DEPARTMENT OF THE ARMY ER 1110-2-1806
U.S. Army Corps of Engineers
CECW-CE Washington, DC 20314-1000

Regulation
No. 1110-2-1806 31 May 2016

Engineering and Design
EARTHQUAKE DESIGN AND EVALUATION FOR CIVIL WORKS PROJECTS

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Engineering and Design
EARTHQUAKE DESIGN AND EVALUATION FOR CIVIL WORKS PROJECTS

1. Purpose. This Engineer Regulation (ER) provides guidance for the seismic design, analysis and evaluation of civil works projects. Additionally, this regulation establishes design earthquakes with associated performance requirements to assure that all features of civil works projects meet minimum seismic standards for serviceability and safety. Seismic design standards for buildings and bridges for civil works projects are also stated in this ER. In addition, all new designs and modifications to existing dams and levees are to be designed to the additional safety standards in applicable engineer regulations.

2. Applicability. This regulation is applicable to all HQUSACE elements and USACE commands having responsibilities for the planning, design, analysis and construction of civil works projects. The user of this ER is responsible for seeking opportunities to incorporate the Environmental Operating Principles (EOP's) wherever possible. A listing of the EOP's is available at: http://www.usace.army.mil/Missions/Environmental/EnvironmentalOperatingPrinciples.aspx

3. Distribution Statement. This document is approved for public release; distribution is unlimited.

4. References. References are listed in Appendix A.

5. Policy. The seismic design of new projects and the seismic evaluation or reevaluation of existing projects must be accomplished in accordance with this regulation. This regulation applies to all projects that have the potential to malfunction or fail during or following 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 shall be focused on assessment of 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. The performance of operating equipment and utility lines can be as important as the performance of the structural and geotechnical features of a project. When justifying

circumstances exist, requests for a waiver from this policy shall be submitted by the District Commander through the Division Commander to HQUSACE (CECW-CE).

Risk evaluation processes and tolerable risk guidelines for the evaluation or re-evaluation of existing dams are provided in ER 1110-2-1156 “Safety of Dams – Policy and Procedures”. The seismic design considerations and principles presented in this regulation are meant to complement the seismic risk evaluation processes described in ER 1110-2-1156. Evaluation of risk should be an integral part of any seismic design or evaluation process.

6. General Provisions.

a. Project Hazard Potential. The hazard potential classification in Appendix B, Table B-1 defines the consequences of project failure, based on the probable loss of human life, the potential for economic losses, environmental damage and/or disruption to lifelines. 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 due to inundation or release of hazardous, toxic or radioactive materials. Such a loss of life could result directly from failure or indirectly from flooding damage to a lifeline facility. 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 must include assessments of the potential ground motions on project features to ensure acceptable performance during and after design events. The level of design required to provide such performance is dependent upon the seismic loadings, the complexity of the project, and the consequences of losing project service or losing control of the pool. The analysis must be performed in phases in order of increasing complexity. Continuity of the design process is important throughout each phase. The plan of study for each phase of design must be consistent with this regulation and with ER 1110-2-1150 “Engineering and Design for Civil Works Projects”.

c. Evaluation. Evaluation or re-evaluation of existing project features differs from the design of new features. The evaluation begins with a review of the project foundation conditions, construction materials and the design of the project features. There must also be an understanding of the construction practices used at the time the project was built. Available information such as geological maps, boring logs, acceleration contour maps, standard response spectra, structural and geotechnical analysis and studies, construction photographs and as-built project records must be used to screen existing project features to check for adequate seismic capacity. Detailed site explorations, site-specific ground motion studies and structural analyses should be undertaken only for projects in a High Seismic Hazard Region (HSHR) or in a Moderate Seismic Hazard Region (MSHR) when seismic loading controls the design. The determination of controlling load cases requires the evaluation of applied loads and the expected performance. Seismic loads are presumed to control the design when the risk assessment (potential failure mode analysis) indicates or if the factors of safety for seismic stability are lower than those computed for other load cases. The map in Appendix C provides locations of the high, moderate and low seismic hazard regions.

d. Remediation. Upgrading existing project features to current seismic design standards is generally expensive and shall be evaluated with a risk-informed process that considers various factors, including but not limited to, expected loadings, expected response and expected consequences. Expert judgment as well as appropriate linear elastic and nonlinear analytical studies may be required to clearly justify the need for remediation. Downstream nonstructural measures that reduce the project hazard must be considered as an alternative to seismic remediation.

