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Seismic Hazard Analysis Overview and Executive Summary

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ABSTRACT

The Site Specific Spectra Project (SSSP) described in this report was a multi-year study funded by the U.S. Nuclear Regulatory Commission (NRC) as part of NRC's Systematic Evaluation Program (SEP). The main objective of this project was to provide assistance to the NRC by developing estimates of the seismic hazard at the nine oldest nuclear power plant sites east of the Rocky Mountains which were included in the SEP.

The SSSP was conceived as a multi-method approach for determining site specific spectra. It encompassed probabilistic approaches for predicting peak acceleration, peak velocities and uniform hazard spectra for different return periods and an empirical approach which includes calculation of 50th and 84th percentile spectra from ensembles of real data at different magnitudes, site conditions and distance ranges. The probabilistic approach utilized is basically that suggested by Cornell which has been modified to formally incorporate "expert" judgments and uncertainty.

This volume gives brief overviews of the SEP and the SSSP including a discussion of the formal elicitation of expert opinion used to obtain a subjective representation of parameters that affect seismic hazard and the development of the seismic hazard at the nine SEP facilities.

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GLOSSARY
TERMS AND ABBREVIATIONS

CIT	The data set of strong motion accelerograms and computed response spectra which the California Institute of Technology published between 1969 and 1974.
CUS	Central United States, roughly the area bounded in the west by the Rocky Mountains and on the east by the Appalachian Mountains, excluding both mountain systems themselves.
EUS	Sometimes used to denote the general geographical region east of the Rocky Mountains, and sometimes used to mean the specific region east of the Central United States (CUS).
Intensity	The intensity at which a specific earthquake is felt, as measured on the Modified Mercalli Scale.
LLNL	Lawrence Livermore National Laboratory; the overall project manager and director of this study.
MM	Modified Mercalli (see intensity).
MMI	Modified Mercalli Intensity (see intensity).
NRC	Nuclear Regulatory Commission.
PGA	Peak Ground Acceleration.
PGV	Peak Ground Velocity.
PSA	Pseudo-absolute acceleration spectrum. See also definition of spectra below and Volume 4, Appendix C, Section 5.
PSRV	Pseudo Relative Velocity Spectrum. See also definition of spectra below and Volume 4, Appendix C, Section 5.
Return Period	Inverse of the annual risk of exceedance.
Seismic Hazard	Seismic hazard is generally defined as the quantification of some geophysical or mechanical characteristics of potential seismic events affecting a particular site.
SEP	Systematic Evaluation Program, which includes this study. See also Volume 1.

Spectra	Used generically to refer to all the different spectra, e.g., Fourier amplitude spectra of the ground motion acceleration, and the relative velocity spectra at various damping levels. Also used specifically in this report: the regression analysis on spectral ordinates were at 5% damping for the pseudo-absolute acceleration spectra (PSA) at nine frequencies (25, 20, 12.5, 10, 5, 3.3, 2.5, 1, 0.5 Hz). These were converted to PSRV by the usual relations.
SSSP	Site Specific Spectra Project.
TERA	LLNL's primary subcontractor in the development and application of the methodology presented in Volumes 2 and 3.
UHM	Uniform hazard methodology.
WUS	The regions in the Western United States where we have strong motion data recorded and analyzed.

SYMBOLS

C_i	Coefficients of different parameters in the equations. The coefficients are determined by regression analysis.
GM	Ground motion parameter, used in discussion a variety of measurements, e.g., peak acceleration (a), and peak velocity (V).
I_s	Local site intensity, as measured on the Modified Mercalli Scale.
I_o	Epicentral intensity, as measured on the Modified Mercalli Scale.
M	Used generically for any of the many magnitude scales but generally m_b, $m_b(Lg)$, or M_L.
M_L	Local magnitude (Richter magnitude scale).
m_b	True body wave magnitude scale, assumed to be equivalent to $m_b(Lg)$.
$m_b(Lg)$	Nuttli's magnitude scale for the Central United States.
M_S	Surface wave magnitude.
M_u	Upper magnitude cutoff.
Q	Seismic quality factor, which is inversely proportional to the anelastic damping factor.
R	Distance metric, generally either the epicentral distance from a recording site to the earthquake of the closest distance between the recording site and the ruptured fault for a particular earthquake.
S	Site factor used in the regression analysis S = 0 for soil and S = 1 for rock sites.

1.0 INTRODUCTION

This report, Volume 1 of the five-volume Seismic Hazard Analysis, completes the work of the Site Specific Spectra Project (SSSP) funded by the Nuclear Regulatory Commission (NRC) to assist in the development of spectra for evaluating the seismic design adequacy of the sites in the Systematic Evaluation Program (SEP). The terminology seismic hazard at a site is generally taken to mean the quantification of some geophysical or mechanical "characteristics" of potential seismic events affecting a given site. The quantification can be by either probabilistic or deterministic approaches and, in fact, both approaches are used in these volumes although the bulk of the discussion is devoted to the probabilistic aspects of our study. The main "characteristics" of potential earthquakes being quantified in this five-volume study are the level of ground shaking, its frequency content, as well as, the likelihood of experiencing this level of ground shaking.

In this volume, we summarize the work presented in Volumes 2-5 and discuss the role of the SSSP in the seismic hazard analyses of the SEP facilities.

This section gives brief overviews of the SEP and the SSSP. Section 2 of this volume summarizes the Uniform Hazard Methodology (UHM). Section 3 describes the formal elicitation of expert opinion to obtain a subjective representation of parameters that affect seismic hazard. Section 4 discusses the application of the UHM to the development of the seismic hazard at the nine SEP facilities located in the Central and Eastern United States (CUS and EUS).

This volume also contains a glossary of terms used throughout the five volumes.

1.1 Systematic Evaluation Program

In the first phase of the SEP, a comprehensive list of 137 topics of safety significance which collectively affect the capability of a plant to respond to various design basis events was developed. In October 1977, the NRC approved the second phase of the program which consists of a plant-specific reassessment of these older reactors, based on current safety criteria. One important element of the SEP is the seismic review program.

The SEP seismic review program has two principal objectives: (1) to reassess the seismic safety of 11 older operating nuclear reactors licensed between 1956 and 1967, and (2) where necessary, to improve seismic safety margins.

The objective to improve safety margins is carried out in accordance with 10CFR50.109, which specifies that backfitting is required only if substantial, additional protection to the public health and safety is necessary.

The SEP seismic review process recognizes and attempts to deal with the inherent and often unquantifiable capability of these facilities to resist seismic forces, and the conservatisms associated with current evaluation methods. The SEP evaluations attempt to quantify unclaimed factors which contribute to seismic resistance capability more realistically.

The general philosophy of the SEP is discussed more fully by Levin (1980) and Newmark and Hall (1978).

1.2 The Site Specific Spectra Project

The SSSP was initially funded as Task 3 of NRC Task Action Plan A-40, Coats (1980). The first major application of the proposed methodology was for the nine reactor sites involved in the SEP located east of the Rocky Mountains: Palisades, Big Rock Point, Dresden, LaCrosse, Yankee Rowe, Connecticut Yankee, Millstone, Oyster Creek, and Ginna. The SSSP provided the following as assistance to the NRC in making seismic reassessments:

- A uniform approach, allowing meaningful comparisons of the estimated hazard between sites.
- A measure of the uncertainty of the results.
- Identification of the factors that govern the seismic hazard at each site.
- As complete a specification of the seismic hazard at each site as possible.

The basic approach to the problem was developed by LLNL, see Bernreuter (1979). The details of the program were carried out under a subcontract to TERA Corporation under close LLNL supervision. The project objectives of developing a methodology and testing it to assure reasonable results were ultimately achieved by a team with staff from the NRC, Dr. Leon Reiter and H. Levin, LLNL, D. L. Bernreuter, and TERA, L. Wight and C. Mortgat, working closely together.

The SSSP was conceived as a multi-method approach for determining site specific spectra (Bernreuter, 1979). It encompassed probabilistic approaches for predicting peak acceleration, peak velocities and uniform hazard spectra for different return periods and an empirical approach which includes calculation of 50th and 84th percentile spectra from ensembles of real data at different magnitudes, site conditions and distance ranges. The probabilistic approach (UHM) utilized is basically that suggested by Cornell (1968) which has been modified to formally incorporate "expert" judgments and uncertainty. This UHM is explained in detail in Volume 2. The empirical aspects are discussed in Volume 4.

Table 1 in Section 3 of this volume gives the chronology of milestones in the history of the SSSP. Out of context, some of the steps appear to have been done out of order, with several digressions. In fact, the progression of the project towards its objectives was directed as much by licensing requirements and deadlines as by the logic of research. For example, to meet NRC's need to make preliminary decisions on seismic hazard, a set of draft reports was issued in August 1979 and a peer review panel was convened before there was time for a formal meeting to obtain feedback from the original panel of experts.

