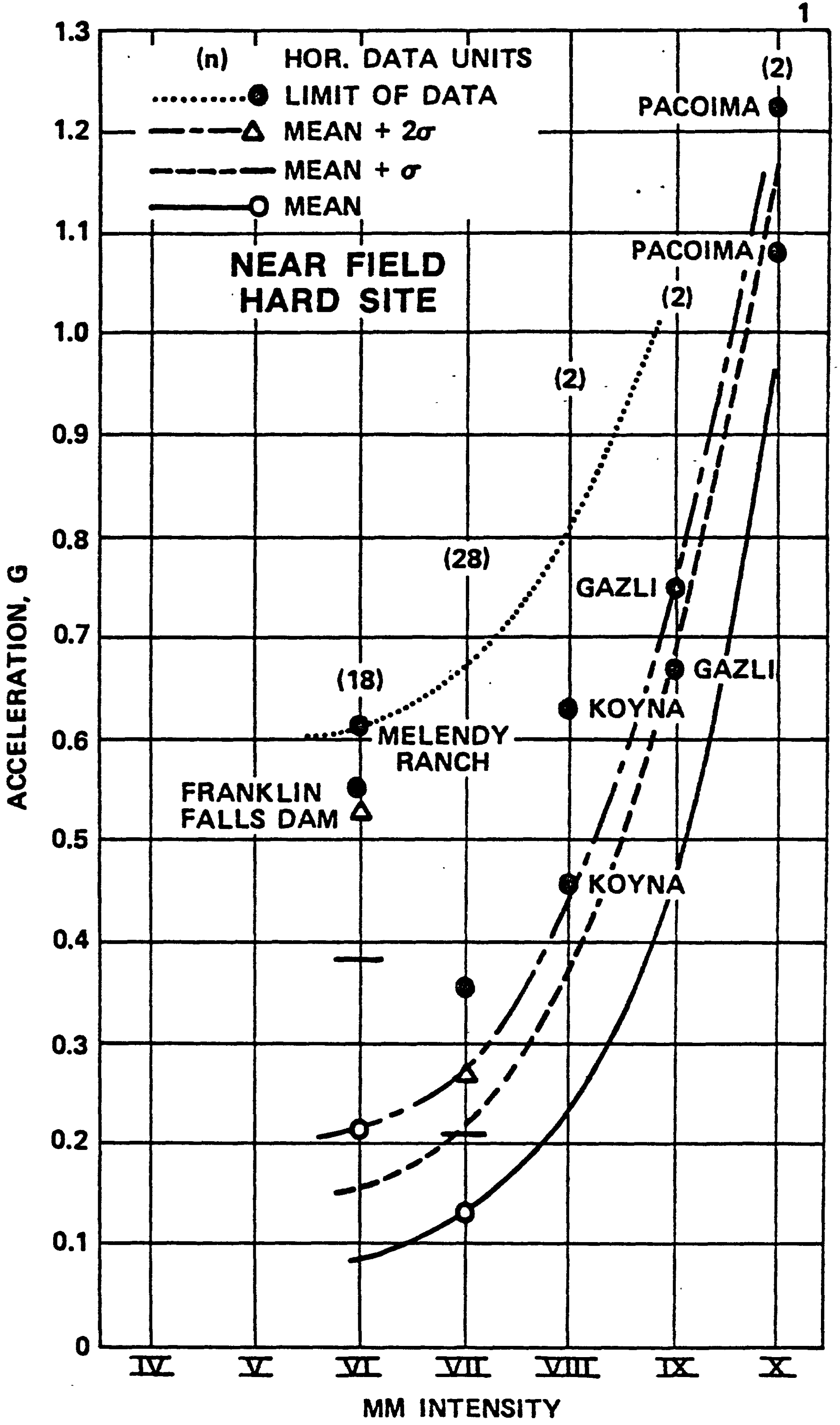

Figure 1. Acceleration as a function of MM intensity for a near-field hard site.

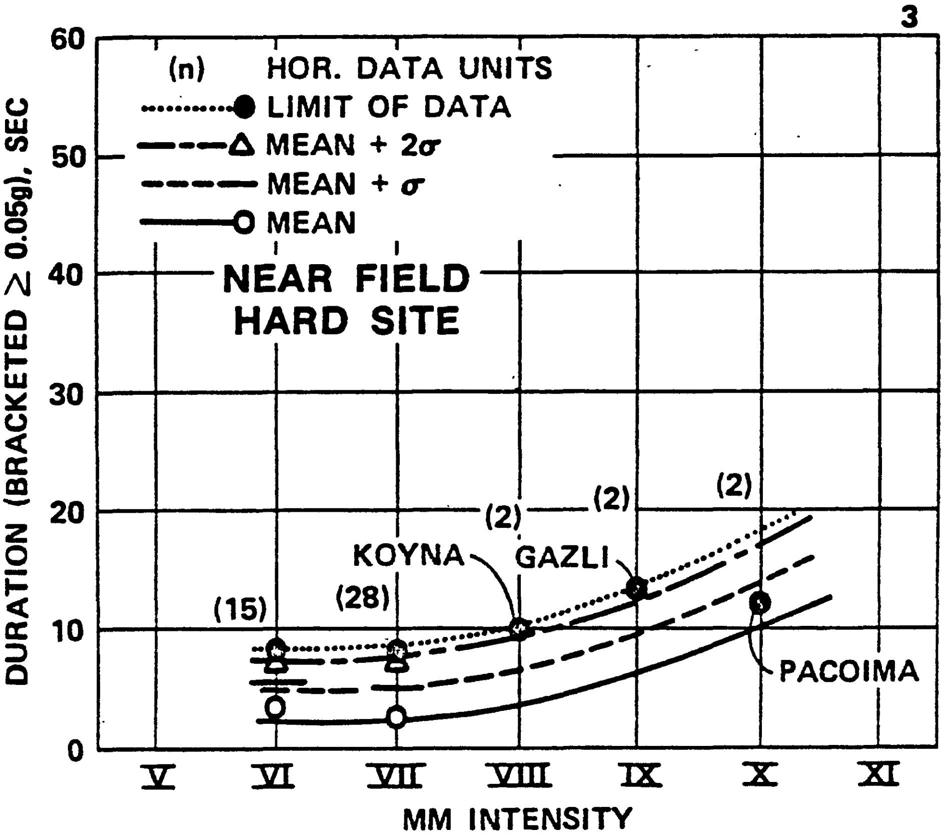

Figure 3. Duration as a function of MM intensity for a near-field hard site.