e. Project Team Concept. Earthquake design, analysis, evaluation or re-evaluation of civil works projects requires close collaboration of an interdisciplinary team that includes specialists in seismology, hydrology and hydraulics, geology, materials, 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 must be responsible for leading the seismic design or evaluation team. Technical experts shall be included on the team to provide guidance on seismic policy, advise on earthquake engineering requirements, insure proper evaluation of results and verify aspects of the seismological and engineering investigations. This team must establish the scope of the entire seismic study early in the design or evaluation process to ensure that resources are used efficiently and that the seismotectonic, geologic, geotechnical and structural investigations are compatible and complete.

f. Consulting Technical Experts. Seismic design or evaluation of civil works project features is a highly complex engineering task that sometimes requires special expertise and substantial engineering judgment in order to be effective. In many instances, especially for large dams located in high seismic regions, the project team must augment the in-house staff with technical experts to ensure independent review of the methodology and results, to add credibility to the results and to help ensure public acceptance of the conclusions. These experts may be from within USACE, other government agencies, academia or the private sector. Technical experts must be included in the early team planning sessions to assist in identifying the full scope of work, selecting approaches and criteria, reviewing results and selecting the initial and final seismic parameters. The experts must participate in meetings, provide memoranda of concurrence and summary of advice.

g. Standard and Site-Specific Studies. Seismic studies must include the seismotectonic, geologic, site, geotechnical and structural investigations required to properly select the design ground motions, and to properly assess the response of the foundation and structures to the earthquake events possible at the project site. Further guidance on design/analysis requirements is 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. Generally, standard studies use preliminary values of the ground motions obtained from published and on-line United States Geological Survey (USGS) spectral acceleration maps. The method to develop standard response spectra and the effective peak ground acceleration (EPGA) for the project site is described in EM 1110-2-6053 “Earthquake Design and Evaluation of Concrete Hydraulic Structures”. A preliminary structural analysis and a simplified assessment of soil liquefaction and deformation will assess how seismic loadings impact the design and will 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 seismicity regions, and may be satisfactory for final design or evaluation in a low seismic hazard region or in some moderate seismic hazard regions. The seismic-study flowchart describing the process is provided in Appendix D.

(2) Site-specific studies use the actual site and structural conditions to evaluate the project hazards and the response of the project features to seismic loading. Detailed field exploration and testing programs must be carefully planned and executed. Geologic studies should characterize the site, describe the seismotectonic province and investigate all seismic sources that can affect the site. Seismologic investigations should describe the earthquake history, earthquake recurrence relationship and strong-motion records to be used in design or evaluation. Special emphasis should be placed on identifying all geological, seismological and geotechnical parameters necessary for the design and for determining the response of the foundations and structures. Structural investigations should accurately account for all relevant factors that affect the seismic hazard at the specific site and the actual dynamic behavior of the structure, including damping and ductility characteristics of the structural systems. Geotechnical investigations should assess the types and spatial distribution of foundation and embankment material and the engineering properties of the 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 evaluated. The final results of site-specific studies must be used as the basis for making design or evaluation decisions and for the design of any remedial measures. Site-specific studies shall be conducted for all projects located in regions of high seismicity and moderate seismicity for which earthquake loading controls the design. Detailed information on the development of site-specific design response spectra can be found in EM 1110-2-6050 “Response Spectra and Seismic Analysis for Concrete Hydraulic Structures”. EM 1110-2-6051 “Time-History Dynamic Analysis of Concrete Hydraulic Structures” provides information on the development of site-specific time-histories. There are two general approaches for conducting site-specific seismic hazard analyses:

(a) Deterministic Seismic Hazard Analysis (DSHA). The DSHA approach uses the known seismic sources that can affect the site along with the 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 at the source closest to the site. The site ground motions are estimated deterministically, given the magnitude, source-to-site distance and site conditions. DSHA is the standard process used to estimate the seismic ground motion parameters for the Maximum Credible Earthquake (MCE) and is typically conducted using a site-specific analysis.

(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 a specified time period. The probability (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 acceptable probability of exceedance during the service life of the structure for a given return period.