Through many different sensitivity runs, major assumptions and parameter choices that led to significant variations in the predicted hazard at the various sites were identified. All results were provided to the NRC via reports and meetings. However, the difficult tasks of obtaining a synthesis among the results and choosing the appropriate seismic hazard level for the seismic evaluation of each site fell to the staff of Geosciences Branch of the NRC.

The five volumes of this series document the methodology developed by the SSSP and the results of applying the methodology to the nine SEP sites. The role that the SSSP results played in the NRC's final assessment is documented in Jackson (1980, 1981). The NRC's preliminary conclusions are given in Jackson (1980) and its final recommendations in Jackson (1981).

2.0 UNIFORM HAZARD METHODOLOGY

The Uniform Hazard Methodology (UHM) is a probabilistic approach to estimating the seismic hazard in the Central and Eastern United States. It is described in detail in Volume 2 of this series. This section presents a summary of the main features of the model and the significant differences between it and other seismic hazard models.

2.1 Seismic Hazard Analysis

A typical seismic hazard analysis proceeds through four steps:

1. Identification of the seismic sources.
2. Definition of an earthquake occurrence model for each source.
3. Formulation of an attenuation model.
4. Evaluation of the seismic hazard.

Although most seismic analysis procedures available involve these four steps, differences in key assumptions and modeling details produce significantly different results.

Both deterministic and probabilistic approaches have been used in the analysis of seismic hazard. The fundamental problem of all approaches is calculating hazards for extreme events at sites for which little or no earthquake data exist and for which the physical process of earthquake generation is not well known. Even in the Western United States, however, where seismically active structures can be identified, subjective input and empirical adjustments are required for the models to predict ground motions realistically.

2.2 Unique Features of the UHM

Four unique features of the UHM make it especially useful in seismic hazard analysis for sites in the Central and Eastern United States. First, the UHM incorporates subjective input from experts explicitly. Second, the final hazard assessment includes all earthquakes, small and large. Third, the spectrum resulting from the UHM does not represent one event or one restricted class of events, but combines exceedance probabilities due to earthquakes from all sources, at all distances from the site. Fourth, the UHM provides for a formal treatment of uncertainty.

Other probabilistic approaches (e.g., Cornell, 1968, McGuire, 1976, and Anderson and Trifunac, 1977) share the last three features. The principal new feature of the UHM is the extent and manner of using expert opinion.

Subjective input from experts. The low level of seismic activity and the lack of instrumental records made it difficult to carry out seismic hazard analyses for the Central and Eastern United States using historic data alone. One of the most innovative features of the UHM is its use of expert opinion to complement the historic data. In this methodology, subjective input from experts is formally solicited and incorporated into the results using state-of-the-art procedures in expert opinion technology.

Expert opinion was solicited on input parameters for the first three steps in the seismic hazard analysis process discussed in Section 2.1. Questions directed to experts covered the following areas: (1) the configuration of seismic source zones in the Central and Eastern United States, (2) the maximum magnitude or intensity earthquake expected in each zone, (3) the earthquake activity rate and recurrence statistics associated with each zone, and (4) methods for predicting ground motion attenuation in the zones from an earthquake of a given size at a given distance.

Using the information provided by the experts, seismic hazard evaluations at a site were performed. Rather than looking for a consensus at the input stage, we processed the input from each expert individually, using his complete set of responses except for the ground motion attenuation information. The uncertainty provided by the experts about the various parameters was also included. This procedure has the advantage of providing hazard curves for each expert and of establishing sensitivity for each set of assumptions. This method of independent analysis accounts for systematic rather than random biases in expert opinion.

The hazard results thus obtained using each expert's input were combined into a single synthesis using a complex weighting method. This method of obtaining a synthesis at the output stage rather than at the input stage is appropriate since the model is nonlinear in the input parameters.

The approach used to generate the subjective input, to assure reliability by feedback loops and cross-checking, and to account for biases and modes of judgment, is summarized in Section 3.0 of this volume and is presented in detail in Volumes 3 and 5 of this series.

The uniform hazard spectrum. With the UHM, a uniform hazard spectrum is developed using probabilistic methods in such a way that each spectral amplitude has the same probability of being exceeded. In the development of the spectrum each frequency is considered independently, and correlation between the spectral amplitudes is not explicitly taken into account. Predictions are made for one frequency at a time. All potential earthquakes, small and large, contributing to the seismicity at the site are considered, using appropriate seismicity, attenuation and exposure models. The cumulative contribution to the loading at the given frequency is computed as a cumulative distribution function of the loading.

The spectral acceleration vs. frequency is then plotted and the loading corresponding to the return period of interest is used as the appropriate spectral amplitude for design at the given frequency. The procedure is repeated for other frequencies within the frequency range of interest and the spectrum is built point by point.

Since each frequency is treated independently, the aspect of a specific spectral shape corresponding to a particular earthquake is lost in the process. Thus, the uniform hazard spectrum is not representative of any single event. For example, if the structure is subjected to a nearby small earthquake, the ground motion will be most likely rich in high frequency energy; the low frequency content of its spectrum will most probably be small. Conversely, if the event is distant, its spectrum will most probably have little energy in the high frequency range. In other words, two spectral amplitudes will not be felt by the structure for any single event. Since the structure will have to resist only one earthquake at a time, using both amplitudes in superposition for analysis is conservative.

Treatment of uncertainty. Both systematic and random uncertainty were considered in this study. In this context, systematic uncertainty is that associated with errors in the form and parameters of the models used in the analysis; e.g., the elements of the attenuation law, upper bound magnitudes, and site amplification factors. Random uncertainty is that associated with independent variation in parameters; e.g., the magnitudes of different earthquakes, given their common distribution.

In this study, systematic uncertainty was treated in several ways, depending on the parameter, as follows:

- The input from each expert was kept separate and processed on an individual basis. This method of independent analysis accounts for systematic bias in expert opinion. A consensus was obtained at the results stage, rather than at the input stage. The method is discussed more fully in Section 3 of this volume.

- Uncertainty in seismic source geometry was treated by considering two bounding hypotheses. No combination of the associated results was attempted.

- Systematic uncertainty in attenuation was also treated through sensitivity analysis by considering different alternatives. No integration of the results was attempted.

- Other uncertainties, such as those in the mean occurrence rate and in the magnitude distribution, including the upper magnitude cutoff, were treated as random.

A detailed discussion of the treatment of systematic and random errors is given in Volume 2, Appendix A, of this series.

3.0 ELICITATION OF EXPERT OPINION

In this section we discuss the unique way in which the UHM uses subjective input from experts to supplement the sparse data available about CUS and EUS earthquakes. Throughout the development of the UHM, the formal incorporation of expert opinion was an essential part of the process. Table 1 is a chronology of the use of questionnaires and other techniques to obtain subjective input and to assure adequate peer review and additional or revised input as required.

Considerable effort was put into selecting the experts to assure knowledgeable and balanced input. Table 2 gives the names of experts who agreed to serve on our panels. A number of other experts were asked to serve on our panels, but for various reasons declined our invitation.

Volumes 3 and 5 of this series give detailed accounts of all of the steps in this process. The steps are summarized in this section.

3.1 Questionnaire to Panel of Experts

The first questionnaire to obtain subjective data for use in seismic hazard assessment for the Central and Eastern United States was sent in January 1979 to 10 experts knowledgeable in the history of seismicity in the EUS. The experts were asked to integrate their knowledge about the geology and seismicity of the CUS and EUS with knowledge gained from other areas and provide us with the seismicity models of the CUS and EUS. In effect, each expert was asked to be a "Bayesian Processor."

This first questionnaire consisted of five sections, asking for input in the following areas:

- Source zone configuration.
- Maximum earthquakes.
- Earthquake occurrences.
- Attenuation.
- Self-ranking.

