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METHODOLOGY FOR MITIGATION OF SEISMIC HAZARDS IN EXISTING UNREINFORCED MASONRY BUILDINGS:

SEISMIC INPUT

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FOREWORD

This topical report is one of several reports prepared by ABK, a Joint Venture, for the National Science Foundation under Contract No. NSF-C-PFR78-19200. The overall objective of the contract is to derive a methodology for the mitigation of seismic hazards in existing unreinforced masonry buildings. This research supports the objective of the Disaster and Natural Hazard Research being conducted under the Applied Science and Research Applications program of the National Science Foundation.

The joint venture ABK consists of the three firms, Agbabian Associates (AA), S.B. Barnes & Associates (SBB&A), and Kariotis & Associates (K&A), all in the Los Angeles area. The principal investigators for the three firms are R.D. Ewing for AA, A.W. Johnson for SBB&A, and J.C. Kariotis for K&A. The editor is J. Athey of AA.

This report presents the selection of earthquake ground motion time histories for analysis and testing of unreinforced masonry buildings and components. It utilizes the Applied Technology Council (1978) procedure for specifying earthquake ground shaking. Principal contributors to this report are S.A. Adham from AA and J.C. Kariotis from K&A.

Dr. J.B. Scalzi served as Technical Director of this project for the National Science Foundation and maintained scientific and technical liaison with the joint venture throughout all phases of the research program. His contributions and support are greatly appreciated.

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EXECUTIVE SUMMARY

Current procedures for the development of earthquake input ground motions for analysis and testing of unreinforced masonry (URM) buildings and components are discussed in this report. The Applied Technology Council 3-06 Report (ATC, 1978) provided a state-of-the-art tool for specifying earthquake ground shaking within a seismic zone in the United States. This report results from a comprehensive effort by a large group of earthquake engineering experts. Although the ATC procedure is still being reviewed and tested, it represents the consensus of opinion on a subject that has many different points of view. Therefore, this research program for the analysis and testing of URM buildings selected its time-history input based on the ATC procedure. However, other rational methods for developing seismic input at a site can be used.

Representative URM buildings at seven U.S. geographical regions were studied under this research program. These regions are designated in the maps shown in Figures 1 and 2, with contours marking four different levels of acceleration. For design purposes, the ATC-3 report furnishes types of earthquake motion at different areas across the United States. The coefficients A_a and A_v (for EPA and EPV, respectively) are used to construct response spectra for earthquake motions at different zones, as illustrated in Figure 3, and can be derived from these maps.

The response spectra for 5% damping for the seven geographical regions selected for this study are shown in Figures 4, 5, and 6. An ensemble of six time-history records was selected to match the ATC spectrum for each region and provide a bound on the design ground motion expected; this accounts for statistical variations in earthquake motions.

Two earthquake components were selected from the ensemble of six records for the time-history nonlinear analysis and testing of URM buildings in the

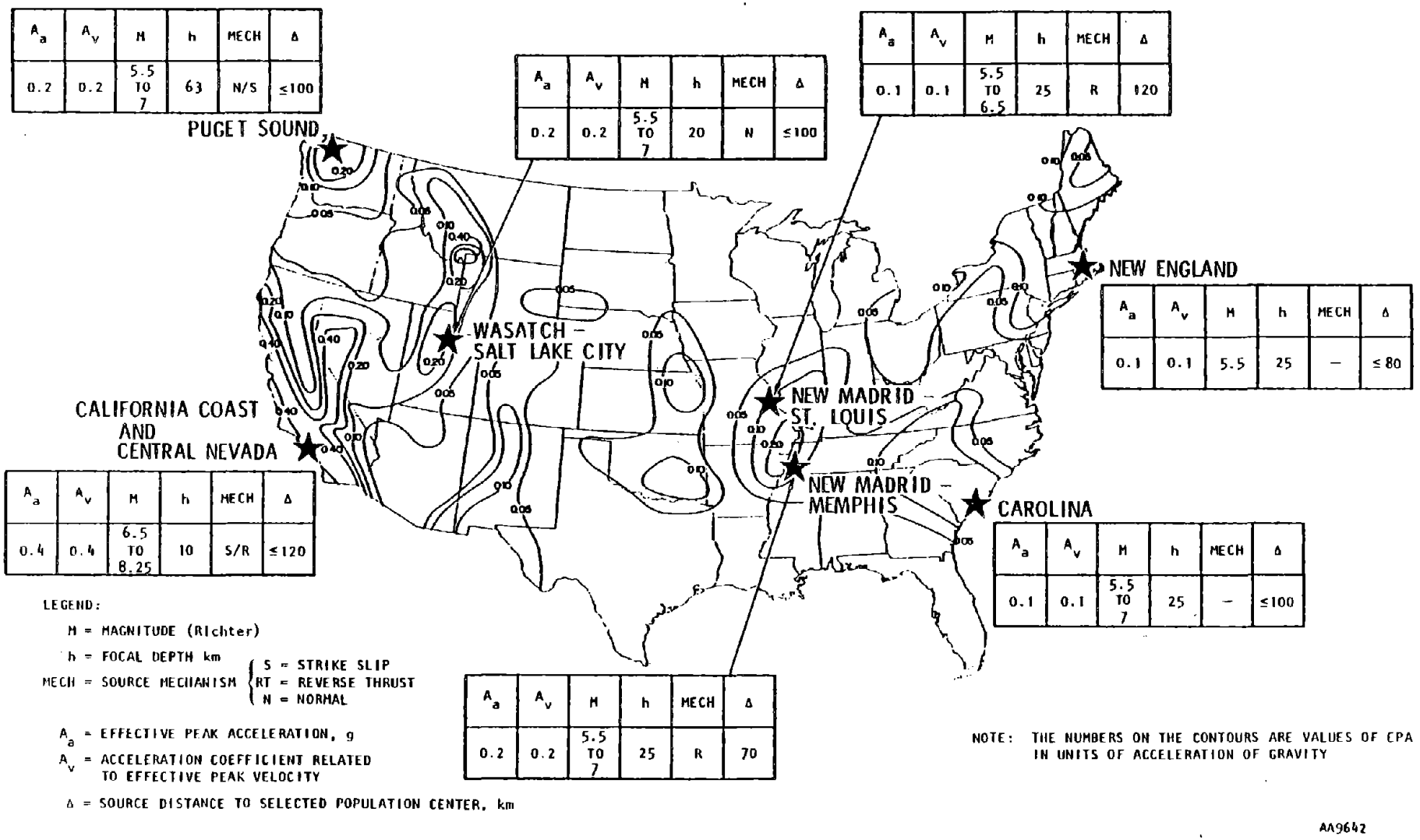
California Coast and Central Nevada region. These components provided the best match for the ATC spectrum for this region. The two spectra are shown in Figures 7 and 8.

The scaled N69W component of 1971 Castaic was selected for the Wasatch-Salt Lake City region, while the scaled S04E components of 1949 Olympia was selected for Puget Sound and New Madrid-Memphis regions (Figs. 9 and 10). The scaled E-W component of 1971 Hollywood Storage P.E. was selected for the New Madrid-St. Louis area (Fig. 11). The scaled N21E component of the 1954 Taft record was selected for time-history analysis and testing of URM buildings in Carolina and New England regions (Fig. 12).

The following table matches the seven regions with their appropriate earthquake record.

SELECTED EARTHQUAKE RECORDS FOR SEVEN U.S. REGIONS

Geographical Region	Effective Peak Acceleration, g	Earthquake Record	Scale Factor
New England Carolina	0.1	Taft, 1954, N21E	1.6
New Madrid-St. Louis	0.1	Hollywood Storage P.E. Lot, 1971, N90E	0.5
Puget Sound New Madrid-Memphis	0.2	Olympia, 1949, S04E	1.1
Wasatch-Salt Lake City	0.2	Castaic, 1971, N69W	1.0
California Coast and Central Nevada	0.4	Castaic, 1971, N69W	1.8
California Coast and Central Nevada	0.4	El Centro, 1940, S00E	1.25



A_a	A_v	M	h	MECH	Δ
0.2	0.2	5.5 TO 7	63	N/S	≤100

A_a	A_v	M	h	MECH	Δ
0.2	0.2	5.5 TO 7	20	N	≤100

A_a	A_v	M	h	MECH	Δ
0.1	0.1	5.5 TO 6.5	25	R	120

A_a	A_v	M	h	MECH	Δ
0.1	0.1	5.5	25	–	≤ 80

A_a	A_v	M	h	MECH	Δ
0.4	0.4	6.5 TO 8.25	10	S/R	≤120

A_a	A_v	M	h	MECH	Δ
0.1	0.1	5.5 TO 7	25	–	≤100

A_a	A_v	M	h	MECH	Δ
0.2	0.2	5.5 TO 7	25	R	70

FIGURE 1. SUMMARY OF SEISMIC INPUT DATA FOR SEVEN MAJOR U.S. GEOGRAPHICAL REGIONS (Adapted from ATC, 1978)

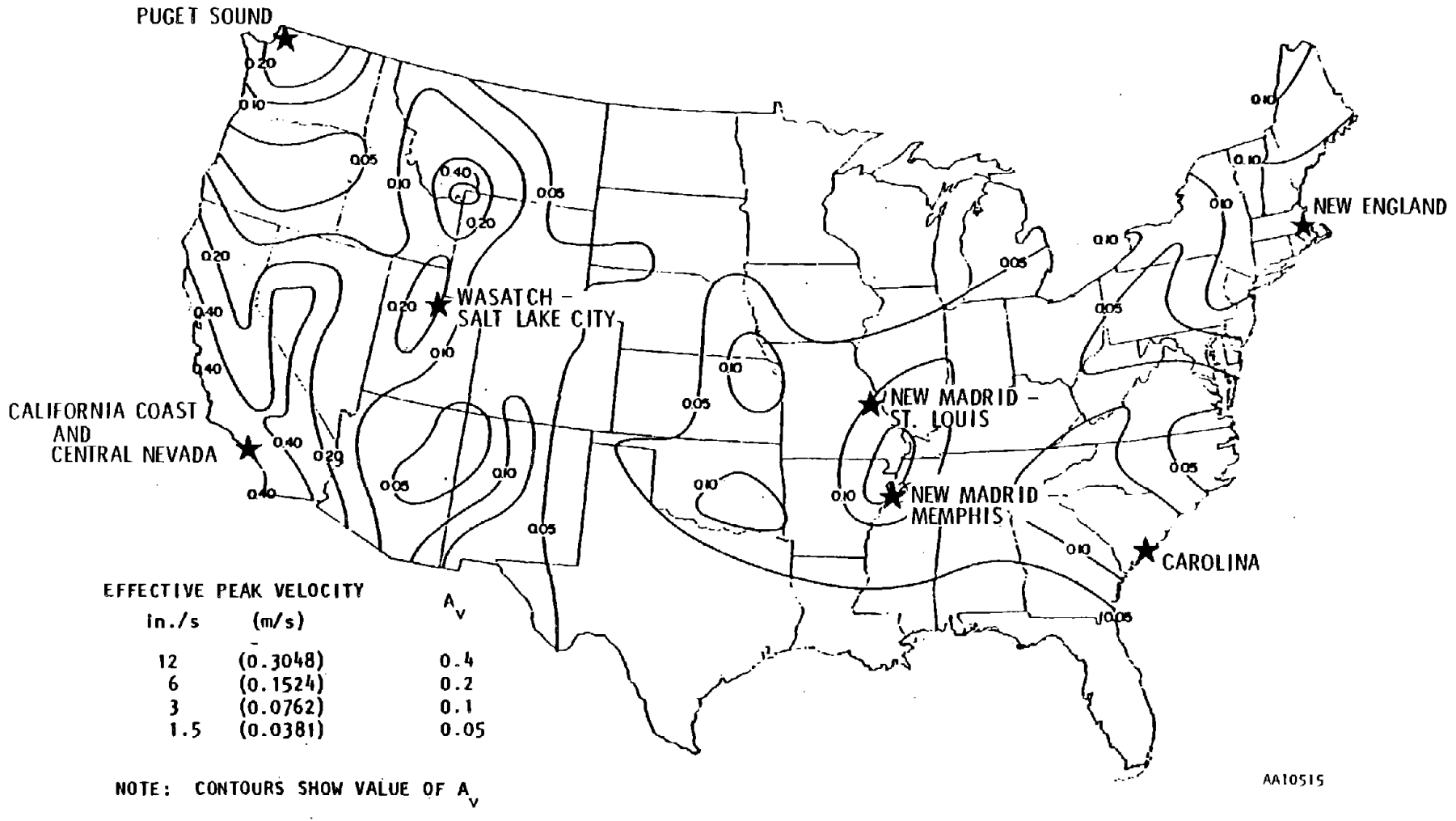


FIGURE 2. LOCATION OF SEVEN SELECTED MAJOR U.S. GEOGRAPHICAL REGIONS ON EFFECTIVE PEAK VELOCITY MAP (from ATC, 1978)

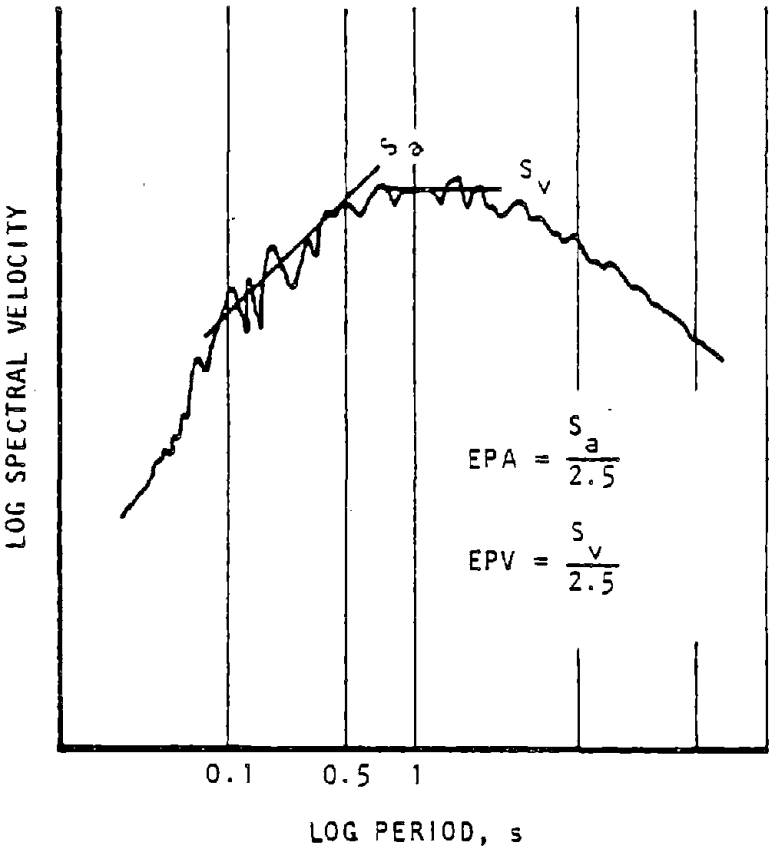


FIGURE 3. SCHEMATIC REPRESENTATION SHOWING HOW EFFECTIVE PEAK ACCELERATION AND EFFECTIVE PEAK VELOCITY ARE OBTAINED FROM A RESPONSE SPECTRUM

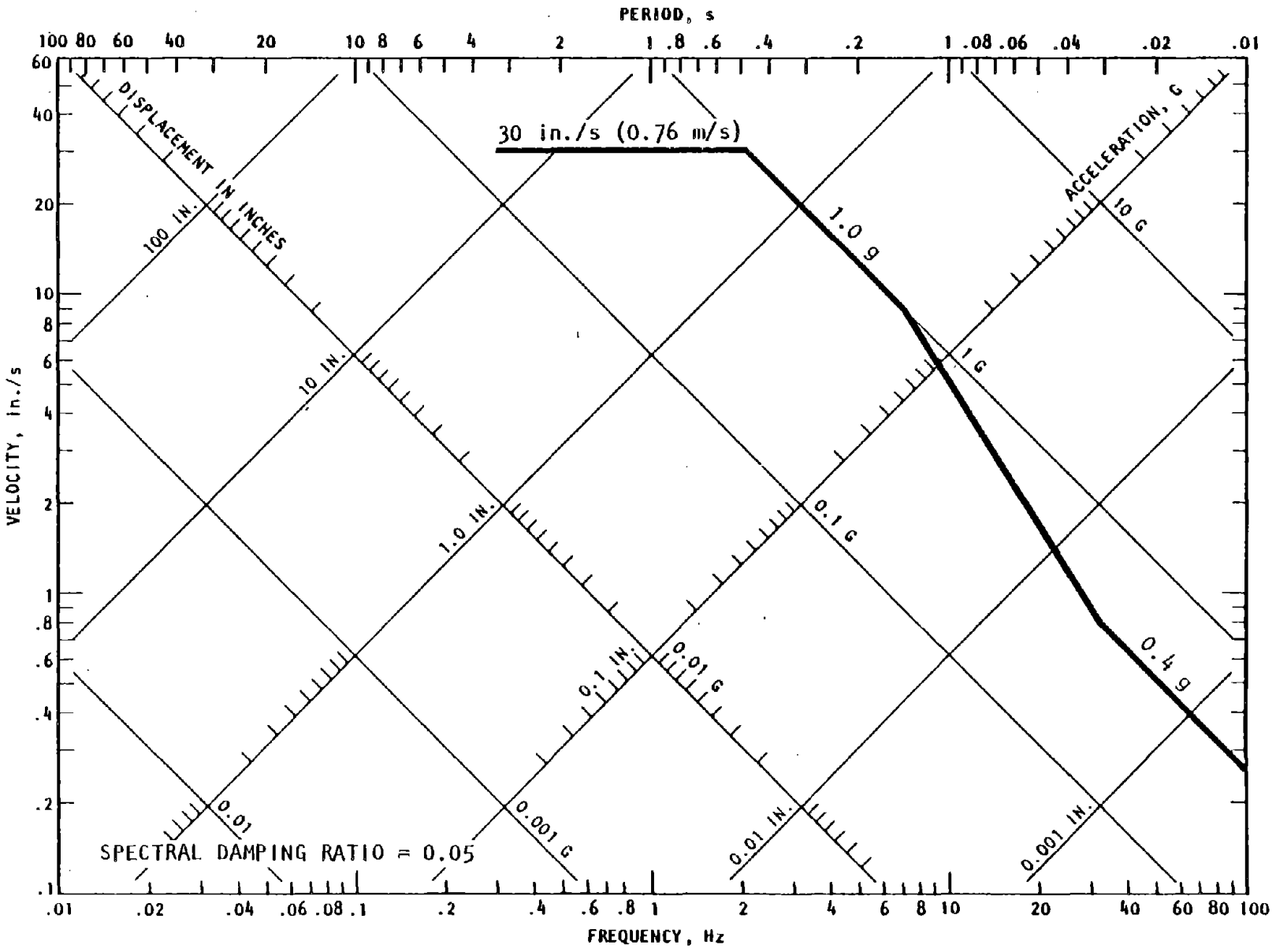


FIGURE 4. ATC GROUND MOTION RESPONSE SPECTRUM FOR THE CALIFORNIA COAST AND CENTRAL NEVADA REGION (A_a = 0.40, A_v = 0.40)

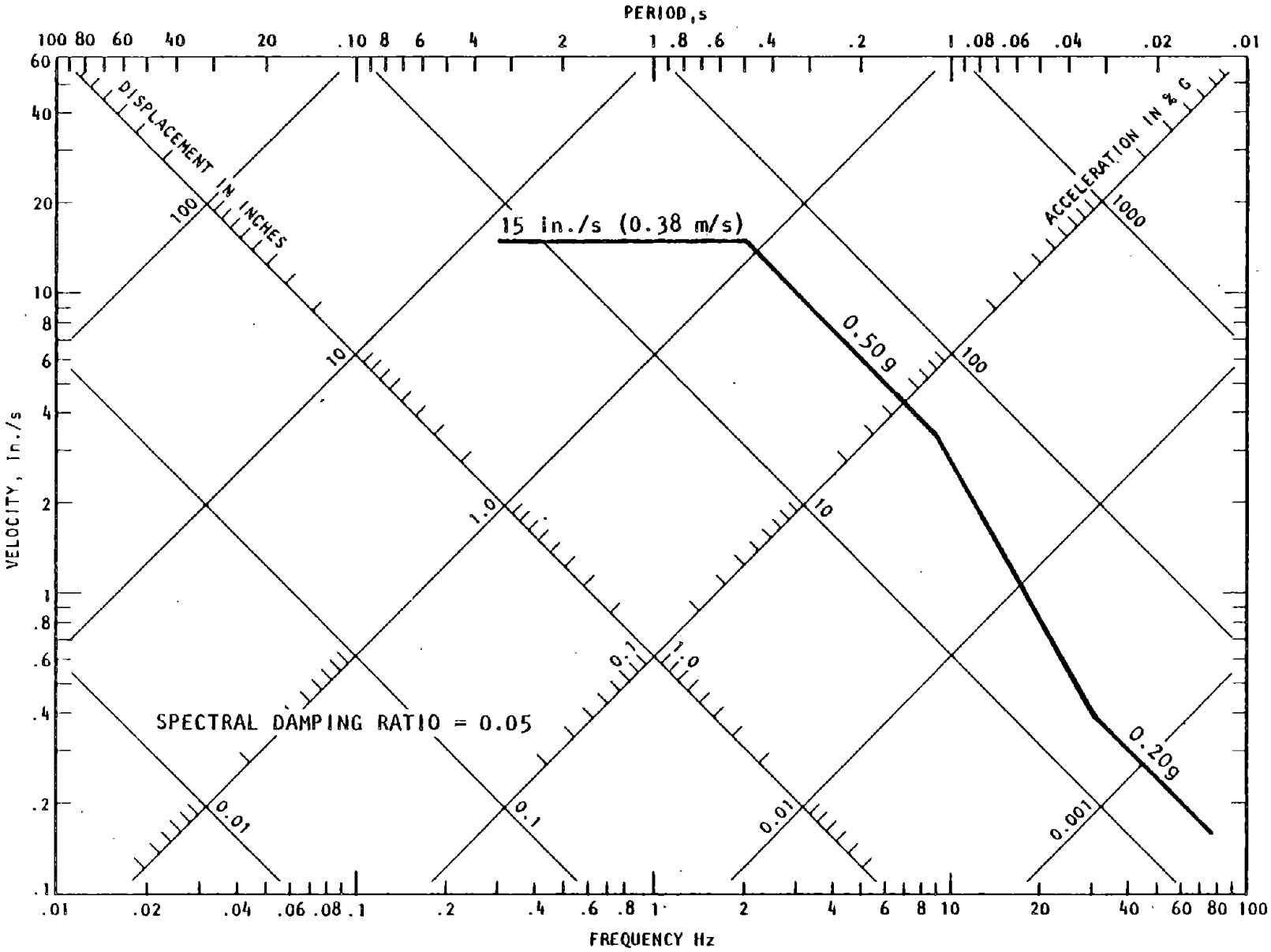


FIGURE 5. ATC GROUND MOTION RESPONSE SPECTRUM FOR THE PUGET SOUND, WASATCH-SALT LAKE CITY, AND NEW MADRID-MEMPHIS REGIONS (A_a = 0.20, A_v = 0.20)

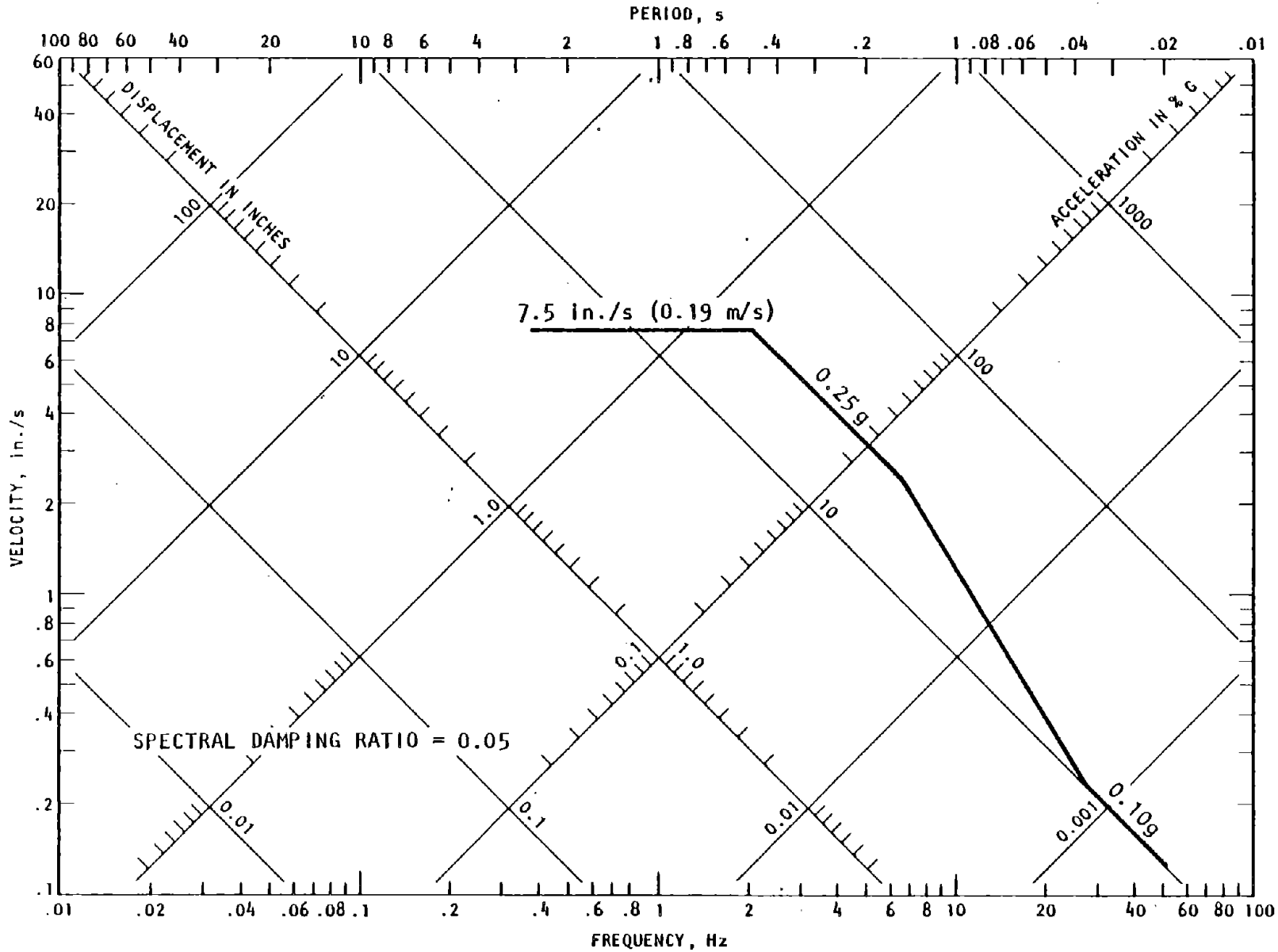


FIGURE 6. ATC GROUND MOTION RESPONSE SPECTRUM FOR NEW MADRID-ST. LOUIS, CAROLINA, AND NEW ENGLAND REGIONS (A_a = 0.10, A_v = 0.10)

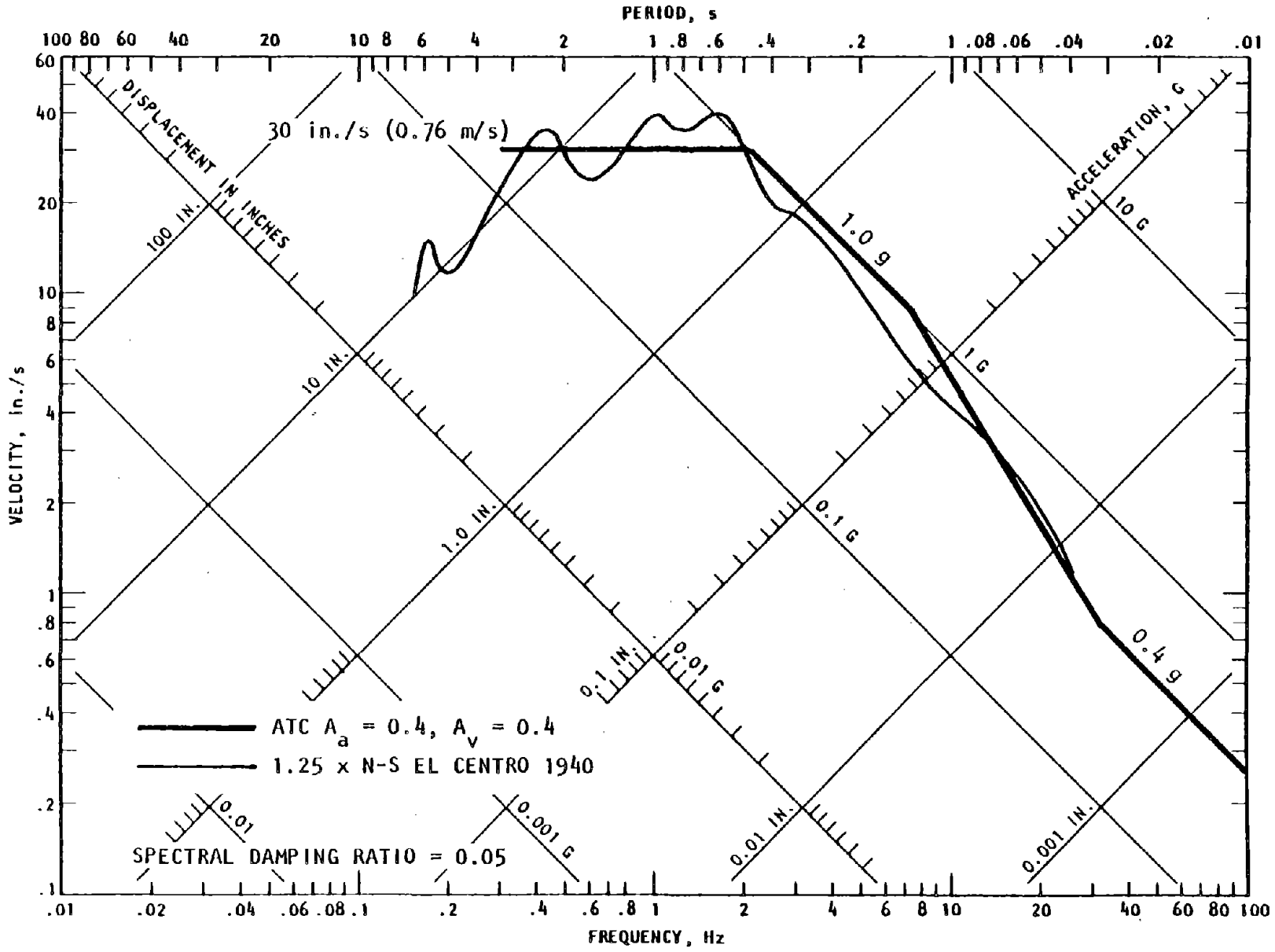


FIGURE 7. COMPARISON OF ATC SPECTRA FOR CALIFORNIA COAST AND CENTRAL NEVADA REGION AND N-S EL CENTRO 1940 SCALED BY A FACTOR OF 1.25

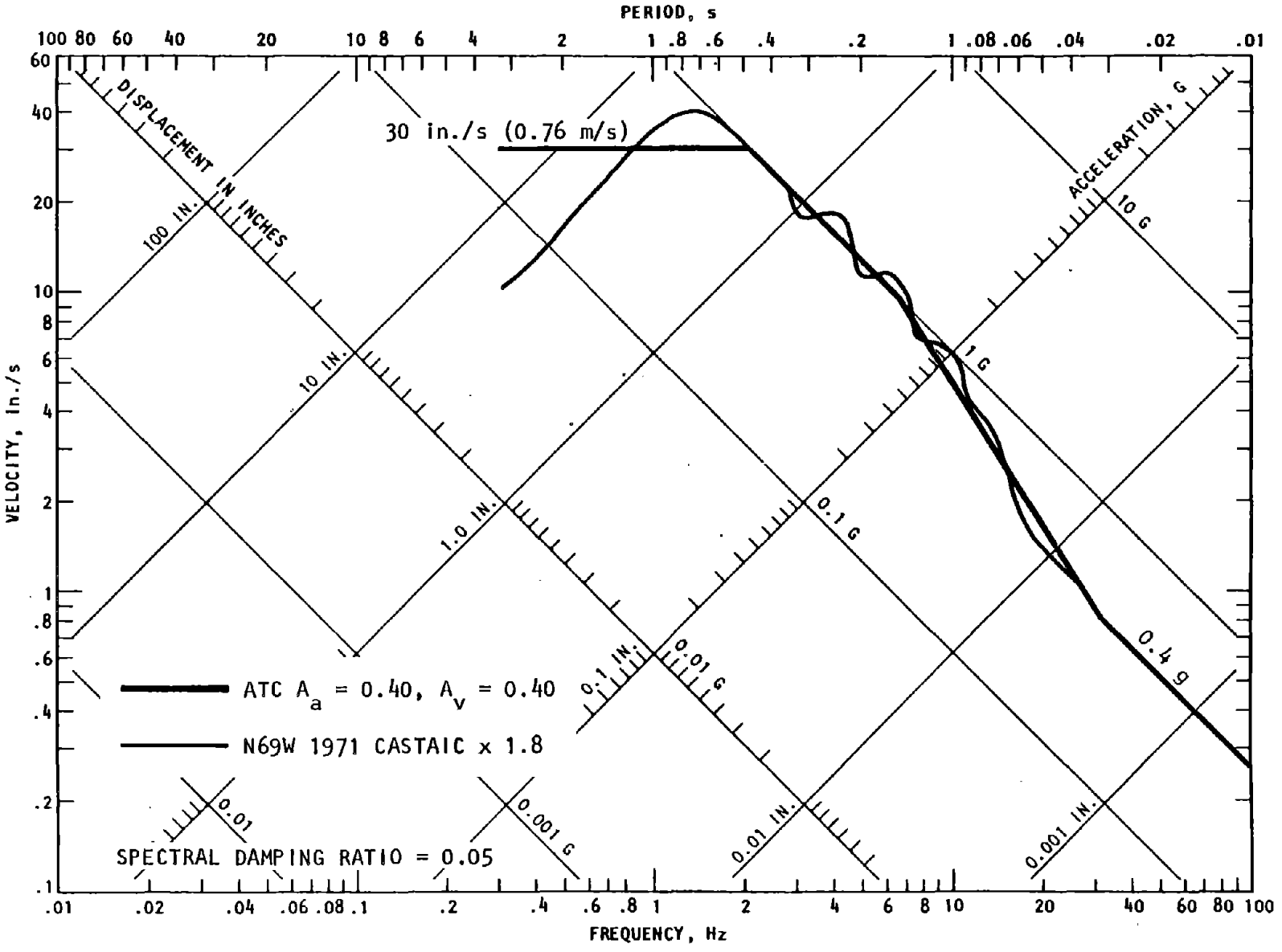


FIGURE 8. COMPARISON OF ATC SPECTRA FOR CALIFORNIA COAST AND CENTRAL NEVADA REGION AND 1971 CASTAIC SCALED BY A FACTOR OF 1.8

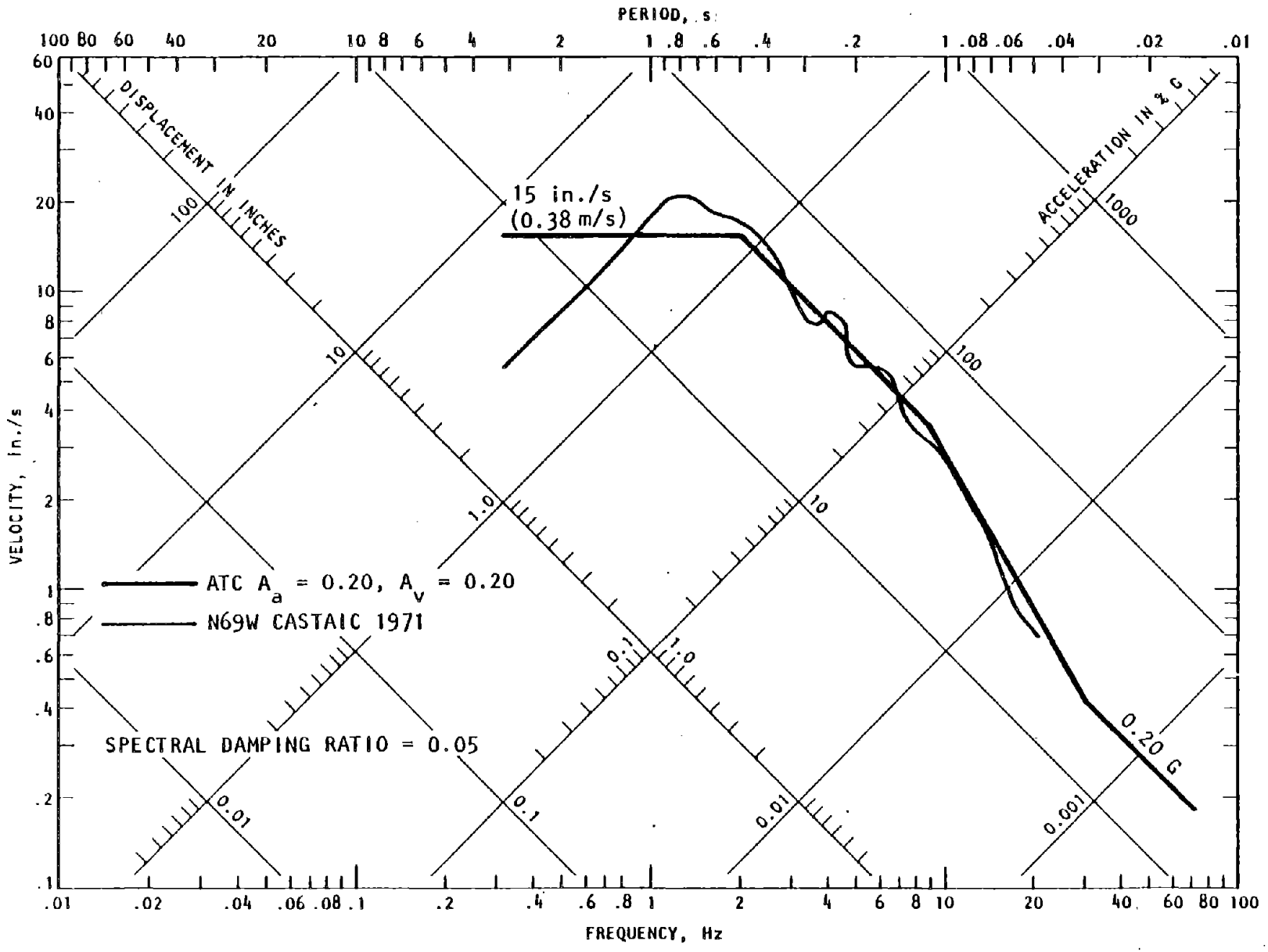


FIGURE 9. COMPARISON OF ATC RESPONSE SPECTRA FOR PUGET SOUND, WASATCH-SALT LAKE CITY, NEW MADRID-MEMPHIS REGIONS AND THE N69W CASTAIC 1971

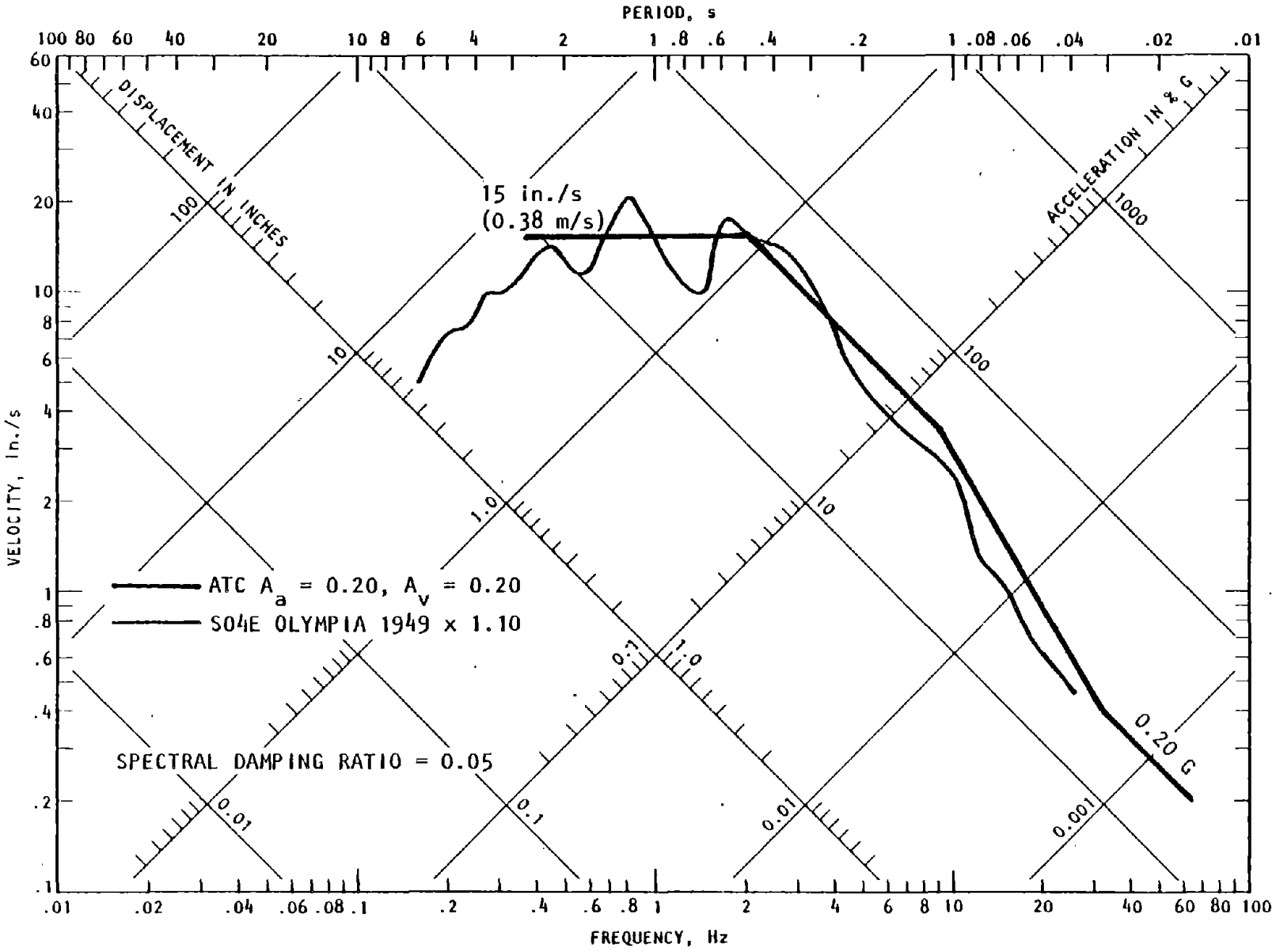


FIGURE 10. COMPARISON OF ATC RESPONSE SPECTRA FOR PUGET SOUND, WASATCH-SALT LAKE CITY, NEW MADRID-MEMPHIS REGIONS AND THE S04E OLYMPIA 1949 SCALED BY A FACTOR OF 1.10