(c) General. The state-of-the-art for assessing ground motion parameters is constantly evolving. While new and better earthquake data are constantly being compiled, instrumental recordings of seismic ground motions are still limited to about 100 years of information. This period of record is short, forcing extrapolation of results to make PSHA estimates of ground motions for events with an Annual Chance Exceedence (ACE) of less than 1E-02 (*i.e.,* less frequent than once in 100 years). In most studies, these extrapolations incorporate certain assumptions about “expected value” trends and associated variance distributions that might not be accurate and in many cases may be overly conservative. For example, the earth’s crust may not be capable of transmitting accelerations estimated from extrapolation, thus overstating expected shaking. This means that PSHA estimates of ground motion parameters may be much larger than DSHA estimates for events with similar ACEs, even when the PSHA uses the same seismic source and attenuation information.

7. <u>Design Earthquakes and Ground Motions</u>.

a. Maximum Credible Earthquake (MCE). The MCE is defined as the largest 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 its own characteristic ground-motion parameters and spectral shape. The MCE is evaluated using DSHA methods informed by results from a PSHA. Since different sources may result in differing spectral characteristics, selection of “maximum” ground motion parameters may need to consider different sources and magnitude events to represent the full range of possible maximum loadings *e.g*., peak ground acceleration from one source may be higher than from another, but reversed for 1s spectral acceleration values. Therefore, both sources may need to be considered in analysis to assess the full range of potential “maximum” loadings. There is no return period for the MCE.

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 performs without loss of life or catastrophic failure (such as an 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 minimum MDE is an event with a 10% probability of exceedance in 100 years (average return period of 950 years) assessed using a PSHA informed by the results of a site-specific DSHA. A shorter or longer return period for non-critical features can be justified by the project team based on the Hazard Potential Classification for Civil Works Projects in Appendix B, Table B-1. A project with a low hazard potential classification may consider return periods less than 950 years, while projects with a significant or high hazard potential classification may consider longer return periods. 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, typically a 50% probability of exceedance in 100 years (average return period of 144 years) assessed using a PSHA informed by the results of a site-specific DSHA. The associated performance requirement is that the project functions 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, therefore, alternative choices of return periods for the OBE may be based on economic considerations.

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 shall be obtained from USGS spectral acceleration maps. The method to develop standard response spectra and effective peak ground acceleration for the required probability of exceedance (return period) for OBE and MDE is described in EM 1110-2-6053, Appendices B and C. Site-specific studies in accordance with paragraph 6g(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 include 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 median or median-plus-standard deviation estimates of deterministic ground motion, or by ensuring consistency of MDE ground motions with a performance goal.

8. <u>Site Characterizations</u>.

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). These can influence propagation of the specified ground motion from a 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 required to design or to operate a project safely. The relevant site conditions shall include the topographic and hydrologic conditions, the nature and extent of foundation materials, the embankment, the natural slopes, the structures at the site and the physical and dynamic engineering properties (such as modulus, damping, density, and cyclic strain softening) of these materials. The site characterization shall be of a progressive nature starting with information from available sources on the geology, seismicity, and project features. A description of the site shall include geology and seismicity (such as known faulting in the region, seismic history, and prior seismic evaluations in the vicinity), and a review of the construction history and of any data related to the project features at or proposed for the site.

b. New Projects. For new projects, field exploration and material testing programs shall be developed to identify the stratigraphy and the physical and engineering properties of the foundation materials at the project features. Prior field investigations in the project area shall be evaluated 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.

9. Concrete and Steel Structures and Substructures.

a. Role of Structural Engineers. Methods for seismic studies/designs vary greatly with the type of structure or substructure. Structural engineers shall be involved in the selection of ground motions from the earliest stages of a study. Their understanding of the ground motions in the form of peak ground acceleration, response spectra, and time histories will be used in the structural analysis as it proceeds through progressively more sophisticated stages as needed to reach definitive conclusions and make sound decisions. Dynamic characteristics are important when selecting design events to assure adequate demand levels in the period range of interest (*i.e.*, near the natural period of the structure). The structural engineer will establish how response spectra and time-histories from standard and site-specific studies will be used in the structural investigations. This progression is related to the level of accuracy or sophistication required by the model and to address inherent uncertainties.