Table 1. Chronology of the Use of Expert Opinion in the Development of the UHM

DATE	EVENT	REMARKS	REFERENCE
October 1977	Program Initiated at LLNL		
May 1978	Detailed Approach Selected		UCRL-52458
October 1978	EUS Seismicity Panel Members Selected	See Table 2 of this Volume for Members	
January 1979	First Questionnaire Sent Out		Vol.3
March 1979	Responses to Questionnaire Returned	Data Analysis Started	
August 1979	3-Volume Draft Report "Seismic Hazard Analysis issued by LLNL and TERA	Vol. 1 & 2 of this report were released in revised form as Vols. 2 & 3 of this series. Vol. 3 of the draft report forms Appendix of Vol. 4.	
	Peer Review Panel Created	4 Peer Review Panel members and other scientists were sent copies of the report and asked to evaluate the methodology, questionnaire and the results	Vol. 5, p. 2
September 1979	Peer Review Panel meeting with representatives from LLNL, TERA, and NRC to discuss report		
October 1979	Written comments from Peer Review Panel submitted to LLNL, submitted to NRC	Vol. 5, Appendixes A and B contain comments from the Peer Review Panel and other scientists, and responses from LLNL/TERA to the comments.	
February 1980	Ground Motion Model Panel created, meeting with LLNL, TERA, NRC	4 Ground Motion Model Panel members were sent copies of UCRL-52458 and other information given in Vol. 5, Appendix C, and asked to comment at meeting. Vol. 5 Appendixes D & E give details of the meeting, results of discussions, and other feedback.	
June 1980	Meeting in Denver with Expert Panel and LLNL	Meeting goals: 1) explain how questionnaire responses were used in seismic hazard analysis; 2) review results; 3) provide opportunity to update or change responses, Vol. 5, Section 4 gives qualitative and quantitative assessments of feedback.	Vol. 5, p. 11
	Memo from Jackson (NRC)	NRC memo gives initial recommendations based on SSSP work so far.	
September 1980	Second Round Questionnaire Sent to Expert Panel	Vol. 5, Appendix F is a copy of the second round.	
March 1981	Assessment of Feedback Loop Completed	Only minor changes to the loading at any site occurred.	Vol. 5 Sec. 4
June 1981	Memo from Jackson (NRC)	NRC memo reaffirms the recommendations made in the June 1980 memo.	

Table 2. SSSP Panels

Eastern United States Seismicity Panel

G. A. Bollinger, Virginia Polytechnic Institute and State University
E. S. Chiburis, Weston Observatory (now at Ensco, Inc.)
M. A. Chinnery, Massachusetts Institute of Technology
R. B. Hermann, St. Louis University
R. J. Holt, Weston Geophysical Research, Inc.
O. W. Nuttli, St. Louis University
P. W. Pomeroy, Columbia University
M. L. Sbar, University of Arizona
R. L. Street, University of Kentucky
M. N. Toksoz, Massachusetts Institute of Technology

Seismic Input Peer Review Panel

A. H.-S. Ang, Univeristy of Illinois
O. W. Nuttli, St. Louis University
L. R. Sykes, Columbia University
D. Veneziano, Massachusetts Institute of Technology

Ground Motion Panel

N. C. Donovan, Dames and Moore, Inc.
R. K. McGuire, Dames and Moore, Inc.
O. W. Nuttli, St. Louis University
M. D. Trifunac, University of Southern California

Questions in the first section were directed to the specification of regions that appear unique in their potential to generate earthquakes and within which the experts felt future earthquake activity would be homogeneous.

In the second section, questions focused on determining the size of the largest event that, in the experts' opinion, could be expected to occur in each of the source zones for a given time interval in the future.

Because extrapolation of results from short time intervals to very long intervals is controversial due to possible nonstationarity of seismicity, we explicitly considered two distinct time periods. The first was 150 years, which is of the same order as the time period of interest and approximately equivalent to the length of recorded historical seismicity in the EUS. The second period was 1,000 years, because such a period excludes uncertainties associated with extremely long-term geological variations, which were outside the scope of our analysis.

The experts were also asked to consider the largest event that they expected to occur within the current tectonic framework in each source zone, irrespective of the time period. We emphasized that they should base their answers not only on recorded data but also on their beliefs on two issues:

- Whether past history can be used for future predictions.
- Whether additional information can be drawn from sources such as tectonics, theoretical studies, and similarity with other regions in the world.

The third section of the questionnaire sought information about the magnitude-frequency relationship for each source zone during the next 150 years. Experts were asked to base their answers on historical data and on their own judgment as to the validity, quality, and completeness of the data. To assist respondents in this task, we provided them with a list, in descending order of intensity, of all historical earthquakes with epicentral intensities IV or greater included in the map, and with a table giving the number of earthquakes for each unit interval of intensity from IV through XII. These tables were not "corrected" for completeness, but rather represented the latest generally available information on location and size of recorded or felt events.

The fourth section of the questionnaire focused on gathering information to critique existing attenuation relationships and to develop a new attenuation relationship applicable to the EUS. The experts were questioned on their knowledge of attenuation in the EUS.

In the fifth section of the questionnaire, the experts were asked to rate on a scale of one to ten the confidence they had in their own responses to the questions in the other four sections. Using this input and weighted-averaging procedures, we obtained a synthesis of opinion.

To assure that the answers truly reflected the experts' opinions, various formats were allowed in answering the questions:

- A best-estimate fixed quantity.
- A range of values defined by upper and lower bounds and associated with a uniform distribution.
- A range of values defined by upper and lower bounds and associated with a non-uniform distribution.
- A written discussion.
- Another format of the expert's choice.

Volume 3 of this series, "Seismic Hazard Analysis: Solicitation of Expert Opinion," gives a detailed tabulation of the experts' answers to the questions. Volume 3 also contains information on the conventions used in interpreting the answers to the questions, on the methods used to obtain feed-back and to cross-check, and additional comments from the experts.

3.2 Peer Review Panel

Because our seismic hazard analysis involved new techniques and complex model-building, we invited seismologists and engineering statisticians to serve as a Peer Review Panel for the UHM. The four Peer Review Panel members (see Table 2) were asked to evaluate (1) the seismic hazard analysis methodology, (2) the expert opinion questionnaire, and (3) the usefulness of the results. Written comments from the Peer Review Panel were forwarded to the NRC. A complete report of the comments of the Peer Review Panel and of other scientists whose opinions were solicited is given in Volume 5 of this series.

3.3 Ground Motion Panel

The section of the questionnaire dealing with the development of ground motion models gave the least satisfying results. We, therefore, invited four experts (see Table 2) with extensive experience in formulating ground motion models to serve as a ground motion panel.

At a meeting between representatives from the SSSP and the ground motion panel, all aspects of building a ground motion model were discussed.

Panel members provided written comments on such topics as intensity attenuation, data base issues, distribution of spectral accelerations, magnitude scales, regression weighting, and near-field models. All responses from the ground motion panel are presented in Volume 5 of this series.

No consensus was reached as to the best way to develop a ground motion model for the EUS. Four basic approaches were identified and discussed in Volume 4 (pages 6-25). Three of the approaches use intensity as an intermediary variable to compare the ground motion between WUS and EUS:

Distance weighting

$I_s = f(I_o, R)$ EUS Data

$\text{Log GM} = G(I_s, R)$ and in some cases $G(I_s, M_L, R)$ WUS Data

Magnitude weighting

$I_s = f(I_o, R)$ EUS Data

$\text{Log GM} = G(I_s, M_L)$ WUS Data

$m_b = M(M_L)$

$I_o = 2m_b - 3.5$ EUS Data

No weighting

$I_s = f(I_o, R)$ EUS Data

$\text{Log GM} = G(I_s)$ WUS Data

The fourth method uses a theoretical approach such as Nuttli's (1979) model. It combines theoretical modeling with measured regional Q values, assumes the near-source ground motion in the EUS is the same as in the WUS, and scales only by magnitude. The implications of these various weighting schemes are discussed in Appendix E of Volume 5.

Because of the great uncertainty about EUS earthquake mechanisms and the resultant ground motion recorded at a site, no attempt was made to obtain a formal statement of the relative degree of belief the different ground motion panel members had about the four different ground motion models proposed by the panel. Instead the sensitivity of the seismic hazard to the different ground motion models was explored in some detail and these results are given in Volume 4.

3.4 Expert Panel Meeting

Informal discussions were carried on with the original group of ten experts during the process of developing and applying the UHM. A formal meeting was held with the following agenda:

- Explanation of how the questionnaire responses were used in the seismic hazard analysis.
- Review of the results obtained using the experts' responses.
- Updating or changing experts' responses.

The agenda provided for considerable discussion about how sensitive the results were to the assumptions made about the experts' input and about the effect of individual and collective uncertainty.

At the meeting we reviewed the results for selected sites and compared varying results from different experts. Key issues such as the basis for zonation, the choice of upper magnitude cutoff, the use of credibilities, and the ground motion model were covered at length.

3.5 Second Questionnaire

Following the meeting, the experts were sent a second questionnaire. In the second questionnaire, the experts had the opportunity to modify their input to the seismicity models used in the analysis. They were also asked to critique the following assumptions and interpretations which were part of the SEP methodology:

- The intensity vs. magnitude correlation used in the analysis.
- The background vs. no-background seismicity model.
- The ground motion model and its uncertainty.

We reviewed the responses to the second questionnaire and assessed the effect each modified model would have on the results presented in Volume 4 of this series and on the preliminary recommendations of the NRC based on those results.

With few exceptions, the modified responses of the experts introduced little or no change in the original results. We therefore limited the reanalysis to the synthesis case developed by the NRC.

A complete report on the responses of the experts to the second questionnaire and our assessment of the modified models is given in Volume 5 of this series.

