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CECW-EC

Engineering and Design
Earthquake Analysis, Evaluation, and Design for Civil Works Projects

FOR THE COMMANDER:

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Purpose. This engineer regulation provides policies for the earthquake analysis, evaluation, and design of Civil Works project features. This regulation establishes minimum standards for serviceability and safety of civil works project features for specific earthquake return periods for ground motion and coincident pool elevations. It also provides requirements for aspects of seismic analysis, evaluation, and design.

Applicability. This regulation is applicable to all Headquarters, United States Army Corps of Engineers elements and commands having responsibilities for the maintenance, operations, planning, evaluation, design, analysis, and construction of new and existing civil works projects. This regulation applies to civil works project features such as water resource and navigation structures, bridges, buildings, coastal, and other pertinent structures.

Distribution statement. Approved for public release; distribution is unlimited.

Proponent and exception authority. The proponent of this regulation is the Engineering and Construction Division (CECW-EC). The proponent has the authority to approve exceptions or waivers to this regulation that are consistent with controlling law and regulations. Only the proponent of a publication or form may modify it by officially revising or rescinding it.

*This regulation supersedes ER 1110-2-1806, dated 31 May 2016.

Summary of Change

ER 1110-2-1806
Earthquake Design and Evaluation for Civil Works Projects

This revision, dated 29 May 2024:

- Updates the requirements for the operating basis earthquake ground motion, maximum design earthquake ground motion, and aftershock events.
- Adds definition and requirements for coincident water surface elevation and coincident hydraulic loading.
- Updates various topics, such as (1) consequence-based project feature classification, (2) requirements for bridges and buildings, (3) appurtenant structures, (4) locations of ground motions for analysis, and (5) site seismic hazard classification based on peak ground acceleration.
- Updates discussions on risk-informed design and evaluation.
- Removes text on topics that were considered as guidance-related and should be included in engineer manuals (such as methods for ground motion determination, design feature, etc.).

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1. Purpose
This engineer regulation (ER) provides policies for the earthquake analysis, evaluation, and design of Civil Works (CW) project features. This regulation establishes minimum standards for serviceability and safety of civil works project features for specific earthquake return periods for ground motions and coincident pool elevations. It also provides requirements for aspects of seismic analysis, evaluation, and design.

2. Distribution statement
Approved for public release; distribution is unlimited.

3. References
See Appendix A.

4. Records management (recordkeeping) requirements
The records management requirements for all record numbers, associated forms, and reports required by this regulation are addressed in the Records Retention Schedule – Army (RRS-A). Detailed information for all related record numbers is located in the Army Records Information Management System (ARIMS)/RRS-A at https://www.arims.army.mil. If any record numbers, forms, and reports are not current, addressed, and/or published correctly in ARIMS/RRS-A, see DA Pam 25-403 for guidance.

5. Associated publications
This section contains no entries.

6. Policies
a. The seismic design of new project features and the seismic evaluation or re-evaluation of existing project features must be accomplished according to this regulation. The performance objectives contained herein must be achieved for project features with a potential for adverse consequences. Adverse consequences include the potential for malfunction, failure, or inability to provide intended project feature functions during or following seismic events. Malfunction or failure includes hazardous conditions leading to loss of life, property damage, disruption of lifeline services, and unacceptable environmental impacts.

b. Design and evaluation for seismic loading must consider project feature-specific risk assessments, seismic analyses, and evaluations. Efforts required can vary greatly based on the subsurface conditions, construction, and operation details. The scope must consider ground motions and other seismic hazard characterizations related to an earthquake. These ground motions and other seismic hazard characterizations include conditions such as fault rupture, seismic strong shaking, seismic-induced landslides, liquefaction, cyclic softening, and seiche. The seismic hazard and performance evaluation will include geologic conditions, site characterization, structure or embankment conditions, structural response, functionality (post-earthquake operability), and other existing static potential hazards that may be exacerbated by an earthquake (such as landslides and backward erosion piping). Earthquake or seismic ground motions and associated performance levels based on project feature type are included in this ER. Additional seismic criteria and guidelines can be found in structure-specific or feature-specific engineer regulations, engineer manuals (EM), building codes, and other applicable federal criteria and guidelines, as appropriate.