b. Design Standards for Buildings and Bridges. New building designs and upgrades to existing buildings must be in accordance with the requirements of the 2012 Edition of the International Building Code. Bridges on civil works projects shall be designed in accordance with the American Association of State Highway Transportation Officials (AASHTO) and state design standards, and evaluated in accordance with Federal Highway Administration (FHWA) and state design standards.

c. Design Requirements for Concrete and Steel Hydraulic Structures. Seismic design requirements for concrete and steel hydraulic structures (CSHS) are provided in EM 1110-2-2104 “Strength Design for Reinforced Concrete Hydraulic Structures”, and

EM 1110-2-6053 “Earthquake Design and Evaluation of Concrete Hydraulic Structures”. It is noted that in ETL 1110-2-584, “Design of Hydraulic Steel Structures”, earthquake loading required for design is currently limited to the operating basis earthquake (OBE) only; this part of the ETL is under consideration for revision by USACE. Design of CSHS must also be in accordance with all applicable references listed in Appendix A. Visual inspections should also be performed of hydraulic steel structures after an unusual earthquake, in accordance with EM 1110-2-6054, “Inspection, Evaluation, and Repair of Hydraulic Steel Structures”. Such an inspection would be considered a “Special Inspection” in accordance with ER 1110-2-8157, “Responsibility for Hydraulic Steel Structures”.

d. Load Combinations. Design load combinations for CSHS must be in accordance with EM 1110-2-2100 “Stability Analysis of Concrete Structures” and in accordance with the referenced USACE design guidance for specific structures. In general, CSHS must 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 must not collapse or endanger lives. Economic considerations will be a factor in determining the acceptable level of damage. 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. Using a seismic coefficient equal to 2/3 PGA or 2/3 EPGA is consistent with the stability analyses contained in EM 1110-2-2100. Details of these methods of analysis can be found in the references listed in Appendix A (EM 1110-2-2100, EM 1110-2-6050, EM 1110-2-6051, and EM 1110-2-6053). Simplified response spectrum analysis procedures are available for some types of CSHS, for example, concrete gravity and arch dams (EM 1110-2-2200; EM 1110-2-2201) and intake towers (EM 1110-2-2400). These methods utilize idealized cross sections and make assumptions concerning the structure’s response to ground motions and its interaction with the foundation and reservoir. The validity of these assumptions should be carefully examined for each project prior to using any simplified analysis procedure. 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 design for a project in moderate or high seismic hazard regions shall use either response-spectrum or time-history methods.

f. Input from Ground Motion Studies*.* Site-specific ground motion studies required in accordance with paragraph 6g(2) at a minimum, should provide the magnitude, duration, and site-specific values for the peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), and the design response spectra and time-histories in both orthogonal horizontal directions and the vertical direction at the ground surface or at a rock outcrop. Site-specific studies should also consider soil-structure interaction effects which may influence ground motions at the base of the structure.

g. Analysis Progression. An important aspect of the design, analysis, or evaluation process is to develop an analytical model of the structure and substructure that can adequately represent seismic behavior. The analysis process should be performed in phases 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 results in the analytical model providing realistic results and forms a logical basis for decisions to revise the structural configuration and/or proceed to a more accurate analysis method. The model used in the structural analysis can range from a simple two-dimensional (2D) beam model to a sophisticated three-dimensional (3D) finite element model. All three components of ground motion may be required to capture the total system response. Dynamic analyses of most massive concrete structures will usually require a model that includes interaction with the surrounding soil, rock, and water. 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 mode shapes must be considered, especially when evaluating the stresses using a response spectrum analysis. The results of a finite element analysis of a reinforced concrete structure shall be expressed in terms of moment, thrust, and shear. Areas where inelastic behavior is anticipated shall be identified and the 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 shall be considered. Such methods are beyond the scope of this ER and must be conducted in consultation with CECW-CE.

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 shall minimize geometric irregularities in the structural configuration, avoid abrupt variations in structural stiffness, and properly detail any structural discontinuities to account for localized effects of stress concentrations. Continuous load paths, load path redundancy, and ductility will improve performance after extensive cracking and are important safe-guards against collapse.