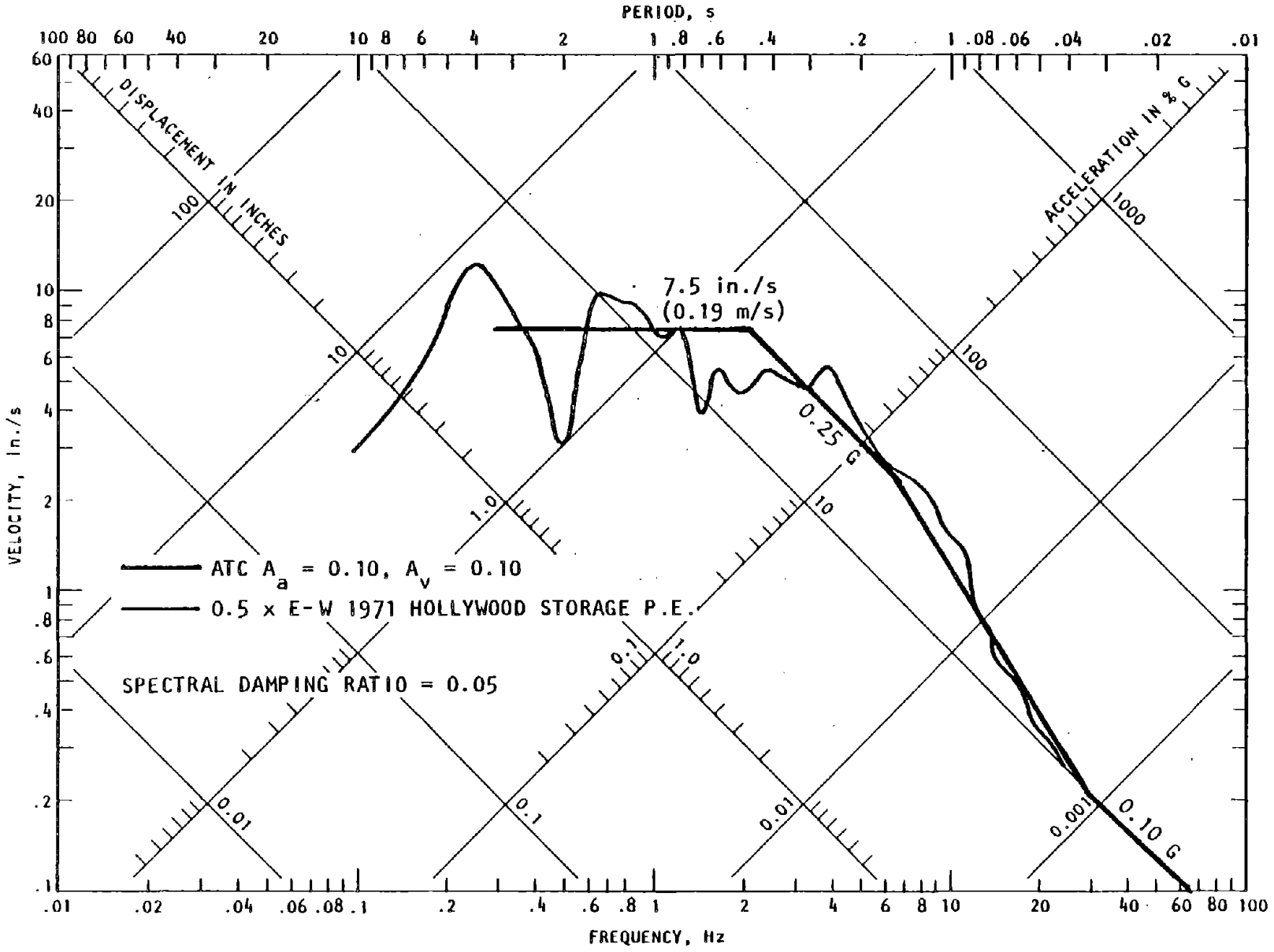


FIGURE 11. COMPARISON OF ATC SPECTRA FOR NEW MADRID-ST. LOUIS, CAROLINA, NEW ENGLAND REGIONS AND E-W HOLLYWOOD STORAGE P.E. 1971 SCALED BY A FACTOR OF 0.50

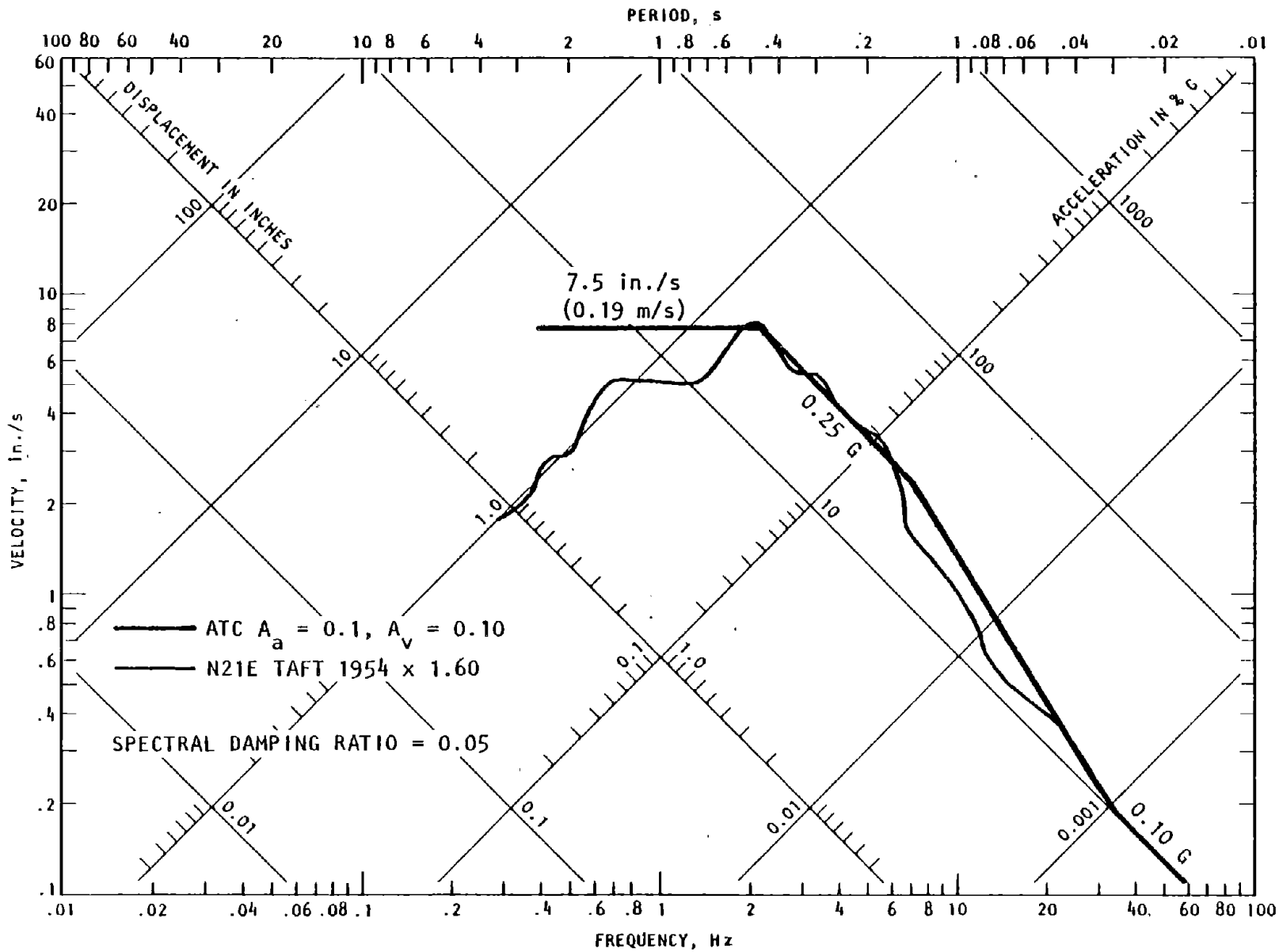


FIGURE 12. COMPARISON OF ATC SPECTRA FOR NEW MADRID-ST. LOUIS, CAROLINA, NEW ENGLAND REGIONS AND N21E TAFT 1954 SCALED BY A FACTOR OF 1.60

SECTION 1

INTRODUCTION

This topical report presents the selection of time-history input for analysis and testing of unreinforced masonry (URM) buildings and components subjected to earthquake ground motions. The Applied Technology Council procedure (ATC, 1978) for specifying earthquake ground shaking is discussed in detail, while current methods for selecting earthquake ground motion input are summarized in the Appendixes.

This report can be placed within the general framework of a larger research project, the overall objectives of which are described in the following paragraphs. This introduction also describes the importance of and the reliance on time histories for the analysis.

Section 2 presents the ATC procedures for specifying ground shaking, using two ATC regional maps. Procedures specific to this study are given in Sections 3 and 4, with Section 3 providing a summary of seismic input for seven geographical regions in the United States and Section 4 providing the concluding ensemble of time histories based on the ATC spectra that can be used for analysis of URM buildings in these geographical regions. General information about earthquakes and their mechanisms is presented in Appendix A. Risk analysis methods and development of design earthquakes are described in Appendices B through F. Appendix G gives the time-history and Fourier spectra of earthquake records for selected sites.

1.1 RESEARCH OBJECTIVE

A 24-month research study was undertaken by ABK, a joint venture comprised of the three firms of Agbabian Associates, S.B. Barnes & Associates, and Kariotis, Kesler & Allys. Their research derived a methodology for the mitigation of seismic hazards in existing URM buildings. The study program was structured to support the objective of Disaster and Natural Hazard Research being conducted under the Applied Science and Research Applications (ASRA) program of the National Science Foundation.

The program is divided into two major efforts, resulting in a series of published reports. The first effort evaluates codes and standards applicable to URM buildings, categorizes nationwide existing masonry construction, evaluates current methods for selecting earthquake ground motion input, categorizes URM damage from past earthquakes, reviews strength data for URM, assesses analytical methods for evaluating URM, and evaluates retrofit methods. In the second effort, a program for analytical verification and testing, including retrofit, is conducted. Both quasi-static and dynamic tests are performed on wood and metal diaphragms and on URM walls subjected to out-of-plane forces. Wall sections subjected to in-plane forces and anchorages are tested. The results of both efforts are integrated in the development of the recommended methodology.

1.2 REQUIRED EARTHQUAKE GROUND MOTION INPUT

Time histories of ground motions are needed for input to proposed analytical models. These models represent wall elements responding to in-plane seismic motions and to seismic forces normal to the wall plane, horizontal diaphragms, and torsional modes of irregular URM buildings. The analysis models require response behavior corresponding to nonlinear models with hysteretic force-displacement plots. It is anticipated that behavior of elements to be tested in a dynamic environment cannot be represented as elastic.

Review of prior tests indicates that (1) for diaphragm test specimens, force-displacement plots are hysteretic; (2) for URM walls tested on a shaking table (ATC-5 Project, UC Berkeley) for ground motions perpendicular to their plane, the collapse displacements are sensitive to the time histories of the input motions; (3) for in-plane dynamic forces, stress computations on URM walls are dependent on estimates of relative story level excursions; and (4) for vertical load carrying systems, predictions of dynamic instability are dependent on upper bounds of relative story level excursions.

1.3 PROCEDURE FOR SPECIFYING REQUIRED EARTHQUAKE GROUND MOTIONS

Various methods have been used to specify earthquake ground shaking at a site (Appendices A through F). The Applied Technology Council 3-06 Report provided a state-of-the-art tool for specifying earthquake ground shaking within a seismic zone in the United States (ATC, 1978). This report was a result of a comprehensive effort of a large group of earthquake engineering experts. The report divided the United States into different seismic zones and specified response spectra associated with these zones. These spectra represent earthquakes that have an accepted probability of occurrence. Each response spectrum is assigned an effective peak acceleration, in addition to an effective peak velocity associated with each seismic zone. The effective peak velocity provides an envelope for motions in the intermediate period range.

The ATC procedure for specifying earthquake ground shaking at various areas was used in the ABK program. However, other rational methods for providing site-specific earthquake input can be considered for the evaluation of unreinforced masonry buildings at a specific site. These site-specific motions should be associated with the probability level given by the ATC document to provide an equivalent design earthquake. Therefore, the methodology developed in this research, while using the ATC procedure to develop seismic input, can accommodate other types of procedures for developing earthquake inputs as well.

1.4 LIMITATIONS OF SELECTED PROCEDURE

The library of U.S. time-history records available for analysis and dynamic testing is mostly based on earthquakes that have been recorded in the western United States and are, for the most part, specific to sites and geology. This geographical limitation can be minimized by the procedures used in this report. Generally, an analyst would prefer to use an ensemble of several earthquake time histories that match the selected design criteria to determine mean data and coefficient of variation. This procedure is applicable to simple analytical models that respond linearly to all input motions. However, for more complex systems that respond nonlinearly to input motions,

the cost of running an ensemble of time-history analyses cases would be expensive. Also, dynamic response of a nonlinear model does not have a dominant relationship to the original elastic period of the model. Period-related variations in time histories of earthquakes, scaled to the ATC spectral shapes, are not significantly reflected in dynamic response. Therefore, judgment should be used in selecting one or two earthquake records that most nearly represent the characteristics of design earthquake motions for a seismic hazard zone. This procedure is consistent with the much more generalized approach of establishing bounds on the performance of both analytical models and test specimens.

The results of the analysis and testing must be generalized to encompass the existing inventory of URM buildings and provide bounds on the response of these buildings in a specific zone. To accomplish this goal, Section 4 provides an ensemble of six time-history records for each seismic hazard geographical region and selects a minimum of one time-history record for the nonlinear analysis or testing of a representative building within the region.

SECTION 2

PROCEDURE OUTLINED BY APPLIED TECHNOLOGY COUNCIL FOR SPECIFICATION OF EARTHQUAKE GROUND SHAKING

2.1 INTRODUCTION

This section describes the procedure outlined by the Applied Technology Council 3-06 report, a state-of-the-art tool for specifying earthquake ground shaking within a zone in the United States (ATC, 1978). A discussion of the seismic risk specified by this procedure is also given.

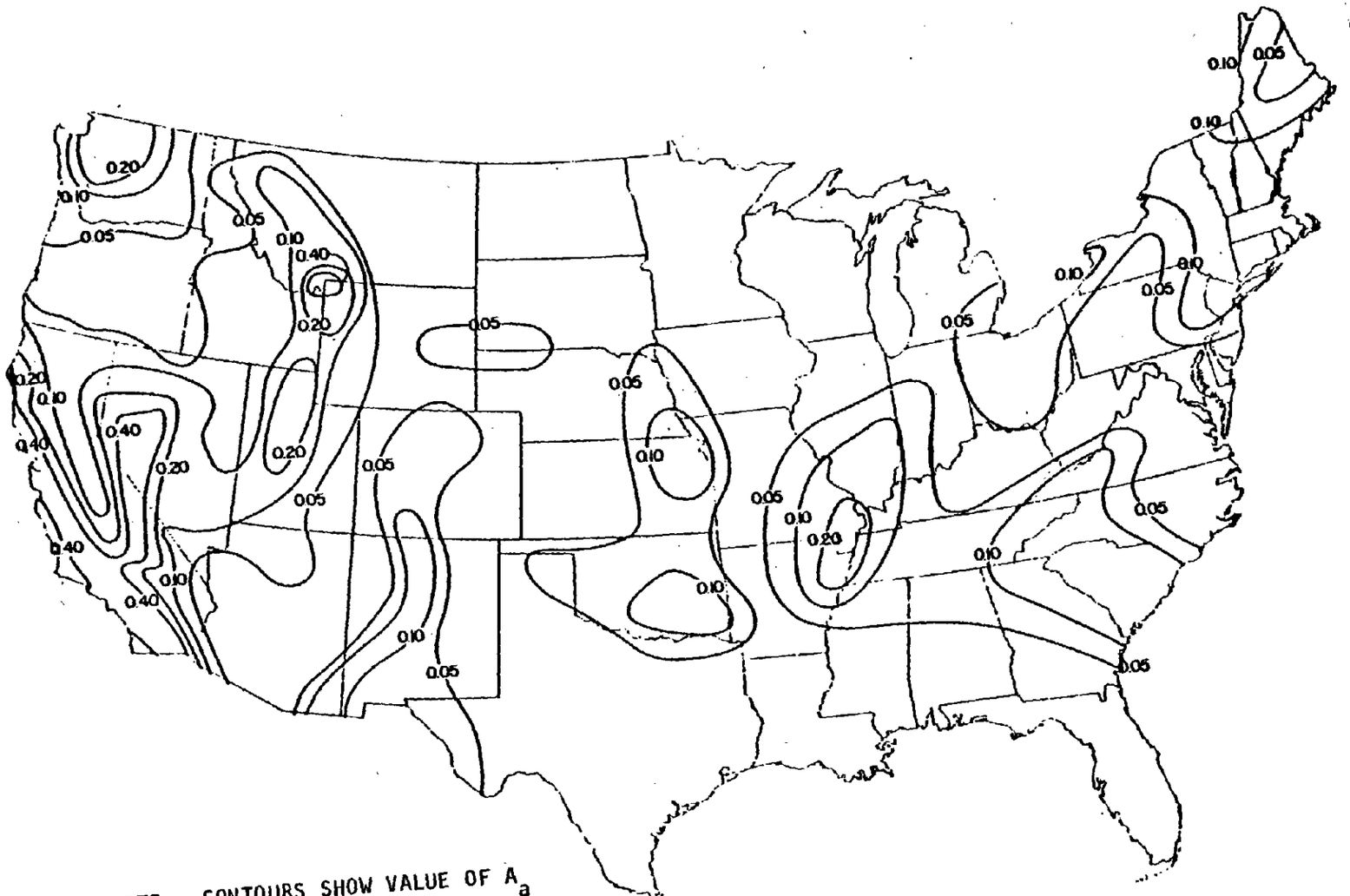
2.2 ATC MAPS

Two earthquake ground shaking regionalization maps were developed by ATC (Figs. 2-1 and 2-2). These maps are based on the following rules: (1) the design lateral force should take into account the distance from anticipated earthquake sources; (2) the probability of exceeding the design ground shaking should, as a goal, be roughly the same in all parts of the country; and (3) the regionalization maps should not attempt to delineate microzones. Any such microzonation should be done by experts who are familiar with the local conditions. See the ATC-3 report (1978) for a complete description of these maps.

The development of the Effective Peak Acceleration (EPA) map (Fig. 2-1) was facilitated by the work of Algermissen and Perkins (1976). Their map, reproduced in Figure 2-3, is based on the principles of seismic risk (Cornell, 1968; Algermissen and Perkins, 1972). ATC-3 (1978) summarized the steps involved in the preparation of such a map as follows:

a. Source zones and faults, in which or along which significant earthquakes can occur, are identified and brought together on a source zone map.

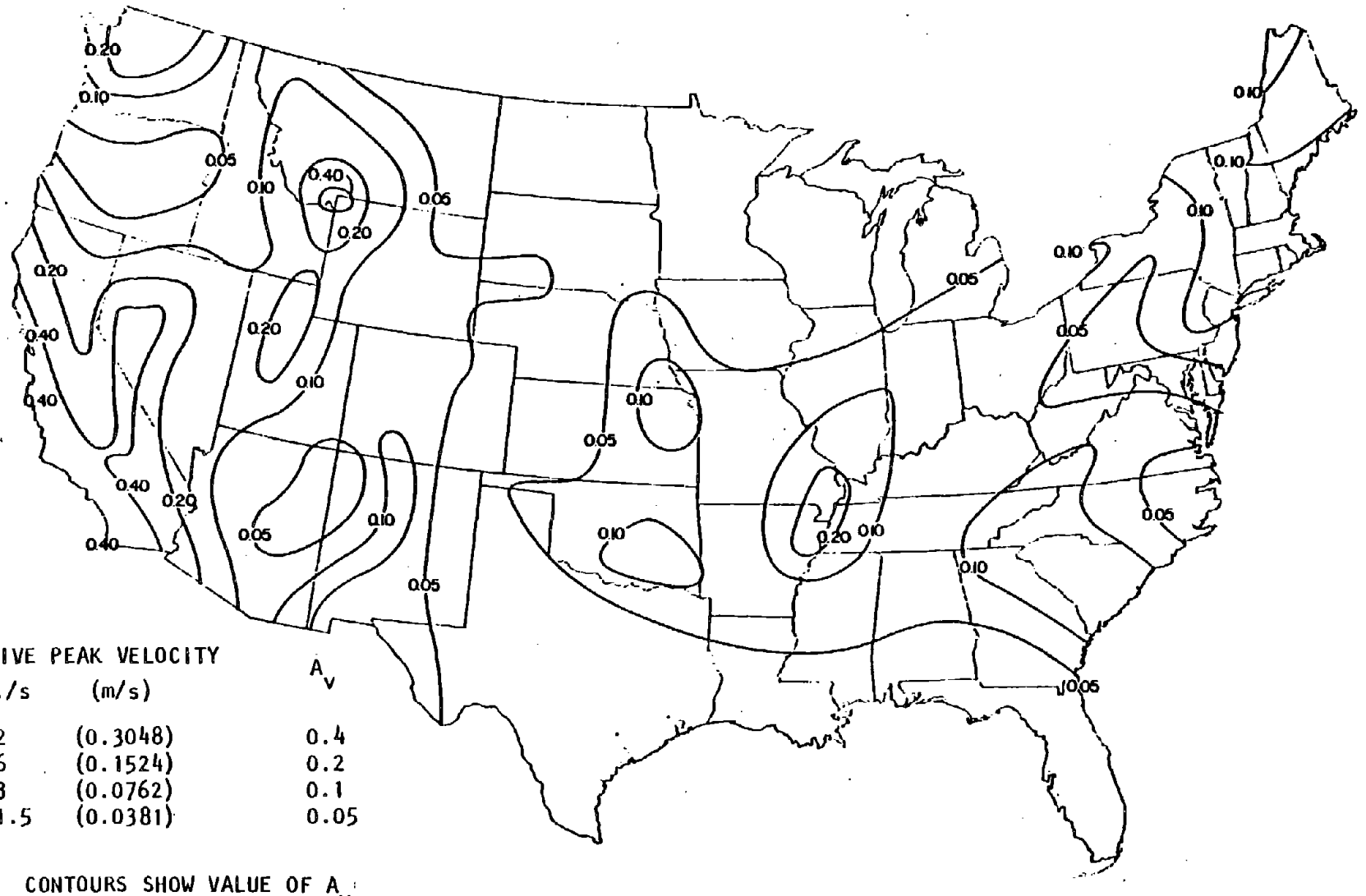
b. For each source zone or fault, the rate at which earthquakes of different magnitude can occur and the maximum credible magnitude are estimated.



NOTE: CONTOURS SHOW VALUE OF A_a

A_a = EFFECTIVE PEAK ACCELERATION, g

FIGURE 2-1. EFFECTIVE PEAK ACCELERATION MAP (ATC, 1978)



EFFECTIVE PEAK VELOCITY in./s	(m/s)	A_v
12	(0.3048)	0.4
6	(0.1524)	0.2
3	(0.0762)	0.1
1.5	(0.0381)	0.05

NOTE: CONTOURS SHOW VALUE OF A_v

FIGURE 2-2. EFFECTIVE PEAK VELOCITY MAP (ATC, 1978)

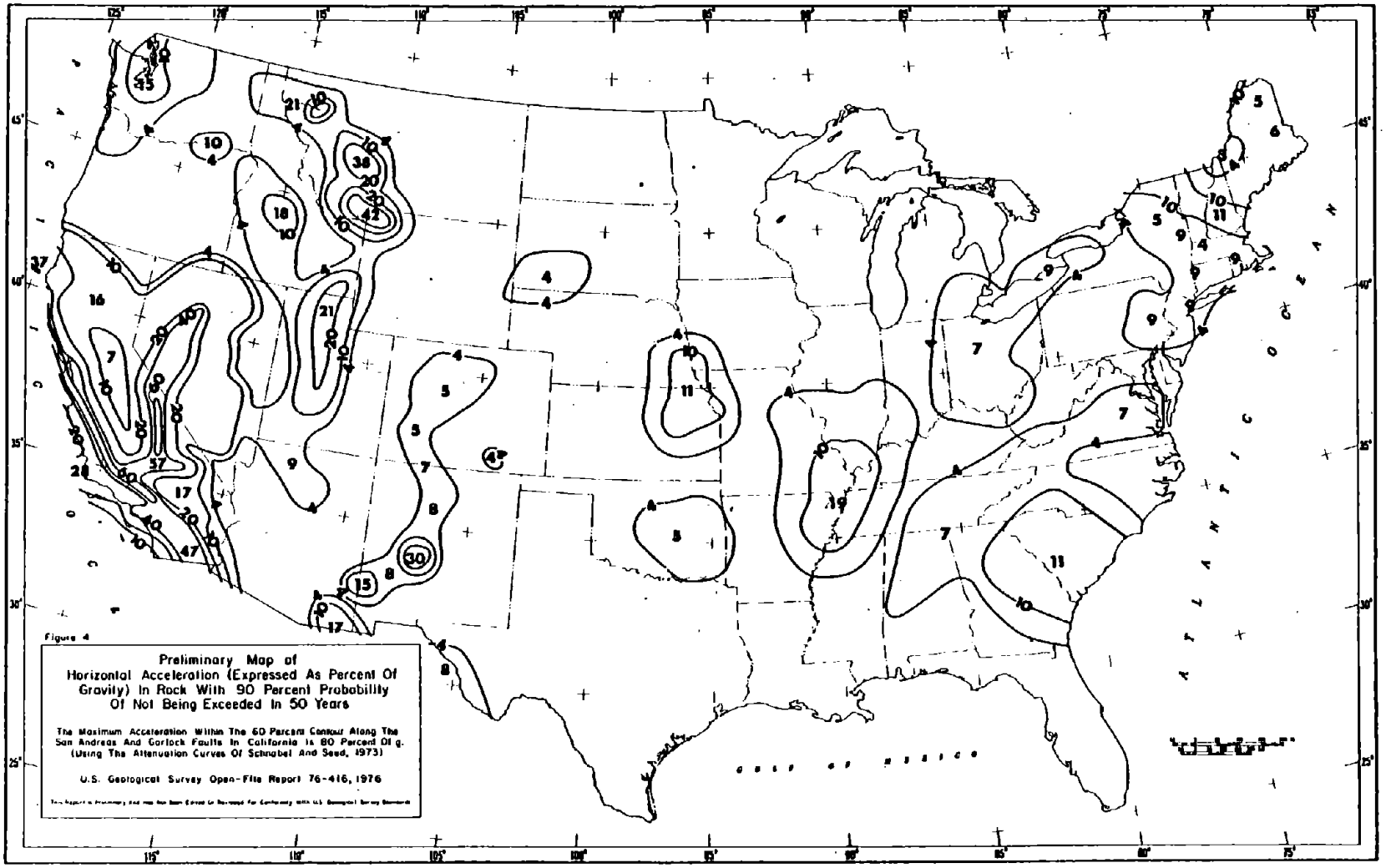


FIGURE 2-3. SEISMIC RISK DEVELOPED BY ALGERMISSEN AND PERKINS

c. Attenuation laws are used to give the intensity of shaking as a function of magnitude and distance from an epicenter.

d. With the foregoing information as input, a computer program based on probabilistic principles can generate values that produce contours of locations with equal probabilities or with specific intensities of ground shaking.

Algermissen and Perkins relied primarily on historical seismicity, adjusted where possible by geological and tectonic information. The Algermissen-Perkins map shows contours of peak accelerations on rock, which have a 10% probability of being exceeded in 50 years.

The EPA contour map of Figure 2-1 gives EPA for firm ground, which includes shallow deposits of stiff cohesive soils and dense granular soils as well as rock. EPA is replaced by the dimensionless coefficient A_a, which is numerically equal to EPA when EPA is expressed as a decimal fraction of the acceleration of gravity. ATC spectra corresponding to this soil condition are used in this study as the basis for developing seismic time-history input for the analysis and testing of unreinforced masonry buildings and components.

ATC-3 (1978) indicated that the Algermissen-Perkins map was heavily influenced by historical seismicity; that is, by the pattern of earthquakes that have occurred during the past 150 years (on the West Coast) to 350 years (on the East Coast). Where there was solid geological evidence that this rather short period of history might be misleading, this evidence was incorporated into the source model. This approach means that areas that have not experienced significant earthquakes during the historical period and for which there is no solid geological basis for suspecting that such earthquakes might occur, end up being designated as areas of low seismic risk. These same difficulties apply to the map of EPA, although some very recent geological and seismological studies did lead to the EPA being increased in some parts of the country where the historical record alone would indicate low seismicity.

The Effective Peak Velocity (EPV) map (Fig. 2-2) was constructed by modifying the map for EPA. It was desirable to express EPV by a dimensionless parameter (A_v), which is a velocity-related acceleration coefficient. A study by McGuire (1975), based on strong motion records in California, has provided data concerning the attenuation of EPV with distance. The strong motion data available to McGuire were inadequate beyond a distance of about 100 miles. To estimate the attenuation of EPV beyond this distance, it was assumed that EPV at large distances from an earthquake is related to the Modified Mercalli Intensity (MMI). For the Midwest and the East, it was necessary to rely entirely on information about the attenuation of MMI (Bollinger, 1976).

2.3 DESIGN EARTHQUAKE GROUND MOTIONS

ATC defines "design ground shaking" for a location as the ground motion that an architect or engineer should have in mind when he designs a building that is to provide protection for life safety. This motion is expressed as a smoothed elastic response spectrum for a single-degree-of-freedom system.

The concept of using a standardized spectrum shape that can be scaled to some appropriate ground motion strength level representative of a design earthquake for a particular site was first developed by Housner (1959). These spectrum shapes were based on evaluation of the frequency content of only four sets of records of strong shaking that were available at the time.

Over the years, considerably more records have been accumulated, thereby providing a substantially larger data base. This data base permitted the development of standardized response spectrum shapes that take into account the geologic, seismic, and soil conditions at a particular site in the United States. These conditions are converted by ATC-3 (1978) into ground motion parameters that are used to construct design elastic response spectra.

2.4 GROUND MOTION PARAMETERS

The intensity of design ground shaking is represented by two parameters, EPA and EPV. The EPA is proportional to spectral ordinates for periods in the range of 0.1 to 0.5 sec, whereas the EPV is proportional to spectral ordinates at a period of about 1 sec. The constant of proportionality (for the 5% damped spectra) is set at a standard value of 2.5 in both cases.

For a specific actual ground motion of normal duration, EPA and EPV can be determined as illustrated in Figure 2-4. The 5% damped spectrum for the actual motion is graphed and fitted with straight lines at the period mentioned above. The ordinates of the smoothed spectrum are then divided by 2.5 to obtain EPA and EPV.

2.5 DESIGN ELASTIC RESPONSE SPECTRA

The maps shown in Figures 2-1 and 2-2 have contours marking four different levels of acceleration. In Figure 2-2, the values of A_v and EPV are related as follows:

Velocity-Related Acceleration Coefficient, A_v	Effective Peak Velocity, in./s (m/s)
0.05	1.5 (0.0381)
0.10	3 (0.0762)
0.20	6 (0.1524)
0.40	12 (0.3048)

For actual design purposes, the ATC-3 report furnishes detailed maps that graph seven types of motion throughout the United States. The coefficients A_a and A_v can be derived from these maps, which appear in the ATC-3 report (1978) as Figures 1-1 and 1-2. To simplify the application of the ATC-3 procedure by the many designers concerned with construction in the various jurisdictions, the boundaries of any area are arbitrarily delimited by county lines nearest the "true" boundaries. A seismic hazard index, which reflects the ability of different types of construction to withstand the effects of earthquake motions, is also correlated with the seven types of map areas.

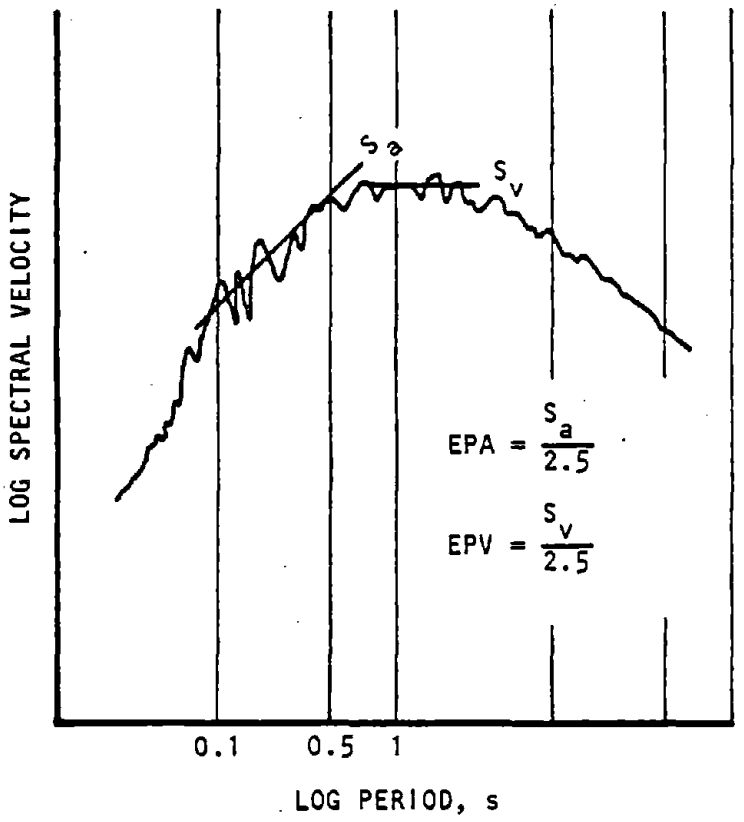


FIGURE 2-4. SCHEMATIC REPRESENTATION SHOWING HOW EFFECTIVE PEAK ACCELERATION AND EFFECTIVE PEAK VELOCITY ARE OBTAINED FROM A RESPONSE SPECTRUM (ATC3, 1978)

The values of the coefficients A_a and A_v and the seismicity indices associated with map areas are as follows:

Map Area	Value of Coefficient, A_a	A_v	Effective Peak Velocity, in./s (m/s)	Seismicity Index
7	0.40	0.40	12.0 (0.3048)	4
6	0.30	0.30	9.0 (0.2286)	4
5	0.20	0.20	6.0 (0.1524)	4
4	0.15	0.15	4.5 (0.1143)	3
3	0.10	0.10	3.0 (0.0762)	2
2	0.05	0.05	1.5 (0.0381)	2
1	0.05	0.05	1.5 (0.0381)	1

Spectral shapes representative of the different soil conditions (Seed et al., 1974) were selected (Fig. 2-5). These spectra were simplified to a family of three curves by combining the spectra for rock and stiff soil conditions and normalized to the spectral curves shown in Figure 2-6.

Recommended ground-motion spectra for 5% damping for the different map zone levels are thus obtained by multiplying the normalized spectra values shown in Figure 5-6 by the values of effective peak ground acceleration. Soil profile factors were also given for the response spectra.

The spectra for 2% damping may be obtained by multiplying the ordinates of Figure 2-6 by a factor of 1.25. Spectra for vertical motions may be obtained by multiplying the ordinates of the spectra for the horizontal motions by a factor of 0.67. A discussion of this factor is given in Appendix D.

In order to simplify the designations of the significant geographic regions for seismic evaluation of URM buildings, seven map areas were used. The A_a and A_v values corresponding to these regions ranged from 0.4 to 0.05, as shown in Figure 3-1. Within each seismic zone is a population center about which seismic input data is known (for example, Charleston is the center for the Carolina region, Boston for the New England region).

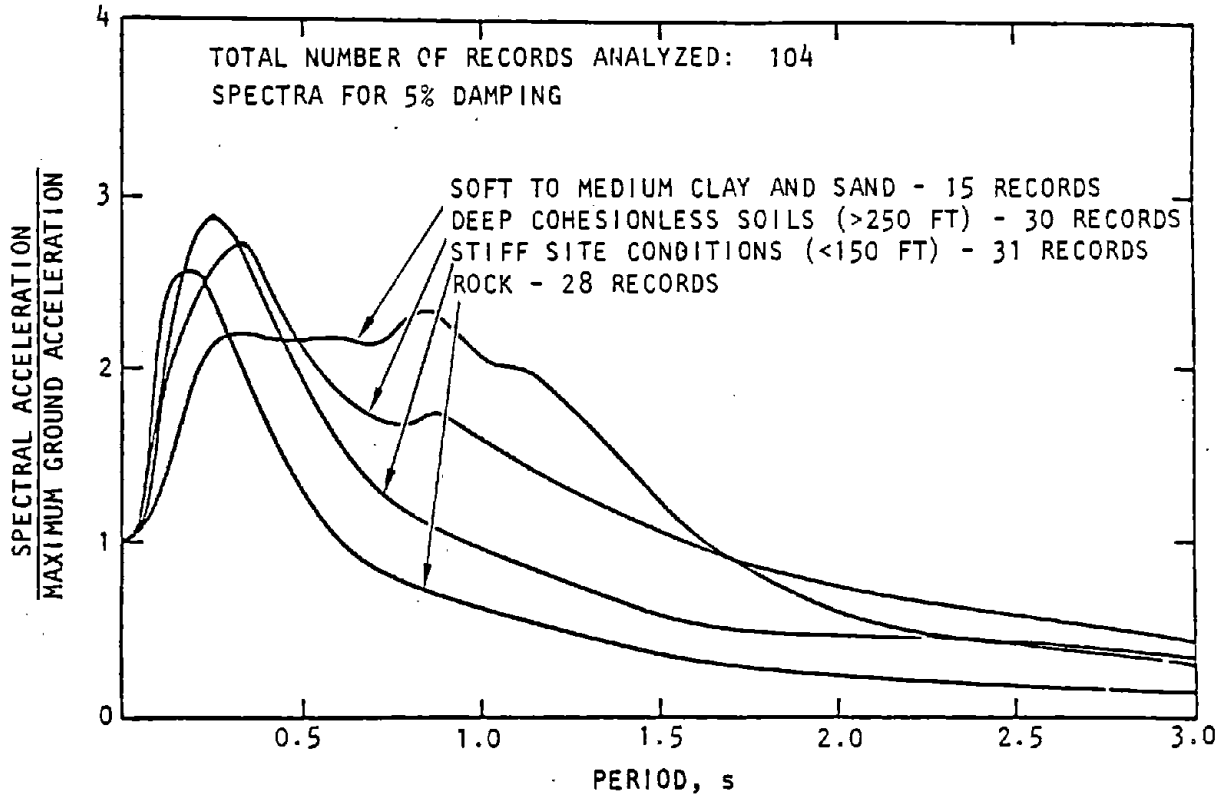


FIGURE 2-5. AVERAGE ACCELERATION SPECTRA FOR DIFFERENT SITE CONDITIONS (Seed et al., 1974)

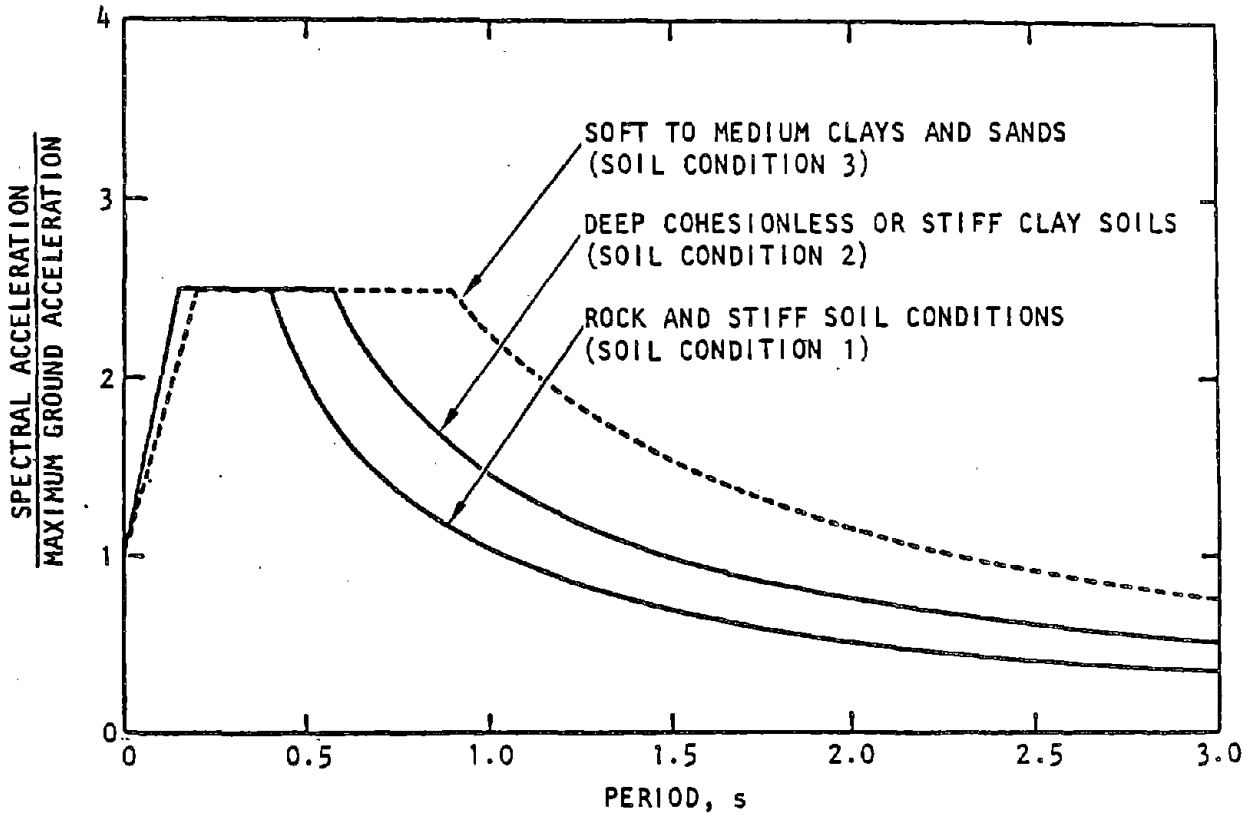


FIGURE 2-6. NORMALIZED SPECTRAL CURVES RECOMMENDED FOR USE IN BUILDING CODE (ATC, 1978)

Effective peak velocities associated with the velocity-related coefficient A_v are from the ATC report (1978). The ground motion velocities amplified by the recommended spectral factor (Fig. 2-6) closely correspond to the spectra recommended for soil condition 2, or deep cohesionless or stiff clay conditions. This mean spectral velocity exceeds the velocity anticipated for rock or stiff soil conditions. Spectral velocity for soft to medium stiff clay may exceed the mean spectral velocity used for selecting time histories. However, in the geographic regions with A_a and A_v equal to 0.4, the effective spectral acceleration may be reduced to 80% of the acceleration for soils Type 1 and 2. This reduction in response for the period range anticipated for URM buildings that are generally low in height and have stiff seismic resisting systems may offset the response effects of the increased spectral velocity.

