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	Engineering and Design EARTHQUAKE DESIGN AND EVALUATION FOR CIVIL WORKS PROJECTS	
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DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

Regulation
No. 1110-2-1806

31 July 1995

Engineering and Design
EARTHQUAKE DESIGN AND EVALUATION FOR CIVIL WORKS PROJECTS

1. Purpose

This regulation provides guidance and direction for the seismic design and evaluation for all civil works projects.

2. Applicability

This regulation is applicable to all HQUSACE elements and USACE commands having responsibilities for the planning, design, and construction of civil works projects.

3. References

References are listed in Appendix A.

4. Policy

The seismic design for new projects and the seismic evaluation or reevaluation for existing projects should be accomplished in accordance with this regulation. This regulation applies to all projects which have the potential to malfunction or fail during major seismic events and cause hazardous conditions related to loss of human life, appreciable property damage, disruption of lifeline services, or unacceptable environmental consequences. The effort required to perform these seismic studies can vary greatly. The scope of each seismic study should be aimed at assessing the ground motions, site characterization, structural response, functional consequences, and potential hazards in a consistent, well-integrated, and cost-effective effort that will provide a high degree of confidence in the final conclusions. Survival of operating equipment and utility lines is as essential as survival of the structural and geotechnical features of the project. When justifying circumstances exist, requests for departures from this policy should be submitted by the District Commander through the Division Commander to HQUSACE (CECW-E).

5. General Provisions

a. Project hazard potential. The classification in Appendix B is related to the consequences of project failure. Critical features are the engineering structures, natural site conditions, or operating equipment and utilities at high hazard projects whose failure during or immediately following an earthquake could result in loss of life. Such a catastrophic loss of life could result directly from failure or indirectly from flooding damage to a lifeline facility, or could pose an irreversible threat to human life due to release or inundation of hazardous, toxic, or radioactive materials. Project hazard potential should consider the population at risk, the downstream flood wave depth and velocity, and the probability of fatality of individuals within the affected population. All other features are not critical features.

b. Design. Seismic design for new projects shall include assessments of the potential earthquake motions and project features to ensure acceptable performance during and after design events. The level of design required to help ensure such performance is dependent upon whether or not seismic loadings control design, the complexity of the project, and the consequences of losing project service or control of the pool. The analysis should be performed in phases in order of increasing complexity. Continuity of the design process is important throughout each stage. The plan of study for each stage of design should be consistent with this regulation and with ER 1110-2-1150. An initial assessment of

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This regulation supersedes ER 1110-1-1806, dated 16 May 1983.

project hazards associated with the earthquake shall be included in the reconnaissance stage of study. The magnitude of seismic motions and an initial evaluation of key project features shall be included in the feasibility stage in design of sufficient detail to determine whether seismic loads control the design. Detailed seismic analysis should be completed during the design memorandum stage. Final detailing should be in the plans and specifications. In-progress review meetings should be accomplished early in the study and at key points within each phase.

c. Evaluation. Evaluation of existing project features differs from the design of new features. The evaluation of existing project features should be initiated for circumstances outlined in paragraph 5*d*. The evaluation begins with a careful review of the project foundation conditions and construction materials, and an understanding of design and construction practices at the time the project was built. Available information such as geological maps, boring logs, acceleration contour maps, standard response spectra, and as-built project records should be used to screen from further consideration project features that have adequate seismic designs, or for which seismic loads do not control the design. Detailed site explorations, site-specific ground motion studies, and structural analyses should be undertaken only for projects in zones 3 and 4, or for zone 2A and 2B projects when seismic loads control the design. All potential modes of failure must be carefully evaluated using field investigations, testing, and appropriate analyses.

d. Basis. Existing project features, designed and constructed to older standards, may not provide adequate seismic protection, or a ductile response to earthquake ground motions for reinforced concrete structures. Evaluation or reevaluation of existing projects should be undertaken for one or more of the following reasons:

(1) Performance is inconsistent with the design intent during a major earthquake.

(2) An alteration of the project functions is made which could cause more stringent loading conditions (higher pools, more frequent high pools, or longer duration) during major earthquakes.

(3) An advance in the state of the art occurs which demonstrates that previous evaluations are inadequate or incomplete and potentially hazardous.

(4) Project modifications are made to improve operational conditions which adversely impact or reduce the seismic resistance of particular project features.

(5) Periodic inspection is required. Reevaluations should be conducted every third periodic inspection or every 15 years, whichever comes first.

e. Remediation. Bringing existing project features up to current seismic design standards is generally expensive. Expert judgment as well as appropriate linear elastic and nonlinear analytical studies may be required to clearly demonstrate the need for remediation. In instances where the capacity of the project feature is less than the earthquake demand, a risk assessment should be performed. The risk assessment should include a probabilistic seismic hazard analysis, as defined in paragraph 5*h*(2)(b), to quantify the threshold event corresponding to failure. This information is needed to evaluate the urgency of remediation, and to justify funding for additional investigations and retrofit design. Downstream, nonstructural measures to reduce the project hazard should be considered as an alternative to seismic remediation.

f. Project team concept. Earthquake design or evaluation of civil works projects requires close collaboration of an interdisciplinary team that includes specialists in seismology, geology, material, and geotechnical and structural engineering. The team is responsible for establishing the earthquake engineering requirements for the project, planning and executing the seismological and engineering investigations, and evaluating results. A senior structural or geotechnical engineer should be responsible for leading the seismic design or evaluation studies related to the principal structural or geotechnical features, respectively, of the project. Technical experts should be included on the team to provide guidance on seismic policy, advice on the overall earthquake engineering requirements, and evaluation of results for the project, or to provide advice on specific aspects of the seismological and engineering investigations. This team should establish the scope of the entire seismic study early in the design or evaluation process to ensure that resources are being used efficiently and that the seismotectonic, geologic, site, and structural investigations are compatible and complete.

g. Consulting technical experts. Seismic design or evaluation of civil works projects is a rapidly evolving and highly complex field of earthquake engineering which requires special expertise and substantial judgment to be effective. In many instances, the project team should augment the inhouse staff with technical experts to ensure independent review of the methodology and results, to add credibility to the results, and to ensure public acceptance of the conclusions. Such experts should be drawn from the fields of geology, seismology, and structural and geotechnical earthquake engineering. These experts may be from within the U.S. Army Corps of Engineers, other government agencies, universities, or the private sector. Technical experts should be included in the early team planning sessions to assist in identifying the scope of earthquake problems, selecting approaches and criteria, reviewing results, and selecting interim and final seismic parameters. The experts shall participate with the team in meetings and provide memoranda of concurrence and summary advice which shall be a part of the formal record of design or evaluation.

h. Standard and site-specific studies. Seismic studies should include the seismotectonic, geologic, site, geotechnical, and structural investigations required to select the design ground motions, and to determine the foundation and structural response for the earthquake events applicable at the project site. Further guidance on the design and analysis requirements are provided in Appendices B-F.

(1) Standard seismic studies are based on existing generic seismological studies, available site data and information, and simplified methods of evaluation developed for similar projects or structures. Generally, standard studies use preliminary values of the ground motions obtained from published seismic zone maps, a preliminary structural analysis, and a simplified assessment of soil liquefaction and deformation to determine if seismic loadings control the design, and to set the scope of any proposed site-specific studies. Standard methods and data in the referenced guidance are useful for preliminary and screening investigations in all seismic zones, and may be satisfactory for final design or evaluation in seismic zones 1 or 2A.

(2) Site-specific studies involve the use of actual site and structural conditions in evaluating the project hazards and the response of project features to seismic loading. Detailed field exploration and testing programs should be carefully planned and executed. Geologic studies should describe the seismotectonic province, characterize the site, and investigate all faults that can affect the site. Seismologic investigations should describe the earthquake history, earthquake recurrence relationship, and the strong motion records to be used in design or evaluation. Special emphasis should be placed on identifying all geological, seismological, and geotechnical parameters necessary to encompass the design and response of foundations and structures. Structural investigations should accurately account for all relevant factors which affect the seismic hazard at the specific site and the actual dynamic behavior of the structure, including damping and ductility of the structural systems. Geotechnical investigations should determine the types and spatial distribution of foundation and embankment maturate and the engineering properties of soil and rock. Propagation of the ground motion through the foundation and embankment, liquefaction potential of foundation and embankment soils, stability of natural and artificial slopes, and estimates of deformations should also be determined. The final results of site-specific studies are used as a basis for making design or evaluation decisions and for designing any remedial measures. Site-specific studies should be conducted for all zone 3 and 4 projects, and for zone 2A and 2B projects for which earthquake loadings control the design. There are two general approaches for conducting site-specific seismic hazard analyses, which are described below:

(a) Deterministic seismic hazard analysis (DSHA). The DSHA approach uses the known seismic sources sufficiently near the site and available historical seismic and geological data to generate discrete, single-valued events or models of ground motion at the site. Typically one or more earthquakes are specified by magnitude and location with respect to the site. Usually the earthquakes are assumed to occur on the portion of the source closest to the site. The site ground motions are estimated deterministically, given the magnitude, source-to-site distance, and site condition.

(b) Probabilistic seismic hazard analysis (PSHA). The PSHA approach uses the elements of the DSHA and adds an assessment of the likelihood that ground motions will occur during the specified time period. The probability or frequency of occurrence of different magnitude earthquakes on each significant seismic source and inherent uncertainties are directly accounted for in the analysis. The results of a PSHA are used to select the site ground motions based on the probability of exceedance of a given magnitude during the service life of the structure or for a given return period.