c. There are significant differences between the standards that govern earthquake analysis, evaluation, and design of hydraulically loaded project features versus non-hydraulically loaded project features. Examples of hydraulically loaded project features include dams, levee embankments, floodwalls, etc. Examples of non-hydraulically loaded project features include buildings, roadway embankments, etc. These differences are often based on the behavior of the structure types during seismic loading. Each structure type has a different modal response, damping, and elastic/inelastic behaviors, as well as specific failure mechanisms based on age, design, construction, materials, and structural details. Earthquake analysis, evaluation, and design must consider the differences in seismic behavior of different types of project features and project feature specific failure or damage mechanisms.

d. The differences in the dynamic behavior of buildings, bridges, and hydraulic structures commonly depend on multiple structural, embankment, and foundation characteristics. Multiple characteristics contribute to potential failure or damage mechanisms resulting from seismic loading, and when combined with consequences, the following can then be used in analysis, evaluation, and design of project features:

(1) Mass and distribution of mass.
(2) Stiffness and distribution of stiffness.
(3) Material strengths (man-made and natural)
(4) Structural and modal response.
(5) Location and nature of loading.
(6) Load transfer, redundancy, location, and type of structural resistance.
(7) Ductility.
(8) Irregularities in geometry.
(9) Foundation types.
(10) Foundation soil and/rock conditions.
(11) Embankment conditions.
(12) Additional structure, foundation, and geologic characteristics.

7. General provisions for buildings

New building designs and upgrades to existing buildings must meet the requirements of ER 1110-2-8161. Exceptions include seismic loadings and performance objectives of buildings located at the top or slope of a dam, levee, or other hydraulic structures. Seismic loading for buildings located at the top or slope of a dam, levee, or other hydraulic structures must be developed per the requirements outlined in paragraph 9c and table 2 and considering propagation through the dam, levee, or other hydraulic structures. Performance requirements for appurtenant structures (para 9c(6)) must be applied to these buildings. Buildings must also comply with the requirements of applicable state earthquake fault zone acts (such as Alquist-Priolo Earthquake Fault Zoning Act in California).

8. General provisions for bridges

a. All new bridge design, major rehabilitation, and existing bridge evaluations must meet the following requirements:

(1) American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) “Bridge Design Specifications,” latest edition.

(2) AASHTO “Guide Specifications for LRFD Seismic Bridge Design,” latest edition.

(3) Federal Highway Administration (FHWA) “Seismic Retrofitting Manual for Highway Bridges,” FHWA-RD-94-052, latest edition.

b. Seismic loading for a bridge (including bridge piers and abutments) located at the top or slope of a dam, levee, or other hydraulic structures must be developed per the requirements outlined in paragraph 9c and table 2 and must consider propagation through the dam, levee, or other hydraulic structures. Performance requirements for appurtenant structures (para 9c(6)) must be applied to these bridges. Impacts of fault rupture displacements from mapped faults within the bridge footprint must be considered in design.

9. General provisions for civil works project features

a. Overview. All new and existing CW design, rehabilitation, upgrades, and evaluations must meet requirements of this paragraph. Appendix A provides a list of regulatory and guidance documents that must be used along with this regulation for earthquake analysis, evaluation, and design of CW project features. The provisions of this paragraph do not apply to most buildings and bridges (see paras 7 and 8). However, seismic loading and performance requirements for buildings and bridges located at the top or slope of a dam, levee embankment, or other hydraulic structures must comply with this paragraph.

b. Consequence-based project feature classification.

(1) To select ground motions for analysis, evaluation, or design, consequences of poor performance resulting from an earthquake must be understood and documented. Consequences are related to the functional integrity of the project features. Table 1 defines the adverse consequences of poor performance of a single or multiple project features within a project. Adverse consequences may include:

(a) probable direct loss of life.

(b) disruption or loss of project service or functionality including loss of service for lifeline facilities and access.

(c) direct property losses.

(d) adverse environmental impacts.

(2) Earthquake ground motions have the potential to cause failure or damage to and/or operations of project features. Failure can be uncontrolled release of impounded water (such as a reservoir or river), liquid-borne solids (such as mine tailings or dredge spoils), or other failures or damage adversely impacting the functionality and/or ability of the project features to operate as intended, resulting in the economic, lifeline, or adverse environmental impacts described in table 1.