4.0 APPLICATION OF THE UHM TO SEP SITES

In this section we discuss the development of the seismic hazard at nine sites in the Central and Eastern United States. We also summarize the extensive sensitivity studies we performed to identify the major assumptions and parameter choices that led to significant variations in the predicted hazard at the various sites. The application of the methodology, the results, and the sensitivity studies are presented in detail in Volume 4 of this series.

The results discussed here and in all volumes of this series represent the overall goal of the SSSP; i.e., to provide the NRC with the results and sensitivities needed to make bottom-line judgments for specific sites.

4.1 Initial Results

Our approach in applying the UHM to the SEP sites consisted of developing a model for the attenuation of site intensity using EUS intensity data, then using existing EUS strong motion data in conjunction with data from the West Coast 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. The site intensity is also retained as an additional measure of the ground motion.

Initial results (Volume 4, Appendix A) were obtained using a distance-weighted ground motion model, characterized by the following features:

- A lognormal distribution is used for the ground motion parameters.
- The distribution is truncated at two standard deviations.
- A value of 0.9 is assumed for the standard deviation.

Results were obtained using each expert's zonation and earthquake occurrence models for each SEP site.

In Volume 4, Appendix A, results are displayed for the SEP sites for the UHM and, for comparison as proposed by Bernreuter (1979), for three other seismic hazard methodologies: the Newmark-Hall Spectra, the Real Time History Spectra, and the Scaled Time History Spectra. The four approaches for generating site-specific spectra are discussed in terms of their differences and the differences in the spectra produced. The methodologies compared were chosen as representative of the current technical approaches available to establish adequate information for evaluating seismic design.

Review of the initial results identified issues requiring more study:

- The distance-weighted ground motion model led to velocities that seemed unreasonably large.
- The treatment of background and credibilities given to each zone by the experts was questionable.
- The sensitivity of the results to ground motion model uncertainty was not evident.
- A formal feedback loop through the expert panel was an important additional element missing from procedure.
- A comparison of results to those of other seismic hazard analyses for the EUS was also missing and valuable.

Consideration of these issues led to an extension of the scope of work, as described below.

4.2 Sensitivity Studies

The extensive sensitivity studies undertaken after a review of our initial results are documented in Volume 4, Appendix B of this series and summarized in this section.

The sensitivity analysis described in these volumes was applied to the assumptions and interpretations placed on the expert input by the researchers and not to the expert input itself. The following points are addressed in the sensitivity studies and discussed briefly below:

- The interpretation of credibility in zonation.
- The choice of the 1000-year period versus the unconstrained time period for the upper magnitude event.
- The choice of a ground motion model, including the uncertainty associated with the attenuation law.

Zonation. Two interpretations of zonation were used for the initial hazard analysis: "background" and "no background." The background interpretation, a more conservative concept, was arrived at as follows: a procedure of zone superposition was used to represent the different zones provided by an expert to model a given source. An additional background zone, defined as the union of the zones presented by all the experts for that source area, was used for each expert. Earthquakes were assigned to this background as a function of the credibilities he assigned to his zones. The object of the background region was to account for the credibilities provided by each expert. In the no-background interpretation, the zonation provided by each expert was used without the overlay zone, assuming that the expert had the highest confidence in his own zones. All the activity and the upper magnitude cutoff were restricted within each of the expert's zones. See Volume 2, pages 21-24 and page E-17, for further discussion of these two treatments of zonation.

The results presented in Volume 4, Appendix B, show that, in general, the change from background to no background reduces the load at the sites by 15 to 25%.

Upper Magnitude Cutoff. For the experts who had specified an upper magnitude cutoff significantly different for the 1000-year than for the unconstrained time period, the analysis was rerun using the unconstrained time period event.

Ground Motion Model. Three ground motion models were used in the sensitivity analysis, one of them the distance-weighted model used in the preliminary results. The other two models are the Ossippee model and Gupta-Nuttli model, both magnitude-weighted models. The sensitivity results show that the ground motion model and its associated uncertainty have a dramatic effect on the results, particularly for long return periods. Increased uncertainty drives the loading up; however, the influence of the shape of the mean varies considerably from site to site. The magnitude-weighted models always resulted in much lower velocities, as expected. The results of this analysis for the SEP sites are summarized in Volume 4, Appendix B, Tables 3 and 4.

To help explain the factors controlling the seismic loading at the sites, additional sensitivities were considered; for example, we have indicated which zones contribute most to the loading for different experts and discuss why certain experts differ greatly from the majority. The contributions of distance and magnitude for the 1000-year return period are treated in Volume 4, Appendix B.

4.3 Discussion and Conclusions

One of the most interesting results of this study is the diversity of views among experts. Not only did they have widely differing views about zonation (see pages C-3 to C-14 of Volume 3 which gives the zones provided by the experts), but they also had diverse views about the largest earthquake that can occur in a given zone and the other parameters of the earthquake occurrence model. For example, Table 3 gives the variation in the estimate of the largest earthquake for the zone containing the Dresden site in central Illinois. As can be seen from Table 3, the variation is large considering the fact that a unit change in magnitude represents about a factor of thirty increase in energy release. Considering the state of knowledge about EUS seismicity, it is not too surprising that such wide variations in interpretation exist.

Although, as noted, the differences among the different experts about the various input parameters of the seismic hazard model are often quite large, the net result on the seismic hazard computed using the input from our experts in the 10^2 to 10^4 return period range is much less signficant. This is illustrated in Figures 1 to 9 which give the 1,000-year return spectra for each of the sites for each of the experts for the no background interpretation of zonation. For the CUS sites the ground motion model referred to as the Gupta-Nuttli model was used; for the other sites the model referred to as the Ossippee Model (see Volume 4, pp. 16-19) was used. The calculations were performed using a value of Σ ln a = 0.9 with the distribution truncated at two standard deviations. Several items are noteworthy:

1. The systematic uncertainty between experts remains relatively constant between sites and in the period range of 0.04 to 0.5 sec. (the period range of most interest for nuclear power plants) is about a factor of 2 to 3. The worst case is for Ginna, and as can be seen, it is the two outlier experts who introduce the large variation.

2. Sites in regions of low seismicity have much lower spectra than sites in regions of relatively high seismicity.

3. Although the uncertainty is large, it does not overwhelm the results.

4. General conclusions are dependent on the site considered and on the return period of interest. The SSSP focused on the 10^2 to 10^4 return period range.

TABLE 3

Variation of the estimate for the largest earthquake for the zone containing the Dresden site in central Illinois.

Number of Experts Giving Estimate in Given Range	Range of Estimate of Largest Earthquake
2	4.5 - 5.0
2	5.0 - 6.0
3	5.8 - 6.4
1	4.3 - 5.8
1	Greater than 7

Considering the widely different views among experts about the key parameters of the analysis, it is useful to compare the results to "what has happened." This is a difficult task because measurements have not been taken, except during the last few years, at the SEP sites or at any other site. The pseudo-historical results given in Appendix C of Volume 4 attempt to fill the gap. The reasonable agreement between the pseudo-historical estimates and our estimates of the seismic hazard given in Volume 4 suggests that our results are reasonable and that our complex model building has led to reasonable estimates of the seismic hazard at the SEP sites.

We could have used several approaches other than expert opinion. One would have been some sort of pseudo-historical approach, e.g., the model in Appendix C of Volume 4 mentioned above. A second approach would have been to develop a large number of different bounding models. We did not think that it was necessary to explore this approach because of the very wide variation in models presented by the different experts. Because of those differences and because each expert's input was used separately, it is possible to argue that the results presented cover the extremes, from complex zonations to the very simple zonation model used by Expert 5, and with upper magnitude cutoffs ranging from small m_b values to intensity XII for the same zone and widely varying "b" values.

It is not a simple task to determine the importance of variations in parameters when they interact; e.g., a large upper magnitude cutoff can be cancelled in part by a "steep" b value so that relatively few large events occur. Changes in parameters for distant zones are generally much less significant than changes in parameters for zones near the site. Our sensitivity studies showed that the "a" value was a relatively insensitive parameter. The uncertainty in the zonation (measured by the difference between the results of the background and no-background models) turned out to be a more sensitive parameter than we originally thought. Both the random and systematic uncertainty in the ground motion model are of considerable importance. At the longer return periods the near-source zone controls the hazard, even in regions of low seismicity.

In our opinion, the single most significant result of the study is our discovery that using expert judgment and insight to help supplement the sparse data set available is a viable approach. The estimates of the seismic hazard at the SEP sites have a significant, but not unmanageable, uncertainty associated with them. There is no way to directly verify our results; in that sense our results can be considered as giving only the relative hazard at the various sites.

Although significant improvements and reductions in the uncertainty of our estimates can be made, the final results presented in this study and discussed in Jackson (1980, 1981) seem to us to have less uncertainty associated with them than any other estimates obtained by any other state-of-the-art methodology.