6. Design Earthquakes and Ground Motions

a. Maximum credible earthquake (MCE). This earthquake is defined as the greatest earthquake that can reasonably be expected to be generated by a specific source on the basis of seismological and geological evidence. Since a project site may be affected by earthquakes generated by various sources, each with its own fault mechanism, maximum earthquake magnitude, and distance from the site, multiple MCE's may be defined for the site, each with characteristic ground motion parameters and spectral shape. The MCE is determined by a DSHA.

b. Maximum design earthquake (MDE). The MDE is the maximum level of ground motion for which a structure is designed or evaluated. The associated performance requirement is that the project perform without catastrophic failure, such as uncontrolled release of a reservoir, although severe damage or economic loss may be tolerated. For critical features, the MDE is the same as the MCE. For all other features, the MDE shall be selected as a lesser earthquake than the MCE which provides economical designs meeting appropriate safety standards. The MDE can be characterized as a deterministic or probabilistic event.

c. Operating basis earthquake (OBE). The OBE is an earthquake that can reasonably be expected to occur within the service life of the project, that is, with a 50-percent probability of exceedence during the service life. (This corresponds to a return period of 144 years for a project with a service life of 100 years.) The associated performance requirement is that the project function with little or no damage, and without interruption of function. The purpose of the OBE is to protect against economic losses from damage or loss of service, and therefore alternative choices of return period for the OBE may be based on economic considerations. The OBE is determined by a PSHA.

d. Estimating OBE and MDE ground motions. Estimates are usually made in two phases. The first estimates are used as a starting point for the study and are obtained from the National Earthquake Hazard Reduction Program (NEHRP) spectral acceleration maps (Appendix D). Site-specific studies in accordance with paragraph 5*h*(2) are often required for selecting the final estimates of OBE and MDE ground motions. Both DSHA and PSHA approaches are appropriate. Combining the results of deterministic and probabilistic analyses is often an effective approach for selecting MDE ground motions. Typical results of a probabilistic analysis are a hazard curve and an equal hazard spectrum which relate the level of ground motion to an annual frequency of exceedance or return period. This information can be used to complement the deterministic analysis by removing from consideration seismic sources that appear unreasonable because of low frequencies of occurrence, by justifying mean or mean-plus-standard deviation estimates of deterministic ground motion, or by ensuring consistency of MDE ground motions with some performance goal.

7. Site Characterization

a. Site studies. The two primary concerns in the site characterization for a project are: the effects of the ground motion on the site, such as loss of strength in foundation materials and instability of natural slopes; and the effects of soil strata and topographic conditions (basin effects, or ray path focus) on the propagation of the specified ground motion from rock outcrop to a particular project feature. The objective of a site characterization study is to obtain all of the data on the site conditions that are essential to design or to operate a project safely. Relevant site conditions normally include topographic and hydrologic conditions; the nature and extent of the material present in the foundation, embankment, natural slopes, and structures at the site; and the physical and dynamic engineering properties (such as modulus, damping, and density) of these materials. The site characterization should be of a progressive nature starting with the information from available sources on the geology, seismicity, and project features at the site. This should include a description of the site geology, seismicity such as known faulting in the region, seismic history, and prior relevant seismic evaluations in the vicinity, and any known data related to specific project features at the site or proposed for the site.

b. New projects. For new projects, field exploration and material testing programs should be developed to identify the stratigraphy and the physical and engineering properties of the foundation materials for the project features. Prior field investigations in the area of the project may also be used to provide additional information.

c. Existing projects. For evaluation or re-evaluation of existing projects, new field investigations may be required where available data are insufficient to resolve all significant safety issues. The project team should integrate this information into the decisionmaking process for designs or resolution of safety issues.

8. Concrete and Steel Structures and Substructures

a. Role of structural engineers. Appropriate methods for seismic studies vary greatly with the type of structure or substructure. Structural engineers should be involved in the selection of ground motions from the earliest stages of study. Their understanding as to how the ground motions will be used in the structural analysis as it proceeds through progressively more sophisticated stages is needed to reach definitive conclusions and make sound decisions. The structural engineer needs to establish how response spectra from standard and site-specific studies and time-histories from site-specific studies will be used in the progressive stages of the structural investigations. This progression is related to the level of accuracy or sophistication of the model needed, and to all the uncertainties which must be dealt with correctly and consistently so that the final result will be reliable and safe but not overly conservative and unnecessarily expensive.

b. Design standards. Minimum standards for the seismic design or evaluation of buildings and bridges are available in national, regional, or local building codes, in Tri-Service technical manuals, and in Federal and state design specifications for highway systems. New building designs and upgrades to existing buildings shall be in accordance with the provisions of Tri-Service manuals TM 5-809-10 and TM 5-809-10-1. Existing buildings conforming to the seismic requirements of the Uniform Building Code, the National Building Code, or the Standard Building Code, including their 1992 supplements and additions, need not follow the seismic design provisions of TM 5-809-10. Bridges on projects which are open to public access shall be designed or evaluated in accordance with the American Association of State Highway Transportation Officials and state design standards.

c. Code requirements. Seismic code requirements for concrete and steel hydraulic structures (CSHS) have not been developed as fully as those for buildings and bridges. Design guidance for CSHS shall be in accordance with the references in Appendix A.

d. Load combinations. Design loading combinations for CSHS shall be in accordance with the referenced guidance for specific structures. In general, CSHS shall have adequate stability, strength, and serviceability to resist an OBE and MDE. The structural and operating requirements are different for these two levels of earthquakes, and either level may control the design or evaluation. The structure should essentially respond elastically to the OBE event with no disruption to service. The structure may be allowed to respond inelastically to the MDE event, which may result in significant structural damage and limited disruption of services, but the structure should not collapse or endanger lives. Economic considerations will be a factor in determining the acceptable level of damage. For critical structures, the MDE is equal to the MCE. In general, the OBE is an unusual loading condition, and the MDE is an extreme loading condition.

e. Analysis methods. Techniques used to evaluate the structural response to earthquake ground motions include seismic coefficient methods, response spectrum methods, and time-history methods. Details of these methods of analysis may be found in the references in Appendix A. Simplified response spectrum analysis procedures are available for analysis of some types of CSHS, for example concrete gravity dams and intake towers (Chopra 1987, Chopra and Goyal 1989). These methods utilize idealized cross-sections and make various assumptions concerning the structure's response to ground motions and its interaction with the foundation and reservoir. The validity of these assumptions must be carefully examined for each project prior to using any simplified analysis procedure; however, in most cases, these methods will be sufficient for use in feasibility level studies. The seismic coefficient method should not be used for final design of any structure where an earthquake loading condition is the controlling load case. Final designs in seismic zones 3 and 4 should use either response spectrum or time-history methods.

f. Input from ground motion studies. Site-specific ground motion studies required in accordance with paragraph 5*h*(2) should provide magnitude, duration, and site-specific values for the peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), and design response spectra and time-histories in both the horizontal and vertical directions at the ground surface or a rock outcrop as a minimum. Site-specific studies should also consider soil-structure interaction effects which may reduce ground motions at the base of the structure.

g. Analysis progression. An important aspect of the design or evaluation process is to develop an analytical model of the structure and substructure which adequately represents the seismic behavior. The analysis process should be performed in phases, in order of increasing complexity, beginning with simplified empirical procedures. These procedures are based on satisfactory experience with similar types of structural materials and systems, and observations of failure due to strong ground motions. These general requirements are outlined in Appendix E. Performing the analysis in phases will ensure that the analytical model is providing realistic results and will provide a logical basis for decisions to revise the structural configuration and/or proceed to a more accurate analysis method. The structural analysis can range from simple two-dimensional (2D) beam models to sophisticated three-dimensional (3D) finite element models. All three components of ground motion may be required to capture the total system response. Dynamic analyses of most massive concrete structures usually require a model which includes interaction with the surrounding soil, rock, and water to produce meaningful results. Differences in structural shapes and variations in foundation materials or ground motion should be accounted for in evaluating the spatial variation in response between points on large structures. The structural significance of the mode shapes must be understood, especially when evaluating the stresses using a response spectrum analysis. The results of a finite element analysis of a reinforced concrete structure should be expressed in terms of moment, thrust, and shear, not just linear stresses at a point, in order to correctly evaluate the behavior of the reinforced cross-section. Areas where inelastic behavior is anticipated should be identified and concrete confinement requirements stated. In general, linear time-history methods applied to 2D or 3D models will provide the most complete understanding of structural performance during an earthquake. If a design is found to be inadequate using linear time-history methods of analysis, then nonlinear time-history methods should be considered. Such methods are beyond the scope of this policy, and shall be conducted in consultation with CECW-ED.

h. Seismic design principles. It is important to incorporate sound seismic engineering concepts in all aspects of the design or evaluation process. In all instances the design engineer should ensure that the structural configuration has minimum geometric irregularities, there are only gradual variations in structural stiffness, and any necessary structural discontinuities are properly detailed to account for the localized effects of stress concentrations. Continuous load paths, load path redundancy, and ductile behavior are important safe-guards to ensure that structures loaded past their elastic limit will continue to perform adequately and will function after extensive cracking. An example of load path redundancy is to lay out concrete gravity dams with a curved axis and keyed monolith joints. This will permit loads to be redistributed to the abutments even if the base foundation is weakened or displaced by an earthquake.

