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SEISMIC HAZARD ANALYSIS: SITE SPECIFIC RESPONSE SPECTRA RESULTS

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1.0 INTRODUCTION

In order to assess the adequacy of a facility's design to resist earthquake loadings, two factors must be considered: an estimate of earthquake hazards at the facility site and an estimate of the facilty's strength to resist those hazards. The integral of these two factors is often termed the earthquake risk, with the consequence measured in economic or public safety terms. This report describes the results of various approaches used to estimate the first factor, earthquake hazard, for sites in the Eastern United States.

The objective of the Site Specific Response Spectra (SSRS) program was to evaluate, from a seismic hazard standpoint, the nine nuclear power plant sites included in the NRC's Systematic Evaluation Program (SEP). The primary product of this evaluation was expected to be a preliminary screening of the nine facilities by seismic design margin. Once potential problem sites were identified, the methodology could readily identify additional analysis which could be conducted into the areas of greatest uncertainty, thus potentially eliminating any possible conservatisms.

Four general methodologies are utilized to produce site-specific response spectra which can be used in the seismic evaluation of these facilities. These four methodologies were chosen to represent a variety of technical approaches that, while differing from the current licensing approach, would be technically viable in terms of establishing an adequate seismic input to be used in the NRC's evaluation of seismic design of these power plants.

While both seismic hazard and facility strength are probabilistic in nature, for convenience, the estimate of a facility's strength is usually conservatively approximated as deterministic. However, the ground motion induced by the earthquake and especially its occurrence at a specific site have not been estimated by purely deterministic techniques due to uncertainty in the specific earthquake process, particularly in the East. Even if truly deterministic

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techniques were available, a probabilistic approach to estimating the earthquake hazard has a unique benefit to a decision-maker because probabilistic estimates allow a quantitative comparison of design or safety margins associated with different approaches. That is generally not possible with a deterministic estimate.

Therefore, the four methodologies used span a broad approach to assessing seismic hazard, including both deterministic and probabilistic considerations. The emphasis in these four methodologies was to provide response spectra which not only recognized the specific characterisitcs of each of the nine sites in the Eastern United States (EUS), but also provided quantitative insights as to the likelihood and uncertainty of the earthquake hazards. These insights are useful in comparing the facility design criteria to current licensing criteria. Although the approaches developed for this study required significantly more effort than the approach normally used in NRC licensing activities, they offer the following advantages:

- Quantification of the hazard in terms of return period
- Incorporation of the complete historical seismic records
- Capability for inclusion of the judgment and expertise of many seismologists
- Explicit consideration of the incomplete knowledge that exists regarding the location of faults and characterization of earthquake hazards
- Flexibility in the evaluation of structural design margins to allow assessment of the risk at the site in terms of spectral acceleration, velocity and displacement for both nearby and distant earthquake hazards

In contrast, using the current licensing approach, a single analyst judgmentally decides that an earthquake of a given magnitude or intensity occurs at a specific location. This ground motion from the earthquake source is then attenuated to the site to determine the effects of that earthquake. Using this approach, it is difficult to define parameters such as margins of safety, or degree of conservatisms, in the design spectra. This inability to assess the degree of conservatism makes it impossible to evaluate other design bases such as those used in the design of older operating reactors. Additionally, it is difficult to trade off changes in structural design approaches that also are typically found in the design of older nuclear power plants with changes in seismic hazard definition.

As a result of these considerations and the growing capability for the use probabilistic approaches to define earthquake hazards, more and more effort has been directed in this area. Apart from the various probabilistic studies of earthquake hazards on the West Coast, the Tennessee Valley Authority has applied statistical evaluation methodology to compare the design spectra for several of its nuclear power plant sites. The NRC's experience in evaluating these results were included in the two methodologies dealing with actual strong motion records. The NRC's Office of Nuclear Material Safety and Safeguards has applied seismic risk analyses in the evaluation of many of the existing licensed facilities. Additionally, the NRC's Office of Research is employing similar probabilistic methodologies in the Seismic Safety Margin Research Program. While this Site Specific Response Spectra effort has benefited from the available results of these programs, much of the effort associated with this probabilistic analysis is new and unique.

This effort, Seismic Hazard Analysis (SHA) for the Eastern United States, has been divided into three reports for presentation purposes. This report, SHA: Site Specific Response Spectra Results, presents a general description of the technical approach used including a description of the four methodologies and their application to the nine Eastern United States sites, a description of the attenuation results used in the probabilistic model and a summary of the results and conclusions, both on a site-specific basis and generic basis. The TERA report, SHA: A Methodology for Eastern United States, describes the major methodology for computing the uniform probability of exceedence for ground motion parameters. The third report, also written by TERA, SHA: Solicitation of Expert Opinion, discusses the expert opinion questionnaire and responses from selected experts.

2.0 GENERAL TECHNICAL APPROACH

The technical approach to estimate seismic hazard for sites in the United States has evolved significantly in the last several years. The fundamental problems in all approaches associated with the prediction of "extreme" seismic hazards are the lack of applicable measured earthquake data and the substantial uncertainty as to first principles associated with earthquake processes. As a result of these problems, no single methodology has been completely sucessful; for example, deterministic models, even where geologic and tectonic conditions are reasonably well defined, must use judgment in selection of certain parameters for simulation of earthquakes. Furthermore, probabilistic models, even where sample size is sufficient for classical statistical techniques to yield usable predictions, cannot resolve uncertainty in the knowledge of basic earth processes.

Regardless of such limitations, estimates of seismic hazard are often required. Therefore new methodologies must be developed which, while unable to yield absolute answers, can combine available knowledge, objective and subjective, in an analytical framework that allows for critical review and useful comparative evaluation. In describing the approach used here, it is instructive to evaluate the basic approaches available to the analyst and their application in seismic hazard assessment.

It is important for users of these estimates to recognize the major effect uncertainty plays in SSRS. By including the uncertainty conservatively, for that is the only prudent approach, the SSRS may have substantial impact that may be found to be unwarranted after future refinement of these uncertainties. For example, the uncertainty associated with attenuation likely results more from a lack of applicable data than from the perversity of nature. This is a generic factor that affects all results. Whether a decision-maker desires to include the full measure of this uncertainty now, or wait for technology to refine this factor would logically be balanced by the risks and impact of the decision. Such consideration is far outside the scope of this study, but it should be explored in cases where the impact is substantial. Additionally, it is important for the

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analyst to indicate where the major uncertainties are, what their effect is and whether it is possible to refine them. An additional factor, equally important, but largely subjective, is whether the uncertainty is a characteristic of nature, and therefore represents real hazard, or whether the uncertainty results from a lack of man's knowledge which can be refined.

2.1 DETERMINISTIC APPROACH

Only recently have pure deterministic approaches been used in analysis of seismic hazard. Here we use the word deterministic in the same sense as in applies to seismic structural analysis. For example, in structural analysis, one uses first principles and models of the structures, which can be very elaborate and reasonably include all of the important parameters to compute the building loads. The major difficulty with completing the structural analysis is modeling failure of the structure. Because little is known about modeling failure, conservative assumptions are often used there.

In the Western United States (WUS), engineering seismology has advanced to the stage that similar, deterministic, first principle models are being applied to the earthquake process. However, even in the West where the specific, seismically active, structures can be identified, sufficient unknowns exist that certain subjective data is required for the models to predict reasonable resultant ground motion. Strict application of this approach to the East is not possible since the source of seismicity is not well known.

As a point of comparison, the NRC approach outlined in Appendix A of 10 CFR 100 is often termed deterministic. However, that approach is not strictly deterministic, in that it is not based on first principles. No true modeling is done and the design acceleration is arrived at by using judgment to choose the largest credible earthquake and a suitable correlation for ground motion. In practice, through expert opinion, measured data is used, together with an empirical-statistical model to determine a design specification. Examined this way, this approach for the specification of the seismic hazard is deterministic only in the way the formal hazard analysis methodology is replaced with judgment and an answer determined. One of the major difficulties with a deterministic approach like Appendix A is that the protection it provides against the seismic hazard is not quantified and therefore can vary from site to site. Because of this, it is a poor tool for the comparative evaluation of different seismic design spectra.

2.2 PROBABILISTIC APPROACH

In contrast to the deterministic approaches discussed above, probabilistic approaches, even those with subjective input, can yield results whose margins can be quantified. However, just as deterministic models require subjective input, the state-of-the-art and available data in Eastern United States do not allow useful probabilistic models based solely on objective input.

Empirical-statistical methods using a conventional statistical model to make direct estimates of the future behavior of the parameter of interest have been developed for west coast sites where substantial applicable objective data, such as real earthquake spectra, exists. Typically, the parameter is peak ground acceleration (PGA) at the site. If enough appropriate records are available for a given site, a response spectrum can be obtained by such statistical models.

This approach avoids theoretical assumptions required by first principle models. However, for all eastern sites the data is insufficient to make meaningful estimates of a low probability event. The method also usually fails to incorporate much other knowledge specific to the site (e.g., location of faults or other source regions) and variations in the seismicity of various nearby source regions. These factors are generally introduced by judgment.

Much of the remaining sections of this report describes the probabilistic methodology developed to predict a uniform risk of exceedance for ground motion parameters (PGA, PGV, and spectral accelerations) in the EUS. This model uses available objective data supplemented with subjective input from selected experts. While suffering from many of the limitations described above, it does allow rational estimates of seismic hazard in the east.

2.3 SSRS METHODOLOGIES

For this study four methods were applied to the nine EUS sites. The Uniform Hazard Method (UHM) is new in its use of subjective input and specific application. The others, Newmark-Hall spectra, and real and scaled spectra, have been developed for some time, and are directed largely at defining spectra shape to be combined with anchor points determined by the UHM. Obviously, other approaches to defining the anchor points are available also (e.g., the approach taken by TVA in the Sequoyah nuclear plant in which expert judgment is used to choose a maximum credible intensity which when converted to magnitude provided the basis for the selection of real time histories).

UNIFORM HAZARD SPECTRA (UHS)

The Uniform Hazard Methodology (UHM) described in the TERA report, SHA: A Methodology for Eastern United States, was used to develop Uniform Hazard Spectra (UHS) for each of the nine sites as well as spectral anchor points for the other methods. The UHM used subjective input from a panel of experts to calculate response spectra with a uniform probability of exceedence at each spectral ordinate. Using the input from each of 10 experts, the seismic hazard is determined at each site in terms of peak ground acceleration (PGA) peak ground velocity (PGV), spectral ordinates (PSA) at nine periods (.04 to 2 seconds), and Modified Mercalli Intensity (MMI). Each of these ground motion parameters was computed as a function of return period for all nine sites. The results from each expert were then combined by weighting each expert's results with his self ranking in several specific areas to form a synthesis for the return periods of 200, 1,000 and 4,000 years.

The UHM treats seismic hazard in four steps:

- Zonation or seismic source geometry
- Zone seismicity
- Attenuation
- Exposure evaluation

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In essence, the expert opinion as to distribution of seismicity by location, magnitude and occurrence is discretinized and then attenuated (Section 5.0) to a site under consideration. The uncertainty in each step of the process is carried through the integration to obtain the probability of exceedence of the various ground motion parameters. This integration is performed over the geophysical area of interest considering each subjective probability distribution with its uncertainty.

NEWMARK-HALL

The Newmark-Hall approach to determining spectral shape addressed the major problems with other approaches, that of a lack of earthquake records in the appropriate categories, with a unique solution based more on first principles. The Newmark-Hall spectrum is typical of response spectra for nearly all types of ground motion and can be physically interpreted as frequency dependent. At the low frequency end the response approaches an asymptote corresponding to the maximum value of ground displacement. From first principles, a low frequency system corresponds to a heavy mass and light spring, so when the ground moves rapidly the mass does not have time to move so the maximum strain in the spring equals the maximum displacement of the ground. For a high frequency system the spring is stiff and the mass is light so when the ground moves the stiff spring forces the mass to follow the ground movement. Thus the mass has the same acceleration as the ground, so the maximum acceleration of the mass equals the maximum acceleration of the ground. These physical phenomena are exhibited by the response spectra line approaching the maximum ground acceleration line at the high frequency side of the graph. At intermediate frequencies there is an amplification of motion corresponding to the dynamical characteristics of the system.

REAL AND SCALED TIME HISTORIES

Virtually every approach to specification of design spectra requires the explicit or implicit use of a suite of real strong motion recordings to develop the spectrum, whether site-specific or generic. For example, the generic NRC Regulatory Guide Spectrum was developed by statistically averaging a suite of records covering a variety of site geologies, magnitudes, and distances. On the other hand, a probabilistic model uses these records more implicitly in, for example, the development of an attenuation relation. The approach to real and scaled time histories is complementary to the probabilistic approaches in that it involves explicit averaging of the records. The key element to this approach is the criteria for the selection of records. There is clearly a potential tradeoff here; the more site-specific the criteria, the smaller the suite of appropriate records and, therefore, the less statistical validity for the conclusions. The basic criteria, however, must be based on the subjective assessment of the class of earthquakes that dominate the hazard at Eastern United States sites.

If it is believed that the principal hazard comes from the occurrence of relatively nearby intermediate earthquakes (e.g., Appendix A to 10 CFR Part 100) the criteria must explicitly account for this hypothesis. In addition the criteria must account for the regional tectonics through, for example, the depth or focal mechanism of earthquakes. Finally, the criteria must account for characteristics of the site that could influence the hazard, most notably the site geology. While this approach is <u>direct</u> in that it does not require many of the sophisticated hypotheses required in probabilistic approaches (e.g., earthquakes being a Poisson process), the approach contains important data-based assumptions. For example, there are statistical biases contained in any suite of digitized strong motion records resulting from highest priority being given by the USGS and others to larger acceleration records at the expense of the small accelerations. Similarly, there is tremendous uncertainty in converting earthquake magnitudes to a common scale. Many times these assumptions are sufficiently uncertain that an extensive sensitivity study is required, thus diluting the value of the results to a decision maker.

In general, the actual strong motion records can be used to develop two types of spectra, Scaled Time Histories and Real Time Histories. For Scaled Time Histories, the records are normalized by their peak acceleration with statistics on their spectral ordinates resulting in a statistical spectral shape. This spectrum is then anchored at a peak acceleration determined separately, from the UHM. For Real Time Histories, the spectral statistics are performed on the raw, unnormalized records, resulting directly in a site specific spectrum. The selection of the appropriate magnitude range of the records was based on UHM estimates of MM Intensity. Therefore, both of these approaches employ the Uniform Hazard Model.

2.4 SIMILARITY OF MODELS AND RESULTS

Since all models developed thus far for the East suffer from the same major weaknesses, paucity of data and uncertainty as to the first principles, two general similarities result. First, subjective input, usually in the form of opinion from one or more experts are included to allow usable prediction of response spectra to be made. Second, the methods often have substantial overlap since analysts attempt to build from past ideas. For example, an analyst can combine the "deterministic" selection of peak ground acceleration of Appendix A to 10 CFR 100 with the spectral shape of scaled time histories for a specific site. Likewise, an analyst can combine the probabilistic selection of peak ground acceleration and velocity with the Newmark-Hall spectra. In the first case, shape is determined by statistical analysis of historic records and in the second case, the shape is based somewhat on deterministically developed first principles. Therefore, since these methods may be combined in a number of ways, some overlapping of methods is inevitable.

Considering the potential variability of results from the four approaches, even given their common use of certain data as anchor points, the SSRS from each of the methods have substantial similarity. In many ways, this is supportive of the general validity of the methods and should be encouraging to decision-makers. On the other hand, where factors of two difference are important, additional sensitivity studies and further refinement of methodologies and input is recommended.

3.0 DATA BASE USED IN SRSS

An important element for any analysis, and particularly a probabilistic one, is the data base used. Three sets of objective data, including historic seismicity data and measured earthquake records, were used in the four methods to develop the SSRS for the nine sites. One, a combination of several historic seismicity data sources, was used in the questionnaire developed to solicit expert opinion. These data are discussed in detail in a companion report, SHA: Solicitation of Expert Opinion. Two, measured U. S. earthquake strong motion records were used to develop the attenuation model. These data are discussed in Section 5. Three, selected earthquake records from the U. S., Japan and Italy were used to develop both the Real Time History Spectra and the Scaled Time History Spectra. A discussion of these records, their selection and use in developing SSRS is presented in Section 4.3 of this report.

In addition to the objective data, previous sections of this report have shown that seismic hazard analysis for Eastern U. S. sites always requires some degree of subjective input, either in the model assumptions, the input data, or both. This should be acknowledged and stated as clearly as possible. In the UHM this subjective input is explicit and formally included as discussed in the companion TERA reports. Since other methods rely on UHM results, Appendix A of this report summarizes the solicitation of expert opinion.

The degree to which the other methodologies rely on subjective data varies substantially as does the way it was included--explicitly or implicitly. In some ways the Real Time History method is the easiest to present. Real Time History Spectra implicitly rely on expert opinion to select the magnitude range and appropriate records for statistical evaluation. The other methods, Newmark-Hall spectra and Scaled Time History spectra, are more complicated since a combination of subjective input is used. Newmark-Hall spectra couple the UHM through explicit use of subjective data for two anchor points of the spectra with certain model assumptions for the other spectral ordinates. Scaled Time History spectra rely on UHM (explicit use of subjective data) for one anchor point of the spectra and statistical analysis of selected earthquake records (implicit use of subjective input in the selection criteria) for the remainder of the spectra.

As a result of the use of both subjective and objective data in SSRS, the results should be viewed as subjective probabilities. However, since each method is rather unique in the degree and way subjective input is treated, it is useful to compare the results in an attempt to determine the effect such input has on the results.

4.0 SSRS METHODOLOGIES

The four methodologies used to develop SSRS for the nine EUS sites are described in this section. Since the results from the Uniform Hazard Method are used as anchor points for two of the other methods in this study, we begin with a summary of the essential elements of the UHM below. A detailed description of the UHM is given in the companion TERA report, "SHA: A Methodology for Eastern United States."

4.1 UNIFORM HAZARD METHODOLOGY

In the UHM, seismic exposure portrays the distribution of the expected value of a ground motion parameter at a given site. The values are estimated for a selected probability of exceedence within a given period of interest, i.e., a selected return period. An exposure distribution can be generated for any ground motion parameter for which appropriate source effects, transmission effects, and site effect can be defined.

A uniform hazard spectrum is developed in such a way that each spectral amplitude has the same probability of being exceeded in a specified time period. In its development, each period is considered independently of another and predictions are made for one period at a time considering all the potential earthquakes contributing to the seismicity at the site. The procedure is repeated for other periods within the frequency range of interest and the spectrum is built point by point.

Hence the spectral amplitude at one period is only weakly correlated with another and their correlation is very low for periods far apart from each other.

A typical seismic exposure procedure leading to the development of a uniform hazard spectrum consists of four parts:

- Seismic source geometry (zonation)
- Source seismicity model
- Attenuation model
- Exposure evaluation model

Several procedures are available for evaluating seismic exposure (e.g., Cornell, 1974; Ang and Der Kiureghian, 1975; McGuire, 1976; Algermissen and Perkins, 1976; Shah et al., 1975; and Mortgat et al., 1977). Although all of these procedures incorporate the four models noted above, differences exist, in the key assumptions and methodology for application of these models, which can result in significant variations in the seismic exposure estimates.

The main characteristic of the seismic exposure evaluation procedure used in the present study is the explicit use, at several levels of input, of subjective expert opinion. The evaluation procedure consisted of the following steps.

Seismic Source Geometry

- Define representations for source geometry and for individual earthquake events on the source.

Source Seismicity Model

For each source in an area of interest:

- Define location and magnitude range
- Define earthquake recurrence:
    (a) mean rate of occurrence
    (b) magnitude distribution

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Attenuation Model

- Define applicable mean attenuation relationships
- Define uncertainty about mean values

Exposure Evaluation Model

- Define procedure for computating probability of exceedence

A flow chart of the procedure is presented in Figure 4-1. A detailed presentation of the methodology is available in the TERA report, "Seismic Hazard Analysis: A Methodology for Eastern United States," the main points of which are summarized below.

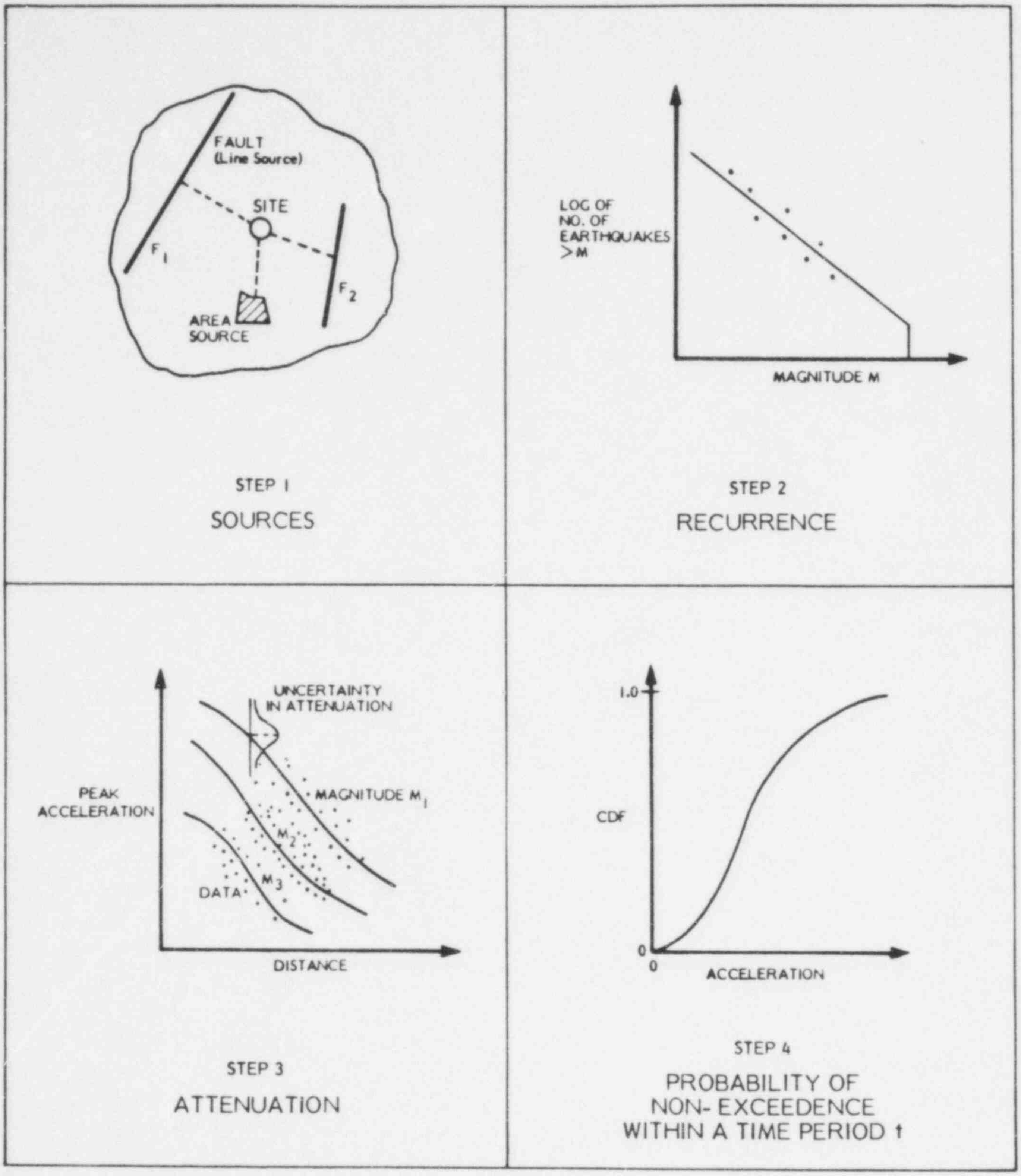
Seismic Source Geometry

Locations of the different seismic sources are determined by using both recorded hypocentral positions of past earthquakes, and geological and seismological information. The spatial distribution of hypocenters is then divided into different sources as a function of their shape and seismicity. Line and area source are used to represent the seismicity of any region. Future seismic activity is restricted to the source and the seismicity is assumed to be homogeneous over the whole source.

Because the shape and location of the sources may have a major influence on the final results, we have taken special care to obtain the best possible estimates of these characteristics. This is done by modeling a seismic source and superpositioning zones with different rates of seismic activity, where the rates are based on input from the experts.

Earthquake Occurrence Model

Magnitude range, upper magnitude cutoff and the recurrence of earthquakes are the basic input parameters of the earthquake occurrence model, and three steps comprise its development:



STEP 1
SOURCES

STEP 2
RECURRENCE

STEP 3
ATTENUATION

STEP 4
PROBABILITY OF NON-EXCEEDENCE WITHIN A TIME PERIOD t

FIGURE 4-1

TYPICAL APPROACH TO HAZARD FOR PEAK VALUES

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(1) Assuming that earthquake occurrences form a Poisson process wherein mean rate of occurrence is independent of magnitude, a distribution is obtained for the number of occurrences in the time period being considered.

(2) Given that an event has occurred, a distribution on the magnitude of events is determined from past data and subjective input. The process generating model can be assumed to be Bernoulli. The probability of success p_{M_i} corresponding to each trial is defined as the probability that the event that has occurred is of magnitude M_i. Thus, at each trial, the probability of failure, $q_{M_i} = 1 - p_{M_i}$, is the probability that the event is not of magnitude M_i. The probability of having r events of magnitude M_i, given that a total of n events have occurred, can therefore be obtained using the binomial distribution.

(3) The distribution of the number of events of each magnitude, independent of the number of trials, is obtained by combining steps one and two.

Attenuation Model

Several relations were combined to produce a final attenuation relation of the form

$$\ln(GM) = C_1 + C_2 I_o + C_3 r + C_4 \ln(r)$$

The ground motion parameters were PGA, PGV, and PSA, at nine frequencies between 25 Hz and 0.5 Hz.

Seismic Exposure Evaluation

Seismic exposure is evaluated by computing the level of ground motion parameters at a site for a particular probability of exceedence.

A typical seismic region contains a number of earthquake sources. In the seismic exposure evaluation, the effects of all sources are combined to provide an estimate of the probability of occurrence of at least one event, within the time period of interest, which is generating a given level of the loading parameter. By repeating the process for a number of levels, a probability distribution function or cumulative distribution function for the parameter can be developed at the site. The information over a range of periods is obtained by repeating the procedure for a number of periods.

Magnitude and Distance Sensitivity

In a uniform hazard spectrum, the probability of exceedence at each period is computed by combining the contribution of all eathquakes capable of affecting the site. This implies that small nearby earthquakes are considered in addition to large distant events. These two classes of events normally have different frequency contents. Since a structure will only be subjected to one earthquake at the time, it is interesting to study the contribution to the hazard of a single type of earthquake. Referring to Section 6.0 of the TERA report "Seismic Hazard Analysis: A Methodology for the Eastern United States," one can use distance and magnitude as earthquake separators.

If, for example, one considers a site in the central stable region, where only two sources are major hazard contributors (the central stable region, which generates rather small nearby events, and the New Madrid area, where large earthquakes can potentially occur), the contribution of each of these zones is treated independently. Figures 4-2 and 4-3 present the 1,000 year spectrum obtained from earthquakes both within and byeond a 200 km radius. As expected, the nearby earthquakes generate a spectrum rich in high frequency content, and the distant earthquakes generate a spectrum rich in low frequency content. Although these spectra do not represent the global hazard at the site, they show that the use of the uniform hazard spectrum in a modal superposition analysis can be quite conservative: no single earthquake will have a spectrum similar to the UHS over the whole range of frequency.

CONTRIBUTION FROM EARTHQUAKES WITHIN 200 KM

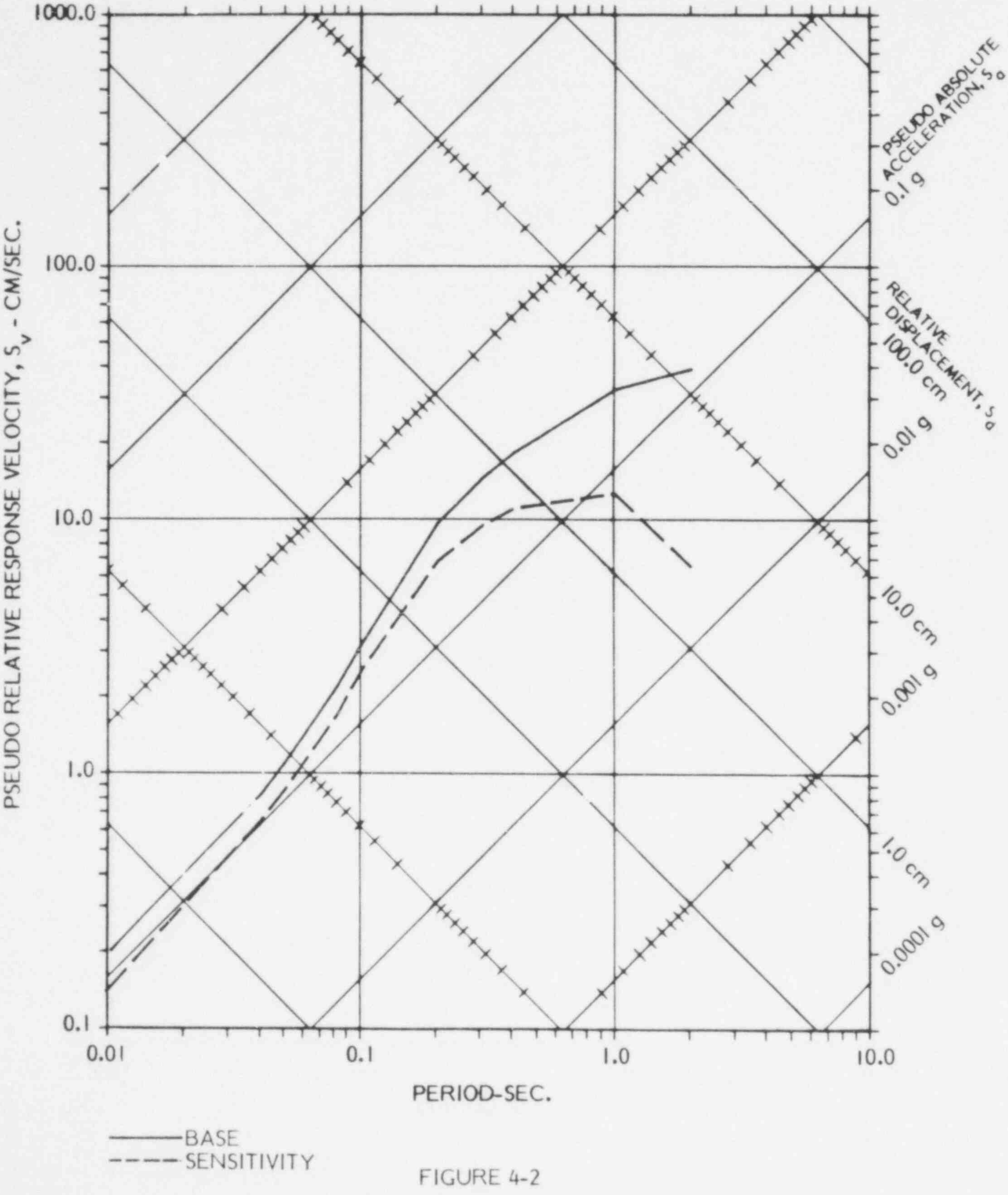

FIGURE 4-2

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CONTRIBUTION FROM EARTHQUAKES BEYOND 200 KM

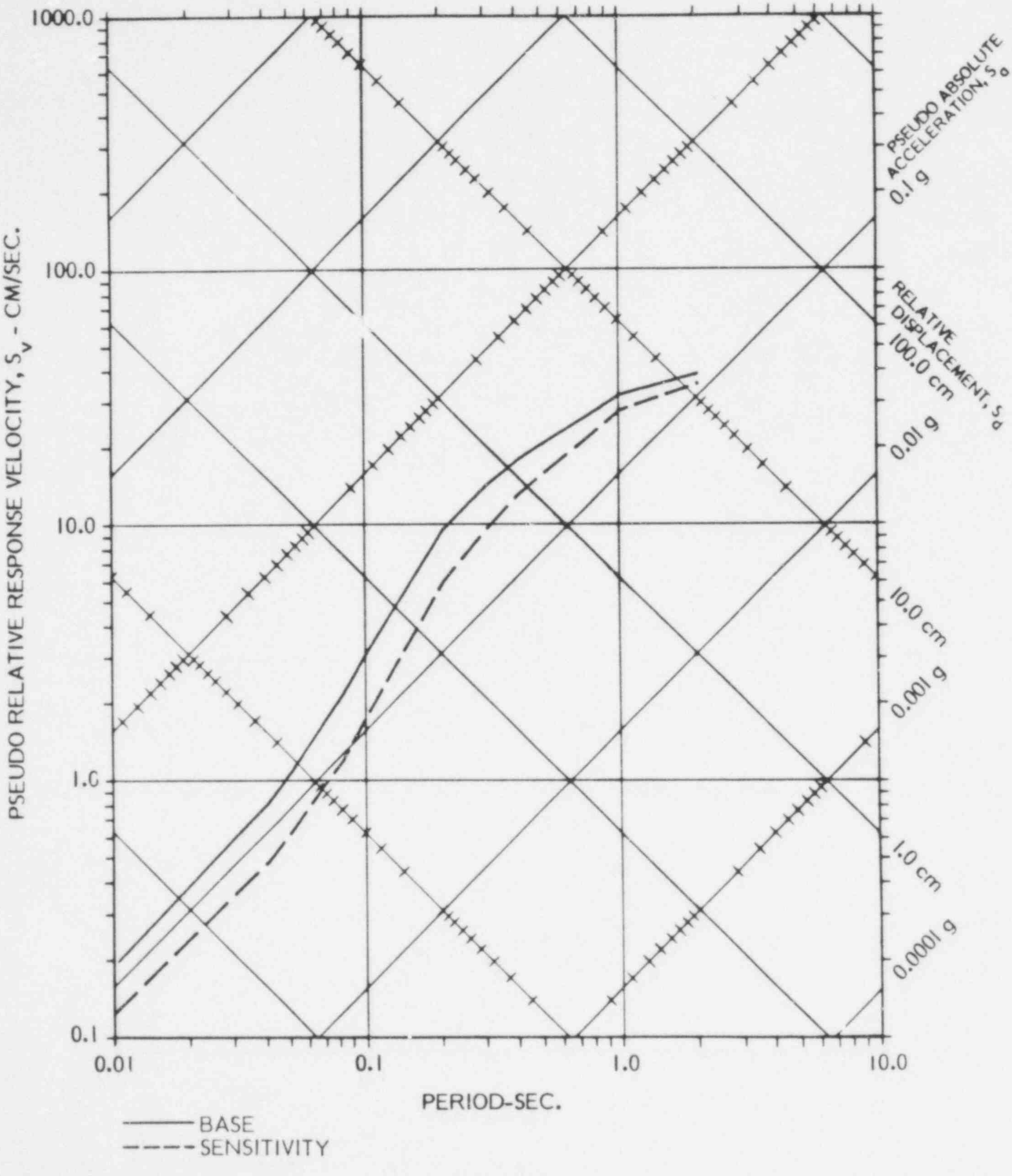

FIGURE 4-3

A similar study can be made regarding magnitude contribution to the hazard. The Appendix A, to 10CFR100, only considers the occurrence of the largest event, whereas a UHS includes the contribution of all events. Figures 4-4 and 4-5 present the 1,000 year spectra from earthquakes of MMI < VII and MMI > VII. They emphasize again that the UHS is an envelope of these two types of contributors.

These points emphasize that, in structural design, a UHS should be used with caution. When a system can be modeled by a single-degree-of-freedom oscillator of period T, the spectral amplitude T of the UHS correctly represents the total hazard of that frequency. When the structure must be analyzed using modal superposition, the combination of several spectral amplitudes from the UHS constitutes a conservative approach. The amount of conservatism is a function of both the type of earthquakes responsible for the hazard at the site and the specific structural model.

4.2 NEWMARK-HALL RESPONSE SPECTRA

The dynamic method of Newmark and Hall has been used to create site-specific response spectra. By definition, the response spectrum is a graphical relationship of the maximum response, to dynamic forces, of a single-degree-of-freedom elastic system with damping. A simple example of such a system would be a mass connected to a spring (with stiffness K) and a dashpot (providing damping).