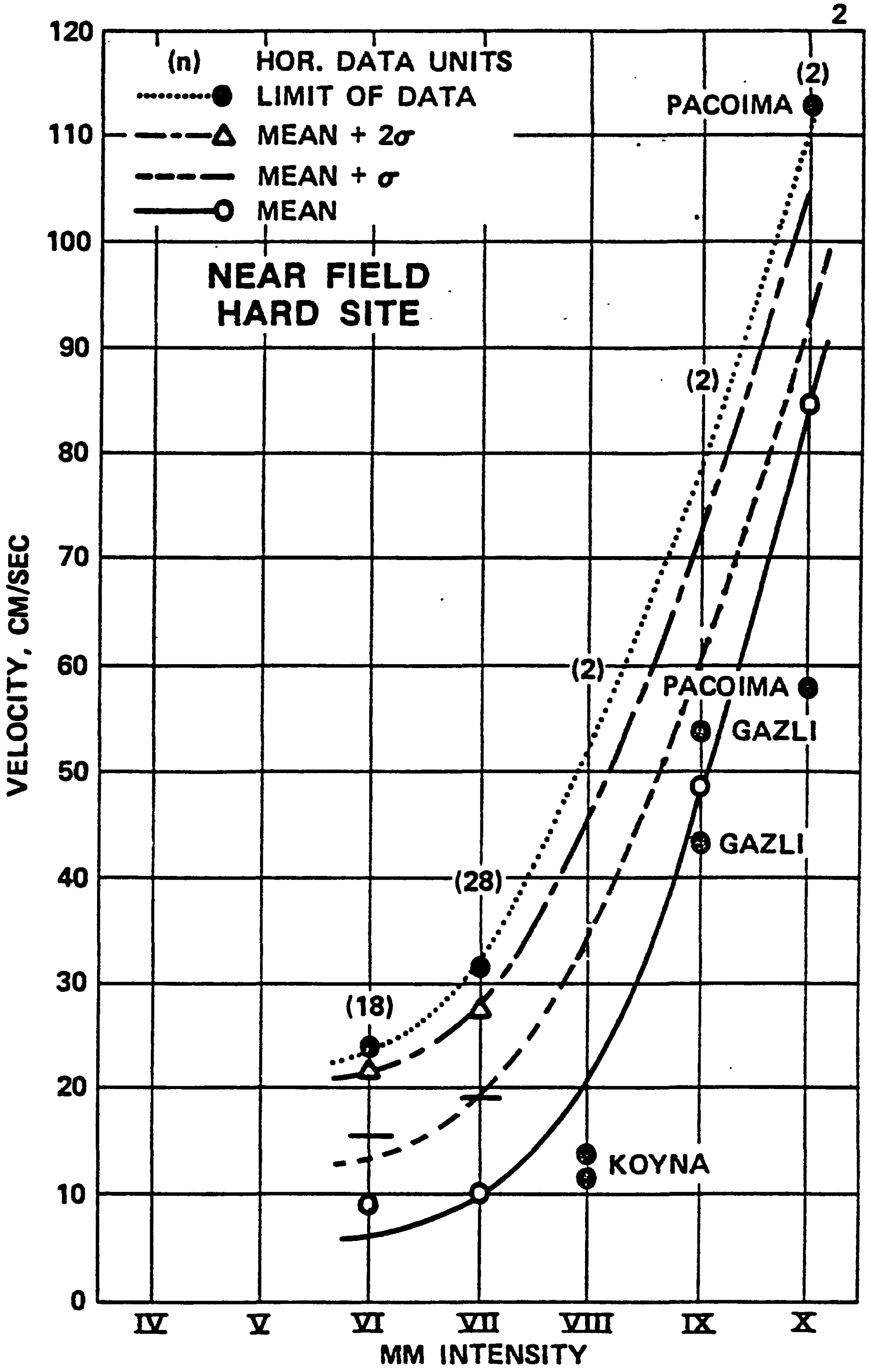

Figure 2. Velocity as a function of MM intensity for a near-field hard site.

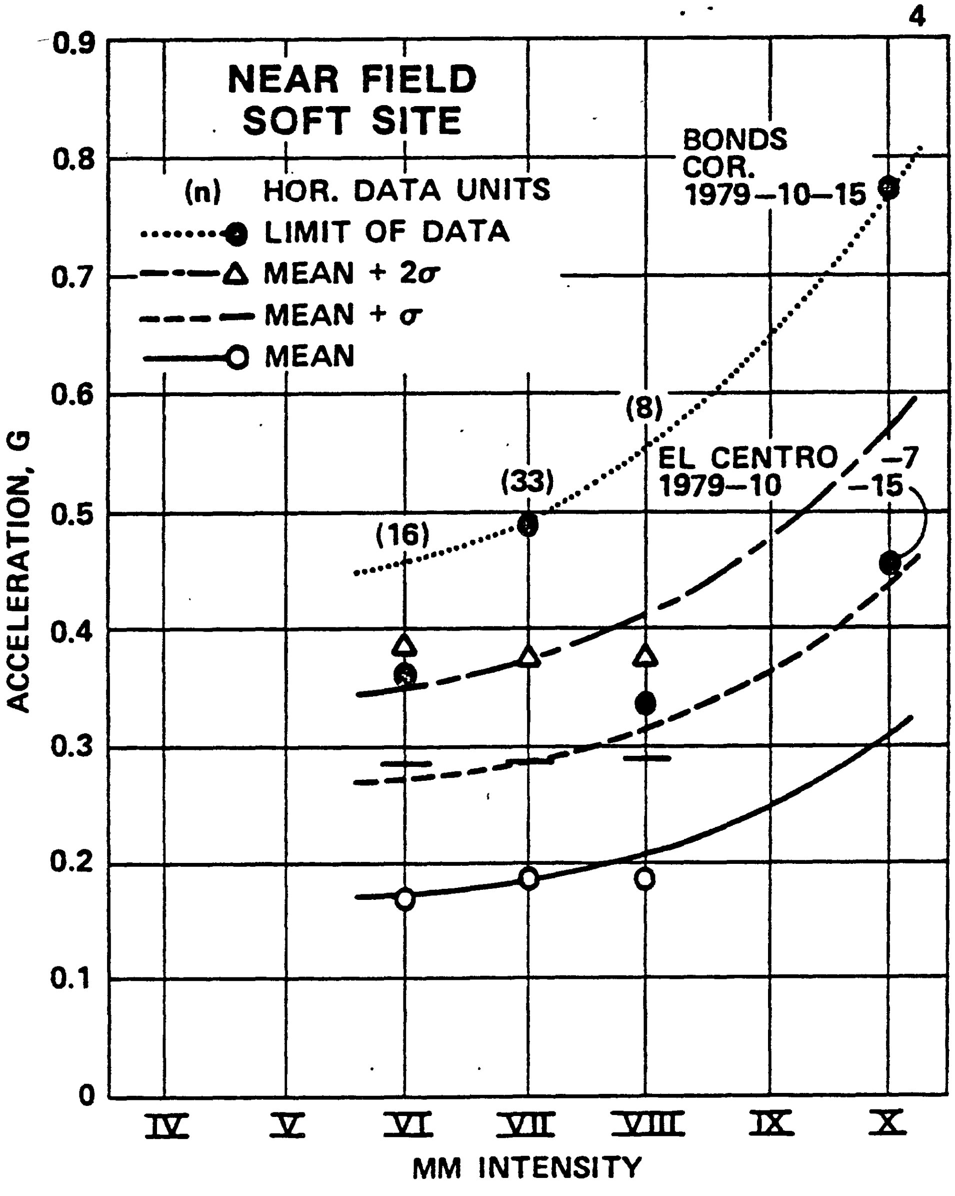

Figure 4. Acceleration as a function of MM intensity for a near-field soft site.

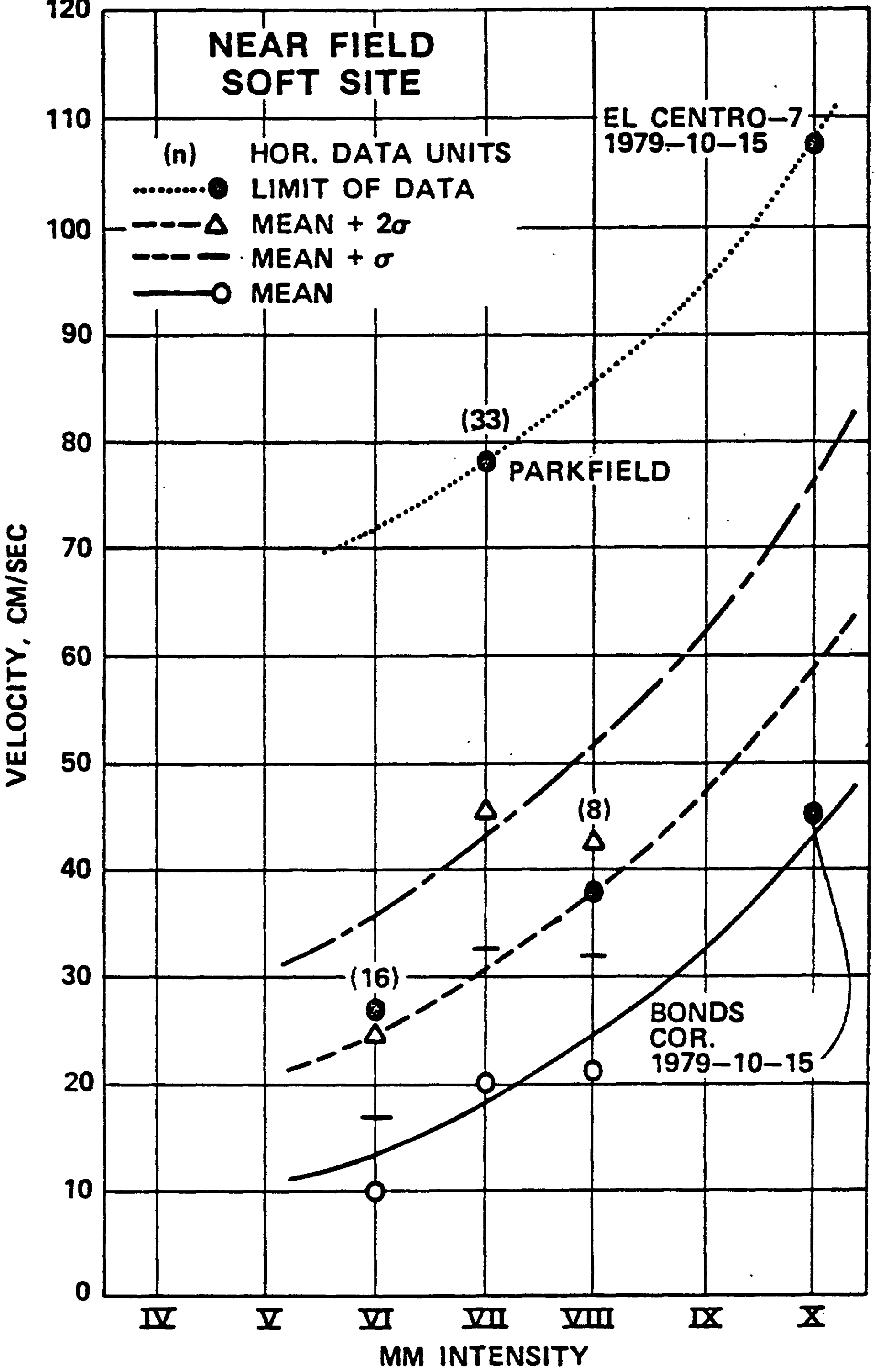

Figure 5. Velocity as a function of MM intensity for near-field soft site.