10. Embankments, Slopes and Soil Foundations.

a. Role of Geologists, Seismologists, and Geotechnical Engineers. 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: 1) field investigations, 2) site characterization, 3) numerical analyses, and 4) 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. The geologists, seismologists, and geotechnical engineers will select the most effective methods to determine the uncertainties which must be dealt with correctly and consistently so that the final result will be reliable and safe but not overly conservative.

b. Embankments. Appropriate methods shall be used to analyze the liquefaction potential and/or to estimate the deformations for embankments (*e.g.*, dams, dikes, levees that retain permanent pool), slopes, and foundation materials.

c. Slopes and Foundations. Slopes to be analyzed shall include natural, reservoir rim, and other slopes, with or without structures, that have the potential to affect the safety or function of the project. All foundation materials that support or affect project features are to be analyzed for liquefaction. The results of investigations and data review as described in paragraph 7 and the seismological evaluation will assess the appropriate methods, including dynamic analysis, to be performed on the project.

d. Evaluations. Evaluation shall be performed on embankments, slopes, and/or foundations that are susceptible to liquefaction or excessive deformation for all projects located in high seismic hazard regions, along with those projects located in moderate seismic hazard regions where materials susceptible to liquefaction or excessive deformation are suspected. This evaluation and analysis shall also be performed regardless of the seismic region location of the project, where capable faults are located or recent earthquakes have occurred.

e. Design Features. Certain design features shall be incorporated, to the greatest extent possible, into the foundation and embankment design regardless of the method of seismic analysis. The details of these features shall be optimized based on the results of the analysis. These design features include, but are not limited to the following;

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

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

(3) Wider transition and filter sections to resist 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, in-situ densification, and/or drainage of foundation materials susceptible to liquefaction.

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

(13) Flaring of embankment sections at the abutment and concrete contacts.

11. 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, shall progress as described in Appendix E and must be in compliance with SMART planning principles.

12. Actions for Existing Projects.

Seismic evaluation requirements are summarized in Appendix F. The seismic evaluation report must adequately explain any seismic deficiency. Also an outline of additional investigations that are required to assess risk shall be assembled. Methods to upgrade the project to meet current seismic criteria should also be listed. The evaluation of existing structures should be done in accordance with ER 1110-2-1156 "Safety of Dams – Policy and Procedures". This report must be submitted for approval to HQUSACE, CECW-CE through the major subordinate command.

FOR THE COMMANDER:

6 Appendices
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D. PETER HELMLINGER
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Chief of Staff

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Appendix A

REFERENCES

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

ER 1110-2-1156 “Safety of Dams – Policy and Procedures”

ER 1110-2-8157, “Responsibility for Hydraulic Steel Structures”

EM 1110-2-2100 “Stability Analysis of Concrete Structures”

EM 1110-2-2201 “Arch Dam Design”

EM 1110-2-2104 “Strength Design for Reinforced Concrete Hydraulic Structures”

ETL 1110-2-584 “Design of Hydraulic Steel Structures”

EM 1110-2-2200 “Gravity Dam Design”

EM 1110-2-2400 “Structural Design and Evaluation of Outlet Works”

EM 1110-2-6050 “Response Spectra and Seismic Analysis for Concrete Hydraulic Structures”

EM 1110-2-6051 “Time-History Dynamic Analysis of Concrete Hydraulic Structures”

EM 1110-2-6053 “Earthquake Design and Evaluation of Concrete Hydraulic Structures”

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EM 1110-2-2502 "Retaining and Flood Walls"

EM 1110-2-2504 "Design of Sheet Pile Walls"

EM 1110-2-2602 "Planning and Design of Navigation Locks"

EM 1110-2-2607 "Planning and Design of Navigation Dams"

EM 1110-2-2906 "Design of Pile Foundation"

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APPENDIX B

Table B-1
HAZARD POTENTIAL CLASSIFICATION FOR CIVIL WORKS PROJECTS

	Category[1]			
Hazard Potential Classification	Direct Loss of Life[2]	Lifeline Losses[3]	Property Losses[4]	Environmental Losses[5]
Low	None Expected	No disruption of services – repairs are cosmetic or rapidly repairable damage	Private agricultural lands, equipment, and isolated buildings	Minimal incremental damage
Significant	None Expected	Disruption of essential facilities and access	Major or extensive public and private facilities	Major or extensive mitigation required or impossible to mitigate
High	Probable (one or more)	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 are not applicable 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 occurred.