If this system is subjected to an acceleration $\ddot{y}$ the equation of motion is:

$$\begin{aligned} M\ddot{u} + c\dot{u} + Ku &= -M\ddot{y} \\ \text{where } u &= x - y \\ \text{and } F_N &= \frac{1}{2\pi}\sqrt{\frac{K}{M}} \end{aligned}$$

When the base of the system moves, the mass is set into motion. The motion of the base can be described by giving one of the following:

SENSITIVITY CASE -- INTENSITIES LESS THAN VII

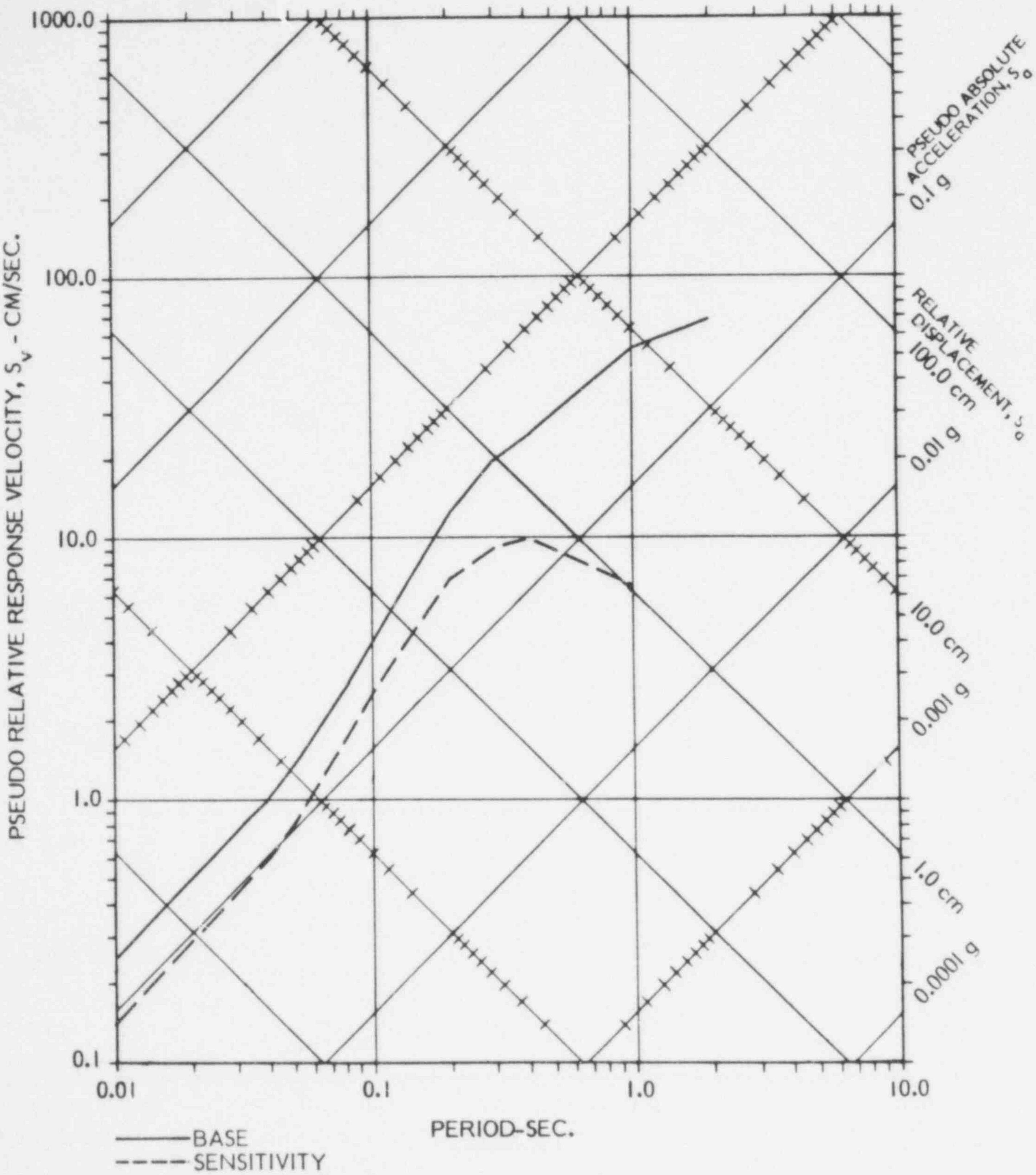

FIGURE 4-4

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SENSITIVITY CASE -- INTENSITIES GREATER THAN VII

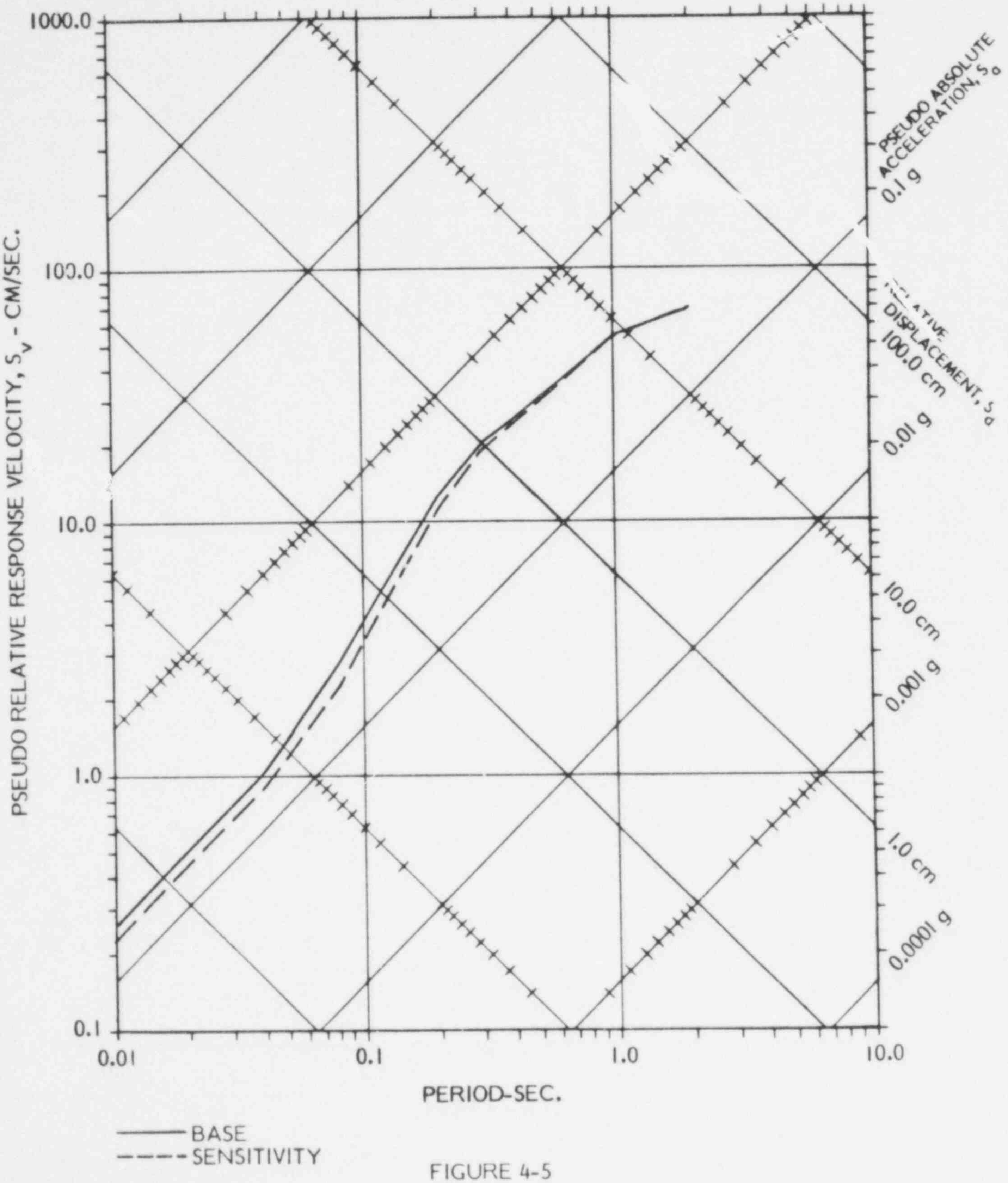

FIGURE 4-5

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1. Displacement as a function of time
2. The velocity time history
3. The acceleration as a function of time

Many strong motion accelerograms have been obtained for a number of earthquakes. These accelerograms, which give the acceleration time history of the earthquake, can be integrated (using base line corrections) to give the non-unique velocity time history. By applying a second integration, a non-unique displacement time history may be obtained. The non-uniqueness is a result of the base line corrections applied, and, while the magnitude of the maximum displacement may vary, the maximum velocity is relatively insensitive to these corrections. The displacement, velocity, and acceleration maximum values are especially important because they help to define the response motions of structures.

The maximum values of the <u>response</u> of the system are of the greatest importance to engineers. Although there are many possible ways to express the maximum values (e.g., maximum strain in the spring, maximum spring force, maximum acceleration, etc.), it is advantageous to express the maximum values by a quantity termed <u>pseudovelocity</u>. With units of velocity, the pseudovelocity (Vp) gives a measure of the maximum energy absorbed in the spring, and is defined so that the energy absorbed in the spring is $\frac{1}{2}mVp^2$. Some useful relations, as provided below, follow from this definition.

For a given particular frequency, F:

$$Vp = w\,D$$

$$Ap = w\,Vp = w^2 D$$

where D represents maximum relative displacement of the spring

Vp represents pseudovelocity

Ap represents pseudo acceleration.

Newmark and Hall have thus characterized the single-degree-of-freedom system in terms of three measures of its responses:

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1. Its maximum displacement, which is a measure of the strain in the spring element of the system
2. Its maximum pseudovelocity, which is a measure of the energy absorption in the spring of the system
3. The maximum pseudoacceleration, which is a measure of the maximum force in the spring of the system.

Newmark and Hall recognized that, because of the relations between Ap, Vp, and D, they could combine the response spectrum plots and thereby create one curve which would yield the values of Ap, Vp, and D for a given frequency. Because of the three parameters involved in the simultaneous display, the threefold plotting paper became known as tripartite paper, where the log of frequency is the abscissa and the log of Vp is the ordinate, and with the log of Ap at $+135^{\circ}$ from vertical, and the log D at $+45^{\circ}$ from vertical. Thus, any one point for a specific frequency will define the displacement (D), pseudovelocity (Vp), and the pseudoacceleration (Ap).

While actual response spectra for earthquake motions are complicated and irregular, by considering the maximum of a wide variety of motions, this approach will typically yield a trapezoidal shape for the response spectra.

This approach to spectral shape not only does not require statistical treatment of many earthquake records, it can be physically interpreted as frequency dependent. At the low frequency end, the response of such a system approaches an asymptote corresponding to the maximum value of ground displacement. Because a low frequency system corresponds to a heavy mass and light spring, when the ground moves rapidly the mass does not have time to move. Thus, the maximum strain in the spring equals the maximum displacement of the ground. For a high frequency system, the spring is stiff and the mass is light, so that when the ground moves, the stiff spring forces the mass to follow the ground movement. Thus, the mass has the same acceleration as the ground, and the maximum acceleration of the mass equals the maximum acceleration of the ground. In this case, the response spectra line approaches the maximum ground acceleration line at the high frequency side of the graph. At intermediate frequencies, there is an amplification of motion corresponding to the dynamic characteristics of the system.

Equations for spectral application factors are presented in Table 4-1. It is important to note that the acceleration amplification has an upper frequency cutoff where the acceleration response spectrum linearly returns to the maximum ground motion curve. Based on their experience and engineering judgment, Newmark and Hall have selected a frequency window, for this linear falloff, of 8 to 33 Hertz.

Damping has been mentioned only with regard to the equation of motion. Increased damping generally reduces and smoothes out the overall response spectrum. Increased damping thus tends to decrease the amplification factors shown in Table 4-2.

In computing SSRS for each of the nine sites, the UHM synthesis values of peak ground acceleration and velocity, obtained from a weighted combination of the opinions of all experts on the appropriate return period, were used to define the acceleration (PGA) and velocity (PGV) constant values. These values were then multiplied by the appropriate dynamic amplification factor (DAFA and DAFV) of Newmark and Hall, thus giving the SSRS. The defined frequency cutoff values of 8 and 33 Hertz were used, as suggested by Newmark and Hall, to linearly drop the amplified acceleration value back to its original value. The displacement part of the curve is not calculated. Figure 4-6 presents the results for a typical site at a recurrence period of 1,000 years. Three curves are shown in this figure: the UHS for comparison, the Newmark-Hall spectrum using mean amplification factors, and the Newmark-Hall spectra using mean plus one sigma amplification factors.

4.3 TIME HISTORY METHODS: REAL AND SCALED TIME HISTORY SPECTRA

As discussed in Section 2.0, a valuable and complementary approach to the development of response spectra is to perform statistical analysis on appropriate sites of strong motion records. The methods used in the SSRS study and some of the problems are discussed in this section, and the criteria implemented in this approach are defined.

TABLE 4-1

EQUATIONS FOR SPECTRUM AMPLIFICATION FACTORS FOR HORIZONTAL MOTION

Quantity	Cumulative Probability (%)	Equation
Acceleration	84.1 (One Sigma)	$4.38 - 1.04 \ln\beta$
Velocity		$3.38 - 0.67 \ln\beta$
Displacement		$2.73 - 0.45 \ln\beta$
Acceleration	50 (Median)	$3.21 - 0.68 \ln\beta$
Velocity		$2.31 - 0.41 \ln\beta$
Displacement		$1.82 - 0.27 \ln\beta$

TABLE 4-2

SPECTRUM AMPLIFICATION FACTORS FOR HORIZONTAL ELASTIC RESPONSE

Damping, % Critical	One Sigma (84.1%)			Median (50%)		
	A	V	D	A	V	D
0.5	5.10	3.84	3.04	3.68	2.59	2.01
1	4.38	3.38	2.73	3.21	2.31	1.82
2	3.66	2.92	2.42	2.74	2.03	1.63
3	3.24	2.64	2.24	2.46	1.86	1.52
5	2.71	2.30	2.01	2.12	1.65	1.39
7	2.36	2.08	1.85	1.89	1.51	1.29
10	1.99	1.84	1.69	1.64	1.37	1.20
20	1.26	1.37	1.38	1.17	1.08	1.01

NEWMARK-HALL SPECTRA COMPARED WITH SYNTHESIS

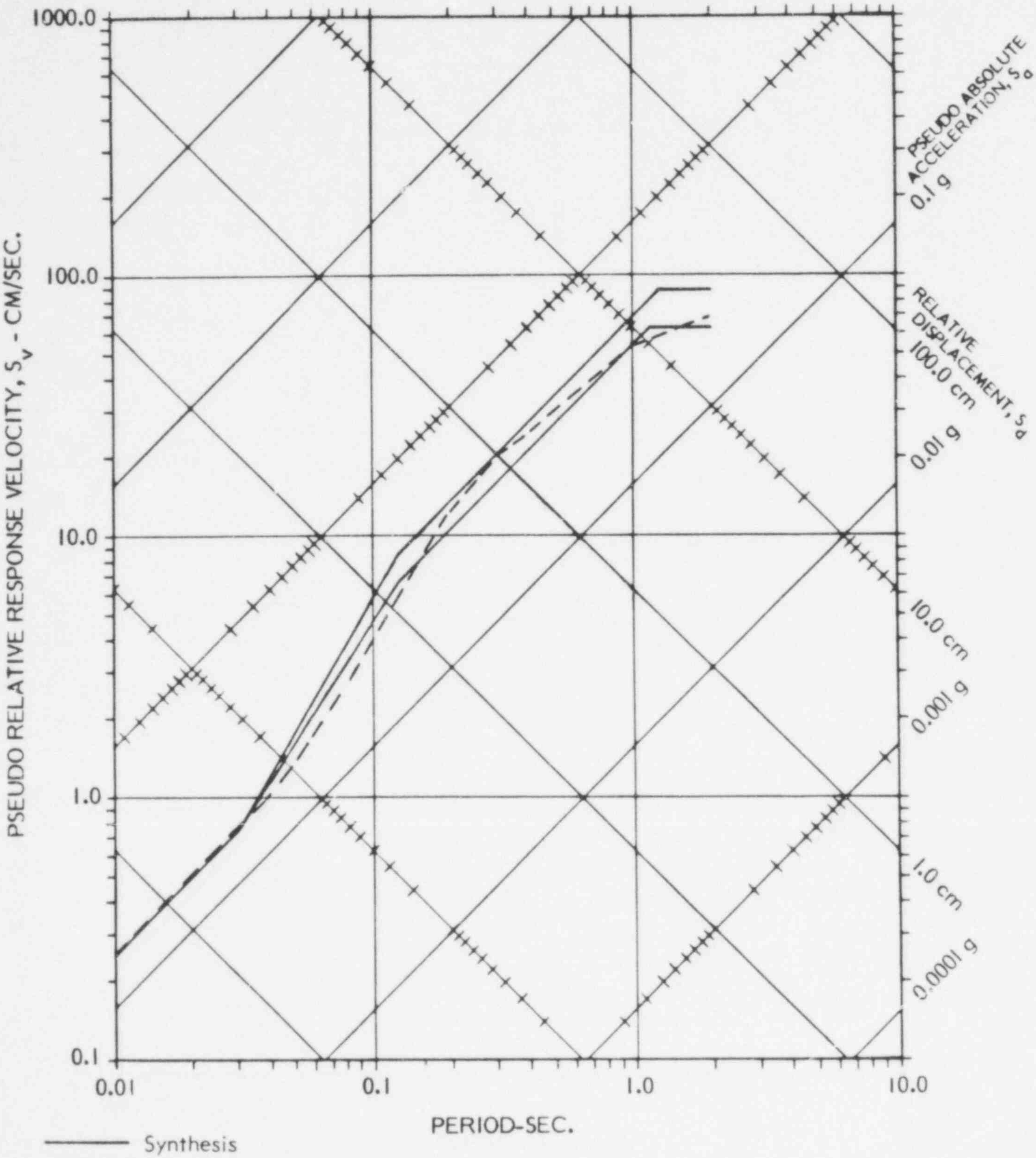

FIGURE 4-6

Selection Criteria for Earthquake Records

The real key to the validity of this approach is selecting of an adequate set of real records.

There are a number of considerations that go into the choice of records:

(1) Magnitude of the earthquake (most EUS earthquakes are specified in terms of m_b, while Western earthquakes are usually in M_L)

(2) Epicentral distance and depth of the earthquake

(3) Site type of the recording station

(4) Source parameters and focal mechanism

There is considerable uncertainty associated with each of the above parameters.

Most important is the difficulty of relating a m_b or m_{bLg} in the East to a Western m_b or M_L. Our study of available data suggests that an Eastern m_b is roughly numerically equivalent (within the uncertainty of the measurement) to a Western M_L within the range 4.8-6.3. Furthermore, NRC postulated MMI site intensities for most Eastern sites are currently considered to be VII or VIII corresponding to m_b 5.3 or 5.8. It thus appears appropriate to base the criteria on a range of m_b or M_L between 4.8 and 6.3. To extend the criteria outside this range would require more investigation into the relation between m_b and M_L.

Another difficulty has to do with the depth of the earthquakes. It is generally accepted that the depth of EUS earthquakes is less than 30 km (TERA, 1979) and thus very deep events should be excluded for suite of records.

One of the major differences between the East and the West, which relates to the site type of the recording station, is that a high shear-wave velocity rock near the surface exists in the East. There are so few records available that we must be content with having only two classifications - soil and rock. A more detailed assessment of each site is beyond the scope of this project, although the issue is getting considerable attention in the SSMRP, (Bernreuter and Chung, 1979).

Several of the questions in the UHM questionnaire dealt with possible differences in source parameters and focal mechanisms between the East and West. As TERA reported, so little is known about EUS focal mechanisms that it seems inappropriate to account for possible differences in focal mechanism between EUS and WUS. It might be possible to consider this factor at some later date when the influence of focal mechanism on strong ground motion is better understood.

A major problem with the selection of real records is that the set of real earthquake records in the range of $4.8 < M_L < 6.3$ is not a good statistical sample. First, many smaller events cause little damage and occur in remote areas. Because of their small size, we rarely get near-field recordings. Even if nearby instrumentation is triggered, the ground motion is often so small that the record is not processed. The solution to this bias problem is to expand the data set by first digitizing certain records that have not been processed and second, obtaining more data from Europe, Asia and the Middle East. A few records have been collected and processed as part of this project but budget and time considerations have limited our effort. One of the tasks of the SSMRP is to consolidate the records that have been processed. This work will be available in the near future should additional, more refined analyses be required.

Choice of Records

The previous section discussed some of the main considerations in our choice of real records. One point that was made is that although it would be useful to use both site and epicentral intensities as part of the selection criteria, it is difficult to do so because site intensities for smaller earthquakes are usually not available. In addition, in complex seismotectonic areas, such as New England, it is difficult to determine which source areas contribute most to the hazard. With these considerations, we have chosen to select four sets of records, which should cover most cases. One natural division is on site type.

The other major consideration is the earthquake magnitude and distance. The choice of the appropriate magnitude range for each site requires considerable judgment and a very careful review of the local tectonics. Because of these difficulties and the need for site specific judgment, we have covered the uncertainties by selecting two sets of magnitude ranges: $4.8 < 5.3 < 5.8$ and $5.3 < 5.8 < 6.3$. These correspond to earthquakes of intensity VII for $M_L \sim 5.3$ and intensity VII for $M_L \sim 5.8$, which covers the range of maximum site intensities expected. The one-half unit variation is to account for the uncertainty in a magnitude-epicentral intensity relation.

Our approach here was to use all of the near field records that we could obtain that fit into one of the four sets (magnitude range and site type). In general we rejected records at epicentral distances of greater than 25 km. Table 4-3 presents the records we have included in our analysis and the time they were obtained and processed.

For each of these sets we did the following:

(1) Compute the mean $E(S_v)$ for each period, assuming that the spectral ordinates are log normally distributed. Use the relations

$$E(S_v) = \exp(E(\ln Sv)) \exp(\tfrac{1}{2}\,\sigma^2_{\ln(S_v)})$$

$$E(\ln Sv) = \frac{\sum_{i=1}^{N\text{-no. of records}} (\ln Sv)_i}{N}$$

$$\sigma^2_{\ln Sv} = \frac{(\ln Sv)_i^2 - ((l_n Sv)_i)^2}{\text{sigma}}$$

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TABLE 4-3

ASSORTED EARTHQUAKE STATISTICS
"A Catalog of Earthquake Records
Used in the Time History Analysis"

(1) ID No.	Earthquake	(2) Date/Time	Station	Sta. Type	M_L	Epicentral Distance (km)	Max. Accel. (g)	Where Processed
A10	San Jose, Cal.	9-4-55	San Jose, BofA	S	5.8	10	.11	Cal Tech
A13	San Francisco	3-22-57	So.Pacific Bldg.	S	5.3	17	.05	Cal Tech
A14	San Francisco	3-22-57	Alexander Bldg.	S	5.3	15	.05	Cal Tech
A15	San Francisco	3-22-57	Golden Gate Park	R	5.3	12	.10	Cal Tech
A16	San Francisco	3-22-57	State Bldg.	S	5.3	15	.09	Cal Tech
A18	Hollister	4-8-61	Hollister City Hall	S	5.6	21	.18	Cal Tech
B21	Long Beach	3-10-33	Vernon CMP Bldg	S	6.3	40[3]	.16	Cal Tech
B25	Helena	3-10-33	Carroll College	R	6.0	7	.15	Cal Tech
B34	Parkfield	6-27-66	Cholame #5	S	5.5	5[4]	.43	Cal Tech
B35	Parkfield	6-27-66	Cholame #8	S	5.5	9[4]	.28	Cal Tech
B37	Parkfield	6-27-66	Temblor	R	5.5	6[4]	.35	Cal Tech
T292	Imperial Valley	12-16-55	El Centro	S	5.4	22	.07	Cal Tech
U299	Santa Barbara	6-30-41	Santa Barbara	S	5.9	16	.24	Cal Tech
U307	Central Cal.	1-19-60	Hollister Library	S	5.0	6	.06	Cal Tech
U309	Central Cal.	4-8-61	Hollister Library	S	5.5	21	.17	Cal Tech
V315	Long Beach	3-10-33	Long Beach Util. Bldg.	S	6.3	27[3]	.20	Cal Tech
V316	Torrance-Gardena	11-14-41	Long Beach Util. Bldg.	S	5.4	6	.06	Cal Tech
V317	Torrance-Gardena	11-14-41	LA Chamber Comm.	R	5.4	27[5]	.02	Cal Tech
V329	S. Calif.	3-18-57	Pt. Hueneme	S	5	6	.17	Cal Tech
W334	Lytle Creek	9-12-70	6074 Park Dr. Wright.	R	5.4	13	.20	Cal Tech
W335	Lytle Creek	9-12-70	Allen Ranch	R	5.4	19	.07	Cal Tech
W338	Lytle Creek	9-12-70	Hall of Rec, San Bdo	S	5.4	18	.12	Cal Tech
Ap8/8	Oroville	8-8-75/0700	Oroville Airport	S	4.9	less than 20	.08	USGS/LLL
S78/8	Oroville	8-8-75/0700	Station 7	S	4.9	less than 20	.16	USGS/LLL
S68/8	Oroville	8-8-75/0700	Station 6	R	4.9	less than 20	.11	USGS/LLL

TABLE 4-3

(CONT.)

(1) ID No.	Earthquake	(2) Date/Time	Station	Sta. Type	M_L	Epicentral Distance (km)	Max. Accel. (g)	Where Processed
S89/27	Oroville	9-27-75	Station 8	R	4.6^6	less than 20	.17	USGS/LLL
S99/27	Oroville	9-27-75	Station 9	R	4.6^6	less than 20	.07	USGS/LLL
Jap4/5	Japan	4-5-66	M-53	S	5^7	less than 10	.60	FUGRO
Jap8/3	Japan	8-3-66	M-262	S	5^7	less than 10	.23	FUGRO
Wak/r	Japan	4-5-66	Wakaho	S	5^7	less than 10	.27	FUGRO
Tol38	Friuli	5-6-76	Tolmezzo	R	6.2	27	.37	CHEN/LLL
Tol54	Friuli	5-9-76	Tolmezzo	R	5.5	22	.04	CHEN/LLL
Tol64	Friuli	5-11-76	Tolmezzo	R	5.3	13	.03	CHEN/LLL
Roc132	Friuli	9-11-76/1631	S. ROCCO	R	5.5	16	.07	CHEN/LLL
Roc139	Friuli	9-11-76/0315	S. ROCCO	R	6.1	9	.12	CHEN/LLL
Roc169	Friuli	9-15-76/0921	S. ROCCO	R	6.0	19	.23	CHEN/LLL
FC59	Friuli	5-11-76/2244	Forgaria-Corn.	S	5.3	10	.31	CHEN/LLL
FC131	Friuli	9-11-76/1631	Forgaria-Corn.	S	5.5	16	.12	CHEN/LLL
Tar133	Friuli	9-11-76/1631	Tarcento	S	5.5	8	.20	CHEN/LLL
FC138	Friuli	9-11-76/1635	Forgaria-Corn.	S	5.9	15	.24	CHEN/LLL
B143	Friuli	9-11-76/1635	Buia	S	5.9	14	.23	CHEN/LLL
B156	Friuli	9-15-76/0315	Buia	S	6.1	6	.11	CHEN/LLL
FC152	Friuli	9-15-76/0315	Forgaria-Corn.	S	6.1	10	.26	CHEN/LLL
B160	Friuli	9-15-76/0438	Buia	S	5.0	7	.04	CHEN/LLL
FC157	Friuli	9-15-76/0438	Forgaria-Corn.	S	5.0	14	.06	CHEN/LLL
FC168	Friuli	9-15-76/0921	Forgaria-Corn.	S	6.0	20	.35	CHEN/LLL
B177	Friuli	9-15-76/0921	Buia	S	6.0	19	.10	CHEN/LLL

(1) ID assigned at processed location

(2) time only given if needed to define EQ

(3) left in because strong record and very few of M=6.3

(4) used distance from fault for Parkfield

(5) left in because Rock records - very few rock records

(6) used to get added rock records

(7) approximate magnitude

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(2) Compute the 84th percentile spectra

$$Sv = \exp.(E(\ln Sv)) \exp.(\sigma_{\ln(S_v)})$$

(3) Scale each spectra to 1-g and repeat steps (1) - (2) for the scaled records.

In Figures 4-7 through 4-10, we present the results of these analyses. Each figure presents four curves, the mean and mean plus one sigma for each site condition, rock or soil. The first two figures present the Real Time History Spectra for selected records with means of 5.3 and 5.8 magnitude. The second two figures present anologous results for the Scaled Time History Spectra. For ease of comparison the scaled records are presented scaled to 1.0 g acceleration at 100 Hz. In subsequent comparisons with the UHS, the scaled mean spectra were then scaled to the acceleration corresponding to the 200, 1,000 and 4,000 year return period for each site.

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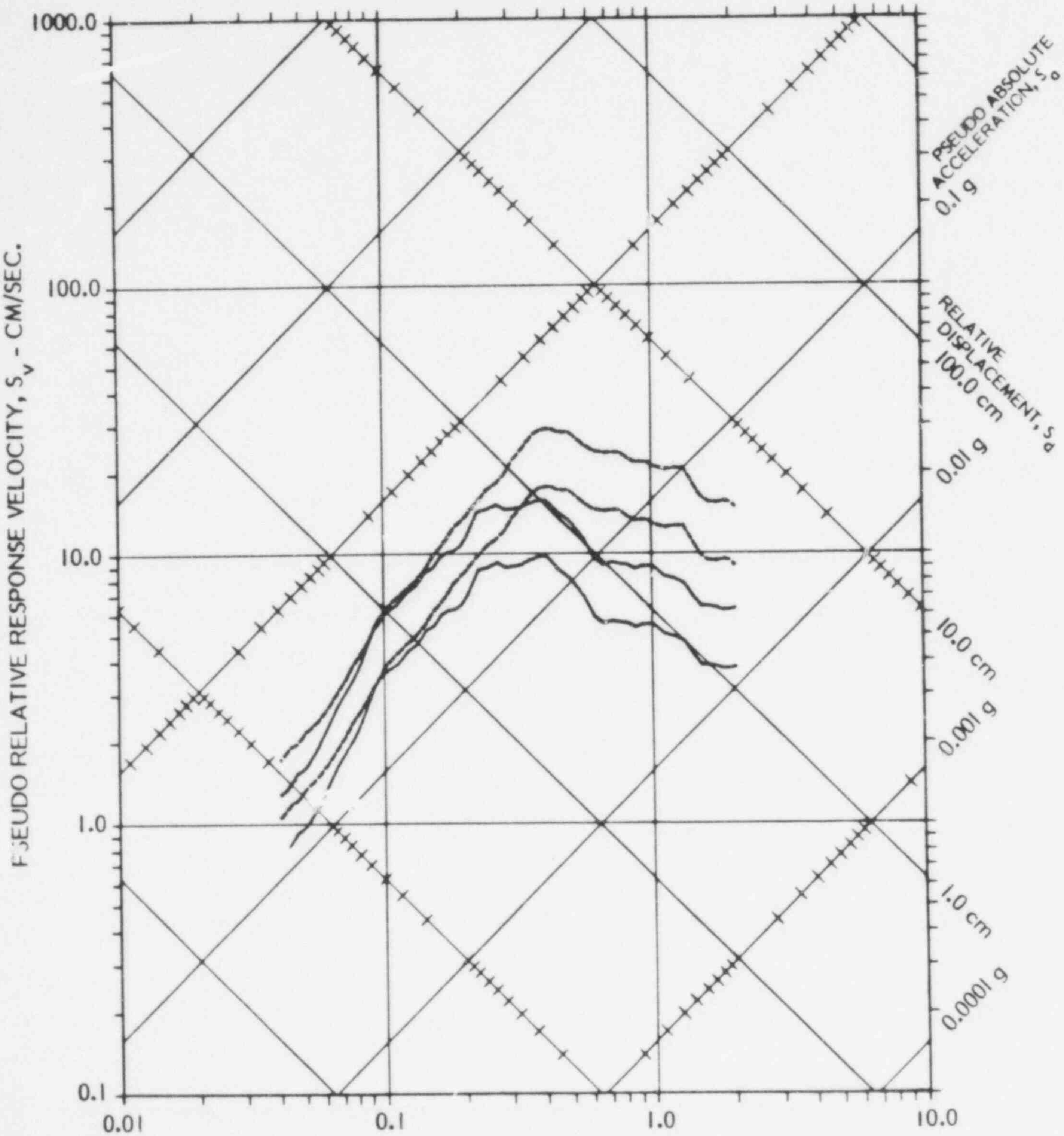
COMPARISON OF REAL TIME HISTORIES AT MAG = 5.3



ROCK ———
SOIL - - - -

FIGURE 4-7

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COMPARISON OF REAL TIME HISTORIES AT MAG = 5.8

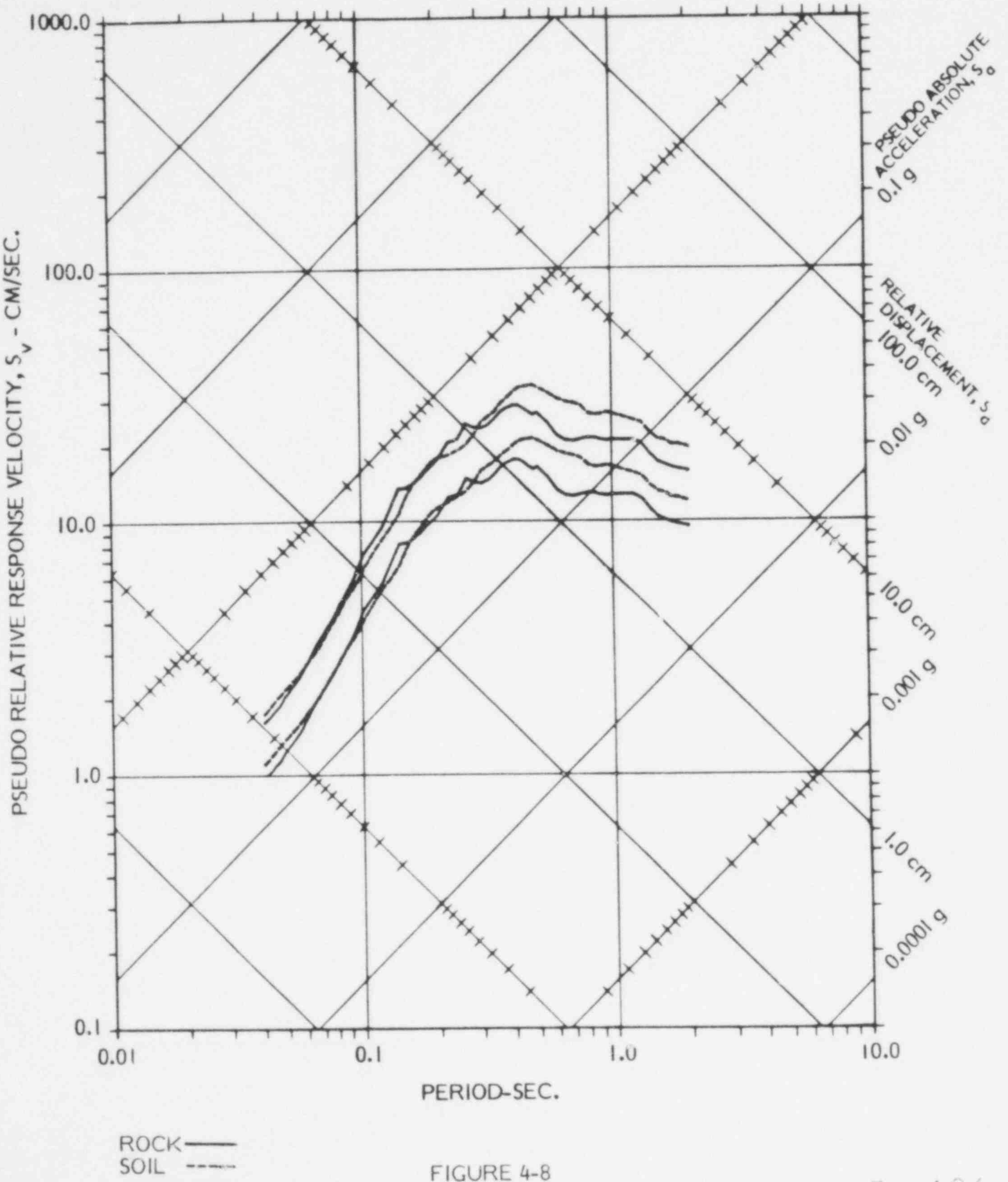

FIGURE 4-8

COMPARISON OF SCALED TIME HISTORIES AT MAG = 5.3

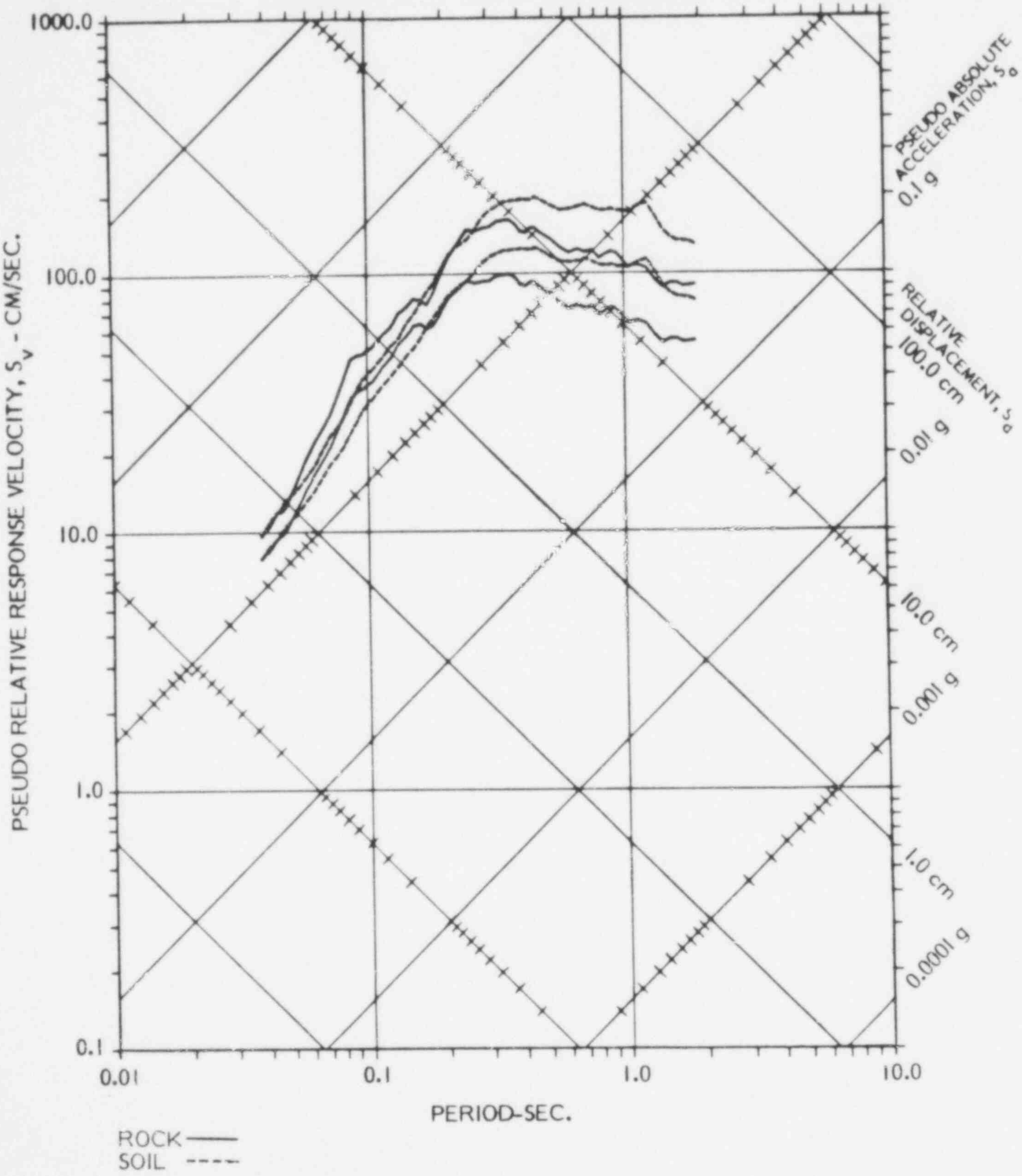

FIGURE 4-9

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COMPARISON OF SCALED TIME HISTORIES AT MAG = 5.8

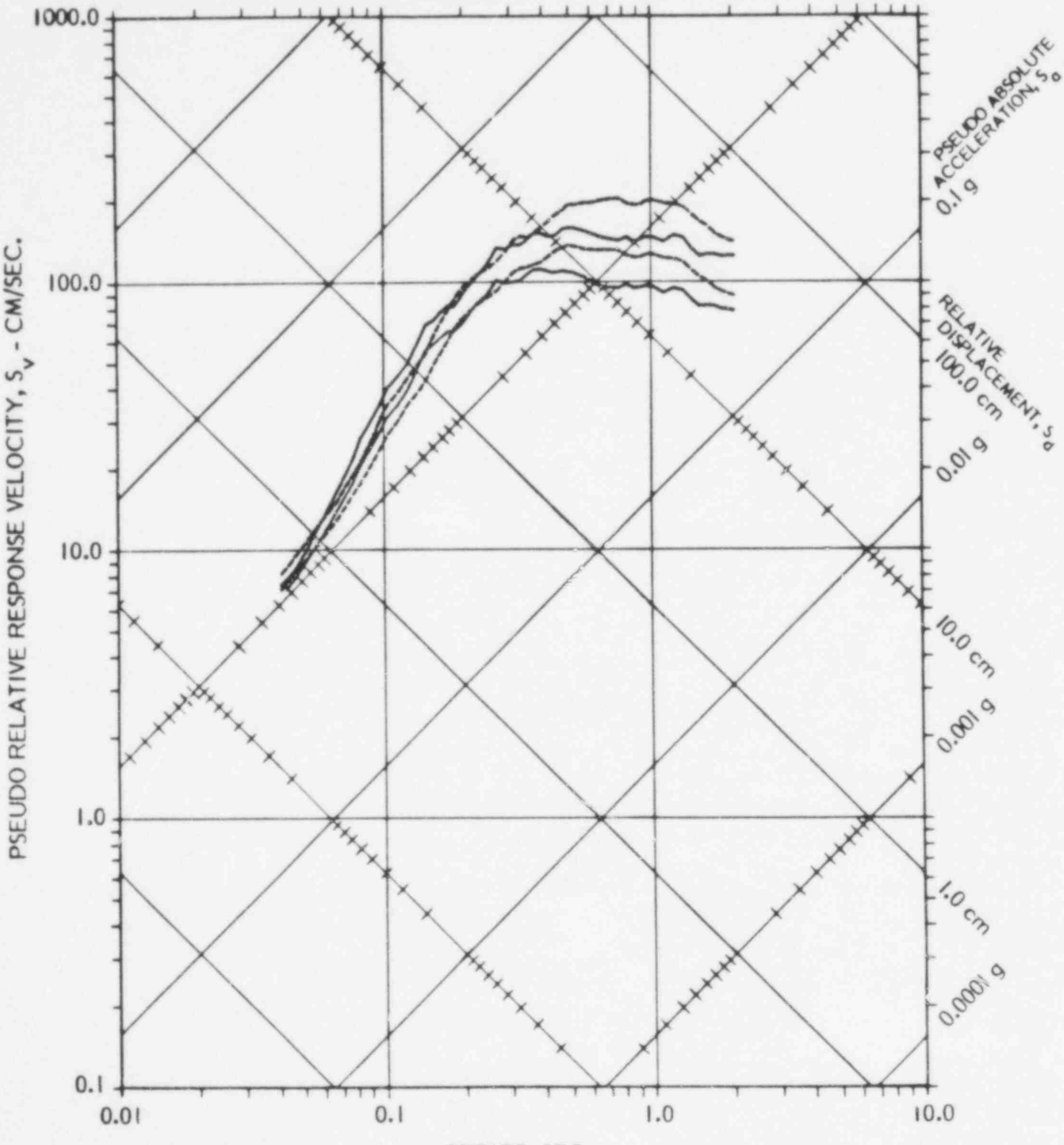

FIGURE 4-10

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5.0 ATTENUATION

The difficulty in quantifying attenuation in the Eastern United States (EUS) results from the almost complete absence of strong-motion data. Inferences thus must be made about the attenuation of ground motion in the East by studying systematic differences or similarities between the EUS and other regions of the world regarding information that is indirectly related to ground motion such as intensity data.