2.6 RISK ASSOCIATED WITH EARTHQUAKE GROUND SHAKING SPECIFIED BY ATC PROCEDURE

ATC-3 (1978) estimated at 90% probability that the recommended EPA and EPV at a given location will not be exceeded during a 50-year period. A 90% probability of not being exceeded in a 50-year interval is equivalent to a mean recurrence interval of 475 years or an average annual risk of 0.002 events per year. Figure 2-7, which is based on information supplied by Algermissen and Perkins (1976), indicates the probabilities of not being exceeded at various levels of EPA selection. The dashed portions of the curves indicate possible extrapolations to larger and smaller annual risk.

The probability that the ordinates of the design elastic response spectrum will not be exceeded, at any period, is approximately the same as the probability that the EPA and the EPV will not be exceeded. This is because the uncertainty in the EPA and EPV that will occur in a future earthquake is much greater than the uncertainty in spectral ordinates given the EPA and EPV. Thus the probability that the ordinates of the design elastic response spectrum will not be exceeded during a 50-year interval is also roughly 90%, or at least in the general range of 80 to 95%.

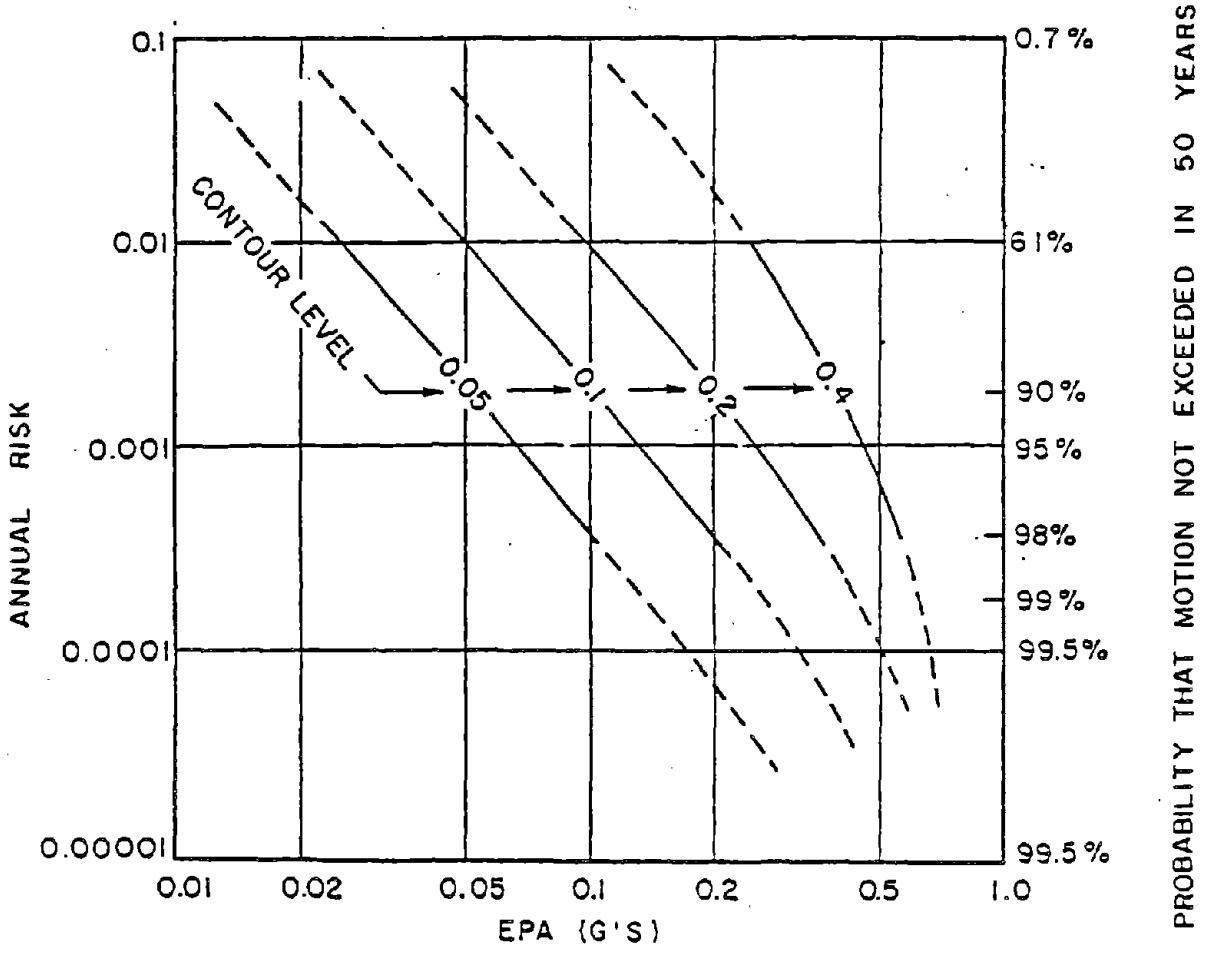


FIGURE 2-7. ANNUAL RISK OF EXCEEDING VARIOUS EFFECTIVE PEAK ACCELERATIONS FOR LOCATIONS ON THE INDICATED CONTOURS OF EPA IN FIGURE 2-1 (ATC, 1978)

SECTION 3

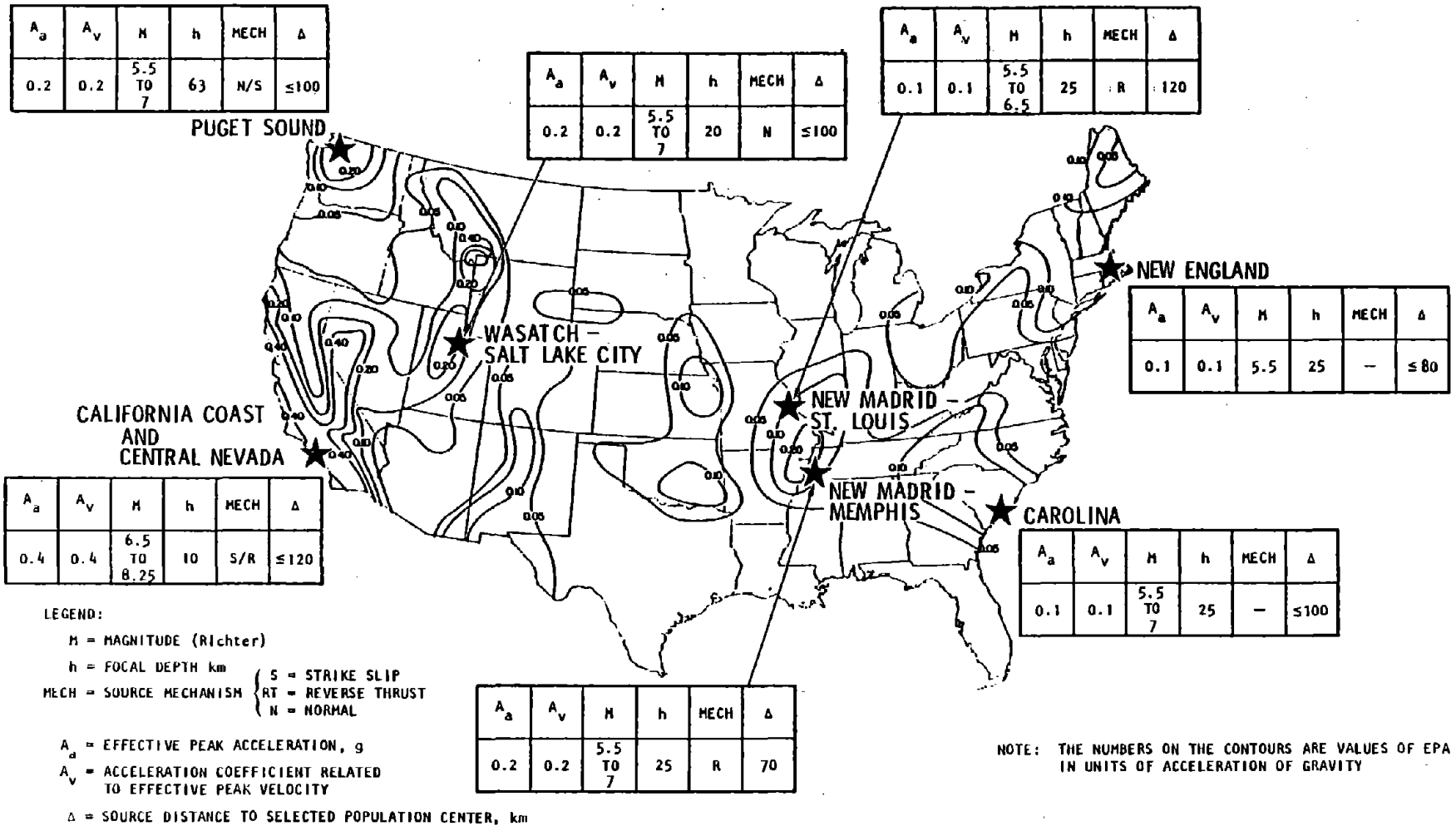
SUMMARY OF DATA BASE FOR DEVELOPING SEISMIC INPUT FOR SEVEN MAJOR U.S. GEOGRAPHICAL REGIONS

3.1 INTRODUCTION

This secton is a compilation of information needed for selecting earthquake ground-motion time-history inputs at the following seven geographical regions: California Coast and Central Nevada, Puget Sound, Wasatch-Salt Lake City, New Madrid-Memphis, New Madrid-St. Louis, Carolina, and New England. Within each region is a major city containing representative URM buildings. The URM construction in these cities has been surveyed and categorized in previous tasks (ABK, 1979). The cities for the seven geographical regions are: Los Angeles, Seattle, Salt Lake City, Memphis, St. Louis, Charleston, and Boston. The seismic input used here is not site specific for the URM construction within that city, but rather is intended to be for a generalized rock or firm ground site within the region.

Information summarized for these regions includes the (1) source magnitude, (2) source mechanism, (3) source distance to the selected population center, (4) source focal depth, (5) attenuation relationship, (6) return intervals, and (7) peak acceleration, velocity, and displacement associated with seismic risks. Figure 3-1 summarizes seismic input data for these seven regions, and Figure 3-2 shows these regions on an Effective Peak Velocity map. These are to be referred to in the following discussions of the individual regions.

It will be noticed that references to seismic frequency and maps of local seismicity are included for all but the West Coast regions. The seismicity of the Western regions is well known, as indicated in the following two sections.



A_a	A_v	M	h	MECH	Δ
0.2	0.2	5.5 TO 7	63	N/S	≤100

A_a	A_v	M	h	MECH	Δ
0.2	0.2	5.5 TO 7	20	N	≤100

A_a	A_v	M	h	MECH	Δ
0.1	0.1	5.5 TO 6.5	25	R	120

A_a	A_v	M	h	MECH	Δ
0.1	0.1	5.5	25	–	≤80

A_a	A_v	M	h	MECH	Δ
0.4	0.4	6.5 TO 8.25	10	S/R	≤120

A_a	A_v	M	h	MECH	Δ
0.1	0.1	5.5 TO 7	25	–	≤100

A_a	A_v	M	h	MECH	Δ
0.2	0.2	5.5 TO 7	25	R	70

FIGURE 3-1. SUMMARY OF SEISMIC INPUT DATA FOR SEVEN MAJOR U.S. GEOGRAPHICAL REGIONS (Adapted from ATC, 1978)

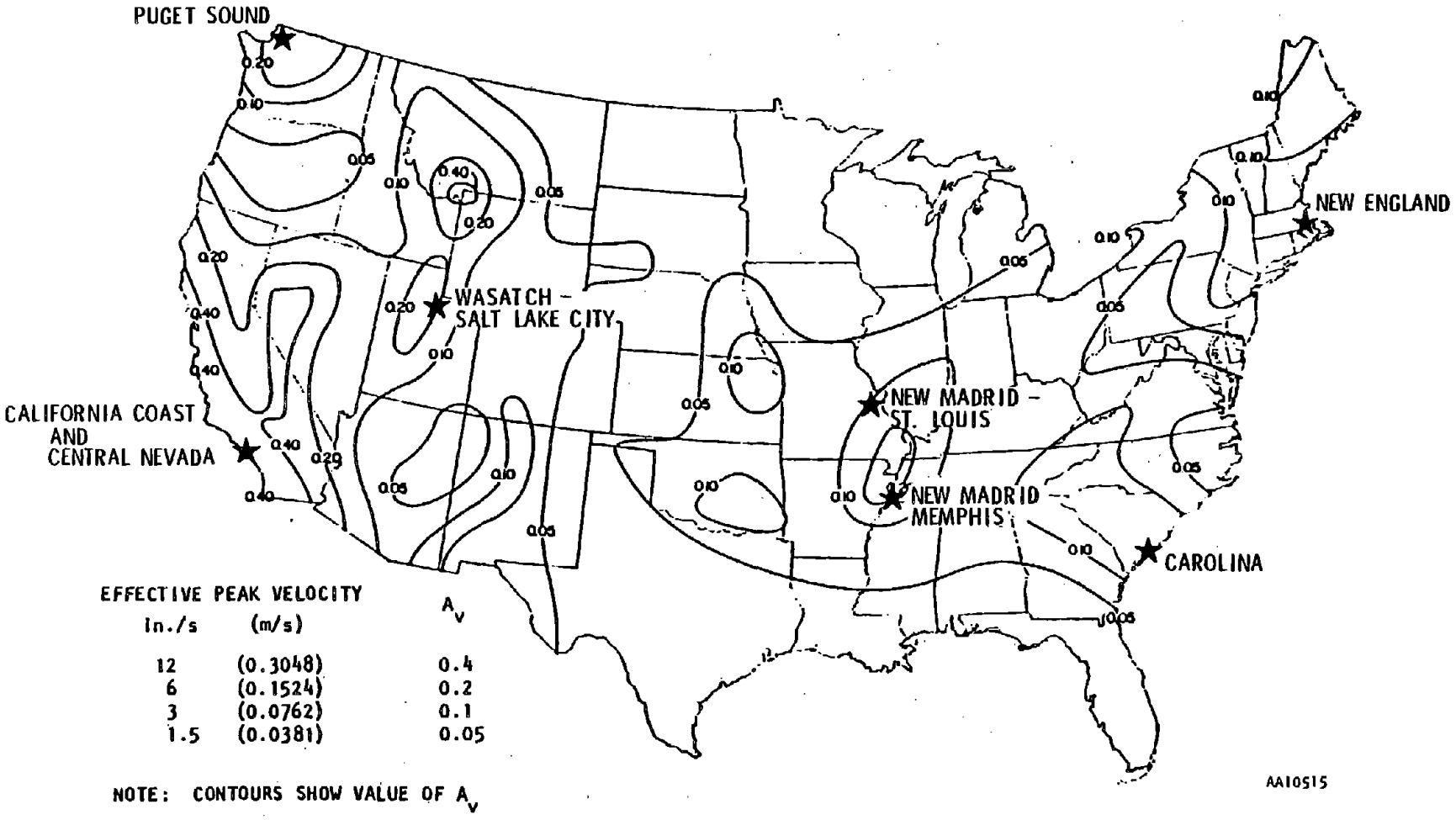


FIGURE 3-2. LOCATION OF SEVEN SELECTED MAJOR U.S. GEOGRAPHICAL REGIONS ON EFFECTIVE PEAK VELOCITY MAP (from ATC, 1978)

3.2 CALIFORNIA COAST AND CENTRAL NEVADA REGION

The California Coast and Central Nevada region is a highly seismic area. A site in this area has an effective peak acceleration of 0.40 g and an effective peak velocity of 12 in./s (0.30 m/s). This acceleration and velocity can be experienced at a site in this area as a result of strong or moderately strong earthquakes along numerous faults within or bordering the area. Geology, faulting, and seismicity of this area have been synthesized and summarized in many investigative reports.* The structure of the California Coast region is dominated by the San Andreas fault system trending in a northwest direction. Other major faults in the region that trend in a northwest direction include Hayward, Calaveras, Nacimiento, San Jacinto, Whittier, Elsinore, Newport-Inglewood, Imperial, and San Gabriel faults. Major faults in the area that trend in an east direction include Garlock, Santa Ynez, San Fernando, and Malibu-Santa Monica-Raymond. Faults of the Basin Ranges bordering California and Nevada trend more northerly than the other faults cited above. This is particularly evident in the Owens Valley and Death Valley areas. The Owens Valley and Sierra Nevada fault zones are examples of this trend.

The threat to population centers in this area would come from moderate to moderately strong earthquakes on nearby smaller faults or from strong earthquakes on a major faults such as the San Andreas fault. Maximum credible magnitudes corresponding to these earthquakes would range between 6.5 and 8.25 on the Richter scale. Focal depth would be approximately 10 km for these events. The ATC spectrum for this region is shown in Figure 3-3.

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*Such as Bailey and Jahns (1954), Barbat (1958), Barrows (1974), Bolt et al. (1968), Brown and Lee (1971), Byerly (1951), Calif. Dept. of Water Resources (1964), Cluff and Bolt (1969), Crowder (1968), Dibblee (1966), Hoots (1931), Jahns (1954), Jennings et al. (1975), Jennings and Burnett (1961), Jennings and Strand (1969), Lander (1966-1973), Oakeshott (1966), Page (1966), Reed (1933), Richter (1958), Roland et al. (1959), Tocker (1959), Wallace (1970), Wentworth & Yerkes (1971), Yerkes et al. (1965).

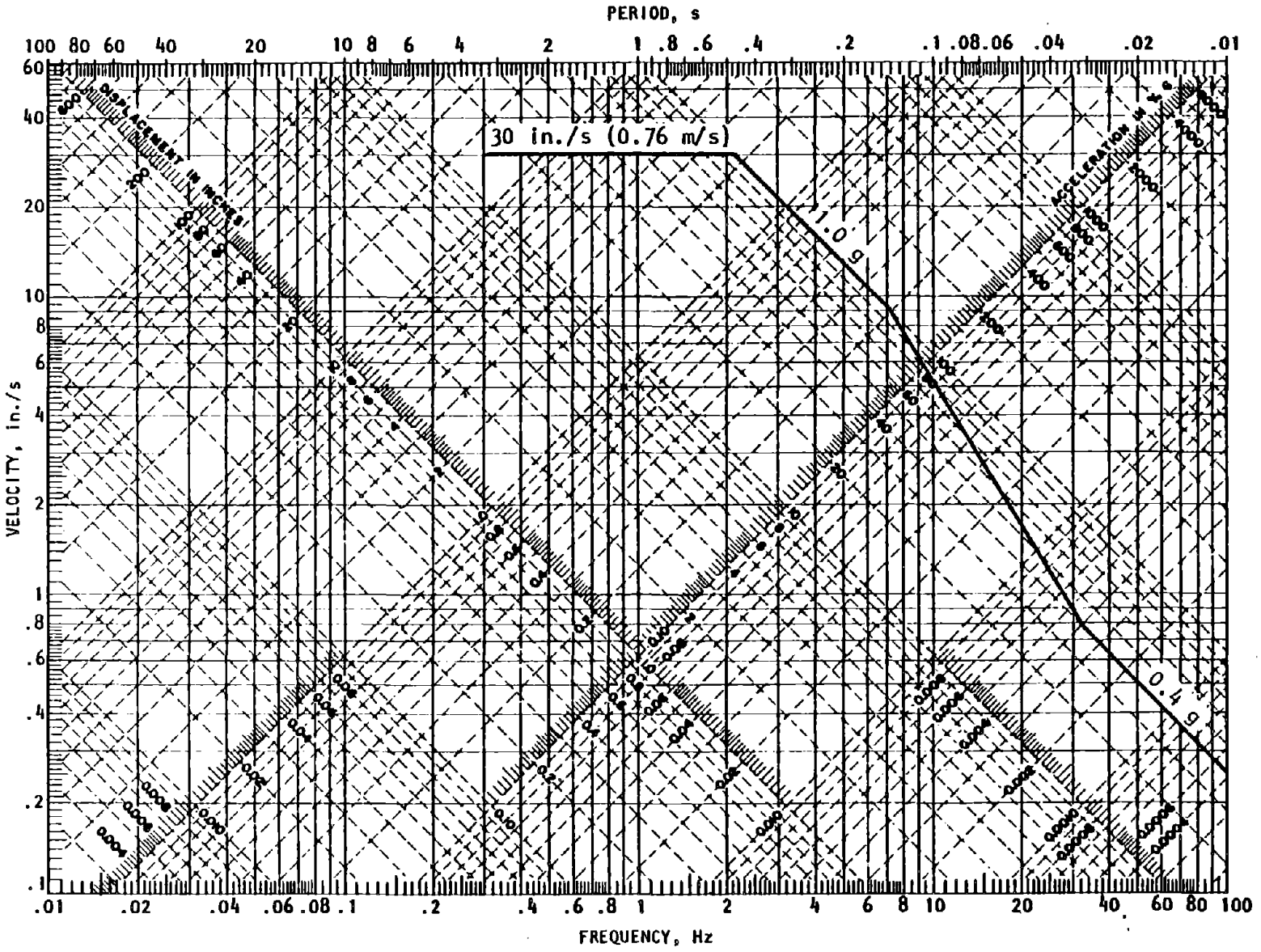


FIGURE 3-3. ATC GROUND MOTION SPECTRUM FOR CALIFORNIA COAST AND CENTRAL NEVADA REGION (A_a = 0.40, A_v = 0.40)

3.3 PUGET SOUND REGION

The Puget Sound region is a moderately high seismic area. For a site in this area the effective peak acceleration is 0.20 g and the effective peak velocity is 6 in./s (0.15 m/s). The geology, faulting, and seismicity of the Puget Sound region has, like that of the California region, been covered in many investigative reports.*

In the Puget Sound region, which includes the city of Seattle, the earth's crust is apparently experiencing a dilatational effect, so that normal faulting predominates, rather than reverse-thrust faulting (Couch and Deacon, 1972). Also, the epicenters have been deeper (approximately 63 km) than for most California earthquakes (approximately 10 km), and faulting has not penetrated to the ground surface. In the Puget Sound epicentral areas, the structural features in general are overlain with deep alluvium sediments. A maximum credible earthquake of magnitude 7.4 has been predicted for this area (Couch and Deacon, 1972). Historically, a magnitude 7.1 earthquake has been experienced in this area. Although the structural features are deeply covered with alluvium, geologic information indicates faulting in this area, and fault lengths of roughly 50 mi (~83 km) have been postulated. The ATC spectrum for the Puget Sound region is shown in Figure 3-4.

3.4 WASATCH-SALT LAKE CITY REGION

The Wasatch-Salt Lake City region is a moderately high seismic area that has an effective peak acceleration of 0.20 g and effective peak velocity of 6 in./s (0.15 m/s). Maximum credible earthquakes of magnitude 7 have been predicted for this area, although the largest earthquake recorded since 1925 was the magnitude 6.6 Hansel Valley (Utah) earthquake of 12 March 1934, at the north end of the Great Salt Lake. This earthquake created surface cracks on which there were vertical displacements of from 2 to 20 in. (0.05 to 0.51 m). The probable causative fault is a normal fault similar to the Wasatch fault

*Such as Agbabian Assoc. (1973), Couch and Deacon (1972), Dehlinger et al. (1971), Rasmussen (1967), Huntting et al. (1961), and Coombs (1953).

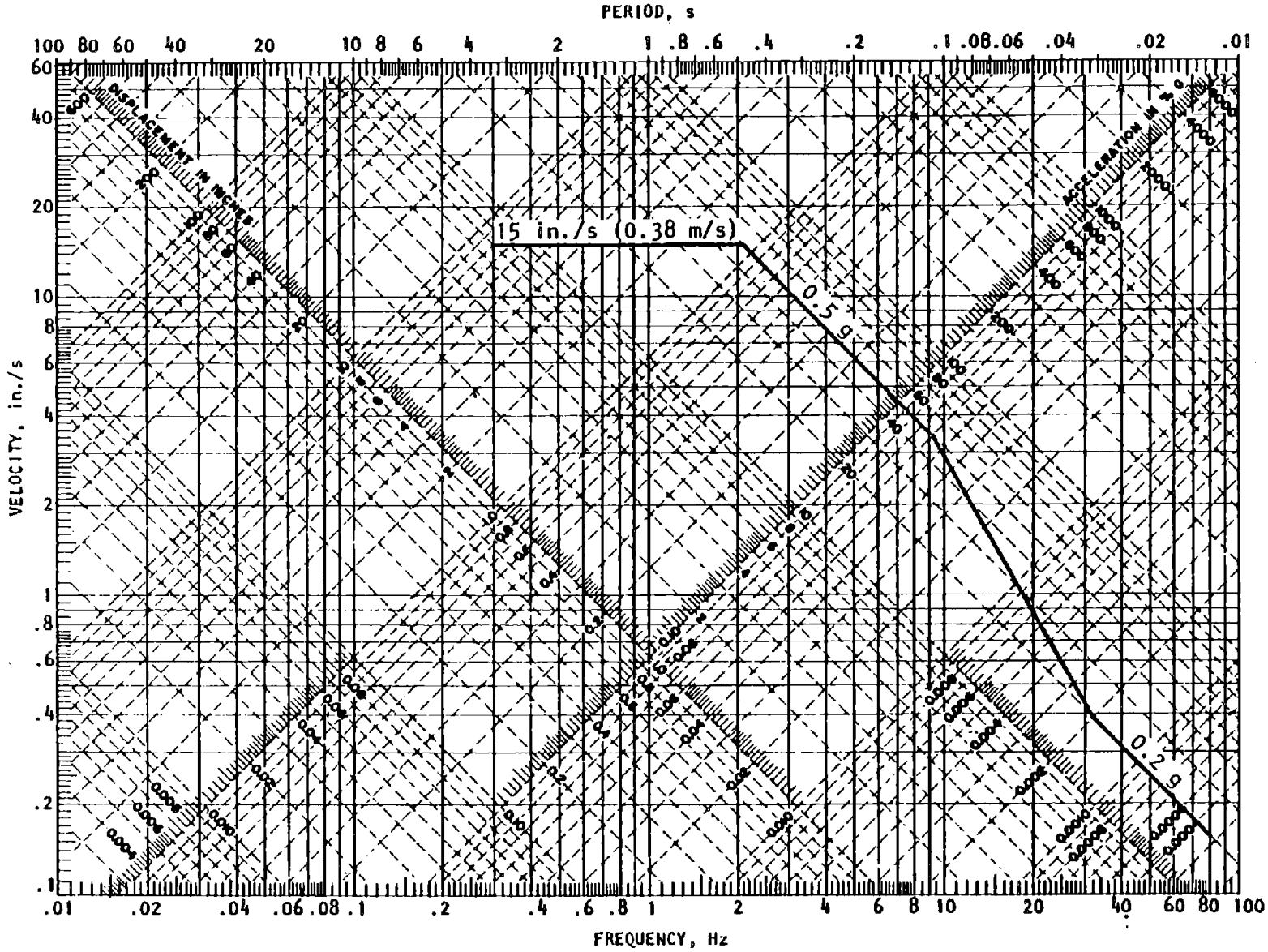


FIGURE 3-4. ATC GROUND MOTION SPECTRUM FOR THE PUGET SOUND, WASATCH-SALT LAKE CITY, AND NEW MADRID-MEMPHIS REGIONS (A_a = 0.20, A_v = 0.20)

zone that passes near Salt Lake City on the south. Figure 3-5 locates the largest historical earthquakes in the Utah region and the Wasatch Fault Zone. Table 3-1 gives the dates and intensities of the largest earthquakes in the Utah region.

Focal depths of earthquakes in this area are shallow, not more than 10 km from the earth's surface (Dewey et al., 1972). The ATC spectrum for the Wasatch-Salt Lake City region is identical to the ATC spectrum for the Puget Sound region given in Figure 3-4.

3.5 NEW MADRID-MEMPHIS REGION

The New Madrid-Memphis region is a moderately high seismic area. Effective peak acceleration of 0.20 g and velocity of 6 in./s (0.15 m/s) are associated with this area. Earthquakes of a maximum magnitude of 7.8 have occurred in this area (Nuttli, 1973b). The structural areas and fault systems in the central Mississippi valley that are significant to New Madrid-Memphis region are shown in Figure 3-6. The epicentral locations of historical earthquakes in this area are shown in Figures 3-7 and 3-8. Note that the larger earthquakes appear to have been associated with the western edge of the New Madrid fault system, which triggered the major New Madrid shocks of 1811 and 1812. However, a far greater number of earthquakes with small epicentral intensities have occurred to the east along the general axis of the Mississippi River. Although this energy has been associated with smaller earthquakes, the total energy release for the period of existing records appears to be nearly equal to that associated with the larger earthquakes to the west for the same period. Therefore, the entire faulted area extending from the New Madrid fault to slightly east of the Mississippi River has been considered by some authorities to represent an area of nearly uniform seismicity (TVA, 1972). This area contributes to the seismic hazard of the Memphis and St. Louis areas. The ATC spectrum for New Madrid-Memphis is shown in Figure 3-4.

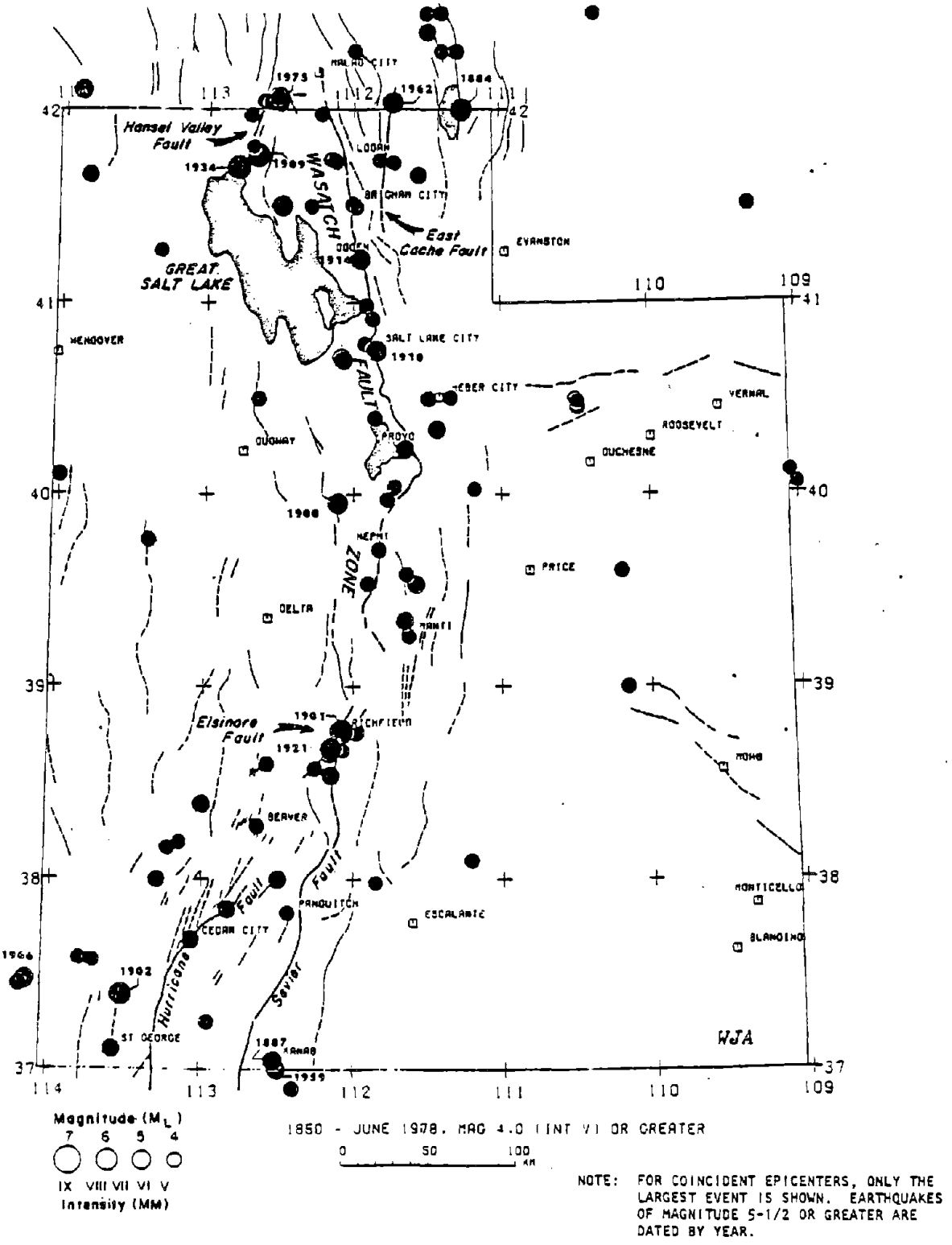


FIGURE 3-5. EPICENTER MAP OF THE LARGEST HISTORICAL EARTHQUAKES IN THE UTAH REGION, 1850-1978 (Arabasz et al., 1979)

TABLE 3-1. LARGEST EARTHQUAKES IN THE UTAH REGION, 1850 THROUGH 1978 (from Arabasz et al., 1979)

Date	Modified Mercalli Intensity	Magnitude, M_L	Location
1884 Nov 10	8	(6)*	Bear Lake Valley
1887 Dec 05	7	(5.5)	Kanab
1900 Aug 01	7	(5.5)	Eureka
1901 Nov 13	9	(6.5+)	Richfield
1902 Nov 17	8	(6)	Pine Valley
1909 Oct 05	8	(6)	Hansel Valley
1910 May 22	7	(5.5)	Salt Lake City
1914 May 13	7	(5.5)	Ogden
1921 Sep 29	8	(6)	Elsinore
1921 Oct 01	8	(6)	Elsinore
1934 Mar 12	9	6.6	Hansel Valley (Kosmo)
1959 Jul 21	6	5.5+	Utah-Arizona border (Kanab)
1962 Aug 30	7	5.7	Cache Valley (Logan)
1966 Aug 16	6	5.6	Nevada-Utah border
1975 Mar 27	8	6.0	Idaho-Utah border (Pocatello Valley)

*Magnitudes in parentheses are estimated from MMI.