(3) Project features must be designated as either Critical or Non-Critical based on a project-specific assessment of consequences using table 1. The associated performance requirements are established according to paragraph 9c.

(4) Project features defined as Critical are engineering structures, natural site conditions, or operating equipment and utilities, etc., whose failure or damage during or immediately following an earthquake could result in direct loss of life. Loss of life could result directly from failure, or uncontrolled release of water or liquid-borne solids, or indirectly from damage causing project feature function loss or access to or disruption of a lifeline or other facilities (such as hospitals, water treatment and supply systems, power generation and/or supply systems, transportation systems, and other lifeline systems).

(5) Project features can be designated as Critical when economic consequences are significant (such as loss of project feature service or functionality, loss of service or access for lifeline facilities, property damages, or major to extensive adverse environmental impacts). These significant consequences may occur with or without life loss, as well as with or without inundation. A project feature can be identified as Critical, if one or more conditions in table 1 is met.

(6) Project features that are not Critical are deemed Non-Critical. Non-Critical project features are analyzed, evaluated, and designed for a different set of criteria than Critical project features.

Table 1
Consequence-based project feature classification

Project Feature Type[1]	Direct Loss of Life[2]	Disruption or Loss of Project Feature Service or Functionality; Loss of Service or Access for Lifeline Facilities[3]	Property Losses[4]	Adverse Environmental Impacts[5]
Non-Critical	None expected	None or damages are cosmetic or rapidly repairable	Minimal	Minimal damage
Critical	None expected to probable or likely (one or more)	Probable or likely	Major to extensive	Major to extensive damage[6]

Notes:
[1] Categories are based on project feature performance. Project performance could be impacted by performance of a single or multiple individual project feature within a project or system.
[2] Loss of life potential is based on failure or inundation mapping of the area downstream of the dam or within the leveed area. In some cases, inundation mapping may also include upstream areas.
[3] Indirect threats to life caused by the interruption of lifeline or other facility services because of project failure or operation loss (such as direct loss of [or access to] critical medical facilities, safe water supply).
[4] Direct economic impact of property damages, project facilities, downstream property, and property within the leveed or upstream area, and indirect economic impact because of loss of project services (such as inundation impact on navigation industry because of the loss of a dam and navigation pool, impact on a community of the loss of water or power supply).
[5] Adverse environmental impacts caused by the project feature failure or loss of water supply for environmental purpose, beyond what would normally be expected for the magnitude flood event if the project did not exist.
[6] In some cases, major to extensive damage may require extensive mitigation and, in some cases, it may be difficult or impossible to mitigate the environmental damage.

(7) The consequence-based project feature classification in table 1 must be used for development of seismic loading (table 2) for evaluations, analysis, and design to provide operations, maintenance, and safety-of-project features. The terms and definitions for Critical and Non-Critical project features in table 1 are generally consistent with the terms and definitions for Priority A and Priority B projects per ER 1130-2-500. Table 1 and associated footnotes provide further clarifications on selection of project feature types for seismic loading and performance criteria for evaluations, analysis, and design of existing and new project features.

c. Earthquake ground motions and associated performance requirements for analysis, evaluation, and design.

(1) *Ground motions for performance-based analysis.* For performance-based analysis, ground motions for seismic analysis can be divided into two levels:

(a) Operating basis earthquake ground motion (OBE-GM). The OBE-GM is a ground motion that can be reasonably expected to occur within the service life of the project feature. The purpose of the OBE-GM criteria is to protect against economic losses from damage or loss of service. The associated performance requirement is that the project feature functions with little or no damage and without interruption of function.

(b) Maximum design earthquake ground motion (MDE-GM). The MDE-GM is the maximum level of ground motion for which a project feature is designed or evaluated. The associated performance requirement is that the project feature performs without loss of life or catastrophic failure (such as an uncontrolled release of a reservoir) although severe damage to the project feature, property losses, or adverse environmental impacts may occur.

(2) *The maximum credible earthquake ground motion (MCE-GM)*. In developing MDE-GM for Critical project features, the MCE-GM is also considered. The MCE-GM for a given project feature site is defined as the largest earthquake ground motion that can reasonably be expected to generate by a specific source, zone, or scenario and is based on seismological and geological characterization of both nearby and more distant potentially active seismic sources.