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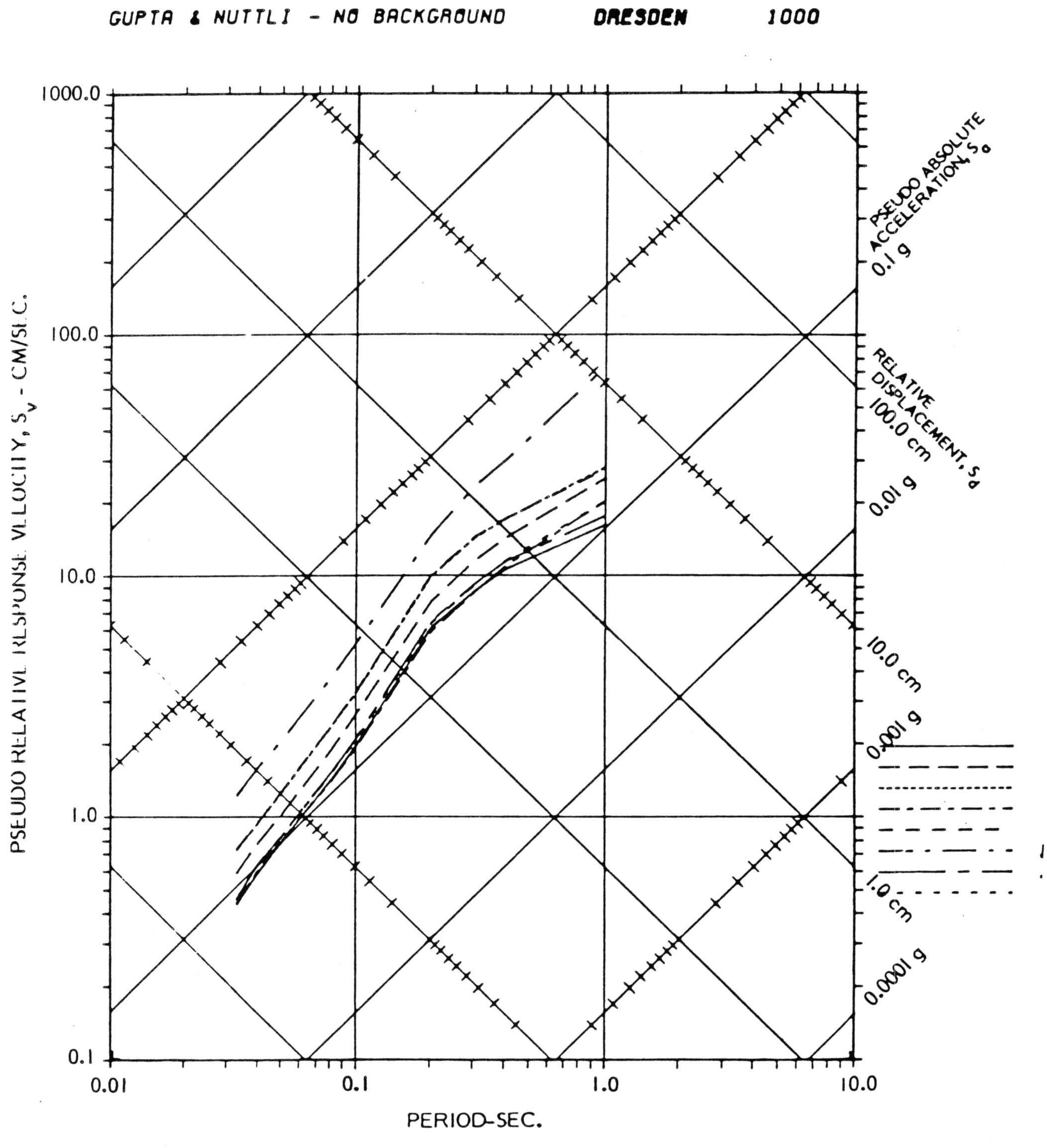

Figure 1. Dresden - no background.

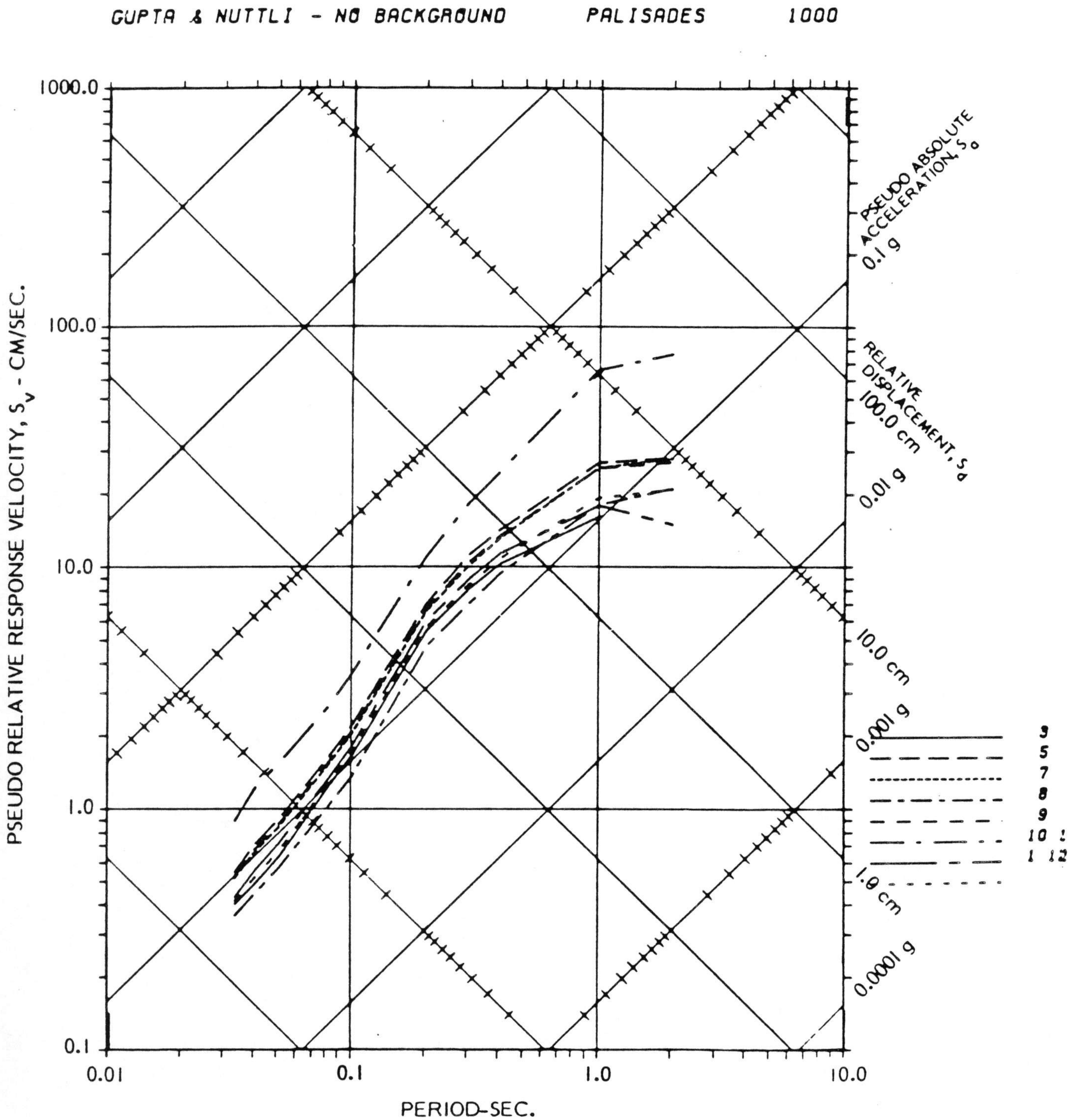

Figure 2. Palisades - no background.