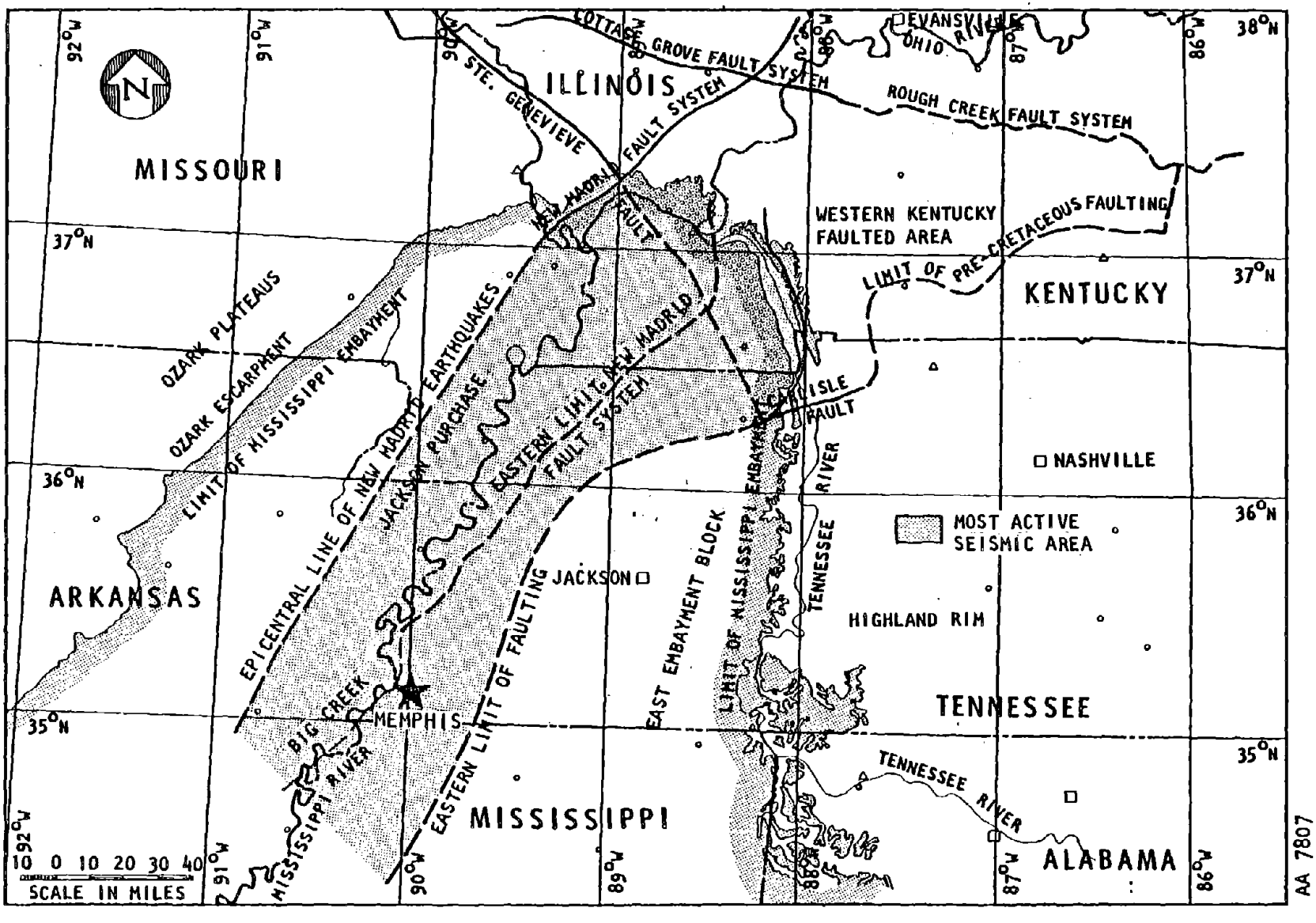


FIGURE 3-6. STRUCTURAL AREAS AND FAULT SYSTEMS IN CENTRAL MISSISSIPPI VALLEY SIGNIFICANT TO NEW MADRID-MEMPHIS REGION (TVA, 1972)

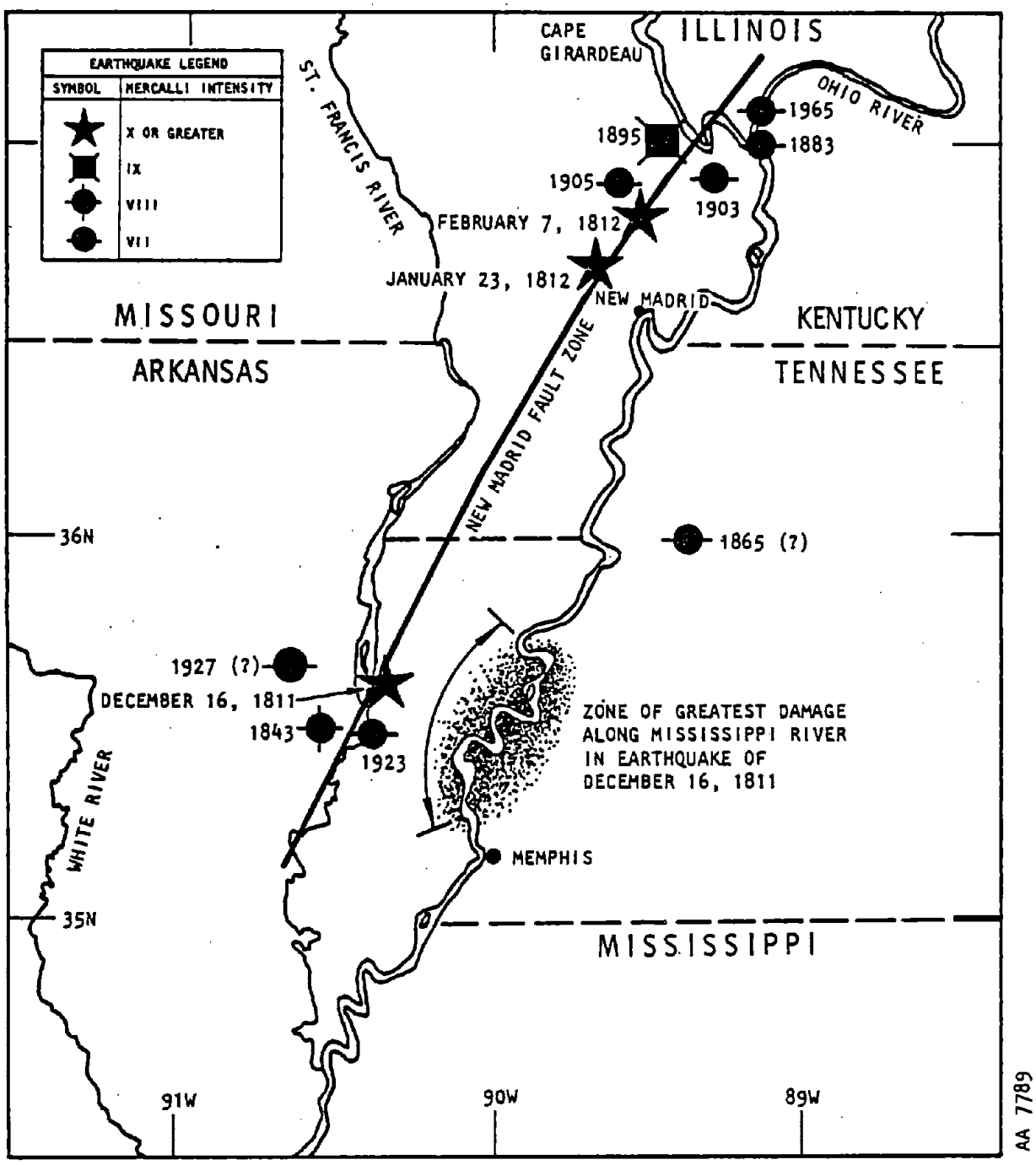


FIGURE 3-7. APPROXIMATE EPICENTRAL LOCATIONS OF EARTHQUAKES IN UPPER MISSISSIPPI EMBAYMENT AREA HAVING EPICENTRAL MM INTENSITIES OF VII OR GREATER (Agbabian Associates, 1976)

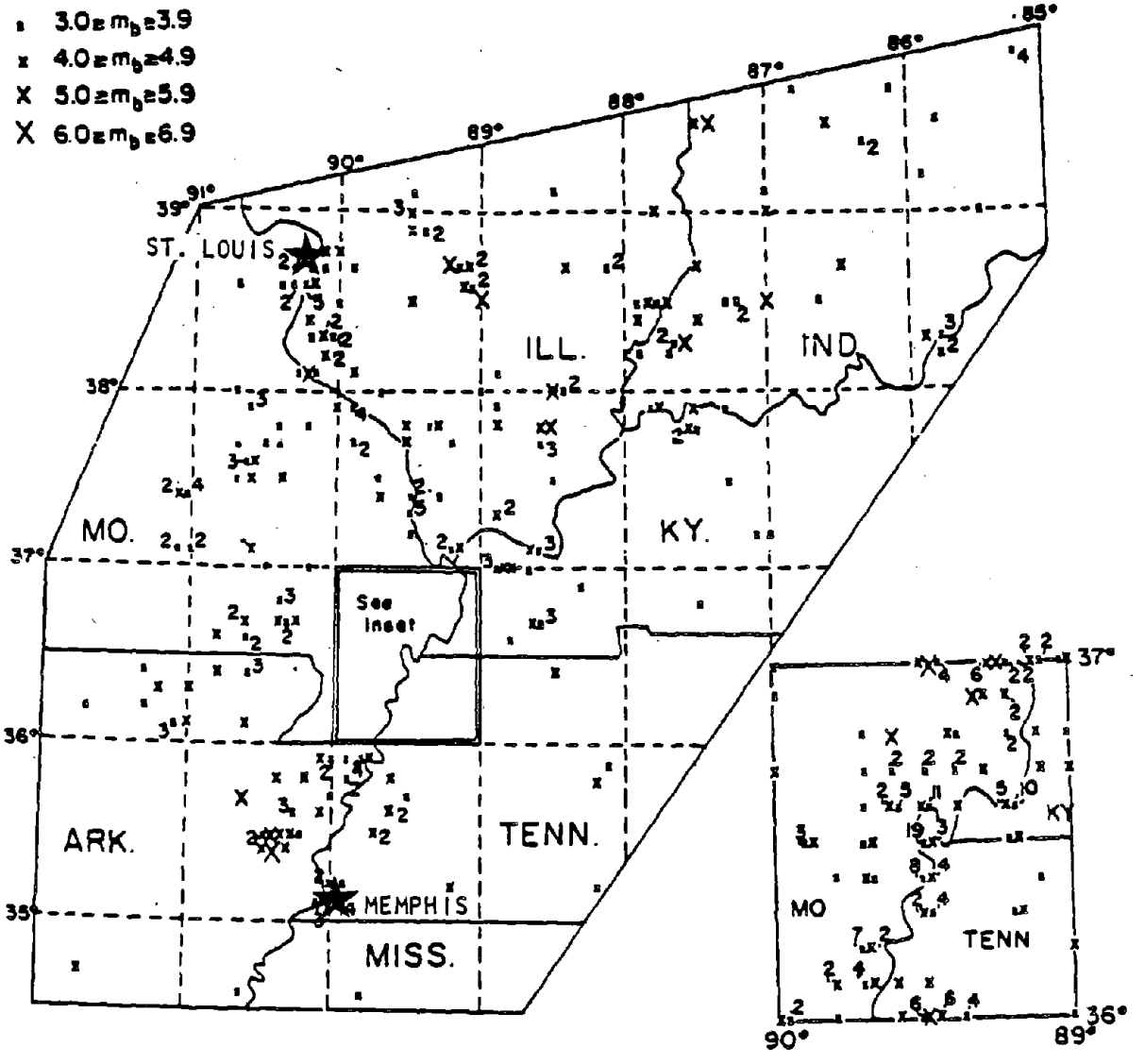


FIGURE 3-8. EARTHQUAKES IN THE CENTRAL MISSISSIPPI VALLEY, 1833 THROUGH 1972 (Nuttli, 1974)

3.6 NEW MADRID-ST. LOUIS REGION

The New Madrid-St. Louis region is a low to moderate seismic area. Effective peak acceleration of 0.10 g and effective peak velocity of 3 in./s (0.08 m/s) are associated with this area. Accordingly, the New Madrid-St. Louis region is exposed to a seismic hazard lower than the seismic hazard for New Madrid-Memphis. It is located more than 70 mi (112 km) away from the New Madrid fault zone. Seismic hazard within the New Madrid-St. Louis region will result mostly from seismic activities southeast of St. Louis. Moderate to moderately strong earthquakes will occur at some distance from the site. However, some more frequent smaller shocks may occur nearby.

The largest earthquake to occur in the central Mississippi seismic region in this century took place in Hamilton County in south-central Illinois on 9 November 1968. The earthquake had a body wave magnitude of 5.54 with a focal depth of about 25 km (Stauder and Nuttli, 1970). The motion was almost entirely dip-slip and was reverse in character. The data from this earthquake shed some light on the mechanism of earthquakes in the central United States. Therefore, a shallow focal depth of approximately 25 km and reverse fault mechanism are assigned to this region. The ATC spectrum for New Madrid-St. Louis region is shown in Figure 3-9.

3.7 CAROLINA REGION

The Carolina region is a low to moderate seismic area. Effective peak acceleration of 0.10 g and effective peak velocity of 3 in./s (0.08 m/s) are associated with this area. The seismic history of the southeastern United States has been studied by Bollinger (1969, 1972, 1973, 1976). Figure 3-10 provides the estimated epicenters of historical earthquakes in this region over a 217-year period, 1754 through 1970. Bollinger (1973) indicates that about 700 earthquakes have been noted in this region, of which about half were aftershocks of the 1886 Charleston earthquake. General distribution patterns in Figure 3-11 show that the occurrences of earthquakes are relatively independent of the geological provinces and exposed geologic structures. The largest earthquake to occur in the Carolina region was the 1886 Charleston

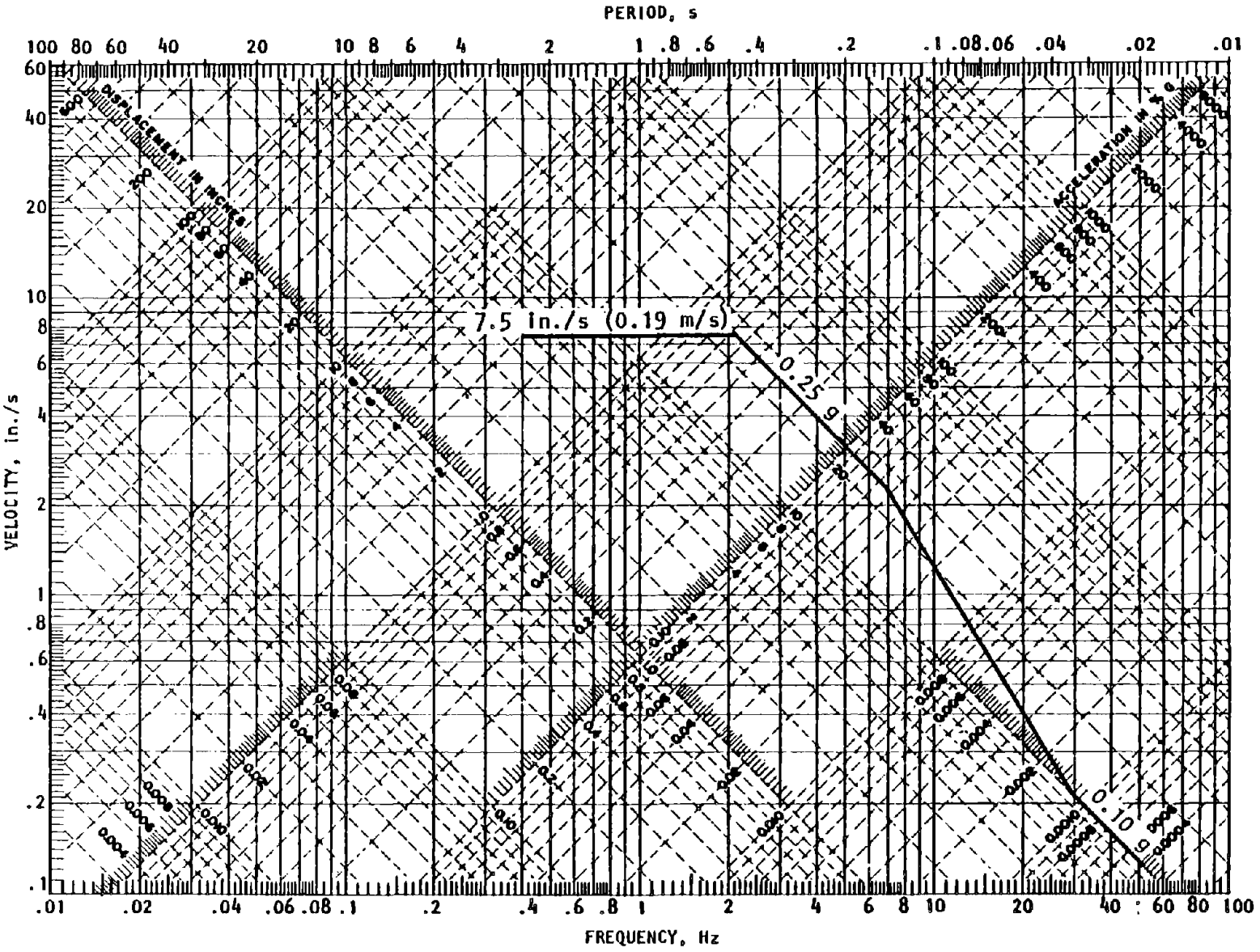


FIGURE 3-9. ATC GROUND MOTION SPECTRUM FOR THE NEW MADRID-ST. LOUIS, CAROLINA, AND NEW ENGLAND REGIONS

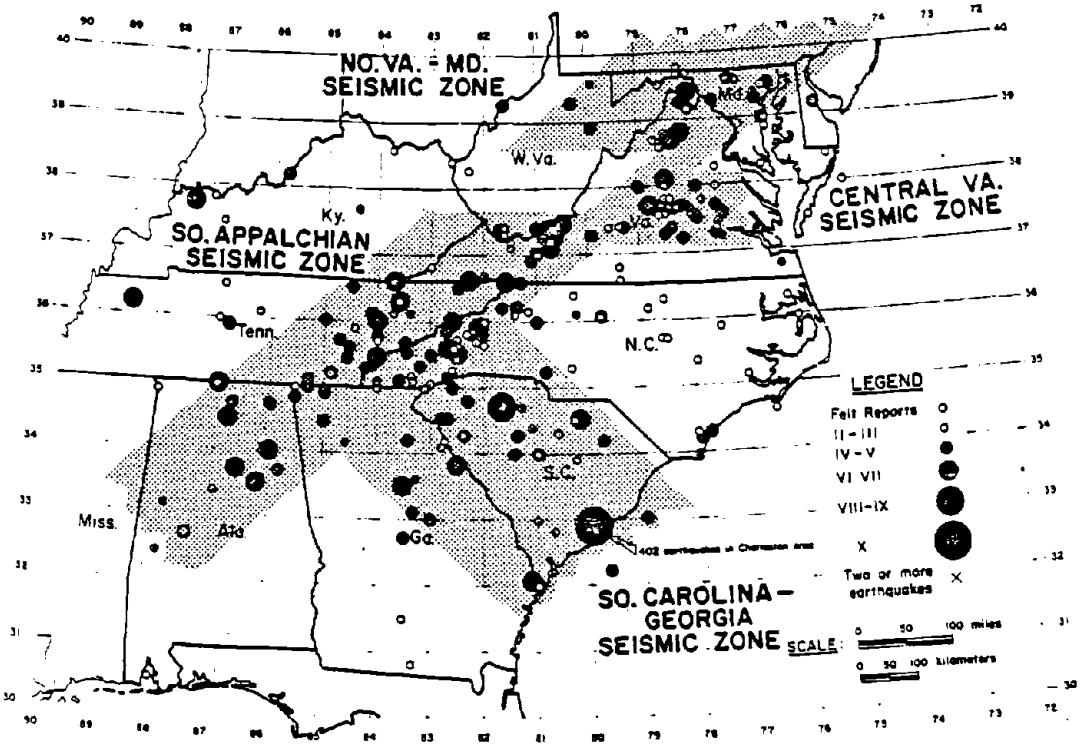


FIGURE 3-10. DEFINITION OF SEISMIC ZONES IN THE SOUTHEASTERN UNITED STATES, 1754-1970 (Bollinger, 1973)

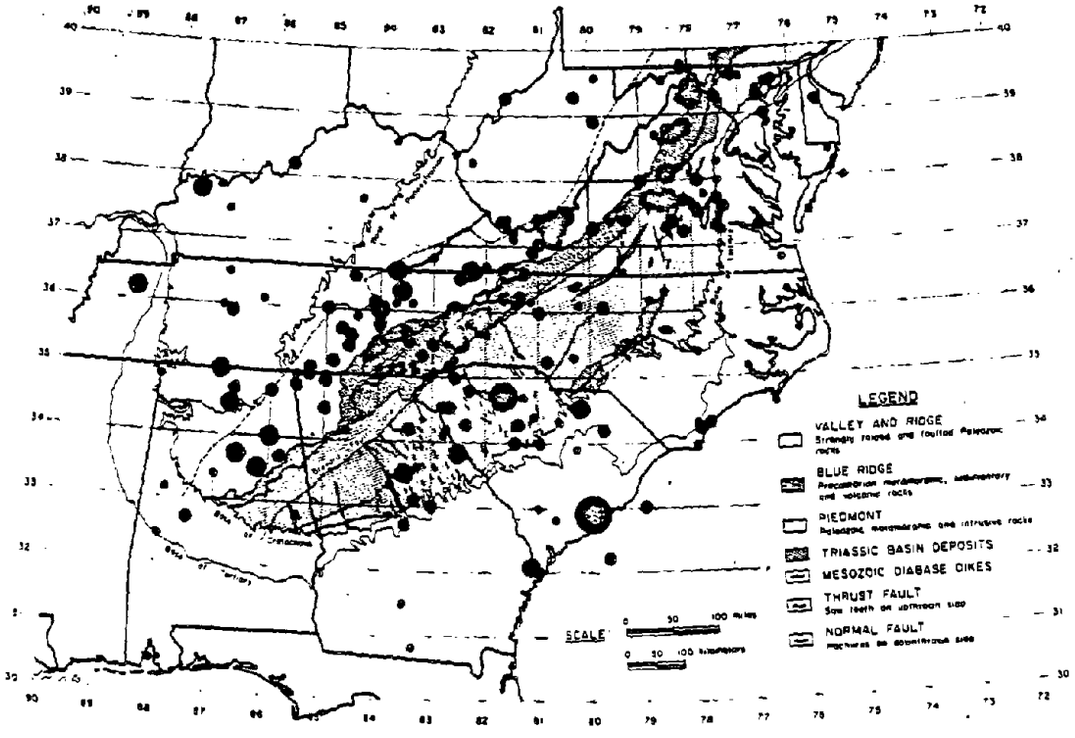


FIGURE 3-11. SEISMICITY AND GEOLOGICAL PROVINCES IN THE SOUTHEASTERN UNITED STATES (Bollinger, 1973)

earthquake, with a maximum Modified Mercalli Intensity (MMI) of X. Table 3-2 lists earthquakes in the southeastern United States. This list shows that an Intensity VII event has not been reported for the past 50 years, so "it would appear that either the region is overdue for their occurrence, or the seismic regime is indeed changing." (Bollinger, 1973)

Focal depth and source mechanism are not well defined for the area; therefore, a focal depth of 25 km (similar to that selected for New Madrid-Memphis) will be assigned to this area. The ATC spectrum for the Carolina region is shown in Figure 3-9.

TABLE 3-2. EARTHQUAKES WITH INTENSITIES GREATER THAN VII IN THE SOUTHEASTERN UNITED STATES SINCE 1870 (From Bollinger, 1973)

Date	Intensity	State	Seismic Zone
1874, Feb. 10	V-VII	North Carolina	Southern Appalachian
1875, Dec. 22	VII	Virgina	Central Virginia
1886, Aug. 31	X	South Carolina	South Carolina-Georgia
1886, Oct. 22	VII	South Carolina	South Carolina-Georgia
1897, May 31	VIII	Virginia	Southern Appalachian
1905, Jan. 27	VII-VIII	Alabama	Southern Appalachian
1912, June 12	VI-VIII	South Carolina	South Carolina-Georgia
1913, Jan. 1	VII-VIII	South Carolina	South Carolina-Georgia
1913, Mar. 28	VII	Tennessee	Southern Appalachian
1916, Feb. 21	VI-VII	North Carolina	Southern Appalachian
1916, Oct. 18	VII	Alabama	Southern Appalachian
1926, July 8	VI-VII	North Carolina	Southern Appalachian
1928, Nov. 2	VI-VII	North Carolina	Southern Appalachian

3.8 NEW ENGLAND REGION

The New England region is a low to moderate seismic area. Effective peak acceleration of 0.10 g and effective peak velocity of 3 in./s (0.08 m/s) are associated with this area. Although the northeastern United States is not considered a highly seismic area in general, there are several zones of repeated seismic activity (Cornell and Merz, 1975). These include zones south of Boston (near New York City) and northwest of Boston (upstate New York and New Hampshire). Historical earthquakes of MMI V or more in the immediate Boston vicinity are shown in Figure 3-12. Estimates of parameter values for seismic zones within the Boston area are tabulated in Table 3-3.

Although no strong motions have ever been recorded at or near the New England region due to lack of instruments at the time, on the basis of observations of such records at other sites, Cornell and Merz (1975) infer that (1) the largest hazard to the New England region will come from a moderately sized, close earthquake; (2) the strong-motion duration will be relatively short, perhaps about 5 sec; and (3) the relative frequency content will emphasize higher frequencies. This latter condition is interpreted to mean that an effective peak ground velocity of about 3.6 in./s (0.09 m/s) is expected with any motion where effective peak ground acceleration is 0.10 g.

TABLE 3-3. BEST ESTIMATES OF PARAMETER VALUES (Cornell-Merz, 1975)

Geometrical source number (See Fig. 3-12)	Mean rate, events per year over entire source	Slope, β	Upper bound MM intensity*
1	0.024	1.1	7.7
2	0.008	1.1	8.7
3	0.004	1.1	6.7
4	0.028	1.1	7.3
5(circular)	0.020	1.1	6.3
6	0.0125	1.1	6.7
7	0.032	1.1	6.7
8	0.037	1.1	7.3

*Lower bound MM intensity is 5.0 except for Source 5 where it is 4.0.

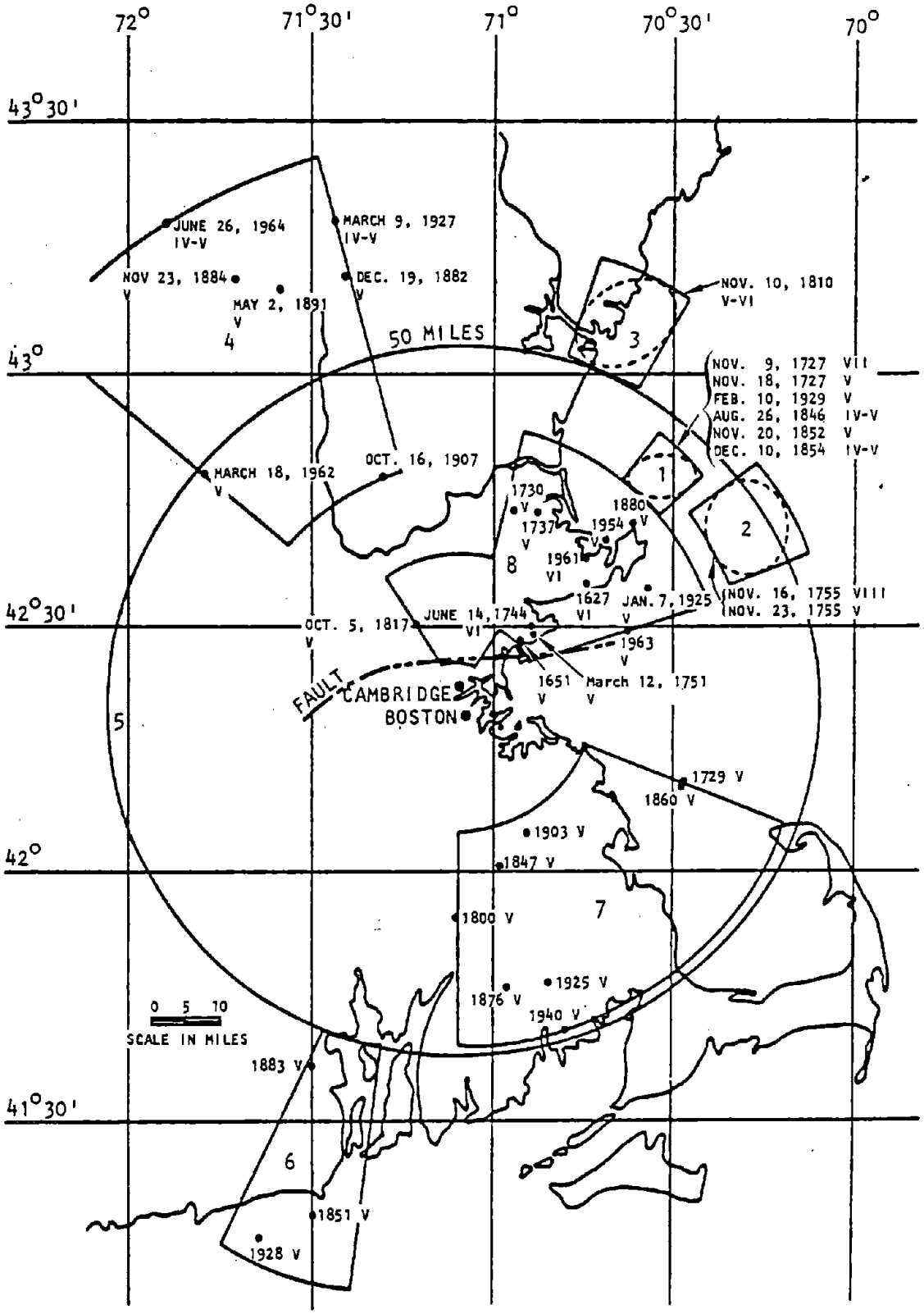


FIGURE 3-12. BOSTON: HISTORICAL EVENTS WITH MMI V (Cornell and Merz, 1975)

Depth of focus of earthquake events in eastern United States and Canada has not been discussed extensively in the literature. However, for this study, a shallow depth of 25 km will be assigned to the New England region. The ATC spectrum for the New England region is shown in Figure 3-9.

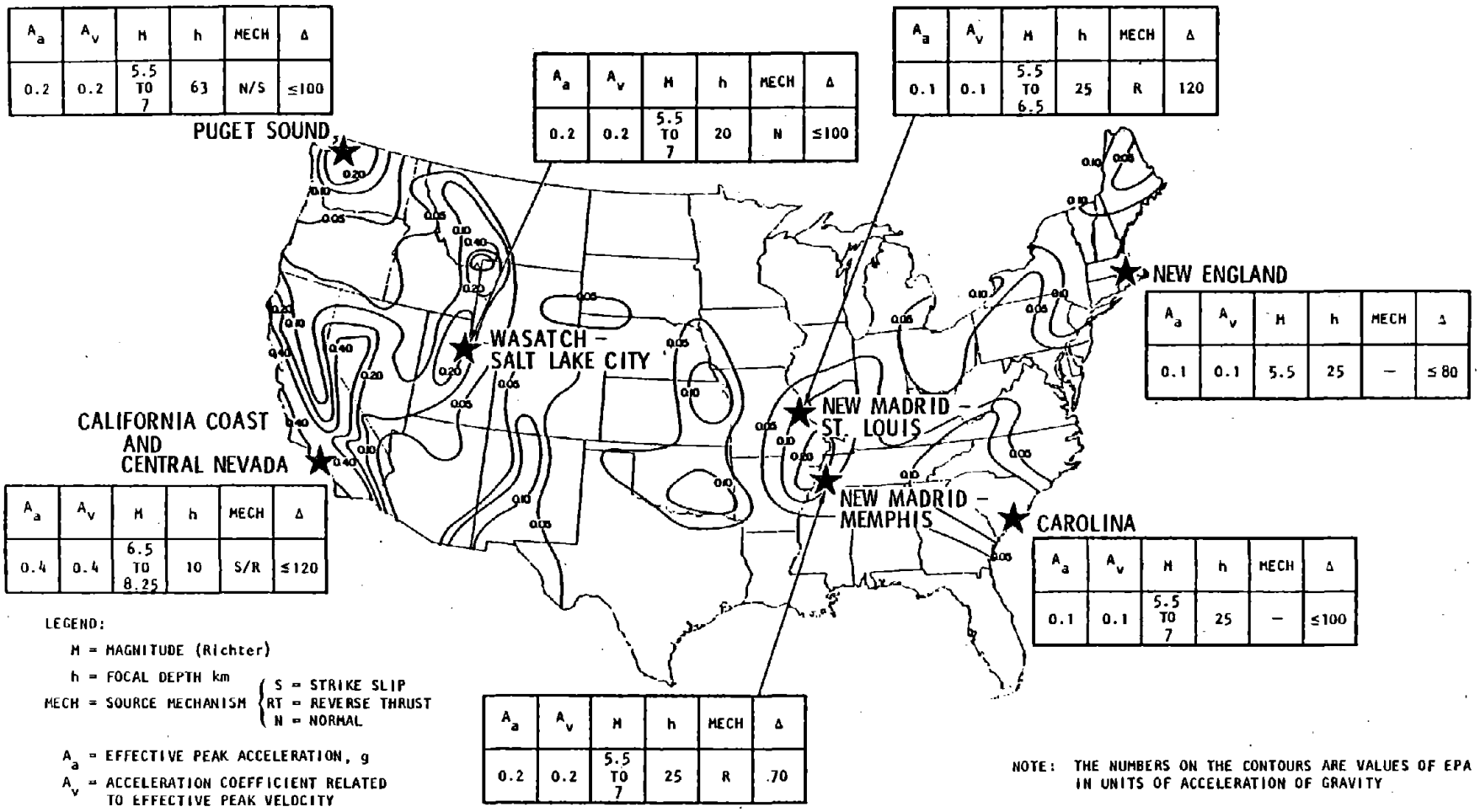
SECTION 4

SELECTION OF EARTHQUAKE TIME-HISTORY RECORDS FOR THE UNITED STATES

4.1 INTRODUCTION

This section describes the approach used to select the earthquake time-history records for the analysis of unreinforced masonry (URM) buildings located in the seven geographical regions of the United States (shown in Fig. 4-1) and presents the selected records. Each selected record should represent the seismological conditions of the particular region, including Richter magnitude, focal depth, source distance, and tectonic province. Figure 4-1 gives this data for each of the seven regions, along with contours of EPA (ATC, 1978). Contours of EPV are shown in Figure 4-2. Local soil conditions are not included in this data, and the results given in this report are based on an average soil condition that ranges from a deep cohesionless soil to a stiff clay soil for all geographical regions. Adjustments for local conditions that differ from these will be made on a case-by-case basis and are beyond the scope of this report.

Earthquake records can be obtained from recorded events or be artificially generated. However, recorded earthquake motions were preferred since they represent realistic frequency and energy content from past events. The current library of strong-motion records is primarily made up of West Coast earthquakes, so careful consideration must be given to the selection of records for the various regions. Accordingly, judgment becomes an important factor in defining those particular features that have the greatest effect on the expected ground shaking at the various regions and in selecting the records that best represent these features. Once the records are selected, they must be approximately scaled to match the ATC design response spectra for each region. The ATC response spectra for the seven geographical regions are shown in Figures 4-3, 4-4, and 4-5.



A_a	A_v	M	h	MECH	Δ
0.2	0.2	5.5 TO 7	63	N/S	≤100

A_a	A_v	M	h	MECH	Δ
0.2	0.2	5.5 TO 7	20	N	≤100

A_a	A_v	M	h	MECH	Δ
0.1	0.1	5.5 TO 6.5	25	R	120

A_a	A_v	M	h	MECH	Δ
0.1	0.1	5.5	25	–	≤ 80

A_a	A_v	M	h	MECH	Δ
0.4	0.4	6.5 TO 8.25	10	S/R	≤120

A_a	A_v	M	h	MECH	Δ
0.1	0.1	5.5 TO 7	25	–	≤100

A_a	A_v	M	h	MECH	Δ
0.2	0.2	5.5 TO 7	25	R	.70

LEGEND:

M = MAGNITUDE (Richter)

h = FOCAL DEPTH km

MECH = SOURCE MECHANISM { S = STRIKE SLIP; RT = REVERSE THRUST; N = NORMAL }

A_a = EFFECTIVE PEAK ACCELERATION, g

A_v = ACCELERATION COEFFICIENT RELATED TO EFFECTIVE PEAK VELOCITY

Δ = SOURCE DISTANCE TO SELECTED POPULATION CENTER, km

NOTE: THE NUMBERS ON THE CONTOURS ARE VALUES OF EPA IN UNITS OF ACCELERATION OF GRAVITY

FIGURE 4-1. SUMMARY OF SEISMIC INPUT DATA FOR SEVEN MAJOR U.S. GEOGRAPHICAL REGIONS (Adapted from ATC, 1978)

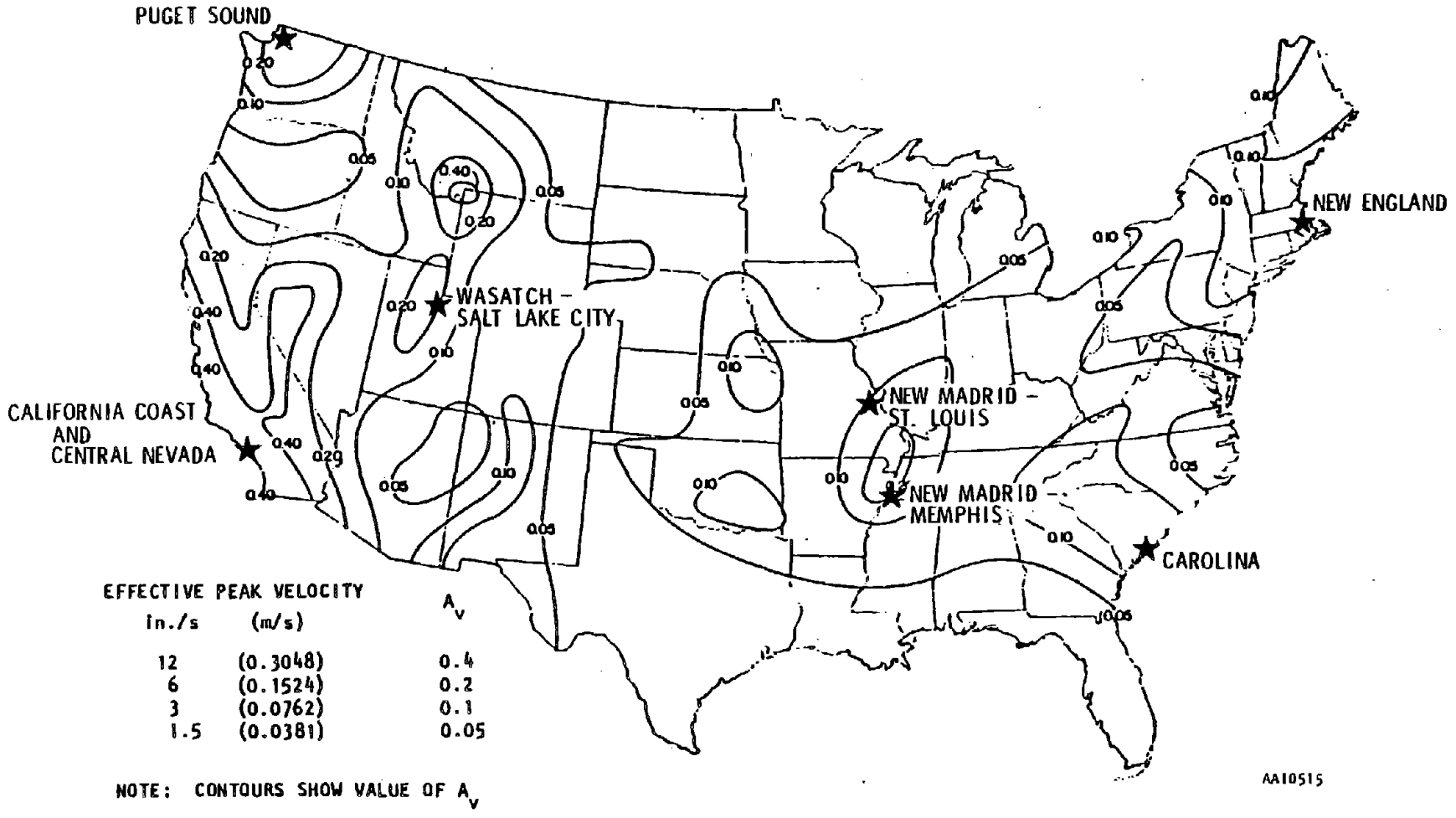


FIGURE 4-2. LOCATION OF SEVEN SELECTED MAJOR U.S. GEOGRAPHICAL REGIONS ON EFFECTIVE PEAK VELOCITY MAP (ATC, 1978)

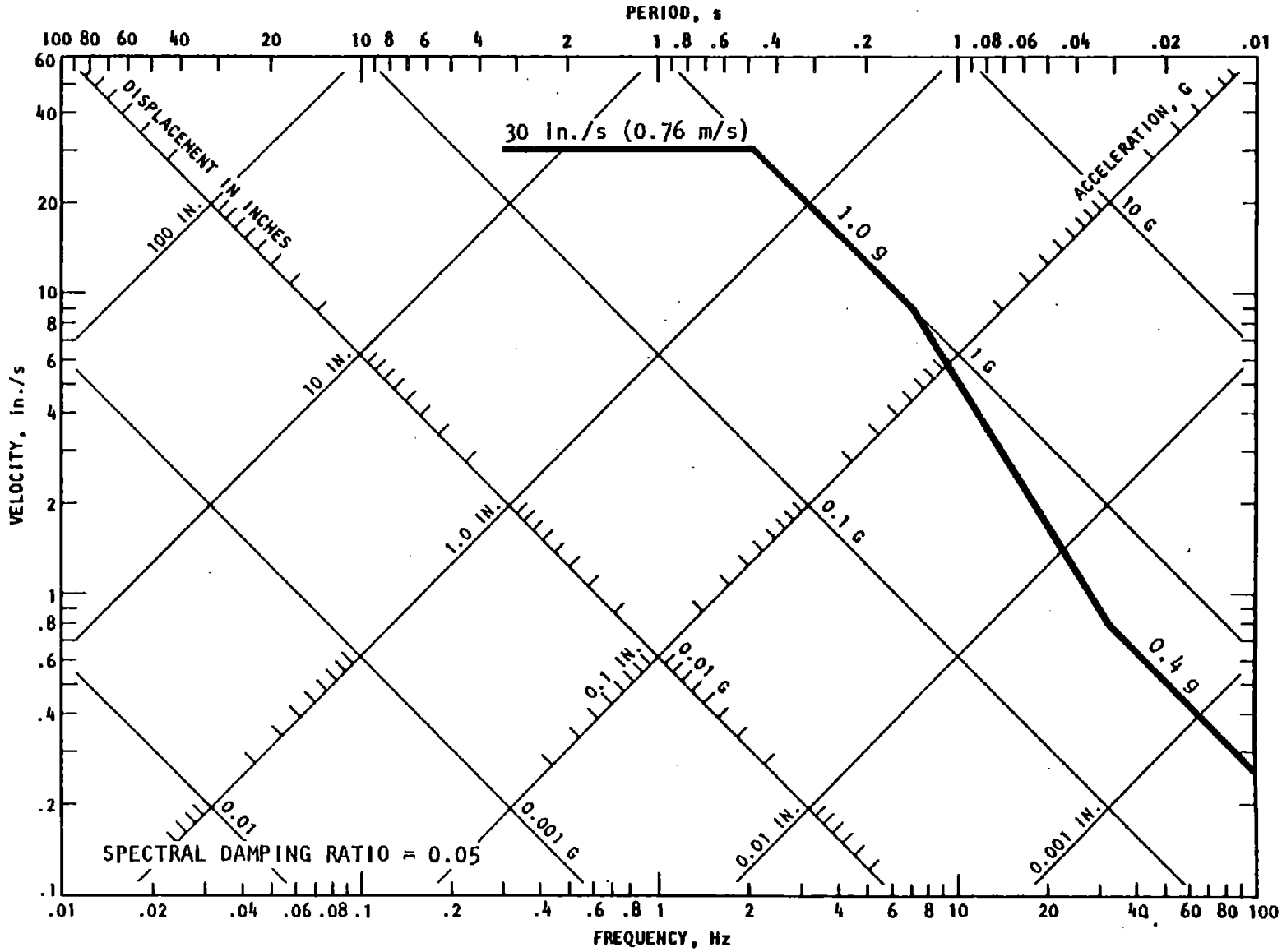


FIGURE 4-3. ATC GROUND MOTION RESPONSE SPECTRUM FOR THE CALIFORNIA COAST AND CENTRAL NEVADA REGION (A_a = 0.40, A_v = 0.40)