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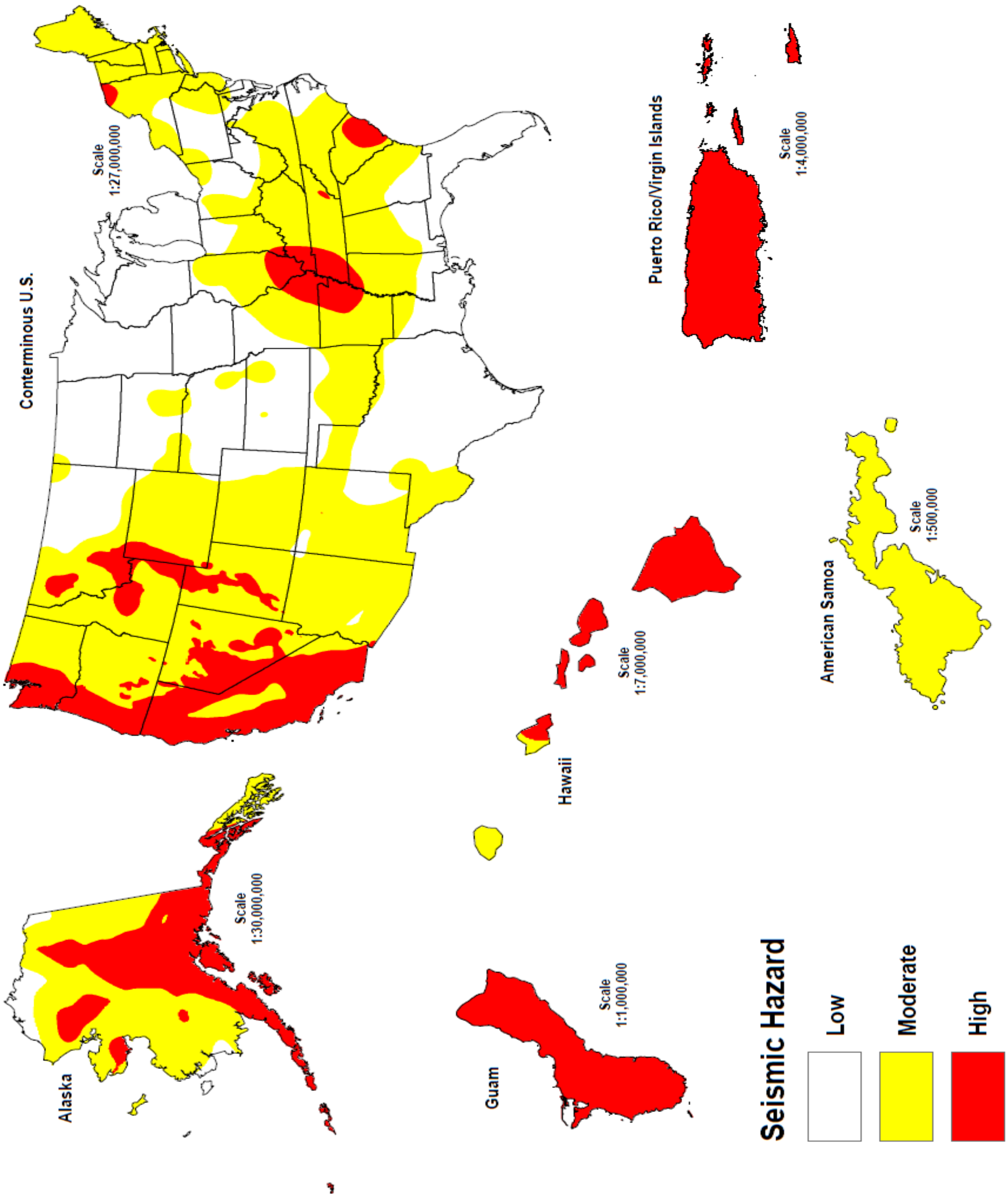
APPENDIX C
Seismic Hazard in USA
(Based on USGS maps of 2013)