As a preliminary attempt to focus on the problem of attenuation in the EUS, it is valuable to list evidence that may shed some light on the differences or similarities between ground motion attenuation in the EUS and the Western United States (WUS). For instance:

- MM intensity attenuates slower in the EUS than in the WUS, based on an abundance of historic intensity data.
- A comparison of ground motion data from the 1968 Illinois earthquake and nuclear blast data recorded in the EUS with similar data in the WUS suggests that the rate of attenuation of PGA in the far field may be the same for both regions.
- There are higher propagation velocities at depth in the EUS than in the WUS.
- There are higher Q-values (lower damping) in the EUS than in the WUS.
- There is no low Q-zone in the upper mantle in the EUS.
- There are systematic differences among magnitude determinations between the EUS and WUS.

Some inferences concerning differences in ground motion characteristics between these two regions may be made from the above evidence. They can tentatively be quantified in terms of differences in frequency content, amplitude and duration of the motion.

- The relative damageability of ground motions in the far field as compared to the near field is greater in the EUS than in the WUS. This implies a relatively larger energy content and
    - (a) larger accelerations, or
    - (b) longer durations, or
    - (c) both (a) and (b)
- The relative contribution of body waves at the larger distances is greater in the EUS. This implies higher amplitudes and longer durations at distance.
- The EUS may be a more efficient propagator of surface waves than the WUS. This would imply relatively longer durations and larger long-period motions in the EUS.
- There may be fewer complexities in the transmission path in the EUS. This could explain in part the lower damping inferred in the EUS. It might imply less scattering of waves, making the EUS a relatively more efficient propagator of the higher frequency motions.
- Since there are more competent rocks at depth in the EUS, earthquake foci may be deeper. This might imply lower attenuation of ground motion as compared to the WUS at distances less than several focal depths. This would not explain differences in attenuation at greater distances.
- Source parameters relative to the "size" of an earthquake may be different in the EUS than in the WUS. The higher competency of the rock and lack of major well developed fault zones might imply higher stress drops and smaller source dimensions in the EUS.

It is interesting to note that some theoretical evidence suggests that source strength parameters (e.g., stress drop) and Q-values may not directly affect the rate of decay of ground motion values among regions. This shows that the energy content, which can be related to peak accelerations, is directly proportional to both stress drop and Q. This suggests that the rate of decay of acceleration may be merely a function of geometrical spreading.

5.1 APPROACH

It would seem that, aside from theoretically modeling, there is only one alternative to EUS attenuation, given the paucity of strong motion data and availability of intensity data. This approach consists of developing a model for the attenuation of site intensity using EUS intensity data then to use existing EUS strong motion data in conjunction with data from the West to convert the site intensity into a ground motion parameter. The ground motion parameters chosen for this analysis are peak ground acceleration (PGA), peak ground velocity (PGV), and several spectral ordinates at frequencies ranging from 25 HZ to 0.5 HZ. In addition, the site intensity is also retained as an additional measure of the ground motion. As discussed elsewhere, we have calculated the seismic hazard at specific sites, using 10 separate sets of input, corresponding to the data and opinion, provided by 10 experts. Many of the experts preferred to deal with seismic hazard in terms of epicentral intensity, and our attenuation relation as described above is appropriate for use with these experts input. Other experts preferred body-wave magnitude, and for these experts we factor out epicentral intensity as a parameter in the attenuation model using a correlation between body wave magnitude and epicentral intensity.

The strength of this approach is that it specifically models the EUS by explicitly incorporating EUS intensity attenuation. The only basic assumption is that site intensity-ground motion correlations are regionally independent.

One weakness of this approach has to do with portioning an attenuation model into submodels. The uncertainty contained in each of the submodels increases the uncertainty in the final prediction, although at the present time there does not appear to be any rational alternative to this.

The added uncertainty has a singificant influence on the seismic hazard results and we are confident that greatly improved estimates of the seismic hazard could be obtained through additional work on this topic. When an attenuation model is derived <u>directly</u> from recorded ground motion, the statistical uncertainty usually corresponds to a one-standard deviation level corresponding to 1.6-2.0 times the mean. When the uncertainty in mean predictions of intermediate parameters, such as intensity, are rigorously included, this multiplicative factor becomes 2.0-2.9 (Cornell, et al., 1977). Clearly, a hazard analysis which integrates out to a 2 or 3 standard deviation ground motion is being driven by this multiplicative factor. While it has been outside the scope of this effort to address this uncertainty in detail, we feel that these uncertainties may be excessive. That is, in spite of their statistical formality, they are derived from data representing all possible earthquake types and all possible travel paths. The seismic hazard at a particular site is usually dominated by a particular type of earthquake (e.g., magnitude range, depth, focal mechanism, etc.), with a particular travel path. We believe that a detailed consideration of this would significantly reduce the attenuation model uncertainty. In the meantime, however, we are forced to rely on a formal statistical definition of the uncertainty. Consistent with the uncertainty contained in each of the submodels for attenuation, we use a value for dispersion or uncertainty of a multiplicative factor of 2.45. Since the data are generally assumed to be lognormally distributed, this is often expressed as a natural logarithan additive factor of ln (2.45) = 0.9. A further basis for this particular value is contained in the work done for TVA by Weston Geophysical, Inc. (1978).

Another weakness is that the infuence of site geology on the predicted site ground motion is more difficult to quantify when the intensity data is incorporated. In the past, several investigators have attempted to quantify site geology effects by including geology (e.g., soil, rock) as a parameter in the regression between ground motion and site intensity. The difficulty in this is that the majority of intensity reports are reports for soil conditions at a location nearby to an accelerograph station. The conventional procedure has been to adjust the intensity report for the difference in location and to then associate this adjusted intensity with the recorded ground motion at the accelerograph site. At best, this approach for characterizing site effects is circular and results in a systematic bias toward soil response. Our appraoch is similar to the one taken by Murphy and O'Brian (1977). Since almost all intensity data corresponds to soil intensity data, we assume that a correlation between site intensity and recorded ground motion will be most representative of soil, and that the intensity data alone are inadequate to quantify a corresponding model for rock. We feel that the best way to accurately define a rock model is through Western

U.S. data for ground motion as a function of distance, magnitude, and site type. None of the intensity biasing problems discussed above exist for this data set, although we acknowledge there are other potential biases such as building foundation effects (Boore, et al., 1978). The data currently available are insufficient to resolve at this level of detail and we, in the end, rely on the overall "reasonableness" of the rock model as a last check. We present the detailed results on our treatment of site geology in a following section, following a summary presentation of the strong motion data base used for analysis.

Summarily, our appraoch to attenuation is to combine EUS intensity attenuation data with WUS instrumental data relating site intensity to a ground motion parameter. When required for compatibility with a particular expert's input, epicentral intensity is converted to body wave magnitude. The resulting attenuation model is considered to be appropriate for soil sites. A scale factor is then developed for WUS data for each ground motion parameter to convert the soil prediction to a rock prediction.

5.2 DATA BASES

As previously discussed, there are two data bases required for our analyses; non-instrumental EUS intensity attenuation data and instrumental WUS strong motion-intensity data. Each is discussed separately below.

INTENSITY DATA BASE

The objective of analysis on this data base is to characterize the rate of intensity attenuation. Given this, the ideal data base consists of an error free set of all site intensities from the epicentral value down to MMI I or II. Furthermore, this ideal data would represent a variety of epicentral intensities. For a number of reasons, this ideal cannot be achieved. First of all, the intensity data is not generally reported in this detail; most commonly, only the isoseismal contours are published. Even when the actual intensity values are available, the

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data are strongly biased toward the higher intensities. This is because it is very difficult to discriminate the intensity reports between I and III and, therefore, these data are almost always reported as an aggregate. This virtually eliminates the smaller earthquakes (epicentral intensity less than V or VI as candidates for the data base.

We have examined all possible sources for this data and have found only four earthquakes that meet the above criteria. These earthquakes and their sources are tabulated in Table 5-1. As will be described in a following section, we infer an intensity attenuation model from the results of regression analysis on the intensity data from these earthquakes. Although it would, of course, be desirable to base the model on additional data, we are not aware of any other available data. Furthermore, we know of no other attenuation model which was based on the actual intensity reports (rather than the isoseismal radii) that uses this many earthquakes. Finally, it is notable that the epicentral intensity of these four earthquakes covers the range of design earthquakes considered to be appropriate for the sites under consideration here.

STRONG MOTION DATA BASE

The requirements of this data set are that it:

- Be readily available
- Be credible and have precedent in application
- Include the digitized time histories and, therefore, the spectral ordinates
- Include an estimated site intensity at the accelerograph station
- Cover a range of distances, magnitudes, and site intensities

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TABLE 5-1

SUMMARY OF EARTHQUAKES USED IN THE INTENSITY DATA BASE

Name	Date	Maximum Intensity	Data Source
Southern Illinois	11/9/1968	VII	G. A. Bollinger
Cornwall-Massena	9/4/1944	VII	R. J. Holt
Ossippee	12/20/1940	VII	R. J. Holt
Giles County	5/31/1897	VII-VIII	G. A. Bollinger

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We have reviewed several candidate data bases and have concluded that the Trifunac and Brady data base (1976) best meets this overall criteria. Most important in this evaluation was the fact that their data base has been extensively used by the NRC in the siting of critical facilities. Furthermore, the data base has been subjected to statistical analysis by several investigators besides Trifunac (e.g., Werner, et al., 1975 or Krinitzsky and Chang, 1975), thus providing a convenient basis for comparison.

The original base included a site geology descriptor as "soft", "intermediate", or "stiff". Such a descriptor will be crucial to us in certain site specific analysis. We feel, however, that it is unnecessary to have such resolution into the site geology and that furthermore, the data is generally incapable of providing this resolution. We have, therefore, converted all site geology classifications in the data base to simply "soil" or "rock" according to the criteria presented by Boore, et al. (1978). For completeness, all the resulting "rock" accelerograms are presented in Table 5-2 according to the CIT record ID number.

EFFECT OF SITE GEOLOGY

Ass discussed above, it is very important to account for the effects of site geology although an approach that relies on site intensity cannot, by itself, accomplish this. Our approach is to predict the soil response at a site and then to correct this prediction by a multipicative factor for rock sites. This factor was derived from a regression analysis on the same data base that was used to predict response as a function of site intensity, but the independent variables were instead magnitude distance, and site geology (soil=0, rock=1). The coefficient derived from the regression analysis for the "dummy variable", site geology, corresponds to the desired muliplicative factor. This appraoch is, of course, not new; it has been applied by several other investigators to slightly different data bases (e.g., McGuire, 1978 or Trifunac, 1976). We are aware of some subtle biases that may effect the statistical conclusions here. For example, as Boore, et al. (1978) have pointed out, there is a cross-correlation between the site type and the type of building that houses the accelerometer. The data at this time is insufficient to separate these effects.

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TABLE 5-2

LIST OF CIT ACCELEROGRAMS RECORDED ON ROCK SITES

CIT Record ID Number	Earthquake Date
15	3/22/57
25	10/31/35
37	6/27/66
38	6/27/66
40	4/8/68
41	2/9/71
54	2/9/71
56	2/9/71
78	2/9/71
81	2/9/71
92	2/9/71
102	2/9/71
106	2/9/71
142	2/9/71
143	2/9/71
144	2/9/71
166	2/9/71
171	2/9/71
179	2/9/71
183	2/9/71
184	2/9/71
185	2/9/71
198	2/9/71
207	2/9/71
208	2/9/71
221	2/9/71
223	2/9/71
241	2/9/71
265	2/9/71
295	10/31/35
297	10/25/35
314	3/10/33
317	11/14/41
319	11/21/52
331	7/15/65
334	9/12/70
335	9/12/70
378	4/8/68

The regression was performed for a set of dependent variable corresponding to peak ground acceleration (PGA), peak ground velocity (PGV) and spectral ordinates (PSA) at nine frequencies (25, 20, 12.5, 10, 5, 3.3, 2.5, 1.0, 0.50, Hz). The results of regression analysis are shown in Table 5-3, which presents the multiplicative factor as a function of frequency. This factor was directly applied to the corresponding predicted soil response when rquired for a rock prediction. Note that these results are not at all inconsistent with previous investigations into the effects of site type and furthermore, appear to be intuitively very reasonable.

INTENSITY ATTENUATION

The intensity attenuation model used in this analysis was derived from the intensity data base described above. Recall that this data base is unique in that it consists of the actual intensity reports rather than simply the isoseismal radii. There are two advantages to using the actual reported intensity data. First, isoseismal radii data, which is more readily available, is the result of a seismologist's opinion or judgement on a set of intensities. The algorithms for constructing the contours are non-uniform and non-rigourous, and furthermore the representation of a complex contour by a single radius involves another layer of judgement and uncertainty. Second of all, using the actual intensity data allows statistical statements to be made about the variability of intensity. This cannot readily be done with isoseismal radii.

Each of the earthquakes listed in Table 5-1 have been analyzed by other investigators, and the results of these analyses form the basis for our attenuation model. Figure 5-1 shows the individual intensity attenuation relations for each of the earthquakes, normalized to the same epicentral intensity. Note that although these earthquakes occurred in different tectonic settings, and were felt over a variety of geologies, the average intensity attenuation is not greatly different.

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TABLE 5-3

SUMMARY OF REGRESSION ON SITE GEOLOGY

(S: soil=0, rock=1)

$$\log(GM) = C_1 + C_2 M + C_3 \log(r) + C_4 S$$

GM	Units	Frequency (H_2)	C_4
PGA	cm/s^2	---	*
PSA	cm/s^2	25.0	*
PSA	cm/s^2	20.0	0.042
PSA	cm/s^2	12.5	0.074
PSA	cm/s^2	10.0	0.089
PSA	cm/s^2	5.0	0.039
PSA	cm/s^2	3.3	-0.038
PSA	cm/s^2	2.5	-0.069
PSA	cm/s^2	1.0	-0.169
PSA	cm/s^2	0.5	-0.192
PGV	cm/s	---	-0.138

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* Statistically insignificant coefficient

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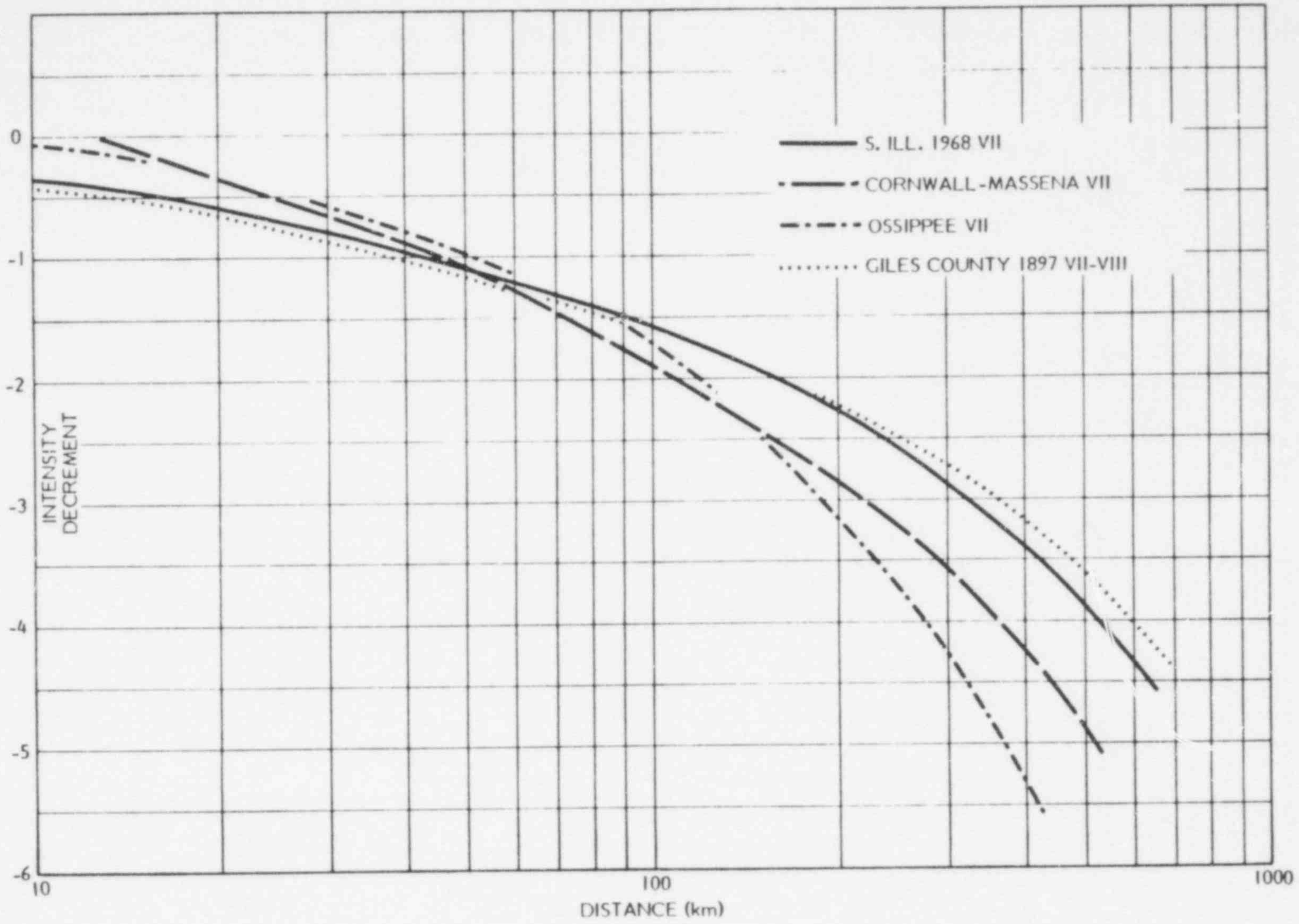

FIGURE 5-1

INTENSITY ATTENUATION RELATIONSHIPS

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Given a goal of defining an overall average attenuation model, two options are presented by this data. First of all, one could combine all the individual data from each of the earthquakes and perform regression on the aggregate data set. Alternatively, one could select a typical earthquake with a typical attenuation relative to the others. We prefer the latter approach because the data from the individual earthquakes is of variable quality depending on the date of the earthquakes, the population density, etc. Among this four, the 1968 Southern Illinois earthquake is probably the best studied earthquake because of its recency and because of the population density in the area. For these reasons, and because its attenuation appears to be most typical, we have selected this earthquake's attenuation as the attenuation model appropriate for this analysis.

Making the common assumption of linear scaling between epicentral intensities, the resulting attenuation function takes the form:

$$I_s = I_o + 0.35 - .0046r - .313 \ln(r)$$

where: r is in kilometers.

The next section describes how this predicted site intensity is converted to a ground motion parameter.

GROUND MOTION - SITE INTENSITY

The strong motion data base described above was used to develop a correlation between various ground motion parameters and site intensity for soil sites. A great deal of work has been performed by other investigators in relating, say, peak ground acceleration to site intensity. Figure 5-2 shows a graphical representation of some of these relations. In reviewing these previous efforts, we concluded that application of relations like these to EUS sites would have one major shortcoming; this is, they could not account for the difference between the accelerations for a site intensity VIII at 1,000 km and one at 10 km. This is

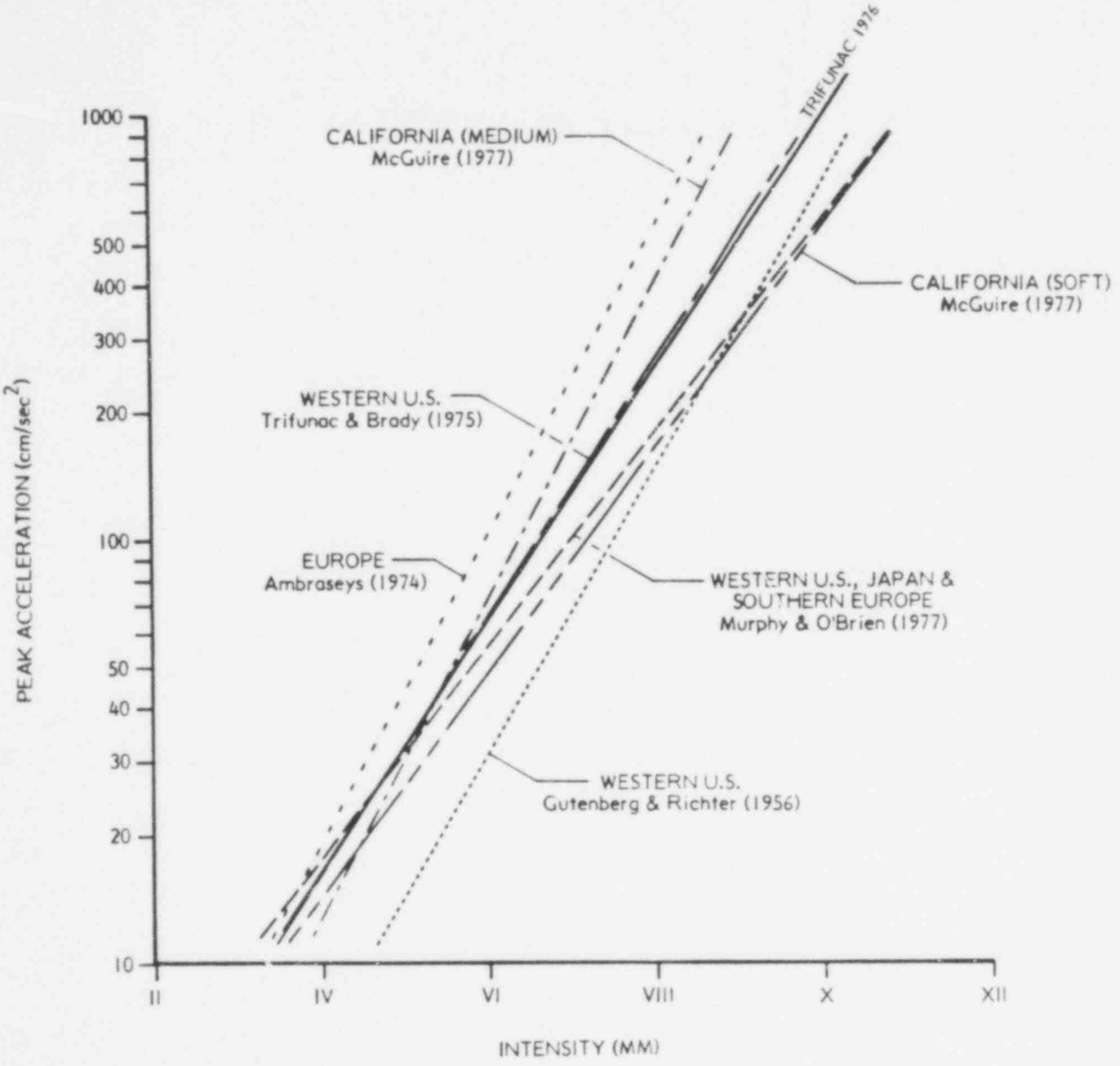

FIGURE 5-2

COMPARISON OF SITE INTENSITY-ACCELERATION RELATIONS

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very important in the EUS since the rate of intensity attenuation is so slow compared to WUS. As a result of this consideration, we concluded that a more rational approach would include distance as an independent variable. The functional form used in regression was, therefore,

$$GM = F(I_s, r)$$

where: GM corresponded to PGA, PGV, and PSA at the nine frequencies summarized above.

The results of the regression analysis are given in Table 5-4. For purposes of comparison with a similar analysis on PGA with a different data base, we present our predictions compared to those of McGuire (1978) in Figure 5-3. Figure 5-4 shows how the predicted spectral shape varies with site intensity and distance in this model. Note that, unlike other generally available models, this model allows the spectral shape to vary with distance and size, and that the predicted variation is intuitively consistent.

INTENSITY - MAGNITUDE

We occasionally require an attenuation relation in terms of body-wave magnitude. When this is the case, we need a relation relating these two items. It is well known that intensity is a poor measure of the size of an earthquake and therefore, particular care must be taken in constructing this relationship. It was for this reason that we solicited expert opinion from the expert panel on this subject. The general feedback from the experts was that the relation

$$I_o = 2\,m_b - 3.5$$

was the most appropriate. This relation, or a close approximation to it, had been derived separately for both Central U.S. (Nuttli, 1974) and Northeastern U.S. (Street and Turcotte, 1977). Furthermore, in both cases, the epicentral intensities used in the correlation were derived not just from the epicentral

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TABLE 5-4

SUMMARY OF REGRESSION RESULTS

$$\ln(GM) = C_1 + C_2 I_s + C_3 \ln(r)$$

I_s - MMI
r - kilometers

GM	Units	Frequency (H_2)	C_1	C_2	C_3
PGA	cm/s^2	--	1.79	.57	-.323
PSA	cm/s^2	25.0	2.16	.55	-.37
PSA	cm/s^2	20.0	2.30	.55	-.393
PSA	cm/s^2	12.5	2.64	.56	-.437
PSA	cm/s^2	10.0	2.79	.56	-.432
PSA	cm/s^2	5.0	2.67	.56	-.312
PSA	cm/s^2	3.3	2.05	.62	-.240
PSA	cm/s^2	2.5	1.37	.649	-.143
PSA	cm/s^2	1.0	-1.50	.816	.155
PSA	cm/s^2	0.5	-3.50	.886	.338
PGV	cm/s	--	-2.94	.76	.06

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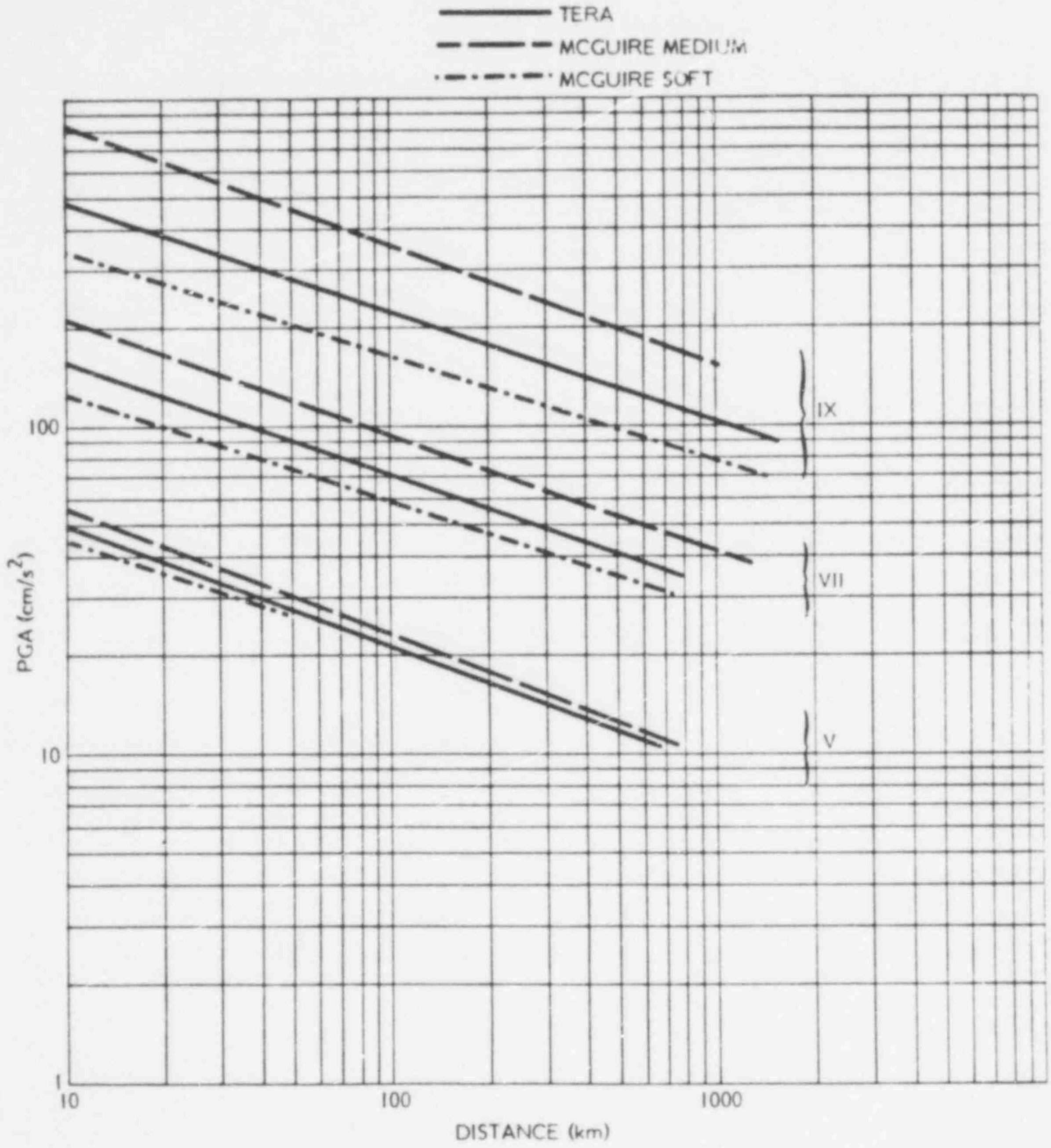

FIGURE 5-3

COMPARISON WITH OTHER ANALYSES

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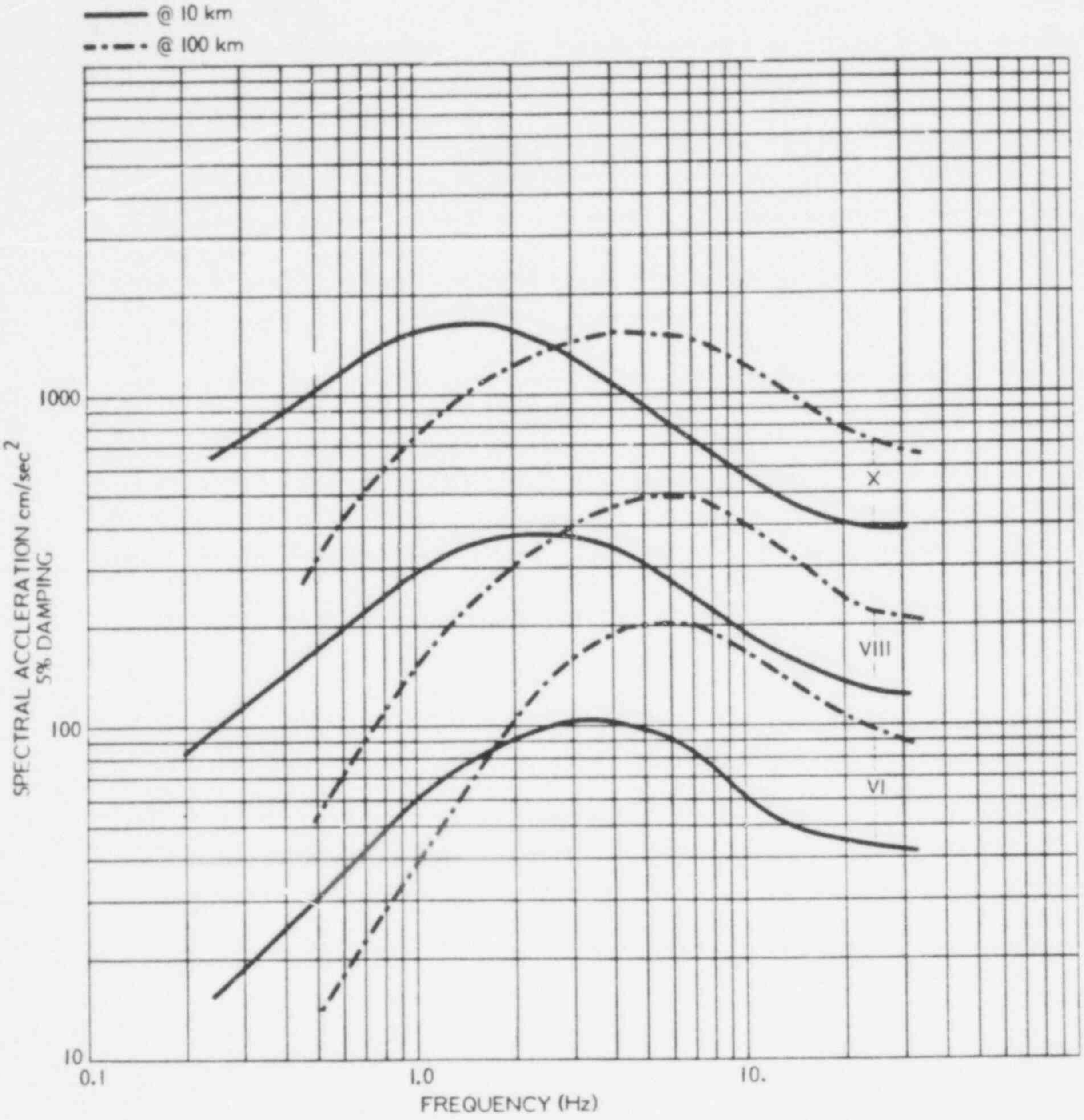

FIGURE 5-4

COMPARISON OF SPECTRAL ORDINATES FOR VARIOUS MMI$_{site}$

value but also such measures as the rate of intensity fall off or the area under the intensity V isoseismal contour. Figure 5-5 compares this relation (labeled "experts") with several other relations for other areas.

FINAL ATTENUATION RELATION

Each of the previously discussed relations were combined to produce a final attenuation relation for soil sites of the form

$$\ln(GM) = C_1 + C_2 I_o + C_3 r + C_4 \ln(r)$$

(When required for a particular expert's input, I_o was converted to m_b through the previously discussed relation.) The ground motion (GM) parameters were PGA, PGV, and PSA at nine frequencies between 25 Hz and 0.5 Hz. The results of this combination of regression results is presented in Table 5-5. Figure 5-6 presents a graphical summary of the attenuation model for various values of m_b.

SCALING TO OTHER DAMPING VALUES

As described above, we have developed attenuation laws for, among other parameters, the 5% damped PSA spectral ordinates. Because of the time and cost in performing the seismic hazard analyses, we have restricted the hazard analyses to using this 5% damped attenuation law. Because the spectral ordinates at other damping values could be of considerable interest, we have developed a scaling law for converting the results of the hazard analysis to other damping values.

The approach was to perform regresion analysis on the same strong motion data base as described elsewhere in this report. The regresion was of the form

$$\ln(GM) = F(I_s, r, \Delta)$$

where: Δ is the decimal fraction damping and GM is the PSA at nine frequencies.