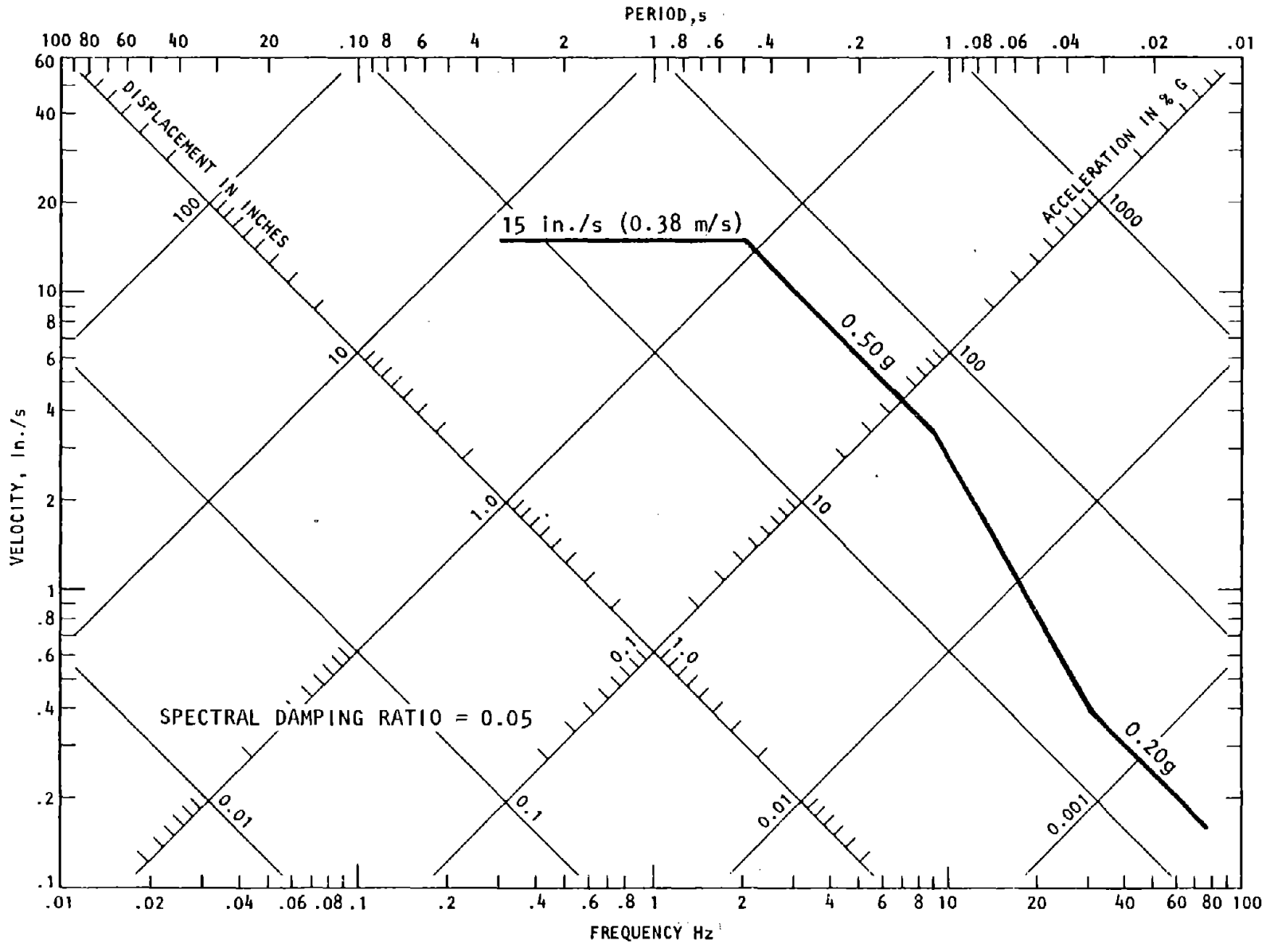


FIGURE 4-4. ATC GROUND MOTION RESPONSE SPECTRUM FOR THE PUGET SOUND, WASATCH-SALT LAKE CITY, AND NEW MADRID-MEMPHIS REGIONS (A_a = 0.20, A_v = 0.20)

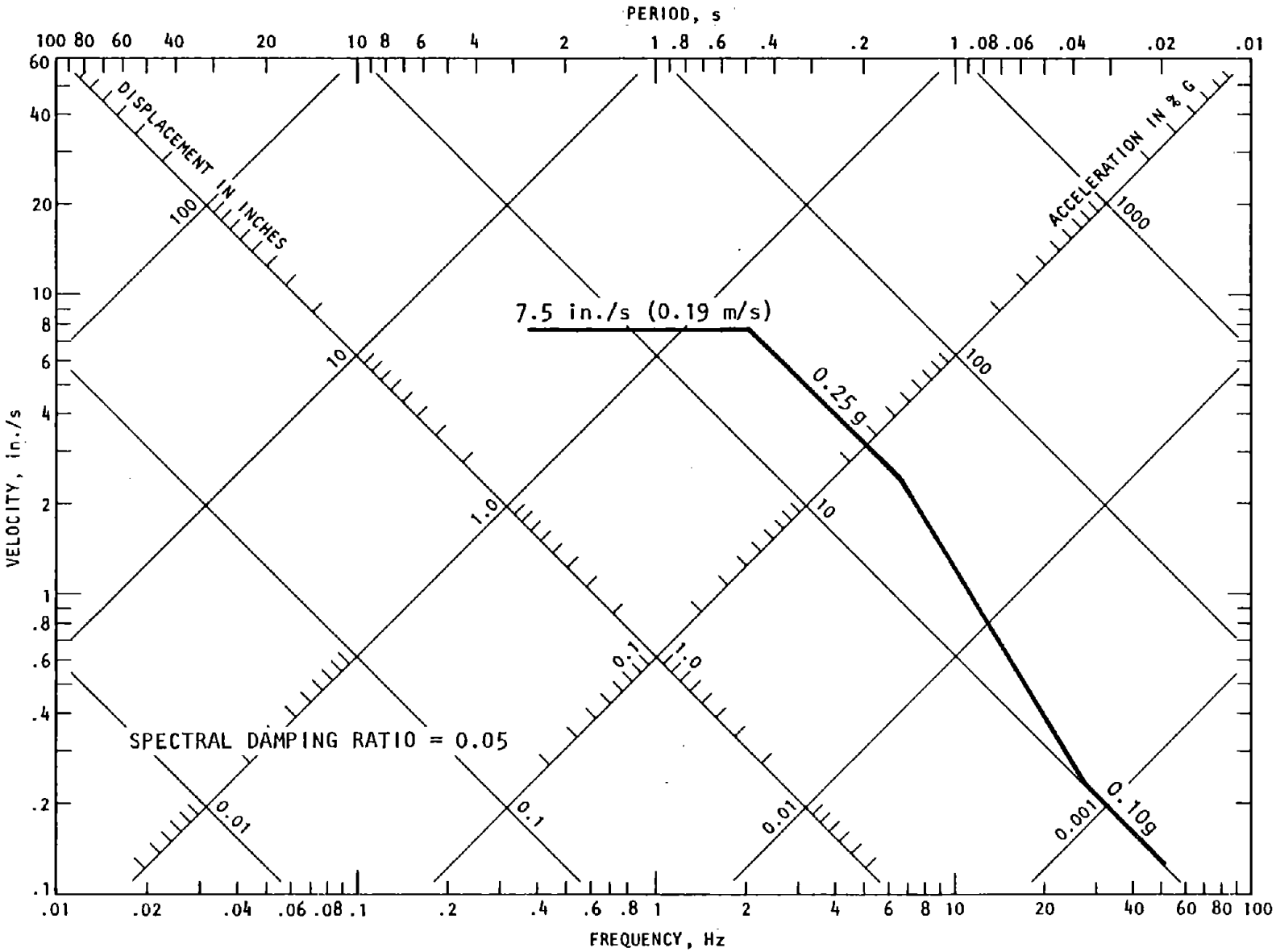


FIGURE 4-5. ATC GROUND MOTION RESPONSE SPECTRUM FOR NEW MADRID-ST. LOUIS, CAROLINA, AND NEW ENGLAND REGIONS (A_a = 0.10, A_v = 0.10)

The ATC response spectra are smoothed spectra and represent mean values of the actual spectra. Figure 4-6 shows how the smoothed EPA and EPV segments are obtained from a response spectrum. The mean of the response spectrum of the selected time-history record should provide a good match with the corresponding ATC response spectrum.

An ensemble of six candidate earthquake time-history components was selected for the design intensity level of each region. These records provided a bound on the type and character of the expected ground motion and account for some statistical variations in earthquake motions. Selected records were obtained from the ensembles.

For the seven regions, Tables 4-1 through 4-6 present (1) the tabulated comparison of ATC spectra and ensemble of records and (2) the ensemble of earthquake records; and Figures 4-7 through 4-22 present the individual comparisons of ATC spectra and a specified record, with scaling factor. These tables and figures follow the end of the text of Section 4 and are grouped by regions.

The ensembles and selected records for the various geographical regions are described in the following sections.

4.2 ENSEMBLE OF EARTHQUAKE TIME-HISTORY RECORDS FOR THE CALIFORNIA COAST AND CENTRAL NEVADA REGION

4.2.1 EARTHQUAKE CONDITIONS

ATC-3 maps (Figs. 4-1 and 4-2) indicate effective peak acceleration of 0.40 g and effective peak velocity of 12 in./s (0.30 m/s) for the California Coast and Central Nevada region. This acceleration and velocity can be experienced at a site in this region as a result of strong or moderately strong earthquakes along numerous faults within or bordering the region. Two types of earthquake motions should be specified to represent bounding design earthquake conditions at the site. The first corresponds to a local earthquake of magnitude ~6.5 on the Richter scale along one of the nearby faults within the region. The second condition corresponds to a magnitude 8.5 centered at one of the major faults, possibly along the San Andreas fault.

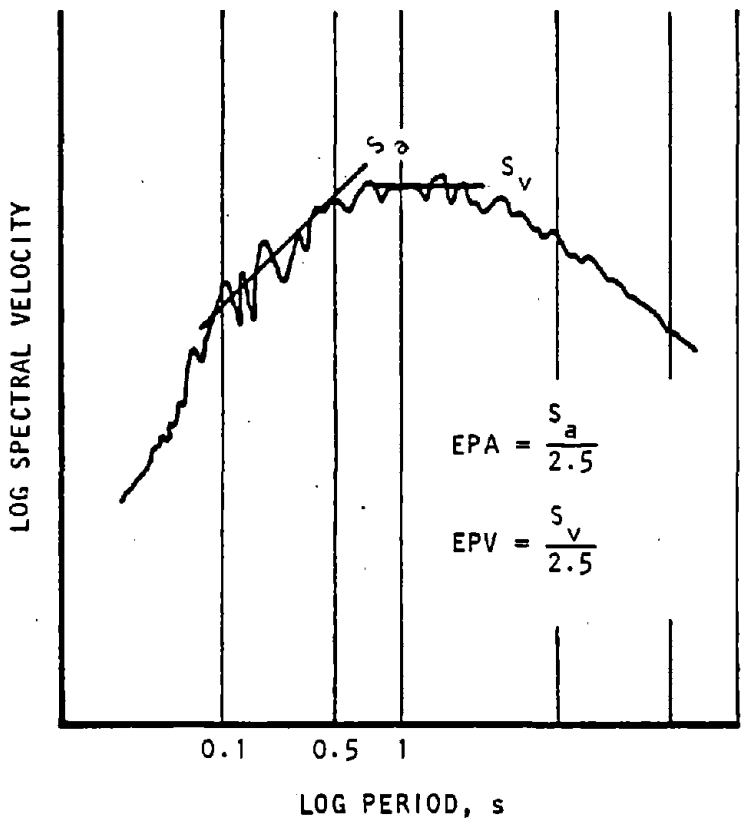


FIGURE 4-6. SCHEMATIC REPRESENTATION SHOWING HOW EFFECTIVE PEAK ACCELERATION AND EFFECTIVE PEAK VELOCITY ARE OBTAINED FROM A RESPONSE SPECTRUM

4.2.2 EARTHQUAKE RECORDS

The ensemble of accelerogram records shown in Table 4-1 was selected to represent ATC spectrum-matched records for the California Coast and Central Nevada region. The spectra of these records are shown in Figures 4-7 through 4-10. The 1940 El Centro record has a long strong-motion duration of approximately 30 sec (CIT, 1969-1975). This duration is representative of a moderately large event on the San Andreas fault. The 1952 Taft record has a considerable wide-band spectrum and represents strong motions from a large event triggered on a reverse-thrust fault system. The 1971 Castaic record has a short duration, high-frequency, strong-motion segment. This record represents the condition of a moderate earthquake event on a nearby fault. In Table 4-2, the spectra of these records are compared to the ATC spectrum. This comparison indicates that the N-S component of the 1940 El Centro and the N69W component of the 1971 Castaic record provide the two bounding design earthquake conditions for a site in the California Coast and Central Nevada region. The time histories for these two records, shown in Appendix G, were selected for the analysis and testing of URM buildings and components selected in this region.

4.3 ENSEMBLE OF TIME-HISTORY RECORDS FOR THE PUGET SOUND, WASATCH-SALT LAKE CITY, AND NEW MADRID-MEMPHIS REGIONS

4.3.1 EARTHQUAKE CONDITIONS

The Puget Sound, Wasatch-Salt Lake City, and New Madrid-Memphis regions are moderately high seismic areas. ATC-3 maps (Figs. 4-1 and 4-2) indicate effective peak acceleration of 0.20 g and effective peak velocity of 6 in./s (0.15 m/s).

The design earthquake threat to the Puget Sound region would come from deep focus earthquakes with maximum credible magnitude of 7.4 on the Richter scale. The design earthquake threat to the Wasatch-Salt Lake City region would come from a shallow, moderately strong event on a normal fault. The design earthquake criteria for the New Madrid-Memphis region are developed for the conditions of an event occurring within 70 km of a site.

4.3.2 EARTHQUAKE RECORDS

The ensemble of accelerogram records shown in Table 4-3 was selected to represent ATC spectrum-matched records for Puget Sound, Wasatch-Salt Lake City, and New Madrid-Memphis regions. The spectra of these records are shown in Figures 4-11 through 4-16 and are compared to the ATC spectrum in Table 4-4. The comparison indicates that the N69W component of the 1971 Castaic record provides a good representation of the earthquake condition for the Wasatch-Salt Lake City region. However, the 1949 S04E component of the Olympia record provides a good match for the earthquake environment considered for the Puget Sound and New Madrid-Memphis regions. Therefore, the time histories for Castaic and Olympia (Appendix G) were selected for the analysis and testing of URM buildings and components at the Wasatch-Salt Lake City region and Puget Sound/New Madrid-Memphis regions, respectively.

4.4 ENSEMBLE OF TIME-HISTORY RECORDS FOR THE NEW MADRID-ST. LOUIS, CAROLINA, AND NEW ENGLAND REGIONS

4.4.1 EARTHQUAKE CONDITIONS

The New Madrid-St. Louis, Carolina, and New England regions are areas of low to moderate seismicity. ATC-3 maps (Figs. 4-1 and 4-2) indicate an effective peak acceleration of 0.10 g and effective peak velocity of 3 in./s (0.08 m/s).

The design earthquake threat to the New Madrid-St. Louis region would come from moderate to moderately strong earthquakes of maximum credible magnitude between 5.5 and 6.5. These earthquakes may occur at a distance as far as 120 km from a site in St. Louis. Depth of focus is approximately 25 km.

The design earthquake threat to the Carolina region would come from moderate to moderately strong earthquakes of maximum credible magnitude between 5.5 and 7. These earthquakes would probably occur at a distance less than 100 km from Charleston. Depth of focus is approximately 25 km.

The design earthquake threat to the New England region would result from moderate earthquake of maximum credible magnitude 5.5. These earthquakes would probably occur within 80 km of Boston. Depth of focus is approximately 25 km.

4.4.2 EARTHQUAKE RECORDS

The ensemble of accelerogram records shown in Table 4-5 was selected to represent ATC spectrum-matched records for the New Madrid-St. Louis, Carolina, and New England regions. The spectra of the three records are shown in Figures 4-17 through 4-22 and are compared to the ATC spectrum in Table 4-6. This comparison indicates that the E-W component of the 1971 Hollywood storage record provides a reasonable correlation with ATC spectrum. Therefore, this record was selected for the time-history analysis of URM buildings in the New Madrid-St. Louis region.

The N21E component of 1954 Taft record from the Wheeler Ridge earthquake provides a good match for the earthquake environment considered for the Carolina and New England regions. The time histories for the N90E component of the 1971 Hollywood storage record and the N21E component of 1954 Taft record (Appendix G) were selected for the analysis and testing of URM buildings and components at the two regions.

TABLE 4-1. ENSEMBLE OF EARTHQUAKE RECORDS FOR CALIFORNIA COAST AND CENTRAL NEVADA REGION

Accelerograph Station		Earthquake Event			Accelerograph Site Classification			Peak Acceleration (1), g's	
Location	Epicentral Distance (2), km	Location	Date	Magnitude (1)	Subsurface Soil Conditions (3)	Local Geology (2,4)	MM Intensity at Site (2)	Horizontal	Vertical
El Centro Imperial Valley Irrigation District	9.3	Imperial Valley, California	5-18-40	6.7	0	0	7,8,9 (5)	0.349 (S00E) 0.214 (S90W)	0.210
Taft Lincoln School Tunnel	43.0	Kern County, California	7-21-52	7.7	0	0	7	0.156 (N21E) 0.179 (S69E)	0.105
Old Ridge Route, Castaic, California	28.6	San Fernando, California	2-9-71	6.4	1	1	6	0.316 (N21E) 0.271 (N69W)	0.156

(1) Data provided by CIT (1969-1975).

(2) Data provided by Trifunac and Brady (1975) and/or Trifunac (1976).

(3) Subsurface soil classifications correspond to those defined by Seed, Ugas, and Lysmer (1976) and are as follows:

0 = Deep soil site
1 = Stiff soil site
2 = Rock site

(4) Local geology classifications correspond to those defined by Trifunac and Brady (1975) and are as follows:

0 = Alluvium
1 = Intermediate rock
2 = Basement rock

(5) Where three numerical values of site intensities are provided, the upper and lower values represent the range of intensities that have been reported for the accelerograph station by various investigators. The intermediate value represents the site intensity actually assigned to the station by Trifunac and Brady (1975).

TABLE 4-2. COMPARISON OF SPECTRA FOR ATC AND ENSEMBLE OF RECORDS FOR CALIFORNIA COAST AND CENTRAL NEVADA REGION

Accelerograph Station		Scaling (1) Factor	Comparison with ATC		Comments	Recommendations
Location and Date	Comp.		Acceleration Segment (2)	Velocity Segment (3)		
El Centro Imperial Valley Irrigation District May 18, 1940	N-S	1.25	ATC slightly higher	ATC approximate average of N-S spectrum	Correlates well with ATC Figure 4-7	Input for distant event
	E-W	1.40	ATC considerably higher	Reasonable correlation	E-W displacements are high Figure 4-8	
Taft Lincoln July 21, 1952	N21E	3.0	ATC approximate average	ATC approximate average	Displacements appear to be high due to scaling Figure 4-9	
	S69E	3.0	ATC approximate average	ATC approximate average	Displacements appear to be high due to scaling Figure 4-9	
Old Ridge Route Castaic, Calif. July 9, 1971	N69W	1.8	ATC approximate average	Castaic has much more of a narrow band shape	Displacements appear to be low Figure 4-10	Input for nearby event
	N21E	1.8	ATC approximate average	ATC considerably higher than N21E spectrum	Displacements appear to be low Figure 4-10	

(1) Linear velocity scaling is used along the vertical axis.

(2) Period 0.1 seconds to 0.5 seconds.

(3) Period longer than 0.5 seconds.

TABLE 4-3. ENSEMBLE OF EARTHQUAKE RECORDS FOR PUGET SOUND, WASATCH-SALT LAKE CITY, AND NEW MADRID-MEMPHIS REGIONS

Accelerograph Station		Earthquake Event			Accelerograph Site Classification			Peak Acceleration (1), g's	
Location	Epicentral Distance (2), km	Location	Date	Magnitude (1)	Subsurface Soil Conditions (3)	Local Geology (2,4)	MM Intensity at Site (2)	Horizontal	Vertical
8244 Orion Blvd First Floor Los Angeles	42.8	San Fernando, California	2-9-71	6.4	0	0	7	0.255 (N00W) 0.134 (S90W)	0.171
Old Ridge Route, Castaic, California	28.6	San Fernando, California	2-9-71	6.4	1	1	6	0.316 (N21E) 0.271 (N69W)	0.156
Olympia Highway Test Lab	16.8	Western Washington	4-13-49	7.1	0	0	8	0.165 (N04W) 0.280 (N86E)	0.092

NOTE: See Table 4-1 for footnote callouts.

TABLE 4-4. COMPARISON OF SPECTRA FOR ATC AND ENSEMBLE OF RECORDS FOR PUGET SOUND, WASATCH-SALT LAKE CITY, AND NEW MADRID-MEMPHIS REGIONS

Accelerograph Station		(6) Scaling Factor	Comparison with ATC		Comments	Recommendations
Location and Date	Comp.		(7) Acceleration Segment	(8) Velocity Segment		
8244 Orion Blvd. First Floor Los Angeles Feb. 9, 1971	N-S	0.82	N-S component falls well below ATC between 4 and 20 Hz	ATC approximate average of N-S spectrum	Fair correlation (Figure 4-11)	
	E-W	0.82	E-W component falls considerably below ATC spectrum	Falls considerably above ATC in the range between 0.3-1 Hz	Poor correlation (Figure 4-12)	
Old Ridge Route Castaic, Calif. Feb. 9, 1971	N69W	1.0	Good correlation between both spectra	ATC approximate average of N69W Castaic	Spectrum for Castaic has much more of a narrow band shape (Figure 4-13)	Input for Salt Lake City
	N21E	1.0	Castaic is higher than ATC in the range of 2 to 8 Hz	Castaic falls considerably below ATC	Spectrum for Castaic has much more of a narrow band shape (Figure 4-14)	
Olympia Highway Test Lab April 13, 1949	N86E	1.10	Olympia higher (2.5-8 Hz) Olympia lower (9-16 Hz)	Olympia falls below ATC (0.5-1.5 Hz)	Fair correlation (Figure 4-15)	
	S04E	1.10	Good correlation between both spectra	ATC approximate average of Olympia	Good correlation (Figure 4-16)	Input for Seattle and Memphis

NOTE: See Table 4-2 for footnote callouts.

TABLE 4-5. ENSEMBLE OF EARTHQUAKE RECORDS FOR NEW MADRID-ST. LOUIS, CAROLINA, AND NEW ENGLAND REGIONS

Accelerograph Station		Earthquake Event			Accelerograph Site Classification			Peak Acceleration (1), g's	
Location	Epicentral Distance (2), km	Location	Date	Magnitude (1)	Subsurface Soil Conditions (3)	Local Geology (2,4)	MM Intensity at Site (2)	Horizontal	Vertical
Hollywood Storage P.E. Lot, Los Angeles	37.1	San Fernando, California	2-9-71	6.4	1	0	7	0.171 (S00W) 0.211 (N90E)	0.089
Ferndale City Hall	56.3	Northwest California	10-7-51	5.8	0	1	5	0.104 (S44W) 0.112 (S90W)	0.027
Taft Lincoln School Tunnel	43.0	Wheeler Ridge, California	1-12-54	5.9	1	0	6	0.065 (N21E) 0.068 (S69E)	0.036

NOTE: See Table 4-1 for footnote callouts.

TABLE 4-6. COMPARISON OF SPECTRA FOR ATC AND ENSEMBLE OF RECORDS FOR NEW MADRID-ST. LOUIS, CAROLINA, AND NEW ENGLAND REGIONS

Accelerograph Station		(6) Scaling Factor	Comparison with ATC		Comments	Recommendations
Location and Date	Comp.		(7) Acceleration Segment	(8) Velocity Segment		
Hollywood Storage P.E. Lot Los Angeles Feb. 9, 1971	N-S	0.67	Fair correlation; however, N-S spectrum is mostly higher	N-S component mostly lower than ATC	Wide band overestimates displacements (Figure 4-18)	
	E-W	0.50	Fair correlation	ATC average of E-W component	Wide band fair correlation overestimates displacements (Figure 4-18)	For time-history analysis of St. Louis
Ferndale City Hall Oct. 7, 1951	S44W	1.15	Fair correlation	S44W component much lower than ATC Spectrum	Narrow band (Figure 4-19)	
	S90W	1.15	Fair correlation	N46W component much lower than ATC spectrum	Narrow band (Figure 4-20)	
Taft Lincoln School Tunnel Jan. 12, 1954	N21E	1.60	Good correlation	Mostly lower than ATC	Narrow band fair correlation (Figure 4-21)	For time-history analysis of Charleston and Boston
	S69E	1.80	Poor correlation	Considerably lower than ATC spectrum	Wider band lower velocities (Figure 4-22)	

NOTE: See Table 4-2 for footnote callouts.

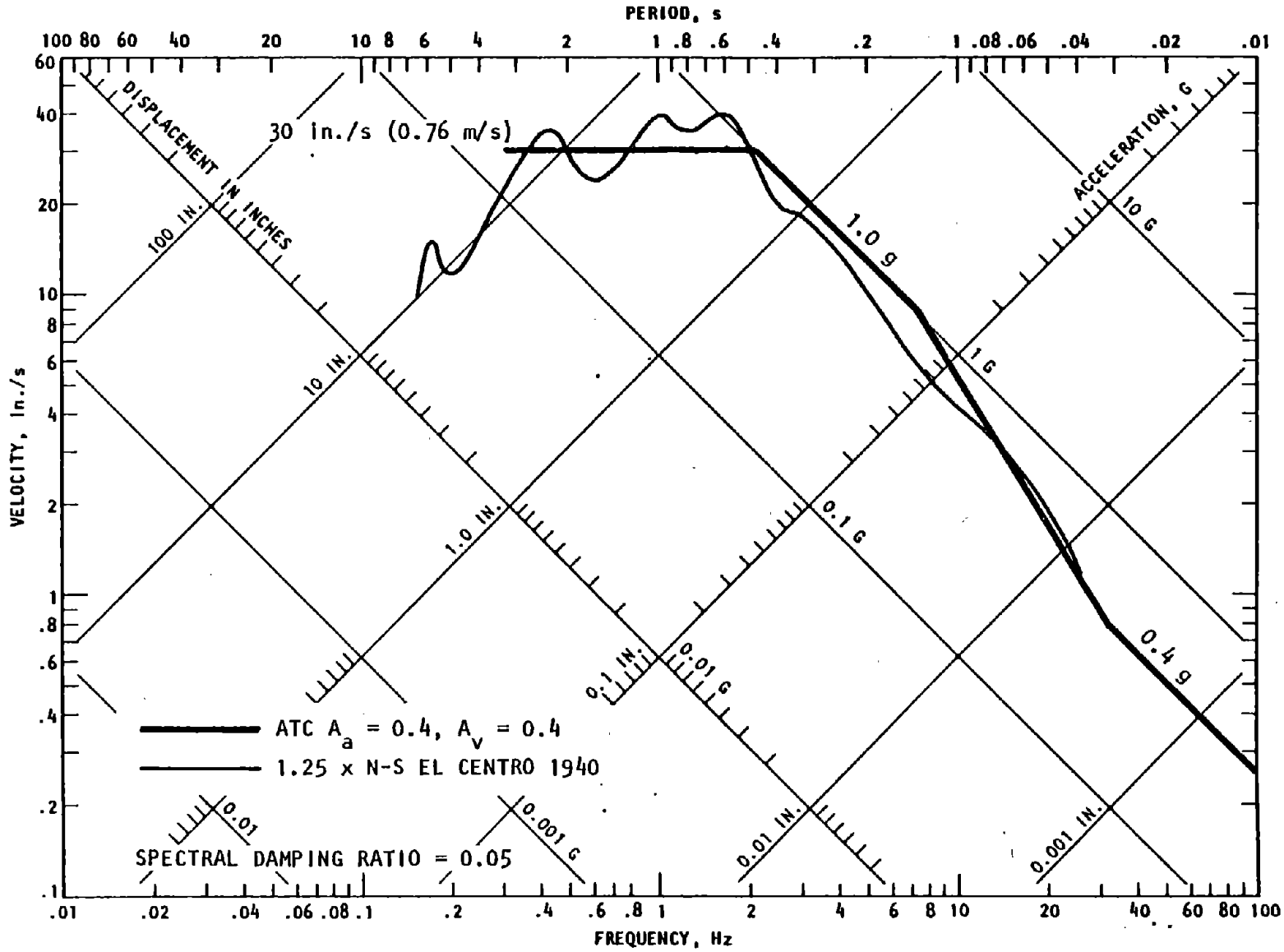


FIGURE 4-7. COMPARISON OF ATC SPECTRA FOR CALIFORNIA COAST AND CENTRAL NEVADA REGION AND N-S EL CENTRO 1940 SCALED BY A FACTOR OF 1.25

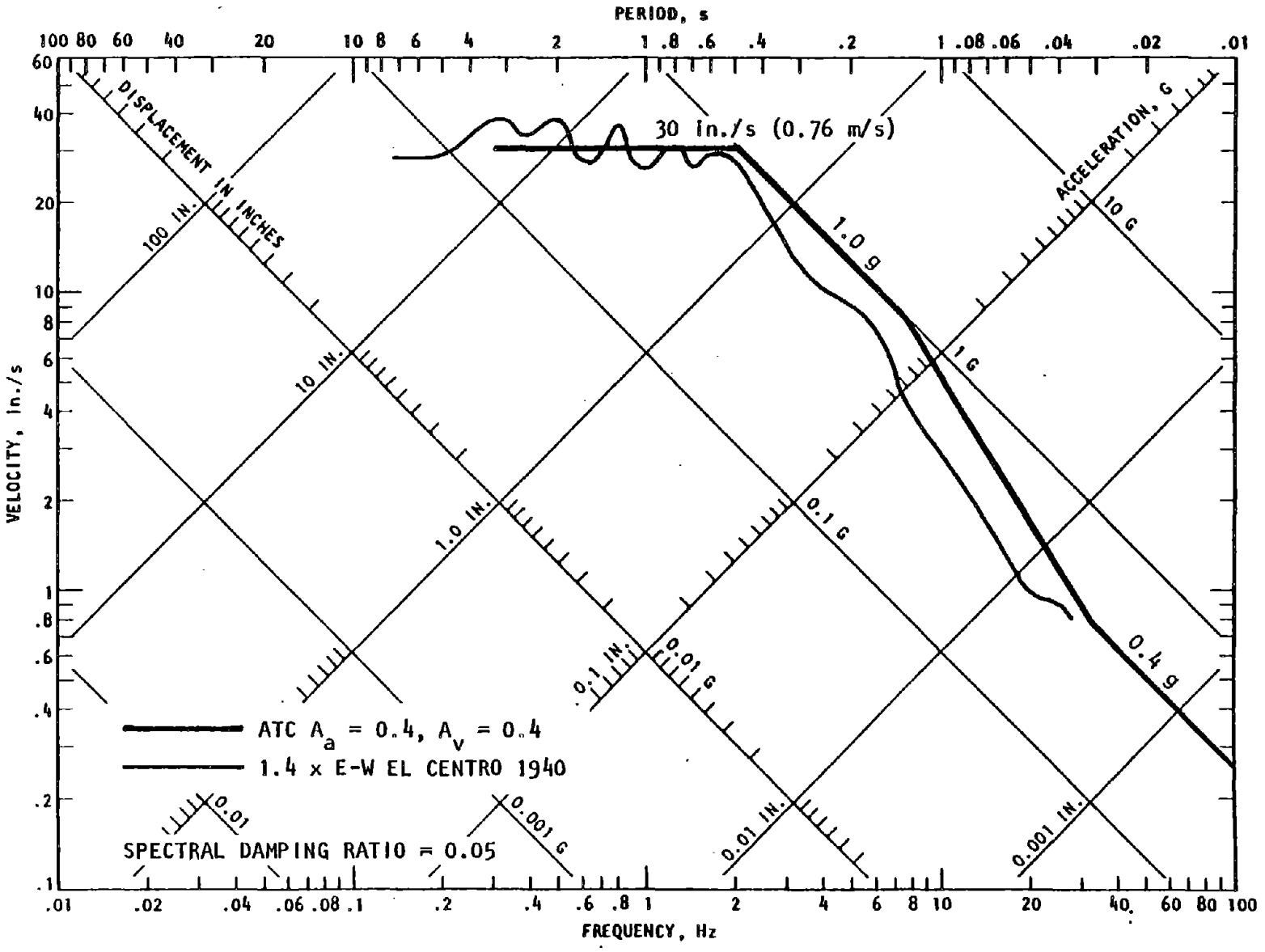


FIGURE 4-8. COMPARISON OF ATC SPECTRA FOR CALIFORNIA COAST AND CENTRAL NEVADA REGION AND EL CENTRO 1940 S90W SCALED BY A FACTOR OF 1.4

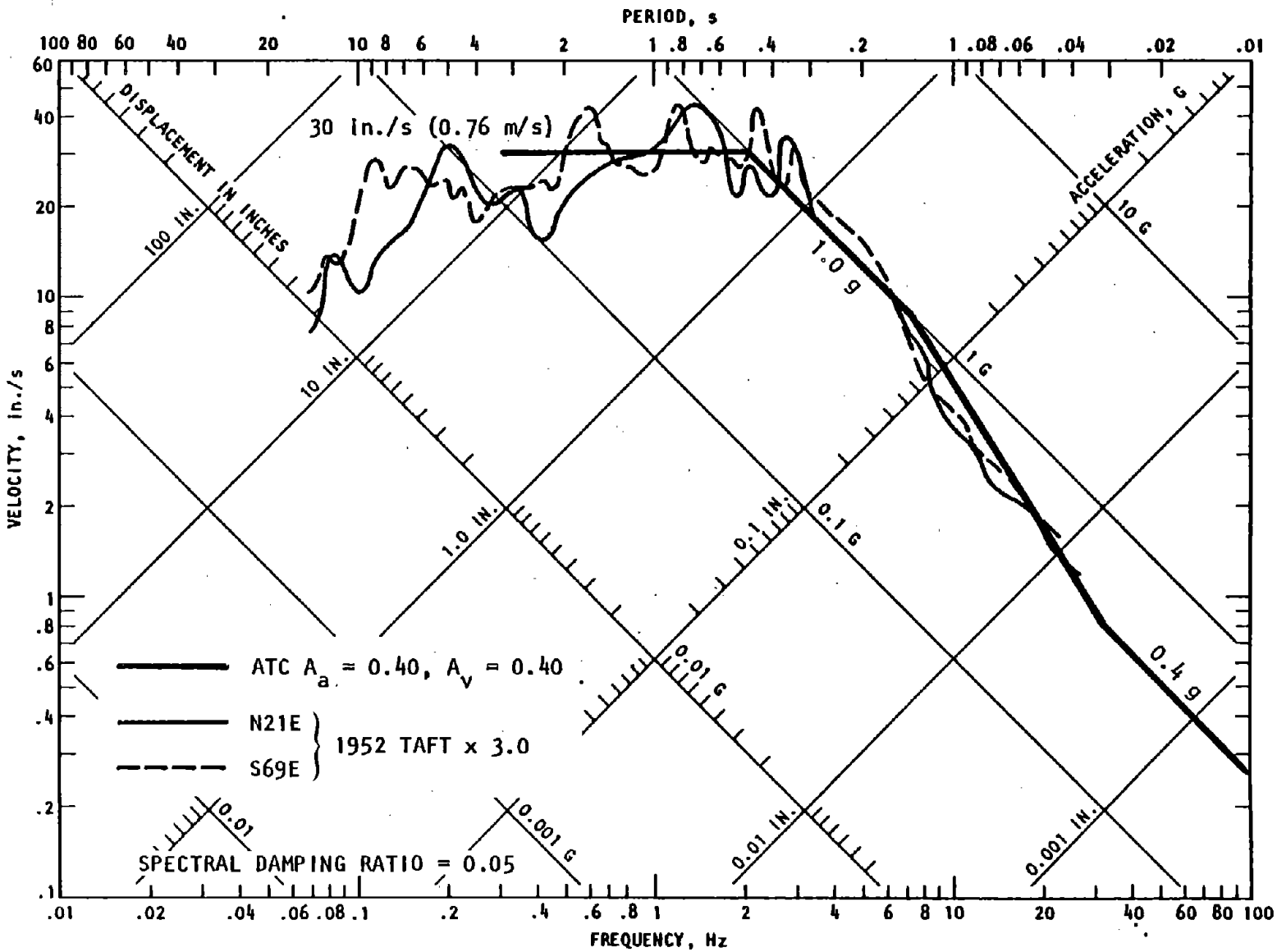


FIGURE 4-9. COMPARISON OF ATC SPECTRA FOR CALIFORNIA COAST AND CENTRAL NEVADA REGION AND 1952 TAFT RECORD SCALED BY A FACTOR OF 3.0

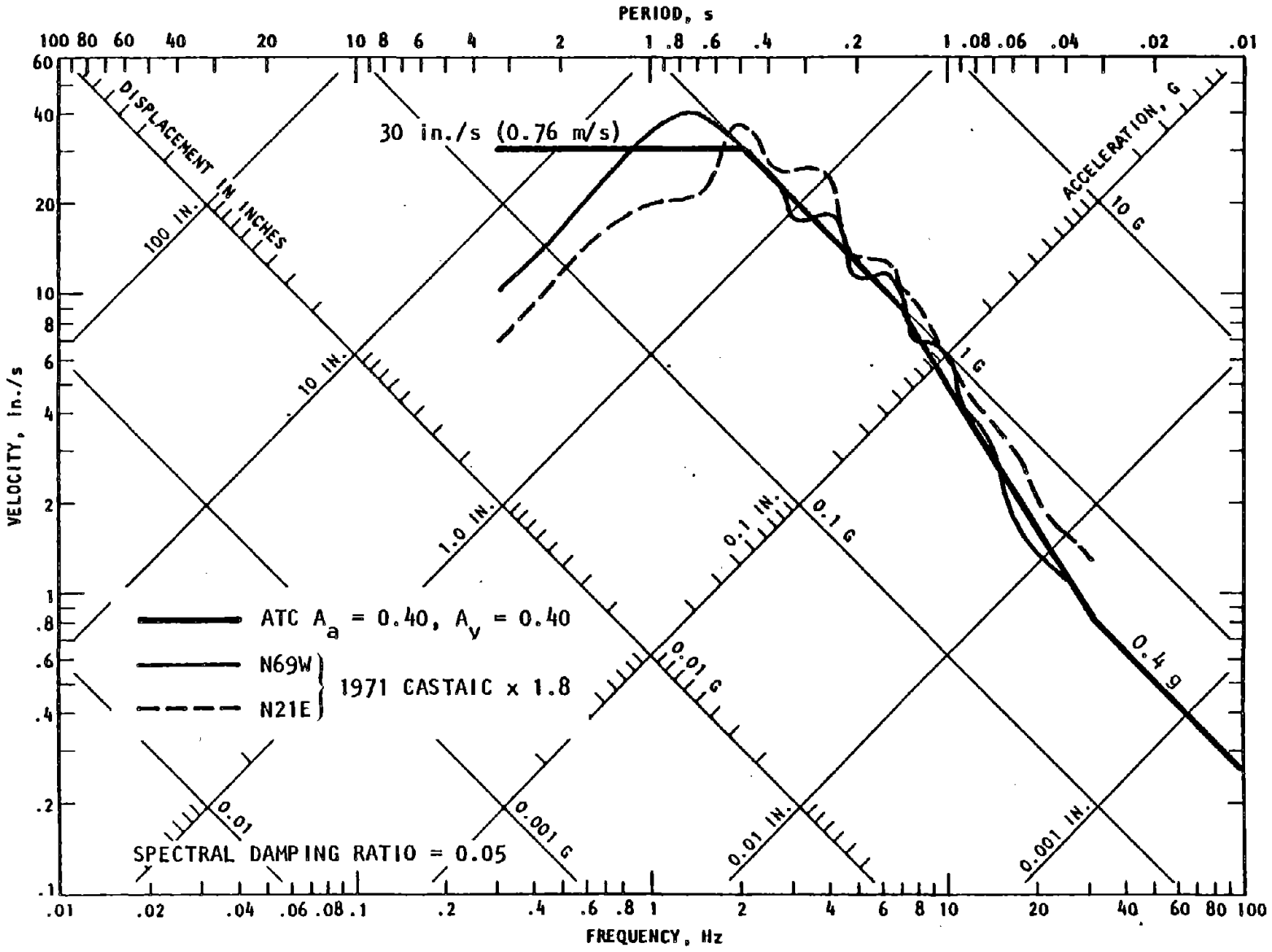


FIGURE 4-10. COMPARISON OF ATC SPECTRA FOR CALIFORNIA COAST AND CENTRAL NEVADA REGION AND 1971 CASTAIC SCALED BY A FACTOR OF 1.8

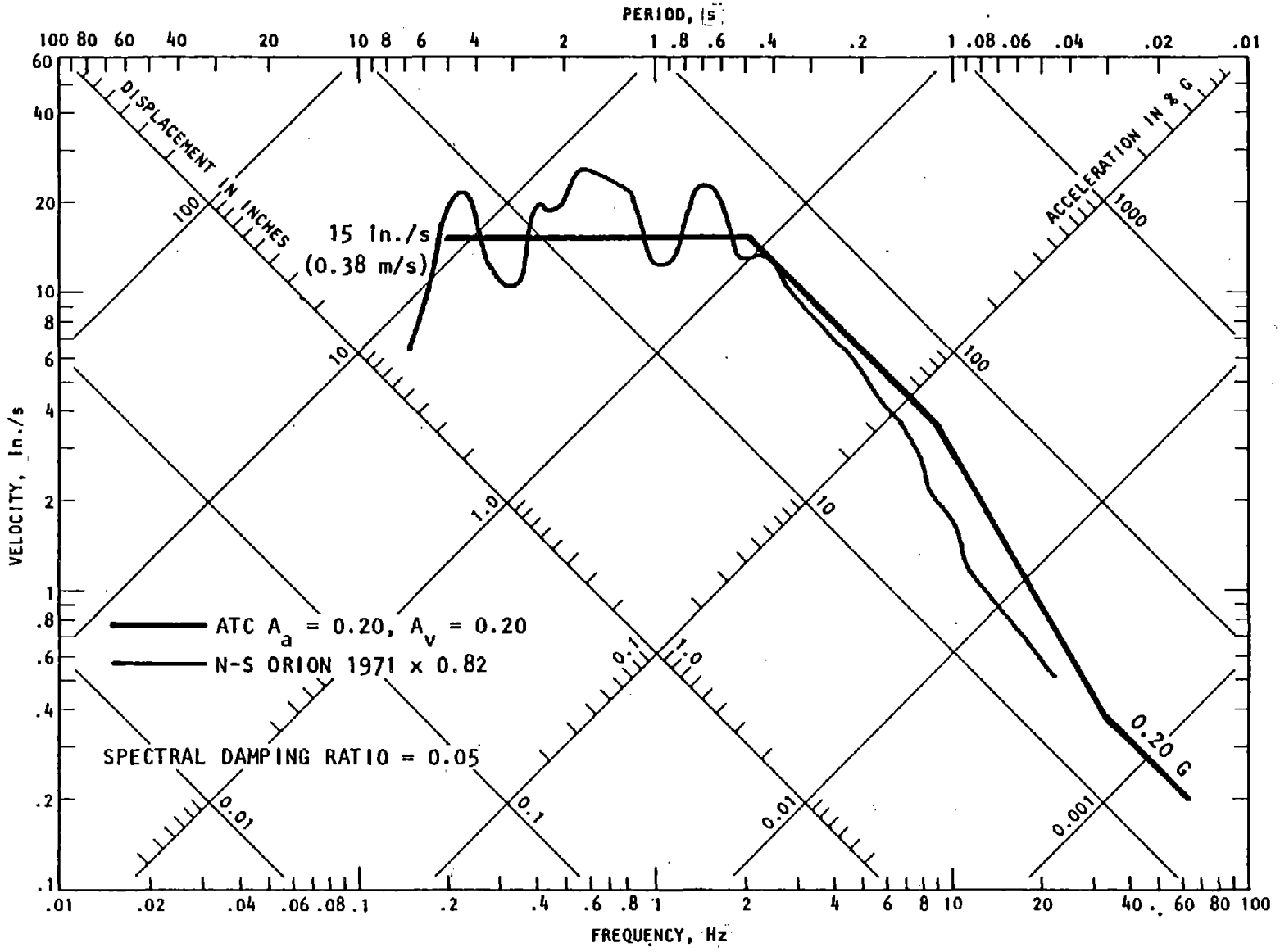


FIGURE 4-11. COMPARISON OF ATC SPECTRA FOR PUGET SOUND, WASATCH-SALT LAKE CITY, NEW MADRID-MEMPHIS REGIONS AND N-S COMPONENT OF 1971 ORION SCALED BY A FACTOR OF 0.82