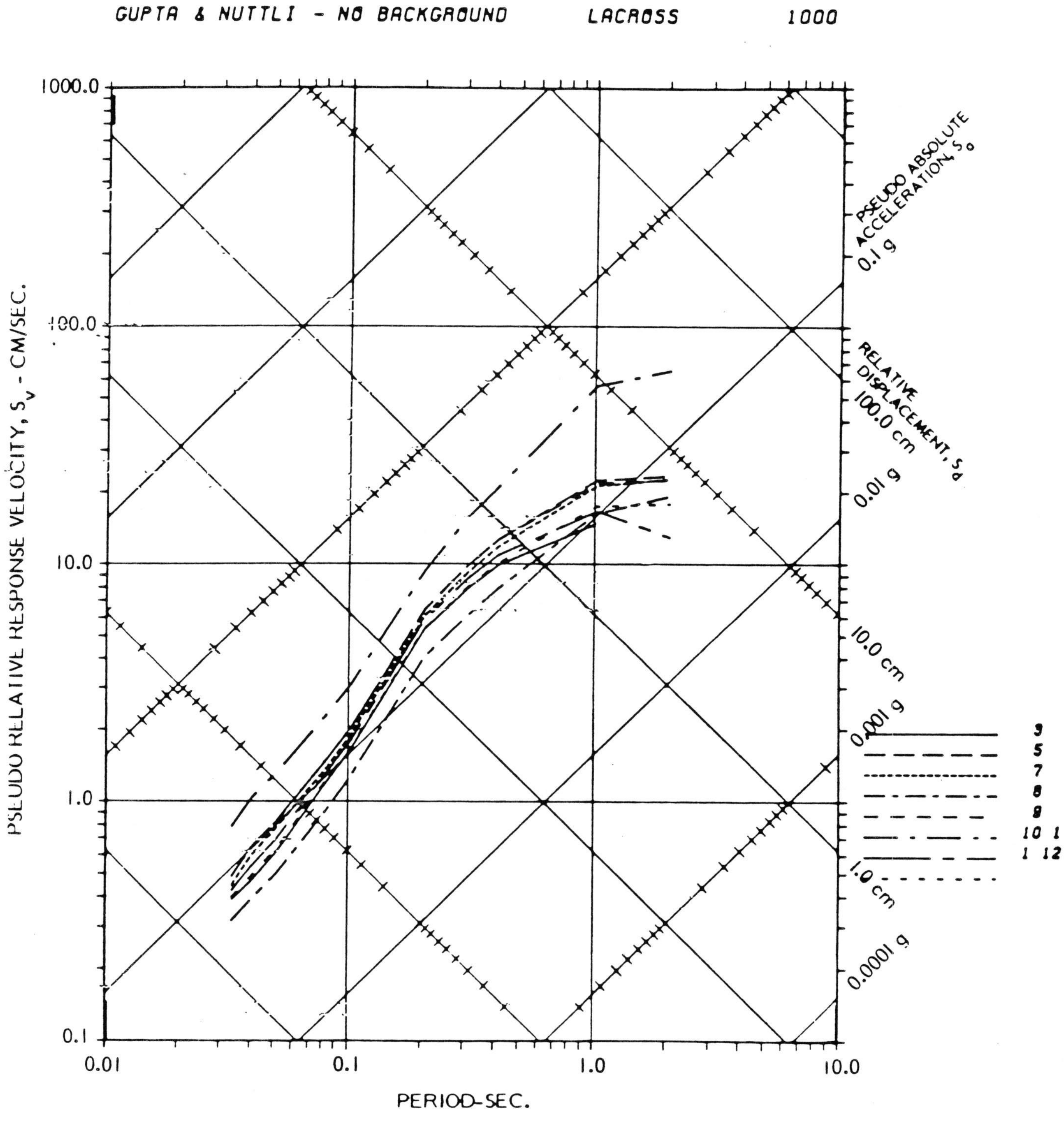

Figure 3. LaCross - no background.

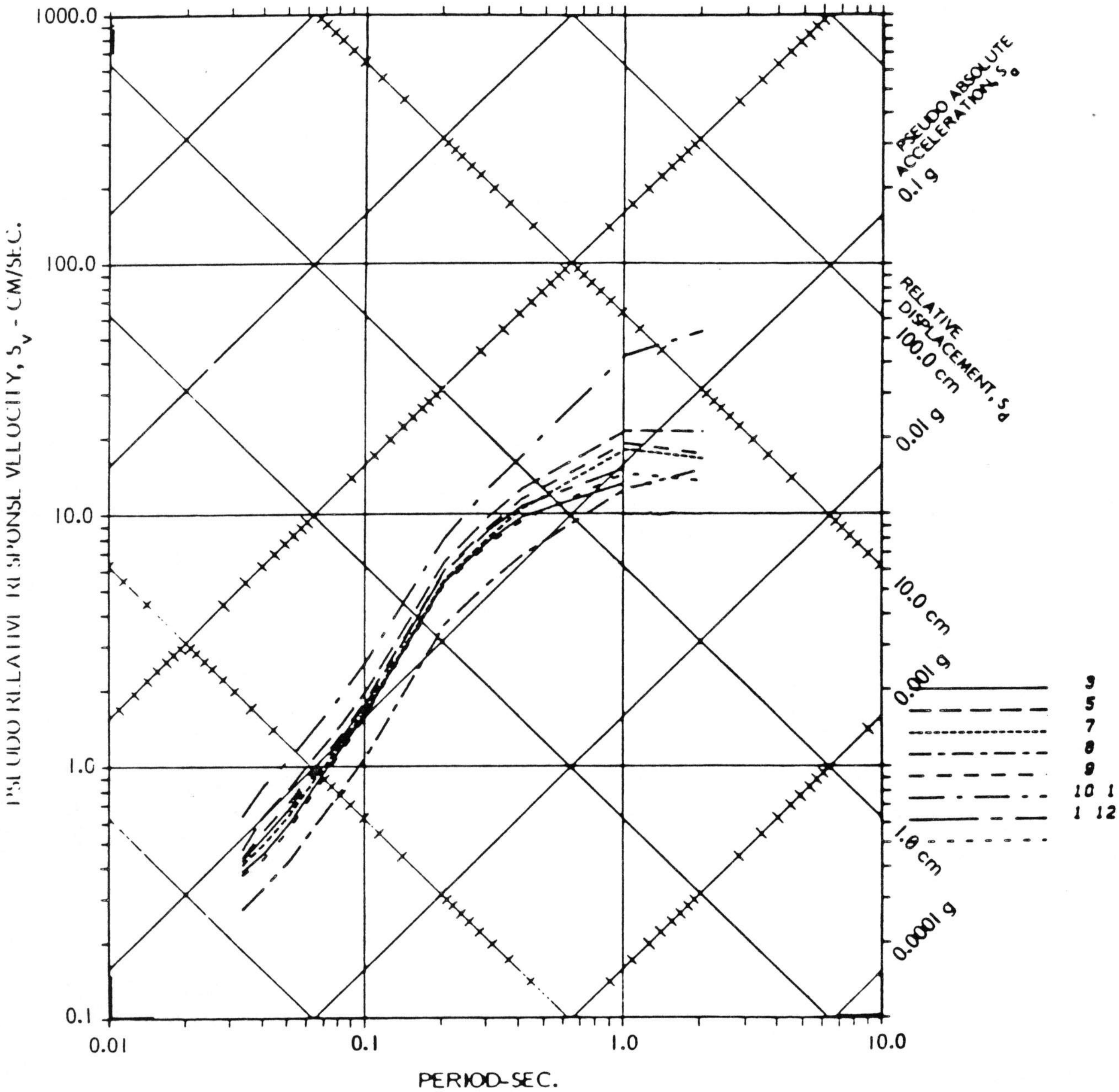

Figure 4. BRP - no background.