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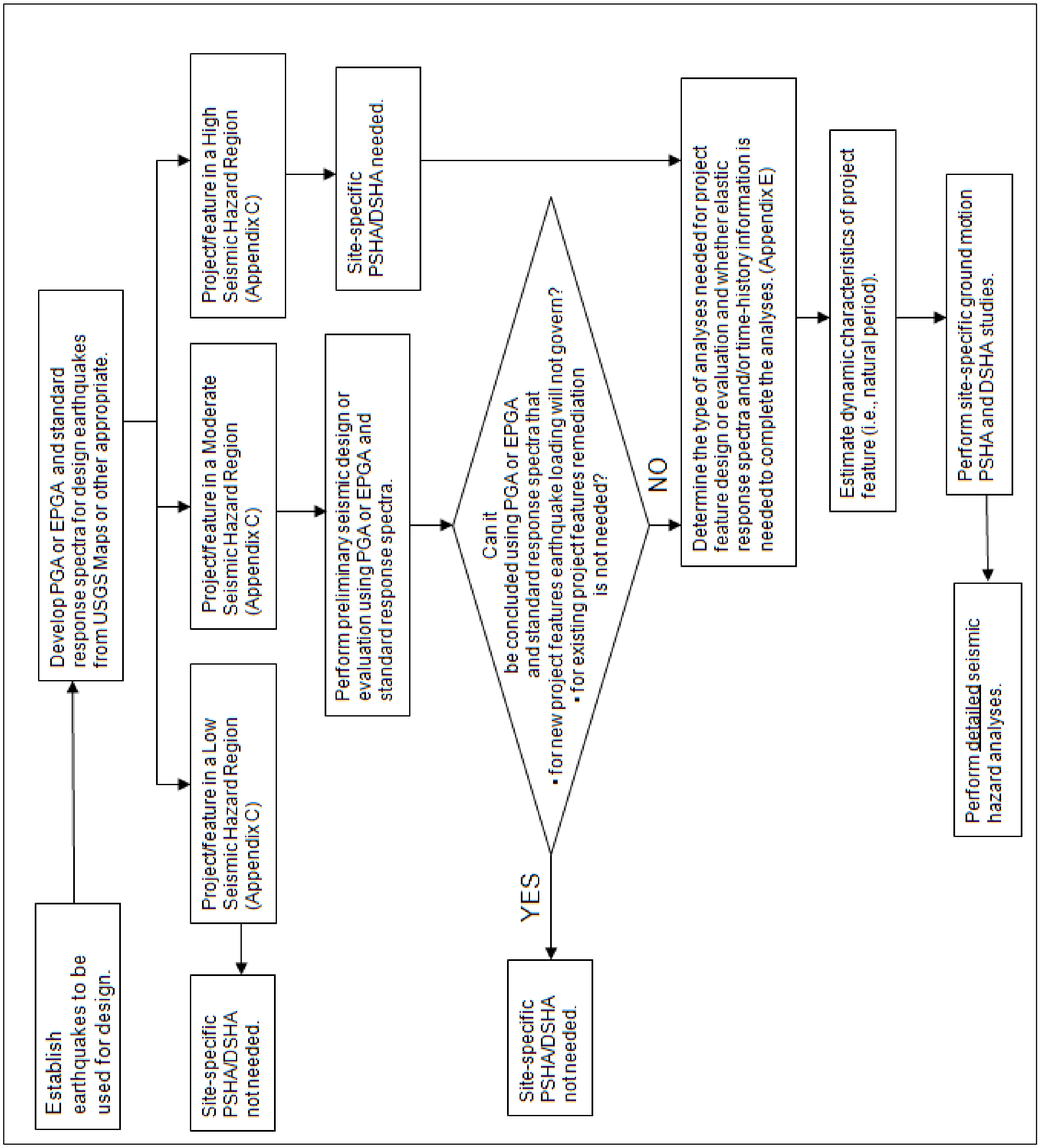
APPENDIX D
Seismic Study- Flow Chart



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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 9e and 9g and in the references in Appendix A. The types of project seismic studies are described in paragraphs 6h and 11.

Table E-1
Seismic Analysis Progression

Seismic Hazard Region	Project Stage				
	Reconnaissance		Feasibility		PED[1]
Low	E	→	SCM	→	RS[2]
Moderate	E SCM[2]	→ →	SCM RS[2]	→ →	RS TH[3]
High	SCM RS[2]	→ →	RS TH[3]	→ →	RS[4] or TH 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, seismic design documentation must be required for all projects in high seismic hazard region 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 should be used in high seismic hazard region for the feasibility and PED phases of project development only if it can be demonstrated that phenomena sensitive to frequency content (*i.e.*, soil structure interaction and structure-reservoir interaction) can be adequately modeled in an RS.

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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 6h. These are minimum requirements.