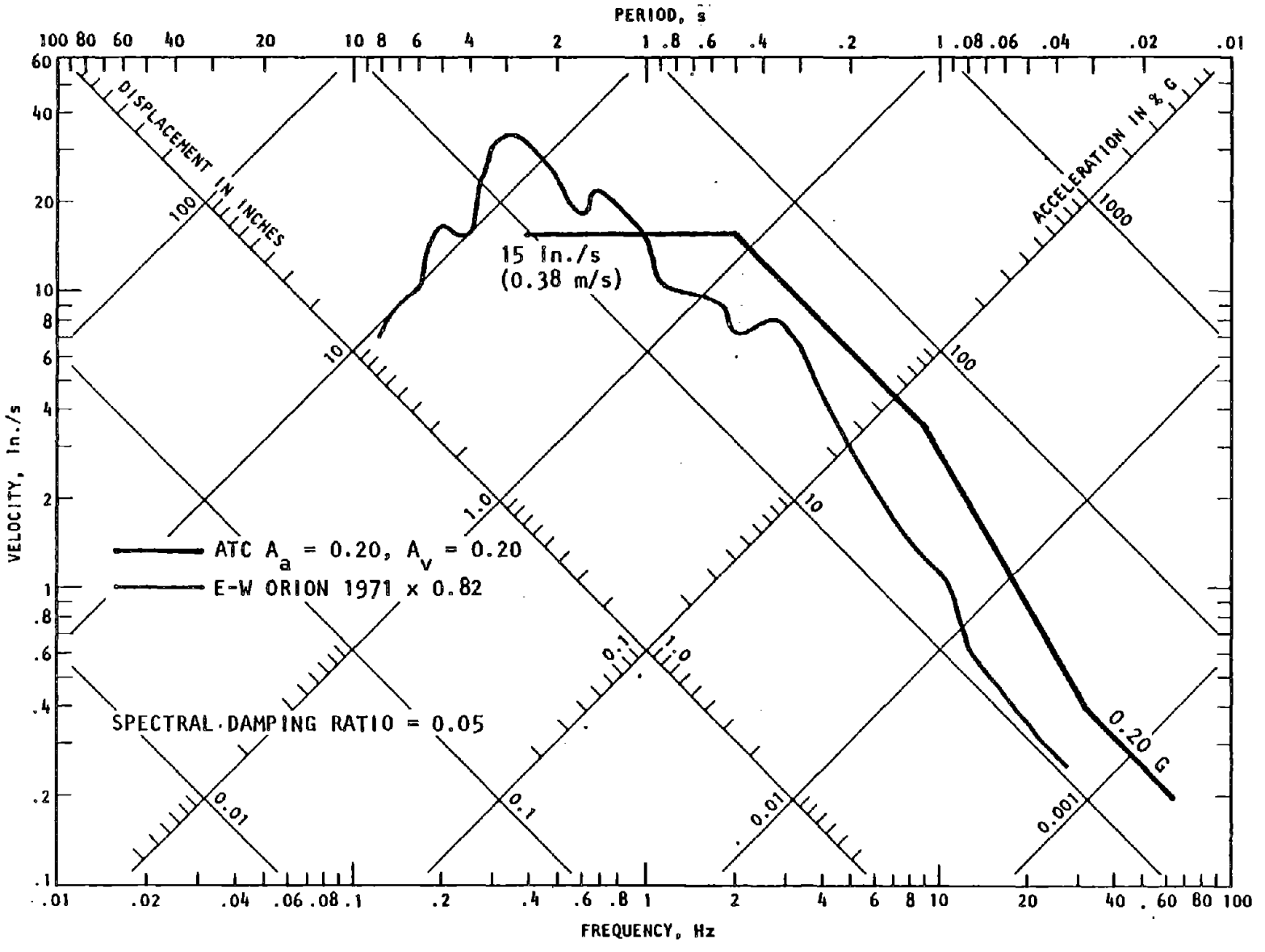


FIGURE 4-12. COMPARISON OF ATC SPECTRA FOR PUGET SOUND, WASATCH-SALT LAKE CITY, NEW MADRID-MEMPHIS REGIONS AND E-W COMPONENT OF 1971 ORION SCALED BY A FACTOR OF 0.82

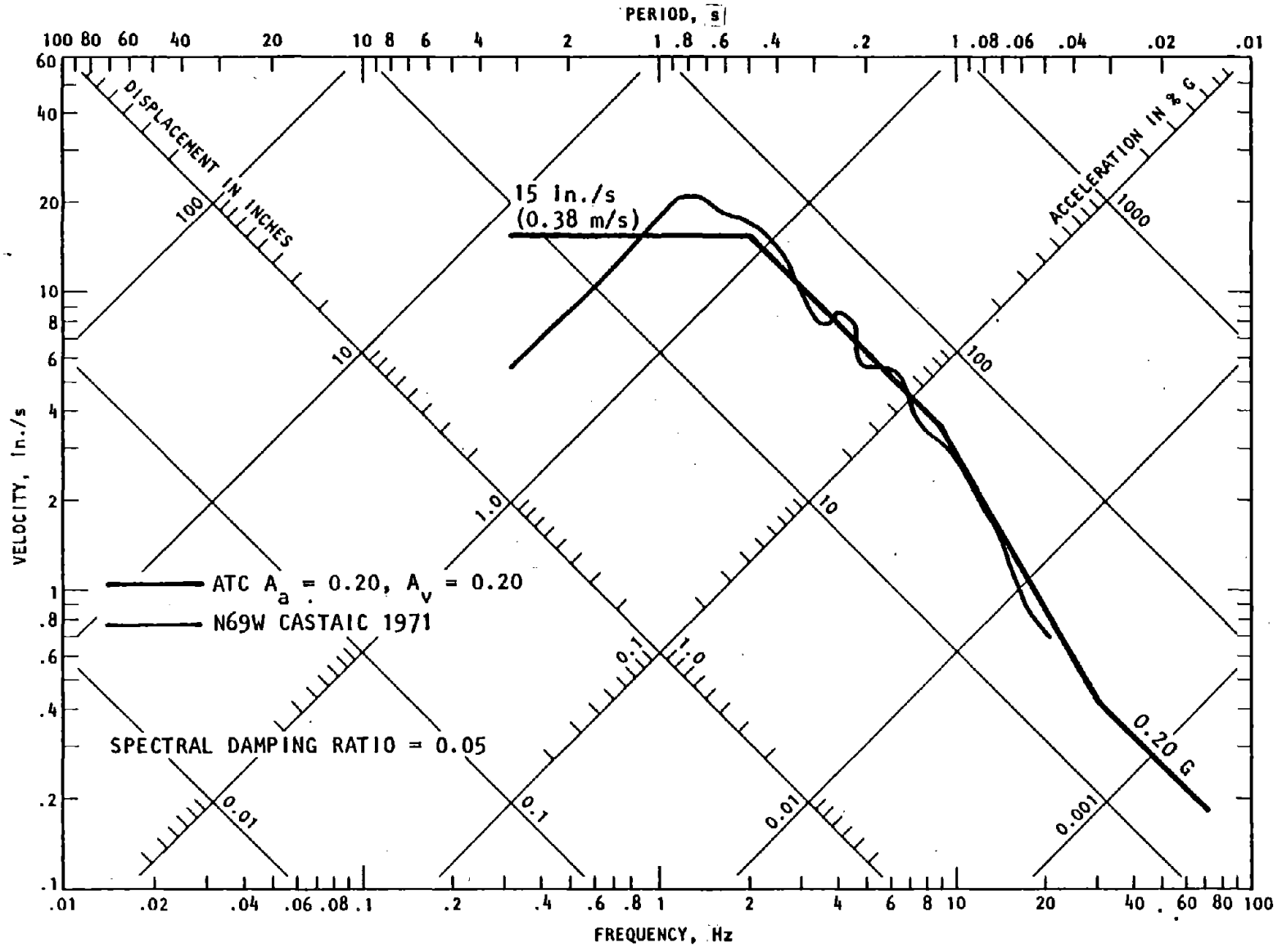


FIGURE 4-13. COMPARISON OF ATC RESPONSE SPECTRA FOR PUGET SOUND, WASATCH-SALT LAKE CITY, NEW MADRID-MEMPHIS REGIONS AND THE N69W CASTAIC 1971

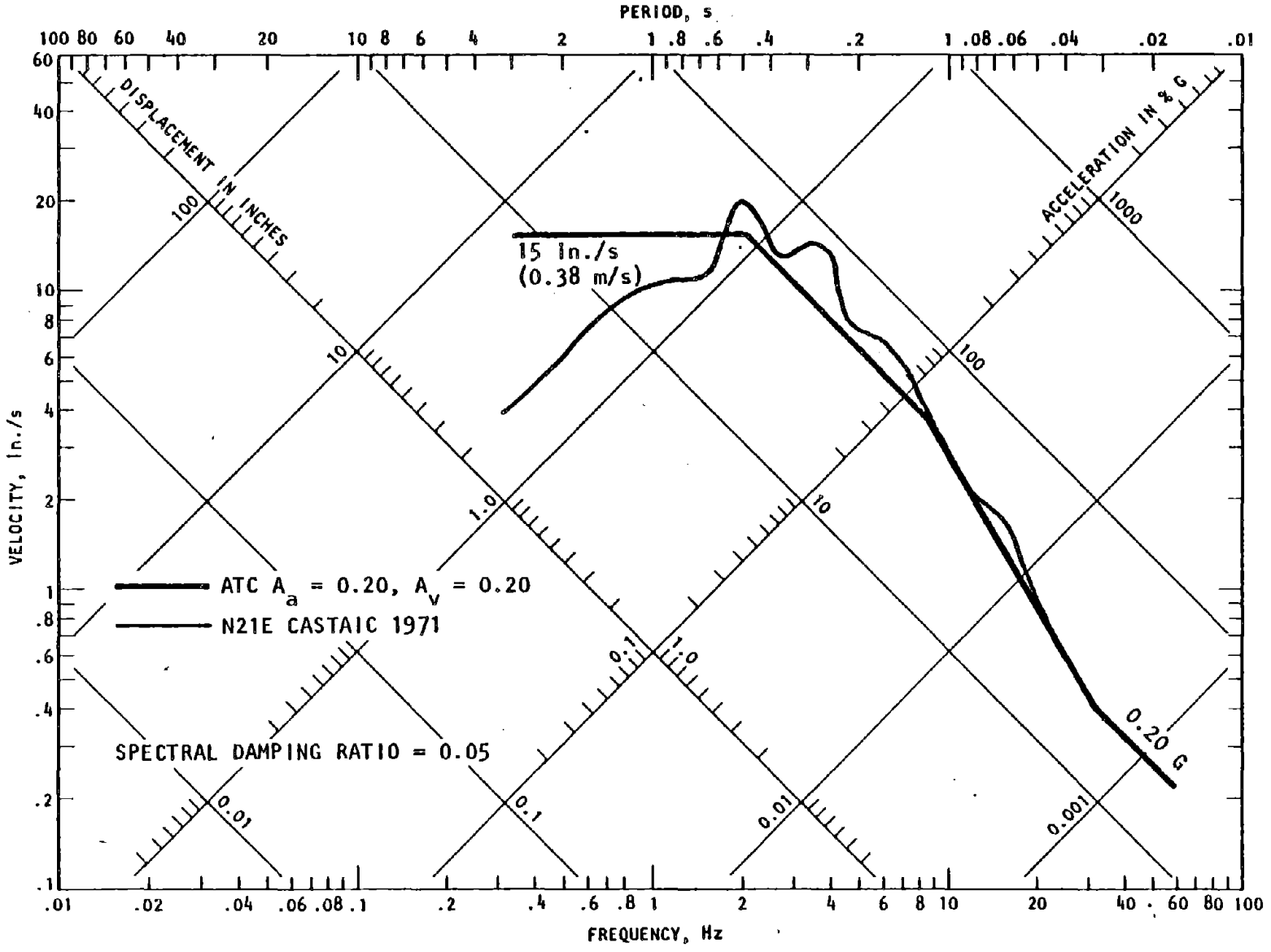


FIGURE 4-14. COMPARISON OF ATC RESPONSE SPECTRA FOR PUGET SOUND, WASATCH-SALT LAKE CITY, NEW MADRID-MEMPHIS REGIONS AND THE N21E CASTAIC 1971

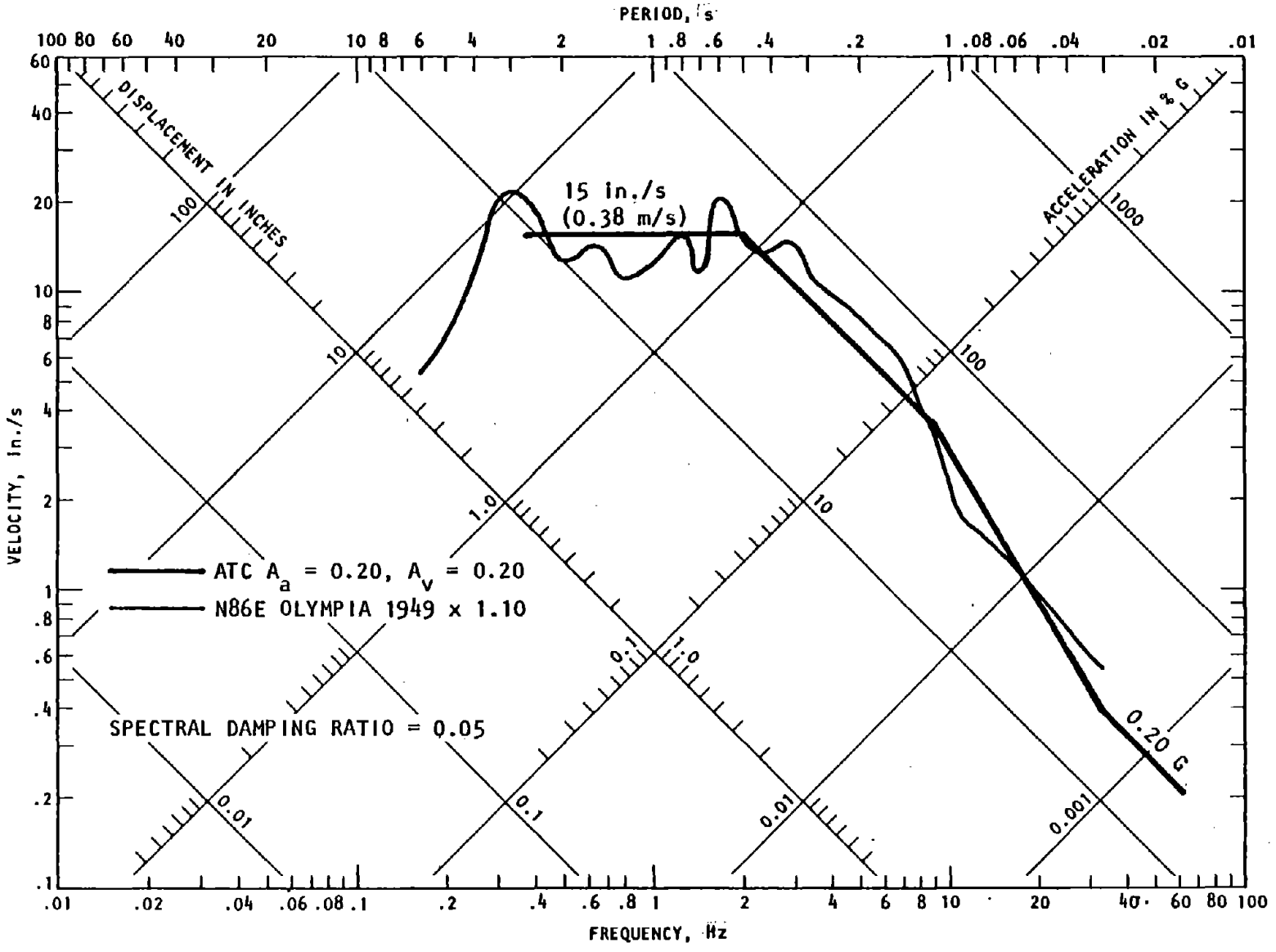


FIGURE 4-15. COMPARISON OF ATC RESPONSE SPECTRA FOR PUGET SOUND, WASATCH-SALT LAKE CITY, NEW MADRID-MEMPHIS REGIONS AND THE N86E OLYMPIA 1949 SCALED BY A FACTOR OF 1.10

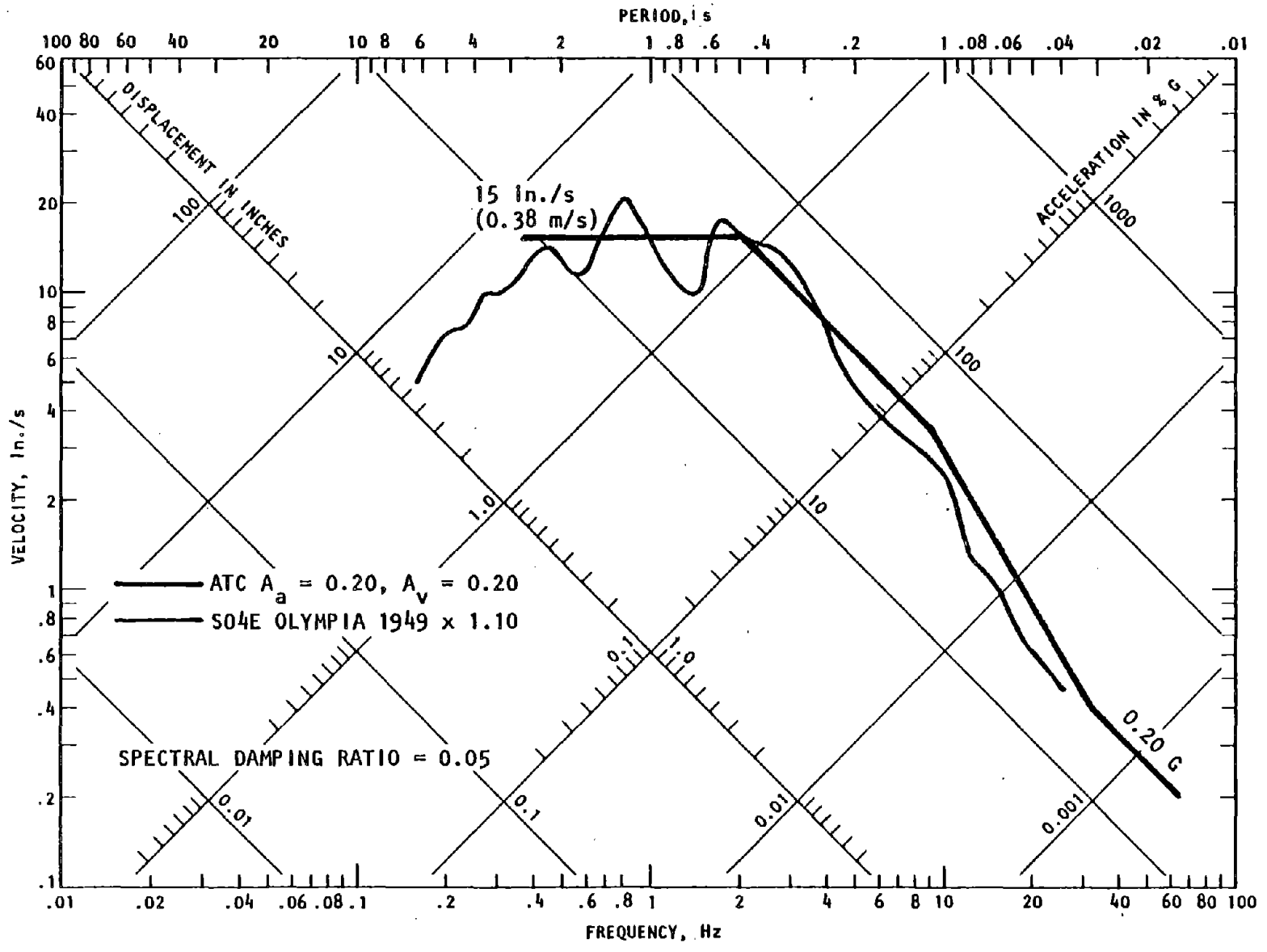


FIGURE 4-16. COMPARISON OF ATC RESPONSE SPECTRA FOR PUGET SOUND, WASATCH-SALT LAKE CITY, NEW MADRID-MEMPHIS REGIONS AND THE S04E OLYMPIA 1949 SCALED BY A FACTOR OF 1.10

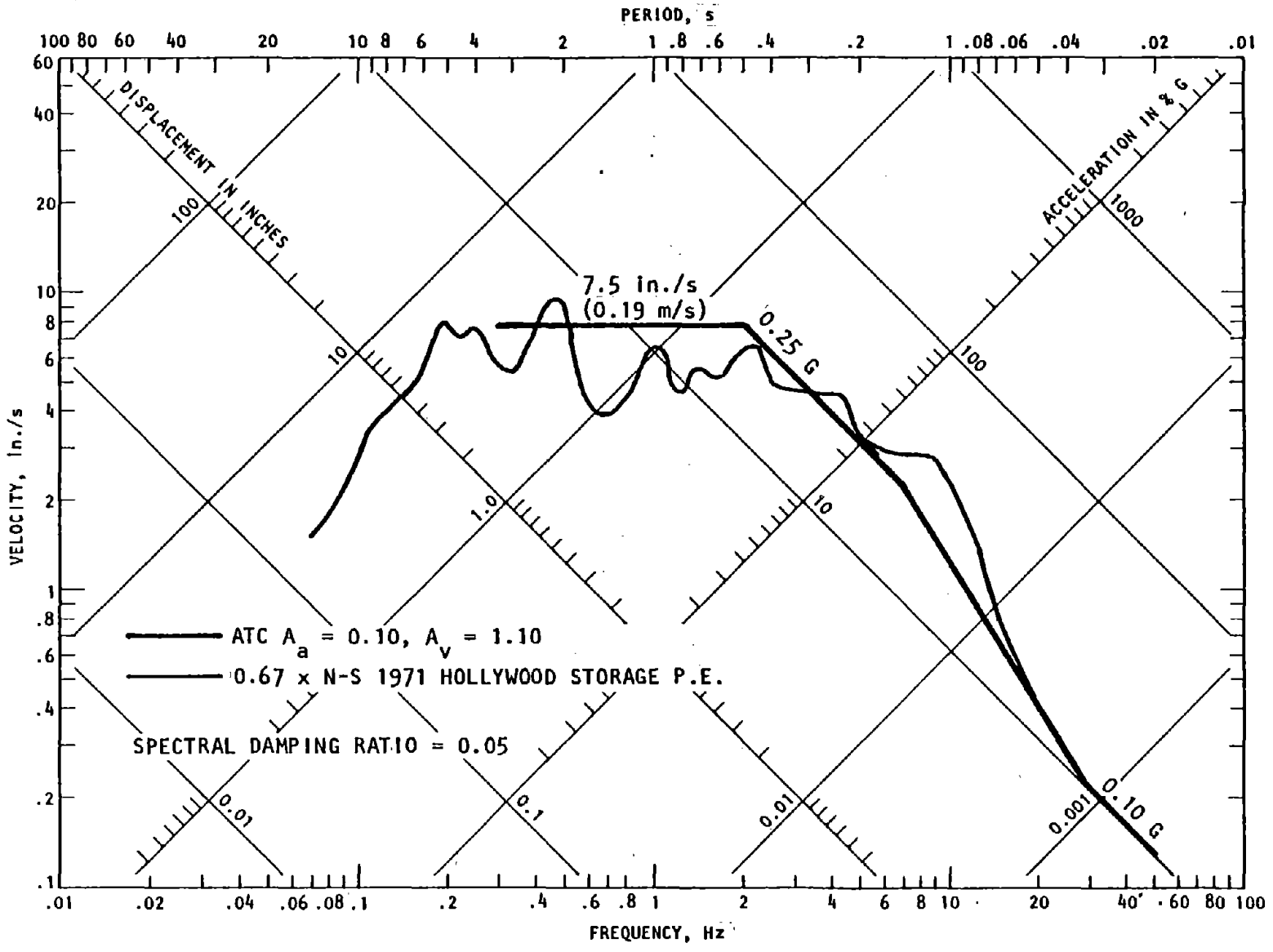


FIGURE 4-17. COMPARISON OF ATC SPECTRA FOR NEW MADRID-ST. LOUIS, CAROLINA, NEW ENGLAND REGIONS AND N-S HOLLYWOOD STORAGE P.E. 1971 SCALED BY A FACTOR OF 0.67

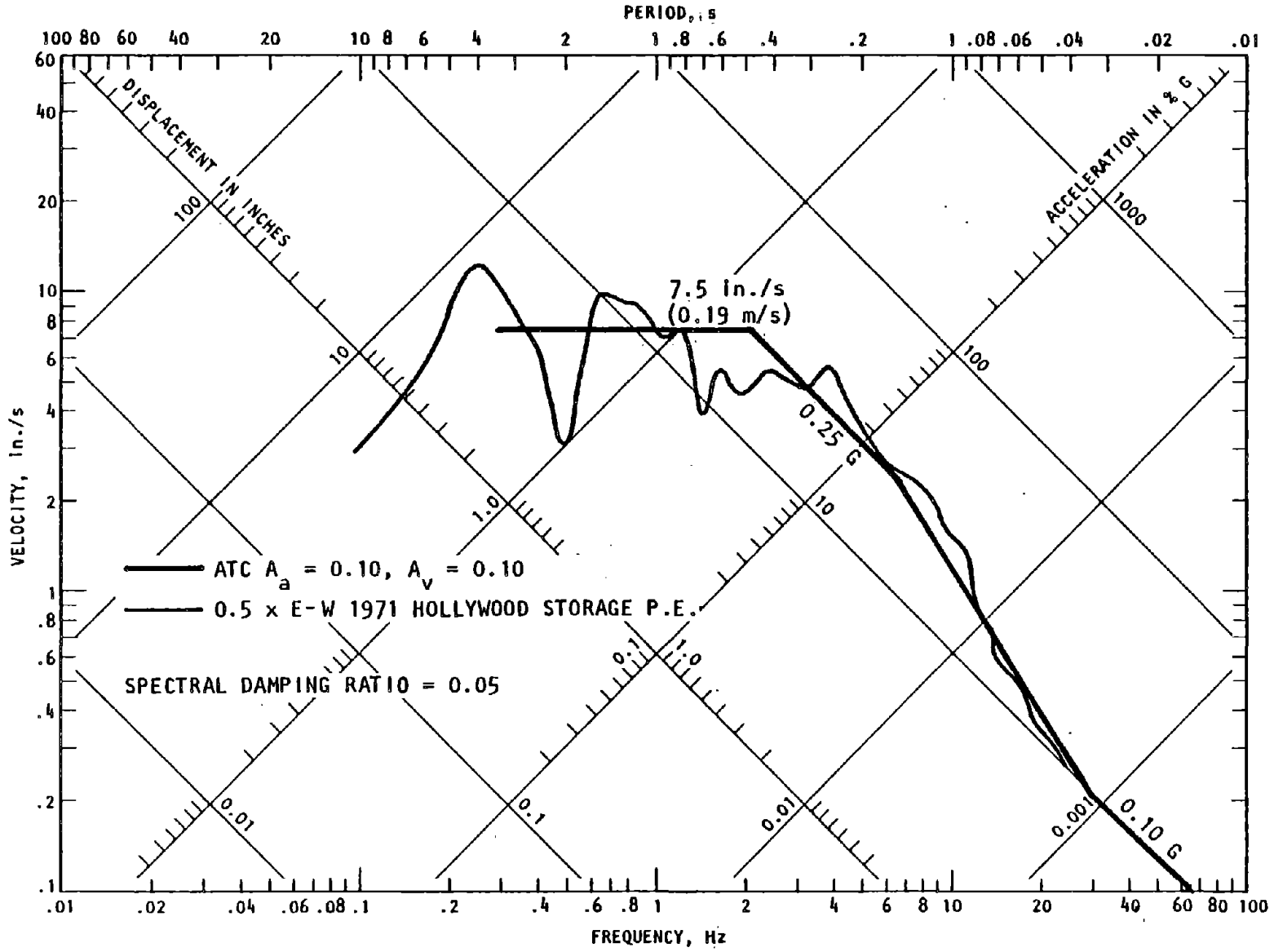


FIGURE 4-18. COMPARISON OF ATC SPECTRA FOR NEW MADRID-ST. LOUIS, CAROLINA, NEW ENGLAND REGIONS AND E-W HOLLYWOOD STORAGE P.E. 1971 SCALED BY A FACTOR OF 0.50

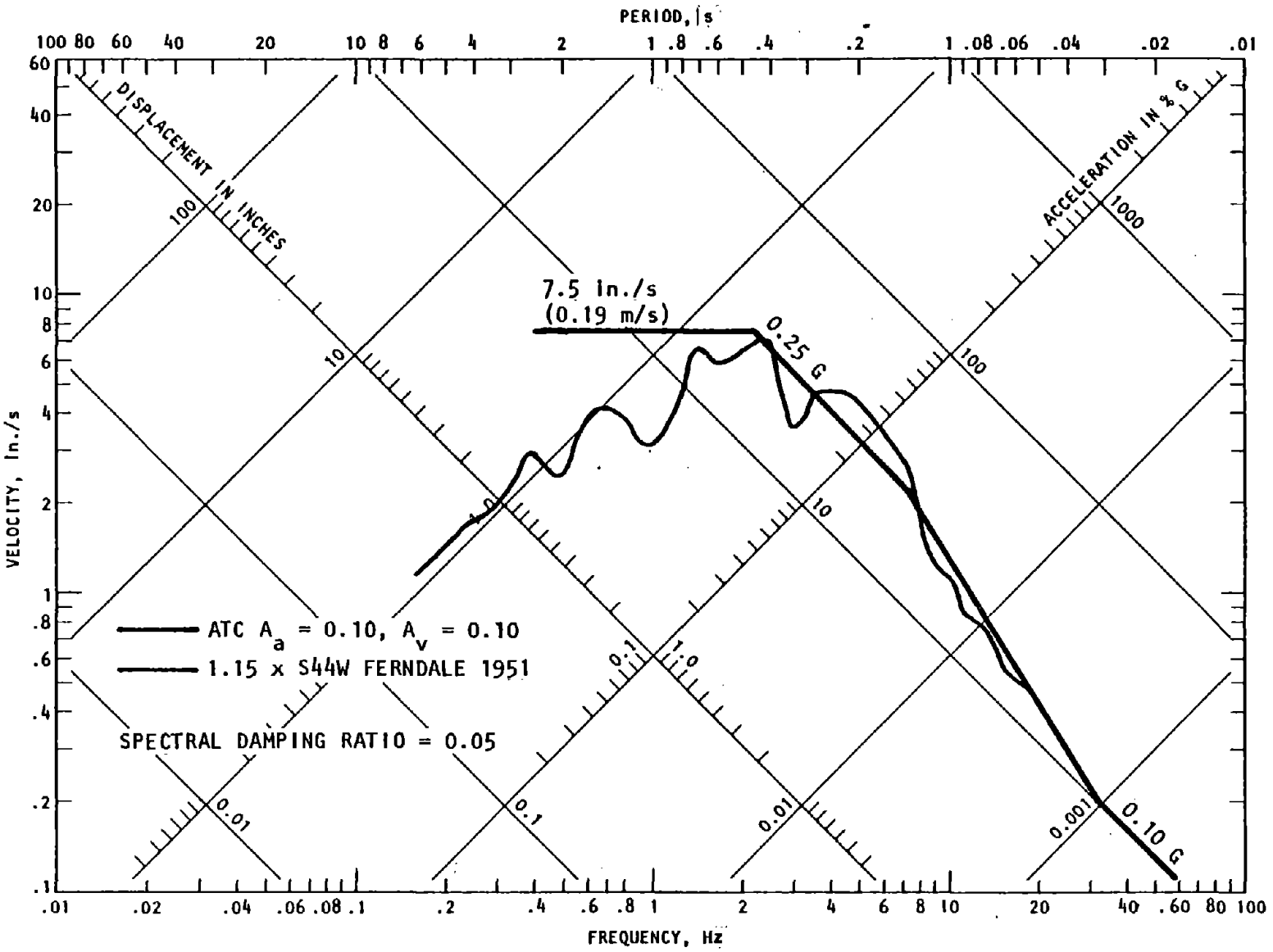


FIGURE 4-19. COMPARISON OF ATC SPECTRA FOR NEW MADRID-ST. LOUIS, CAROLINA, NEW ENGLAND REGIONS AND S44W FERNDALE 1951 SCALED BY A FACTOR OF 1.15

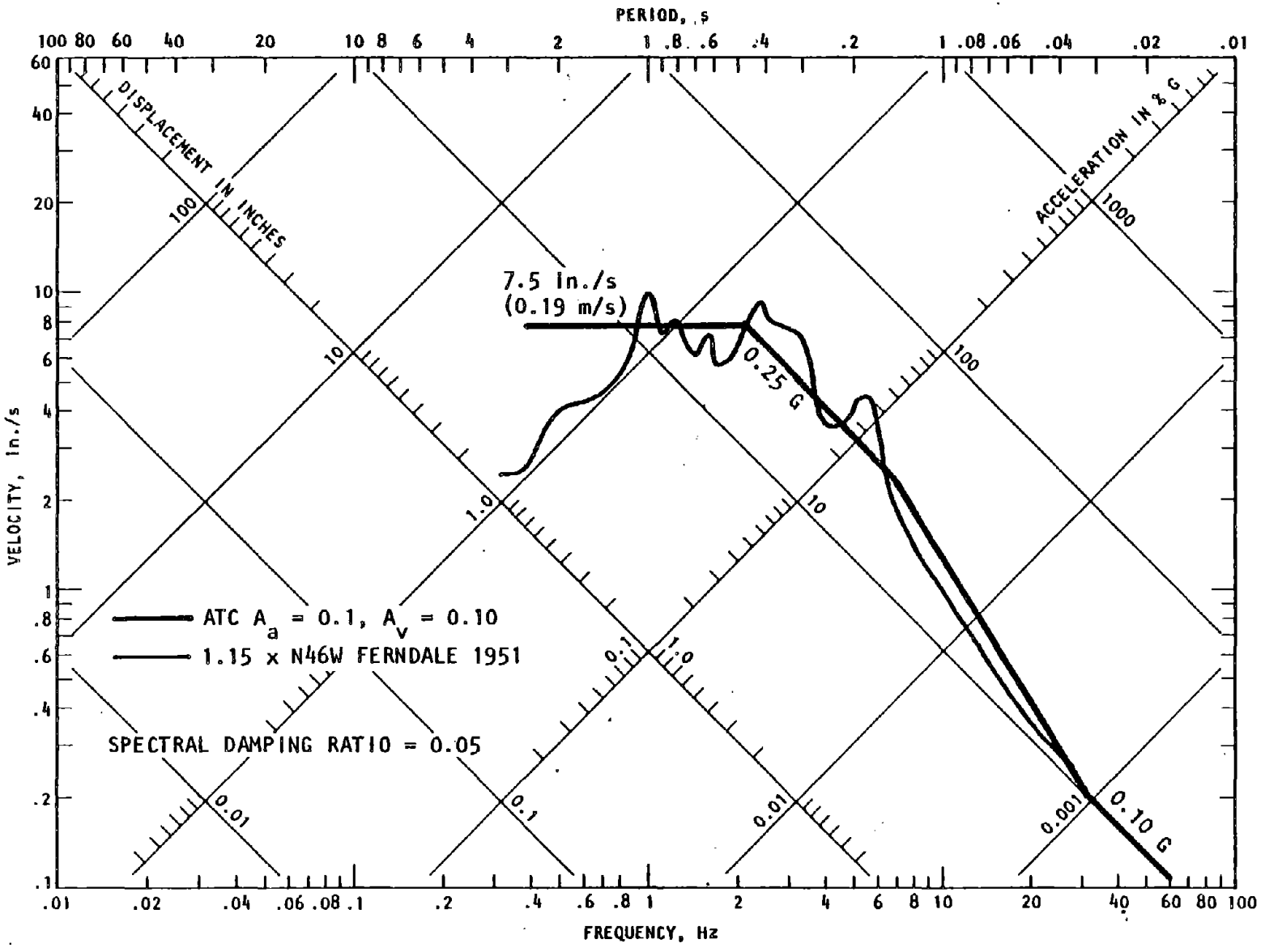


FIGURE 4-20. COMPARISON OF ATC SPECTRA FOR NEW MADRID-ST. LOUIS, CAROLINA, NEW ENGLAND REGIONS AND N46W FERNDALE 1951 SCALED BY A FACTOR OF 1.15

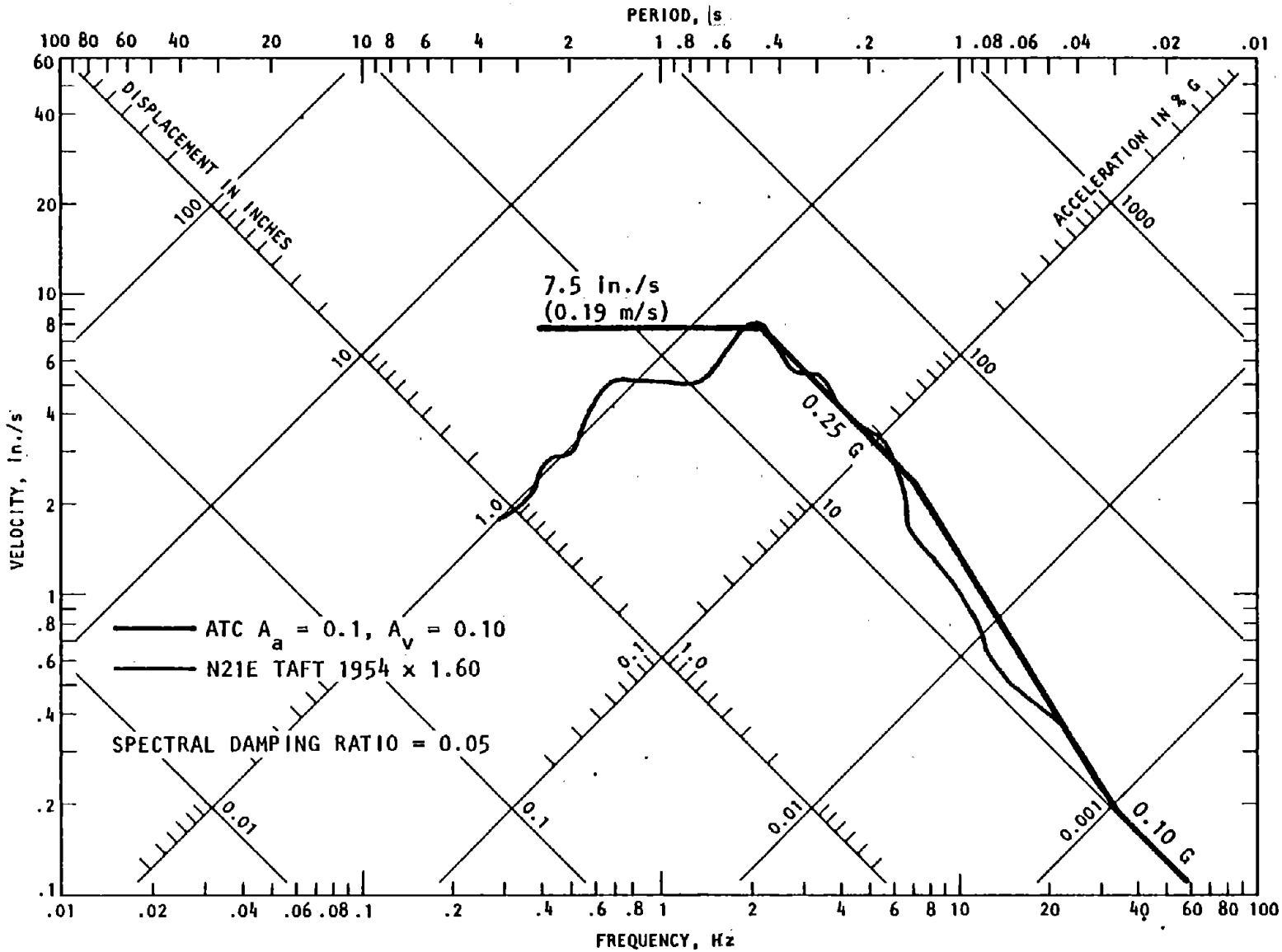


FIGURE 4-21. COMPARISON OF ATC SPECTRA FOR NEW MADRID-ST. LOUIS, CAROLINA, NEW ENGLAND REGIONS, AND N21E TAFT 1954 SCALED BY A FACTOR OF 1.60