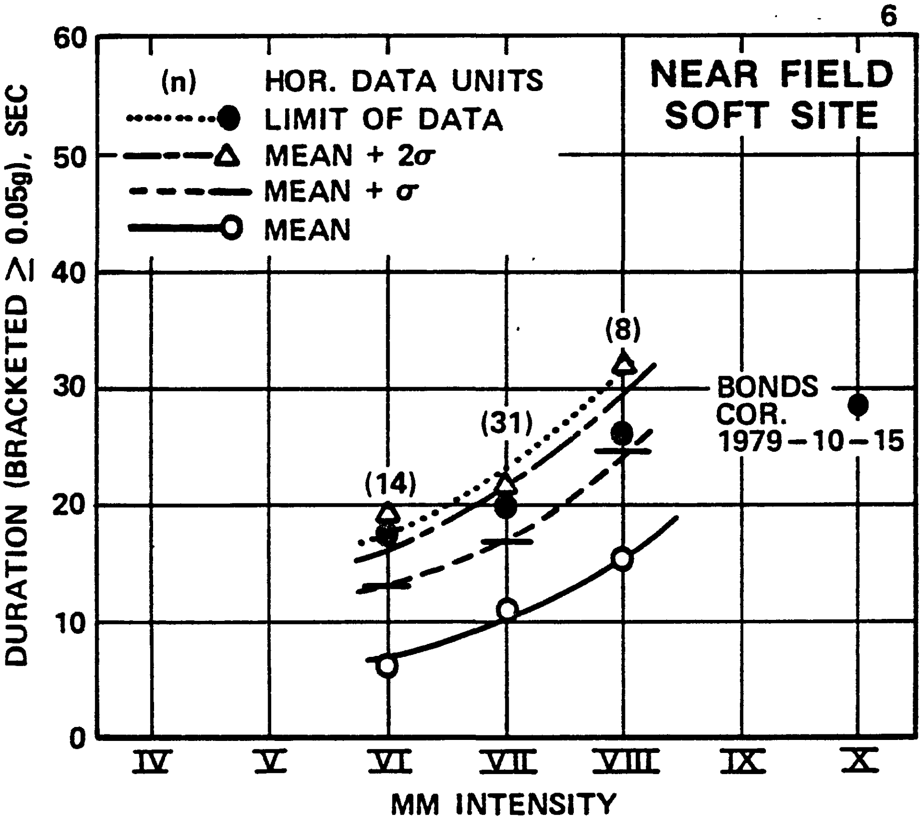

Figure 6. Duration as a function of MM intensity for a near-field soft site.

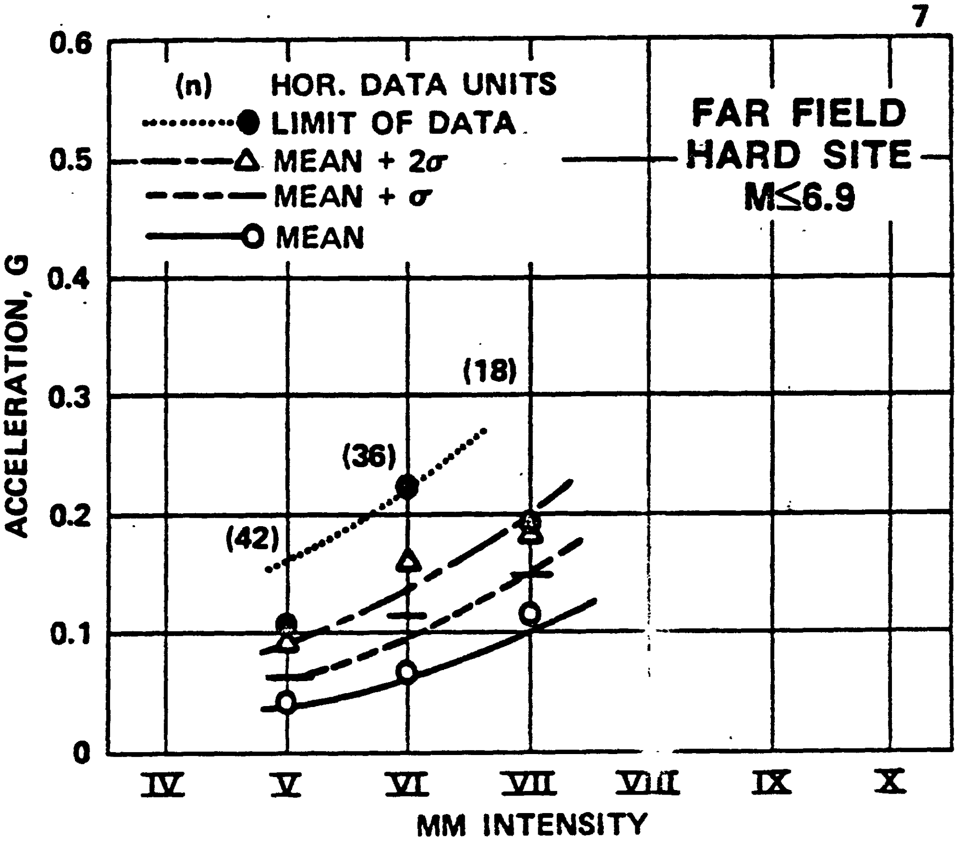

Figure 7. Acceleration as a function of MM intensity for a far-field hard site, M $\leq$6.9.

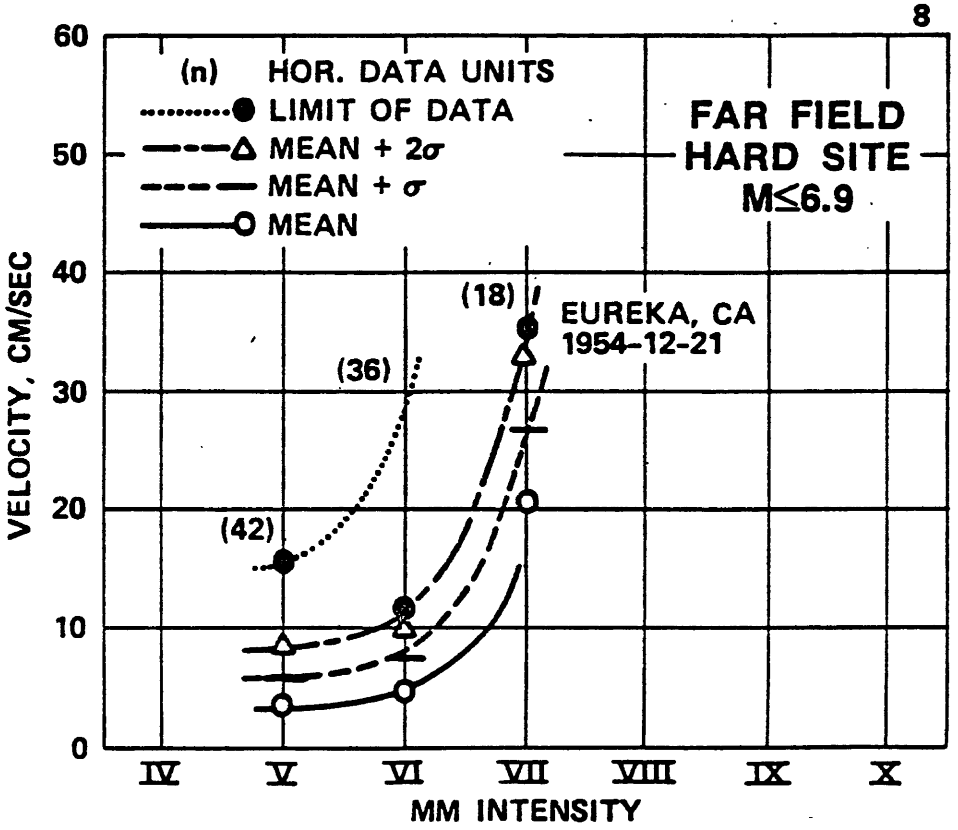

Figure 8. Velocity as a function of MM intensity for a far-field hard site, M ≤ 6.9.