9. Embankments, Slopes, and Soil Foundations

a. General. The seismic evaluation and design of soil foundations, slopes, and embankments involves the interaction of geologists, seismologists, and geotechnical engineers. The activities for this effort can be grouped into four main areas: field investigations, site characterization, numerical analyses, and evaluation. It is essential that the investigations and site characterization adequately portray the nature, extent, and in-situ physical properties of the materials in the foundation, embankment, or slope being investigated.

b. Embankments. Appropriate methods should be used to analyze the liquefaction potential and/or to estimate deformations for embankment (dams, dikes, levees that retain permanent pools), slope, and foundation materials when subjected to ground motions corresponding to the MDE and the OBE.

c. Slopes and foundations. Slopes to be analyzed should include natural, reservoir rim, and other slopes, with or without structures, with the potential to affect the safety or function of the project. Foundation materials to be analyzed for liquefaction of the project include all foundation soils that support project features or the liquefaction of which would affect project features. The results of investigations and data review as described in paragraph 7 and the seismological evaluation will determine the appropriate methods, including dynamic analysis, to be performed on the project.

d. Evaluations. Evaluations of embankment, slope, and/or foundation susceptibility to liquefaction or excessive deformation will be performed for all projects located in seismic zones 3 and 4, and those projects in zone 2 where materials exist that are suspected to be susceptible to liquefaction or excessive deformation. Such evaluation and analysis should also be performed regardless of the seismic zone location of the project, where capable faults or recent earthquake epicenters are discovered within a distance that may result in damage to the structure.

e. Defensive design measures. Defensive design features should be incorporated in the foundation and embankment design regardless of the method of seismic analysis. These details of these features should be optimized based on the results of the analysis. Defensive features include:

(1) Additional dam height to accommodate the loss of crest elevation due to deformation, slumping, and fault displacement.

(2) Crest details that will minimize erosion in the event of overtopping.

(3) Wider transition and filter sections as a defense against cracking.

(4) Use of rounded or subrounded gravel and sand as filter material.

(5) Adequate permeability of the filter layers.

(6) Near vertical drainage zones in the central portion of the embankment.

(7) Zoning of the embankment to minimize saturation of materials.

(8) Wide impervious cores of plastic clay materials to accommodate deformation.

(9) Well-graded core and filter materials to ensure self healing in the event cracking should occur.

(10) Stabilization of reservoir rim slopes to provide safety against large slides into the reservoir.

(11) Removal and replacement of liquefaction susceptible material in the foundation.

(12) In-situ densification of foundation materials.

(13) Stabilization of slopes adjacent to operating facilities to prevent blockage from a slide associated with the earthquake.

(14) Flaring embankment sections at the abutment contacts.

10. Actions for New Projects

For new projects, the phases of study required for the seismic analysis and design shall be in accordance with ER 1110-2-1150 and shall progress as described in Appendix E. These requirements are summarized below.

a. Reconnaissance phase. This study phase shall include the initial assessment of the seismic ground motions at the project site for each of the design earthquakes, the potential impact of these motions on the project's design, and the engineering effort required for the seismic design during the feasibility study phase. If no site-specific ground motions are available for the design earthquakes, the ground motions can be estimated as described in paragraph 6*d*.

b. Feasibility phase. This study phase shall include the preliminary seismic analysis and design of the key features of the project in sufficient detail to prepare the baseline cost estimate and determine the contingencies appropriate for the level of sophistication of the analysis. The preliminary seismic analysis should also be of sufficient detail to develop a design and construction schedule, and allow detailed design on the selected plan to begin immediately following approval of the feasibility report. For projects for which seismic loads control the design, the feasibility study phase should include site-specific studies to determine the design ground motions and preliminary stability and response spectra analyses for design of the project.

c. Design memorandum phase. This study phase requires a seismic analysis and design in sufficient detail to serve as the basis for preparing plans and specifications (P&S). Subsequent engineering for preparing the P&S should generally be limited to detailing and preparing specifications. The design memorandum study phase will also include detailed site-specific studies to determine the design ground motions 2D and 3D response spectrum analyses, and time-history analyses. When the project studies proceed directly to P&S from the feasibility phase, the design memorandum seismic studies should be conducted during the feasibility stage or as a separate study prior to the P&S phase.

11. Actions for Existing Projects

For existing projects, the phases of study required for seismic analysis shall be in accordance with ER 1110-2-1155 or the current major rehabilitation program guidance as provided by CECW-O. These requirements are summarized below and in Appendix F.

a. Preliminary evaluation. When an evaluation of existing project features must be initiated for reasons stated in paragraph 5*d*, the preliminary results should be presented in a Dam Safety Assurance or Major Rehabilitation Evaluation Report (DSAER or MRER, respectively) using the latest guidance. The report will adequately explain the seismic deficiency, and will outline additional investigations necessary to access the risk and to upgrade the project to meet current seismic criteria. This report will be submitted to HQUSACE, through the major subordinate command, for approval.

b. Special studies. After approval of the DSAER or MRER, special studies may be required, and should proceed in three phases as defined in the current major rehabilitation program guidance as provided by CECW-O. Phase one studies can be reported as a letter report addendum to the evaluation report or as a supplement to an existing design memorandum. Phase two studies should be reported in a design memorandum.

12. Funding

General Investigation, Construction General, or Operation and Maintenance General funds should be used as appropriate to accomplish the investigations.

FOR THE COMMANDER:

6 Appendices
APP A - References
APP B - Hazard Potential Classification
  for Civil Works Projects
APP C - Uniform Building Code Seismic
  Zone Map
APP D - National Earthquake Hazard Reduction
  Program Spectral Acceleration Maps
APP E - Progressive Seismic Analysis
  Requirements for Concrete and Steel
  Hydraulic Structures
APP F - Design and Analysis Requirements
  for Seismic Evaluation Reports

ROBERT H. GRIFFIN
Colonel, Corps of Engineers
Chief of Staff

APPENDIX A
REFERENCES

A-1. Required Publications

ER 1110-2-1150
Engineering and Design for Civil Works Projects

ER 1110-2-1155
Dam Safety Assurance

TM 5-809-10/NAVFAC P-355/AFM 88-3, Chap. 13, Sec A
Seismic Design for Buildings

TM 5-809-10-1/NAVFAC P-355.1/AFM 88-3, Chap. 13, Sec A
Seismic Design Guidelines for Essential Buildings

Chopra 1987
Chopra, A. K. 1987. "Simplified Earthquake Analysis of Concrete Gravity Dams," *ASCE Journal of the Structural Division*, 113ST8.

Chopra and Goyal 1989
Chopra, A. K., and Goyal, A. 1989. "Earthquake Analysis and Response of Intake-Outlet Towers," Report No. UCB/EERC-89-04, Earthquake Engineering Research Center, University of California, Berkeley, CA.

A-2. Related Publications

EM 1110-2-1902
Stability of Earth and Rockfill Dams

EM 1110-2-2200
Gravity Dam Design

EM 1110-2-2201
Arch Dam Design

Algermissen 1983
Algermissen, S. T. 1983. "An Introduction to the Seismicity of the United States," Earthquake Engineering Research Institute, Berkeley, CA.

Chopra 1981
Chopra, A. K. 1981. *Dynamics of Structures, A Primer*, Earthquake Engineering Research Institute, Berkeley, CA.

Clough and Penzien 1993
Clough, R. W., and Penzien, J. 1993. *Dynamics of Structures*, McGraw-Hill, New York.

Cornell 1968
Cornell, C. A. 1968. "Engineering Seismic Risk Analysis," *Bulletin of the Seismological Society of America*, Vol 58, pp 1583-1606.

Earthquake Engineering Research Institute Committee on Seismic Risk 1989. "The Basics of Seismic Risk Analysis," *Earthquake Spectra*, Vol 5, pp 675-702.

Ebeling 1992
Ebeling, R. M. 1992. "Introduction to the Computation of Response Spectrum for Earthquake Loading," Technical Report ITL-92-11, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

FEMA 1992
Federal Emergency Management Administration. 1992. "NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings," 1991 Edition, FEMA 222 and 223, Washington DC.

Finn et al. 1986
Finn, W. D. L., Yogendrakumar, M., Yoshida, N., and Yoshida H. 1986. "TARA-3: A Program to Compute the Response of 2-D Embankments and Soil-Structure Interaction Systems to Seismic Loadings," Department of Civil Engineering, University of British Columbia, Vancouver, Canada.

Housner and Jennings 1982
Housner, G. W., and Jennings, P. C. 1982. "Earthquake Design Criteria," Earthquake Engineering Research Institute, Berkeley, CA.

Hudson 1979
Hudson, D. E. 1979. "Reading and Interpreting Strong Motion Accelograms; Engineering Monographs on Earthquake Criteria, Structural Design, and Strong Motion Records," Vol 1, Earthquake Engineering Research Institute, Berkeley, CA.

Hynes-Griffin and Franklin 1984
Hynes-Griffin, M. E., and Franklin, A. G. 1984. "Rationalizing the Seismic Coefficient Method," Miscellaneous Paper GL-84-13, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

International Committee on Large Dams 1989
International Committee on Large Dams. 1989. "Selecting Seismic Parameters for Large Darns," *Guidelines*, Bulletin 72.