(3) *Criteria for seismic design ground motions.* Table 2 provides criteria for seismic design ground motions for CW project features. Table 2 criteria include minimum earthquake return periods for OBE-GM and MDE-GM for Critical and Non-Critical project features. Additional clarifications regarding service life of a new project or additional service life of an existing project, considerations for higher earthquake return periods (such as consequences, project feature functionality, project feature service life, and/or post-earthquake response and repair), and MDE-GM for areas without mapped seismic sources are included in footnotes table 2.

Table 2
Criteria for seismic design ground motions

Project Feature Type	Minimum Earthquake Return Period for OBE-GM[1]	Earthquake Return Period for MDE-GM
Non-Critical	145-year return period[2]	975-year return period
Critical	475-year return period[3]	Greater[4] of the following: 1) 2,475-year return period[5,6] 2) MCE-GM (84th percentile values from ground motion models for source slip rate, SR ≥ 0.9 mm/year, median or 50th percentile values for SR ≤ 0.3 mm/year, and interpolation for SR values between 0.3 mm/year and 0.9 mm/year (see paragraph 9c(4))

Notes:
[1] Earthquake return periods are based on 50 years of new project feature service life or additional 50 years of service life for an existing project feature.
[2] A higher earthquake return period for OBE-GM, such as a 225-year return period, can be used for a Non-Critical project feature based on the consequences, project feature functionality, project feature service life, and/or post-earthquake response and repair.
[3] A higher earthquake return period for OBE-GM, such as a 975-year return period, can be used for a Critical project feature based on the consequences, project feature functionality, project feature service life, and/or post-earthquake response and repair.
[4] If the 84th percentile MCE-GM (irrespective of slip rates) is lower than the 2,475-year return period GM in a low seismic ground motion hazard region (paragraph 9d), the 84th percentile MCE-GM can be considered for MDE-GM of the Critical project feature based on the significance of the consequences, project feature functionality, project feature service life, and/or post-earthquake response and repair. However, the selected MCE-GM value cannot be lowered below 90 percent of the 2,475-year return period GM.
[5] A higher earthquake return period for MDE-GM (such as 5,000 or 10,000 years) can be used for a Critical project feature based on the consequences, project feature functionality, project feature service life, and/or post-earthquake response and repair.
[6] In regions where mapped seismic sources are not available for MCE-GM determination, a minimum earthquake return period of 2,475 years will be used for MDE-GM.

(4) *The MCE-GM percentile for ground motions from sources with slip rates between 0.3 mm/year and 0.9 mm/year*. Use equation 1 to obtain ε for SR between 0.3 mm/year and 0.9 mm/year and then interpolate the corresponding percentile using ε = 0 for SR = 0.3 mm/year (50th percentile) and ε = 1 for SR = 0.9 mm/year (84th percentile):

$$\varepsilon = \frac{log_{10}\,(SR/0.3)}{log_{10}\,(3)} \qquad \text{Equation 1}$$

where, ε is the fraction of the standard normal term used for calculating the corresponding percentile, and SR is the slip rate of the source in mm/year.

(5) *Ground motion intensity measures*.

(a) The peak ground acceleration (PGA) is a commonly used intensity measure to express ground motion hazards at a site. The PGA is the peak spectral acceleration at

zero period (for practical purposes, at a very low period such as 0.01 second) at a specific site location.

(b) A uniform hazard response spectrum captures the spectral acceleration at different periods ranging from very low period (such as 0.01 second) to high period (such as 10 seconds) for the same probability of exceedance at all response periods and site geologic conditions (expressed as shear wave velocity, V_S for input location). It represents excitation levels for a single degree of freedom harmonic oscillator with a specified percentage of critical damping (typically 5 percent), and it is used in characterizing ground motions for seismic analyses including selecting and developing ground motion time series for seismic analysis.

(c) A uniform hazard response spectrum, including the PGA value, is the primary intensity measure for a site. Other intensity measures such as Arias intensity, significant duration, peak ground velocity, cumulative absolute velocity, pulse, and fling are also used in selection and modification of ground motion time series for analysis.

(6) *Requirements for appurtenant structures and equipment*.