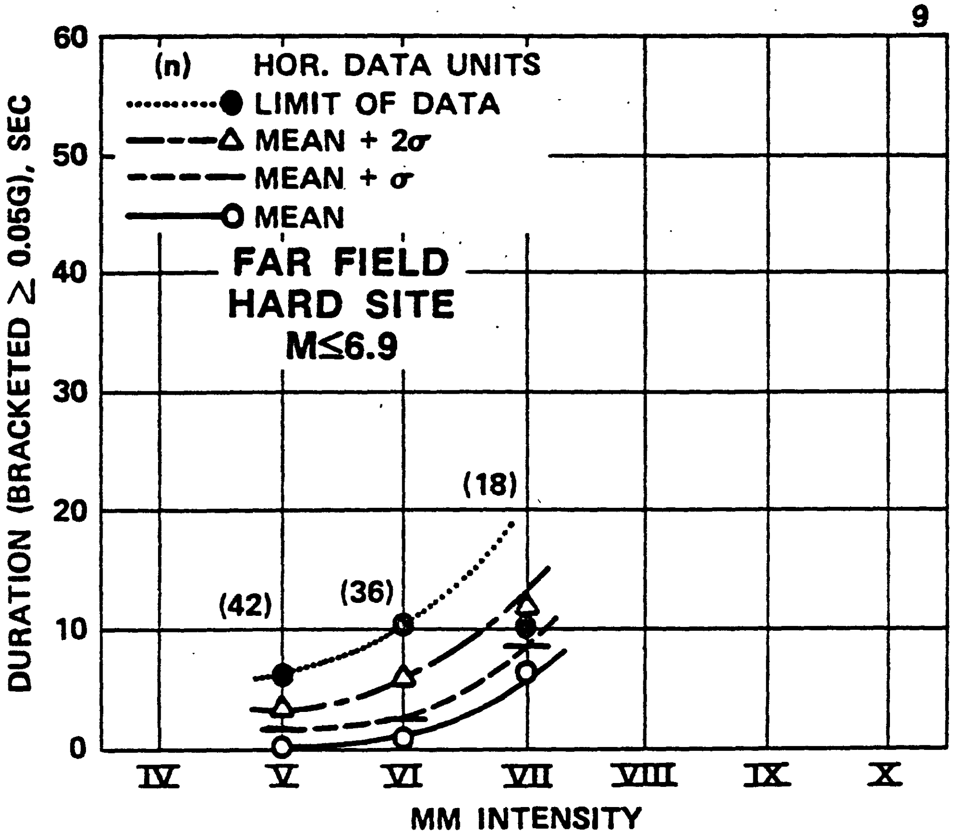

Figure 9. Duration as a function of MM intensity for a far-field hard site, M ≤ 6.9.

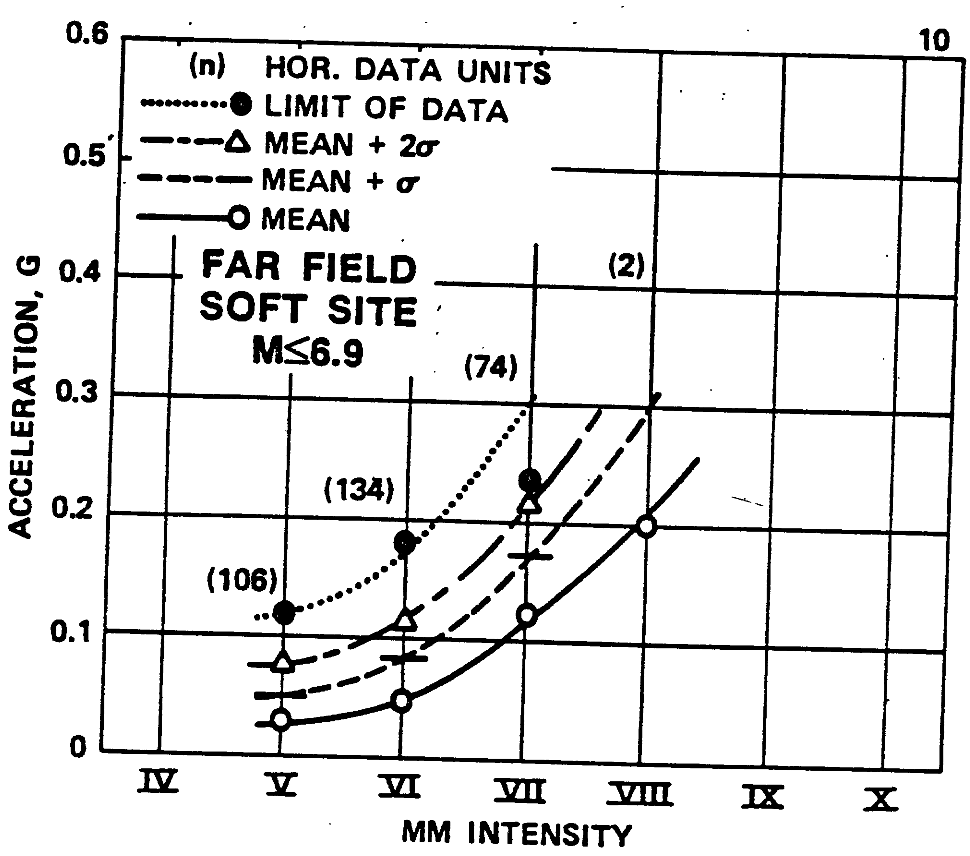

Figure 10. Acceleration as a function of MM intensity for a far-field soft site, $M \leq 6.9$.

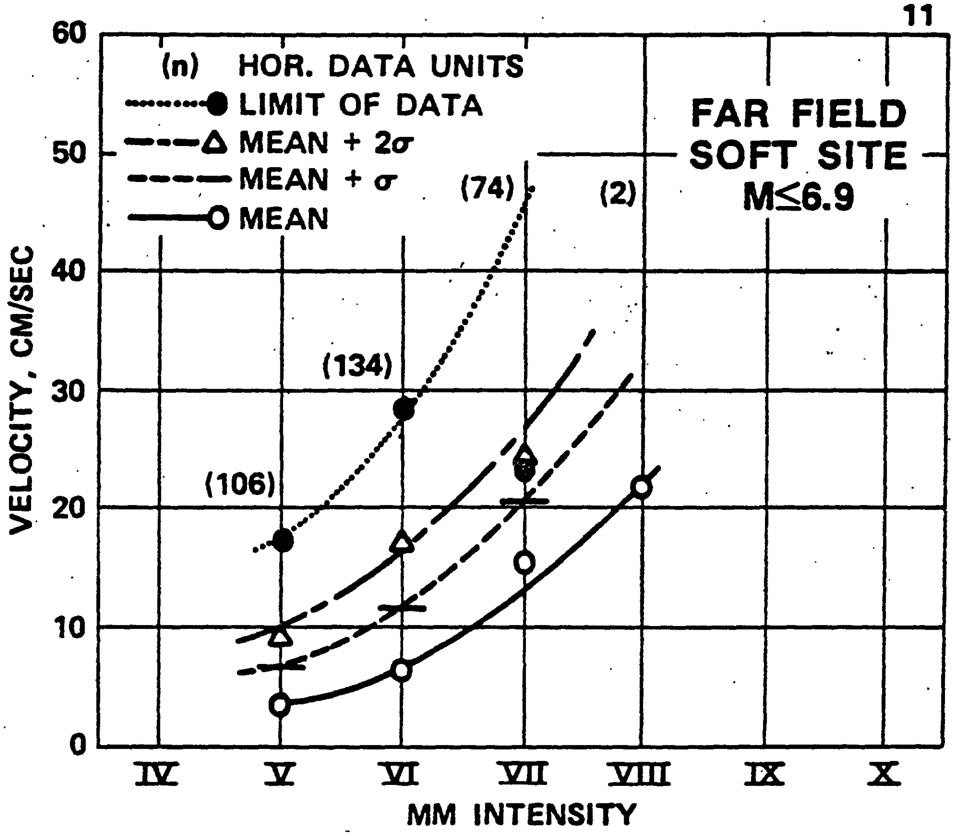

Figure 11. Velocity as a function of MM intensity for a far-field soft site, M ≤6.9.