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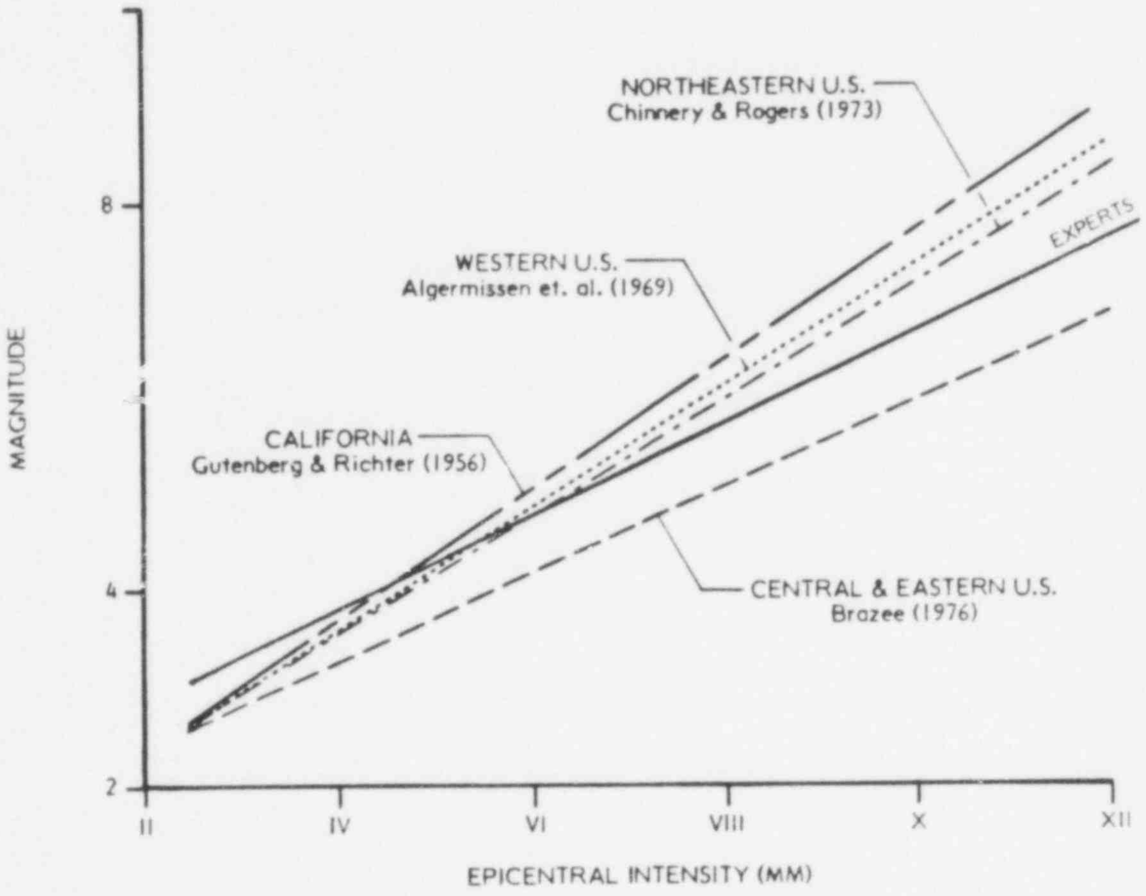

FIGURE 5-5

COMPARISON OF MAGNITUDE-INTENSITY RELATIONS

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TABLE 5-5

SUMMARY OF REGRESSION RESULTS

$$\ln (GM) = C_1 + C_2 I_o + C_3 r + C_4 \ln(r)$$

I_o - MMI
r - kilometers

GM	Units	Frequency (H_2)	C_1	C_2	C_3	C_4
PGA	cm/s^2	--	1.98	.57	-.0026	-.501
PSA	cm/s^2	25.0	2.35	.55	-.0025	-.542
PSA	cm/s^2	20.0	2.49	.55	-.0025	-.565
PSA	cm/s^2	12.5	2.84	.56	-.0026	-.612
PSA	cm/s^2	10.0	2.98	.56	-.0025	-.605
PSA	cm/s^2	5.0	2.87	.56	-.0026	-.487
PSA	cm/s^2	3.3	2.27	.62	-.0028	-.433
PSA	cm/s^2	2.5	1.60	.65	-.0030	-.346
PSA	cm/s^2	1.0	-1.21	.816	-.0038	-.100
PSA	cm/s^2	0.5	-3.19	.886	-.0041	.061
PGV	cm/s	--	-2.67	.76	-.0035	-.178

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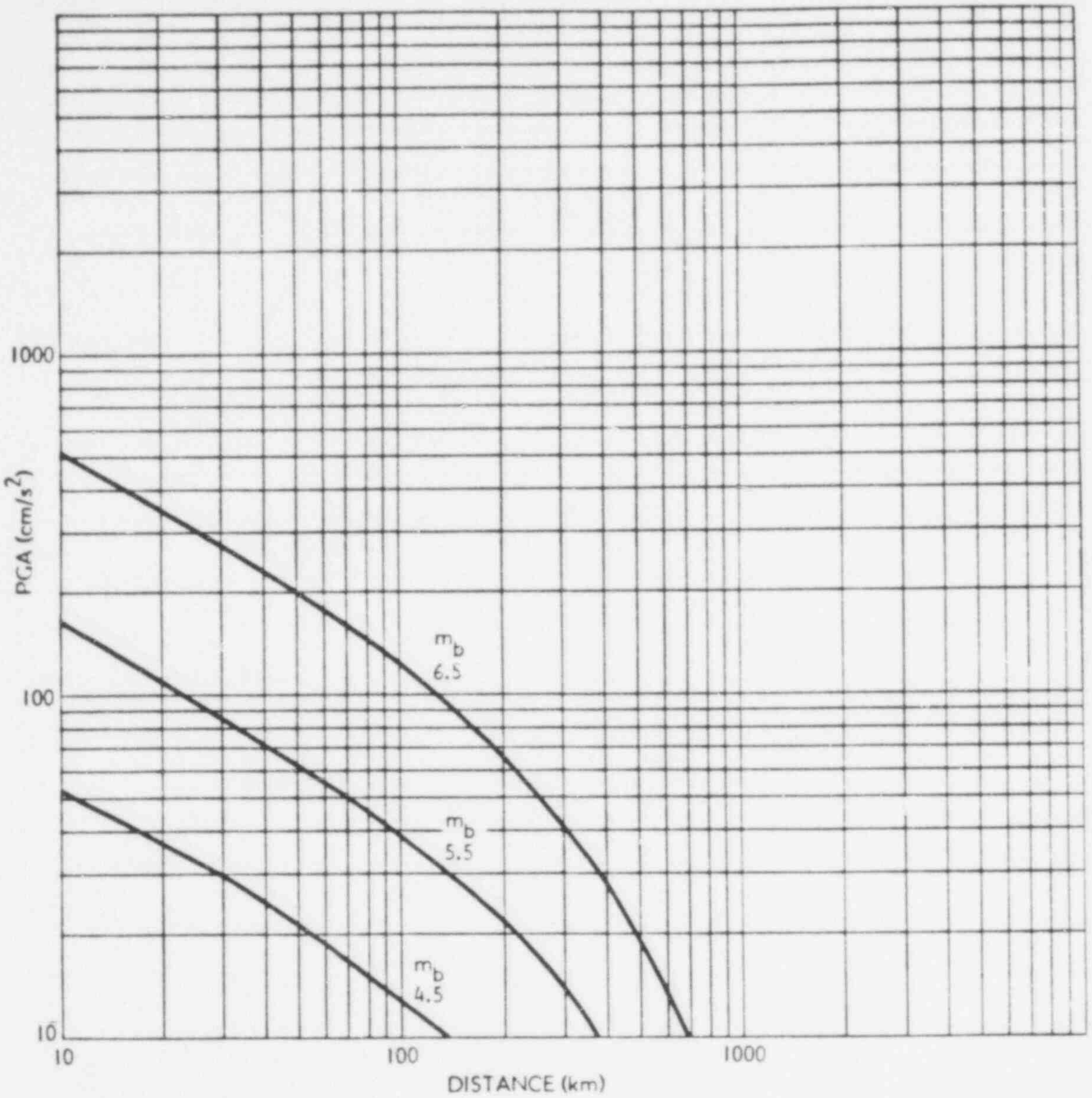

FIGURE 5-6

PEAK ACCELERATION ATTENUATION RELATIONS

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Although the data set consisted of spectral ordinates at 0.00, .02, .05, .10, and .20 damping factors, we excluded the undamped ordinates because of their statistical instabilities. The results of this regression are tabulated in Table 5-6. As expected, the spectral ordinates become much less dependent on the damping factor with increasing frequency. These results appear to be consistent with related analyses performed by McGuire (1977) and Husid (1963). Of course, since this method is approximate, the results should be used accordingly.

TABLE 5-6

SUMMARY OF REGRESSION RESULTS

$$\log(GM) = C_1 + C_2 I_s + C_3 \quad + C_4 \log(r)$$

I_s - MMI
r - kilometers
- decimal damping

GM	Units	Frequency (H_2)	C_3
PSA	cm/s^2	25	*
PSA	cm/s^2	20	*
PSA	cm/s^2	15.3	-.337
PSA	cm/s^2	12.5	-.639
PSA	cm/s^2	10.0	-.954
PSA	cm/s^2	7.7	-1.31
PSA	cm/s^2	5.0	-1.68
PSA	cm/s^2	3.3	-1.9
PSA	cm/s^2	2.5	-1.92
PSA	cm/s^2	1.33	-1.75
PSA	cm/s^2	1.0	-1.90
PSA	cm/s^2	0.50	-1.52

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* Statistically insignificant coefficient

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6.0 SRSS RESULTS AND CONCLUSIONS

As stated in Section 1.0, the objective of this study was to develop SSRS, for each of nine sites, that considered the unique site conditions and allowed quantification of uncertainty and conservatism associated with definition of the seismic hazard. This SSRS would be used to identify those sites where the seismic margins are clearly acceptable. Furthermore, for those sites where the margins required additional investigation, the SSRS methodology could readily identify the most significant and uncertain parameters. This identification could provide a basis for more detailed investigations. Four specific methodologies were to be used in this effort.

To a large measure the results presented in this section accomplish this objective, in that the quantification of uncertainty by the variety of approaches provides a most useful tool for comparative evaluation of other definitions of seismic hazard, e.g., the FSAR definition.

We want to emphasize that the state of the art of probabilistic risk assessment and seismology does not justify the use of these results as an absolute measure of the earthquake hazard. In addition, consistent with the recommendations of the Lewis Report or Wash 1400, we strongly recommend that these results be complemented, when necessary at particular sites, by extensive sensitivity studies. We furthermore encourage a peer review of the results — and more important of the expert opinion solicitation. In this study, our major effort was directed at processing the experts' opinions. The methodology developed integrated the expert opinion and uncertainty with a statistical model of earthquake occurrence. Care was taken to preserve each expert's opinion and not supplant it with our opinion. Therefore, while the expert panel response is eloquent testimony to the uncertainty in seismology (particularly in the northwest U.S.), their response can be used to focus the additional effort that might be required at one or two sites.

Any additional effort should focus on a better quantification of the degree to which uncertainty due to nature and the degree to which uncertainty due to lack of man's knowledge affect the SSRS results. Uncertainty dominates the results in seismic hazard definition, so it is important for decision makers to recognize these different factors. Additional studies that we recommend here can often reduce the uncertainty associated with a lack of knowledge, but the inherent uncertainty of natural phenomena will always have to be included in seismic hazard definition.

6.1 IMPORTANT PARAMETERS

This study has identified several important parameters which, in general, fall into two sets: basic decisional issues and analytical areas with significant sensitivity. In the first set, two major parameters must be determined prior to selection of SSRS for design evaluation: the return period or likelihood of occurrence and the type of earthquakes to consider. So that judgments about these parameters can be made, seismic risk must be understood: the seismic hazard, the facility's resistance and the consequence of failures. While these judgments are obviously beyond the scope of this study, several points can be made regarding the results.

The effects of return period on SSRS are substantial as can be seen from the tables and figures presented below. A good frame of reference for evaluating return period effects is the Real Time History Spectra (RTHS) which are independent of return period. The figures below present SSRS for return periods of 200, 1000 and 4000 years for UHS, NHS and STHS; the RTHS are independent of return period and represent the 84 percentile of magnitude 5.3 records. This spectrum roughly represents an Intensity VII at the site with 84 percent of the spectral amplitudes captured. For comparison, the tables below present estimates for each site of the MMI return period.

Regarding the type of earthquake considered, the basic issue that must be considered is to what degree all earthquakes, both big and small, near and far must be considered in design evaluations. Section 4.1 above discussed this issue in some detail for the UHS. Basically, the UHS, and by inference, the Newmark-Hall spectra capture the effects of all earthquakes. The Real and Scaled Time

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History Spectra capture only the effects of large nearby earthquakes. As can be seen in the SSRS figures below, this difference is most significant in the longer periods. From a structural resistance point of view, this may not be significant for many nuclear power plant structures. From a regulatory viewpoint, the emphasis of Appendix A to 10CFR100, is on seismic design for large nearby earthquakes. In any event, three approaches to this issue are possible: one, use a spectrum that conservatively envelopes all earthquakes, such as the UHS or NHS; two, use one spectrum that is developed from large nearby earthquakes such as a RTHS or STHS; or, three, use two spectra, one developed from nearby earthquakes and one from distant earthquakes. It is interesting to note that Housner originally proposed two seismic design spectra; one for the near field events and another for the distant events. In Section 7.0 of the TERA report, SHA: A Methodology for Eastern United States, Option 1 above, is rejected as too conservative, and the probabilistic theory for Option 3 is developed.

The second set of parameters involves areas in which significant sensitivity have been found. A seismic exposure analysis combines the effects of various parameters representing source function, source seismicity, attenuation and seismic exposure evaluation models and the associated uncertainty. The sensitivity of the analysis to these parameters is often a function of the location of the site with respect to the seismic sources and the seismicity of the sources. Hence, a detailed sensitivity analysis is necessary on a site-specific basis to determine the importance of the parameters quantitatively. The sensitivity is also a function of the Return Period of interest and the frequency range considered. However, the following general comments are of particular interest.

Attenuation Relationships

Seismic hazard studies are particularly sensitive to the attenuation relationships used. In the analysis the uncertainties lie at two levels. First, the mean of the attenuation is often ill-defined in the near field where few data are available. The addition or exclusion of a few data points in the near fields as well as the choice of a given mathematical model will often have a dramatic effect on the mean and consequently on the exposure. Second, for a fixed mean, the type of

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uncertainty associated with it and the way this uncertainty is modeled make for a very sensitive parameter. In this analysis, it is described by log-normal distribution with a sigma equal to 0.9. Such large uncertainty, justified by the poor quality of the data, leads to large accelerations for low probability of exceedence: the acceleration corresponding to the 2 and 3 sigma probability of exceedence is equal to 6 and 15 times the mean, respectively. This implies that if the mean is 0.3 g the 3 sigma acceleration would be 4.5 g . This is an area where there is clearly room for significant improvements.

Both the size of the sigma and the distribution truncation are very sensitive parameters, and their effects are more pronounced at larger RP. Variations of 100 percent in the results are not uncommon for 1,000 year RP. It should be noted that for a fixed number of sigmas, a variation of sigma has a multiplicative effect. Conversely, for a fixed sigma, the variation in the number of sigmas has an asymptotically decreasing effect since the added probability of exceedence decays as the tail of the log normal distribution.

These conclusions apply to each expert and each site and therefore further study in this area is most important.

Zonation

The sensitivity to the zonation is very site specific. For the sites located in the central stable region, little difference is noticeable because the main contributing sources are the host region which does not undergo any change and the New Madrid area which is too distant to reflect minor variations in boundary conditions. This conclusion is typical of all experts. In the northeast, the complexity of the zonation and the variation between experts would require a detailed study to determine the sensitivity of this parameter.

Upper Magnitude Cutoff

The sensitivity to the upper magnitude cutoff is a function of two parameters: the upper magnitude cutoff specified by the expert for the sources governing the

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hazard and the magnitude distribution. Little change would occur for an expert who specifies a large upper magnitude cutoff and a large increase would occur for an expert with a relatively low cutoff for nearby zones. These conclusions depend on the magnitude distribution. The calculated hazard is relatively insensitive to changes in the upper magnitude cutoff if the expert's b-value is large.

Sensitivity Model Uncertainty

Usually, the exposure is relatively insensitive to a variation of the overall seismicity of a region (variation of "a" parameter by 10-20%) whereas it is very sensitive to variation of the earthquake distribution (b-value).

In a sensitivity analysis, the expected value of these parameters is kept constant and only the uncertainty about the mean is varied as modeled by the parameters of the gamma and beta distributions. The larger uncertainty increases the probability of a higher level of seismicity at the expense of a lower one. Hence, for a rather short return period, the effect is not unique and depends upon the size of events governing the hazard.

For longer return periods one expects a global increase which may become very significant. For the 4,000-year spectrum increases of 30-50 percent over the whole spectrum is not uncommon. Such conclusions are generally applicable for all experts and all sites.

6.2 SSRS FOR SITES IN CENTRAL UNITED STATES

Four of the sites, Dresden, Palisades, La Crosse and Big Rock Point are located in the Central United States. Since the seismological factors influencing the SSRS for these sites are substantially different from those influencing the Eastern United States, they are presented together in this section. The results for each site are presented in Tables 6-1 through 6-4 and Figures 6-1 through 6-4 respectively for the Dresden, Palisades, La Crosse and Big Rock Point sites. The UHS results presented in the tables are those used as anchor points for

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TABLE 6-1

DRESDEN

PGA, PGV and MMI FOR 200, 1000, and 4000 YEAR RETURN PERIOD

RETURN PERIOD (YEARS)	200		1000		4000	
	SYNTHESIS	RANGE	SYNTHESIS	RANGE	SYNTHESIS	RANGE
PGA (cm/sec^2)	83	62-124	159	112-261	268	176-435
PGV (cm/sec)	17	9-34	38	19-84	70	31-156
MMI	6.2	5.6-7.4	7.2	6.4-8.4	7.8	7.0-8.9

TABLE 6-2

PALISADES

PGA, PGV and MMI FOR 200, 1000, and 4000 YEAR RETURN PERIOD

RETURN PERIOD (YEARS)	200		1000		4000	
	SYNTHESIS	RANGE	SYNTHESIS	RANGE	SYNTHESIS	RANGE
PGA (cm/sec^2)	71	53-105	128	87-200	202	103-307
PGV (cm/sec)	14	9-26	29	17-55	52	28-97
MMI	5.8	5.4-6.8	6.7	6.0-7.7	7.3	6.6-8.2

TABLE 6-3

LACROSSE

PGA, PGV and MMI
FOR 200, 1000, and 4000 YEAR RETURN PERIOD

RETURN PERIOD (YEARS)	200		1000		4000	
	SYNTHESIS	RANGE	SYNTHESIS	RANGE	SYNTHESIS	RANGE
PGA (cm/sec^2)	59	41-82	110	70-155	180	104-256
PGV (cm/sec)	10	6-18	21	13-38	36	23-67
MMI	5.5	4.9-6.4	6.3	5.7-7.2	6.8	6.2-7.6

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TABLE 6-4

BIG ROCK POINT

PGA, PGV and MMI FOR 200, 1000, and 4000 YEAR RETURN PERIOD

RETURN PERIOD (YEARS)	200		1000		4000	
	SYNTHESIS	RANGE	SYNTHESIS	RANGE	SYNTHESIS	RANGE
PGA (cm/sec^2)	54	36-73	102	63-141	137	93-238
PGV (cm/sec)	7	1-13	16	3-27	27	10-46
MMI	5.0	3.3-5.9	5.8	4.7-6.6	6.4	5.3-7.5

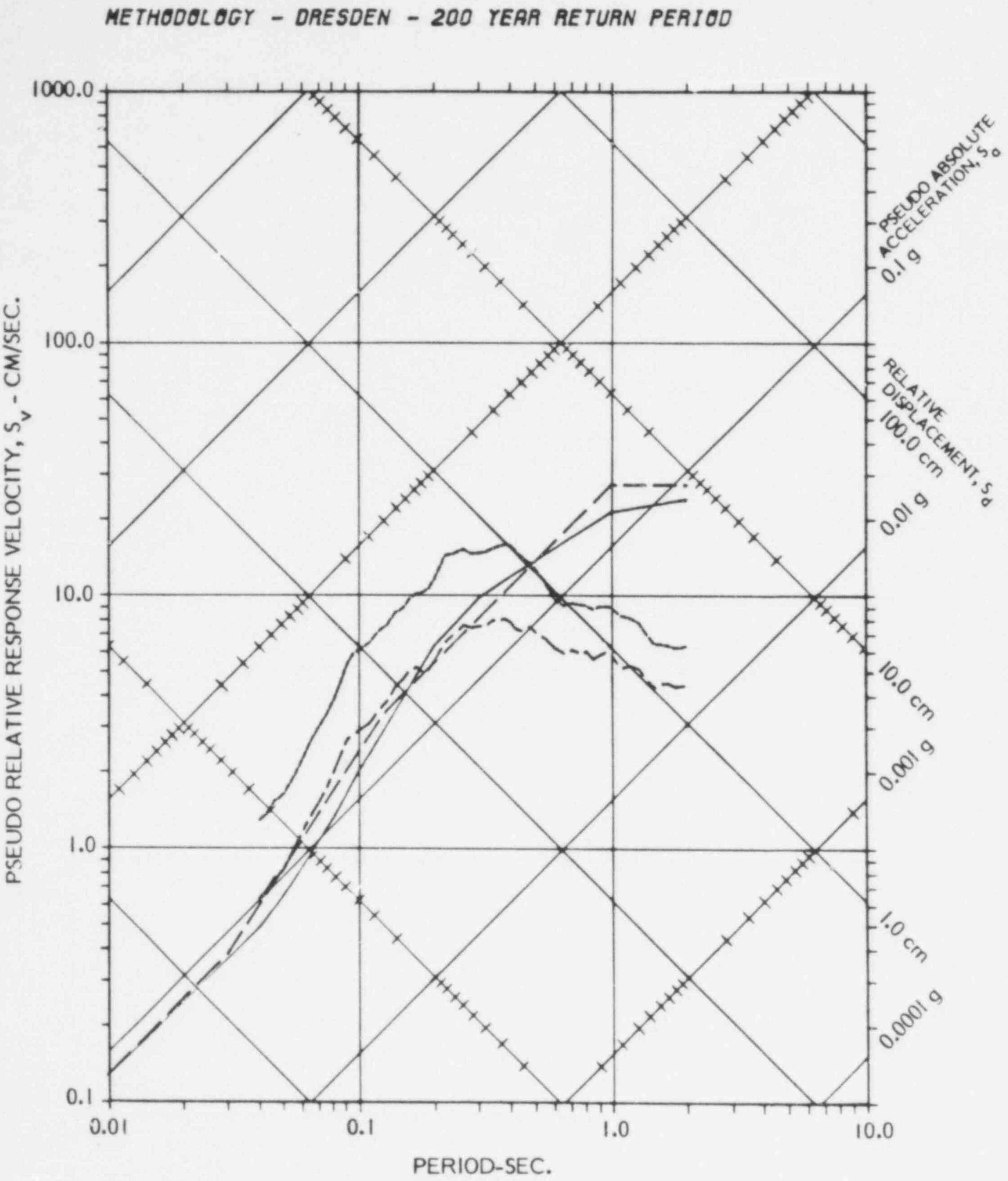

FIGURE 6-1a

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METHODOLOGY - DRESDEN - 1000 YEAR RETURN PERIOD

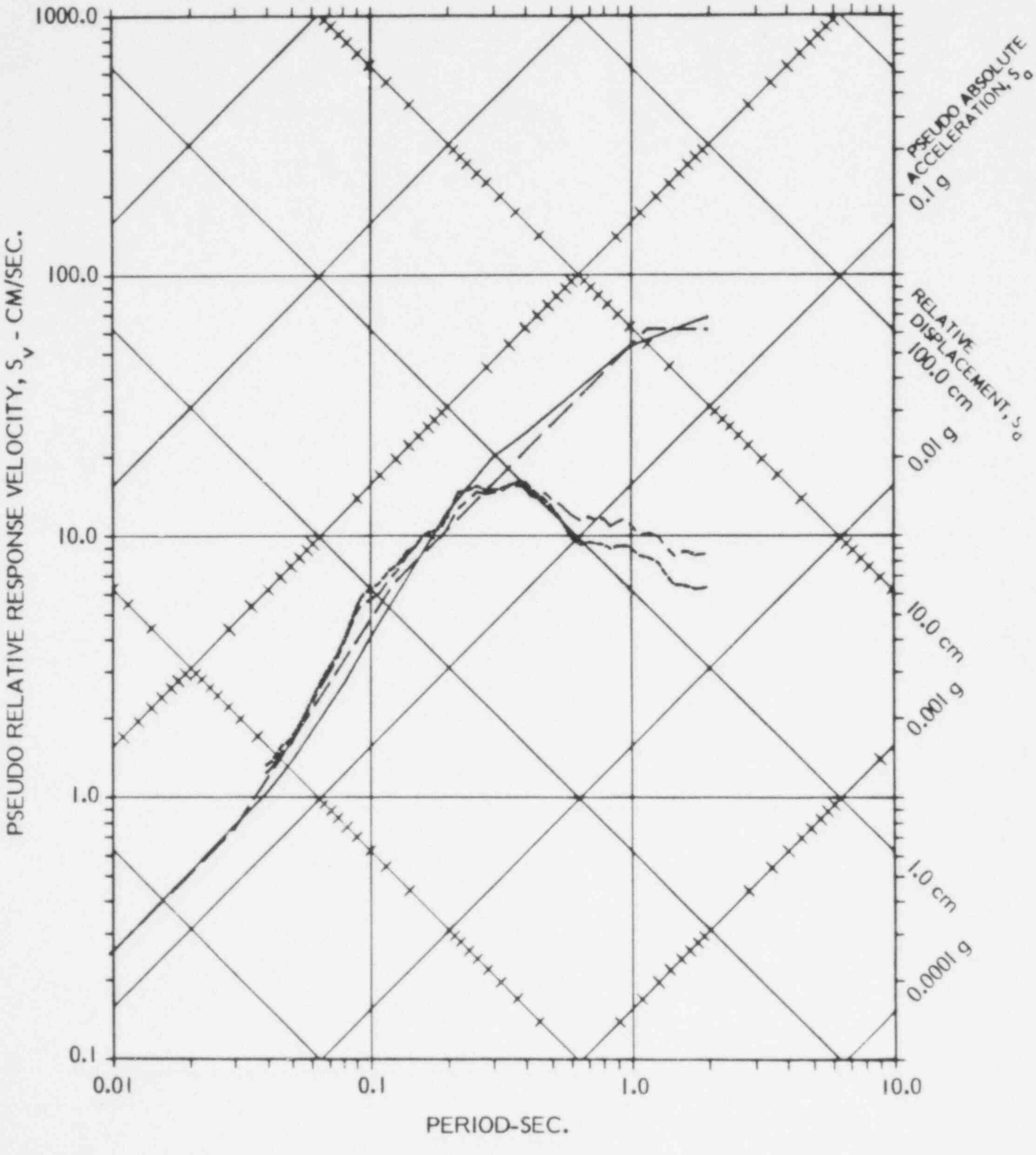

FIGURE 6-1b

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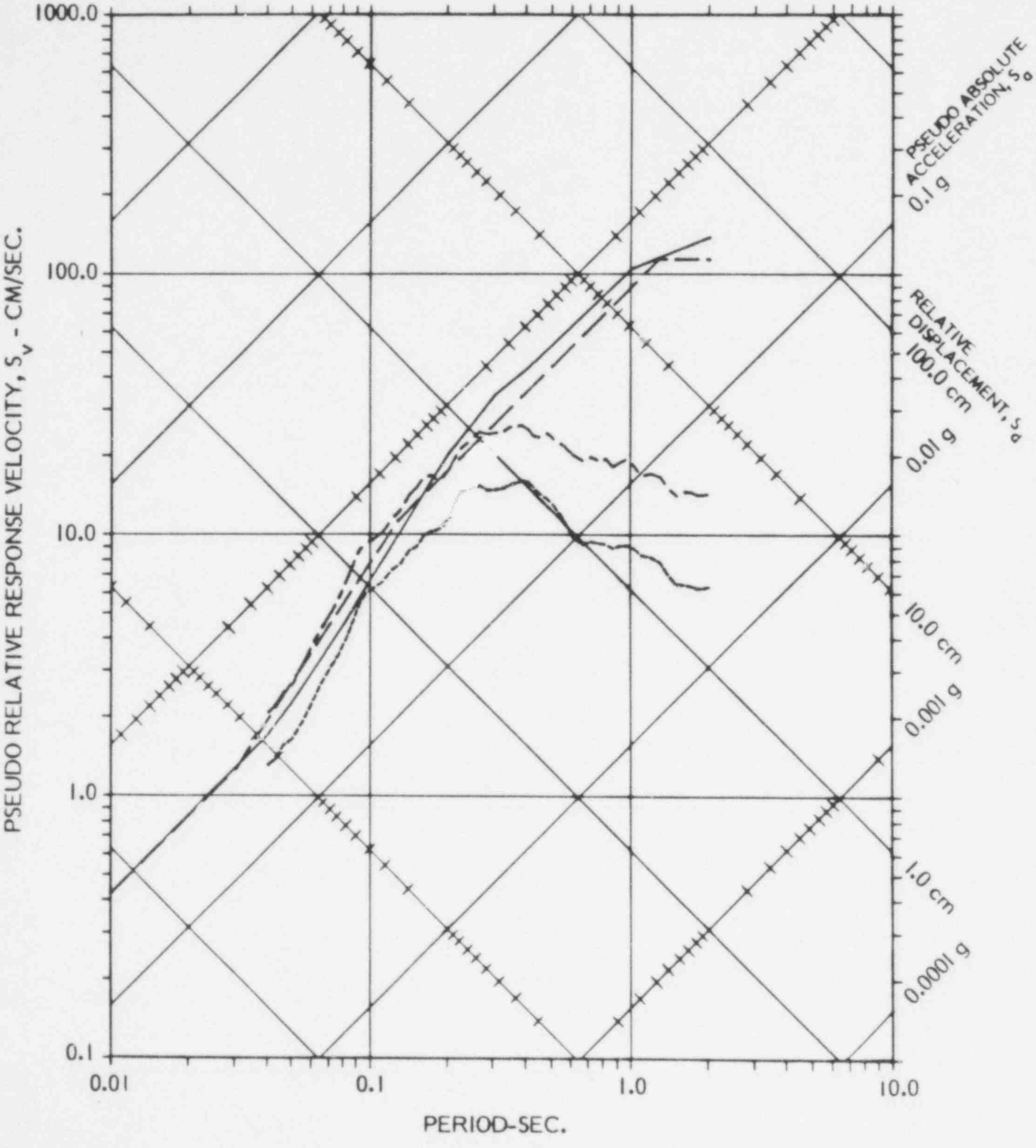
METHODOLOGY - DRESDEN - 4000 YEAR RETURN PERIOD



——— Synthesis

— — — Newmark-Hall

········ Real Time History

—·—·— Scaled Time History

FIGURE 6-1c

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ALL EXPERTS -- DRESDEN -- 1000 YEAR RETURN PERIOD