(a) Performance requirements of appurtenant structures and equipment must be determined based on their purpose. If an appurtenant structure or equipment (such as spillway gates and piers, inlet towers, outlet towers and tunnels, electrical and mechanical equipment, penstock) is required to be serviceable in order to lower pool elevation or close a levee system (such as closure structure) after a major earthquake (such as after experiencing MDE-GM), it must be functional or operational after a major earthquake event. In some cases, an appurtenant structure or equipment can experience some damage; however, it must still reliably provide required functions of the project feature.

(b) The coincident water surface elevation and the coincident hydraulic loading (paragraph 9f) and capability to lower the reservoir pool or close a levee system by other measures (such as functioning low-level outlet with adequate capacity) must be considered to determine the performance objective of appurtenant structure or equipment. If the appurtenant structure or equipment is not required to control pool elevation or close a levee system after an earthquake, performance objectives and seismic loading of the appurtenant structure or equipment will be determined based on table 2.

(7) Requirements for levee embankments and floodwalls.

(a) A frequently loaded levee embankment and floodwall is defined as experiencing a water surface elevation of 1 foot (0.3 meter) or higher above the elevation of the landside embankment or floodwall toe for at least once a day for more than 36 days per year on average (10 percent of the number of days in a year). Performance requirements and seismic loading will be determined based on table 2.

(b) An intermittently loaded levee embankment and floodwall does not meet the definition of a frequently loaded levee embankment and floodwall. Design and evaluation will consider the seismic loading in table 2.

(c) In moderate and high seismic ground motion hazard regions (paragraph 9d), mitigation measures for non-seismic potential failure modes (PFMs) cannot increase the risk for seismic PFMs. Cost effective seismic mitigation measures will be implemented when justified based on the results of a project-specific risk assessment including considerations for post-earthquake response and repair (feasibility and cost).

(8) *Damage metrics for performance evaluations.* Potential damage metrics for evaluating performance of CW project features to meet required performance objectives of OBE-GM and MDE-GM are project feature specific (such as geotechnical, structural, electrical, mechanical, hydraulics, and other conditions). The project teams are required to (a) establish potential damage metrics (such as factors of safety, allowable compressive and tensile stress, cracks, deformations, displacements, operability, drift, and other metrics) and (b) select and develop analysis and evaluation protocols to evaluate performance at OBE-GMs and MDE-GMs. Potential damage metrics, analysis, and evaluation protocols can be established based on project feature-specific EMs (see Appendix A).

(9) *Aftershock events.* For Critical project features, the performance requirements for evaluation-level ground motions, such as OBE-GM and MDE-GM, are also applicable for aftershock events. The main intent of the aftershock analysis is to evaluate whether the project features that are close to not meeting performance objectives of the OBE-GM and MDE-GM, or other GM levels, are able to meet performance objectives during and after the aftershock events. An aftershock seismic analysis will be performed after performing a seismic analysis for the mainshock ground motions. Based on the tectonic environment, the strength of aftershock ground motions can vary significantly. Seismic loading estimates for aftershock events can be developed by project feature-specific seismic hazard evaluations. The aftershock seismic analysis must be performed using the post-mainshock conditions of the project features (undamaged or minor to severely damaged conditions with the same coincident pool elevation).

(10) *Fault rupture*. For Critical project features, impacts of fault rupture displacements from faults mapped within the project feature footprint and vicinity must be considered in analysis, evaluation, and design. Ground motions for analysis must consider impact of near-source effects due to fault rupture within 30 km (~19 miles) from the project feature site.

(11) *Pre-existing landslides*. Potential for triggering pre-existing landslides in a reservoir or near a dam must be evaluated at the evaluation-level ground motions (such as OBE-GM and MDE-GM) and coincident pool. Project features must meet performance objectives of table 2 for pre-existing landslides triggered by an earthquake event.

(12) *Seiche*. Potential for seismically induced reservoir waves or seiche at the evaluation-level ground motions (such as OBE-GM and MDE-GM) must be considered in the overtopping evaluation of dams.

d. Site seismic ground motion hazard classification based on peak ground acceleration.