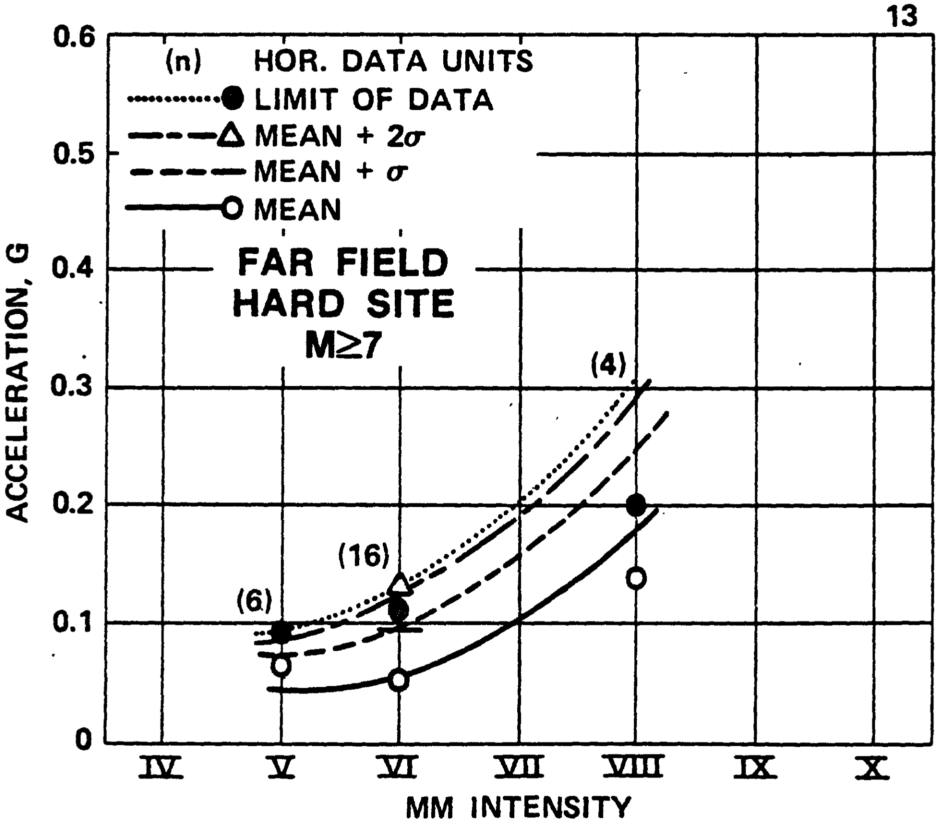

Figure 13. Acceleration as a function of MM intensity for a far-field hard site, M≥ 7.

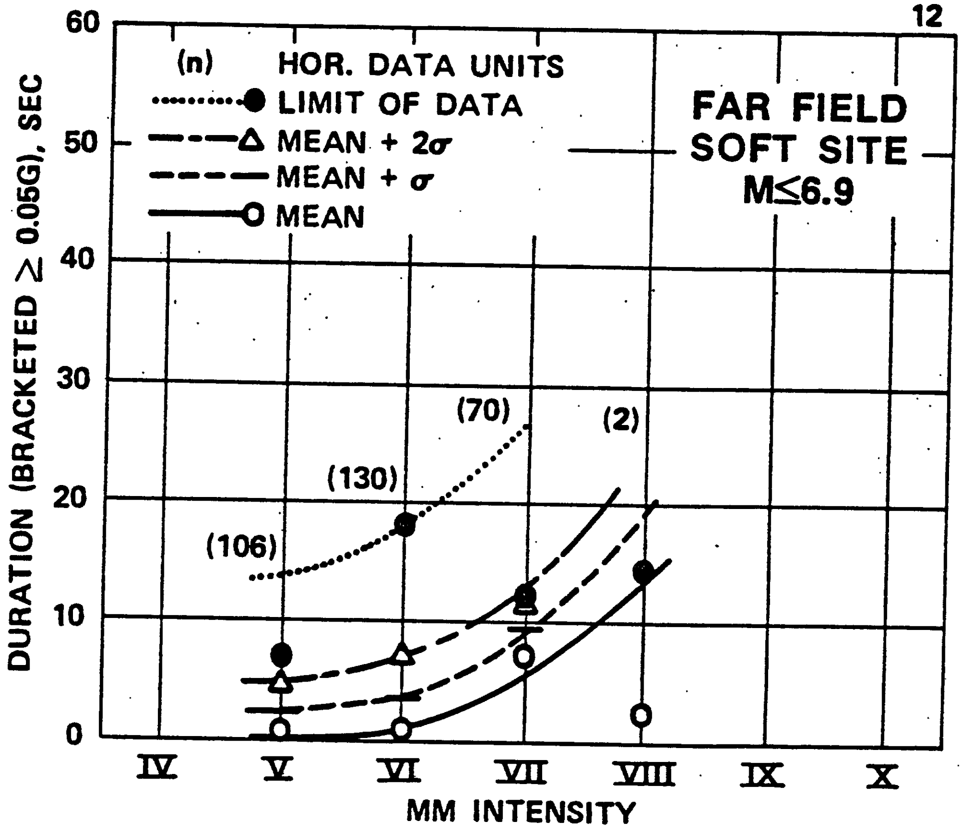

Figure 12. Duration as a function of MM intensity for a far-field soft site, M ≤6.9.

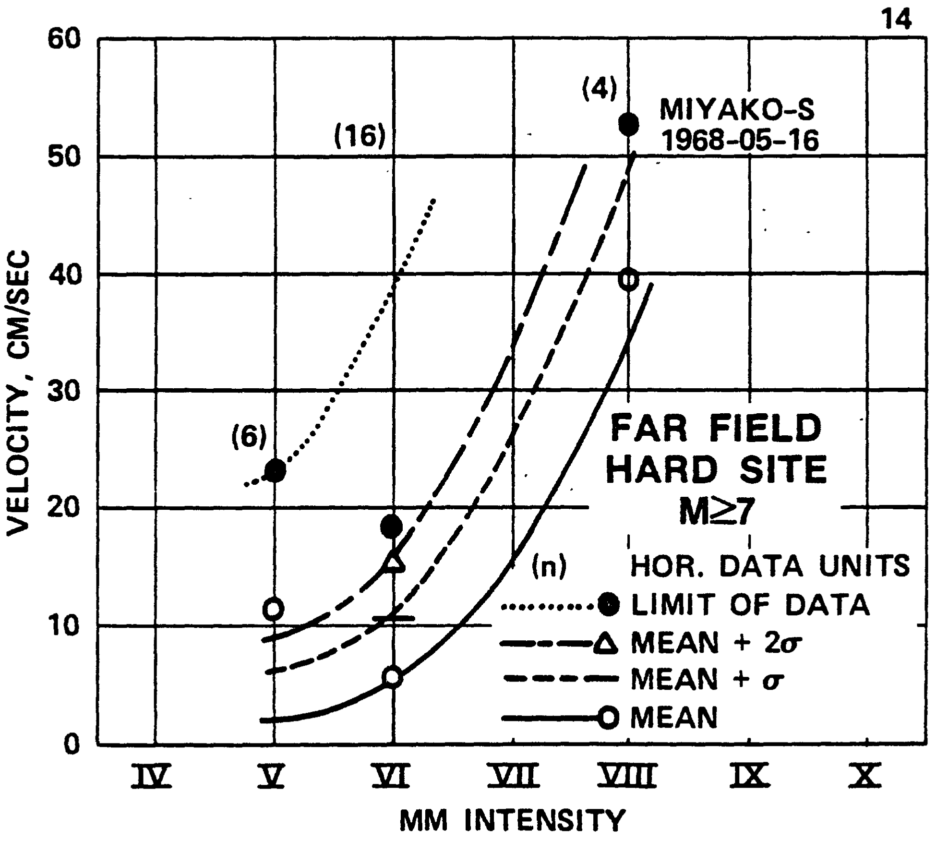

Figure 14. Velocity as a function of MM intensity for a far-field hard site, M ≥ 7.