Krinitzsky and Chang 1987
Krinitzsky, E. L., and Chang, F. K. 1987. "Parameters for Specifying Intensity-Related Earthquake Ground Motions," Report 25, "State-of-the-Art for Assessing Earthquake Hazards in the United States," Miscellaneous Paper S-73-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Makdisi and Seed 1978
Makdisi, F. I., and Seed, H. B. 1978. "Simplified Procedure for Estimating Dam and Embankment Earthquake Induced Deformations," *Journal of the Geotechnical Engineering Division*, ASCE, Vol 104, No. GT7, pp 849-867.

Marcusen, Hynes, and Franklin 1990
Marcusen, W. F., III, Hynes, M. E., and Franklin, A. G. 1990. "Evaluation and Use of Residual Strength in Seismic Safety Analysis of Embankments," *Earthquake Spectra*, Vol 6, No. 3, pp 529-572.

National Research Council 1988
National Research Council. 1988. "*Probabilistic Seismic Hazard Analysis*," National Academy Press, Washington, DC.

Newmark and Hall 1982
Newmark, N. M., and Hall, W. J. 1982. "Earthquake Spectra and Design; Engineering Monographs on Earthquake Criteria, Structural Design, and Strong Motion Records," Vol 3, Earthquake Engineering Research Institute, Berkeley, CA.

Newmark and Rosenbleuth 1971
Newmark, N. M., and Rosenbleuth, E. 1971. *Fundamentals of Earthquake Engineering,* Prentice-Hall, Englewood Cliffs, N.J.

Poulos, Castro, and France 1985
Poulos, S. J., Castro, G., and France, J. W. 1985. "Liquefaction Evaluation Procedure," *Journal of Geotechnical Engineering Division, ASCE,* Vol 111, No. 6, pp 772-792.

Poulos, 1988
Poulos, S. J. 1988. "Liquefaction and Related Phenomena," *Advanced Dam Engineering for Design and Construction and Rehabilitation,* Ch. 9, Robert B. Jansen, ed. Van Nostrand Reinhold, New York.

Reiter 1990
Reiter, L. 1990. *Earthquake Hazard Analysis, Issues and Insights,* Columbia University Press, New York.

Seed et al. 1975
Seed, H. B., Lee, K. L., Idriss, I. M., and Makdisi, F. I. 1975. "The Slides in the San Fernando Dams During the Earthquake of February 9, 1971," *Journal of Geotechnical Engineering Division, ASCE,* Vol 101, No. GT7, pp 651-688.

Seed 1979
Seed, H. B. 1979. "Soil Liquefaction and Cyclic Mobility Evaluation for Level Ground During Earthquake," *Journal of Geotechnical Engineering Division, ASCE,* Vol 105, No. GT2, pp 201-225.

Seed 1979
Seed, H. B. 1979. "19th Rankine Lecture: Considerations in the Earthquake Design of Earth and Rockfill Dams," *Geotechnique,* Vol 29, No. 3, pp 215-263.

Seed, Idriss, Arango 1983
Seed, H. B., Idriss, I. M. and Arango, I. 1983. "Evaluation of Liquefaction Potential Using Field Performance Data," *Journal of Geotechnical Engineering Division, ASCE,* Vol 1005, No. 3, pp 458-482.

APPENDIX B
HAZARD POTENTIAL CLASSIFICATION FOR CIVIL WORKS PROJECTS

Table B-1
Hazard Potential Classification

Category[1]	Direct Loss of Life[2]	Lifeline Losses[3]	Property Losses[4]	Environmental Losses[5]
Low	None (rural location, no permanent structures for human habitation)	No disruption of services (cosmetic or rapidly repairable damage)	Private agricultural lands, equipment, and isolated buildings	Minimal incremental damage
Significant	Rural location, only transient or day-use facilities	Disruption of essential facilities and access	Major public and private facilities	Major mitigation required
High	Certain (one or more) extensive residential, commercial, or industrial development	Disruption of critical facilities and access	Extensive public and private facilities	Extensive mitigation cost or impossible to mitigate

[1] Categories are based upon project performance and do not apply to individual structures within a project.

[2] Loss of life potential based upon inundation mapping of area downstream of the project. Analyses of loss of life potential should take into account the population at risk, time of flood wave travel, and warning time.

[3] Indirect threats to life caused by the interruption of lifeline services due to project failure, or operation, i.e direct loss of (or access to) critical medical facilities.

[4] Direct economic impact of property damages to project facilities and downstream property and indirect economic impact due to loss of project services, i.e. impact on navigation industry of the loss of a dam and navigation pool, or impact upon a community of the loss of water or power supply.

[5] Environmental impact downstream caused by the incremental flood wave produced by the project failure, beyond which would normally be expected for the magnitude flood event under which the failure occurs.

APPENDIX C
UNIFORM BUILDING CODE SEISMIC ZONE MAP

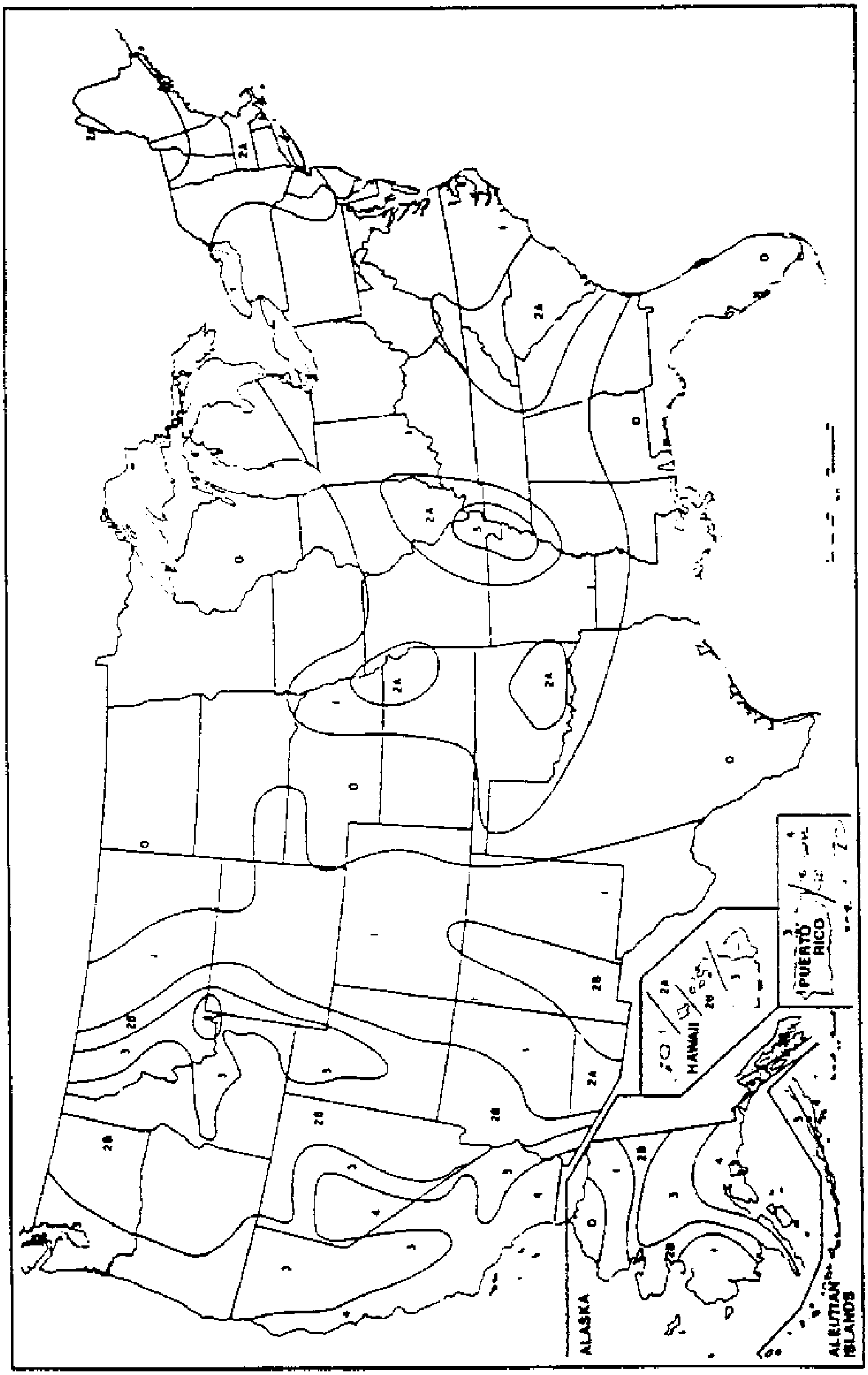

Figure C-1. Seismic zone map of the United States

APPENDIX D
NATIONAL EARTHQUAKE HAZARD REDUCTION PROGRAM SPECTRAL ACCELERATION MAPS

NOTES

1. Irregularly spaced contours are at intervals of 2, 5, 7.5, 10, 15, 20, 30, 40, 60, 80, 100, 200, and 300 percent g. In a few locations, supplemental contours are provided. Supplemental contours, if included, are always labeled. Spot values are included to supplement contours.

2. Contour variation with distance is rapid and complex in California, particularly near major faults and coastal regions. More detailed maps should be used when information is required in these areas.

3. The dashed curvilinear north-south line labeled "attenuation boundary" is the approximate division between western seismic source zones, modeled with Joyner and Boore's (1982) attenuation for soil, and eastern seismic source zones, modeled with Boore and Joyner's (1991) attenuation for soil.