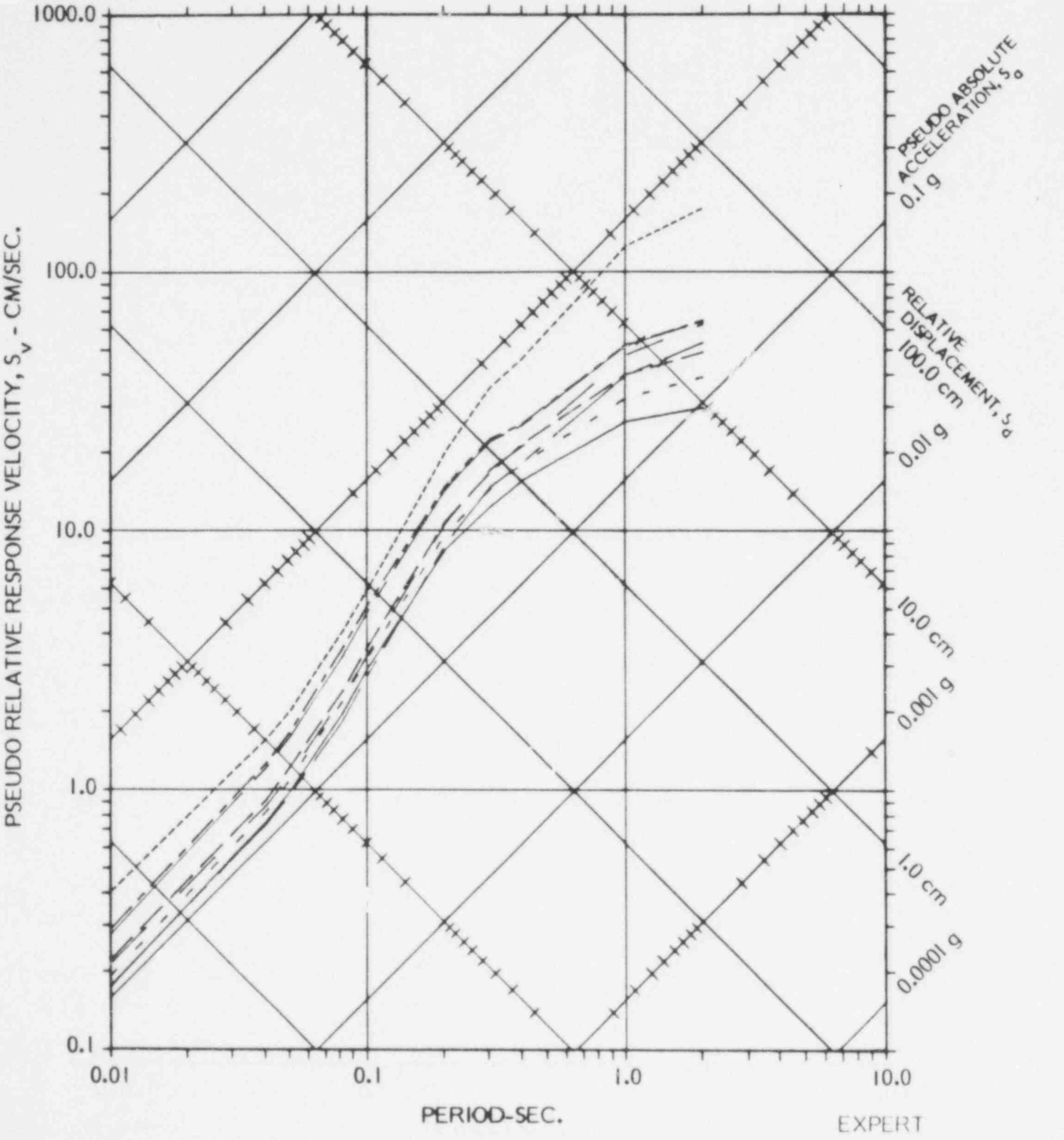

FIGURE 6-1d

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METHODOLOGY - PALISADES - 200 YEAR RETURN PERIOD

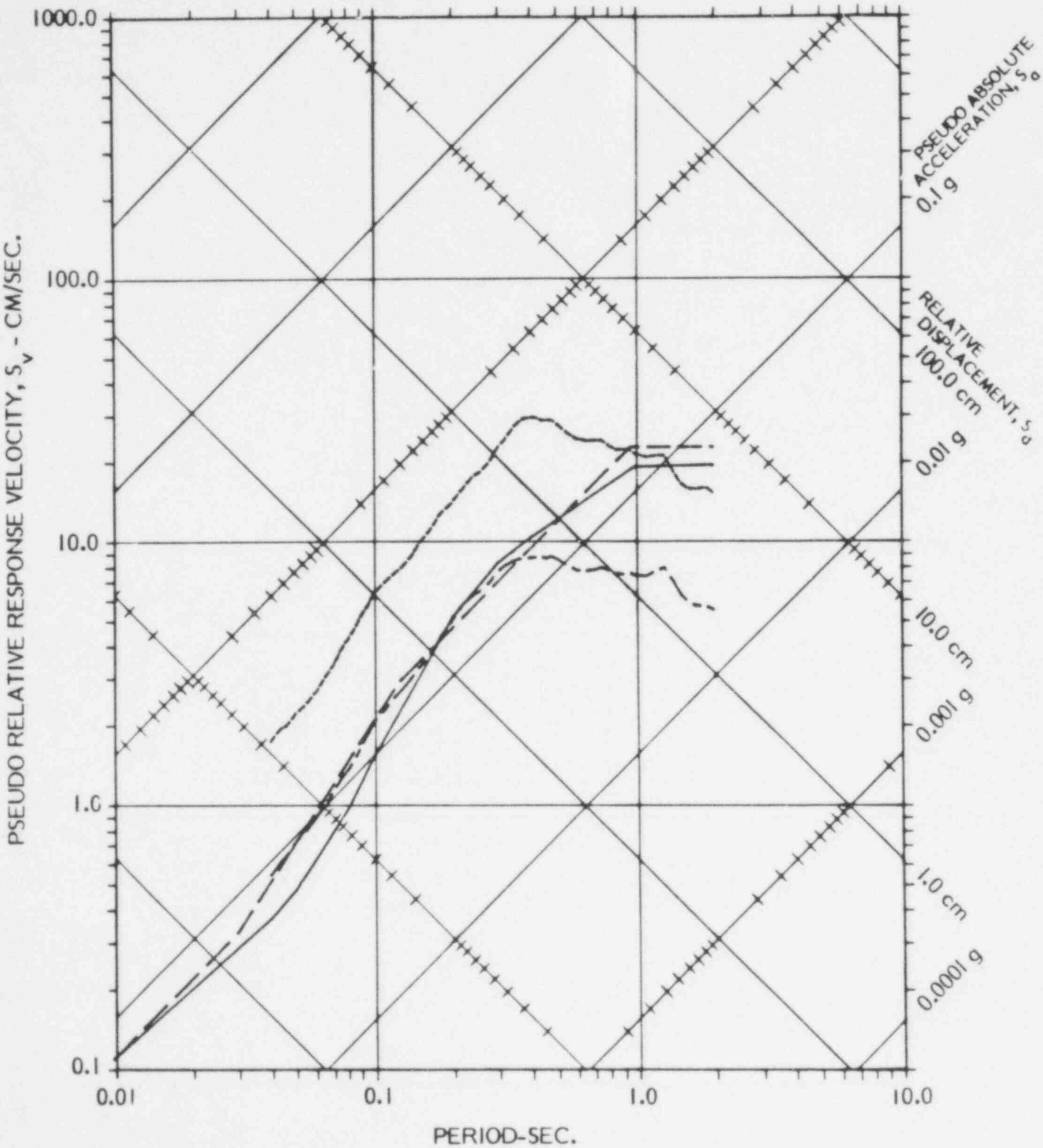


FIGURE 6-2a

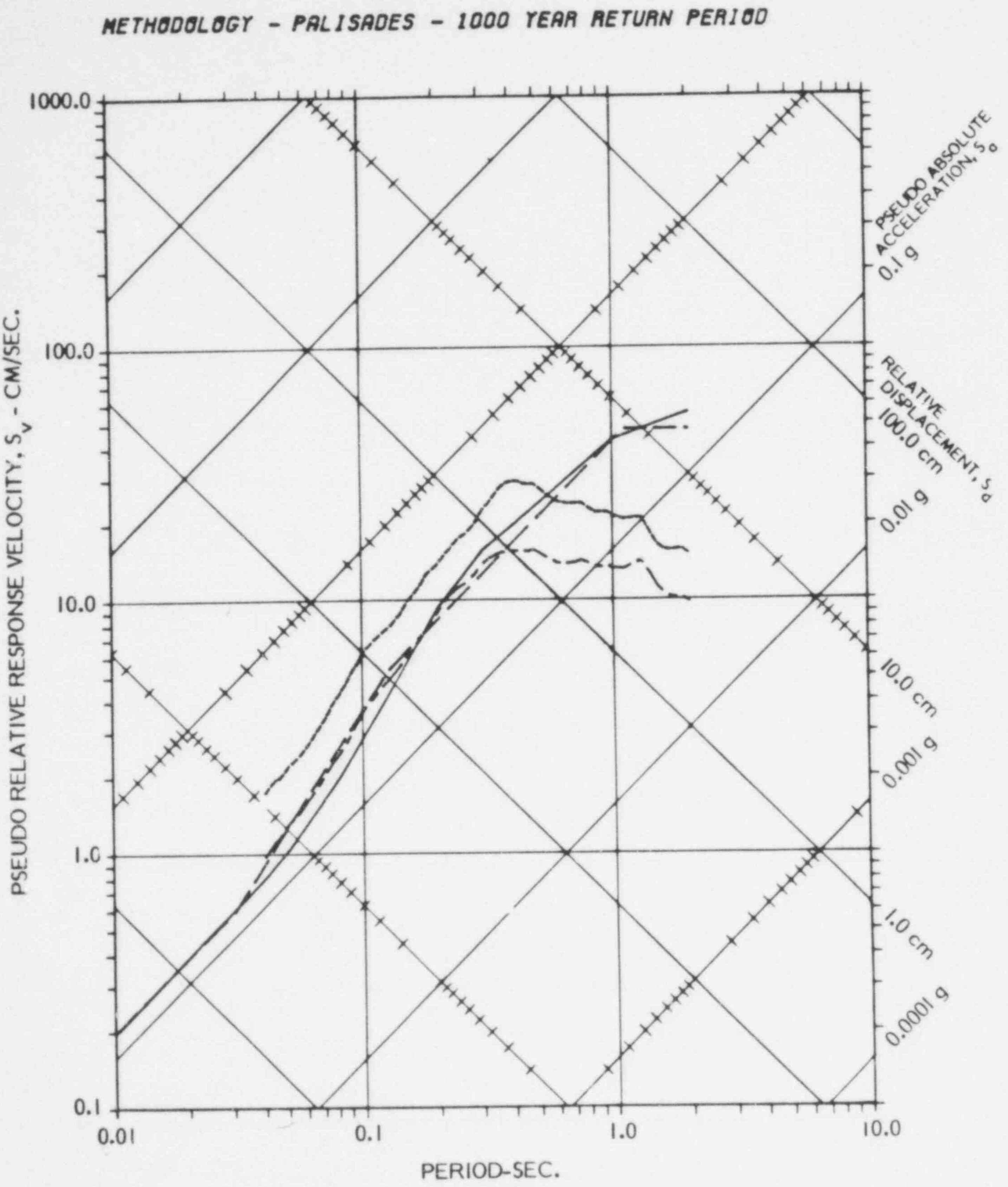


FIGURE 6-2b

923 237

METHODOLOGY - PALISADES - 4000 YEAR RETURN PERIOD

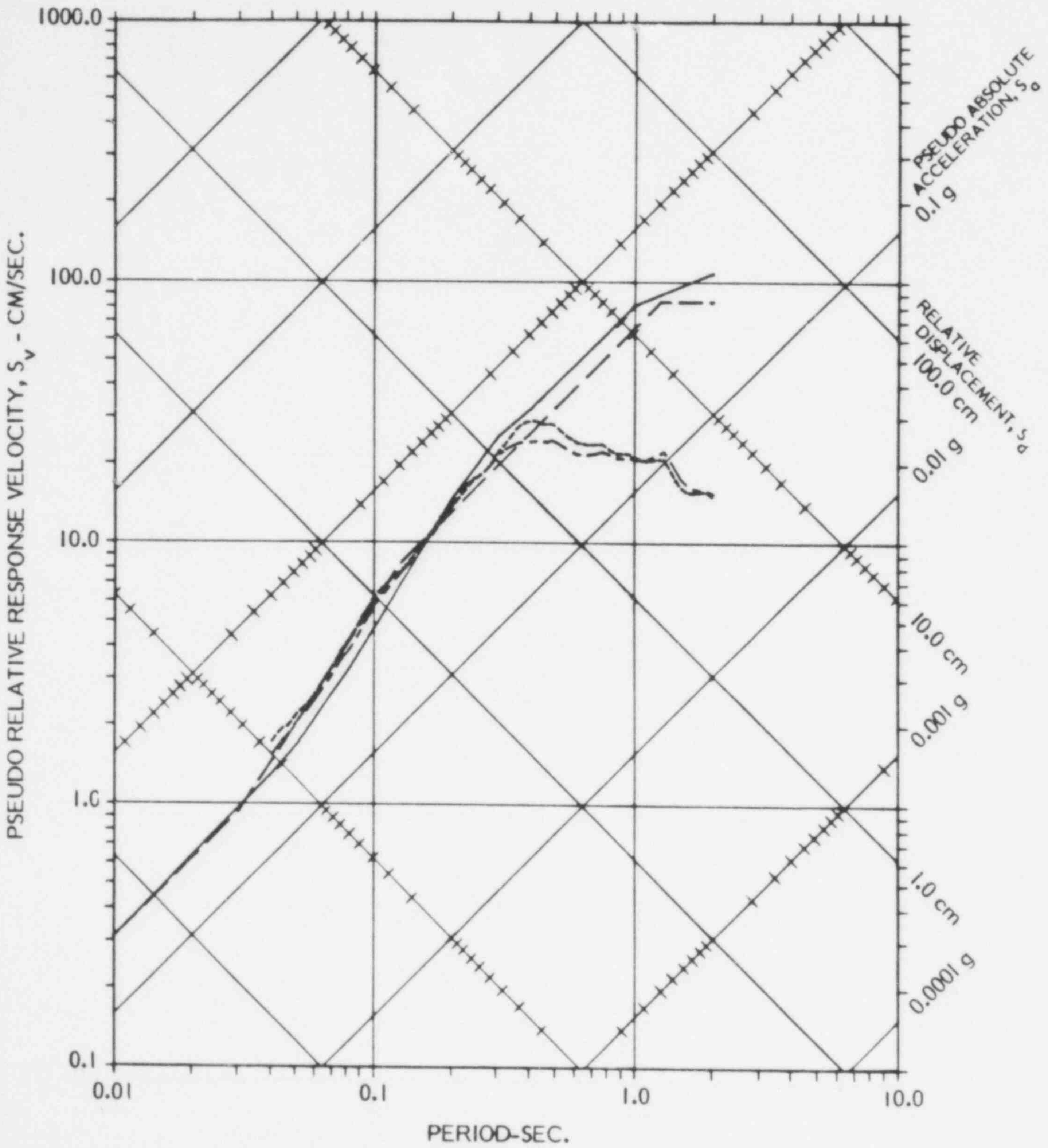
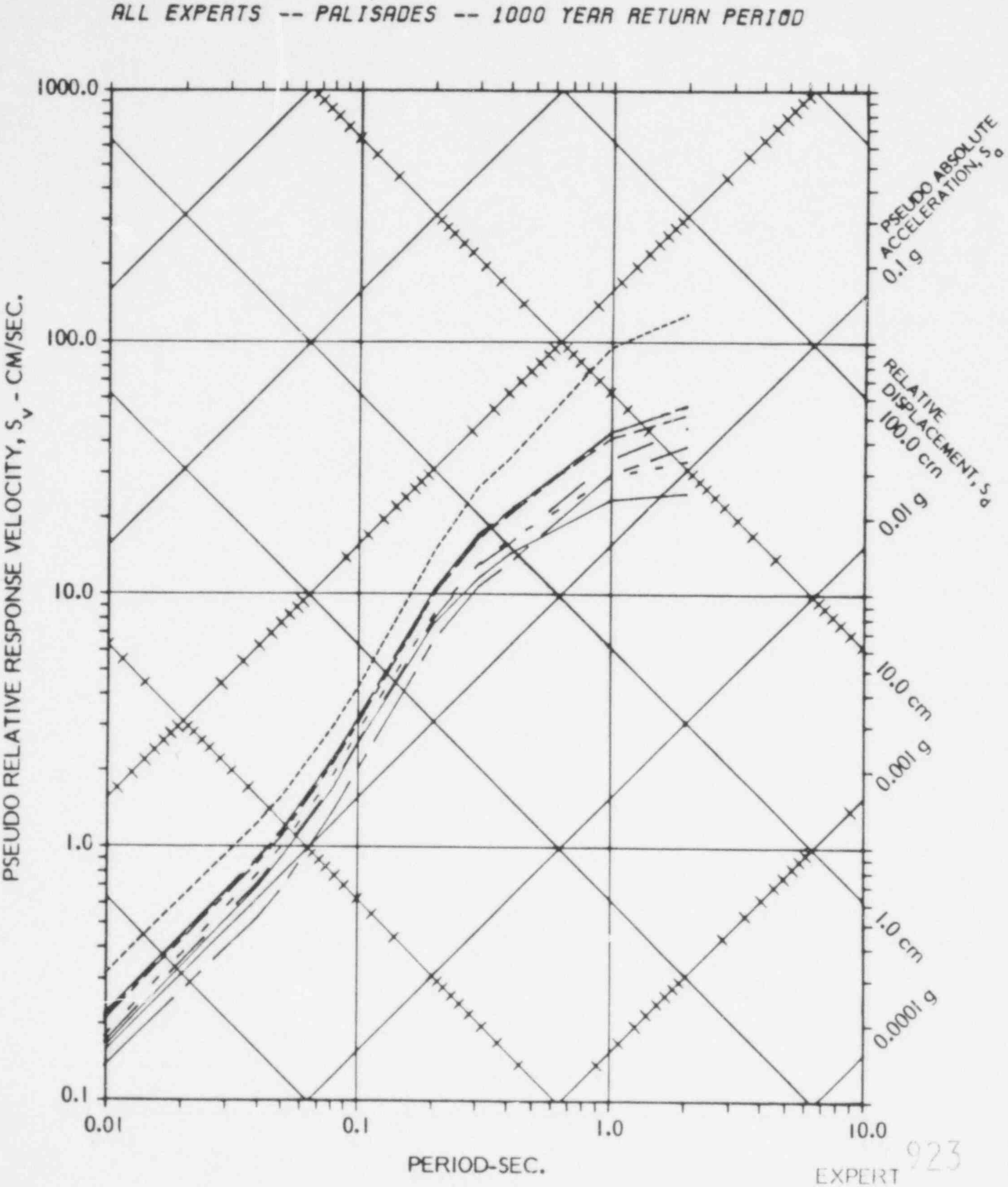


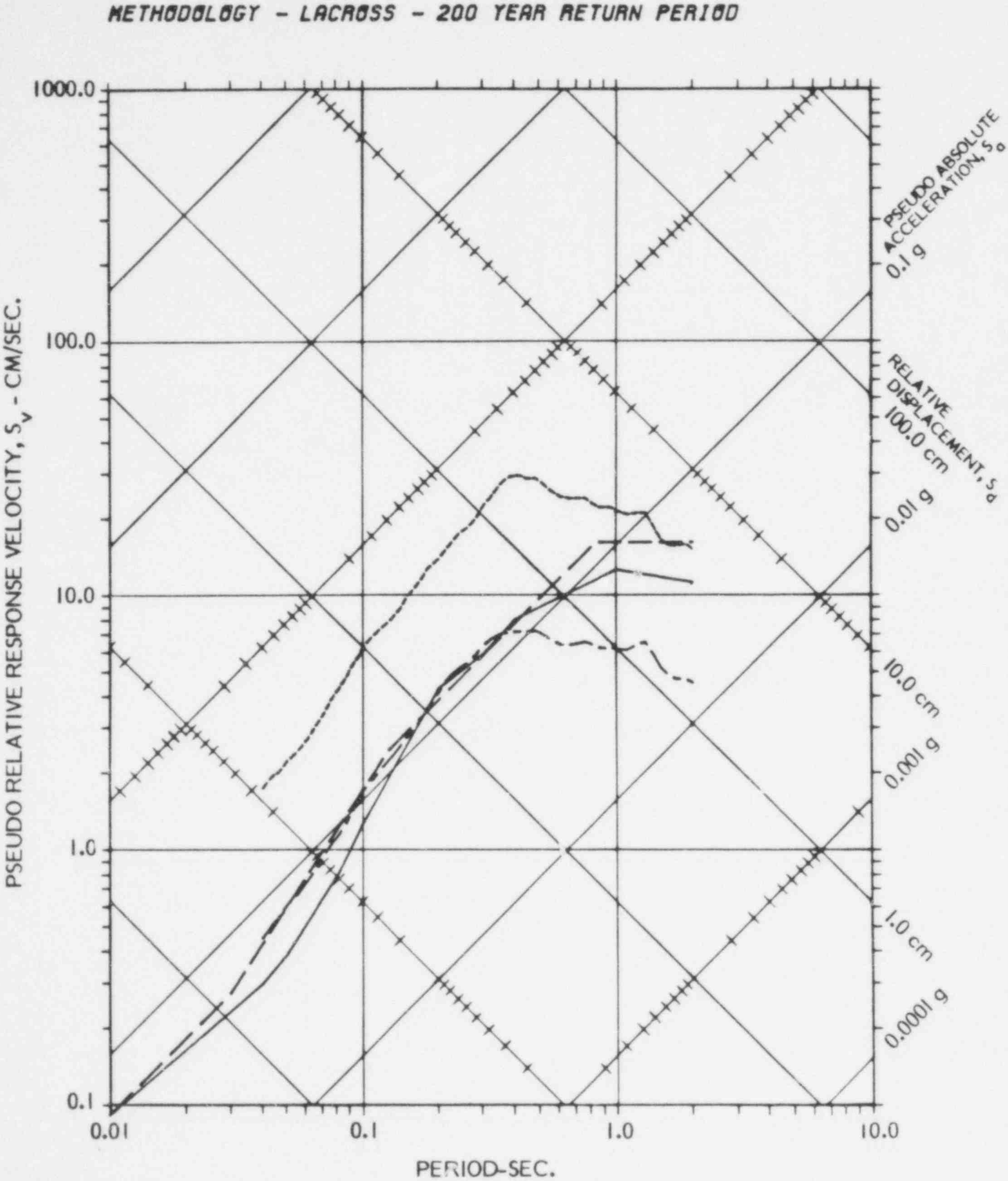
FIGURE 6-2c

923 238



923 239

FIGURE 6-2d



——— Synthesis

— — — Newmark-Hall

-------- Real Time History

-·—·— Scaled Time History

FIGURE 6-3a

923 240

METHODOLOGY - LACROSS - 1000 YEAR RETURN PERIOD

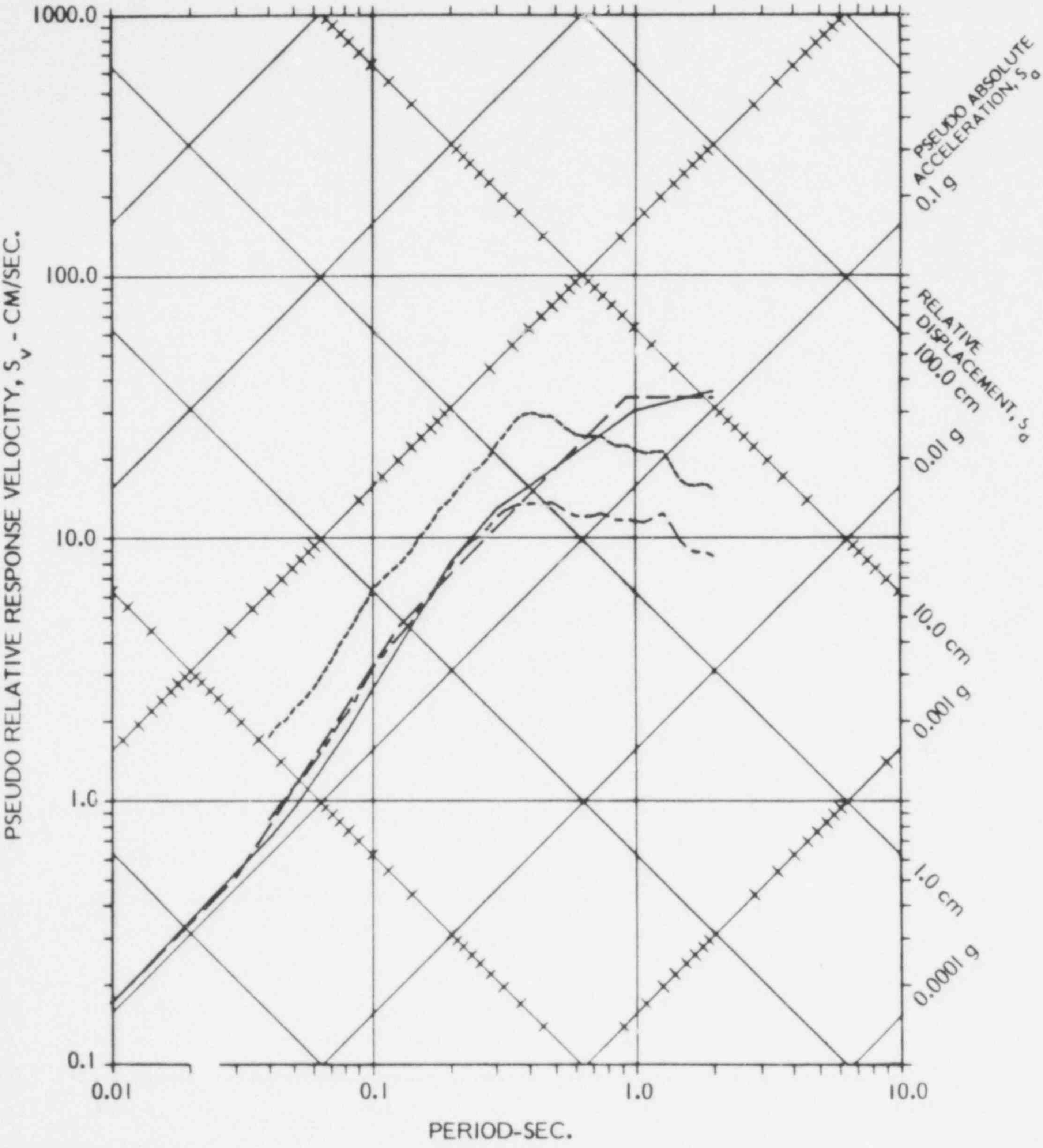


FIGURE 6-3b

METHODOLOGY - LACROSS - 4000 YEAR RETURN PERIOD

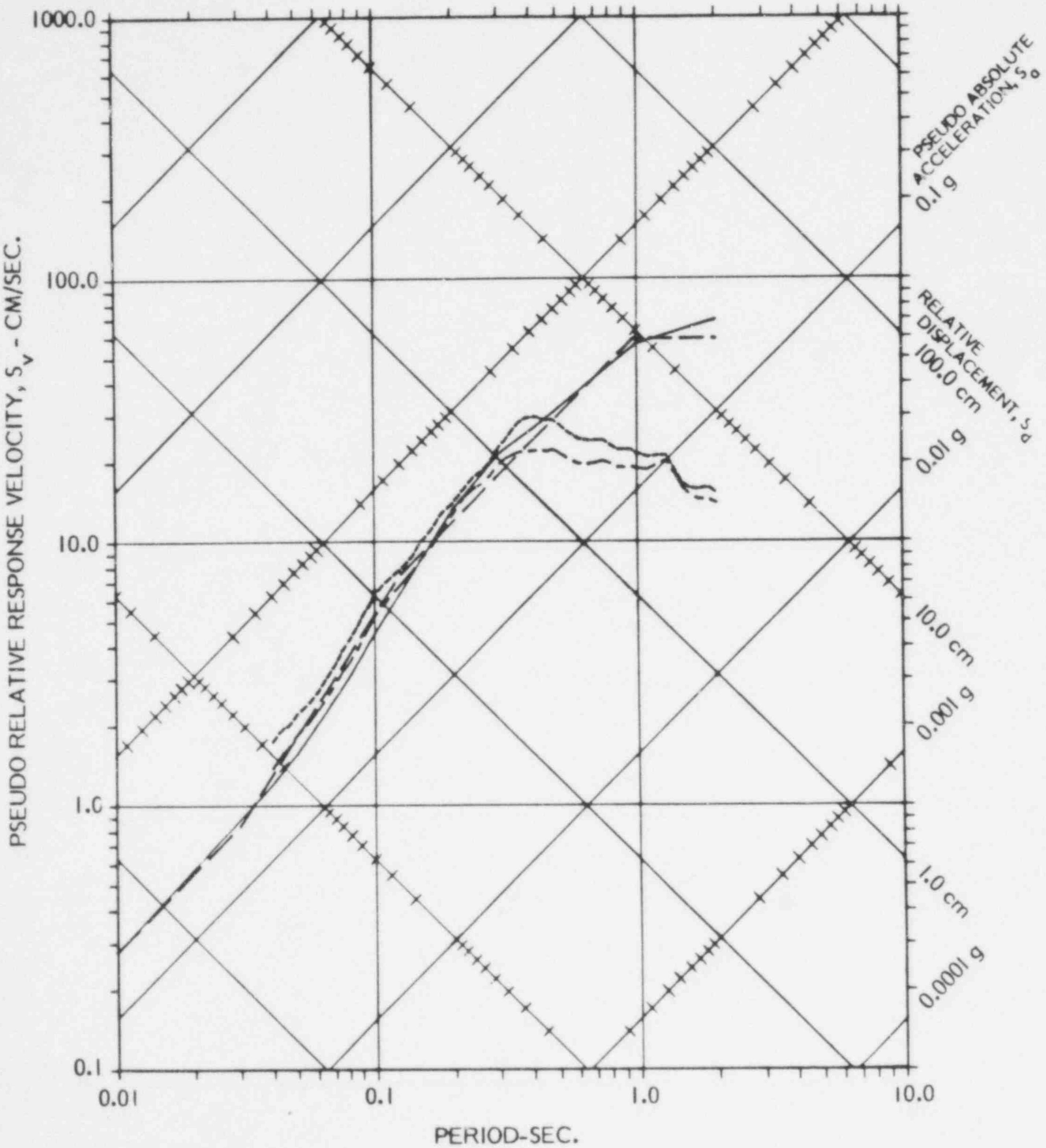


FIGURE 6-3c

923 242

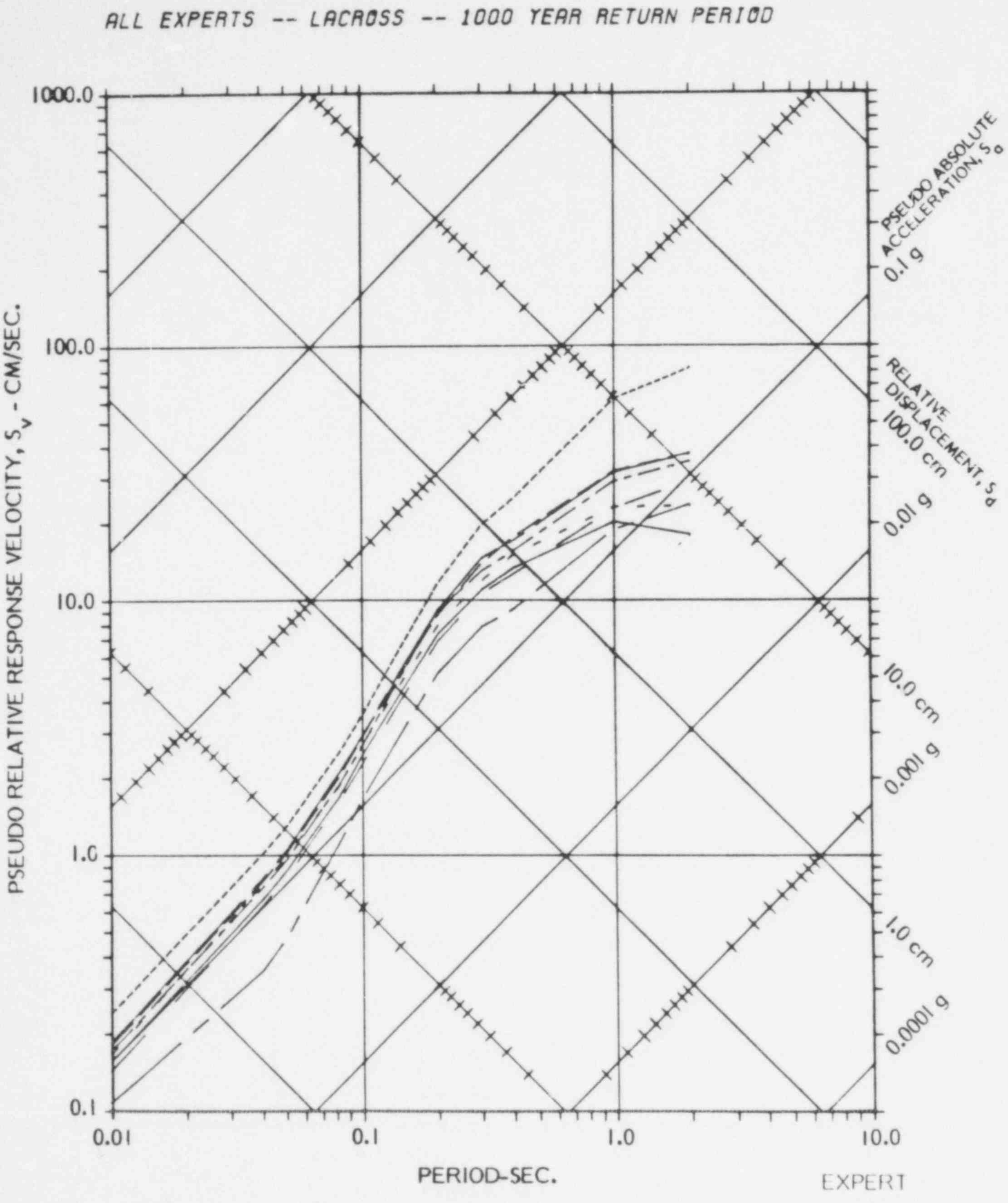


FIGURE 6-3d

923 243

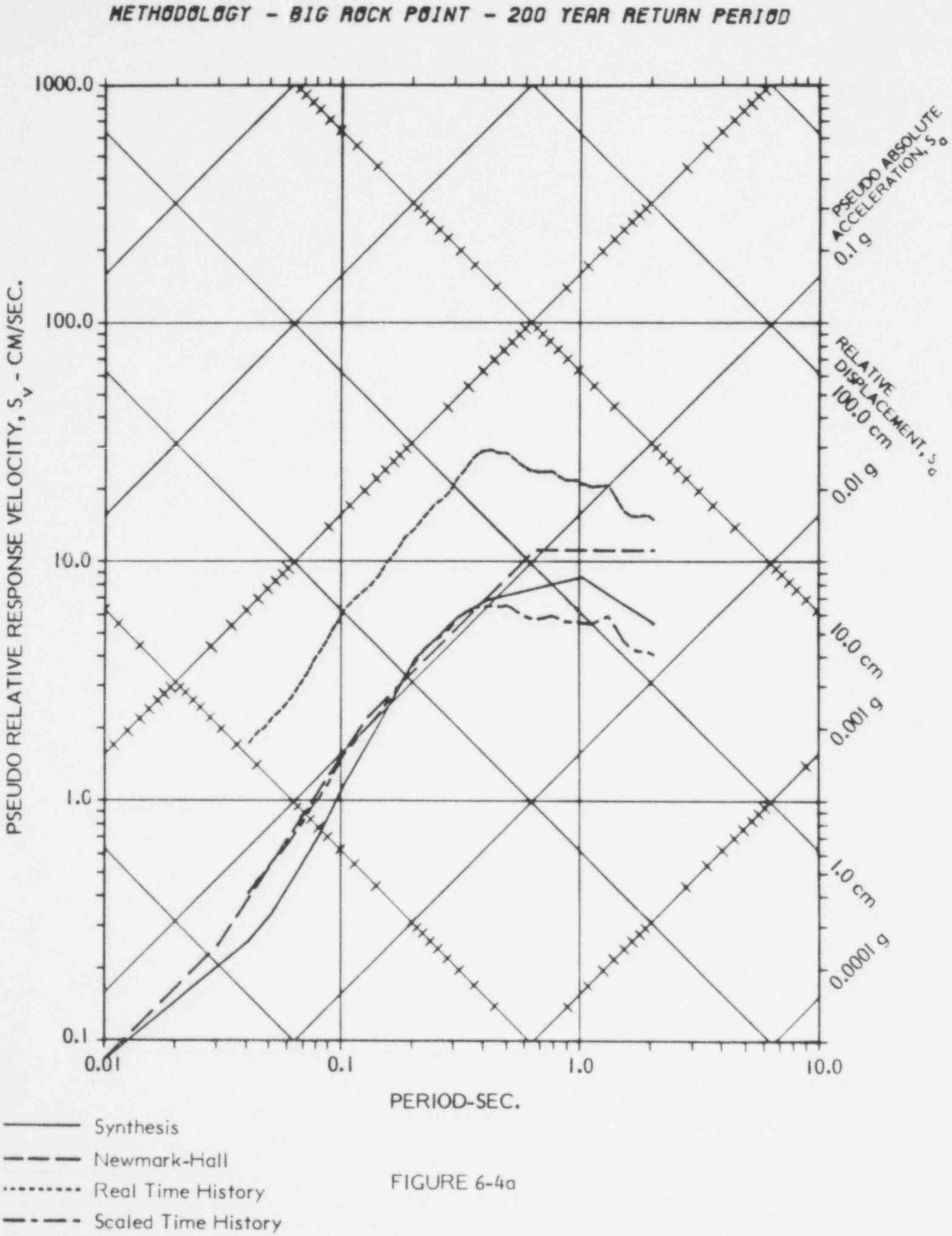

METHODOLOGY - BIG ROCK POINT - 200 YEAR RETURN PERIOD
PSEUDO RELATIVE RESPONSE VELOCITY, S_v - CM/SEC.
1000.0
100.0
10.0
1.0
0.1
0.01
0.1
1.0
10.0
PERIOD-SEC.
PSEUDO ABSOLUTE ACCELERATION, S_a
0.1 g
0.01 g
0.001 g
0.0001 g
RELATIVE DISPLACEMENT, S_d
100.0 cm
10.0 cm
1.0 cm
Synthesis
Newmark-Hall
Real Time History
Scaled Time History

FIGURE 6-4a

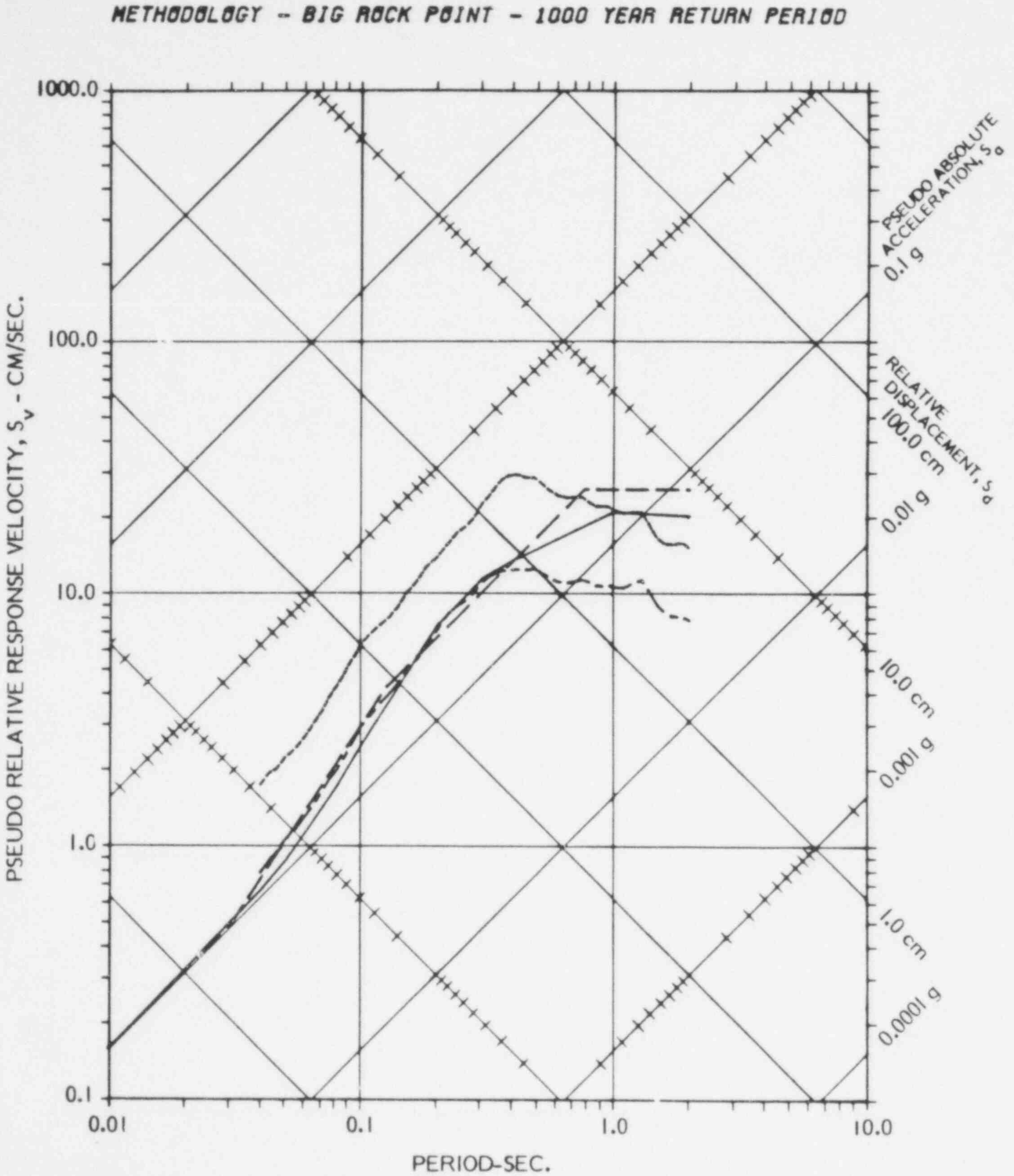

METHODOLOGY - BIG ROCK POINT - 1000 YEAR RETURN PERIOD
PSEUDO RELATIVE RESPONSE VELOCITY, S_v - CM/SEC.
1000.0
100.0
10.0
1.0
0.1
0.01
0.1
1.0
10.0
PERIOD-SEC.
PSEUDO ABSOLUTE ACCELERATION, S_a
0.1 g
RELATIVE DISPLACEMENT, S_d
100.0 cm
0.01 g
10.0 cm
0.001 g
1.0 cm
0.0001 g
Synthesis
Newmark-Hall
Real Time History
Scaled Time History

FIGURE 6-4b

METHODOLOGY - BIG ROCK POINT - 4000 YEAR RETURN PERIOD

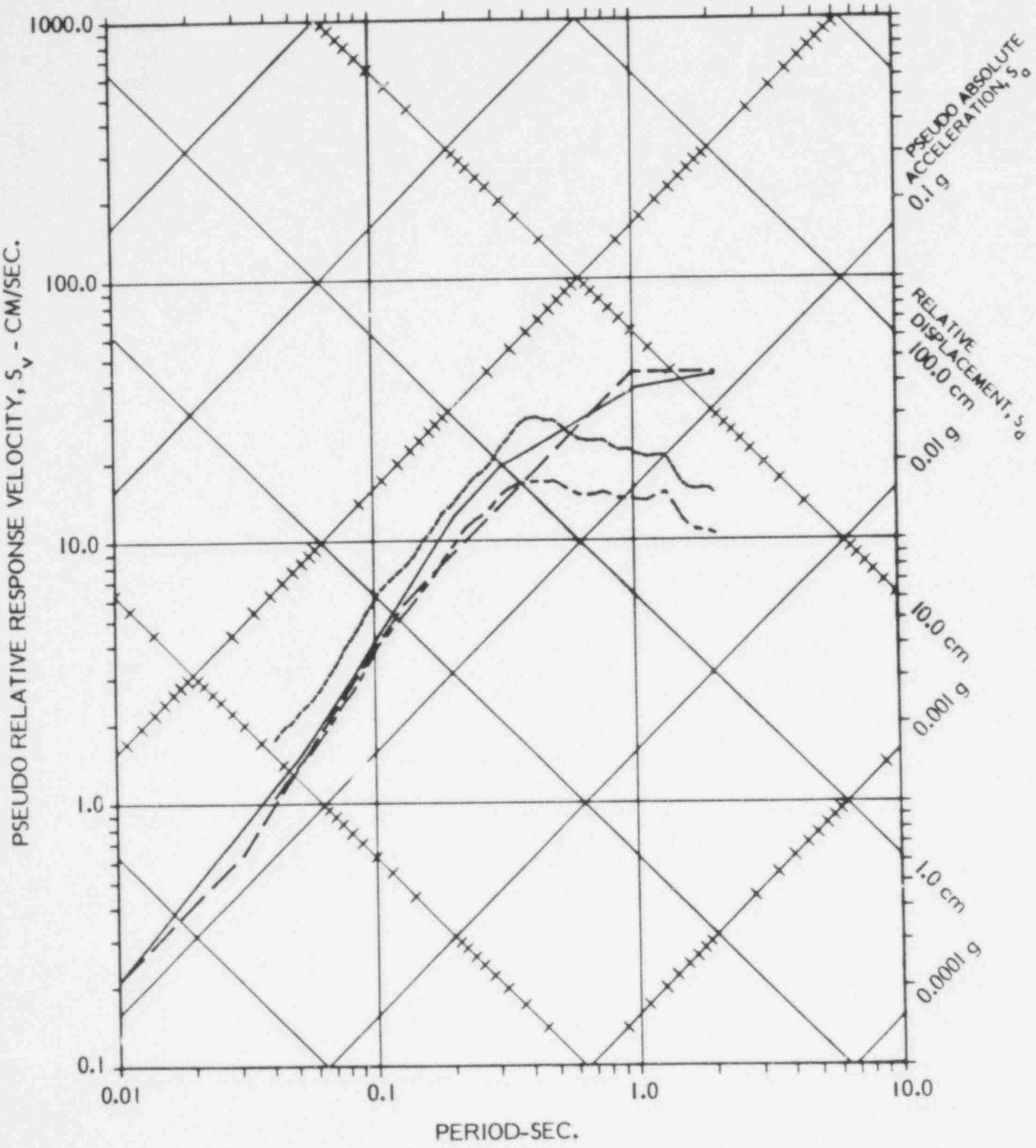
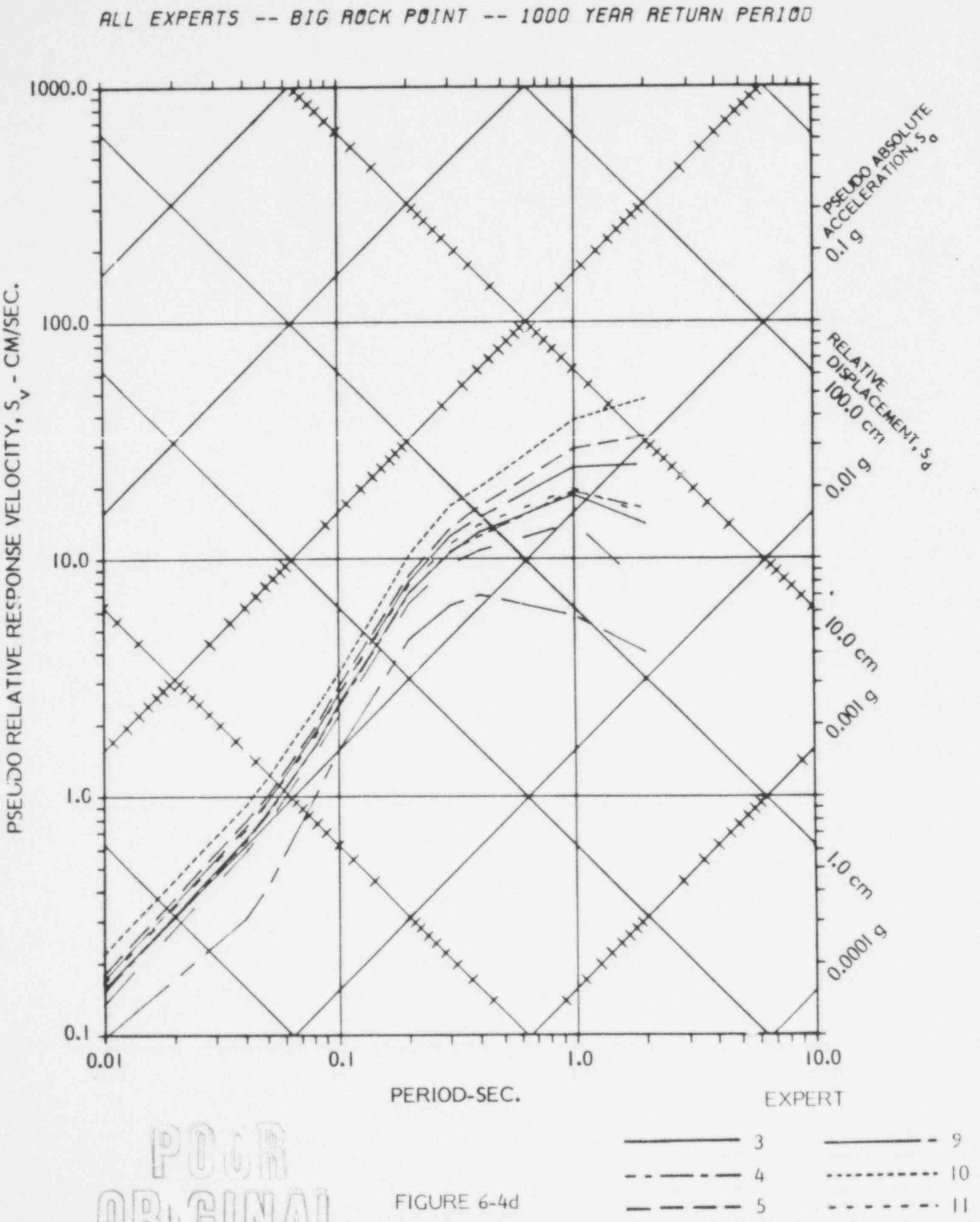


FIGURE 6-4c

923 246



POOR ORIGINAL

FIGURE 6-4d

923 247

Newmark-Hall spectra and Scaled Time History Spectra. The MMI values presented in the tables are only appropriate for soil sites since, as discussed in Section 5.0, the intensity attenuation relation was developed exclusively for soil. An adjustment for the site type was made, in our model, directly to the ground motion parameter. Other things being equal, rock site intesities are usually slightly less than soil intensities; Medvedev (1965) provides a basis for this adjustment. The figures of SSRS for each site are in four sets representing 200, 1,000 and 4,000 year return periods and UHS for each expert at a 1,000 year return period. The first three figures each present four curves: the Uniform Hazard Spectrum, the Newmark-Hall Spectrum, anchored at two points on the UHS curve (peak acceleration and peak velocity), the Scaled Time History Spectra, anchored at one point on the UHS curve (peak acceleration) and the Real Time History Spectrum (for selected records of mean magnitude 5.3). The STHS and RTHS are for soil sites except those for the Dresden site which are for rock. All curves include a measure of the overall uncertainty: the UHS, NHS and STHS by use of the UHM for spectral anchor points, and the RTHS through the use of the 84 percentile of the data.