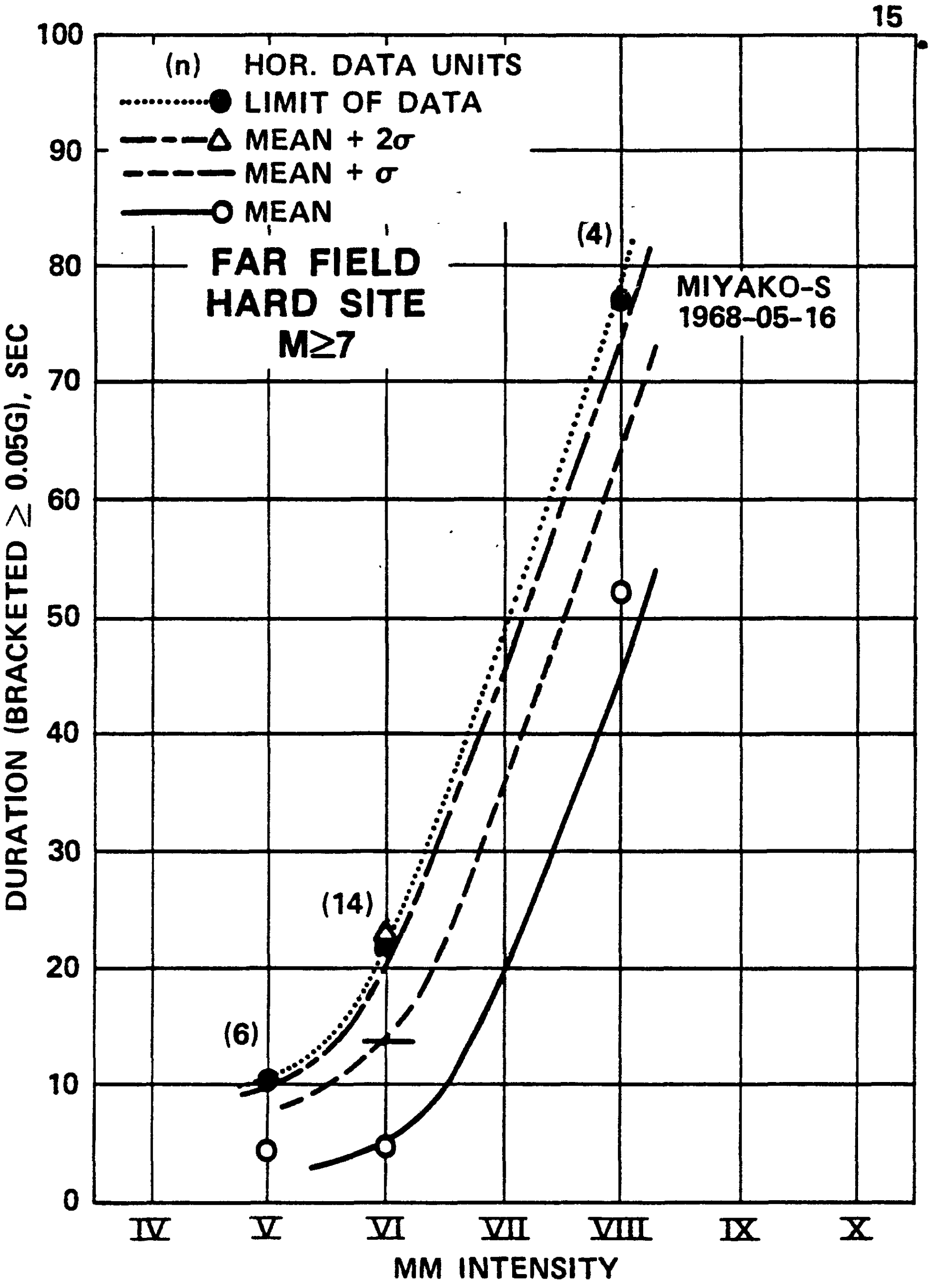

Figure 15. Duration as a function of MM intensity for a far-field hard site, $M \geq 7$.

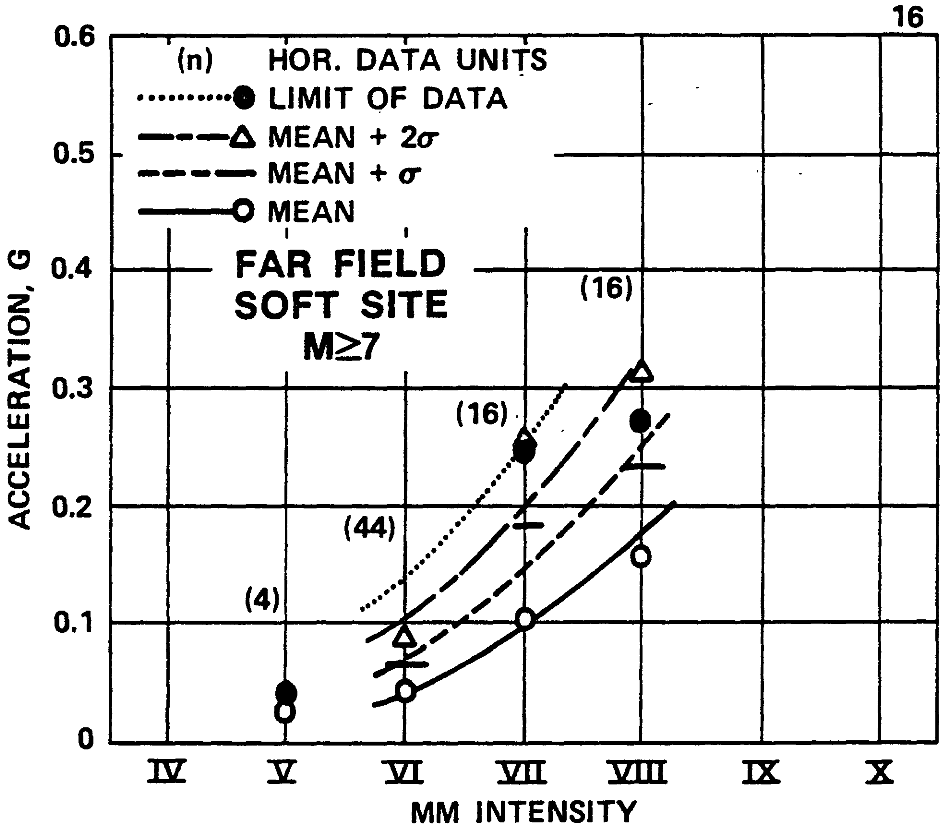

Figure 16. Acceleration as a function of MM intensity for a far-field soft site, M≥7.

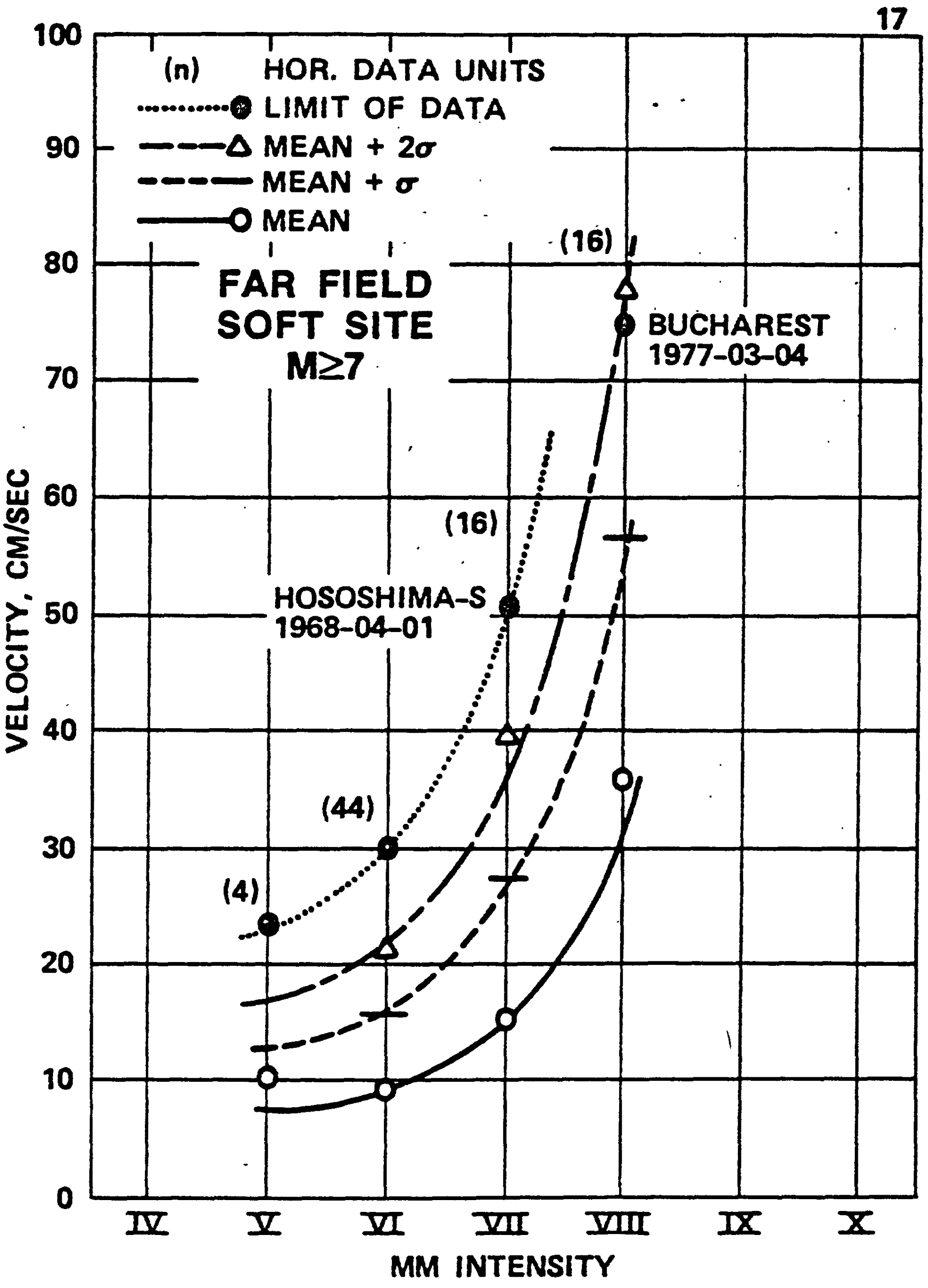

Figure 17. Velocity as a function of MM intensity for a far-field soft site, M ≥7.