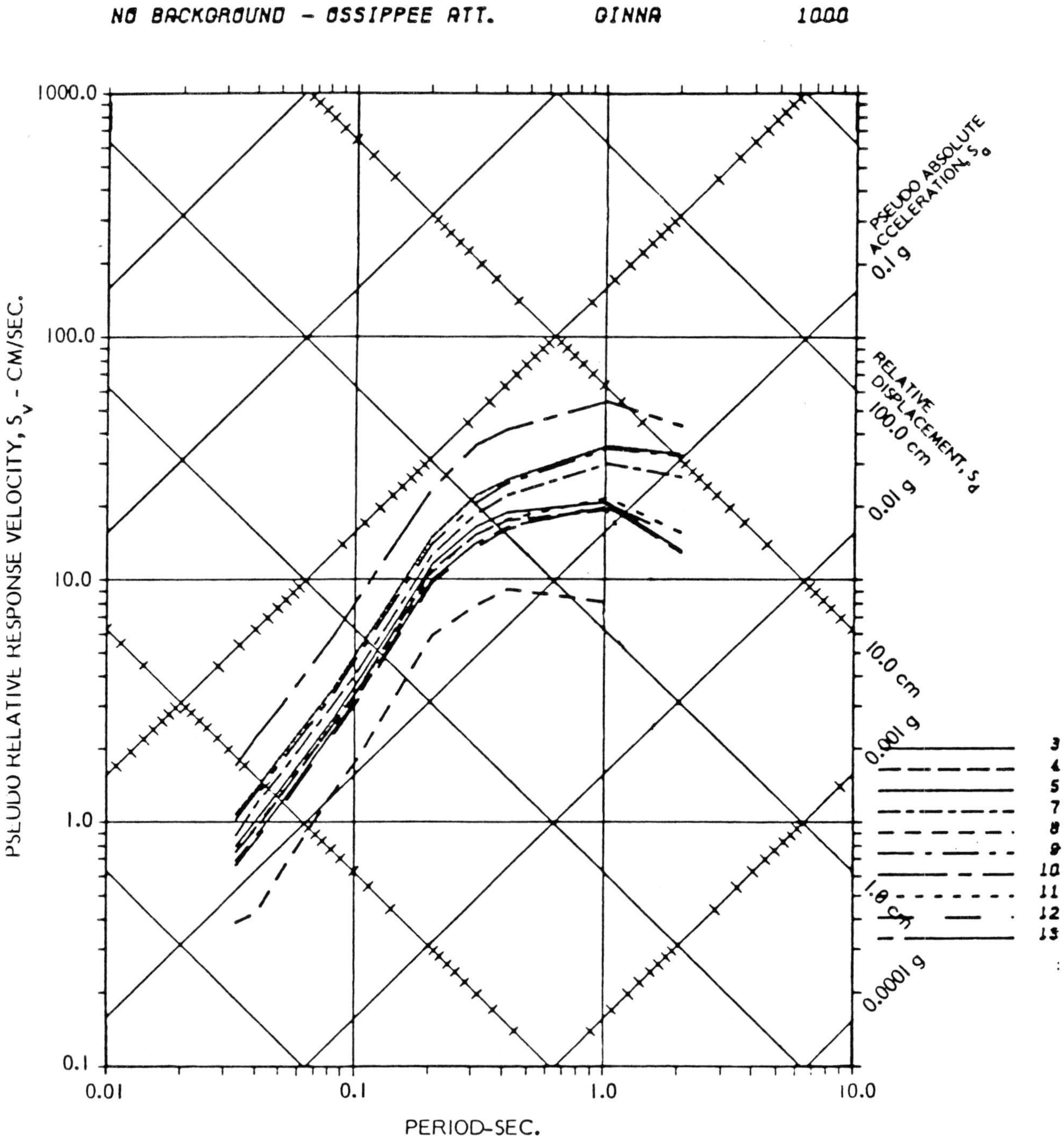

Figure 5. Ginna - no background.

NO BACKGROUND - OSSIPPEE ATT.   C. Y.   1000

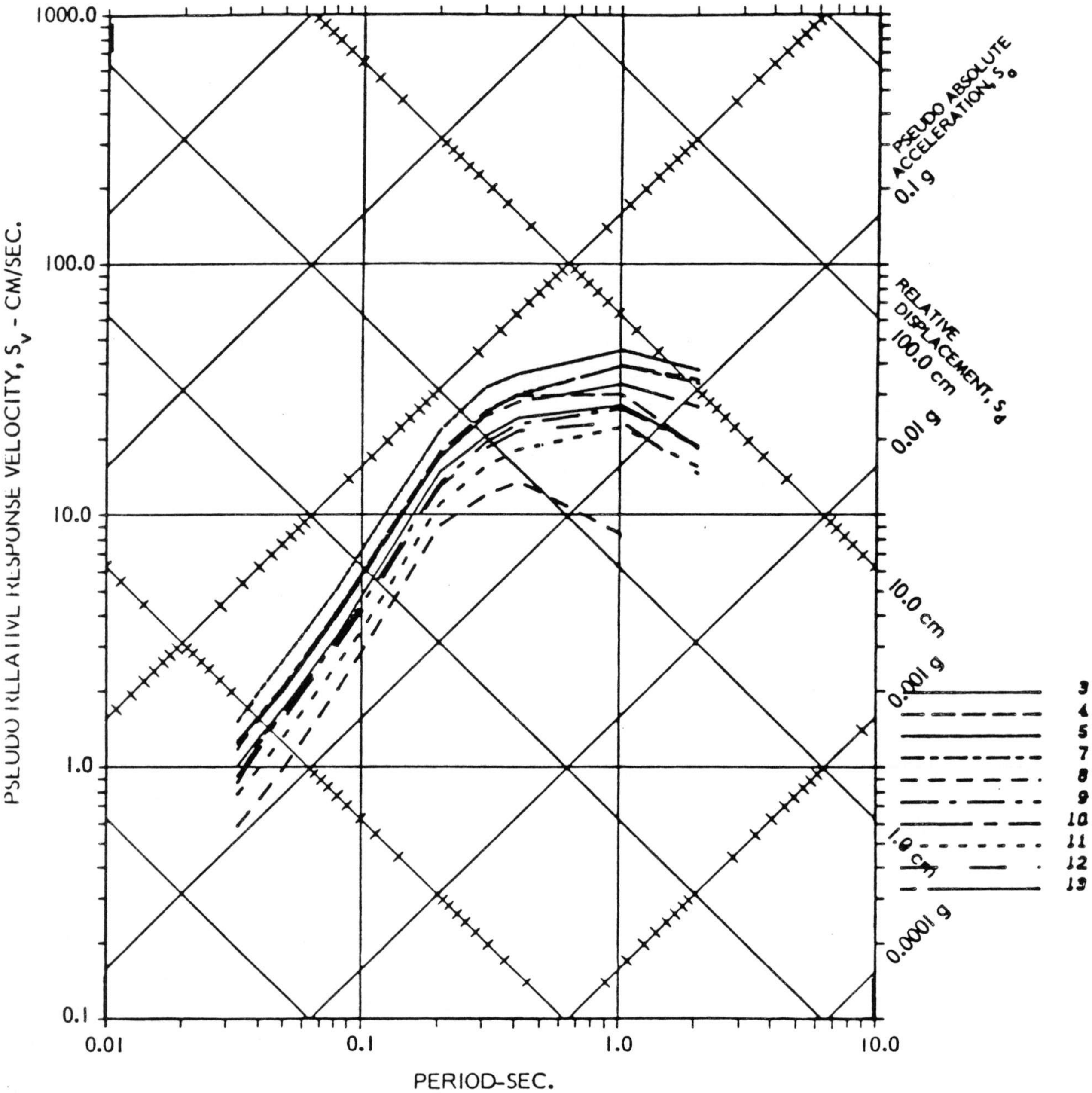

Figure 6. C. Y. - no background.

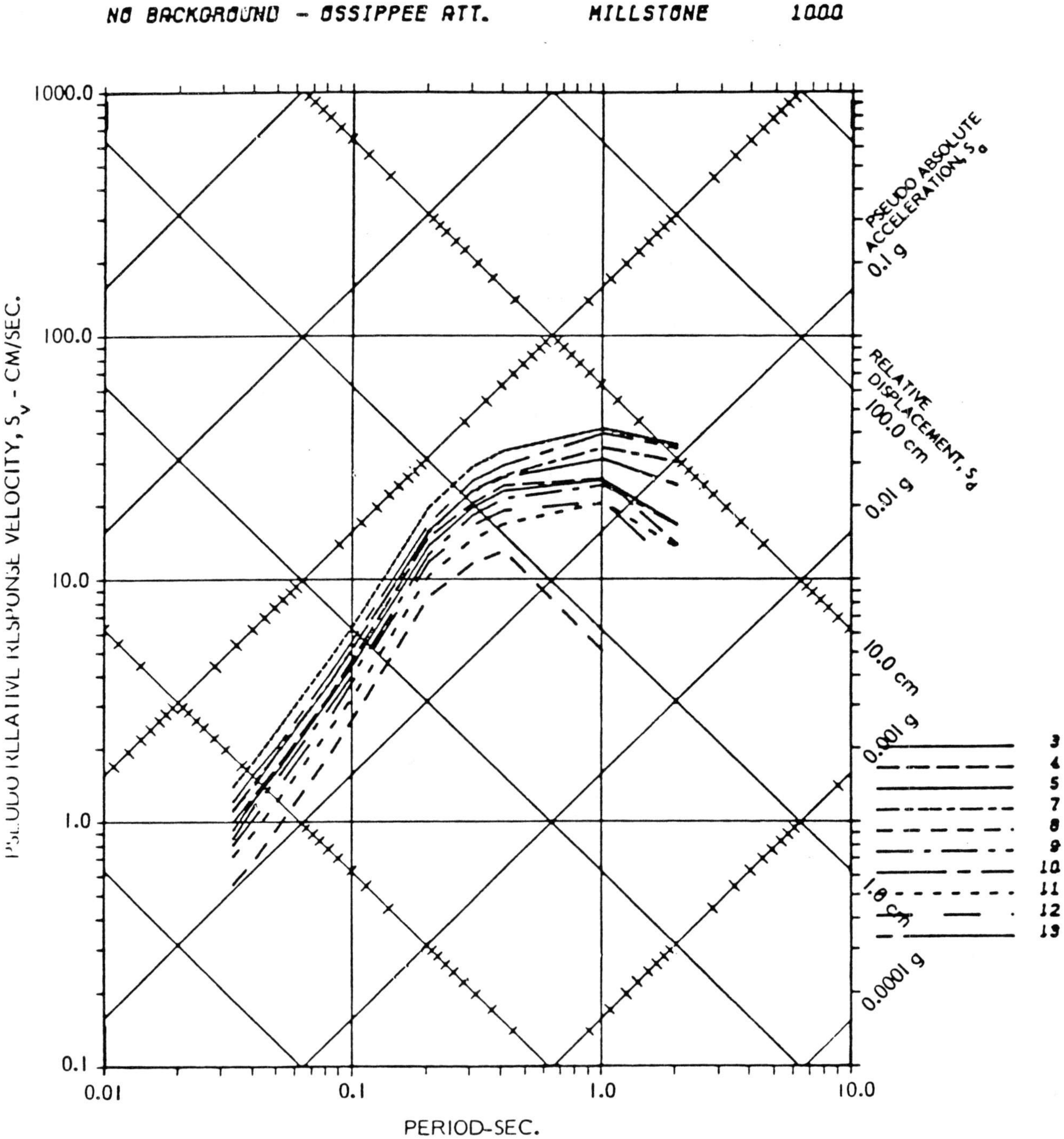

Figure 7. Millstone - no background.