(1) Seismic ground motion hazard regions are classified into low, moderate, and high categories. Low seismic ground motion hazard regions are associated with a PGA that is less than or equal to 0.1g (PGA ≤ 0.1g). Moderate seismic ground motion hazard regions have a PGA between 0.1g and 0.2g (0.1g < PGA < 0.2g). High seismic ground motion hazard regions have a PGA that is equal to or greater than 0.2g (PGA ≥ 0.2g). These intensity measures should be determined for each project feature considering the following:

(a) Site geologic conditions expressed by the average small-strain shear wave velocity in the upper 100 feet (30 meters) of the site profile, V_{S30} values, using equation 2.

$$V_{s30} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{V_{si}}} \qquad \text{Equation 2}$$

where,

d_i = Thickness of any layer between 0 and 100 feet (30 meter),

V_{si} = Shear wave velocity in ft/sec (m/sec) [measured or estimated using geophysical or geotechnical in situ methods]

$\sum_{i=1}^{n} d_i$ = 100 feet (30 meter)

(b) Free-field conditions considering site geology and geotechnical characteristics; and

(c) An earthquake ground motion return period of 975 years.

(2) Site seismic ground motion hazard classifications will be used to determine the analysis methods (as discussed in paragraph 9g).

e. Adjustment of ground motion parameters for seismic analysis.

(1) Ground motion parameters including design ground motion time series will be developed considering the input location for seismic analysis, which may vary based on location of the project feature, seismic analysis type, structure type (such as concrete dam, embankment dam or levee, or natural slope), and foundation and site geologic conditions.

(2) Appropriate ground motions for a project feature must include amplification through the project feature. Such amplification must incorporate (1) the dynamic response through the project feature and (2) topographic or geometric effects.

(3) Liquefaction or other types of strength and stiffness loss in foundation or embankment layers may result in partial base isolation. A partial base isolation may alter the seismic demand at different locations of the project feature. Additionally, the embankment or slope may experience seismic deformations that can represent an additional displacement load or hazard condition. In these cases, the performance of a project feature (such as a floodwall) located near the crest of a dam, embankment, or slope will potentially be subject to topographic amplification of seismic motions as well as deformations in the dam, embankment, or slope.

(4) Based on the criticality of the project feature (see paragraph 9b), the project feature must be designed to remain safely functional for stronger shaking with and without soil liquefaction or other types of strength and stiffness loss.

f. Coincident water surface elevation and coincident hydraulic loading.

(1) The coincident water surface elevation and/or the coincident hydraulic loading are the surface water levels and groundwater phreatic conditions that must be used in combination with seismic loading for analysis, evaluation, and design.

(2) The coincident water surface is the elevation of the top of a body of water (such as a reservoir, river, or canal) that must be safely retained during an earthquake.

The associated coincident hydraulic loading conditions (including phreatic surface, pore pressures and seepage forces) are based on the coincident water surface elevation and an assumed fully developed steady-state seepage condition. The coincident water surface elevation represents a relatively high but normal level that can be expected to occur every year. It has a 10 percent expected annual duration of exceedance, meaning the water surface is expected to be at or above this elevation 36 days per year (10 percent of the time) on average or is expected to be below this elevation for the remaining 90 percent of the time. The coincident water surface elevation must be used for seismic analysis, evaluation, and design of dams, levees, and other water retention structures.

(3) For run-of-the-river conditions or situations in which no body of water must be safely retained (such as retaining walls), the coincident hydraulic loading is the set of hydraulic and phreatic conditions (including internal phreatic surfaces, pore pressures, and steady-state seepage forces) that are assumed to exist at the time of the earthquake. The coincident hydraulic loading represents a relatively high but normal hydraulic loading that can be expected to occur every year. It can be based on either a 10 percent annual duration exceedance for a headwater water level or a 10 percent annual duration exceedance for a differential hydraulic head between a headwater and tailwater level, whichever results in the largest hydraulic loading on the project feature.

(4) The water levels to assess coincident water surface elevation and coincident hydraulic loading are obtained from an annual stage-duration exceedance relationship for a reservoir, stream, coast, etc., as well as expected groundwater levels. The coincident hydraulic loading will be higher for some water supplies, hydroelectric dams, and coastal/delta levees, where high water levels may exist for significant portions of the year. In drier regions, the coincident hydraulic loading will be lower where low retained water surface elevations or groundwater levels may exist for significant portions of the year.