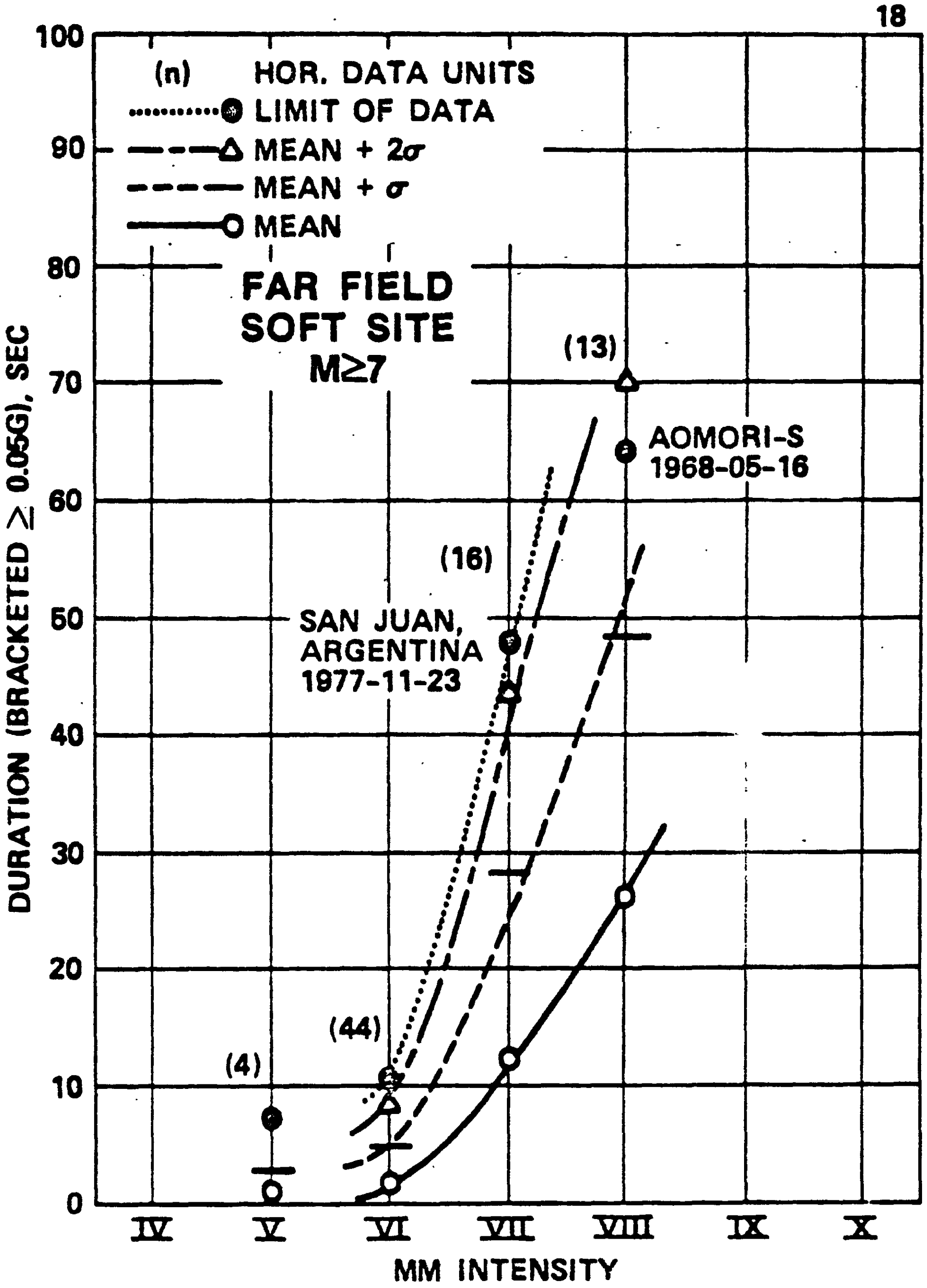

Figure 18. Duration as a function of MM intensity for a far-field soft site, $M \geq 7$.

7 GLOSSARY

Subcommittee 3 strongly recommends the development of a standard terminology for use in the evaluation of earthquake hazards and risk. The meanings given below are suggested for consideration and use. These meanings are consistent with those proposed by Earthquake Engineering Research Institute

Accelerogram. The record from an accelerometer showing acceleration as a function of time. The peak acceleration is the largest value of acceleration on the accelerogram.

Acceptable Risk. A probability of occurrences of social or economic consequences due to earthquakes that is sufficiently low (for example in comparison to other natural or manmade risks) as to be judged by appropriate authorities to represent a realistic basis for determining design requirements for engineered structures, or for taking certain social or economic actions.

Active fault. A fault is active if, because of its present tectonic setting, it can undergo movement from time to time in the immediate geologic future. This active state exists independently of the geologists' ability to recognize it. Geologists have used a number of characteristics to identify active faults, such as historic seismicity or surface faulting, geologically recent displacement inferred from topography or stratigraphy, or physical connection with an active fault. However, not enough is known of the behavior of faults to assure identification of all active faults by such characteristics.

Selection of the criteria used to identify active faults for a particular purpose must be influenced by the consequences of fault movement on the engineering structures involved.

Attenuation. A decrease in seismic signal strength with distance which depends not only on geometrical spreading, but also may be related to the physical characteristics of the transmitting medium that cause absorption and scattering.

Attenuation law. A description of the average behavior of one or more characteristics of earthquake ground motion as a function of distance from the source of energy.

b-value. A parameter indicating the relative frequency of earthquakes of different sizes derived from historical seismicity data.

Capable fault. A fault along which future surface displacement is possible, especially during the lifetime of the engineering project under consideration.

Design earthquake. A specification of the ground motion at a site based on integrated studies of historic seismicity and structural geology used for the earthquake-resistant design of a structure.

Design spectra. Spectra used in earthquake-resistant design which correlate with design earthquake ground motion values. Design spectra typically are smooth curves that take into account features peculiar to a geographic region and a particular site.

Design time history. One of a family of time histories used in earthquake-resistant design which produces a response spectrum enveloping the smooth design spectrum, for a selected value of damping.

Duration. A qualitative or quantitative description of the length of time during which ground motion at a site exhibits certain characteristics such as being equal to or exceeding a specified level of acceleration such as 0.05g.

Earthquake hazards. The probability that natural events accompanying an earthquake such as ground shaking, ground failure, surface faulting, tectonic deformation, and inundation, which may cause damage and loss of life, will occur at a site during a specified exposure time. See earthquake risk.

Earthquake risk. The probability that social or economic consequences of earthquakes, expressed in dollars or casualties, will equal or exceed specified values at a site during a specified exposure time.

Earthquake waves. Elastic waves (P, S, Love, Rayleigh) propagating in the Earth, set in motion by faulting of a portion of the Earth.

Effective peak acceleration. The peak ground acceleration after the ground-motion record has been filtered to remove the very high frequencies that have little or no influence upon structural response.

Epicenter. The point on the Earth's surface vertically above the point where the first fault rupture and the first earthquake motion occur.

Exceedance probability. The probability (for example, 10 percent) over some period of time that an event will generate a level of ground shaking greater than some specified level.

Exposure time. The period of time (for example, 50 years) that a structure is exposed to the earthquake threat. The exposure time is sometimes related to the design lifetime of the structure and is used in seismic risk calculations.

Fault. A fracture or fracture zone in the Earth along which displacement of the two sides relative to one another has occurred parallel to the fracture. See Active and Capable faults.

Focal depth. The vertical distance between the hypocenter and the Earth's surface in an earthquake.

Ground motion. A general term including all aspects of motion; for example, particle acceleration, velocity, or displacement; stress and strain; duration; and spectral content generated by a nuclear explosion, an earthquake, or another energy source.