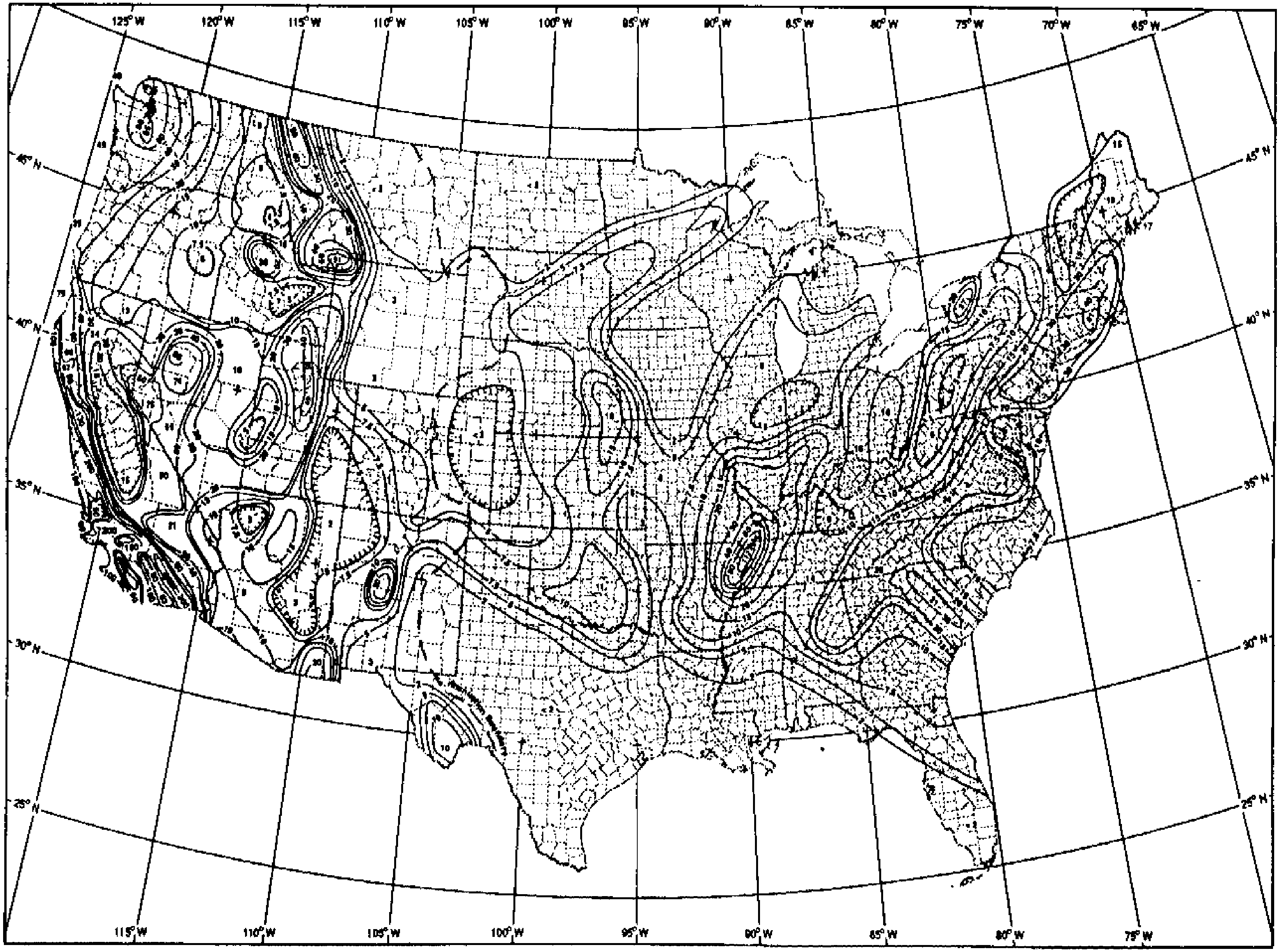

Figure D-1. 1991 U.S. Geological Survey (USGS) map of the 5-percent damped, 0.3-sec pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10-percent probability of exceedance in 50 years

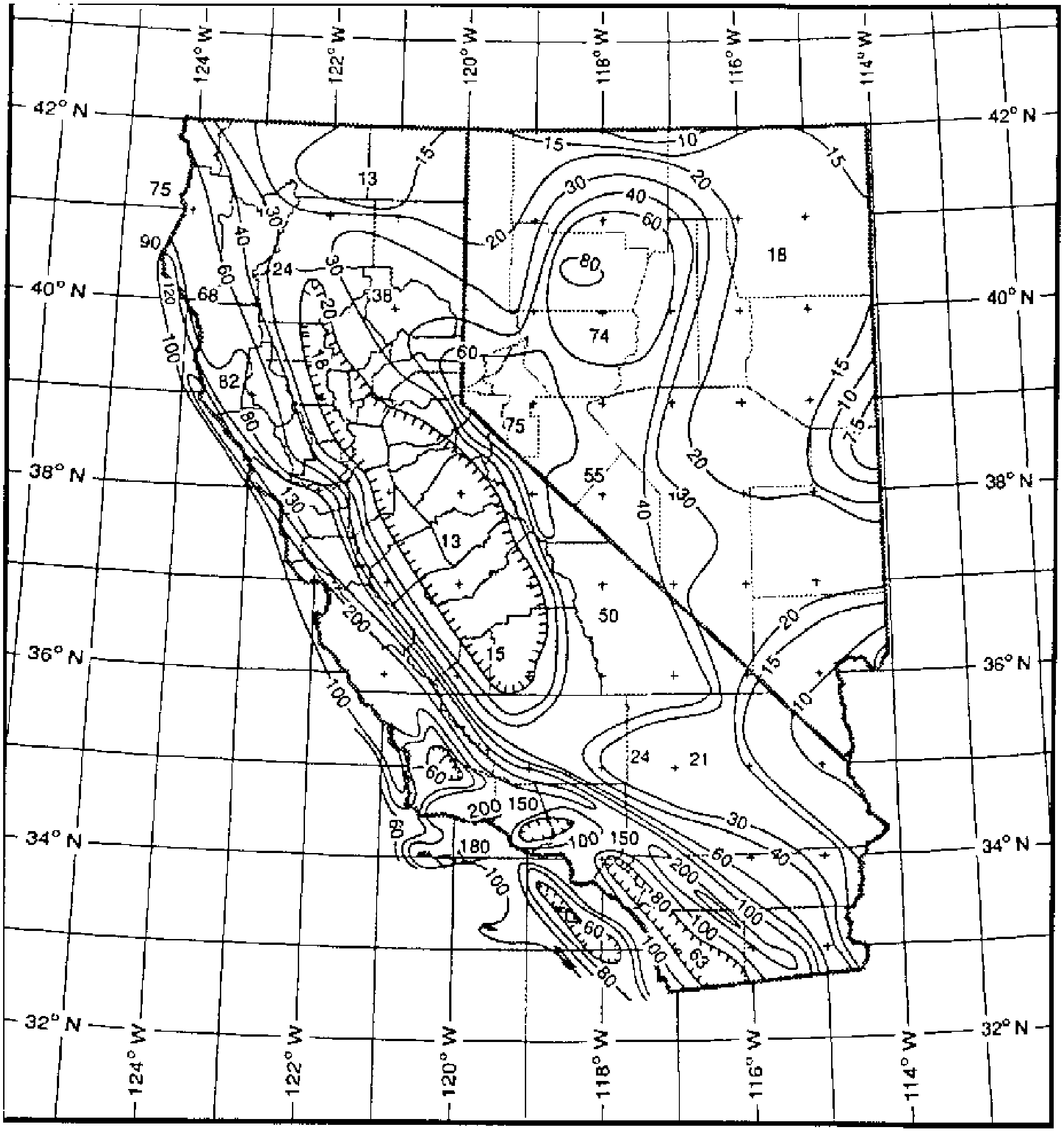

Figure D-2. 1991 USGS map of the 5-percent damped, 0.3-sec pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10-percent probability of exceedance in 50 years