(5) An assessment must be performed to determine if additional lower and/or higher coincident water surface elevations or coincident hydraulic loading condition(s) are needed to evaluate performance and resiliency, as these may be Critical considering feature-specific seismic responses and consequences.

g. Analysis methods.

(1) Project feature seismic analyses and resulting evaluations of risk and hazard levels are generally performed in phases in order of increasing complexity from simplified methods such as seismic coefficient up to more advanced analysis methods (such as response spectra, time history, and fully nonlinear deformation and displacement seismic analysis methods). The appropriate level of complexity will depend on the phase of the design or assessment, project feature-specific conditions, project feature criticality, and structure type.

(2) Simplified seismic analysis methods are approximate. These can be used for screening and feasibility studies, provided the appropriate level of uncertainty is accounted for in decision making. Applicability and limitations of simplified methods need to be considered in evaluations of results.

(3) The final design or evaluation of Critical project features in high seismic ground motion hazard regions (paragraph 9d) must be performed by advanced analysis methods (such as response spectrum analysis, ground motion time series analysis, and

nonlinear seismic analyses). For Critical project features in moderate seismic ground motion hazard regions, analysis methods must be based on project feature-specific considerations. In such cases, documentation must be prepared to justify the use of the selected seismic analysis methods, if advanced analysis methods are not used. Implementation of advanced analysis methods for Critical project features from initial phases of a project is beneficial to identify data gaps, collect data, and optimize results in the final phases with more accurate results. Duration of the expected earthquakes can be considered in selecting analysis methods (such as expected longer durations in subduction zones).

(4) For Non-Critical project features in all seismic ground motion hazard regions, a higher level of analysis can be adopted, if reasonably justified. In some cases, the advanced nonlinear analysis may result in improved reliability as well as economic benefits to the project features. This may be beneficial for designing Non-Critical project features in all seismic ground motion hazard regions and Critical features in low seismic ground motion hazard regions.

(5) The Project Delivery Team (PDT) can adopt a higher degree of complexity in seismic analyses at the initial phases of the project considering project feature-specific conditions such as hazards, criticality of the structure, schedule, and consequences. A higher degree of complexity during the initial phase may be needed if the limitations of a simplified analysis method are considered unacceptable. Continuity of the design process needs to be considered throughout each phase. The plan of study for each phase of design must be consistent with this regulation and with ER 1110-2-1150.

(6) Analysis progression for structural features by performing the analysis in phases can result in the analytical model providing realistic results and forms a logical basis for decisions to revise the structural configuration and/or to 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.

(a) 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 variations in ground motions must be accounted for in evaluating the spatial variation in response between points on large structures. The structural significance of modal shapes must be considered, especially when evaluating the stresses using a response spectrum analysis.

(b) The results of a finite element analysis of a reinforced concrete structure must be expressed in terms of moment, thrust, and shear. Areas where inelastic behavior is anticipated must be identified and the concrete confinement requirements stated. In some cases, linear time-history methods applied to 2D or 3D models will provide adequate understanding of structural performance during an earthquake. If linear time-history methods of analysis cannot demonstrate the adequacy of a particular design, then nonlinear time-history methods must be considered.

(7) For geotechnical features, appropriate analytical methods must be used to estimate deviatoric and volumetric deformations and displacements, cracking potential, and other potential types of damage.

h. Engineering parameters for seismic analysis, evaluation, and design.

(1) The ability of seismic analysis using appropriate ground motions and coincident water surface elevations or coincident hydraulic loading to identify project hazards (including performance of existing and new structures) depends on knowledge of existing conditions and proper application of appropriate engineering analysis methods. Engineering properties that are required for seismic analyses include but are not limited to geologic features; foundation soil and rock geology and properties; groundwater and phreatic conditions; and structure and embankment geometries, stratigraphy, zones, and properties. Even detailed site-specific ground motion characterizations and advanced seismic analyses can result in incomplete and misleading conclusions if geological, geotechnical, and structural conditions and properties are not adequately characterized.

(2) The required parameters and their determination must be based on structure-specific EMs. The PDT is required to assess the existing data adequacy, collect required data using the appropriate methods, and develop parameters for seismic analyses with higher reliability.