F-1. Summary of Applicable Seismic Criteria.

a. Hazard potential classification from Appendix B, Table B-1 (Include consequences of project failure)

b. Ground Motion Study and Flow Chart (Appendix D), Seismic Hazard Region from map in Appendix C

c. Design earthquakes; MCE, MDE and OBE

d. Provide PGA, PGD, PGV, duration and response spectra for each earthquake

e. Define critical project features (See paragraph 6a)

f. Impact of seismic loads on project design (for new designs)

g. Impact of seismic loads on project safety (for existing projects)

F-2. Description of Seismic Design or Evaluation Procedure.

a. Progressive seismic analysis process (Appendix E)

b. Input motions used in the analysis

c. Loading combinations analyzed

d. Modeling techniques used for the following; Structure, Soil-Structure Interaction, Structure-Reservoir Interaction, Attenuation of ground motion

e. Material properties, including mass, stiffness and damping properties

f. Computer programs used in the analysis including dynamic analysis programs and ground motion programs

F-3. Presentation of Results of Ground Motion Studies.

a. Standard spectra used for preliminary studies and/or final designs

b. DSHA site-specific design response spectra, MCE (Median) and MCE (84^{th} percentile)

c. PSHA site-specific response spectra. Equal hazard median spectra for return periods evaluated at the site.

d. Time-history records including; Natural time-history records used for final design, synthetic time-history records used for final design (natural time-histories modified to match target design response spectrum analysis), natural time-history scaling procedures, synthetic time-history development procedures, and comparison of time-histories with design response spectra

F-4. Results of Dynamic Analysis.

a. Periods of vibration and mode shapes, modal mass participation factors, and modal combination procedure

b. Governing loads and load combinations

c. Maximum forces (moments and shears)/or stresses where appropriate, and maximum displacements

d. Time-history analysis including plots of stress (or forces) with time for critical location, plots of displacements with time, including the procedure used to determine effective stresses and stress contour plots

e. Stability results including resultant locations and sliding factors of safety

F-5. Structural Design Performance Guidelines.

The structure should be configured to include a simple arrangement of structural elements with clearly defined load paths that provide sufficient ductility and redundancy. Configurations and geometries that complicate load path behavior add to the complexity of analysis and uncertainty in predicting structural performance and should be avoided to the greatest extent possible. These include but are not limited to:

a. Large changes in structure stiffness

b. Large changes in structure mass

c. Interaction of two or more structural components through a common base

d. Significant column transfers or offsets

e. Gravity-induced horizontal shear forces caused by system eccentricities

f. Limited connectivity of bracing elements

Consideration should also be made to target yielding to occur in components that are capable of ductile response. Some of the desirable modes of inelastic response include:

a. Flexural yielding in reinforced concrete elements

b. Tension yielding in structural steel braces and tension/compression yielding in buckling-restrained braces

c. Post-buckling compression in non-structural steel braces

d. Shear yielding in structural steel components such as panel zones in moment frames and shear links in eccentric braced frames

e. Yielding in ductile fuses or energy dissipation devices

F-6. Results of Embankment Analyses.

a. Material properties assumptions

b. Shear strength parameters

c. Pool loading and seismic loading conditions

d. Seepage/pore pressure measurements or assumptions

e. Pseudostatic slope stability analyses

f. Embankment evaluation including materials zoning/saturations, seismic loading/amplification, trial failure surfaces, method of analysis and liquefaction/lateral spread evaluations

g. Discussion of shell, filter zones and impervious core

h. Discussion of cyclic strain softening of fine-grained soils in high seismic regions, if appropriate

i. Settlement/internal deformation potential

j. Damage potential evaluation of internal features

F-7. Results of Foundation Analyses.

a. Foundation site classification and ground motion amplification including IBC site classification, site-specific field measurements/investigations, and shake analysis

b. Foundation liquefaction potential including site-specific field investigations, site-specific soil profile and liquefaction screening level evaluation

c. Foundation lateral spread potential and bearing capacity

d. Foundation settlement and deformation analyses

e. Drainage susceptibility to seismically induced damage

f. Seismically induced landslides potential in abutments

g. Seismically induced landslides and seiche wave potential in reservoir area

F-8. Verification of Analysis Results.

a. Comparison of simplified procedure results with dynamic analysis results

b. Comparison of response spectra with time-history results

c. Comparison of results with similar type structures