Regional Factors Affecting the Results

In evaluating the factors contributing to the SSRS results, three of the methodologies explicitly depend upon expert opinion either for spectral anchor points (NHS or STHS) or the entire spectrum (UHS). Therefore, any analysis of these results necessitates a discussion of the subjective input from individual experts. For consistency, the experts are numbered in the same manner (e.g., E_8 for Expert 8) as in the TERA report, SHA: Solicitation of Expert Opinion. The reader is referred to that report for detailed information concerning the expert opinion used and to the TERA report, SHA: A Methodology for the Eastern United States.

The following discussion compares the contribution of various factors to the seismic hazard. The contribution of a source is measured relative to the contributions of the other sources. Hence, if one source has a constant effect and the others a decreasing one (e.g., as a function of distance), the global exposure decreases and the contribution of that source increases.

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It is interesting to notice how the contribution of the different sources to the SSRS varies as a function of the return period and the period of the spectrum. Generally, as the RP increases, sources with higher upper magnitude cutoff become more important and outweigh sources with lower upper magnitude cutoffs located at the same distance. This trend is expected since for RP greater than the one corresponding to the largest event in a lower seismicity zone, the zone contributes to the exposure only through the uncertainty associated with attenuation relationships. The contribution of the low seismicity zone decreases along the tail of the distribution modeling this uncertainty. Sources with larger upper magnitude cutoff, on the other hand, still generate events at those RP and contribute to a greater degree to the total exposure. For higher seismicity sources located at a greater distance, there is a trade-off between higher seismicity and greater attenuation. The global effect cannot be predicted but must be assessed case-by-case.

Similarly, over the frequency range of the spectrum, the contribution shifts from nearby events, rich in high frequency energy, toward distant events whose high frequency is filtered out and contribute mainly to the long period end of the spectrum.

The two dominant zones for all four sites are the Central Stable Region (the location of the sites) and the New Madrid Region (NMR). Their contributions to the SSRS loads vary from expert to expert as a function of their zonation, their upper magnitude cutoff and their recurrence relationships, but several trends are constant.

Expert Opinion

The variation in the uniform hazard spectra for individual experts (Figures 6-1d, 6-2d, 6-3d and 6-4d) can be broadly explained by identifying the major differences in input from expert to expert. The results from E_8 are consistently low because he specifies very low upper magnitude cutoff for the CSR. E_7 and E_9 provide a specific zone for northern Illinois. This concentrates the seismicity within that zone close to the sites and increases the hazard. E_5 specifies an

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upper magnitude cutoff of MMI-XII. This increases the hazard, but not to the extent that might be expected since recurrence slope is fairly steep (0.575 = 0.125). E_{10} has a very gentle recurrence slope (0.6 ±0.2) for New Madrid. This drives the hazard upward throughout the CSR.

Contribution from CSR and NMR

For a specific spectral ordinate the seismicity of the Central Stable Region is assumed practically uniform (except for E_7 and E_9) and therefore the CSR absolute contribution to the hazard is the same for each plant. Therefore, as the distance of the sites to the New Madrid Region increases, the exposure decreases and the relative importance of the CSR becomes more and more apparent. For example, considering the synthesis PGA at 1,000 year RP, the average contribution for each site is as follows:

	Contribution (%)	
	CSR	NM
DRESDEN	45	47
PALISADES	56	24
LACROSSE	82	25
BIG ROCK POINT	93	3

These zone contributions must be interpreted with caution since, as mentioned previously, they are exposure dependent.

Contribution Variation with Return Period

As the Return Period increases, the contribution to the hazard is shifted from low-level activity sources toward more seismic sources. This is presented below for Dresden and Palisades. This trend is general since, for long Return Period sources with low upper magnitude cutoffs contribute to the hazard only through the uncertainty in attenuation relationships whereas sources with higher seismicity still generate events. However, a number of parameters (level of seismicity, upper magnitude cutoff, distance) with competing effects mitigate the impact of this phenomenon. It is in general of little importance.

Variation of Source Contribution to Hazard (PGA) versus Return Period (%)

RETURN PERIOD (Years)	DRESDEN			PALISADES		
	200	1,000	4,000	200	1,000	4,000
Central Stable Region	60	61	58	68	79	82
New Madrid	34	35	40	12	13	15
Anna	4	--	--	18	7	2

Contribution Variation with Frequency

The contribution of the different sources varies greatly as a function of the frequency considered. As shown below, the effect of the New Madrid region increases dramatically with period.

Such a trend is expected since the energy of motion attenuates faster with distance in the high frequency range than in the low frequency. Hence the large earthquakes from New Madrid effect the distant sites mainly in the long period range corresponding to the surface waves.

Variation of Source Contribution with Frequency Content (1,000 year RP) (%)

		PERIOD (SEC)						
	PGA	0.04	0.1	0.4	1.0	2.0	PGV	MMI
Dresden								
CSR	58	68	70	46	25	8	17	17
NM	37	31	28	49	72	92	83	83
ANNA	5	1	2	5	3	--	--	--
Big Rock Point								
CSR	98	100	100	96	90	77	91	96
NM	2	--	--	2	9	33	9	4

Site Specific Factors Affecting the Results

As discussed above the contribution of different sources vary with frequency and return period. In the following discussion, a 1,000 year return period and frequency associated with PGA were chosen to evaluate the contribution.

DRESDEN

E_8 has a very low upper magnitude cutoff for CSR, which leads to a low exposure at the site and an apparent overcontribution for NM (87 percent for NM versus 13 percent for CSR). E_{10} has a gentle recurrence slope (.6) or for NM which gives a high exposure at Dresden and a high contribution from NM (59 percent) vs CSR (32 percent). The same ratio is recorded for E_{12} which has an average seismicity for NM and a low upper magnitude for CSR. For the other experts, NM contributes about 35 percent.

Anna has a rather low contribution, an average of 5 percent with a range from 0 to 9 percent. E_7 and E_9 have a specific source in northern Illinois and model the Sandwich fault explicitly. The contributions of their sources are very similar to each other: CSR (24 percent), northern Illinois (30 percent), Sandwich fault (7 percent).

PALISADES

For this site the influence of New Madrid is decreased in favor of CSR and Anna (20 percent). E_8, E_{10} and E_{12} stand out for the same reason as described above, CSR (40 percent) vs. NM (40 percent). The other experts show a much lesser influence of NM (16 percent) versus CSR (66 percent). The Sandwich fault only contributes for 1 percent.

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LACROSSE

The same trend as discussed above is accentuated at this site with E_8 and E_{10} giving CSR (65 percent) vs. NM (33 percent), E_{12} giving CSR (80 percent) vs. NM (20 percent) and the others CSR (85 percent or more) vs. NM (13 percent or less). For E_7 and E_9, the contribution is divided between CSR (63 percent) and northern Illinois (23 percent) with NM (14 percent). Anna and the Sandwich fault add a negligible contribution to the hazard.

BIG ROCK POINT

For this site the contribution of CSR is overwhelming (87 percent to 100 percent) and NM negligible (4 percent or less) except for E_{10}, CSR (81 percent) vs. NM (10 percent). The Upper Michigan Source contributes a few percent (5 or less) and Anna does not affect the site except for 3 experts (5 percent or less).

6.3 SSRS FOR SITES IN EASTERN UNITED STATES

The remaining five sites, Ginna, Connecticut Yankee, Millstone, Yankee Rowe and Oyster Creek, are located in the eastern United States. Strictly speaking, Ginna is located in the Central Stable Region but it is close enough to the eastern seismic sources to be influenced by them. The results for each site are presented in Tables 6-5 through 6-9 and Figures 6-5 through 6-9 respectively for the Ginna, Connecticut Yankee, Millstone, Yankee Rowe and Oyster Creek sites. The UHS results presented in the tables are those used as anchor points for the Newmark-Hall spectra and Scaled Time History Spectra. The MMI values presented in the tables are only appropriate for soil sites since, as discussed in Section 5.0, the intensity attenuation relation was developed exclusively for soil. An adjustment for the site type was made, in our model, directly to the ground motion parameter. Other things being equal, rock site intensities are usually slightly less than soil intesities; Medvedev (1965) provides a basis for this adjustment.

METHODOLOGY - GINNA - 200 YEAR RETURN PERIOD

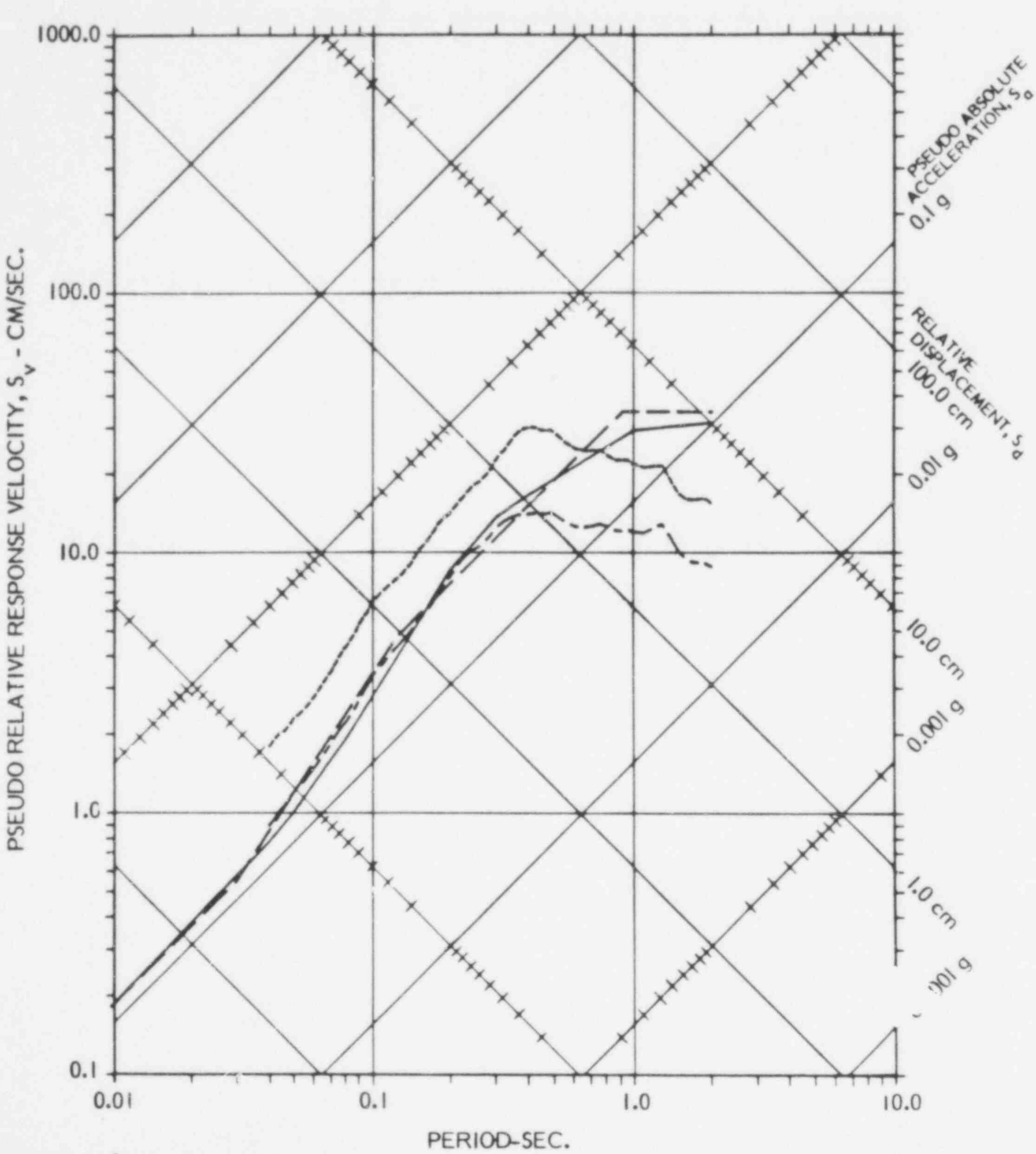
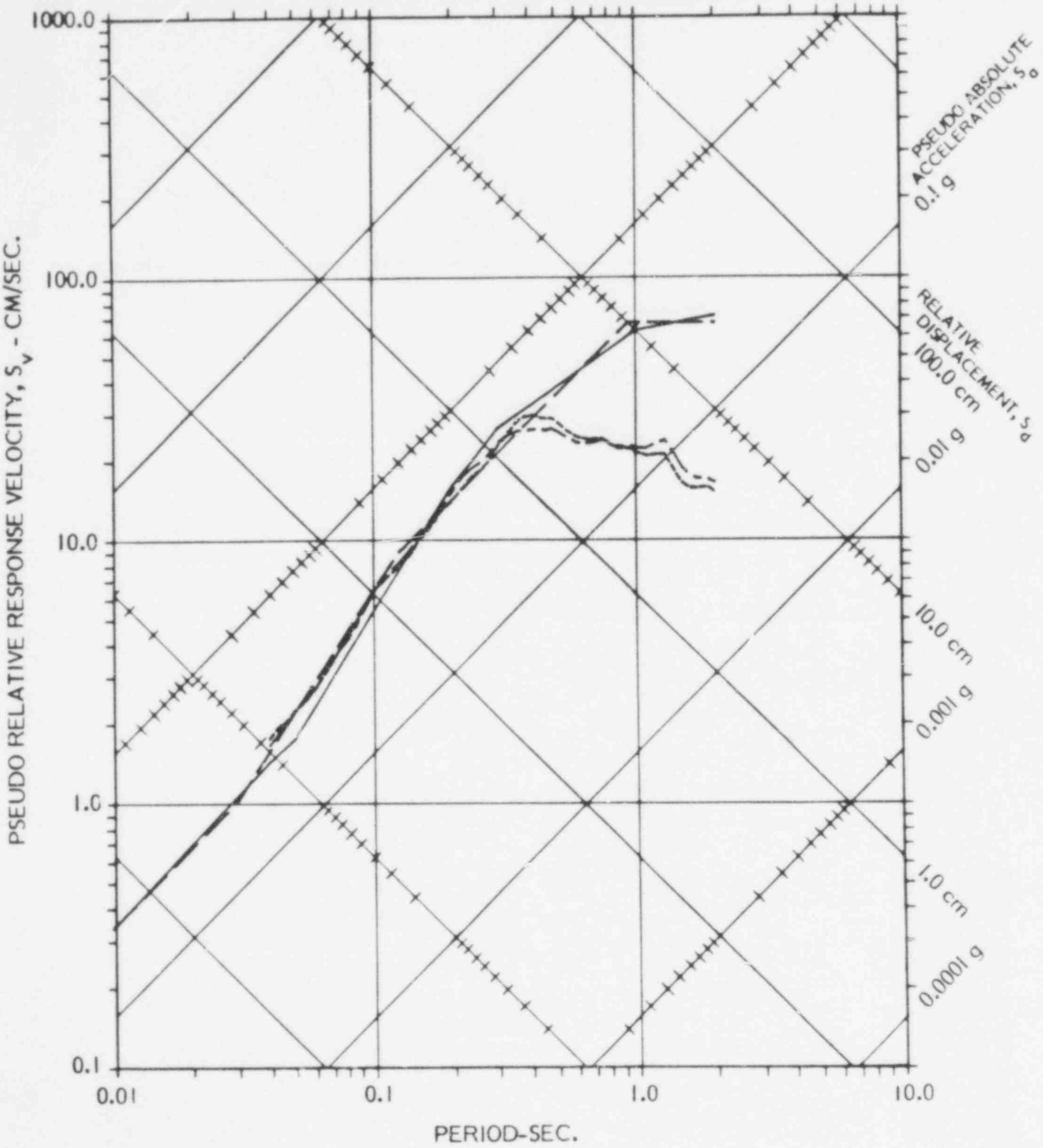


FIGURE 6-5a

923 254

METHODOLOGY -GINNA - 1000 YEAR RETURN PERIOD



—— Synthesis

— — Newmark-Hall

-------- Real Time History

—·—· Scaled Time History

FIGURE 6-5b

923 255

METHODOLOGY - GINNA - 4000 YEAR RETURN PERIOD

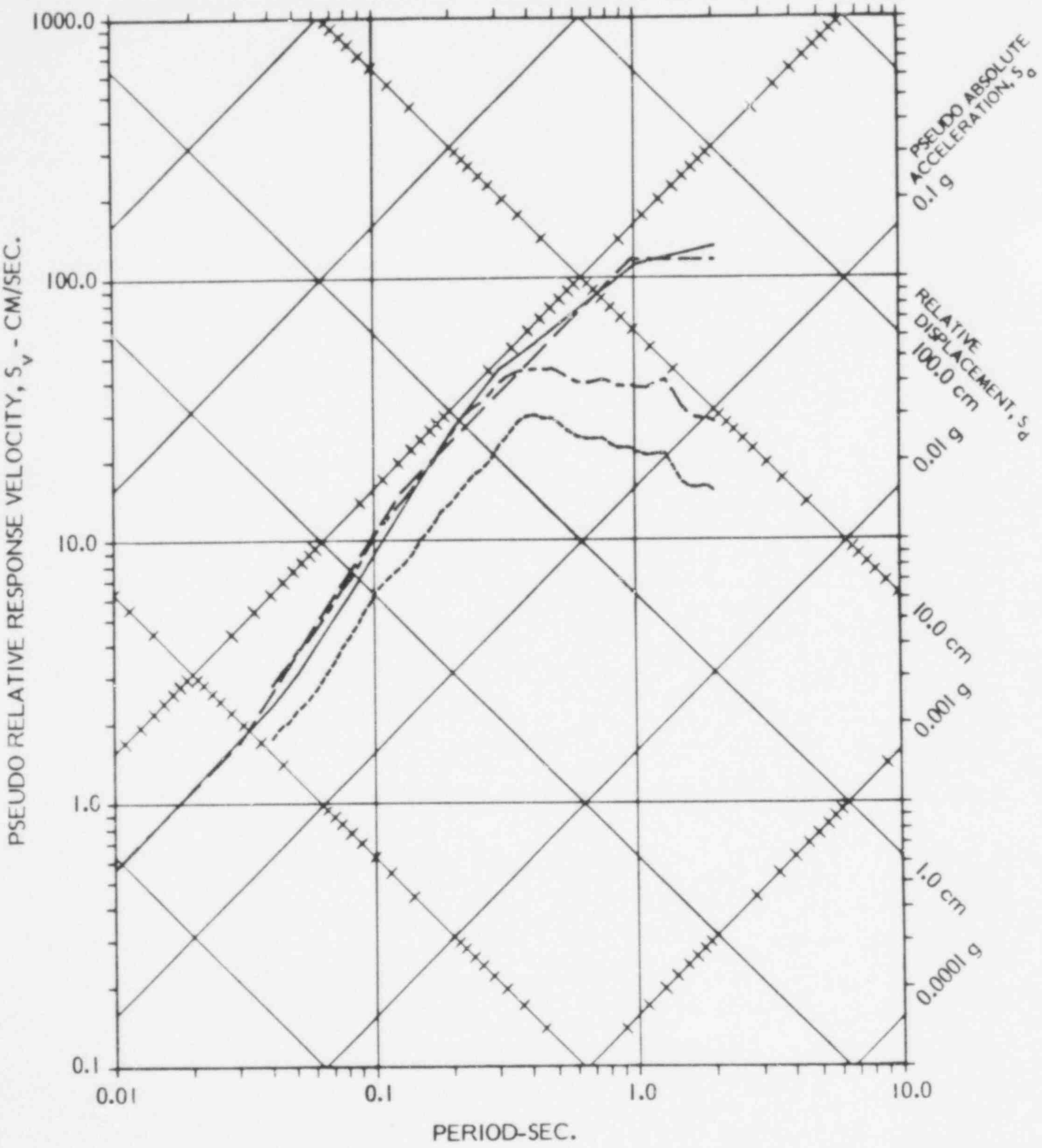


FIGURE 6-5c

923 256

ALL EXPERTS -- GINNA -- 1000 YEAR RETURN PERIOD

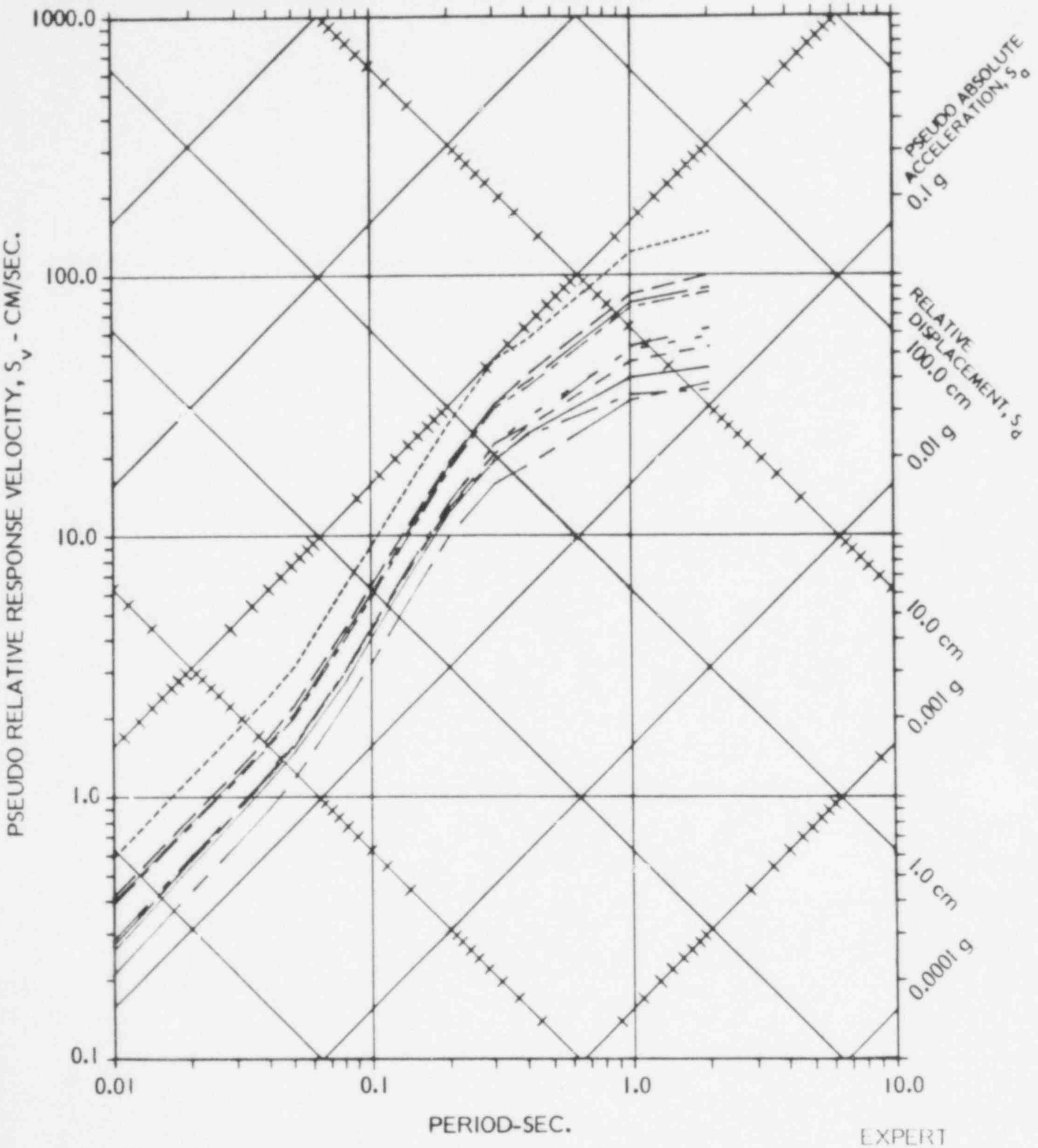


FIGURE 6-5d

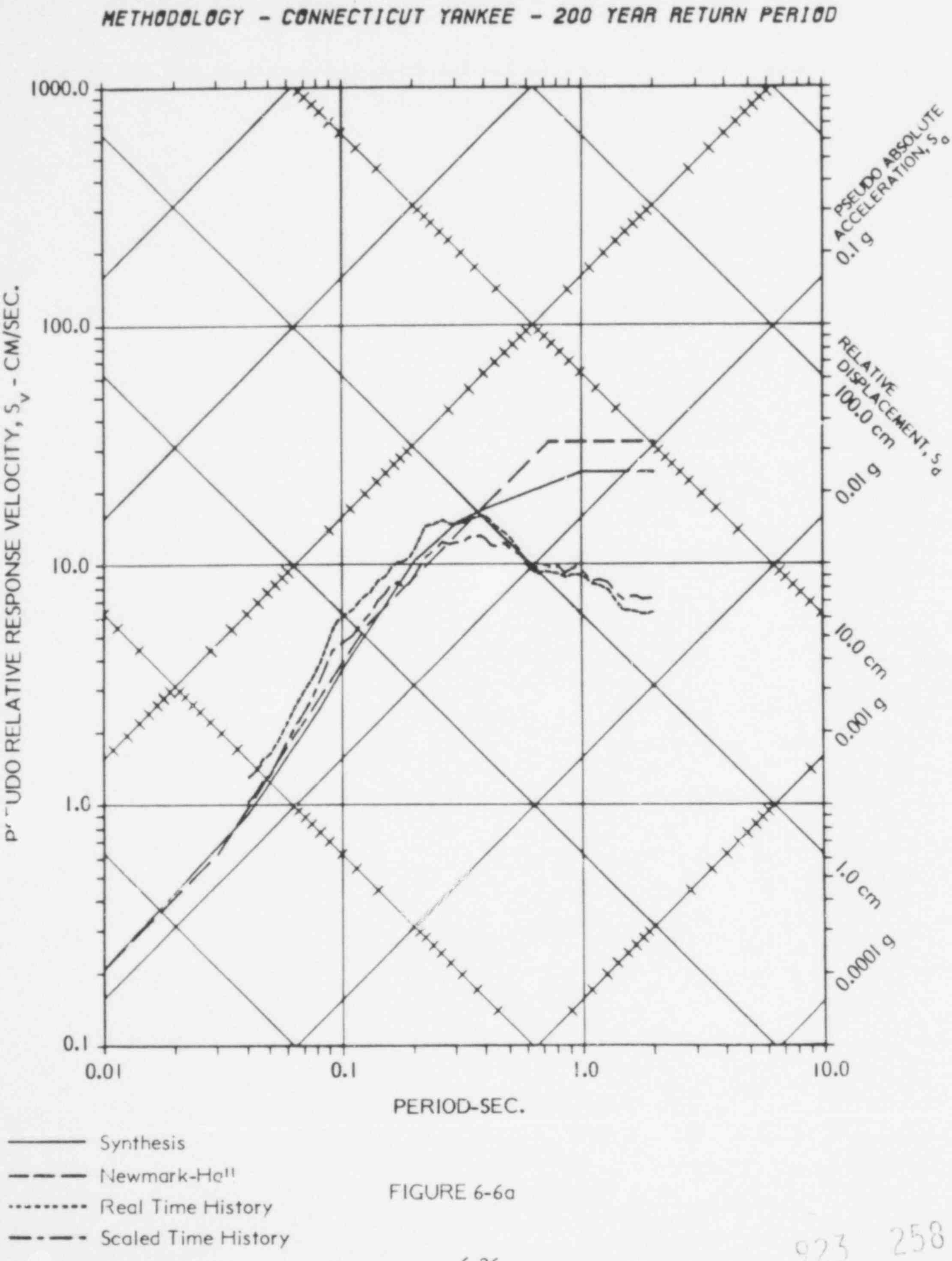
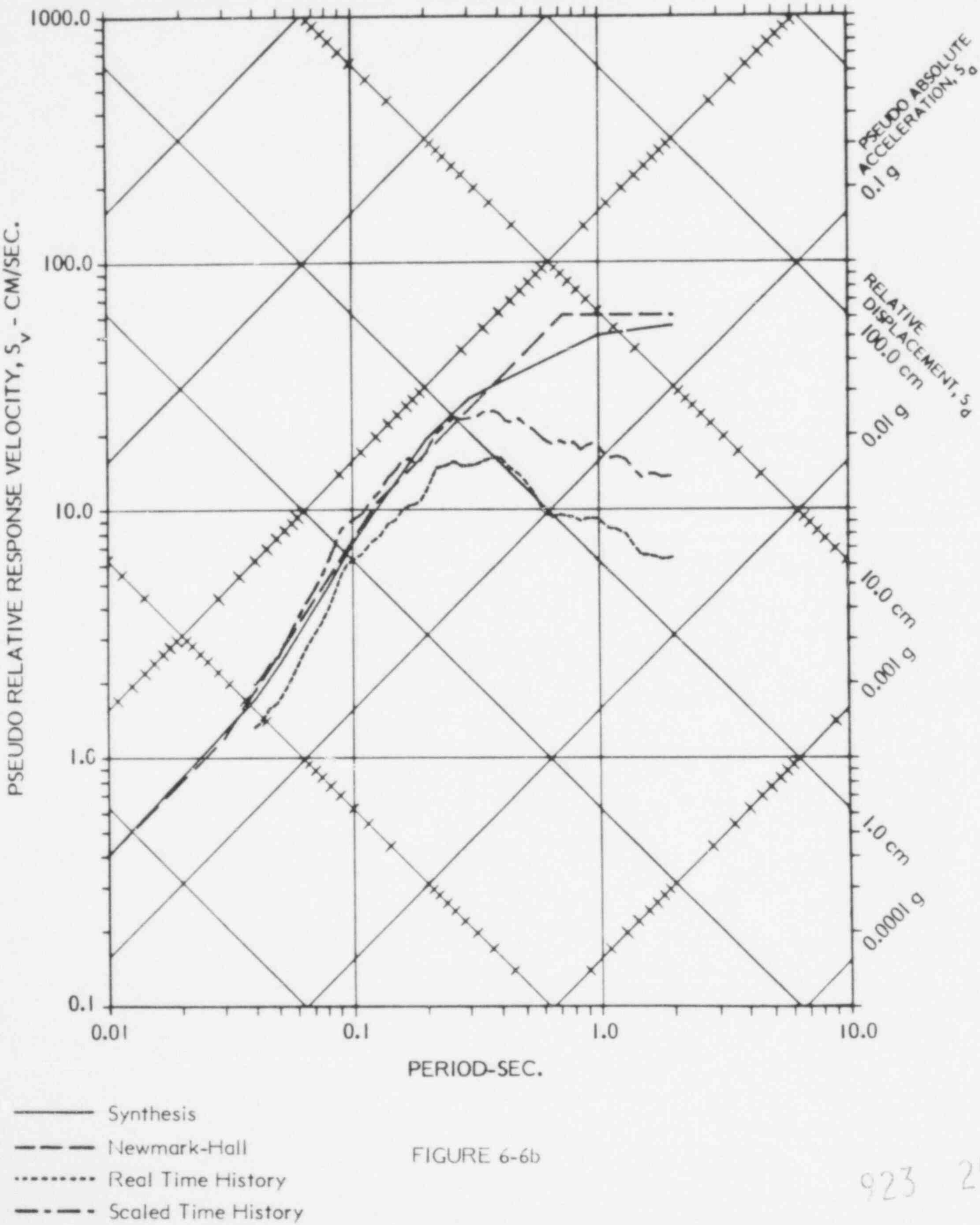