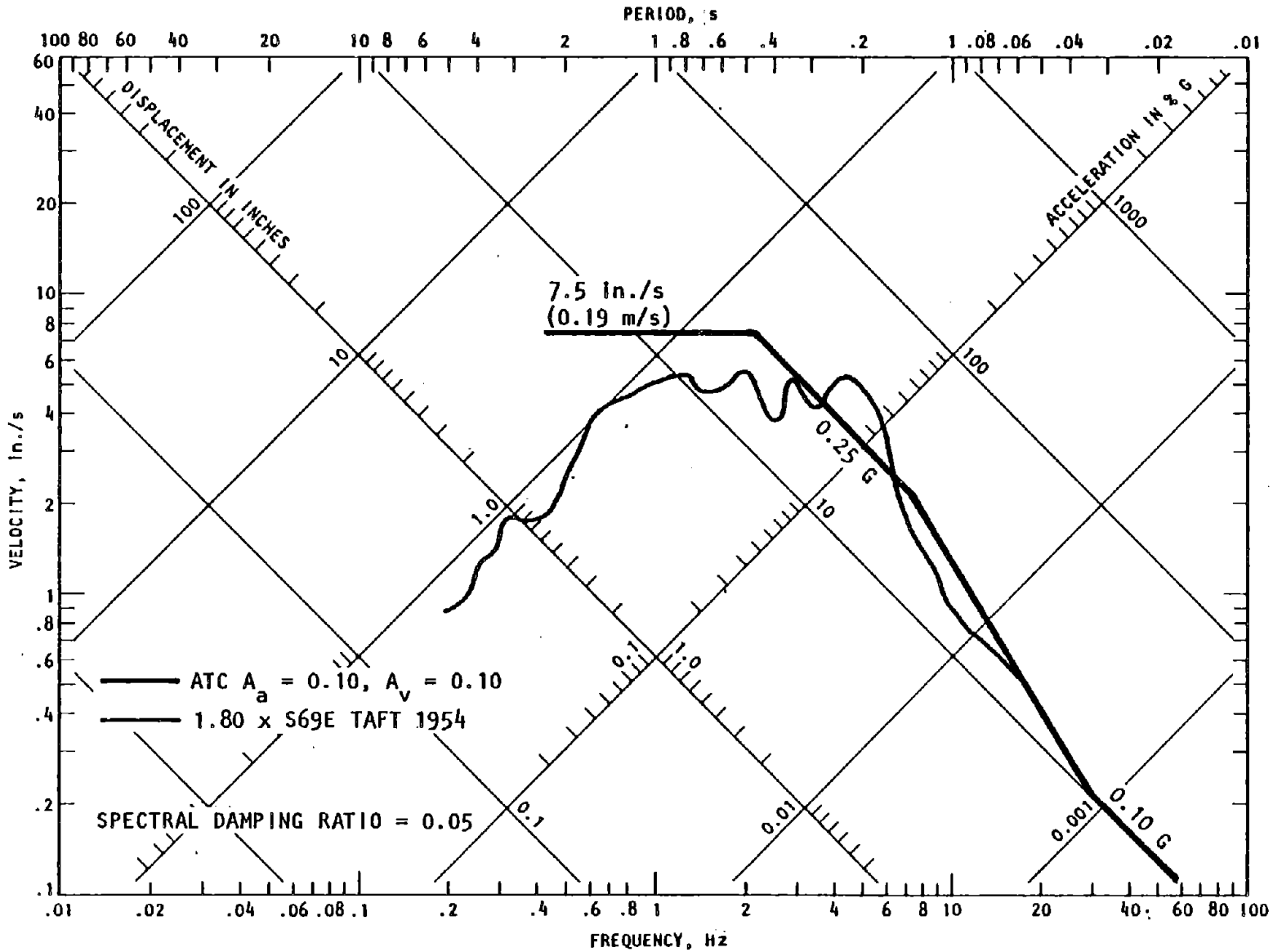


FIGURE 4-22. COMPARISON OF ATC SPECTRA FOR NEW MADRID-ST. LOUIS, CAROLINA, NEW ENGLAND REGIONS AND S69E TAFT 1954 SCALED BY A FACTOR OF 1.80

SECTION 5

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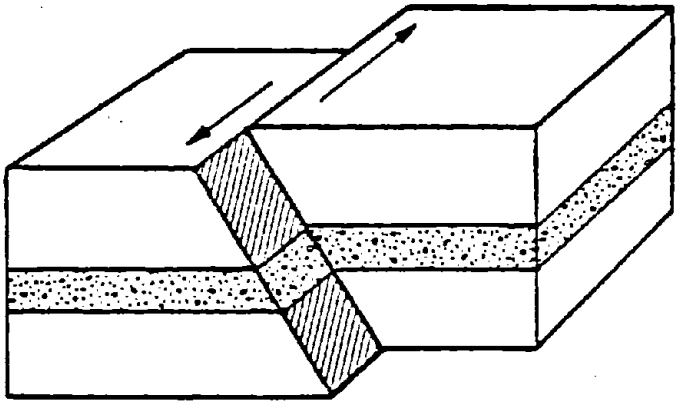
APPENDIX A
EARTHQUAKE CAUSES AND EFFECTS

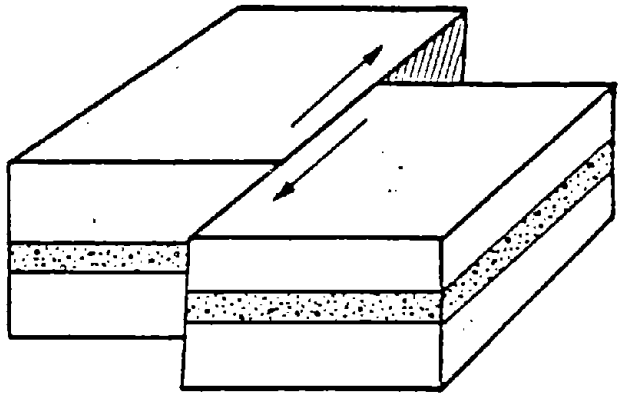
A.1 CAUSES

Earthquakes are normally caused by the release of stored energy during sudden displacement in the earth's crustal rock either along a specific fault or by rupture of the crustal rock itself (Fig. A-1). This sudden motion of the crustal rock generates stress waves that propagate outward from the fault length along which the energy is released, resulting in an earthquake (Fig. A-2). It is the ground shaking induced by the passage of the stress wave, not only the actual surface rupture of the fault, that causes much of the earthquake damage.

Faults are considered active or potentially active according to evidence of past geologic activity. Also, an earthquake can occur along a fault that may have been considered permanently inactive, or a new fault may be produced. An example of this is the fault that generated the February 9, 1971 San Fernando earthquake. Few geologists credited its potency in the San Gabriel Mountains behind Los Angeles until it ruptured, registering 6.4 to 6.6 magnitude on the logarithmic Richter scale. Parts of the mountain were vertically displaced 8 ft (2.44 m). There was severe ground shaking in the surrounding area, lasting 10 to 12 sec. The earthquake resulted in the death of 64 persons; 1000 buildings were demolished or badly damaged, including 3 hospitals; 5 highway overpasses collapsed, and utilities were disrupted. This earthquake can be compared with the 8.3 magnitude earthquake that destroyed San Francisco in 1906. However, the energy released in the 1906 earthquake was 350 times the energy generated by the 1971 San Fernando earthquake. Figure A-3 relates various earthquake magnitudes in Richter units with equivalent energy release expressed in tons of TNT, comparing the energies released by well-known earthquakes as well as those released by nuclear weapons.

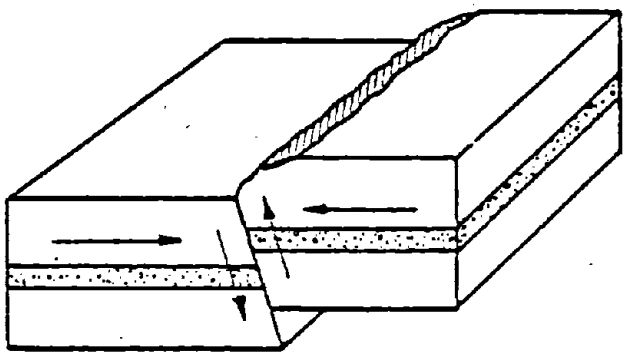


LEFT-LATERAL MOVEMENT

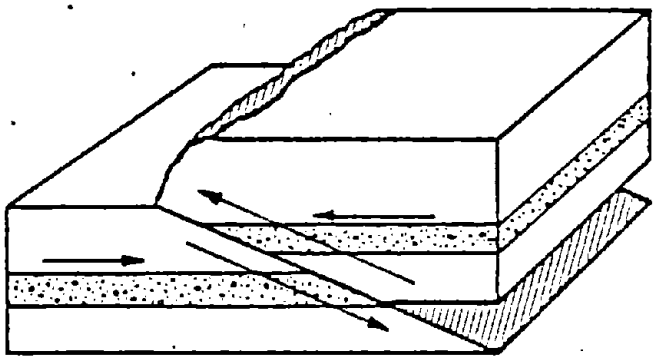


RIGHT-LATERAL MOVEMENT

(a) STRIKE-SLIP FAULT



HIGH-ANGLE REVERSE FAULT



LOW-ANGLE REVERSE, OR THRUST, FAULT

(b) REVERSE FAULTS

FIGURE A-1. FAULT TYPES

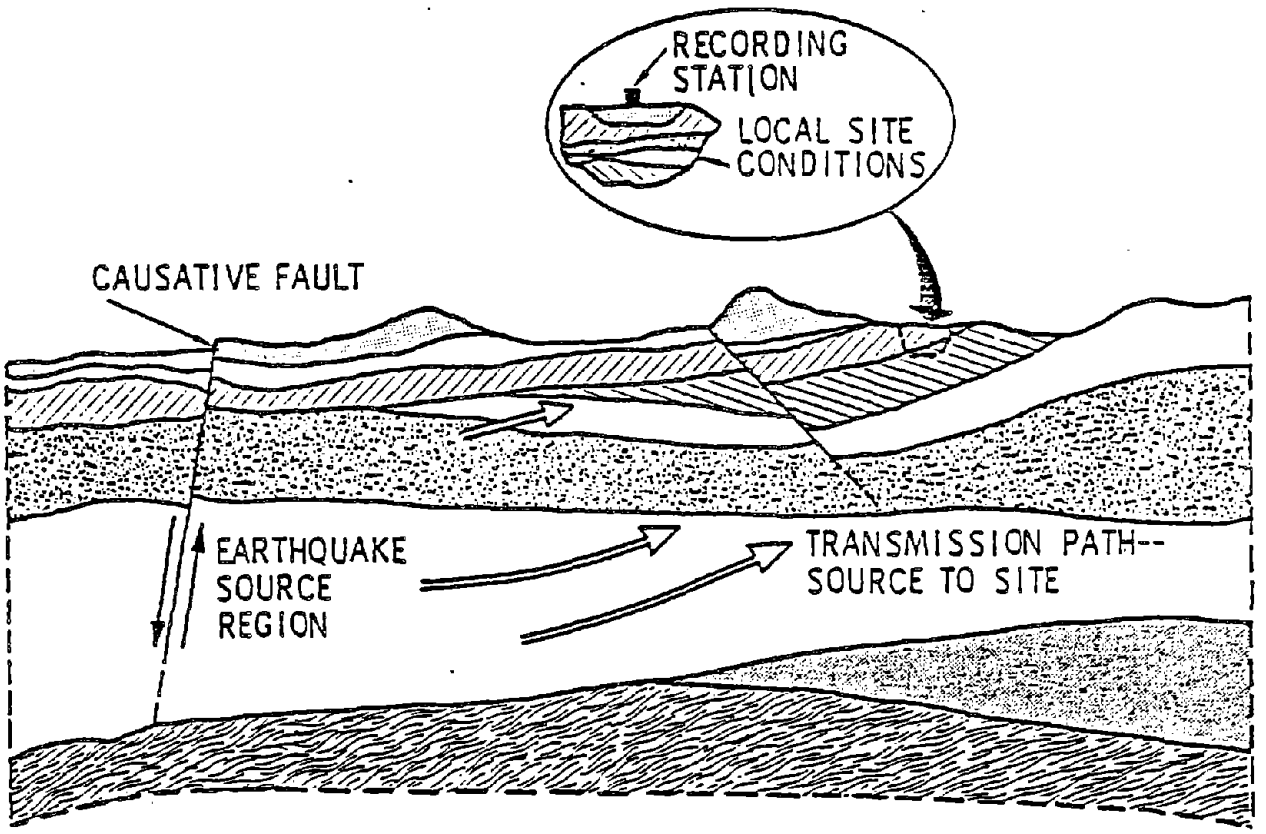


FIGURE A-2. GENERATION AND TRANSMISSION OF SEISMIC WAVES
(Adapted from Hudson, 1972)

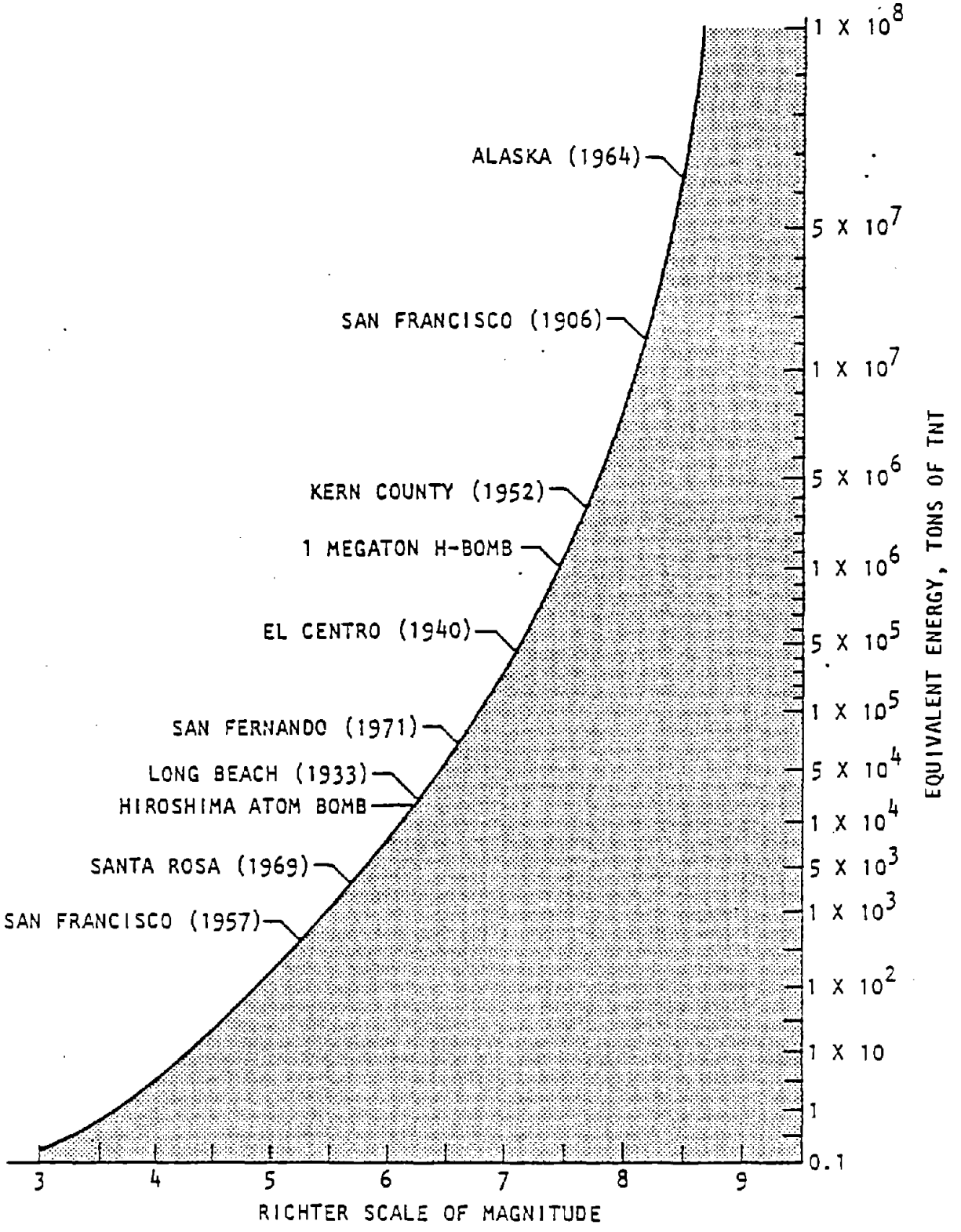


FIGURE A-3. COMPARISON OF RICTER SCALE MAGNITUDE VS. EQUIVALENT ENERGY OF TNT (Lew, et al 1971)

A.2 MODES OF EARTHQUAKE DAMAGE

Modes of damage associated with seismic events include ground shaking, ground failure, water flooding, and tsunamis.

A.2.1 GROUND SHAKING

Ground shaking is probably the most damaging effect of an earthquake, because such a large area is subjected to the shaking. Seismic zoning of hazard due to earthquake is primarily concerned with ground shaking. Other modes of earthquake failure are site specific and dependent on soil strength or proximity to natural or man-made hazards.

A.2.2 GROUND FAILURE

Ground failure is the result of seismic activity on earthquake materials and includes landsliding, surface rupture, liquefaction, and compaction and subsidence.

a. Landsliding depends on the stability of the slope, which is influenced by rock-type and geologic structure; slope gradient, precipitation, or moisture penetration; and ground shaking from earthquakes.

b. Surface rupture (faults, fissures, cracks, and fractures) normally occurs in close proximity to the fault zone as the result of a seismic event on these factors.

c. Liquefaction, the sudden loss of strength of soils under saturated conditions, can be caused by earthquake shock. Ground material is temporarily transformed into a fluid mass.

d. Compaction and subsidence of low-density alluvial material can result from ground shaking, depending on the physical properties of the material.

Landsliding can cause serious buiding damage due to foundation failure. Liquefaction can cause building foundations to settle or slide. Compaction of material can cause settlement of the foundations.

A.2.3 FLOODING

Flooding is a potential earthquake hazard at some sites, if hillside water reservoirs above the sites fail as a result of ground shaking or ground failure.

A.2.4 TSUNAMIS

A tsunami is a seismic sea wave with wave periods in the 5- to 60-min range, generated impulsively by mechanisms (Weigel, 1970). It is likely that the major cause of tsunamis is a rapidly occurring tectonic displacement of the ocean bottom. Major tsunamis have caused great loss of life and vast property damage.

APPENDIX B

EARTHQUAKE RISK ANALYSES

Earthquake risk analyses provide probability levels and return periods associated with a given intensity of ground shaking at the building site within the life of the building. These analyses require data that define (1) the frequency of occurrence of earthquake events and (2) the attenuation of ground shaking with distance from the fault. Probabilistic procedures are then applied to this data in order to perform earthquake (seismic) risk analyses. Two basic types of seismic risk analyses were described in an Agbabian Associates report (1975) and are summarized in the remainder of this section.

B.1 UNIFORM SEISMICITY APPROACH

The first probabilistic method is the uniform seismicity approach, originally developed by Housner (1969) and applied to assess the seismic hazard in California. This approach was later extended to the Puget Sound area by Ts'ao (1974).

The basic assumptions involved in this method are that (1) the specified region has uniform seismicity and (2) any one earthquake occurrence within the specified region is independent of any other occurrence and is Poisson distributed (AA, 1975). With uniform seismicity assumed, the resulting calculations will provide probabilities that are too high for some areas and too low for others. Therefore, this approach is most applicable to those regions that do not exhibit any strong localized patterns of higher or lower seismicity.

The various steps involved in performing probability calculations using this approach are as follows:

a. Develop a relationship between the earthquake recurrence rate and either magnitude or epicentral intensity.

b. Develop intensity-attenuation curves corresponding to various epicentral intensity levels, using isoseismal maps of past earthquakes in the region. A single set of these curves is considered to apply for the entire region.

c. Define an appropriate interrelationship between site intensity and peak acceleration.

d. Perform the probability calculations for the region. In this, it is assumed that any earthquake occurrence is independent of any other occurrence. From this, it can be shown that for the probability of occurrence of a given site intensity I, within L years, $P(I,L)$ is

$$P(I,L) = 1 - \exp\left[- \sum_{I_o} \frac{a(I_o,I) \cdot N(I_o) \cdot L}{A} \right] \qquad \text{(B-1)}$$

where

A = Total area of region being considered

$a(I_o,I)$ = Area experiencing intensity I due to earthquake event with epicentral intensity I_o (as determined in Step b)

$N(I_o)$ = Mean number of occurrences of earthquakes with epicentral intensity I_o per unit period of time (as determined in Step a)

$\sum_{I_o}$ = Summation over the entire range of epicentral intensities of earthquake events centered within the region

e. The peak acceleration corresponding to the intensity I in Equation B-1 is readily obtained by utilization of the intensity-acceleration conversion relationships defined in Step c above.

f. The return period for this level of ground shaking can be computed as

$$T(I) = \sum_{I_o} \frac{1}{\frac{a(I,I_o)}{A} \cdot N(I_o)} \qquad \text{B-2)}$$

and is related to the probability $P(I,L)$ by

$$P(I,L) = 1 - \exp\left[-\frac{L}{T(I)}\right] \qquad \text{(B-3)}$$

Results of the applications of this approach to the California and Puget Sound areas are shown in Figure B-1 for a structure life of 50 years. The results of these applications, in terms of curves relating the probability of occurrence to the peak acceleration, clearly indicate the relative seismic hazard of the two areas investigated; as expected, California exhibits the greatest seismic hazard.

B.2 VARIABLE SEISMICITY APPROACH

The second approach is the variable seismicity approach, developed primarily through the efforts of Cornell and his associates at MIT (Cornell and Vanmarcke, 1969; Cornell, 1970). The primary feature of this approach is that variations in the seismicity of the region, due to predominant active faults for example, can in theory be considered. The method also accounts for different source geometries and superimposes the effects of the earthquakes at each source to develop probability estimates for the ground motions at a particular location within the region being investigated. The approach is based on the assumption that occurrences in time of the ith potential event are random (i.e., Poisson arrivals) with a constant average rate per year. It is further assumed that those earthquake events that have actually occurred within a line or area source are equally likely to have occurred anywhere within that source.

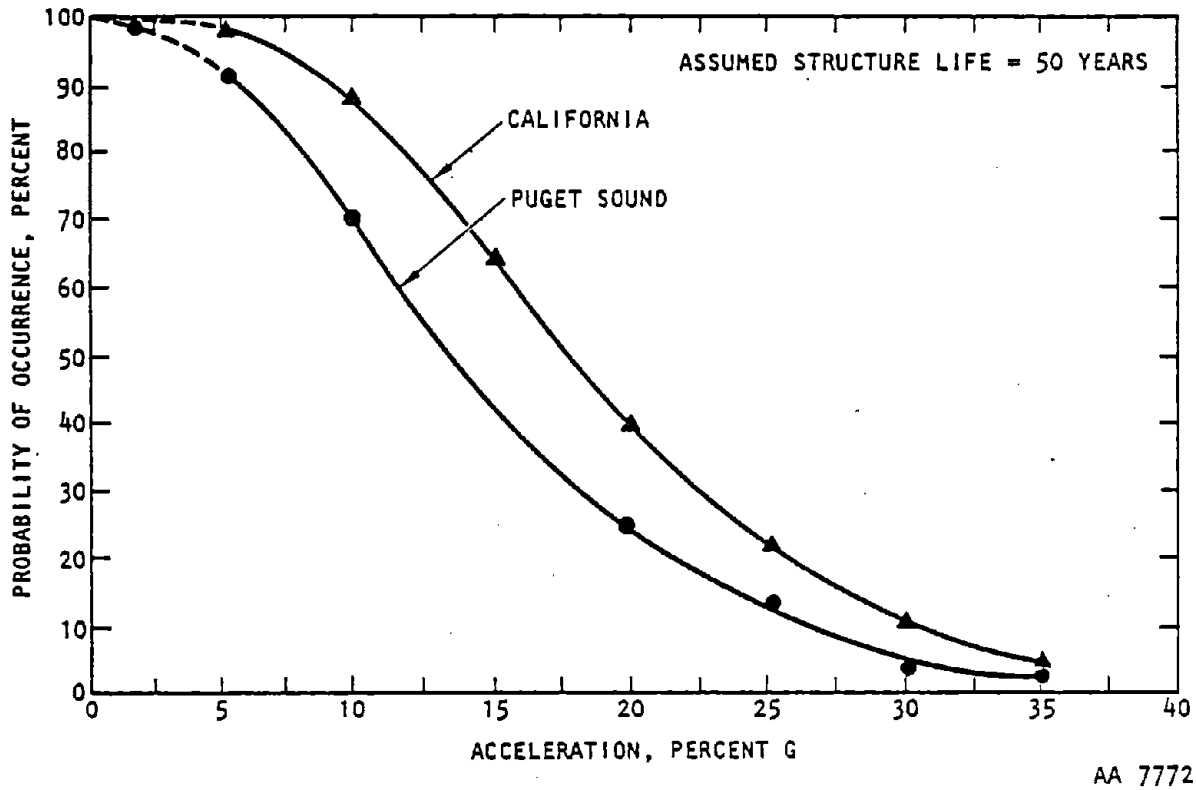


FIGURE B-1. EXAMPLE APPLICATIONS OF UNIFORM SEISMICITY APPROACH FOR PERFORMING SEISMIC HAZARD ANALYSES (Ts'ao, 1974)

Basically, the variable seismicity approach first requires that the engineer define each of the various potential earthquake sources; these could be line sources such as faults, point sources such as relatively short faults located far from the site, or area sources such as tectonic provinces in regions where earthquakes cannot be definitely correlated with a causative fault. For each of these potential sources the engineer must then assign (1) an activity level in the form of an average annual rate of occurrence to earthquakes of magnitude M_o or greater and (2) an attenuation rate for ground motion as a function of magnitude and distance. These assigned activity levels and attenuation rates are based on the seismic history and tectonics of this and other geologically similar regions.

The first computation step in this approach is to relate the ground motion Y (displacement, velocity, or acceleration) to the earthquake magnitude M and the focal distance R by the formula

$$Y = b_1 \exp(b_2 M) R^{-b_3} \tag{B-4}$$

where b_1, b_2, and b_3 are selected from the geologic conditions of the area. Esteva (1970) showed that for the western United States $b_1 = 2000$, $b_2 = 0.8$, and $b_3 = 2$ for the case where Y is the peak acceleration (cm/sec^2), R is in kilometers, and M is the Richter magnitude.

The next step is to express the frequency of occurrence of earthquakes at each source. The computational procedure assumes that the frequency distribution $F(M)$ expressed in terms of magnitude M is

$$F(M) = \frac{1 - e^{-\beta(M - M_o)}}{1 - e^{-\beta(M_1 - M_o)}}; \qquad M_o \leqq M \leqq M_1 \tag{B-5}$$

where

M_o = Minimum magnitude of interest

M_1 = Maximum possible magnitude

$\beta = b \cdot \ell n\ 10$

b = Magnitude coefficient in the recurrence rate expression $\log_{10}N = a - bM$

Utilizing Equation B-1 and the assumptions indicated above and combining results from all potential earthquake sources, the probability that the peak motion at the site exceeds some critical value $\tilde{Y}$ during a time period T is

$$p(Y > \tilde{Y}, T) = 1 - \exp\left\{ e^{\beta M_o} T \nu G \left[\frac{\tilde{Y}}{b_1} \right]^{\frac{-\beta}{b_2}} \right\} \qquad \text{(B-6)}$$

where

$$\nu G = \sum_{i=1}^{n} \nu_i G_i$$

ν_i = Average arrival rate of earthquakes from ith source

n = Total number of sources considered in analysis

G_i = Theoretical geometry factor for ith source (which depends on whether source is point, line, or area type; see Cornell and Vanmarcke (1969) for a tabulation of G_i for various source types)

There are a number of applications of the variable seismicity approach in the literature. Cornell and Vanmarcke (1969) used their technique on a hypothetical site and compared the effects of using a point, line, or area source on the seismic hazard. In this application, the seismic hazard was shown to be relatively insensitive to the upper bound magnitude M_1 and most dependent on the more frequent, smaller earthquakes at closer sources. Donovan and Valera (1972) applied the approach to a site located in the San Francisco bay

midway between the Hayward and San Andreas faults and provided results in terms of return periods for different levels of peak acceleration.

B.3 DISCUSSION OF APPROACHES

Two different approaches have been presented for computing the probability that the ground shaking at a site will exceed a certain level within a specified time. The first, a uniform seismicity approach, does not consider any variations in the seismic characteristics of the region. The second approach, a variable seismicity method, considers the presence of individual earthquake sources within the region and superposes the effects of each source in the determination of the ground motion probabilities. Both approaches consider the occurrence of earthquake events to be Poisson distributed.

An important advantage of the uniform seismicity approach is that it can be easily applied to an existing site, since the theory is relatively simple and the data requirements are usually not difficult to meet. The only data required to implement this method is the recurrence curve for the past earthquake events of the region and the attenuation of intensity with distance for various epicentral intensity levels. This type of data is often readily available from earthquake frequency studies and from isoseismal maps of past earthquake events. Furthermore, the restriction of equal seismicity within the region is not serious for many regions of the United States, which do not exhibit apparent patterns of markedly higher or lower seismicity.

The variable seismicity approach is more detailed than the uniform seismicity method; its data requirements are more extensive and often must be provided for each potential earthquake source rather than generally for an entire region. For some regions this approach is necessary, but this data may be difficult to obtain. For example, the variable seismicity approach requires a description of the geometry, extent, location, and recurrence rates for each potential earthquake source. The geometry of each source is incorporated in the approach through some theoretically derived parameters for point sources, line sources, or area sources (note the G_i parameter in Eq. B-6); the form of these parameters requires verification, possibly using

field measurements. In addition, for many regions, such as the eastern and midwestern United States, the extent and location of causative faults (line sources) and the boundaries of tectonic provinces (area sources) cannot be established with certainty. Because of this difficulty, a definitive association of certain earthquake events with one source or another may not always be possible. Finally, the applicability of the variable seismicity method is limited to consideration of those sources for which the available earthquake data is sufficient to define recurrence rates for that source; other potential earthquake sources for which inadequate data are available cannot be incorporated into the variable seismicity approach.

It is noted that both the uniform seismicity method and the variable seismicity approach utilize a deterministic representation of earthquake recurrence rates and intensity-attenuation characteristics. Several examples of the application of the two approaches are given in the Agbabian Associates report (1976).

In summary, the uniform seismicity approach represents a reasonable engineering tool for assessing the seismic hazard at a site, provided the region surrounding the site does not exhibit strong patterns of higher or lower seismicity. The variable seismicity approach can be applied in regions dominated by a number of discrete earthquake sources only if (1) the geometry, extent, and location of all potential earthquake sources can be reasonably well defined and (2) sufficient earthquake data can be associated with each source to define meaningful earthquake recurrence rates for that source.

B.4 PROBABILITY CALCULATIONS

Using the above discussed seismic risk analyses models, the probability that the site or the region will experience earthquakes of prescribed intensities during a specified time, or recurrence period, can then be estimated. The seismic risk is expressed as a relationship between return periods (years) and earthquake intensities at a given locale. Generally, the best of the parameters that describe this intensity is the effective peak ground acceleration.

B.5 SELECTON OF SEISMIC RISK LEVEL

Risk is defined as the probability of an undesirable or unacceptable event. In other terms, risk is a function of the probability of the event and the undesirability of the event. It is not sufficient to establish whether an event is undesirable or not; it is the degree of undesirability that is of interest. Undesirability can be measured in monetary value, life safety (loss of life or injury), damage to the environment, or adverse effects on social and economic systems.

Risk decisions on whether to retrofit or accept the existing element or structure are based on economic and political decisions made by the owner or by a regulatory body representing the public interest. These decisions, supported by seismic analysis, may be based on these philosophies:

a. For moderate earthquakes in general, or for a single earthquake that has a high probability of occurring in the useful extended life of the existing structure, little structural damage should result. This decision would usually be made by an owner using a value analysis.

b. For high intensity earthquake ground motion, structural damage will occur, but life-threatening damage should have a low probability of occurrence. The order of this low probability of damage would be based on a general appraisal of the investment required to mitigate the hazard and would be considered in the context of all natural hazards. This decision would probably by made by a political body with regulatory powers.

c. For very high intensity earthquakes equal to the maximum expected in a seismic zone, life-threatening damage would be significantly reduced by retrofit required to conform to a decision based on the previous philosophy (in b), with even structural collapse reduced to a small probability. Again, this decision would be made by a political body considering public interests.

High intensity earthquake ground motions can be generated and studied by a design earthquake event, which is discussed in Appendix C.

APPENDIX C

DESIGN EARTHQUAKE EVENT

C.1 DEFINITION

A design earthquake event specifies the peak values of certain characteristic parameters that are associated with high intensity earthquake ground motions. These motions are associated with the seismic risk level selected for the site (App. B). The design earthquake generally specifies the maximum ground displacements, velocities, and accelerations that are likely to occur. Some meaure of the time duration of the ground motions is also included. An important tool used to represent design earthquake motions is the response spectrum, which actually represents the peak response of a series of simple (single-degree-of-freedom) structures to given ground motions. Each earthquake ground-motion history produces a unique spectrum, and the design spectrum is usually a composite average, or envelope, of the spectra of such records that are appropriate for the site of the proposed building.

Development of a design earthquake event for a specific site generally requires consideration of major geological features: tectonics for the site, i.e., the types, locations, and arrangement of faults; seismic history, including records of intensity and ground motion, if available; and local soil conditions. Engineering judgment and, in some cases, ground-motion calculations provide the basis for selecting the shape of the required design earthquake event.

C.2 GOVERNING EARTHQUAKE CONDITIONS AT THE SITE

High intensity shaking at a site may come from different conditions. In many cases, two earthquake conditions govern the design earthquake intensity at the site. The first corresponds to a nearby earthquake. The second condition corresponds to a distant event. Frequency content and duration of the record vary from one conditon to the other, and one condition may be more detrimental to a certain building than the other condition.

C.3 EARTHQUAKE GROUND MOTION CORRESPONDING TO DESIGN EARTHQUAKE EVENT

C.3.1 INFORMATION NEEDED TO SELECT GROUND MOTION

The choice of earthquake ground motion at the site that corresponds to the design earthquake event requires information on (1) source magnitude, (2) source mechanism, (3) source distance, (4) source focal depth, (5) attenuation relationship, (6) return intervals, and (7) peak acceleration, velocity, and displacement associated with seismic risk for the site. These factors are considered in the three methods used to develop ground motion discussed in this section. These methods are (1) soil response analyses, (2) site-matched records, and (3) Seed-Ugas-Lysmer shapes. These are in addition to a fourth method based on the Applied Technology Council recommendation (ATC-3, 1978) which was summarized in Section 2.

C.3.2 SOIL-RESPONSE ANALYSES

This method requires constructing a mathematical model for the soil profile at the site. Well-defined soil properties obtained from the geotechnical investigation of the site are used to define the material properties of the model. A selection is made of an ensemble of rock-outcrop motions for use as input to the computations. This ensemble is selected at the site to correspond to the intensity level associated with the design earthquake event developed for the site. The ensemble of rock-outcrop motions is selected based on the following: (1) the motions must be taken from accelerograph stations that are underlain by rock materials; (2) the earthquake magnitude, source mechanism, and causative-fault distances should be as close as possible to that of the design earthquake event; and (3) where possible, the peak acceleration of the rock-outcrop records should be reasonably close to the peak acceleration specified for the design earthquake event.

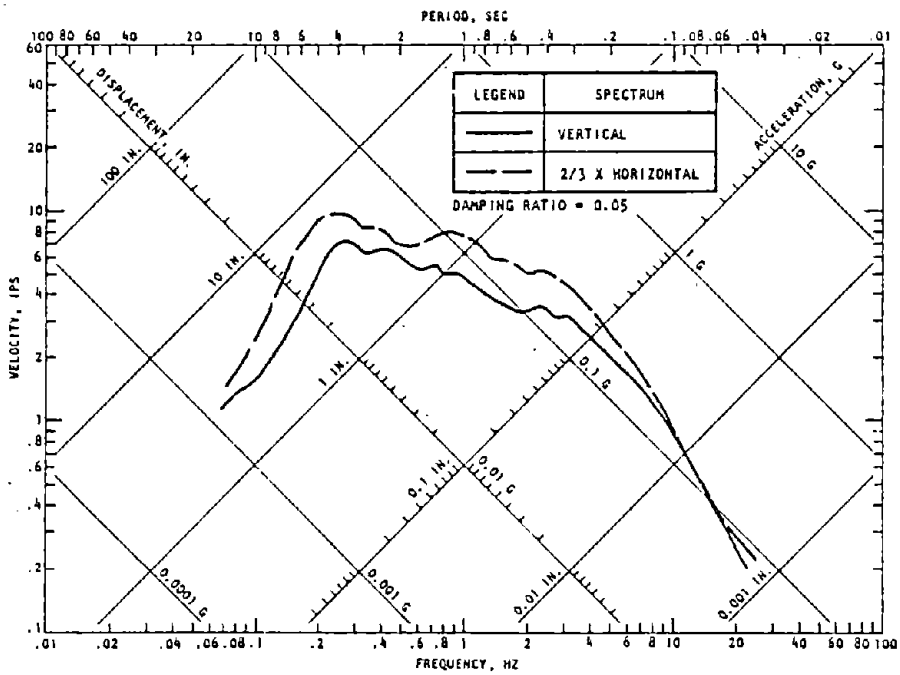
The SHAKE computer code (Schnabel et al., 1972) is used for the analysis of soil profiles that can be modeled as infinite horizontal layers. However, for inclined layers, a two-dimensional analysis should be used. The results of soil response analyses are used to develop composite response spectra for the site. The mean and mean-plus-one standard deviation spectrum can be developed from these results.

APPENDIX D

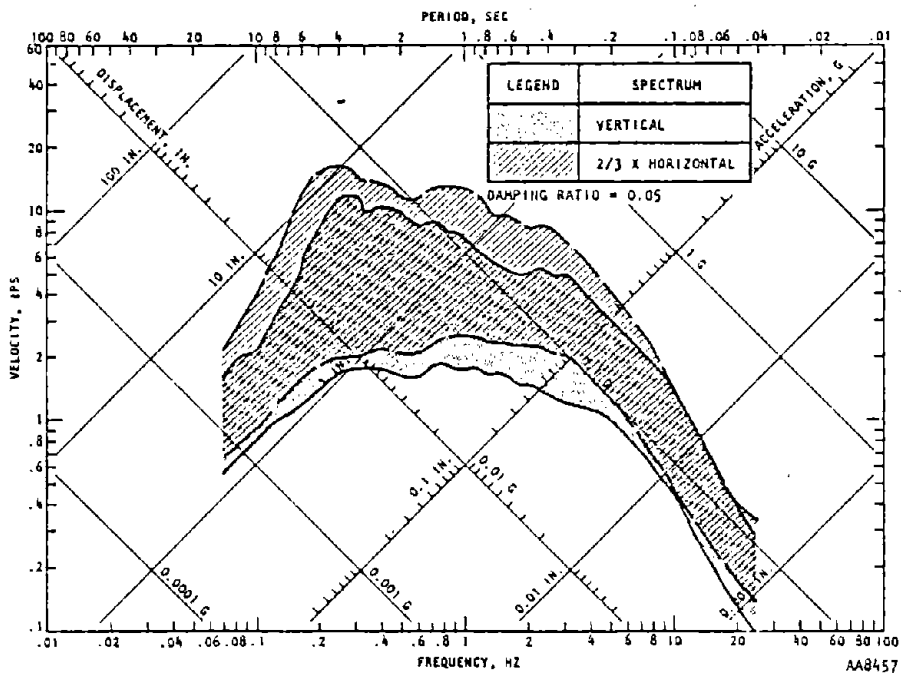
VERTICAL GROUND MOTION RESPONSE SPECTRA

Recently a considerable number of records of strong vertical ground shaking have been accumulated, thereby providing a substantially larger vertical motion data base than was available when the above approach for representing vertical motion spectra was first suggested. In fact, this data base now appears sufficient to permit development of standardized vertical response spectrum shapes by processing vertical motion records in the same manner as has been employed with respect to horizontal motions when developing horizontal response spectrum shapes. Despite this, design practice through the years has consistently represented vertical ground response spectra as 2/3 of the horizontal spectra (Newmark and Hall, 1969; Hall, Mohraz, and Newmark, 1976). The only notable exception to this trend has been the RG 1.60 spectrum shapes in which this 2/3 proportionality factor was not followed over the entire frequency range.

Werner and Ts'ao (1977) provided an assessment of this practice for specifying vertical response spectra. Their assessment is based on comparisons of composite vertical spectra with 2/3 of the composite horizontal spectra developed for Intensities V, VI, and VII, which are intensities with sufficient data for meaningful statistical comparisons. These comparisons in terms of mean spectra and 68% bands are shown in Figure D-1 for intensity level VII. These figures indicate that the 2/3 horizontal composite spectra tend to slightly exceed the corresponding vertical composite spectra. Therefore, from a standpoint of conservatism, these comparisons indicate that the representation of vertical design spectra using 2/3 of the horizontal design spectra is reasonable.