Intensity. A numerical index describing the effects of an earthquake on the Earth's surface, on man, and on structures built by him. The scale in common use in the United States today is the Modified Mercalli scale of 1931 with intensity values indicated by Roman numerals from I to XII. The narrative descriptions of each intensity value are summarized below.

I. Not felt--or, except rarely under especially favorable circumstances. Under certain conditions, at and outside the boundary of the area in which a great shock is felt: sometimes birds and animals reported uneasy or disturbed; sometimes dizziness or nausea experienced; sometimes trees, structures, liquids, bodies of water, may sway--doors may swing, very slowly.

II. Felt indoors by few, especially on upper floors, or by sensitive, or nervous persons. Also, as in grade I, but often more noticeably: sometimes hanging objects may swing, especially when delicately suspended; sometimes trees, structures, liquids, bodies of water, may sway, doors may swing, very slowly; sometimes birds and animals reported uneasy or disturbed; sometimes dizziness or nausea experienced.

III. Felt indoors by several, motion usually rapid vibration. Sometimes not recognized to be an earthquake at first. Duration estimated in some cases. Vibration like that due to passing of light, or lightly loaded trucks, or heavy trucks some distance away. Hanging objects may swing slightly. Movements may be appreciable on upper levels of tall structures. Rocked standing motor cars slightly.

IV. Felt indoors by many, outdoors by few. Awakened few, especially light sleepers. Frightened no one, unless apprehensive from previous experience. Vibration like that due to passing of heavy or heavily loaded trucks. Sensation like heavy body of striking building or falling of heavy objects inside. Rattling of dishes, windows, doors;

glassware and crockery clink or clash. Creaking of walls, frame, especially in the upper range of this grade. Hanging objects swung, in numerous instances. Disturbed liquids in open vessels slightly. Rocked standing motor cars noticeably.

V. Felt indoors by practially all, outdoors by many or most; outdoors direction estimated. Awakened many or most. Frightened few--slight excitement, a few ran outdoors. Buildings trembled throughout. Broke dishes and glassware to some extent. Cracked windows--in some cases, but not generally. Overturned vases, small or unstable objects, in many instances, with occasional fall. Hanging objects, doors, swing generally or considerably. Knocked pictures against walls, or swung them out of place. Opened, or closed, doors and shutters abruptly. Pendulum clocks stopped, started or ran fast, or slow. Move small objects, furnishings, the latter to slight extent. Spilled liquids in small amounts from well-filled open containers. Trees and bushes shaken slightly.

VI. Felt by all, indoors and outdoors. Frightened many, excitement general, some alarm, many ran outdoors. Awakened all. Persons made to move unsteadily. Trees and bushes shaken slightly to moderately. Liquid set in strong motion. Small bells rang--church, chapel, school, etc. Damage slight in poorly built buildings. Fall of plaster in small amount. Cracked plaster somewhat, especially fine cracks chimneys in some instances. Broke dishes, glassware, in considerable quantity, also some windows. Fall of knickknacks, books, pictures. Overturned furniture in many instances. Move furnishings of moderately heavy kind.

VII. Frightened all--general alarm, all ran outdoors. Some, or many, found it difficult to stand. Noticed by persons driving motor cars. Trees and bushes shaken moderately to strongly. Waves on ponds, lakes, and running water. Water turbid from mud stirred up. Incaving to some extent of sand or gravel stream banks. Rang large church bells, etc. Suspended objects made to quiver. Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc. Cracked chimneys to considerable extent, walls to some extent. Fall of plaster in considerable to large amount, also some stucco. Broke numerous windows and furniture to some extent. Shook down loosened brickwork and tiles. Broke weak chimneys at the roof-line (sometimes damaging roofs). Fall of cornices from towers and high buildings. Dislodged bricks and stones. Overturned heavy furniture, with damage from breaking. Damage considerable to concrete irrigation ditches.

VIII. Fright general--alarm approaches panic. Disturbed persons driving motor cars. Trees shaken strongly--branches and trunks broken off, especially palm trees. Ejected sand and mud in small amounts. Changes: temporary, permanent; in flow of springs and wells; dry wells renewed flow; in temperature of spring and well waters. Damage slight in structures (brick) built especially to withstand earthquakes. Considerable in ordinary substantial buildings, partial collapse, racked, tumbled down, wooden houses in some cases; threw out panel walls in frame structures, broke off decayed piling. Fall of walls, cracked, broke, solid stone walls seriously. Wet ground to some extent, also ground on steep slopes. Twisting, fall, of chimneys, columns, monuments, also factory stacks, towers. Moved conspicuously, overturned, very heavy furniture.

IX. Panic general. Cracked ground conspicuously. Damage considerable in (masonry) buildings, some collapse in large part; or wholly shifted frame buildings off foundations, racked frames; serious to reservoirs; underground pipes sometimes broken.

X. Cracked ground, especially when loose and wet, up to widths of several inches; fissures up to a yard in width ran parallel to canal and stream banks. Landslides considerable from river banks and steep coasts. Shifted sand and mud horizontally on beaches and flat land. Changes level of water in wells. Threw water on banks of canals, lakes, rivers, etc. Damage serious to dams, dikes, embankments. Severe to well-built wooden structures and bridges, some destroyed. Developed dangerous cracks in excellent brick walls. Destroyed most masonry and frame structures, also their foundations. Bent railroad rails slightly. Tore apart, or crushed endwise, pipelines buried in earth. Open cracks and broad wavy folds in cement pavements and asphalt road surfaces.

XI. Disturbances in ground many and widespread, varying with ground material. Broad fissures, earth slumps, and land slips in soft, wet ground. Ejected water in large amounts charged with sand and mud. Caused sea-waves ("tidal" waves) of significant magnitude. Damage severe to wood-frame structures, especially near shock centers. Great to dams, dikes, embankments often for long distances. Few, if any (masonry) structures, remained standing. Destroyed large well-built bridges by the wrecking of supporting piers or pillars. Affected yielding wooden bridges less. Bent railroad rails greatly, and thrust them endwise. Put pipelines buried in each completely out of service.

XII. Damage total--practically all works of construction damaged greatly or destroyed. Disturbances in ground great and varied, numerous shearing cracks. Landslides, falls of rock of significant character, slumping of river banks, etc., numerous and extensive. Wrenched loose, tore off, large rock masses. Fault slips in firm rock, with notable horizontal and vertical offset displacements. Water channels, surface and underground, disturbed and modified greatly. Dammed lakes, produced waterfalls, deflected rivers, etc. Waves seen on ground surfaces (actually seen, probably, in some cases). Distorted lines of sight and level. Threw objects upward into the air.

Liquefaction. Temporary transformation of unconsolidated materials into a fluid mass.

Magnitude. A quantity characteristic of the total energy released by an earthquake, as contrasted to intensity that describes its effects at a particular place. Professor C. F. Richter devised the logarithmic scale for local magnitude (M_L) in 1935. Magnitude is expressed in terms of the motion that would be measured by a standard type of seismograph located 100 km from the epicenter of an earthquake. Several other magnitude scales in addition to M_L are in use; for example, body-wave magnitude (m_b) and surface-wave magnitude (M_s), which utilize body waves and surface waves, and local magnitude (M_L). The scale is open ended, but the largest known earthquake have had M_s magnitudes near 8.9.

Region. A geographical area, surrounding and including the construction site, which is sufficiently large to contain all the geologic features related to the evaluation of earthquake hazards at the site.

Response spectrum. The peak response of a series of simple harmonic oscillators having different natural periods when subjected mathematically to a particular earthquake ground motion. The response spectrum may be plotted as a curve on tripartite logarithmic graph paper showing the variations of the peak spectral acceleration, displacement, and velocity of the oscillators as a function of vibration period and damping.

Return period. For ground shaking, return period denotes the average period of time or recurrence interval between events causing ground shaking that exceeds a particular level at a site; the reciprocal of annual probability of exceedance. A return period of 475 years means that, on the average, a particular level of ground motion will be exceeded once in 475 years.

Risk. See earthquake risk.

Rock. Any solid rock either at the surface or underlying soil having a shear-wave velocity 2,500 ft/sec (765 m/s) at small (0.0001 percent) strains.

Seismic zone. A generally large area within which seismic design requirements for structures are uniform.

Seismotectonic province. A geographic area characterized by similarity of geological structure and earthquake characteristics. The tectonic processes causing earthquakes have been identified in a seismotectonic province.

Source. The source of energy release causing an earthquake. The source is characterized by one or more variables, for example, magnitude stress drop, seismic moment. Regions can be divided into areas having spatially homogeneous source characteristics.

Strong motion. Ground motion of sufficient amplitude to be of engineering interest in the evaluation of damage due to earthquakes or in earthquake-resistant design of structures.