FIGURE 6-6a

923 258

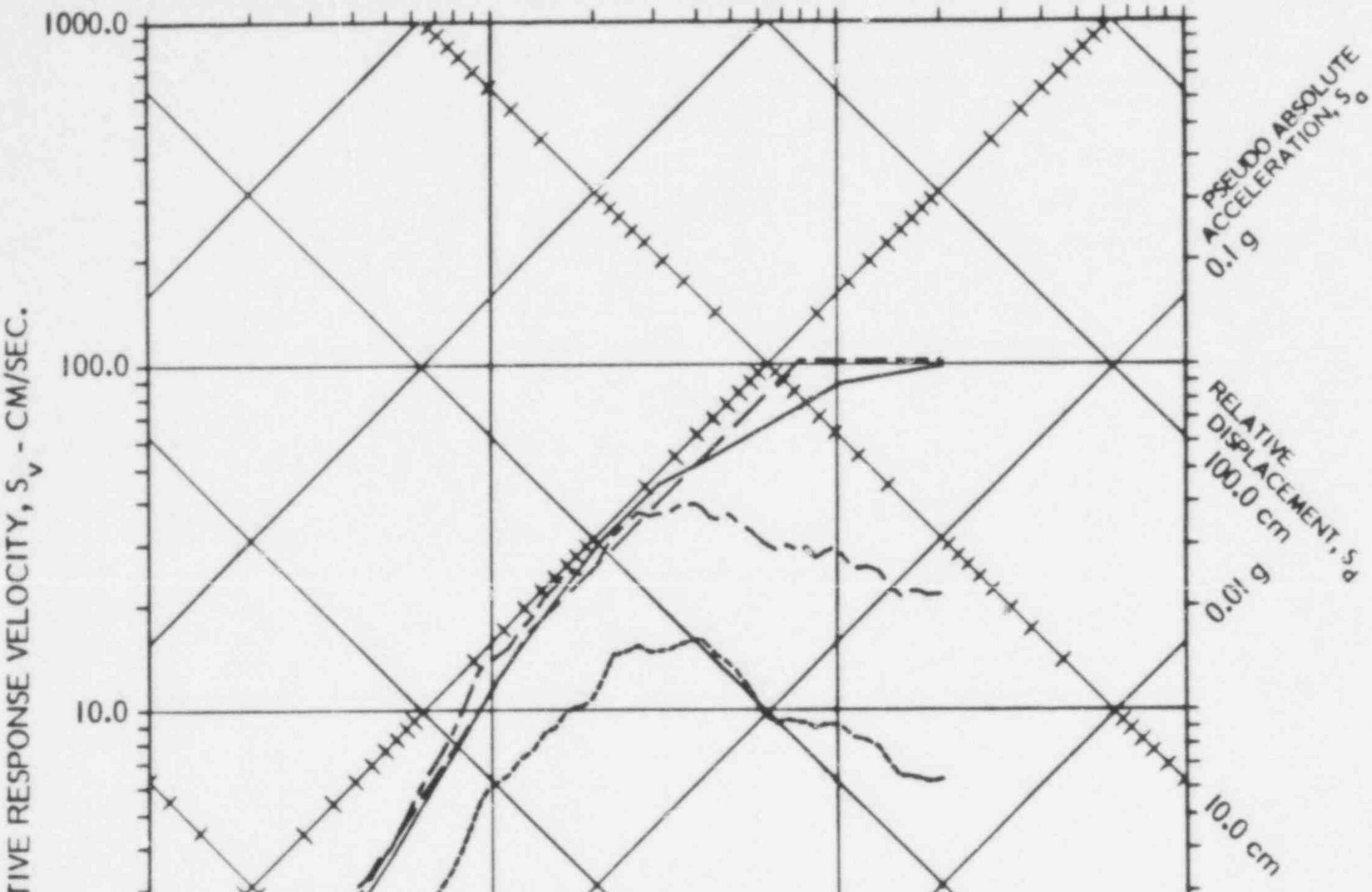


METHODOLOGY - CONNECTICUT YANKEE - 1000 YEAR RETURN PERIOD

FIGURE 6-6b

923 259

METHODOLOGY - CONNECTICUT YANKEE - 4000 YEAR RETURN PERIOD



——— Synthesis

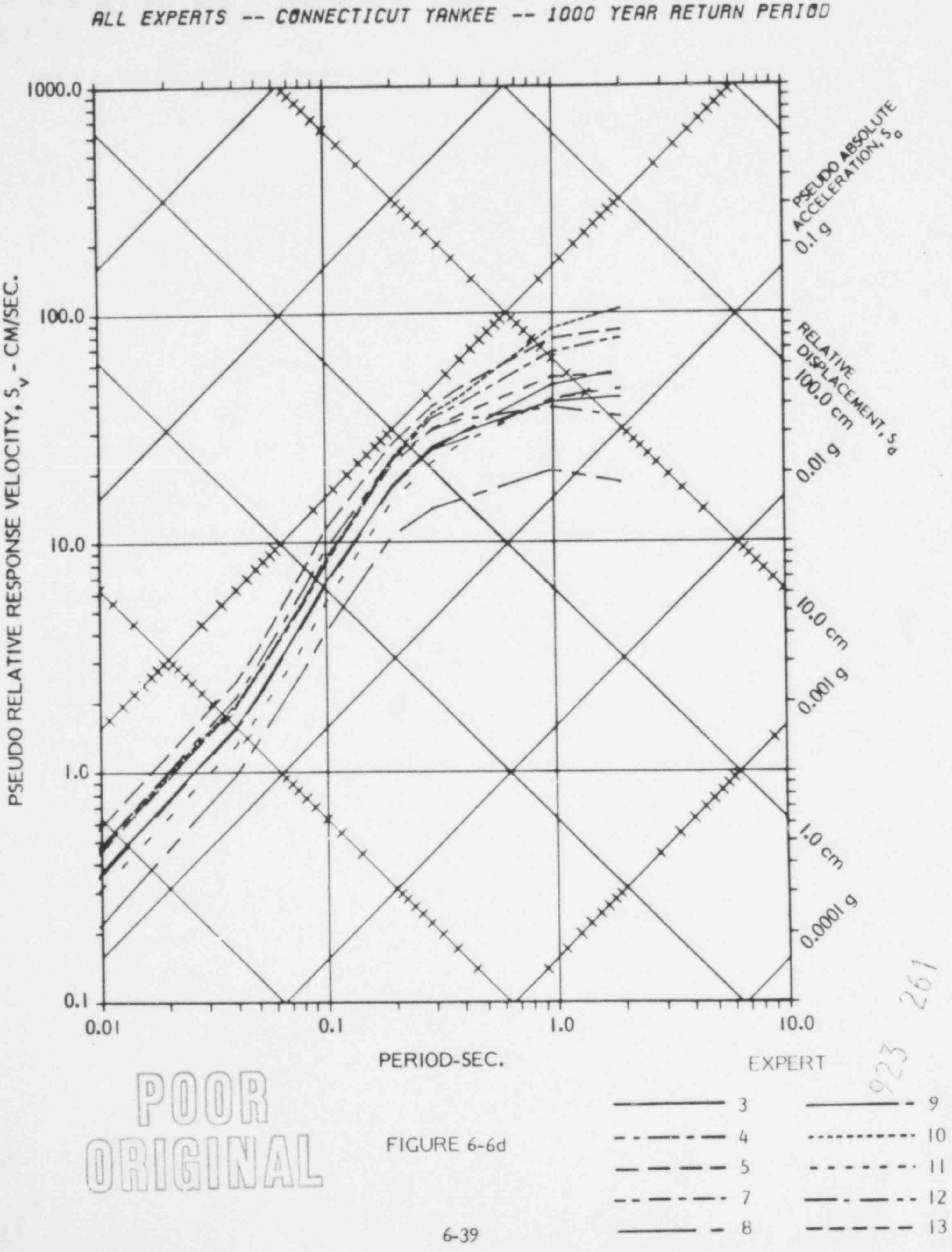
— — — Newmark-Hall

········ Real Time History

—·—·— Scaled Time History

FIGURE 6-6c

923 260



POOR ORIGINAL

FIGURE 6-6d

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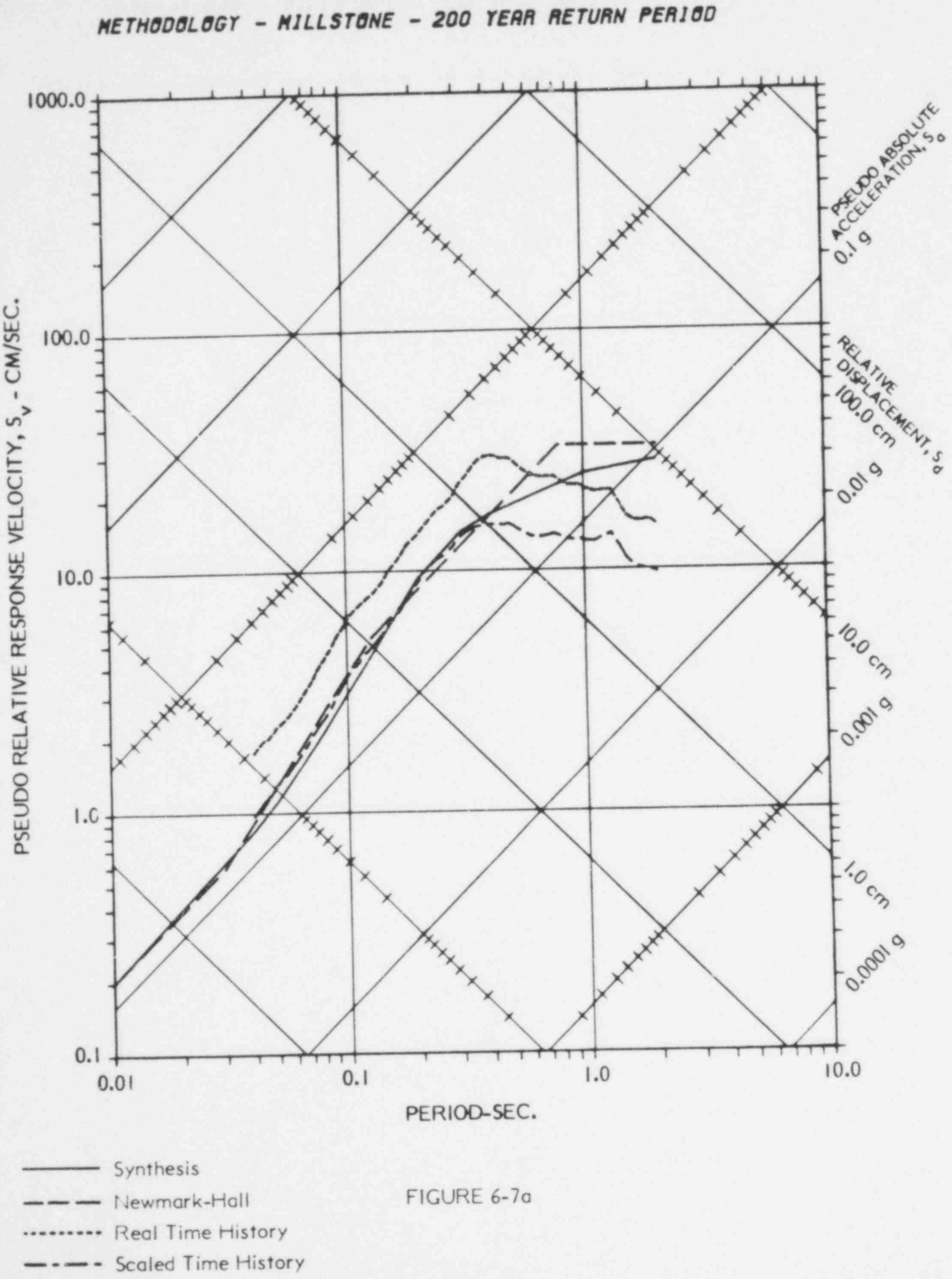
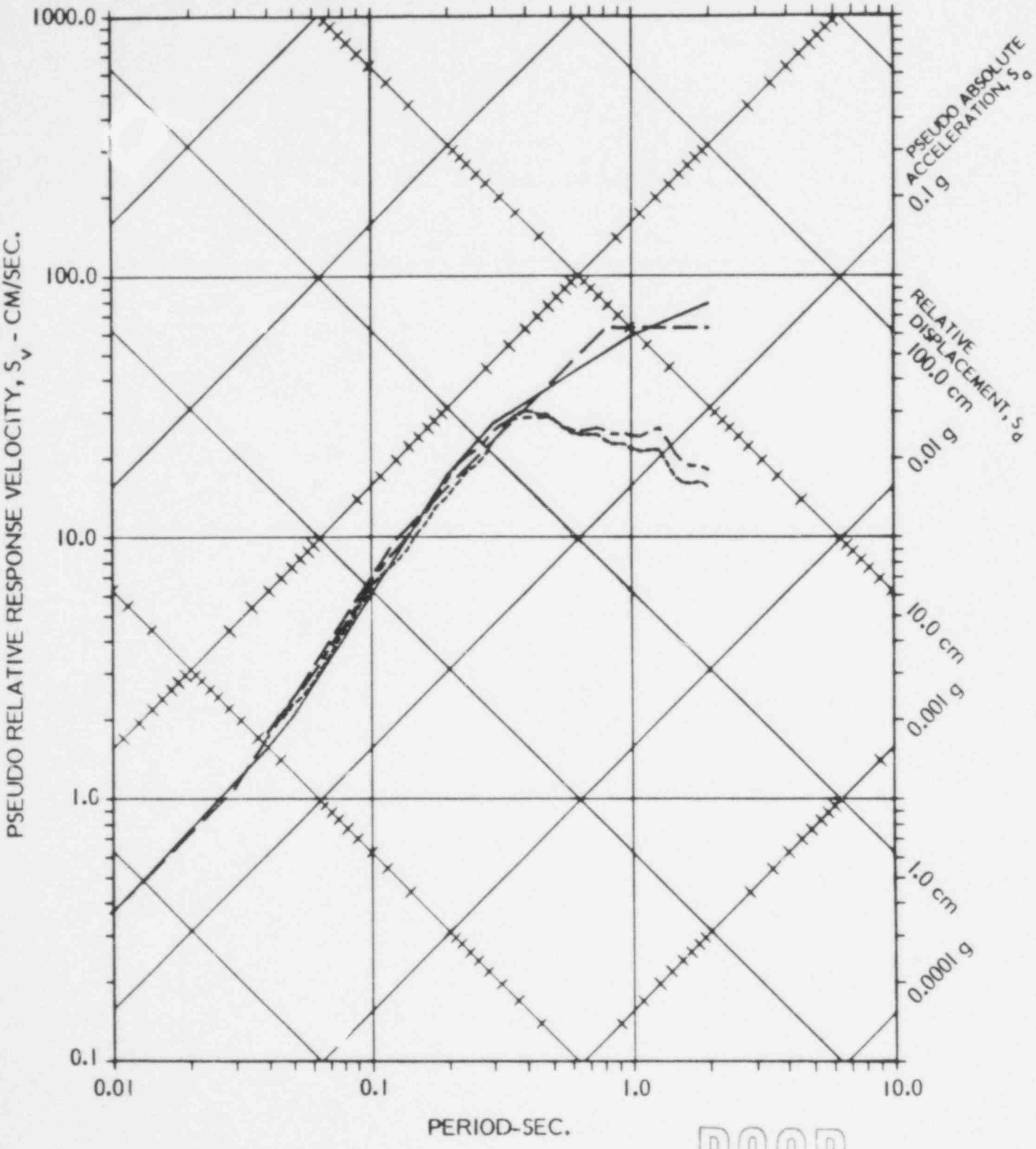

METHODOLOGY - MILLSTONE - 200 YEAR RETURN PERIOD
PSEUDO RELATIVE RESPONSE VELOCITY, S_v - CM/SEC.
1000.0
100.0
10.0
1.0
0.1
0.01
0.1
1.0
10.0
PERIOD-SEC.
PSEUDO ABSOLUTE ACCELERATION, S_a
0.1 g
0.01 g
0.001 g
0.0001 g
RELATIVE DISPLACEMENT, S_d
100.0 cm
10.0 cm
1.0 cm
Synthesis
Newmark-Hall
Real Time History
Scaled Time History

FIGURE 6-7a

METHODOLOGY - MILLSTONE - 1000 YEAR RETURN PERIOD



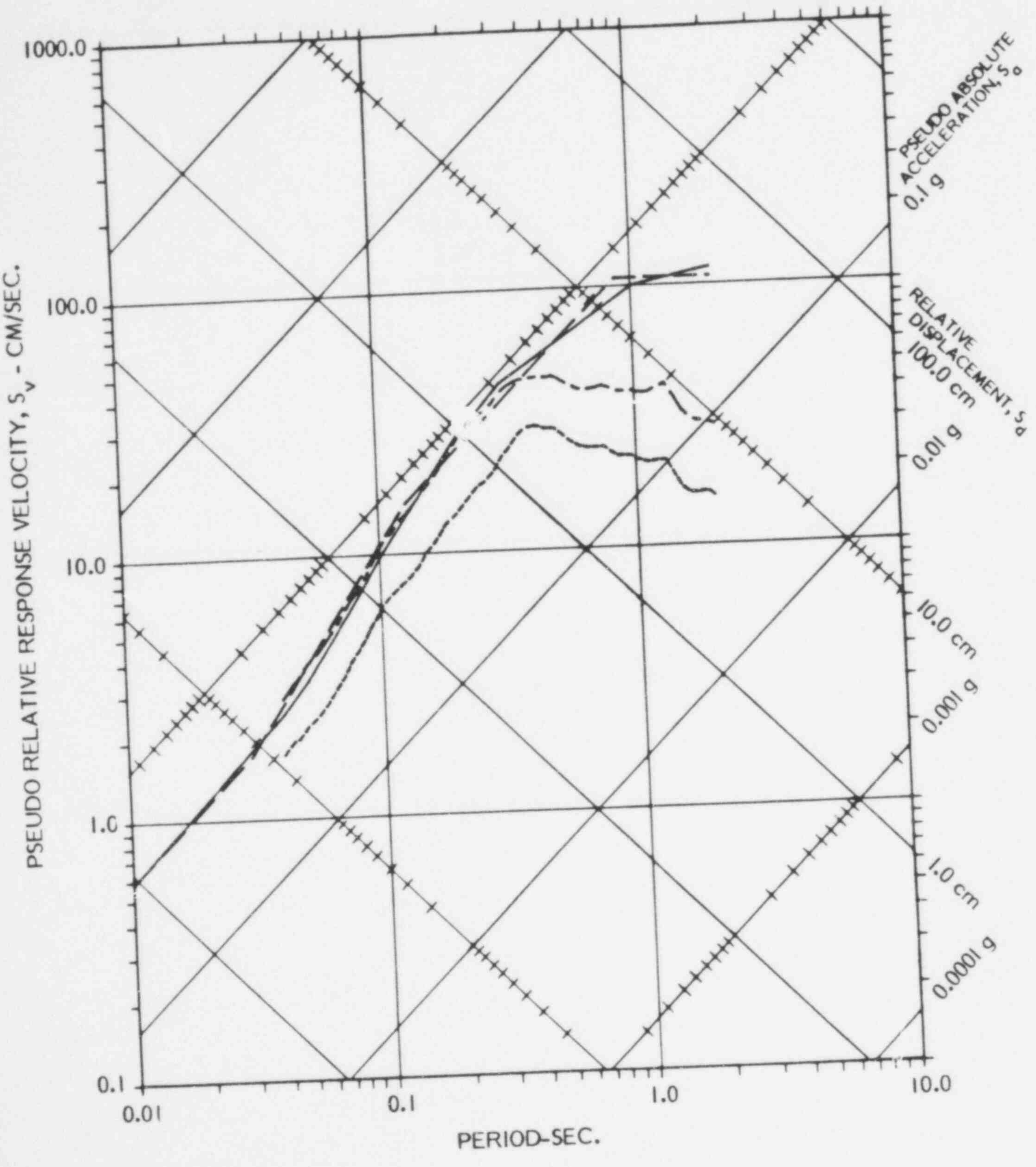
——— Synthesis
— — — Newmark-Hall
········ Real Time History
—·—·— Scaled Time History

FIGURE 6-7b

POOR ORIGINAL

923 263

METHODOLOGY - MILLSTONE - 4000 YEAR RETURN PERIOD



Synthesis
Newmark-Hall
Real Time History
Scaled Time History

FIGURE 6-7c

923 264

ALL EXPERTS -- MILLSTONE -- 1000 YEAR RETURN PERIOD

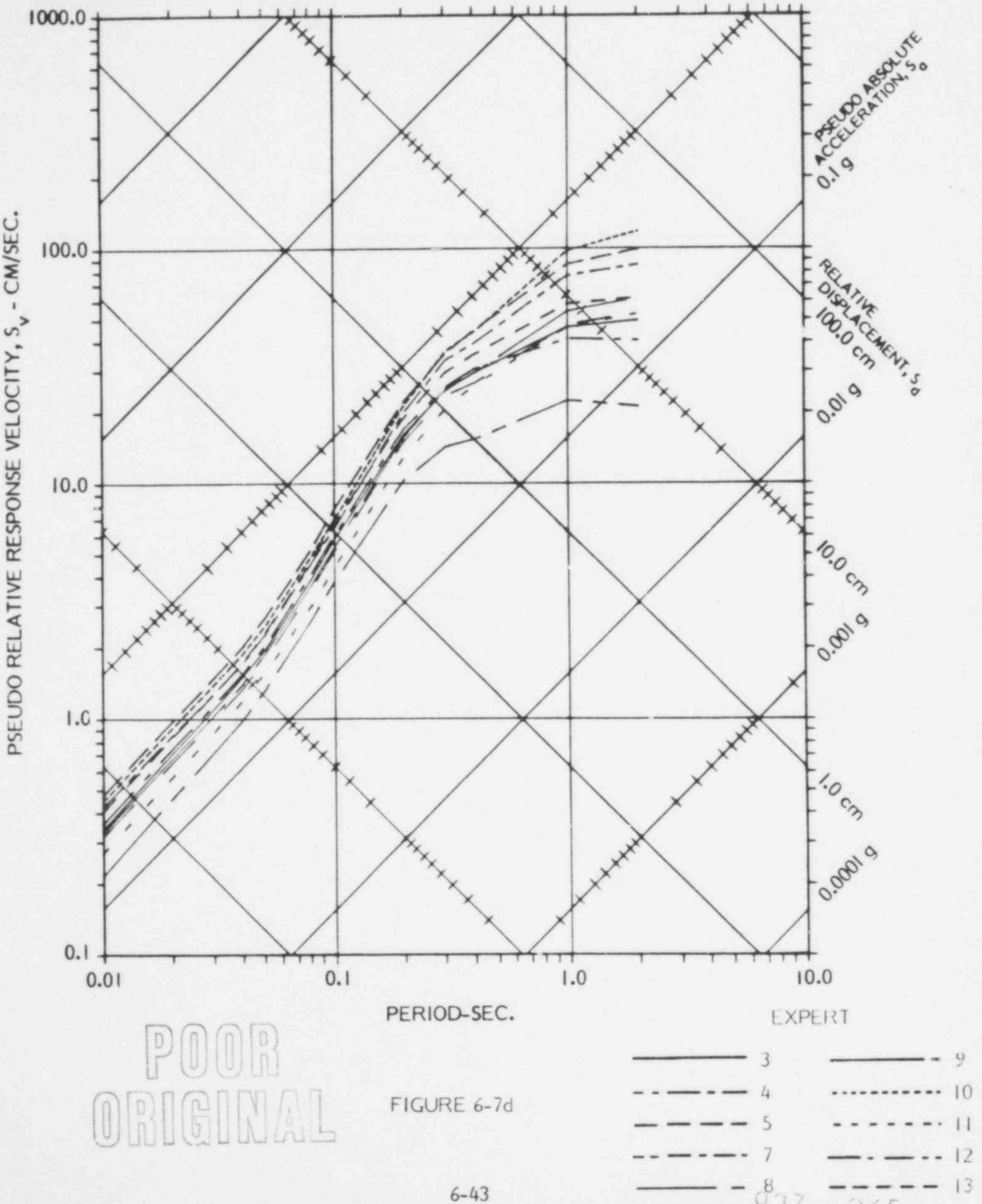


FIGURE 6-7d

METHODOLOGY - YANKEE ROWE - 200 YEAR RETURN PERIOD

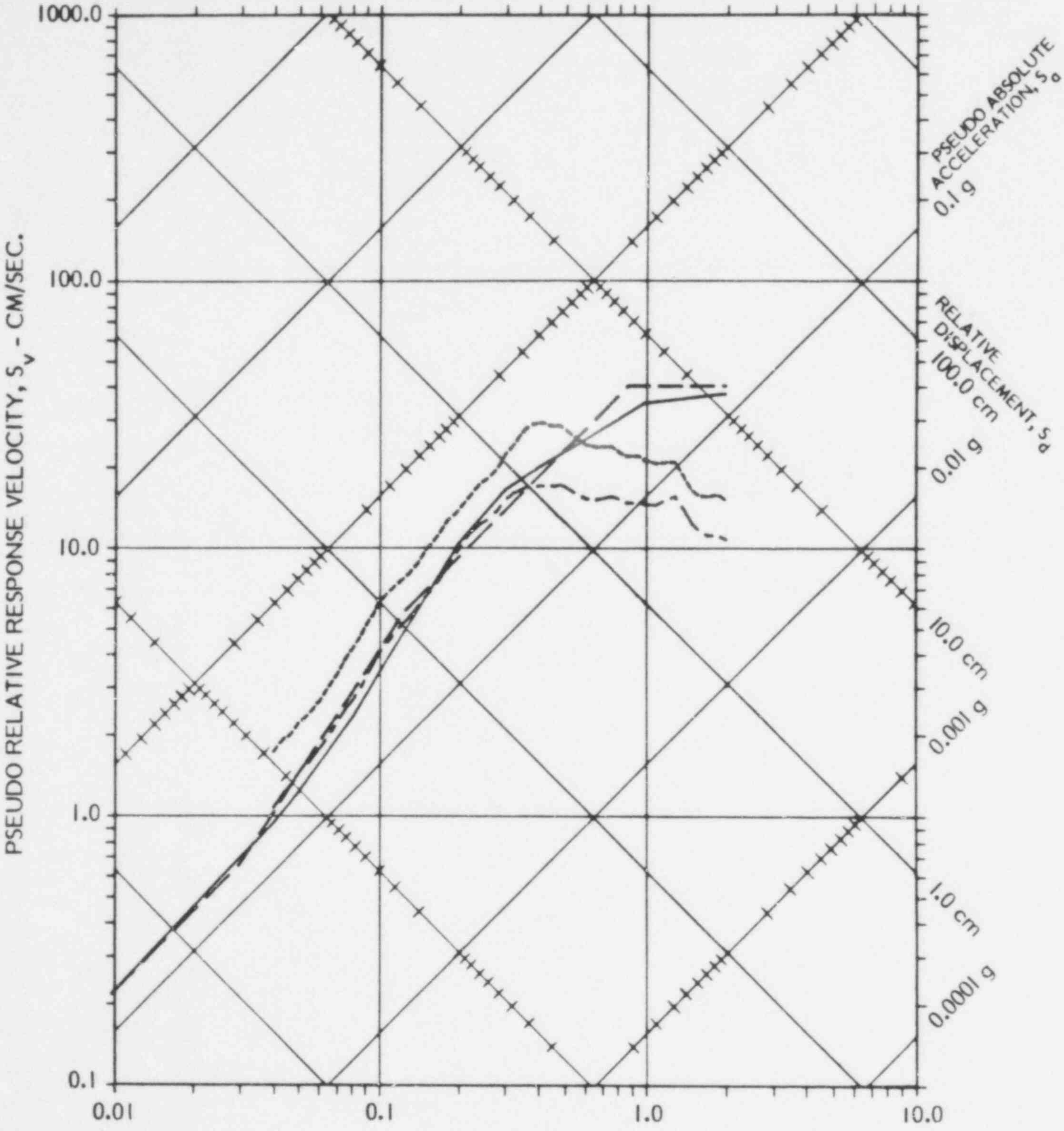
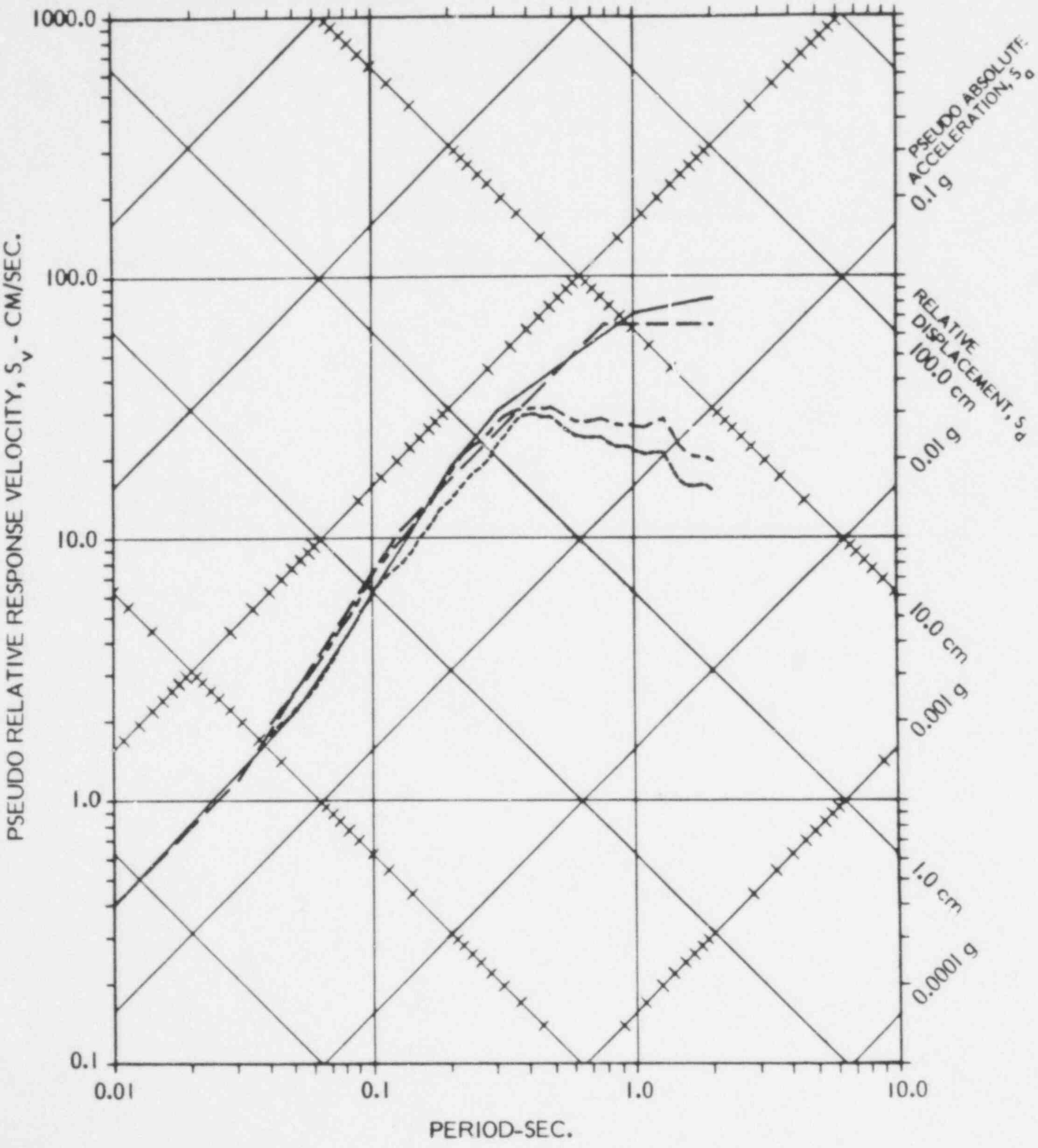


FIGURE 6-8a

METHODOLOGY - YANKEE ROWE - 1000 YEAR RETURN PERIOD



——— Synthesis
— — — Newmark-Hall
-------- Real Time History
—·—·— Scaled Time History