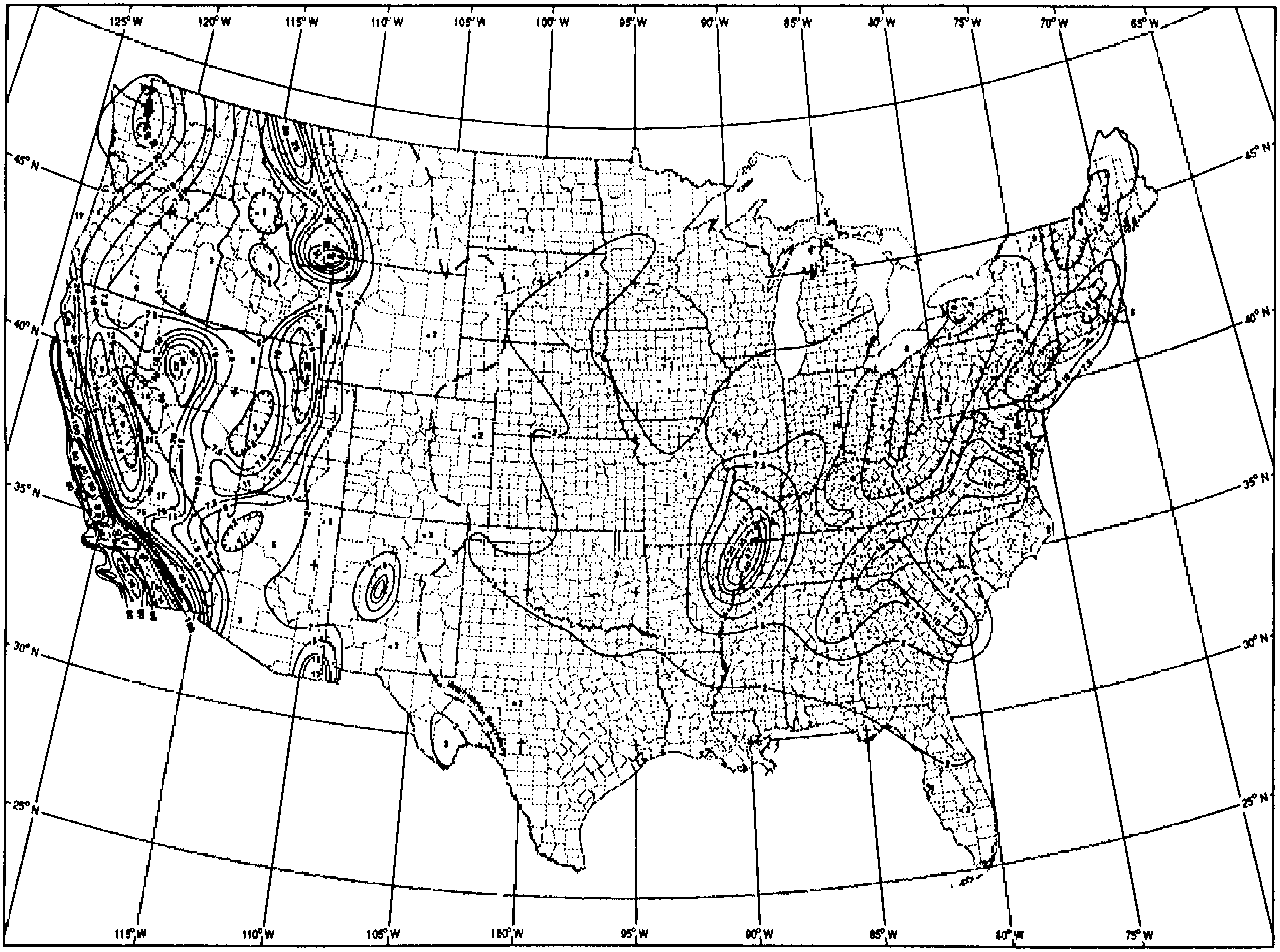

Figure D-3. 1991 map of the 5-percent damped, 1.0-sec pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10-percent probability of exceedance in 50 years

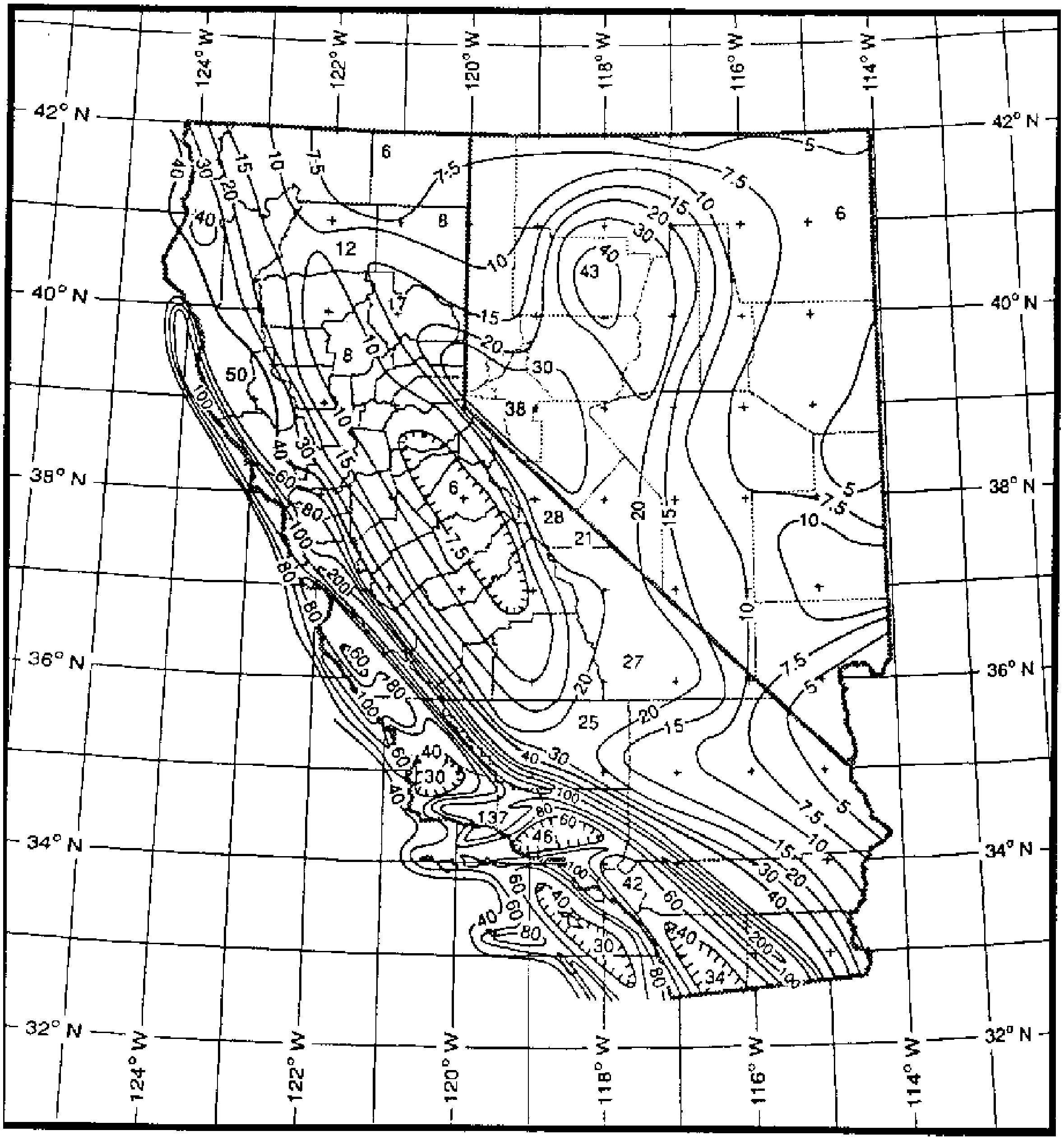

Figure D-4. 1991 USGS map of the 5-percent damped, 1.0-sec pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10-percent probability of exceedance in 50 years

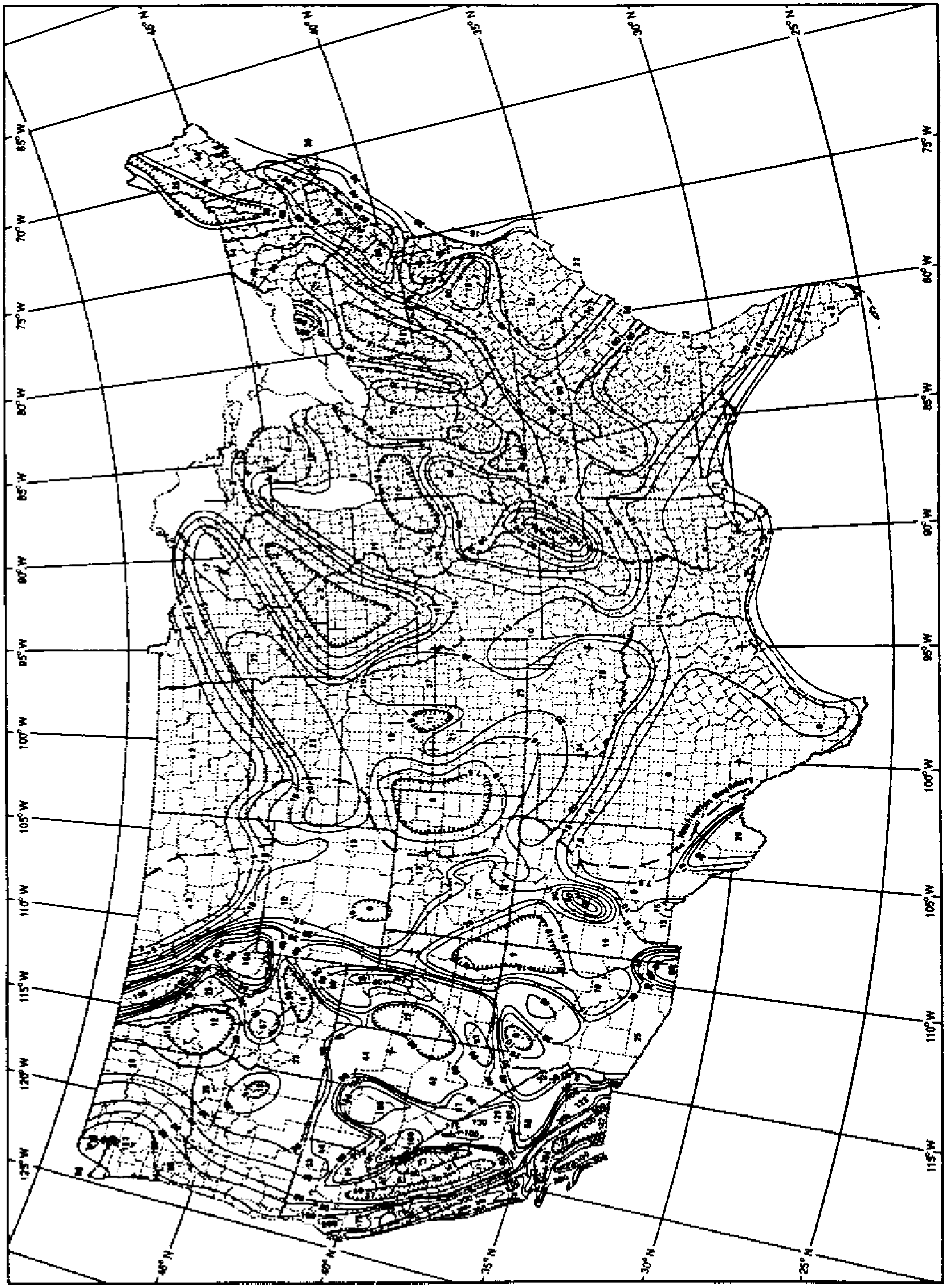

Figure D-5. 1991 map of the 5-percent damped, 0.3-sec pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10-percent probability of exceedance in 250 years