(a) Mean



(b) 68-percent scatter bands

FIGURE D-1. VERTICAL SPECTRA VS. 2/3 X HORIZONTAL SPECTRA--INTENSITY = VII (Werner and Ts'ao, 1977)

APPENDIX E

RELIABILITY OF EARTHQUAKE DATA

The lack of information concerning ground movements in the eastern United States means that estimates are less reliable than those for more active and more studied seismic regions. The general mean rate of earthquake occurrence on the eastern edge of the United States is about one-twentieth of that on the western edge. The eastern rate is about 18 events greater than or equal to MMI V/100 yr/100,000 km^2 (Algermissen, 1969).

In order to facilitate seismic study of a region such as the Boston area, the geometrical zones or sources are identified by number, as in Figure 3-12. Then, since occurrence rates near the site of strong motions are of greater interest, the numbered zones are presented as a mean annual number of events, as in Table 3-3.

The source of these New England estimates (Fig. 3-12) is Weston Geophysical Research, Inc., Westboro, Massachusetts. Several of their estimates differ from those of the U.S. Geological Survey. In particular, the epicentral intensity of the important 1755 Cape Ann earthquake has been estimated as high as IX and as the cause of intensity in Boston of VII to VIII. Weston seismologists, however, set the epicentral intensity at VIII and the maximum Boston intensity at VII. The issue is that even historical seismic events are subject to continuing reevaluation and uncertainty. Correlation between intensity estimates and known geotectonic structure is weak.

There are inherent limitations on the energy release and the MM epicentral intensity generated by earthquakes in northeastern states. This upper bound depends on the source used, and the values appearing in Table 3-3 are based on conversations with Weston Geophysical. For example, a number such as 7.3 means that the source indicated "a low seven." As mentioned previously, the lower bounds are MMI V (except for Source 5), a number below which one expects only a very incomplete catalog of events.

APPENDIX F

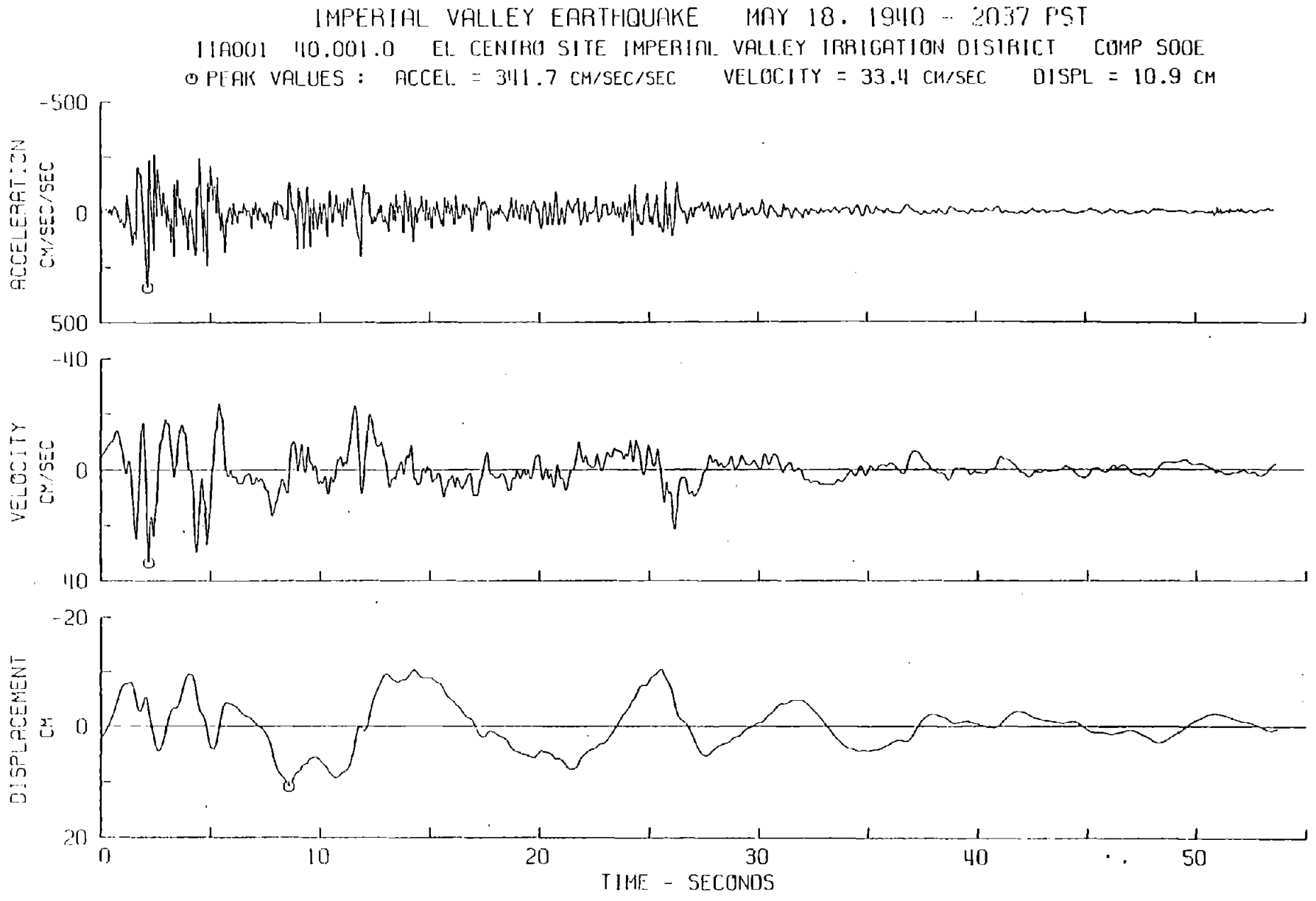
EARTHQUAKE VIBRATORY GROUND MOTION ATTENUATION RELATIONSHIPS

There are two procedures generally used to predict the attenuation of the intensity of strong earthquake vibratory ground motion with respect to distance from the epicenter, or causative fault, of a postulated earthquake. The first relates peak horizontal ground acceleration, earthquake magnitude, and distance. The second relates epicentral MMI, distance, and attenuated MMI. The report by Agbabian Associates (1978) provides a review of the state of the art of these relationships.

In general, earthquakes attenuate faster in the western United States than in the eastern United States and Canada. The unusually low attenuation of earthquake shock in the eastern regions is assumed to be associated with a greater homogeneity of the crustal structure (Milne and Davenport, 1969). Within a uniform crust, specific waves can be propagated over large distances with very little attenuation. Spatial attenuation of intensities for the central United States has been studied by Gupta and Nuttli (1975, 1976), Nuttli (1973a, b, c), and Herrmann and Nuttli (1975a, b). The studies indicate lower attenuation of ground motion in the central United States than in the western United States.

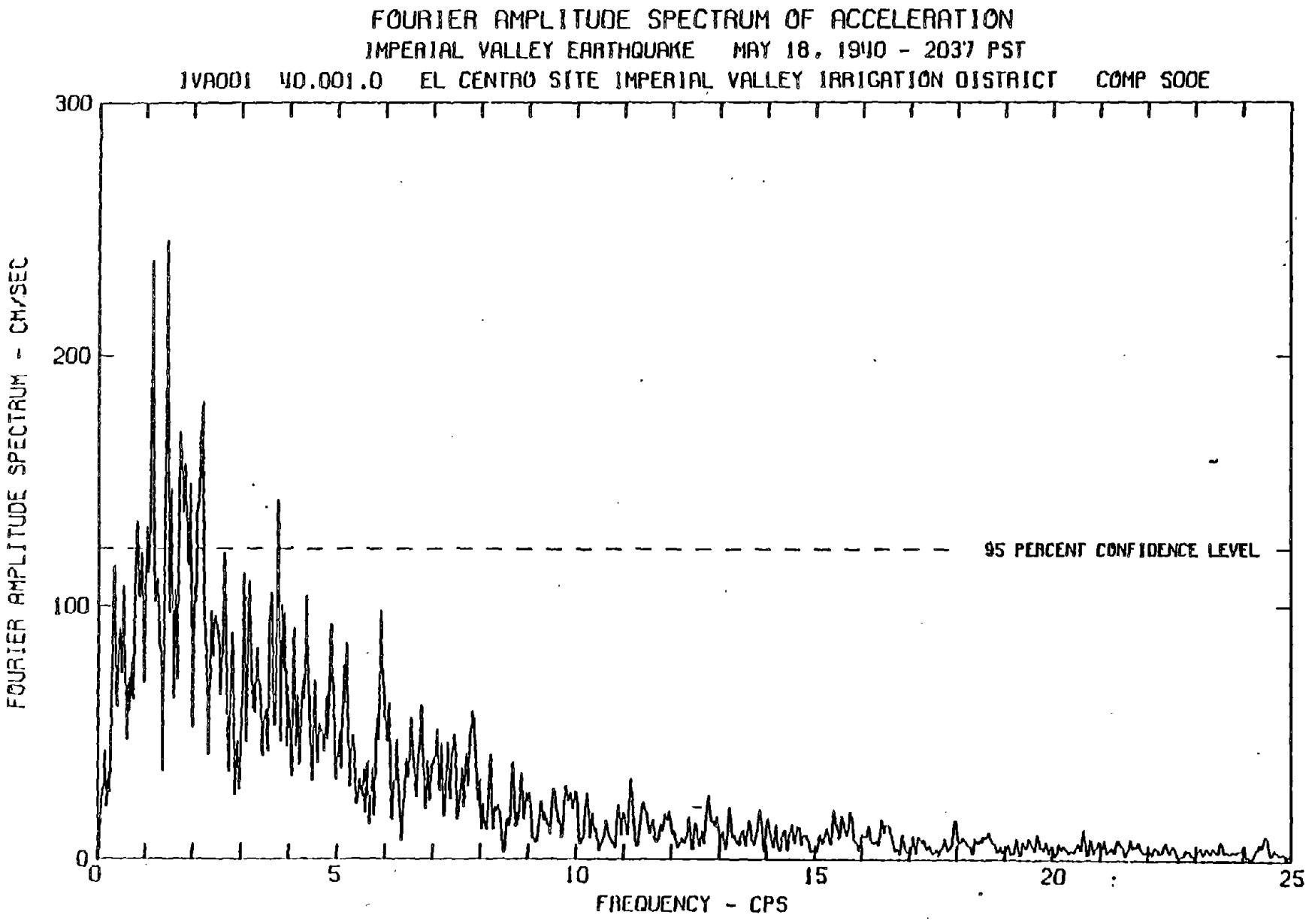
APPENDIX G

TIME-HISTORY AND FOURIER SPECTRA FOR SELECTED SITES (FROM CIT 1969-1975)



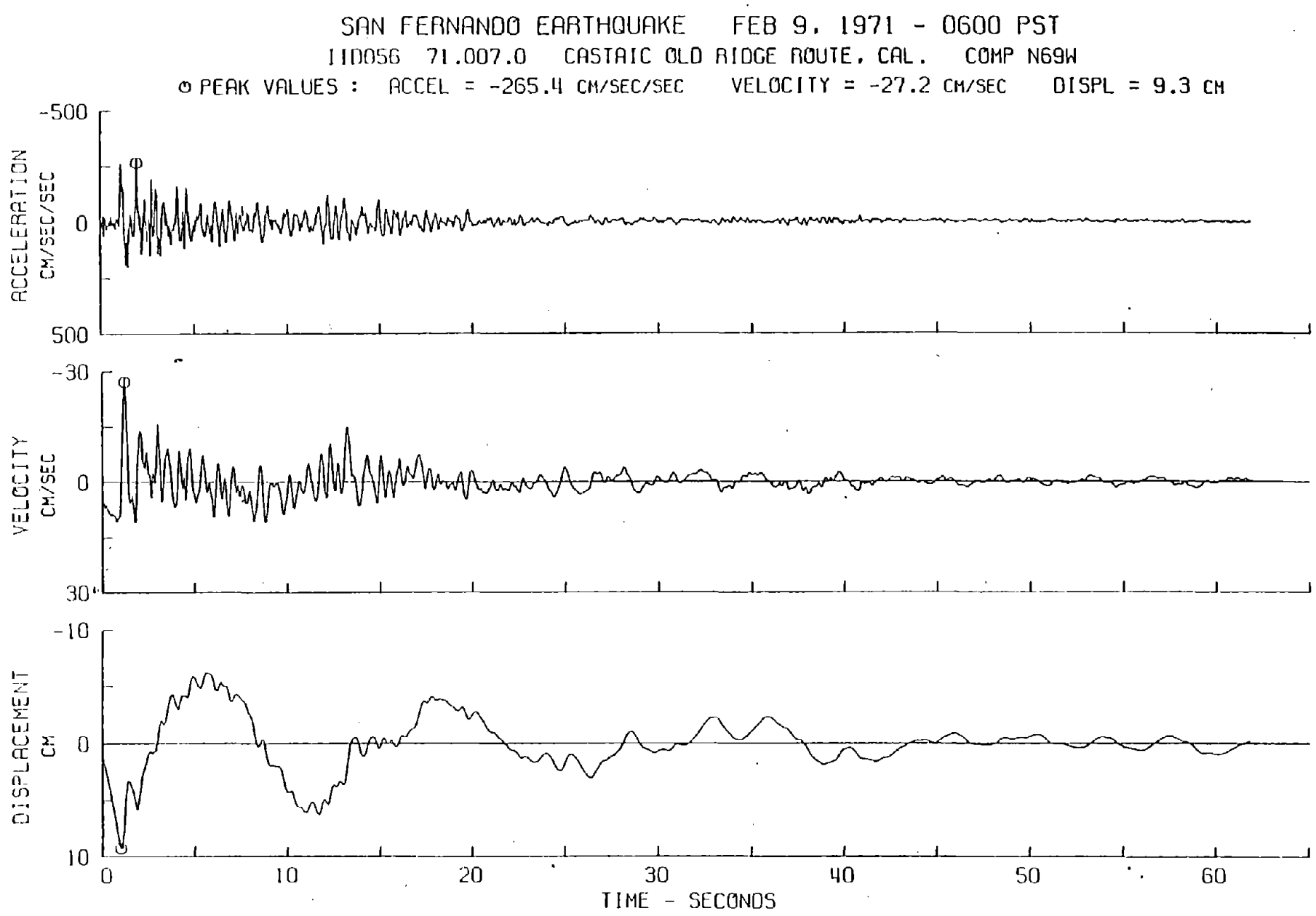
(a) Time-history

FIGURE G-1. TIME-HISTORY AND FOURIER SPECTRUM FOR 1940 EL CENTRO RECORD (CIT, 1969-1975)



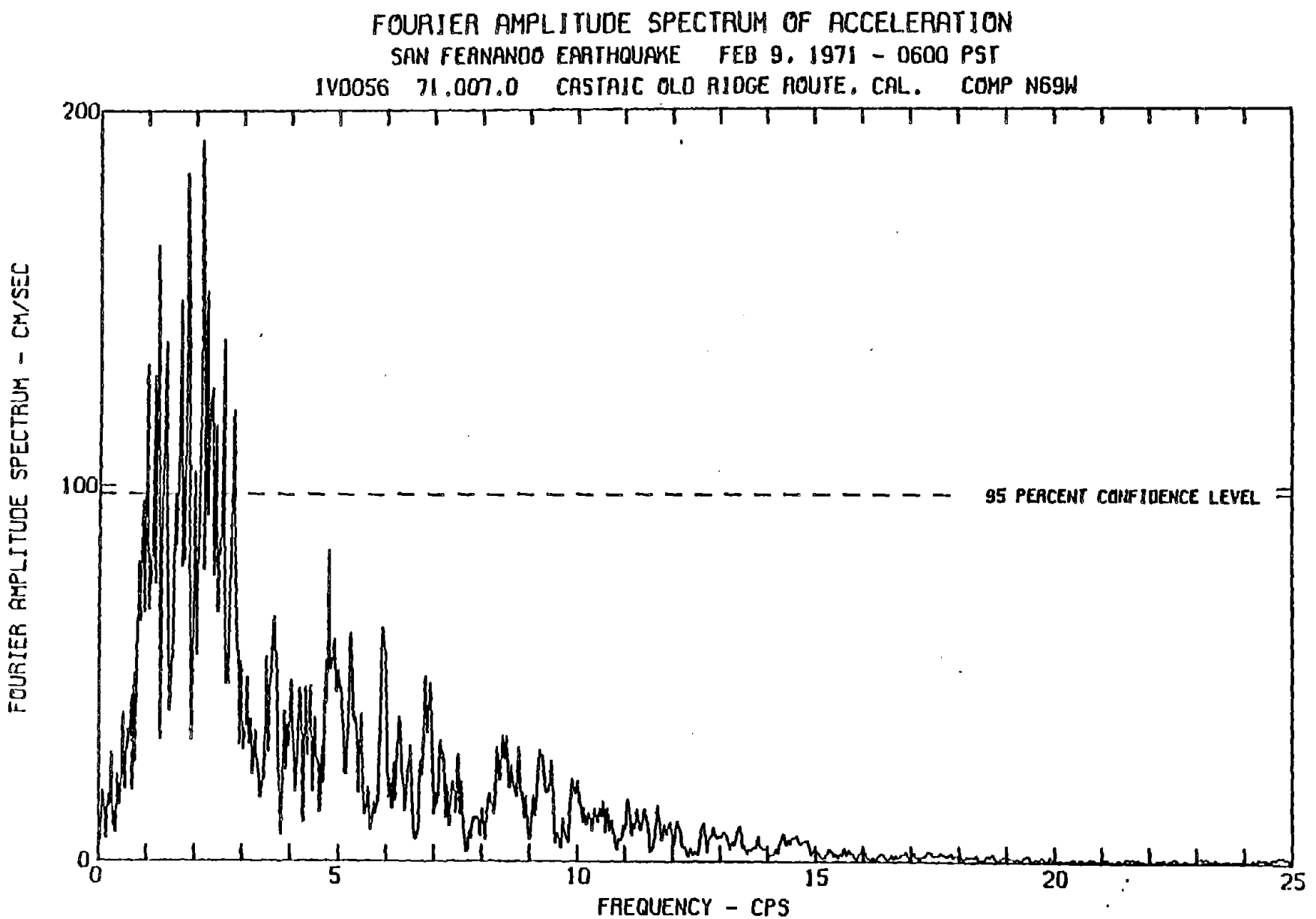
(b) Fourier spectrum

FIGURE G-1. (CONCLUDED)



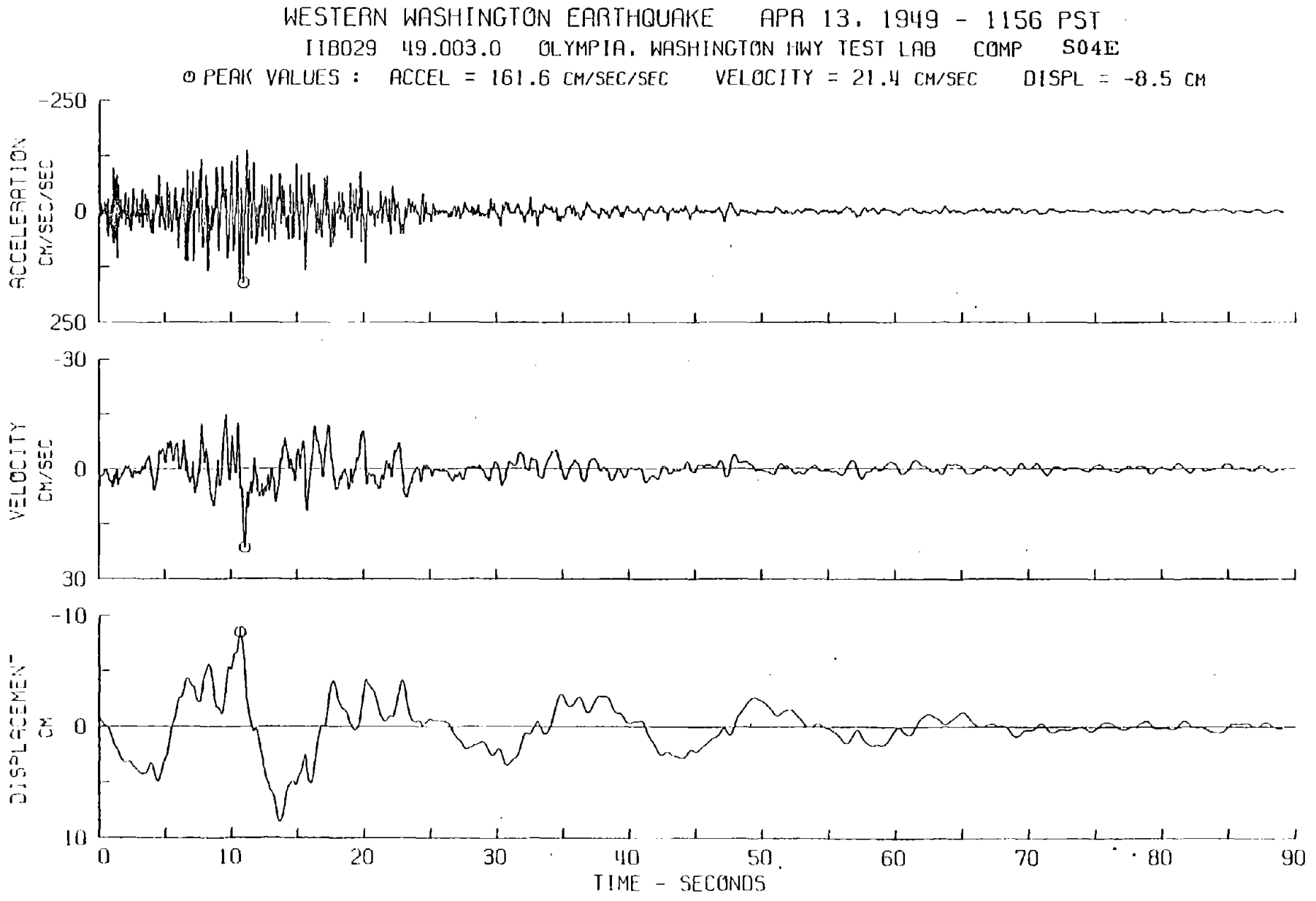
(a) Time-history

FIGURE G-2. TIME-HISTORY AND FOURIER SPECTRUM FOR CASTAIC RECORD (CIT, 1969-1975)



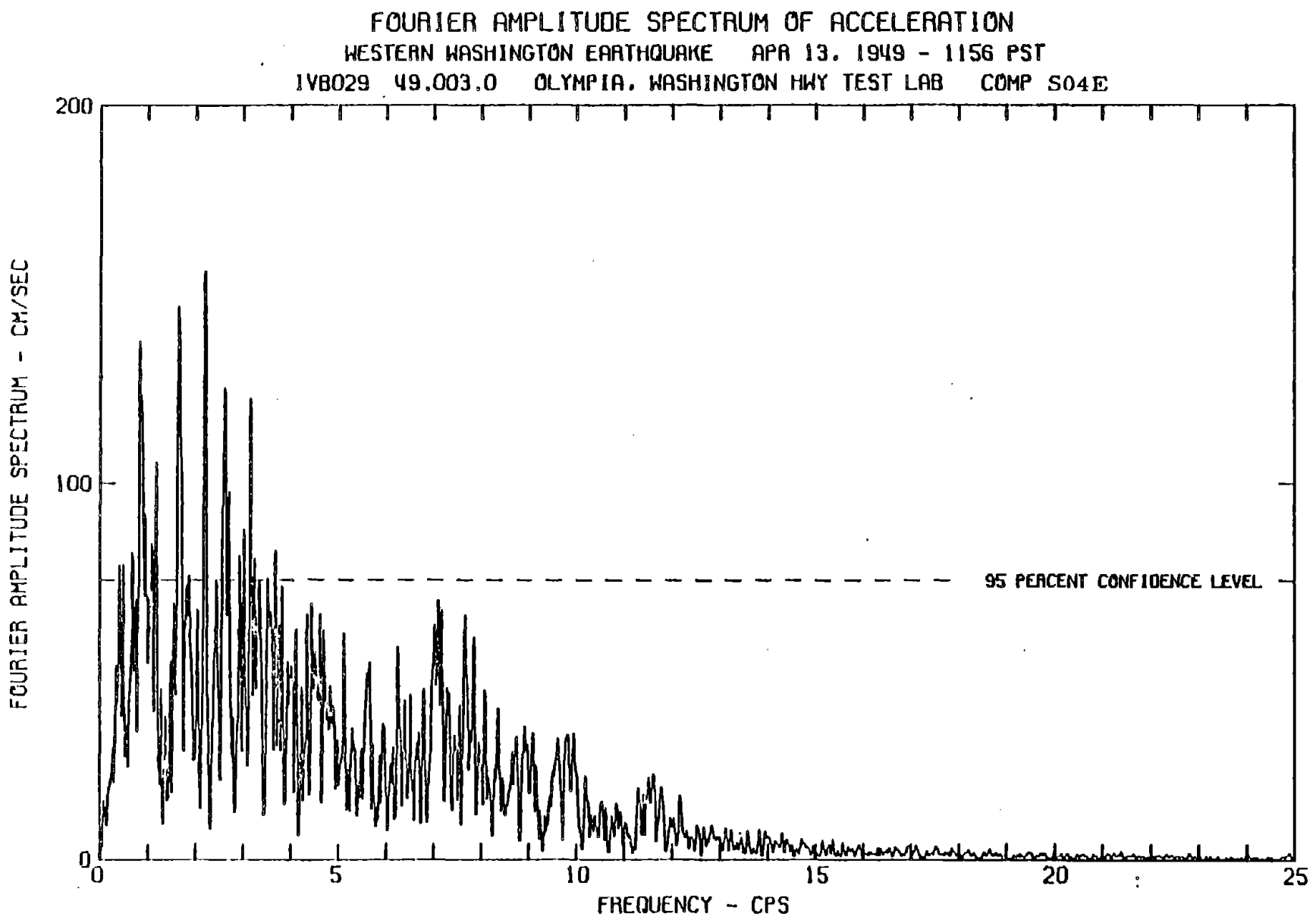
(b) Fourier spectrum

FIGURE G-2. (CONCLUDED)



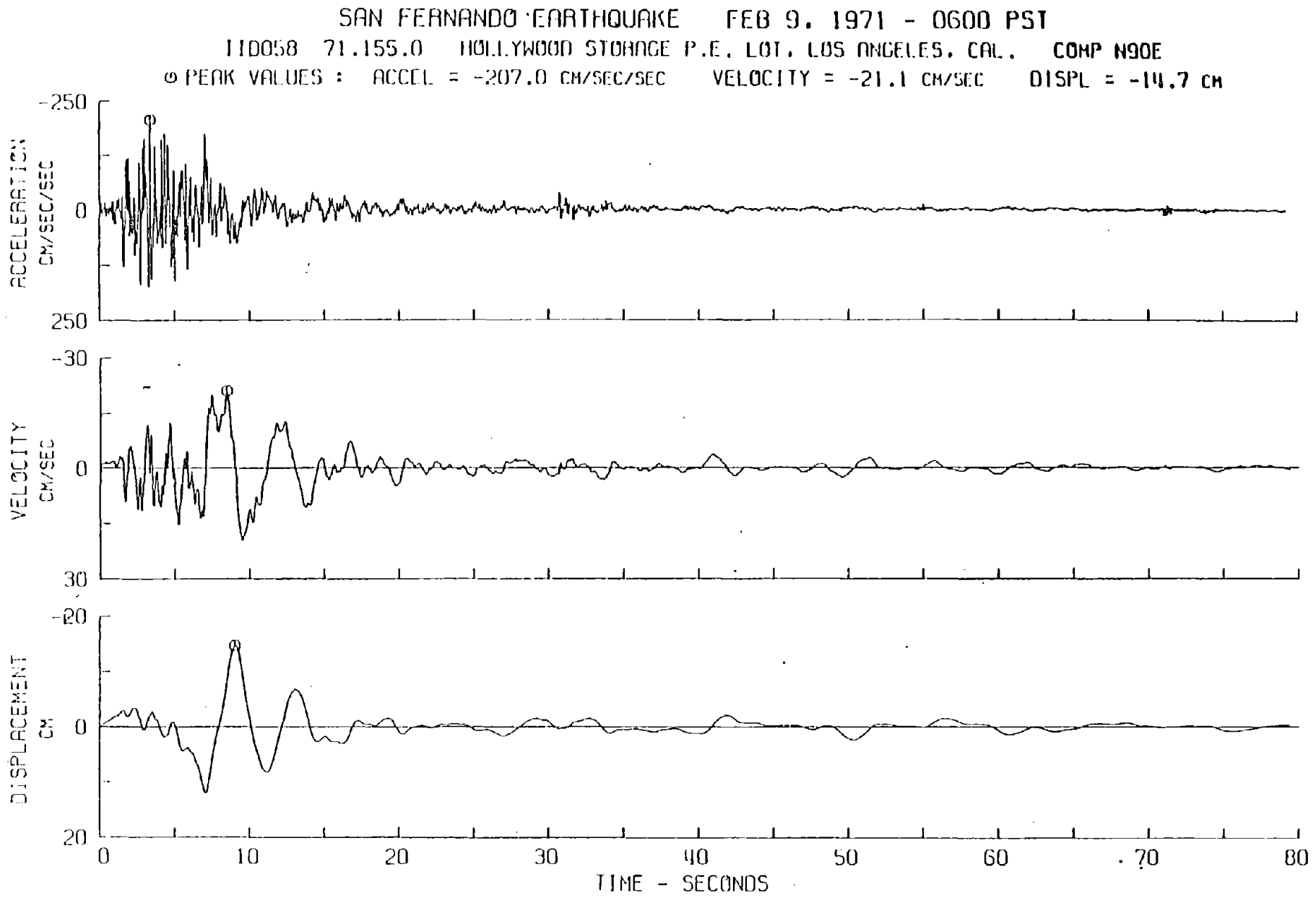
(a) Time-history

FIGURE G-3. TIME-HISTORY AND FOURIER SPECTRUM FOR 1949 OLYMPIA RECORD (CIT, 1969-1975)



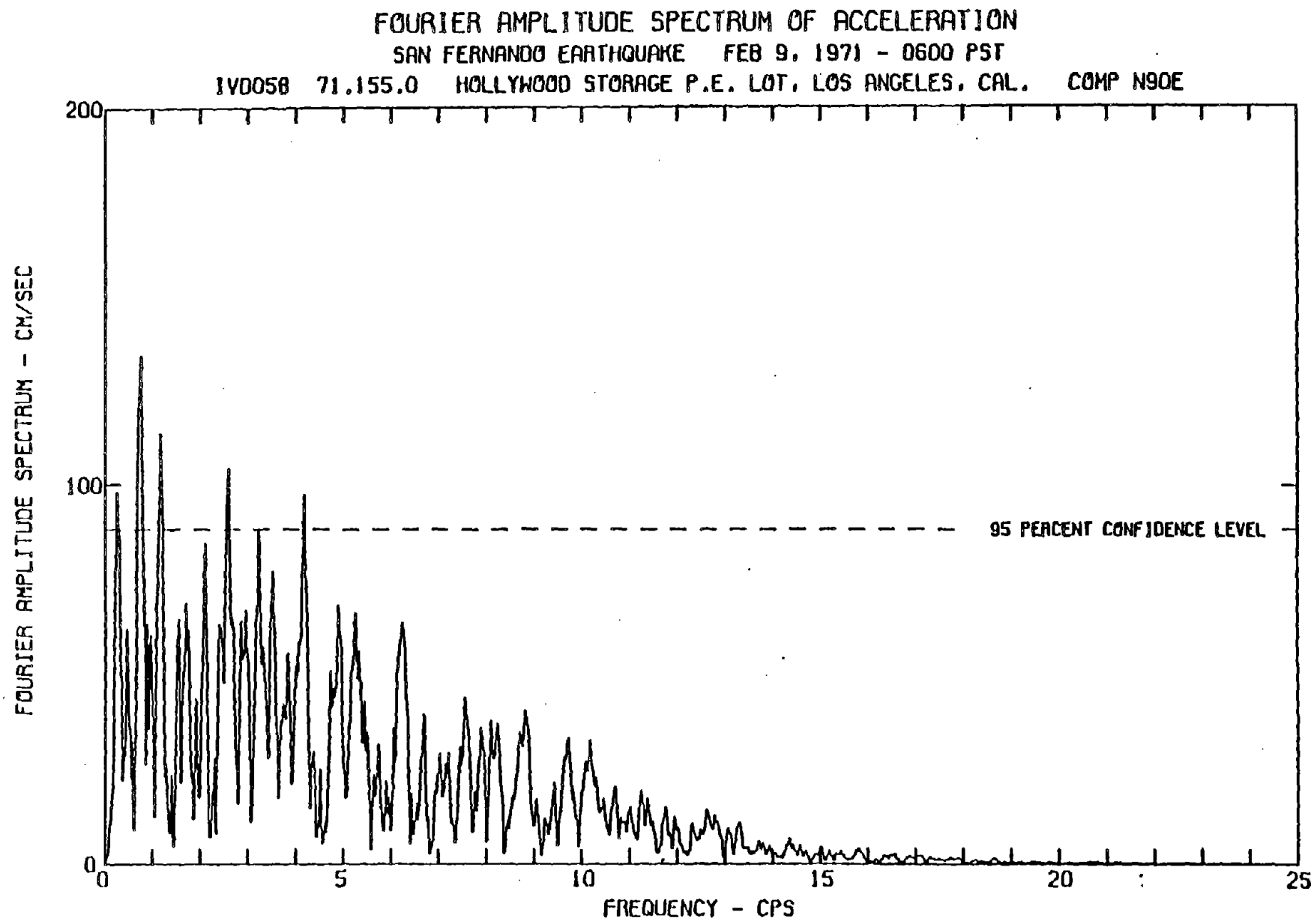
(b) Fourier spectrum

FIGURE G-3. (CONCLUDED)



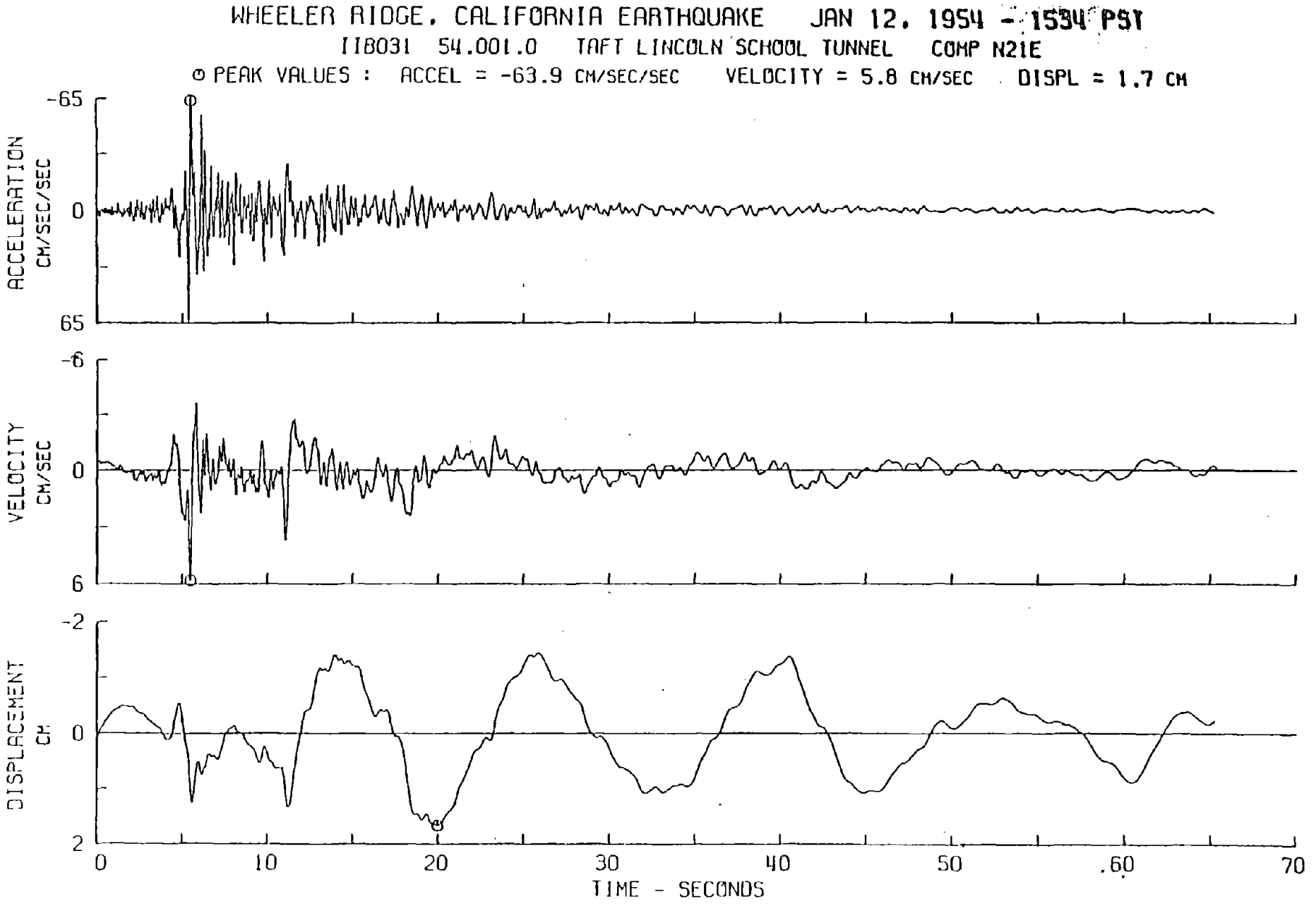
(a) Time-history

FIGURE G-4. TIME-HISTORY AND FOURIER SPECTRUM FOR 1971 HOLLYWOOD STORAGE RECORD (CIT, 1969-1975)



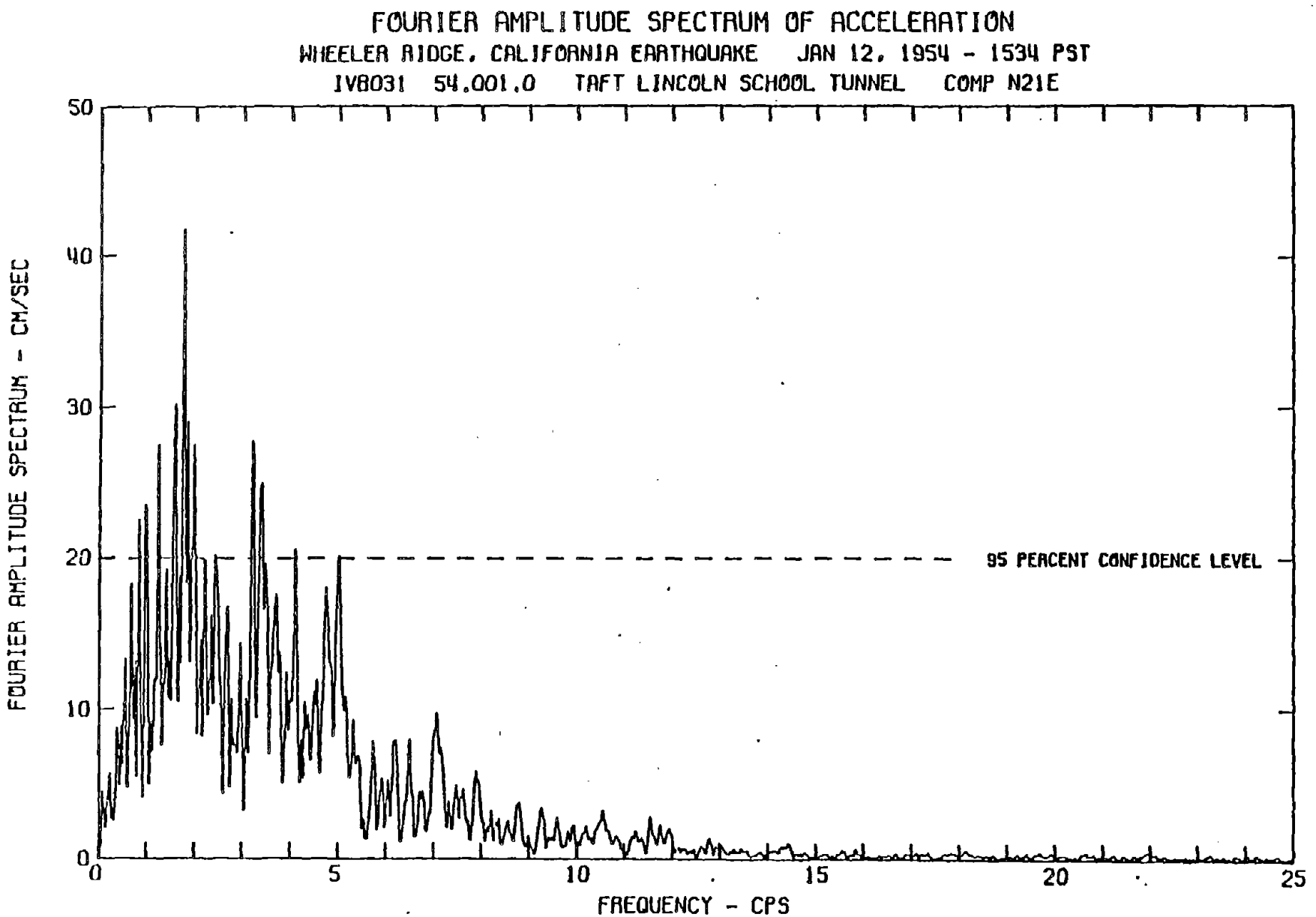
(b) Fourier spectrum

FIGURE G-4. (CONCLUDED)



(a) Time-history

FIGURE G-5. TIME-HISTORY AND FOURIER SPECTRUM FOR 1974 TAFT RECORD (CIT, 1969-1975)



(b) Fourier spectrum

FIGURE G-5. (CONCLUDED)