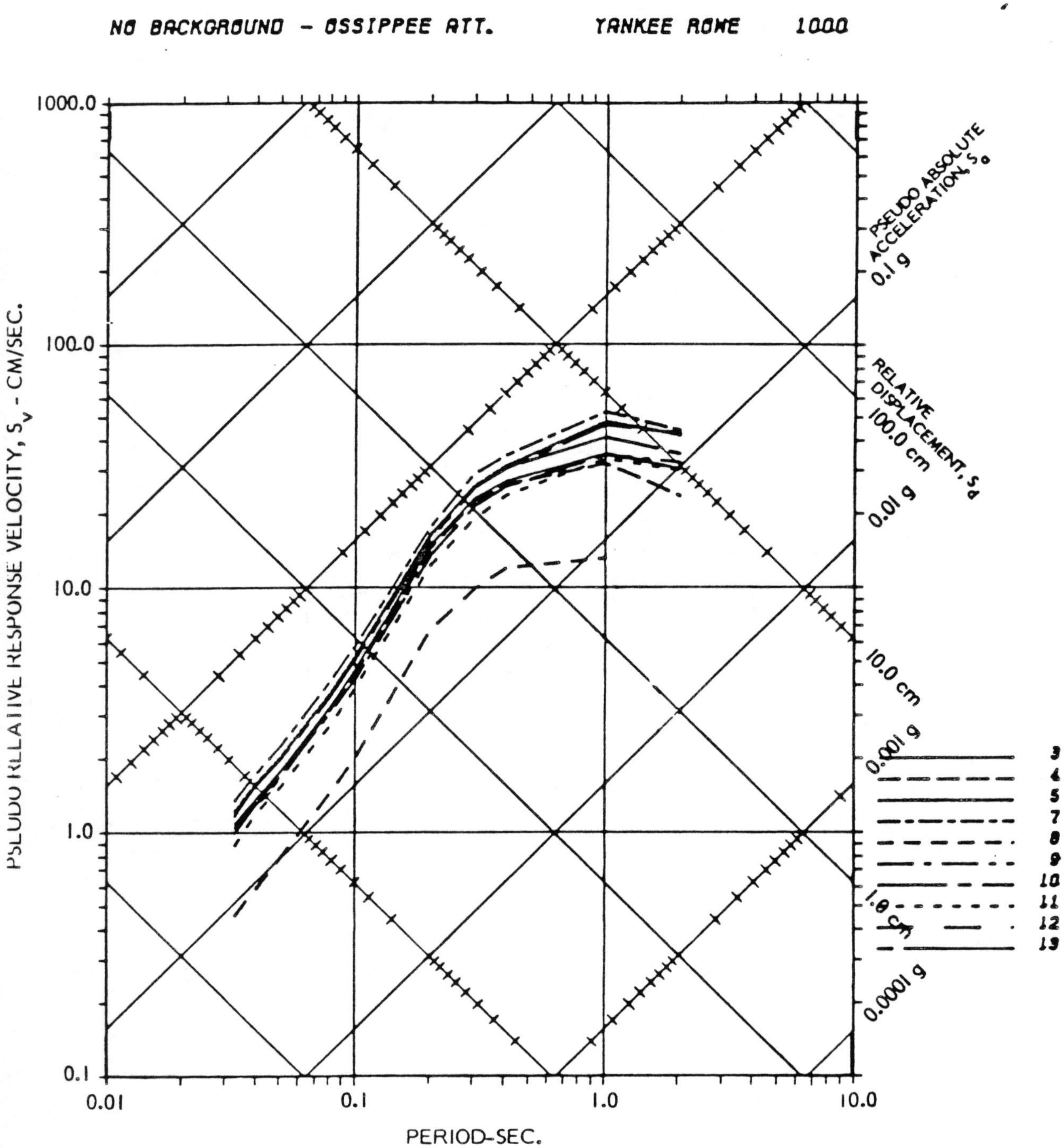

Figure 8. Yankee Rowe - no background.

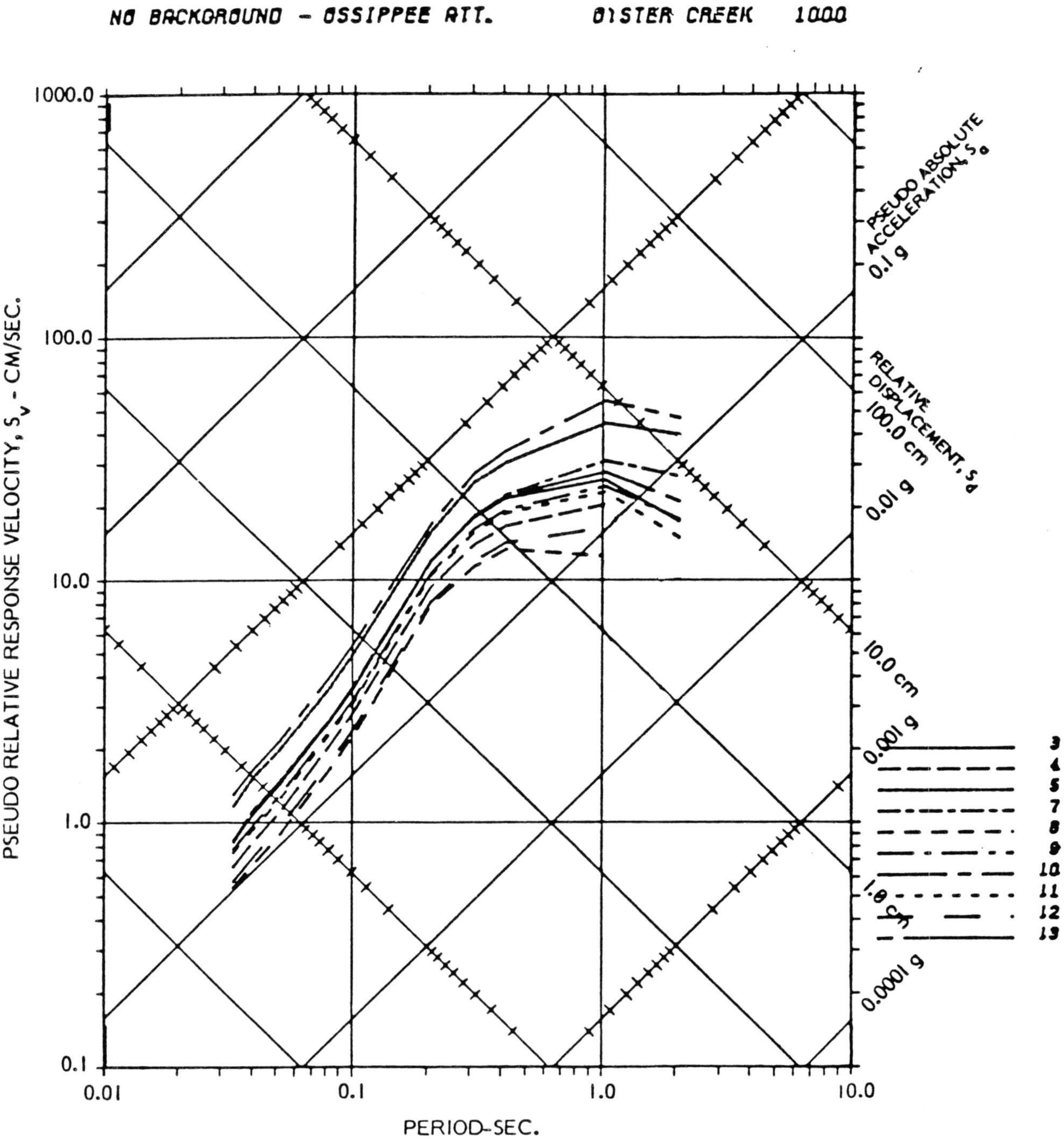

Figure 9. Oyster Creek - no background.