(3) If reliable data is not available, sensitivity analyses must be performed to evaluate the impacts of parameter ranges on potential performance. In some cases, sensitivity analysis may indicate a need for further data collection to reduce uncertainty. It is important to recognize that in certain situations a particular assumption may cause unconservative or conservative results in different parts of the analysis and that there is sometimes no sufficiently conservative assumption that can be made in such conditions without reliable material property characterization.

i. Risk-informed design and evaluation of dams and levees.

(1) USACE has adopted a risk-informed approach for new designs and/or modifications to dam and levees. Evaluation of OBE-GM and MDE-GM-level performance requirements in accordance with paragraphs 9a through 9h is performed in conjunction with a risk assessment. Dam features are required to meet performance objectives of this regulation (para 9c) and the tolerable risk guidelines, as outlined in ER 1110-2-1156.

(2) Risk-informed design and evaluation will be performed using a risk assessment process. For an existing dam or levee, an evaluation of a full range of seismic loading helps determine the ground motion levels where the project feature transitions from potentially no damage or limited damage conditions (OBE-GM-level performance objectives) to increasing damage and potential nonlinear conditions with higher shaking intensity levels. The full range of the earthquake hazards and ground motions must be developed considering seismologic and geologic conditions, tolerable risk guidelines, and project feature type.

(3) In risk-informed design and evaluation, system response functions (conditional probability of failure or damage state as a function of ground motion intensity measures and other seismic hazards and/or coincident hydraulic loading) for each potential failure mode must be developed for the project feature to determine the adequacy of the existing or potential design measures. The OBE-GM and MDE-GM are two earthquake ground motions out of a full range of earthquake ground motion levels that must be evaluated as part of the risk-informed design and evaluation process. The scope of the risk assessment can be scaled to the project's feature size, complexity, site ground

motion hazards, criticality, and consequences of a project feature. Risk assessments must consider loss of serviceability as well as failure scenarios.

Appendix A
References

Section I

Required Publications

Unless otherwise indicated, all U.S. Army Corps of Engineers publications are available on the USACE website at https://publications.usace.army.mil.
Army publications are available on the Army Publishing Directorate website at https://armypubs.army.mil.

AASHTO Guide Specifications for LRFD Seismic Bridge Design
Latest edition. (Available at https://transportation.org/)

AASHTO Load and Resistance Factor Design (LRFD) Specifications
Latest edition. (Available at https://transportation.org/)

Alquist-Priolo Earthquake Fault Zoning Act (Available at https://leginfo.legislature.ca.gov/faces/codes_displayText.xhtml?division=2.&chapter=7.5.&lawCode=PRC)

DA Pam 25-403
Army Guide to Recordkeeping

EM 1110-2-1913
Design and Construction of Levees

EM 1110-2-2100
Stability Analysis of Concrete Structures

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

EM 1110-2-2107
Design of Hydraulic Steel Structures

EM 1110-2-2200
Gravity Dam Design

EM 1110-2-2201
Arch Dam Design

EM 1110-2-2502
Flood Walls and Other Hydraulic Retaining Walls

EM 1110-2-2503
Design of Sheet Pile Cellular Structures Cofferdams and Retaining Structures

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

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

EM 1110-2-2902
Conduits, Culverts, and Pipes Associated with Dams and Levee Systems

EM 1110-2-2906
Design of Pile Foundations

EM 1110-2-3001
Planning and Design of Hydroelectric Power Plant Structures

EM 1110-2-3104
Structural and Architectural Design of Pumping Stations

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

ER 1105-2-101
Risk Assessment for Flood Risk Management Studies

ER 1110-2-103
Strong-Motion Instruments for Monitoring and Recording Earthquake Motions

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

ER 1110-2-1156
Safety of Dams – Policies and Procedures

ER 1110-2-1802
Post-Earthquake Inspections and Reporting for Civil Works Structures

ER 1110-2-8157
Responsibility for Hydraulic Steel Structures

ER 1110-2-8159
Life Cycle Design and Performance

ER 1110-2-8161
Structural Design and Evaluation of Civil Works Buildings

ER 1130-2-500
Partners and Support (Work Management Policies)

FHWA RD-94-052
Seismic Retrofitting Manual for Highway Bridges
(https://www.fhwa.dot.gov/publications/)

Section II

Prescribed Forms

This section contains no entries.