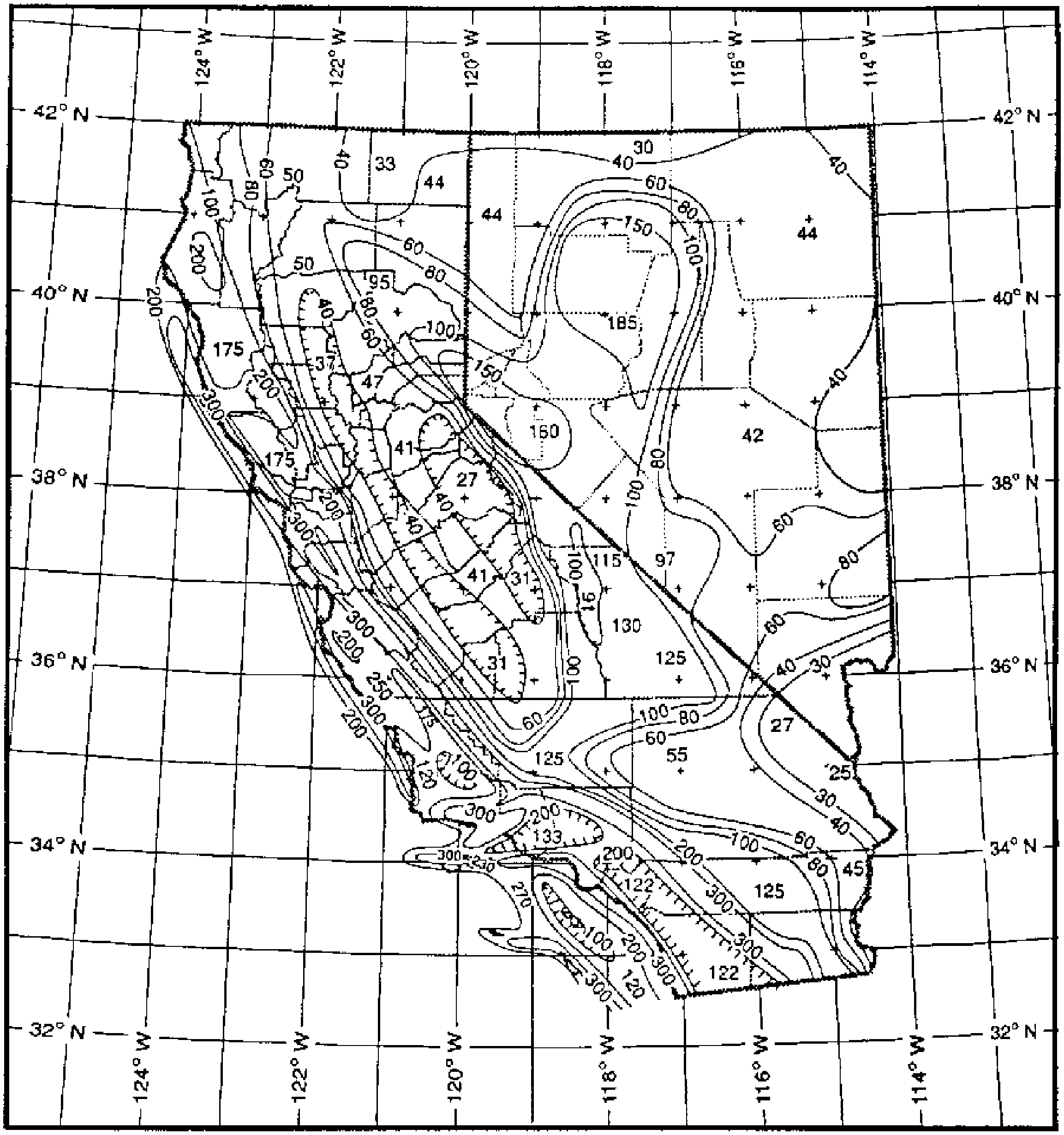

Figure D-6. 1991 USGS map of the 5-percent damped, 0.3-sec pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10-percent probability of exceedance in 250 years

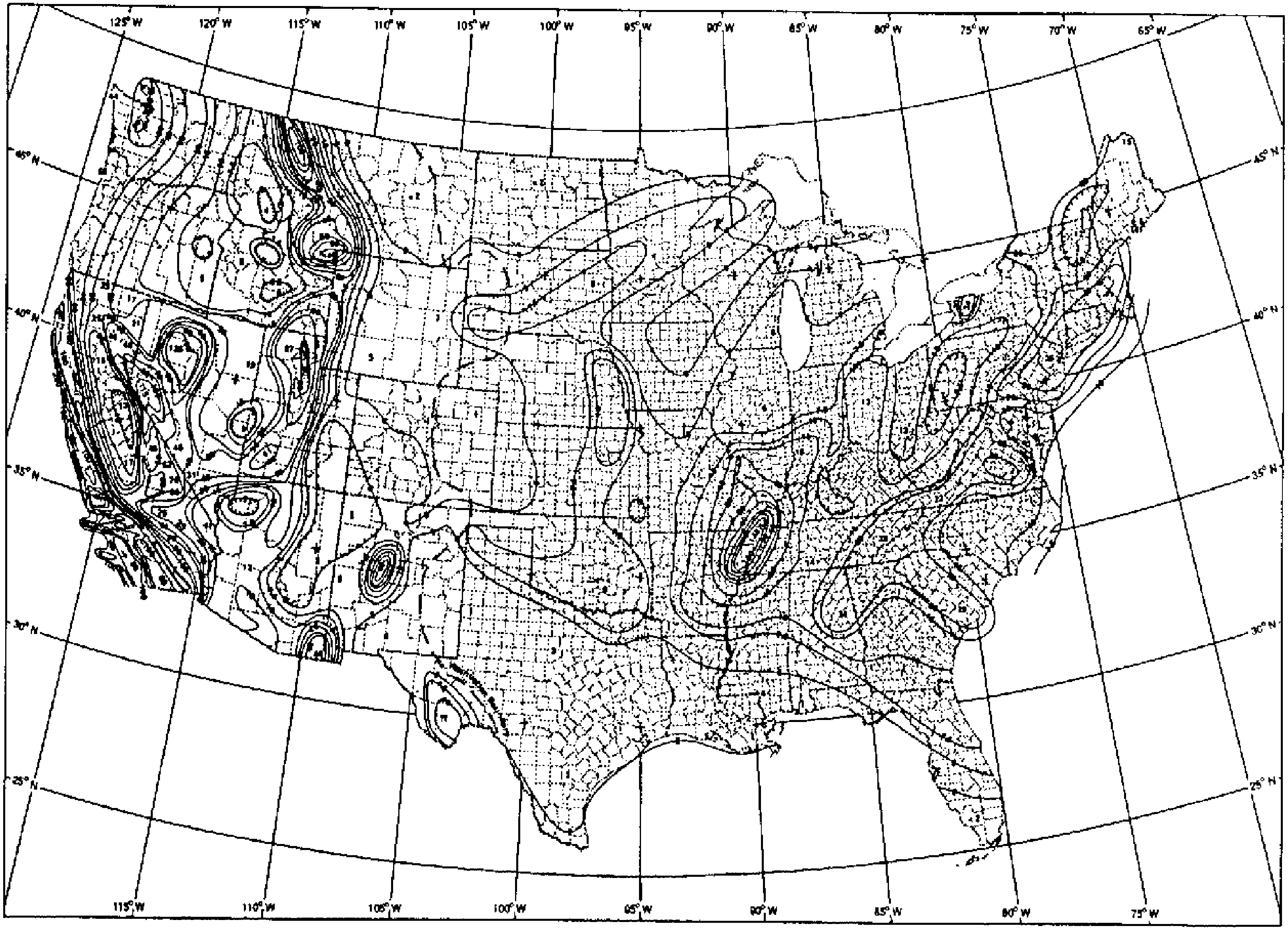

Figure D-7. 1991 map of the 5-percent damped, 1.0-sec pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10-percent probability of exceedance in 250 years