FIGURE 6-8b

923 267

METHODOLOGY - YANKEE ROWE - 4000 YEAR RETURN PERIOD

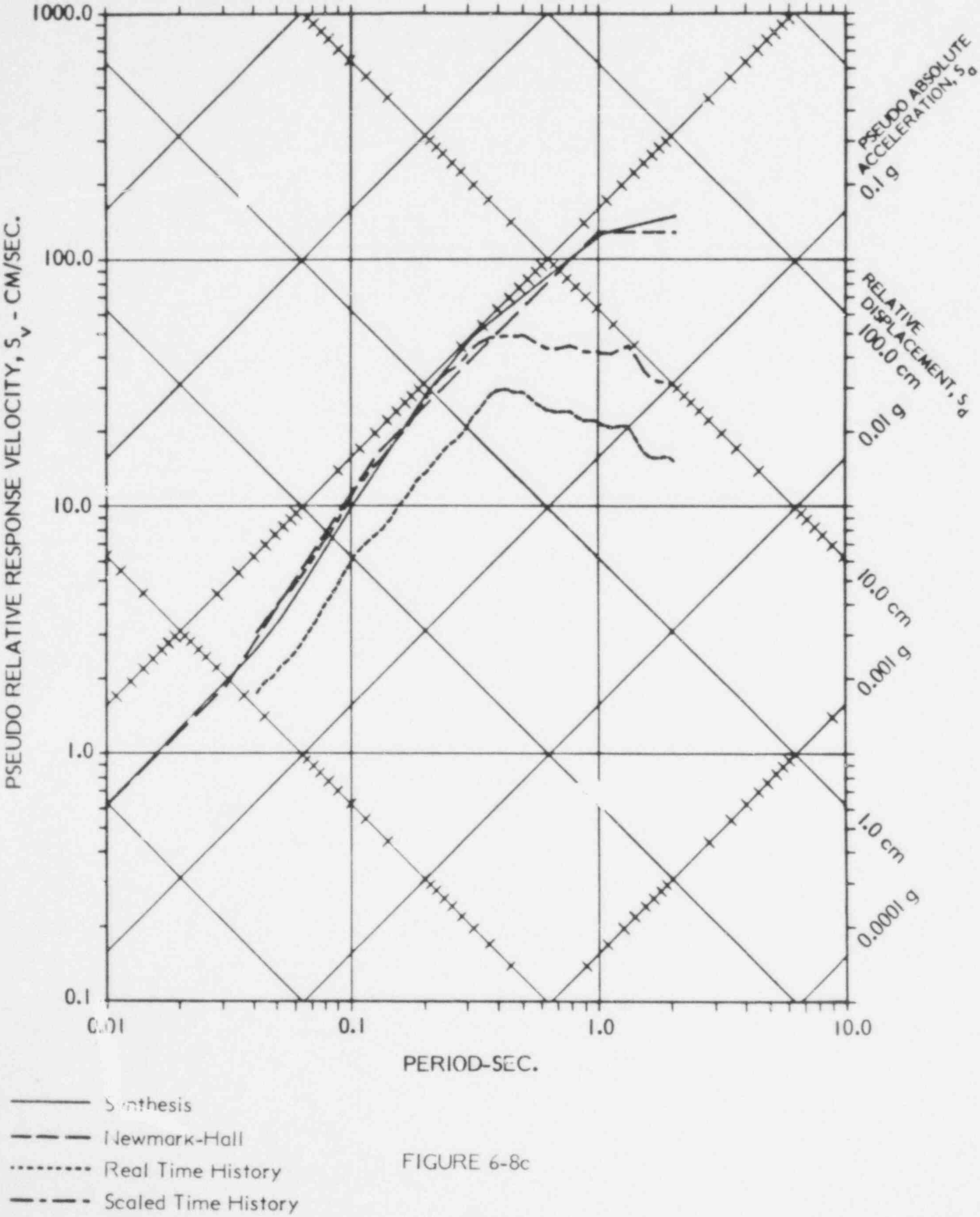


FIGURE 6-8c

923 268

ALL EXPERTS -- YANKEE ROWE -- 1000 YEAR RETURN PERIOD

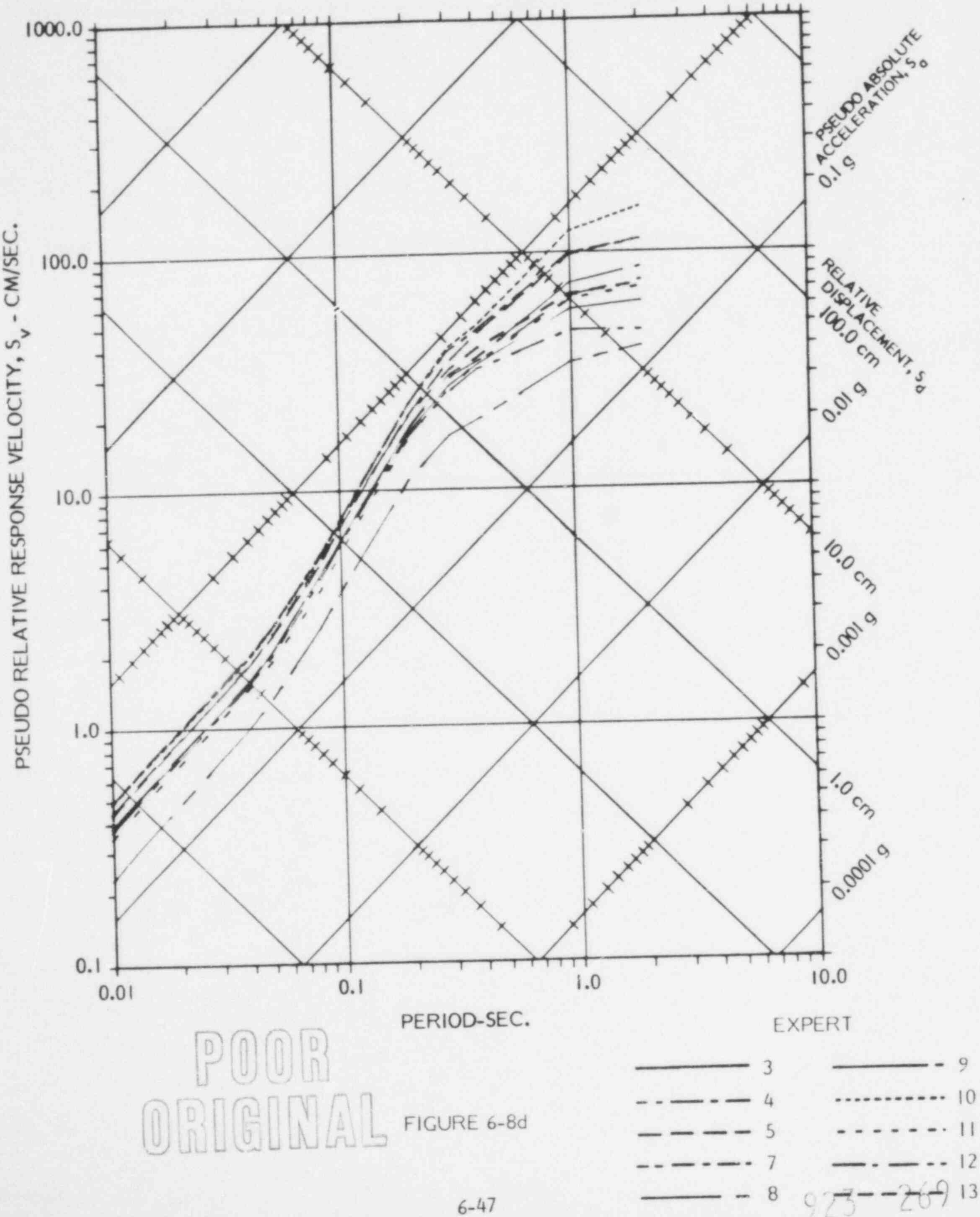


FIGURE 6-8d

923 269

METHODOLOGY - OYSTER CREEK - 200 YEAR RETURN PERIOD

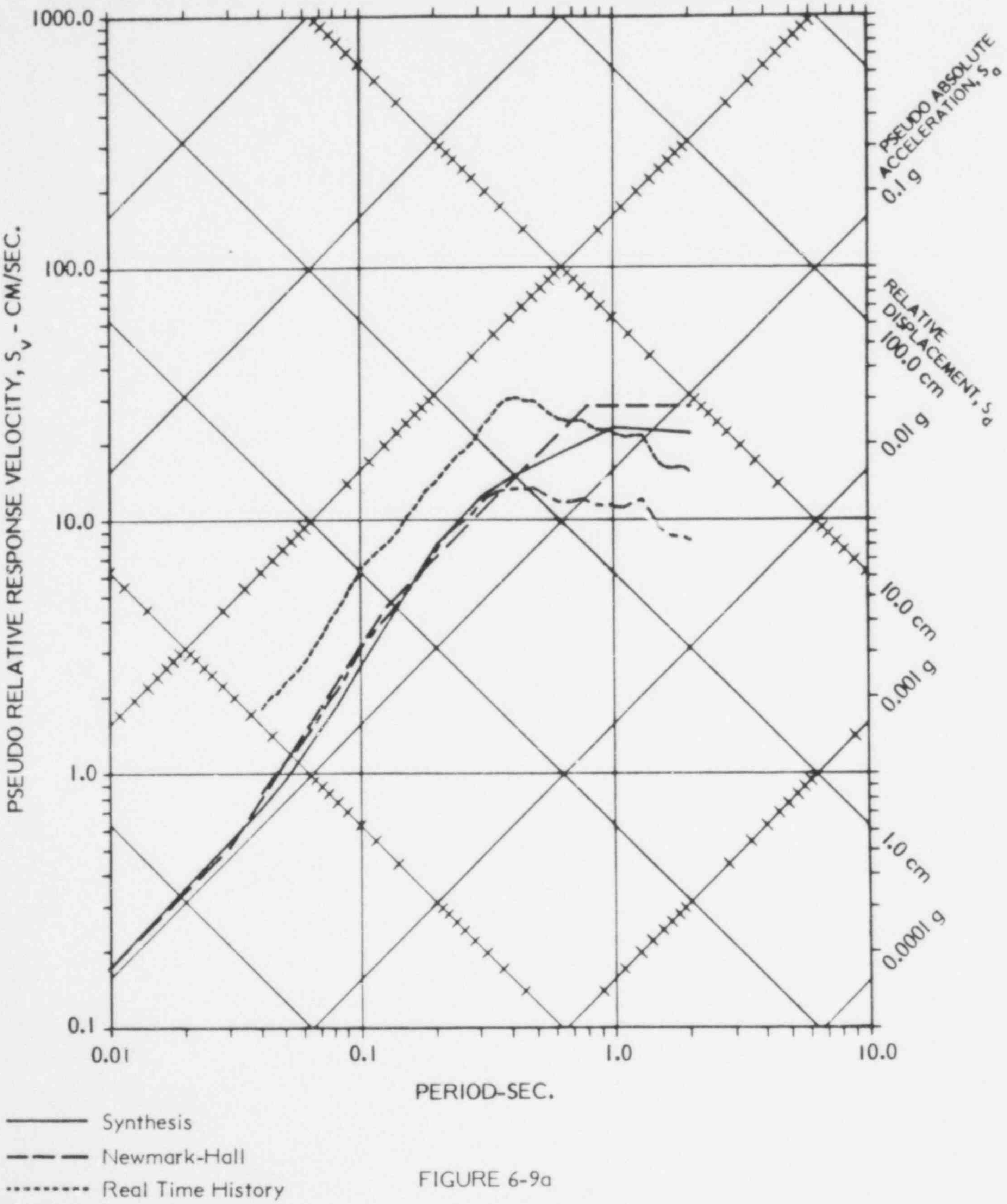


FIGURE 6-9a

923 270

METHODOLOGY - OYSTER CREEK - 1000 YEAR RETURN PERIOD

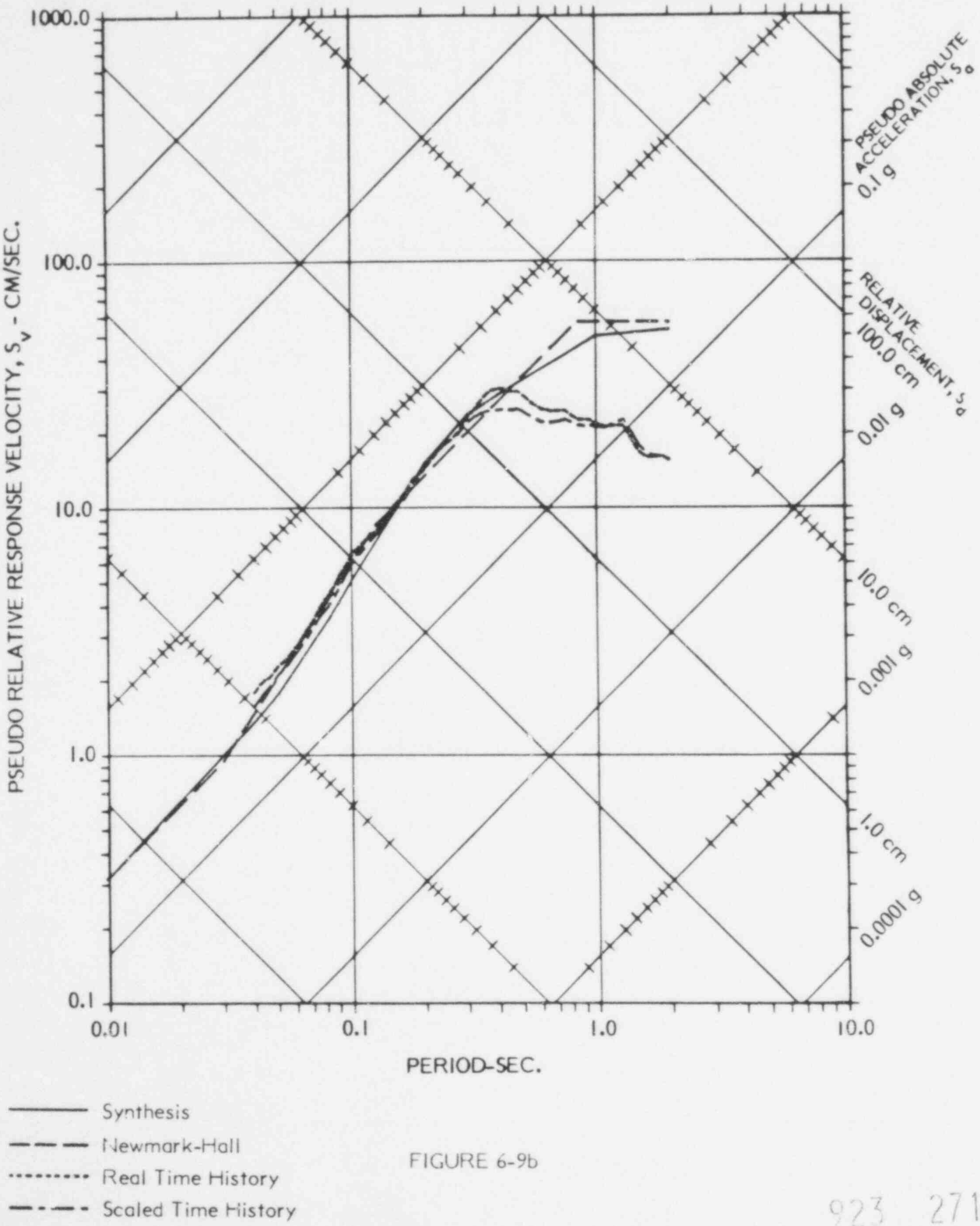


FIGURE 6-9b

923 271

METHODOLOGY - OYSTER CREEK - 4000 YEAR RETURN PERIOD

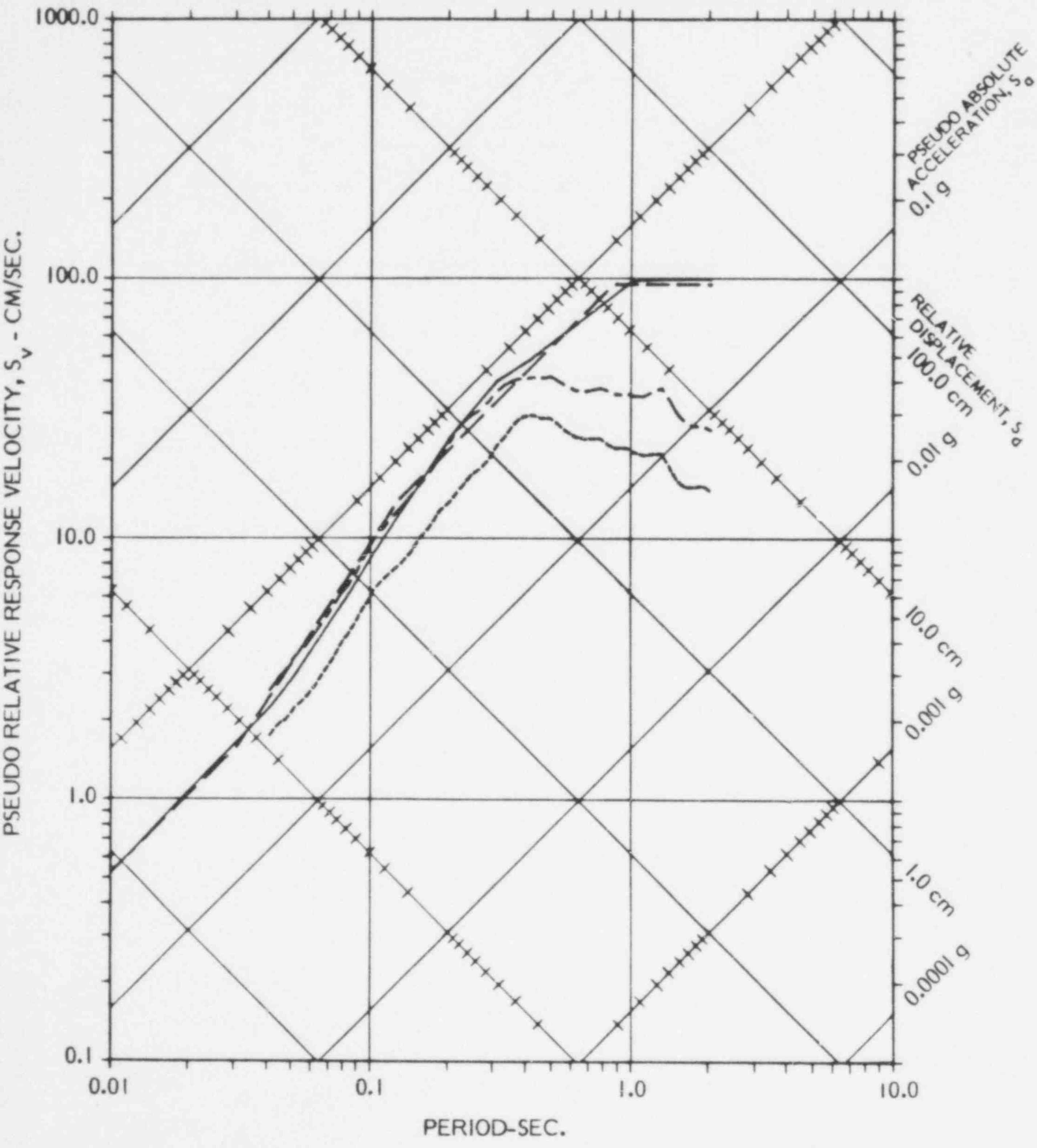
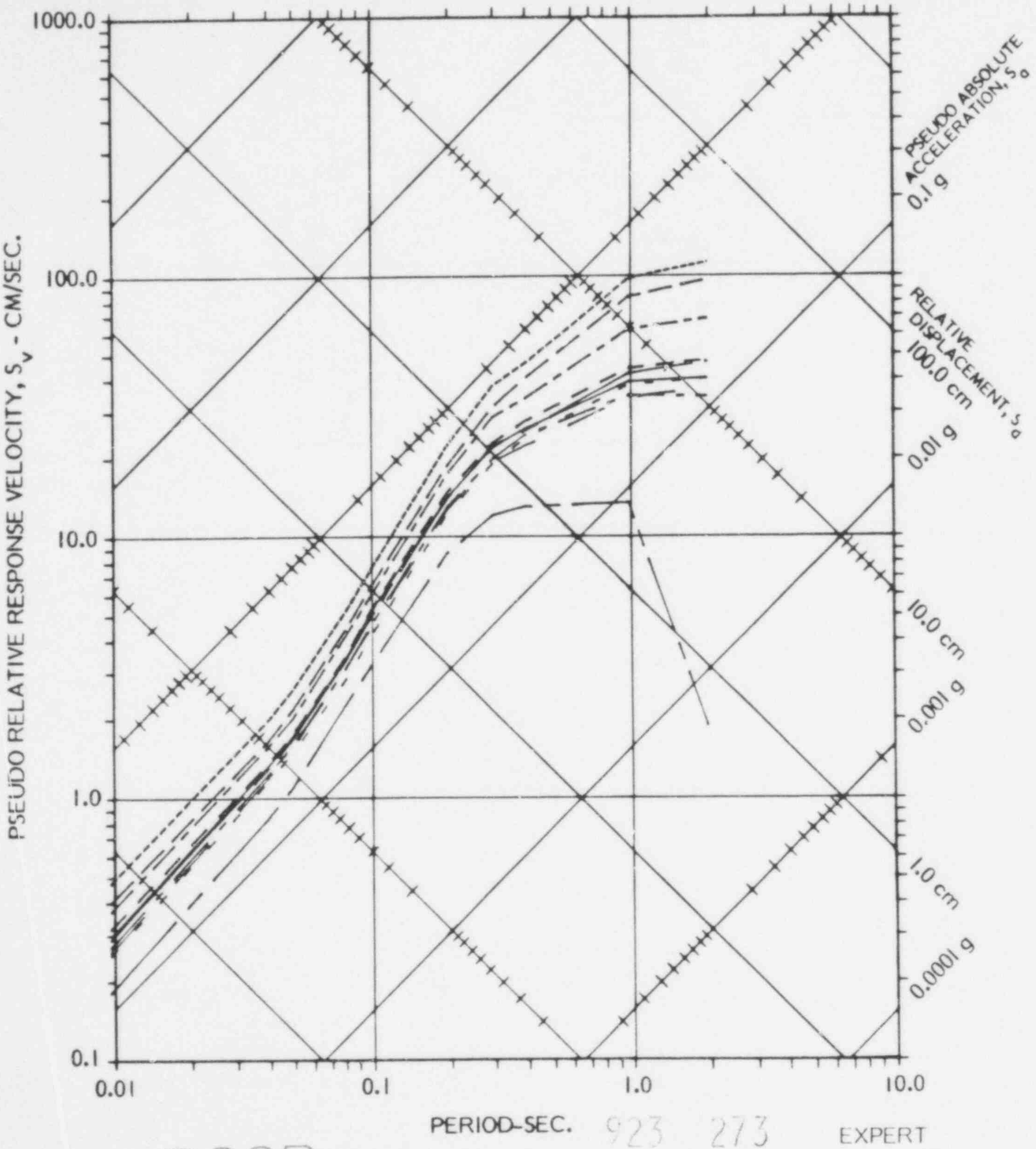


FIGURE 6-9c

923 272

ALL EXPERTS -- OYSTER CREEK -- 1000 YEAR RETURN PERIOD



923 273

POOR ORIGINAL

FIGURE 6-9d

TABLE 6-5

GINNA

PGA, PGV and MMI FOR 200, 1000, and 4000 YEAR RETURN PERIOD

RETURN PERIOD (YEARS)	200		1000		4000	
	SYNTHESIS	RANGE	SYNTHESIS	RANGE	SYNTHESIS	RANGE
PGA (cm/sec^2)	113	80-170	214	132-369	361	203-661
PGV (cm/sec)	21	13-35	41	24-76	71	34-131
MMI	6.4	5.8-7.3	7.1	6.3-8.1	7.6	6.5-8.7

923 274

TABLE 6-6

CONNECTICUT YANKEE

PGA, PGV and MMI FOR 200, 1000, and 4000 YEAR RETURN PERIOD

RETURN PERIOD (YEARS)	200		1000		4000	
	SYNTHESIS	RANGE	SYNTHESIS	RANGE	SYNTHESIS	RANGE
PGA (cm/sec^2)	135	86-167	252	135-359	404	189-668
PGV (cm/sec)	20	11-29	37	17-61	63	25-115
MMI	6.4	5.4-7.0	7.1	5.7-7.9	7.6	5.9-8.9

923 275

TABLE 6-7

MILLSTONE

PGA, PGV and MMI FOR 200, 1000, and 4000 YEAR RETURN PERIOD

RETURN PERIOD (YEARS)	200		1000		4000	
	SYNTHESIS	RANGE	SYNTHESIS	RANGE	SYNTHESIS	RANGE
PGA (cm/sec^2)	125	86-149	229	138-302	370	200-549
PGV (cm/sec)	20	10-29	38	17-61	65	23-122
MMI	6.4	5.3-6.9	7.1	6.7-7.8	7.7	5.8-8.8

TABLE 6-8

YANKEE ROWE

PGA, PGV and MMI FOR 200, 1000, and 4000 YEAR RETURN PERIOD

RETURN PERIOD (YEARS)	200		1000		4000	
	SYNTHESIS	RANGE	SYNTHESIS	RANGE	SYNTHESIS	RANGE
PGA (cm/sec^2)	141	99-166	254	151-317	398	204-505
PGV (cm/sec)	25	15-36	47	25-74	79	34-136
MMI	6.6	5.8-7.3	7.3	6.2-8.0	7.8	6.4-8.9

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TABLE 6-9

OYSTER CREEK

PGA, PGV and MMI FOR 200, 1000, and 4000 YEAR RETURN PERIOD

RETURN PERIOD (YEARS)	200		1000		4000	
	SYNTHESIS	RANGE	SYNTHESIS	RANGE	SYNTHESIS	RANGE
PGA (cm/sec^2)	106	69-137	199	115-300	337	170-567
PGV (cm/sec)	17	6-27	34	11-62	58	16-122
MMI	6.2	4.8-6.9	7.0	5.3-8.1	7.5	5.5-9.0

The figures of SSRS for each site are in four sets representing 200, 1,000 and 4,000 year return periods and the UHS for each expert at a 1,000 year return period. The first three figures each present four curves: the Uniform hazard Spectrum, the Newmark-Hall spectrum, anchored at two points on the UHS curve (peak acceleration and peak velocity), the Scaled Time History Spectra, anchored at one point on the UHS curve (peak acceleration) and the Real Time History Spectra, for selected records of mean magnitude 5.3. The STHS and RTHS are for soil sites except those for the Connecticut Yankee site which are for rock. All curves include a measure of uncertainty: the UHS, NHS and STHS by use of the UHM for spectral anchor points, and the RTHS through the use of the one sigma bound (84 percentile) of the data.

Regional Factors Affecting the Results

As discussed in Section 6.2, these results are presented according to the opinion of each expert on the contribution of his specific source of seismicity. The same general variation in return period and period of the spectrum is observed as previously discussed. However, the patterns are not as clearly defined due mainly to the complexity of the sources and the large variations from expert to expert in zonation and zone credibility. In general, the background zones in the east contribute a sizeable amount (10 to 30 percent) to the hazard at the sites. This is due to the rather low credibility experts assigned to source zones and also to a sometimes large number of earthquakes unaccounted for after each source seismicity was substracted from the background. In both cases these earthquakes were allowed to "float" over the whole background.

Expert Opinion

As in the central United States, the variation in the uniform hazard spectra for individual experts (Figures 6-5d, 6-6d, 6-7d, 6-8d, and 6-9d) can be broadly explained by identifying major differences in input from expert to expert. The results from E_8 are consistently low because he specifies very low upper magnitude cutoff for many sources. E_5 specifies an upper magnitude cutoff of MMI = XII for all sources, but since his recurrence slope is fairly steep (0.575 ±

0.125; MMI) the effect on the exposure is not as dramatic as could be expected. Most of the hazard for this expert comes from the background since he assigned low credibility to most of the other seismic sources. Finally E_{10} has very gentle recurrence slopes (0.6 ± 0.2) for several regions: Attica, Northern St. Lawrence, Appalachian Plateau and Atlantic Coastal Plain. This, in general, noticeably increases the exposure and gives large weights to those sources.

Site Specific Factors Affecting the Results

GINNA

Four sources are the main contributors for this site. The Attica source (30-40 percent for high frequency (HF) down to 10-30 percent for low frequency (LF)), the background (25-50 percent down to 15-25 percent for high and low frequency, respectively). For more distant sources the contribution increases with period. The contribution of sources varies from 5-27 percent (HF) to 25-40 percent (LF) for Southern St. Lawrence and from 1-10 (HF) percent to 6-25 percent (LF) for Northern St. Lawrence.

A few anomalies are worth noting: for E_8 the contribution of the Southern St. Lawrence source jumps to 75 percent for T = 2.0 sec due to a comparatively high upper magnitude in that source. For E_5, 60 percent of the exposure comes from the background for the whole frequency range.

CONNECTICUT YANKEE AND MILLSTONE

Due to their proximity the contribution to the exposure of these two sites from the different sources is very similar. Three main regions contribute to their seismic hazard: the Piedmont, the combination of Cape Ann, Maine and Boston-Ottowa regions, and finally the background. The Atlantic Coastal Plain, Southern St. Lawrence and Adirondack contribute to a lesser extent. The Piedmont Region is the major contributor with 12-50 percent (HF) down to 6-45 percent (LF). Cape Ann contributes mainly in the low frequency range with 8-22 percent (HF) to 14-40 percent (LF). Maine is only specified by a few experts and gives 9-14 percent (HF) to 1-20 percent (LF), while the contribution of Boston-Ottowa is somewhat constant over the whole frequency range (10-15 percent). The background contribution varies from 14-40 percent (HF) to 12-20 (LF). The Atlantic Coastal Plain is somewhat less important than expected due to the rather low upper magnitude cutoff and zone credibility: 5-15 percent (HF) to 0-5 percent (LF). The influence of the Southern St. Lawrence varies greatly from expert to expert: 0-6 percent (HF) to 0-20 percent (LF). The contribution of Adirondack never goes beyond 5 percent.

For E_4, one zone covering Cape Ann and part of the Piedmont contributes for about 40 percent of all periods. The particular zonation of E_5 gives the following distribution: Background 45 percent (HF) to 65 percent (LF); Green Mountain zone 30 percent (HF) to 7 percent (LF) and Piedmont 15 percent (HF) to 10 percent (LF). The low upper magnitude cutoff of E_8 make the Northern and Southern St. Lawrence zones stand much above the average at long periods: 53 percent and 30 percent respectively. The recurrence slope of 0.6 for the Atlantic Coastal Plain (E_{10}) increases its influence for long periods (20 percent). Finally the localized zone of E_{13} in the northern part of the Piedmont increases the influence of that area: 68 percent (HF) to 45 percent (LF).

YANKEE ROWE

Due to its proximity to the apparently complex tectonic function of New England, the experts' opinion about the contribution of each source varies. Thus a more detailed sensitivity analysis would be required to determine the impact of each of them in a more quantitative manner. Three major contributors are observed: the Piedmont, the New England zones, including in particular Cape Ann and Boston-Ottowa, and the Background. Adirondack remains at all times a rather low contributor. The contribution of the Piedmont varies from 16-40 percent (HF) to 10-30 percent (LF) except for E_8 for which it varies from 5 percent to 0. Cape Ann and its alternate zones contribute for 10-40 percent (HF) to 10-35 percent (LF) except for E_3 (5 to 12 percent).

The influence of the Boston-Ottowa zone goes from 7-18 percent (HF) to 10-38 (LF) except for E_{10} (4 percent). The Background contributes from 14-37 percent (HF) to 13-25 (LF) and Adirondack from 5-10 (HF) to 3-7 (LF).

For some experts ($E_{4, 10, 11, 12}$) the Southern zone has a noticeable effect of 8-19 percent (HF) to 19-23 percent (LF). For E_{10} the Northern St. Lawrence influence varies from 9 percent to 27 percent. Finally due to the usually low upper magnitudes of E_8 both Northern and Southern St. Lawrence zones become very important in the long period range 37 and 40 percent, respectively. Due to the particular function of E_5 the Background takes an unusually large importance of 60 percent.

OYSTER CREEK

For this site, three sources are well defined major contributors: Background, 25-60 percent (HF) to 25-55 percent (LF); Piedmont, 15-45 percent (HF) to 10-50 percent (LF); and the Atlantic Coastal Plain, 11-33 percent (HF) to 4-34 percent (LF).

Again for E_5 the Background stands out as the primary contributor at 77 percent, and for E_8 the Northern and Southern St. Lawrence become important at long periods: 64 percent and 36 percent, respectively.

6.4 CONCLUSIONS

This report has compared four possible techniques for generating site specific spectra. It has been emphasized that there are important differences between these approaches that are manifested in the differences between the spectra presented in this section. Summarily, the four approaches appear to yield <u>spectral shapes</u> that are, broadly speaking, comparable or at least their differences explainable. On the other hand, there is much less basis for comparing the important spectral anchor points predicted by the UHM; recall that both the

Newmark-Hall and the Sealed Time History Spectra were all normalized to the PGA estimate. The PGA is such a provocative parameter due to its precedent and use as a scale parameter, that the predictions from this study deserve special comment.

First of all, we note that the level of predicted PGA is quite high in the northeastern U.S. relative to central U.S. This regional difference results mainly from a much greater uncertainty in northeastern U.S. seismotectonics by the expert panel. Recall that in the UHM, even if the means are equal, a greater uncertainty is translated into a higher value. A review of the seismotectonic maps provided by the experts (TERA, 1979) will graphically illustrate the differences among experts which demonstrates the greater uncertainty. While it is obvious from the expert panel that objective data in this area are limited, it is not obvious that the underlying natural phenomena are inherently this uncertain. Therefore, additional investigations which would reduce this uncertainty should dramatically reduce these PGA predictions.

A second major point is that there is an inherent conservatism contained in a uniform hazard spectra since real structures and systems are not single degree of freedom oscillators. This conservatism must be taken into account in interpreting the results. The nature of the conservatism, which was described in detail in the TERA report on methodology development (TERA, 1979) effects not simply the PGA, but <u>all</u> of the spectral ordinates. It is noteworthy that the sensitivity results presented in this section suggest that the conservatism is independent of frequency (Figures 4-2 and 4-3), thus reinforcing the value of these spectral shape predictions. The suggestion of Figures 4-2 and 4-3 is, therefore, that there is a margin of conservatism contained in the PGA prediction. Additional analysis into UHS conservatism and more sensitivity studies would permit, if necessary, more specific conclusions at particular sites.

A third topic that strongly influences the PGA (as well as other spectral ordinates) is the model for dispersion about the mean attenuation predictions. While the dispersion used in this analysis (natural log normal dispersion of 0.9, truncated at the 2-sigma level), has technical basis and precedent, the sensitivity

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studies show that this is the most significant generic parameter. We strongly encourage a detailed investigation into acceleration dispersion with the objective of refining this model.

Summarily, the significant contribution of this effort is a focussing of the issues such that future analyses, should any be required, can be directed at the most significant parameters and the most crucial sites.

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APPENDIX A

SUBJECTIVE INPUT FROM EXPERT OPINION

Sections 1 and 2 in this report have shown that seismic hazard assessment for Eastern U. S. sites always requires some degree of subjective input, either in the model assumptions, the input data or both. In addition to acknowledging this, the subjective input was formally solicited for the Uniform Hazard Methodology (UHM).

As described in the TERA report, SHA: A Methodology for Eastern United States, the attempts to use technology in obtaining subjective input through the use of a questionnaire and an expert panel. The results of this solicitation are summarized in a companion TERA report "Seismic Hazard Analysis: Solicitation of Expert Opinion."

The purpose of this appendix is to summarize the needs for subjective input and the formalized approach used to generate subjective input for the Uniform Hazard Method. The concepts of expert opinion solicitation, its biases and various synthesis techniques, are discussed and we conclude the Appendix with an elaboration on the questionnaire used in this study and a discussion on the expert panel.

A.1 EXPERT OPINION AND EASTERN U. S. SEISMICS

The analysis of seismic hazard in the eastern United States presents several challenging problems that a probabilistic approach can answer, but only with expert opinion and subjective probabilities.

1. The central and eastern regions are notable for their low level of seismic activity somewhat uniformly distributed in space. It seems that minor to moderate earthquakes may occur in just about any location. Above this moderate background seismicity, a few restricted areas have experienced a few major earthquakes together with a much above average continuous activity. Since the correlation between epicentral location and geological

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and geomorphocic features is generally extremely low, the determination of tectonic regions or seismic source boundaries is usually made subjectively. The introduction of experts' opinions regarding the seismic sources appears to be the only way a credible tectonic model can be developed for the East. Although such input is not introduced in the UHM as a consensus, the procedure addresses this question at the final stage by synthesizing each expert's results using a method of self weighing.

2. The low rate of activity of these regions that are disturbed so rarely by major events does not provide a good basis for classical statistics applications. At level of probability usually desired, classical statistics give results driven by the large uncertainties. Often the uncertainties result from two questions: (1) To what extent should the large events be treated as anomalies? (2) What are the possibilities for such events to occur elsewhere? As insufficient geological and seismological data are available to answer these questions, only experts' opinions can be used to shed a light on them. Subjective probabilities provide a rational way to include them in the analysis. In the UHM they are introduced at three levels; rate of occurrence, distribution of magnitudes, and upper magnitude cutoffs.

3. The almost complete lack of instrumental recording in the East forces the analyst to work from intensity data. At the epicenter the data show a large scatter when correlated with magnitude; at the site, they contain much less information than a strong motion recording which explicitly provides the peak value as well as the frequency content of the shaking. Such limitations suggest that the development of attenuation relationships could greatly benefit from the additional input of qualified experts.

In conclusion, as it appears that a seismic analysis in the East cannot be based on the historic data alone and that, at a minimum, the data would have to be modified to reflect certain judgments. Summarily, the UHM approach to the problem provides:

- The explicit input from recognized experts
- The explicit weight that this additional information will have in the analysis

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- The integration of these subjective opinions with the recorded data.

A.2 MODES OF JUDGMENT

Modes of judgment are the methods by which people assess uncertainty. They use intuitive assessment procedures that are often based on cues of limited reliability and validity. Three common features of these modes of judgment are worth noting (Spetzler and von Holstein, 1974):

- Generally people are not aware of the cues their judgments are based on
- Controlling the cues people base their judgments on is difficult
- People can be made aware of biases and make a conscious attempt to control them

It is convenient to divide the modes of judgments into the four categories of representativeness, availability, adjustment and anchoring, and unstated assumptions.

Representativeness is the tendency to assign the probability of an event according to the degree of similarity it has with a broader group of events from which it is issued. Often a simple event is given more weight than it should because it is well defined and considered representative while the whole population carries more generalized information. The biases resulting from representativeness can often be reduced or eliminated by structuring the problem in more detail (Spetzler and von Holstein, 1974).

Availability refers to how easily occurrences can be brought to mind. For instance, present or recent occurrences or information that made a strong impression at the time it was presented are more available than occurrences from a long time ago or that did not make a strong impression. One may assess the risk of heart attack among middle-aged people by recalling such occurrences among one's acquaintances, and often such information will be given more weight than it should because it is still vivid in one's memory. Such bias can usually be removed by conditioning the subject and forcing him to broadly survey his information base before starting the scaling.

The subject often adjusts his responses to further questions according to the first or most available piece of information. Typically the subject's adjustments will be insufficient and lead to a central bias. Such a phenomenon is called anchoring. Anchoring often occurs when the starting point is given to the subject, or when he is first asked a question which he considers very important (such as a mean value), to the extent that he bases the remainder of his answers on those. Such biases can be reduced by covering a wide range of values at the beginning, or by eliciting answers which cannot be correlated.

If there is room for unstated assumptions, the subject will, consciously or not, restrict himself to particular cases with which he feels more at ease, or he will implicitly disregard situations that he feels are too far-fetched to need consideration. Therefore, his probability distribution will not reflect his total uncertainty. This obstacle can be removed by properly structuring the problem and making sure that conditional probabilities are explicitly stated.

A.3 BIASES

Biases are discrepancies between the expert's answers and his real knowledge. Such discrepancies can take several forms and can be either conscious or unconscious.

- Displacement biases consist of a translation of the whole distribution function either upward or downward but with no change in the shape.
- Variability biases consist of a variation in the shape of the distribution function. The bias can result either in a tighter distribution (central bias) or in a broader distribution (more uncertainty) than is justified by the expert's state of knowledge. These discrepancies are often a mixture of both biases unless the subject consciously

modifies his answers in accordance with a well-defined pattern.

The sources of bias can be divided into two categories--motivational or cognitive--both of which can be either conscious or unconscious.

- When obeying motivational biases, the subject influences the decision in his favor by modifying his answers. For example, he might reduce the uncertainty beyond what his knowledge would allow him because he feels that an expert in his position is expected to talk about this subject with a high level of confidence. In other cases, an expert might broaden the uncertainty to influence the decision one way or another.
- Cognitive biases are systematic adjustments introduced by the way the expert formulates his judgment. For example, one expert may give more weight to the last piece of information he has acquired simply because it is fresher in his mind.

A.4 SCALING TECHNIQUES

The goal of the encoding session is to obtain an accurate representation of the experts' judgment on a well-defined parameter of uncertainty. This judgment will be sought not only on the "most probable value" or on the expected value of the distribution, but also, when possible, on the entire probability distribution.

A judgmental probability distribution is encoded in a session between the expert whose judgment is being encoded and the analyst conducting the interview. In this case, the questionnaire was sent to each expert, and followed up by a personal interview during which additional questioning resolved inconsistencies and other problems.

It is convenient to divide the different stages of scaling sessions into three steps.

- Pre-conditioning - the expert is conditioned to think fundamentally about his judgment and to avoid cognitive biases

- Scaling - the judgment is quantified in probabilistic terms
- Verifying - the responses obtained in the scaling are checked for consistency

The purpose of pre-conditioning is to pinpoint biases that might surface during the scaling and to force the subject to think about how he makes his judgment. This step will reveal the information which seems to be most available, the anchors which are being used and the assumptions which are being made.

It is during the scaling session that the subjective probability associated with the quantities of interest are obtained from the expert. Scaling methods can be sorted in different ways since they differ in several aspects, such as in the properties of the scale (ordinal, interval, ratio), the nature of the response (direct, indirect), the nature of the uncertain quantity (probability, value, both: P, V or PV methods), the experimental procedures, etc. Each of these aspects can be used to classify the scaling methods.

For the purpose of this study, it is useful to sort them as follows:

Ordinal Questioning (Indirect or Direct Response Technique)

In the indirect response technique, to be used during interview, the subject is asked to choose between two or more alternatives. The choices are then repeatedly adjusted until he feels indifferent about choosing between them. The level at which indifference is reached can be translated in terms of probabilities (P methods) or values of the variable being scaled (V methods). In the case of the external reference process, one alternative is expressed in terms of the uncertain quantity and the other in terms of a familiar reference event. When the external reference is used, it is important that the expert be familiar and at ease with this external reference. References can be of two types: either a standard list of events of fixed probabilities or graphic displays such as the probability wheel or the probability segment. The internal reference process, on the other hand, uses alternatives defined in terms of the same value scale. For example, the subject is asked to choose between two possible ranges of values of the uncertain quantity.

In the direct response technique, the subject is asked to assign a probability corresponding to a given value (P method) or to assign a value corresponding to a given probability (V method).

Graphs

By graphing his subjective input, the subject provides both the probability and value of the uncertain quantity. He graphs this subjective input either by directly drawing the CDF or by giving a number of pairs of points from which a curve can be drawn.

Semantic Variables

This method requires that the scaling be done in two phases. First, the expert characterizes the event in terms of descriptors he is familiar with (such as "likely," "most probably," "rare," etc.) and then he must encode these descriptors in quantitative terms himself. This last step is necessary because the quantitative meaning of the verbal labels is extremely subjective (Lichtenstein and Newman, 1967). Although this method may be useful when the quantities of interest have no ordinal value scale, it is not thought practical for this project.

Finally, in the verifying phase of the session, judgments are tested for consistency. Since feedback and cross-checking play an important role in the process interviews are highly recommended to complete the procedure.

A.5 QUESTIONNAIRE FOR EUS SEISMICS

A questionnaire was developed to elicit expert opinion on seismicity and intensity attenuation in the Eastern United States. Because it is difficult, or perhaps impossible, to precisely quantify such factors given the sparse historical record, expert judgment was considered crucial.

Subsequent analysis using the responses to this questionnaire is clearly not Bayesian since a formal Bayesian analysis would consider, independently, both

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subjective opinion and historical data. It would then rigorously combine them, each with their corresponding weight, to provide a "posterior" input to be used in the analysis. However, such an analysis implies independence between subjective opinion and data. Due to their inherent knowledge of historical seismicity and attenuation in the East, it was considered unreasonable to expect the experts to divorce themselves from these data while forming an opinion. Therefore, such an opinion is necessarily a "posterior" estimate and cannot be used in a formal Bayesian analysis without double weighting the data. What was asked, then, was that each expert consider the available seismic data in the eastern United States and temper this by his general experience in the region, possible similarities between the East and other regions, geologic and tectonic considerations, expert judgment and similar types of information. In other words, we asked that each expert was asked to be a "Bayesian processor."

In order to help the respondents in answering the questionnaire, they were supplied with seismicity data for various source zones in the East. These data were based on an integrated catalog of earthquake occurrences generated from various regional catalogs for the East. For each of the zones they were supplied with (1) a listing of all earthquakes having epicentral intensities of IV or greater, and (2) a table giving the number of occurrences of earthquakes of each Modified Mercalli (MM) intensity unit from IV through XII.

The following points were emphasized:

- The level of confidence the respondents associated with their answers would be explicitly considered. Therefore, since their input would undergo filtering and weighting when combined with the opinion of other experts, they were asked not to feel reluctant to express non-classical viewpoints.
- Nine sites were specified for analysis and the experts were asked to concentrate their effort on regions whose seismicity might affect these sites, leaving in the background those regions whose contributions would be negligible.
- Answers were to be based on general experience, geologic and tectonic considerations, as well as available data.

- The questionnaire was designed to contain redundancy, which was necessary for cross-checking and for establishing consistency in the results. The experts were asked not to try to produce answers consistent with earlier answers, or to backfigure from previous answers, since this would defeat the purpose of the redundancy.

- concentration should be on their area of expertise and focus on the part of the questionnaire they felt most comfortable.

- They should attempt to answer all questions and to skip questions only if they felt uncomfortable with the format of the question or if they had no confidence in their ability to answer. Large uncertainties would be reflected in the range of values presented and through the confidence the experts associated with their response.

The questionnaire was divided into the following five sections:

- Source Zone Configuration
- Maximum Earthquakes
- Earthquake Occurrence
- Attenuation
- Overall Level of Confidence

In the Source Zone Configuration section, the specification of various areas or regions that appear to be unique in their potential to generate earthquakes was addressed. In particular, the definition of regions within which the experts felt future earthquake activity would be homogeneous was obtained. As a point of reference, maps were provided giving two possible seismic zonations of the eastern United States. The experts were asked to carefully review these figures and to indicate where they thought there might be inadequacies by modifying, deleting and adding zones. The experts were asked to indicate their "degree-of-belief" in each source zone and source zone alternative by estimating the chances that seismicity within these zones is part of the background seismicity of the entire region. They were acquested to identify any localized tectonic structures that might be important to the seismic hazard of nearby sites and to indicate their "degree-of-belief" in the activity at these sites.

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In the Maximum Earthquake section, the question of the size of the largest event that, in the experts' opinions, could be expected to occur in each of the source zones for a given time period in the future was first addressed. Since extrapolation of results from short time periods to very long ones is controversial, due to possible long-term variations in seismicity and other parameters, two distinct time periods were explicitly considered. The first one was chosen to be 150 years, this being generally on the order of our time period of interest and approximately equivalent to the length of recorded history in the East. The second time period was chosen to be 1,000 years, since such a period covers most non-catastrophic perturbations in seismic activity and leaves out the uncertainties associated with the extremely long-term geological variations outside the scope of the questionnaire.

The experts were also asked to consider the largest event that they might expect to occur within the current tectonic framework in each source zone without specifying any time period. It was emphasized that they should base their answers not only on the recorded data, but also on their feelings about:

- Whether the past history is a good estimator of the true state of nature
- Whether the future activity is likely to be similar or different from the past
- Whether this feeling could be based on any external source of information such as tectonics, theorectical studies, similarity with other regions in the world, or simply educated judgment.

The Maximum Earthquake section was divided into two parts. In the first part, we considered the size of the largest event expected to occur in a zone. In other words, knowing that a certain number of earthquakes will occur, we were interested in determining the size of the largest one and the uncertainty associated with that size. In the second part we considered the <u>return period</u> of the largest event.

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The Earthquake Occurrence section considered the occurrence of earthquakes within the next 150 years for each source zone. Occurrences were expressed either in terms of the number of earthquakes expected to occur within that period (for example: 47 in 150 years) or as the mean rate of occurrence per year (i.e., 0.313 per year). The experts were asked to subjectively assess the future seismicity in the East based on the available data and their judgment as to the validity, quality and completeness of these data to represent the true seismicity in the East. To aid in their decision-making, we presented an accompanying seismicity booklet of earthquake occurrence data for the source zones presented in the zonation maps. These data included (1) a listing, in descending order of intensity, of all earthquakes having epicentral intensities IV or greater and (2) a table giving the number of occurrences of earthquakes of each MMI unit from IV through XII. These data were not "corrected" for completeness, but rather represented the latest generally available information on locations and sizes of recorded or felt events.

The limited strong motion data in the East can be supplemented by inferring from theoretical or experimental information, the difference in peak acceleration and velocity ground motion between the eastern United States and the western United States, and correspondingly modifying the Western attenuation relations and intensity-ground motion correlations to make them applicable in the East. The section on Attenuation was intended to provide general information concerning the validity of existing attenuation relationships and ground-motion correlation for use in the eastern United States. Attenuation data were not specifically provided for this task; rather, we asked the experts to rely on their inherent knowledge of eastern United States attenuation.

In order to obtain a measure of the overall confidence the experts had in their answers, the final section asked them to rate, on a scale of 1 to 10 (10 being the highest), their confidence in their responses to the different sections of the questionnaire and in the various source zones. In this way, a synthesis or partial synthesis could be reached among the experts through weighted average procedures based on self-assigned levels of confidence.

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The responses to each question could be made in any one of several ways, where all could be converted to a usable format for analysis. Acceptable answers were:

- A best estimate only (fixed quantity)
- A range of values defined by lower and upper bounds and associated with a uniform distribution
- A range of values defined by lower and upper bounds and associated with a non-uniform distribution
- A written discussion

A.6 THE EXPERT PANEL

An obvious keystone to any expert opinion solicitation is the selection of the expert panel. The criteria used for this project were simple; employ as many as possible of the best experts in EUS seismology. Thirteen experts were contacted and their availability determined. Of these, only ten were able to complete the questionnaire. These experts, listed by region, were:

Dr. Robert Herrmann
Dr. Otto Nuttli
Dr. Ronald Street
Dr. Gilbert Bollinger
Dr. Edward Chiburis
Dr. Michael Chinnery
Dr. Richard Holt
Dr. Paul Pomeroy
Dr. Nafi Toksöz
Dr. Marc Sbar