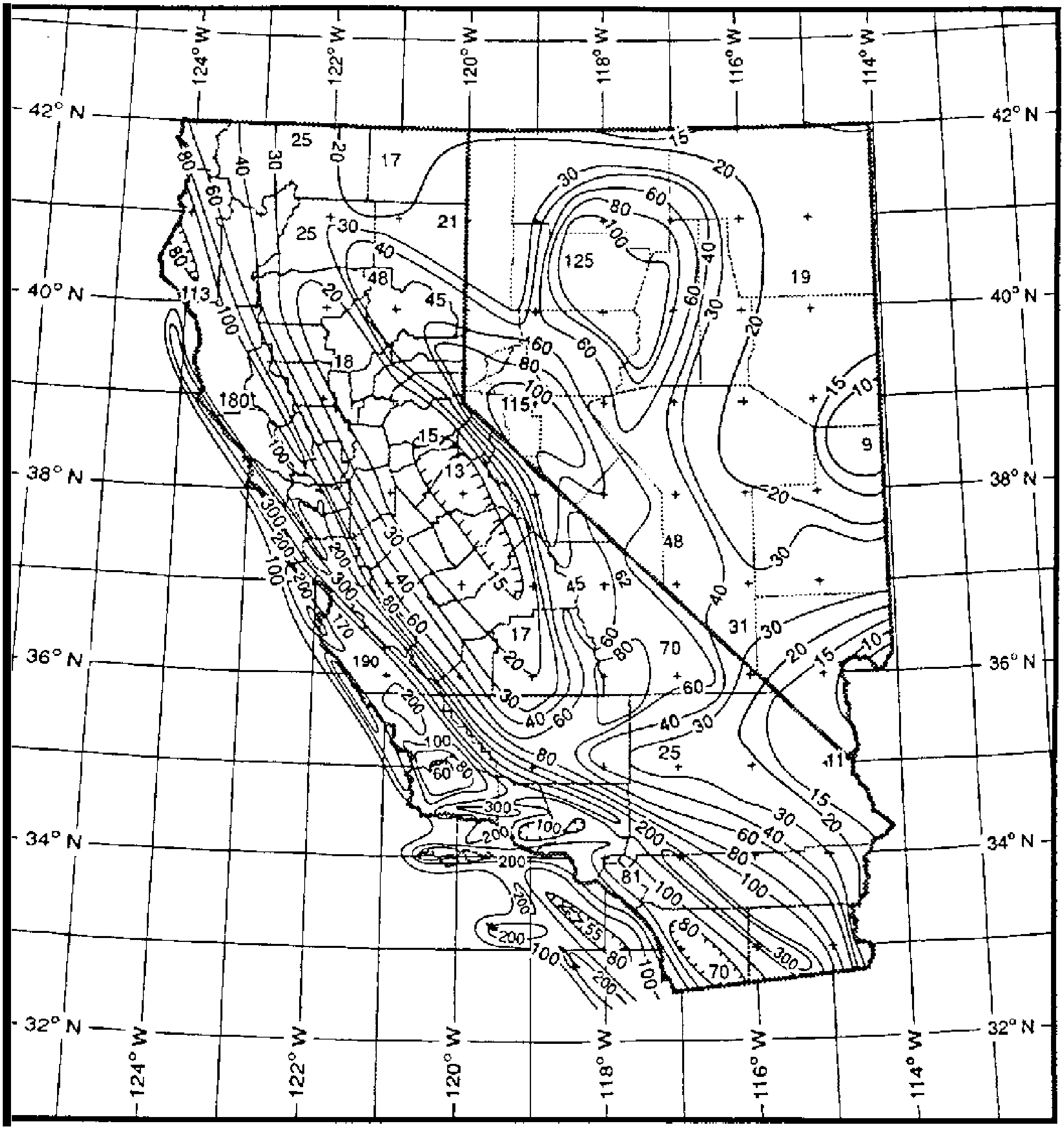

Figure D-8. 1991 USGS map of the 5-percent damped, 1.0-sec pseudo-acceleration spectral response, expressed in percent of the acceleration of gravity, with a 10-percent probability of exceedance in 250 years

APPENDIX E
PROGRESSIVE SEISMIC ANALYSIS REQUIREMENTS FOR CONCRETE AND STEEL HYDRAULIC STRUCTURES

Table E-1 shows the progression of seismic analyses required for each phase of project design. Additional guidance concerning these methods of analysis is provided in paragraphs 8*e* and 8*g*, and in the references in Appendix A. The types of project seismic studies are described in paragraphs 5*h* and 10.

Table E-1
Seismic Analysis Progression

	Project Stage				
Zone	Reconnaissance		Feasibility		DM[1]
0 and 1	E	→	SCM	→	RS[2]
2A and 2B	E	→	SCM	→	RS
	SCM[2]	→	RS[2]	→	TH[3]
3 and 4	SCM	→	RS	→	TH
	SCM	→	RS	→	RS[4]
	RS[2]	→	TH[3]	→	TH[3]

Note:
E = Experience of the structural design engineer.
SCM = Seismic coefficient method of analysis.
RS = Response spectrum analysis.
TH = Time-history analysis.

[1] If the project proceeds directly from feasibility to plans and specifications stage, a seismic design memorandum will be required for all projects in zones 3 and 4, and projects for which a TH analysis is required.

[2] Seismic loading condition controls design of an unprecedented structure, or unusual configuration or adverse foundation conditions.

[3] Seismic loading controls the design requiring linear or nonlinear time-history analysis.

[4] RS may be used in seismic zones 3 and 4 for the feasibility and design memorandum phases of project development only if it can be demonstrated that phenomena sensitive to frequency content (such as soil-structure interaction and structure-reservoir interaction) can be adequately modeled in an RS.

APPENDIX F
DESIGN AND ANALYSIS REQUIREMENTS FOR SEISMIC EVALUATION REPORTS

The following outline summarizes the reporting requirements for seismic design and evaluation studies for both standard seismic studies and site-specific seismic studies as described in paragraph 5*h*. These are **minimum requirements** and should be supplemented as needed on a case-by-case basis.

A. Summary of Applicable Seismic Criteria

1. Hazard potential classification from Table B-1 (Include consequences of project failure)
2. Uniform Building Code seismic zone from map in Appendix C
3. Design earthquakes
   a. MCE
   b. MDE
   c. OBE
   d. For each design earthquake provide:
      (1) PGA, PGD, PGV
      (2) Duration
      (3) Response spectra
4. Critical project features (See paragraph 5*a*)
5. Impact of seismic loads on project design (for new designs)
6. Impact of seismic loads on project safety (for existing projects)

B. Description of Seismic Design or Evaluation Procedure

1. Progressive seismic analysis process
2. Input motions used in the analysis
3. Loading combinations analyzed
4. Modeling techniques used for:
   a. Structure
   b. Substructure
   c. Reservoir
   d. Backfill or sediment
5. Material assumptions
   a. Mass
   b. Stiffness
   c. Damping
6. Computer programs used in the analysis
   a. Dynamic analysis programs
   b. DSHA and PSHA ground motion programs
   c. Soil column effects programs

C. Presentation of Results of Ground Motion Studies

1. Standard spectra used for preliminary studies and/or final designs
2. DSHA site-specific response spectra
   a. Design response spectra
   b. MCE (Mean)
   c. MCE (84th percentile)
3. PSHA site-specific response spectra. Equal hazard mean spectra for return periods of:
      72 years
      144 years
      475 years
      950 years
      2,000 years

  5,000 years
  10,000 years

4. Time-history records
   a. Natural time-history records used for final design
   b. Synthetic time-history records used for final design (Natural time-histories modified to match target design response spectrum analysis)
   c. Natural time-history scaling procedures
   d. Synthetic time-history development procedures
   e. Comparison of time-histories with design response spectra

D. Results of Dynamic Analysis

1. Periods of vibration
2. Mode shapes
3. Modal mass participation factors
4. Modal combination procedure (square root sum of squares, complete quadratic combination, etc.)
5. Governing loads and load combinations
6. Maximum forces (moments and shears)/or stresses where appropriate
7. Maximum displacements
8. For time-history analysis:
   a. Plots of stress (or forces) with time for critical location
   b. Plots of displacements with time
   c. Procedure used to determine effective stresses (or forces) for design
   d. Stress contour plots at points in time when stresses are maximum
9. Stability
   a. Resultant locations (permanent rotations)
   b. Sliding factors of safety (permanent translations)

E. Design Measures Taken to Obtain:

1. Ductility
2. Redundancy
3. Continuous and direct load paths
4. Prevent hammering of adjacent structures or components
5. Prevent loss of support at bridge bearings or other bearing locations
6. Smooth changes in mass or stiffness

F. Results of Embankment Analyses

1. Slope stability
2. Liquefaction potential
3. Settlement potential
4. Defensive design measures

G. Results of Foundation Analyses

1. Liquefaction potential
2. Bearing capacity
3. Settlement and deformation analyses
4. Defensive design measures

H. Verification of Analysis Results

1. Comparison of simplified procedure results with dynamic analysis results
2. Comparison of response spectra with time-history results
3. Comparison of results with those for similar type structures
4. Results of consultant review

I. Presentation of Seismic Design or Evaluation Results

1. Assessment of the project and project features to resist the design earthquake results
2. Defensive design measures taken to protect project features from the damaging effects of earthquakes
3. Remedial measures required for existing projects