Chapter 1
Introduction

1-1. Purpose

This manual describes the development and use of response spectra for the seismic analysis of concrete hydraulic structures. The manual provides guidance regarding how earthquake ground motions are characterized as design response spectra and how they are then used in the process of seismic structural analysis and design. The manual is intended to be an introduction to the seismic analysis of concrete hydraulic structures. More detailed seismic guidance on specific types of hydraulic structures will be covered in engineer manuals and technical letters on those structures.

1-2. Applicability

This manual applies to all USACE Commands having responsibilities for the design of civil works projects.

1-3. Scope of Manual

Chapter 1 provides an overview of the seismic assessment process for hydraulic structures and the responsibilities of the project team involved in the process, and also briefly summarizes the methodologies that are presented in Chapters 2 and 3. In Chapter 2, methodology for seismic analysis of hydraulic structures is discussed, including general concepts, design criteria, structural modeling, and analysis and interpretation of results. Chapter 3 describes methodology for developing the earthquake ground motion inputs for the seismic analysis of hydraulic structures. Emphasis is on developing response spectra of ground motions, but less detailed guidance is also provided for developing acceleration time-histories.

1-4. References

References are listed in Appendix A.

1-5. Responsibilities of Project Team

The development and use of earthquake ground motion inputs for seismic analysis of hydraulic structures require the close collaboration of a project team that includes the principal design engineer, seismic structural analyst, materials engineer, and geotechnical specialists. The principal design engineer is the leader of the project team and has overall responsibility for the design. The seismic structural analyst plans, executes, and evaluates the results of seismic analyses of the structure for earthquake ground motions for the design earthquakes. The materials engineer characterizes the material properties of the structure. The geotechnical specialists conduct evaluations to define the design earthquakes and input ground motions and also characterize the properties of the soils or rock foundation for the structure. Any potential for seismically induced failure of the foundation is evaluated by the geotechnical specialists. The geotechnical evaluation team typically involves the participation of geologists, seismologists, and geotechnical engineers.

1-6. Overview of Seismic Assessment

The overall process of seismic assessment of concrete hydraulic structures consists of the following steps: establishment of earthquake design criteria, development of design earthquakes and characterization of earthquake ground motions, establishment of analysis procedures, development of structural models, prediction of earthquake response of the structure, and interpretation and evaluation of the results. The following paragraphs present a brief description of each step, the objectives, and the personnel needed to accomplish the tasks.

a. Establishment of earthquake design criteria. At the outset, it is essential that the lead members of the project team (principal design engineer, seismic structural analyst, materials engineer, and lead geotechnical specialist) have a common understanding of the definitions of the project operating basis earthquake (OBE) and maximum design earthquake (MDE). Structure performance criteria for each design earthquake should also be mutually understood. Having this understanding, the geotechnical team can then proceed to develop an overall plan for developing design earthquakes and associated design response spectra and acceleration time-histories, while the structural team begins establishing conceptual designs and analysis and design methods leading to sound earthquake-resistant design or safety evaluation.

b. Development of design earthquakes and characterization of earthquake ground motions.

(1) Assessing earthquake potential. The project geologist and seismologist must initially develop an understanding of the seismic environment of the site region. The seismic environment includes the regional geology, regional tectonic processes and stress conditions leading to earthquakes, regional seismic history, locations and geometries of earthquake sources (faults or source areas), and the type of faulting (strike slip, reverse, or normal faulting). Analysis of remote imagery and field studies to identify active faults may be required during this step. Next, maximum earthquake sizes of the identified significant seismic sources must be estimated (preferably in terms of magnitude, but in some cases in terms of epicentral Modified Mercalli intensity). Earthquake recurrence relationships (i.e., the frequency of occurrence of earthquakes of different sizes) must also be established for the significant seismic sources.

(2) Determining earthquake ground motions. After the geologist and seismologist have characterized the seismic sources, the geotechnical engineer and/or strong-motion seismologist members of the geotechnical team can then proceed to develop the design (OBE and MDE) ground motions, which should include response spectra and, if needed, acceleration time-histories as specified by the principal design engineer. The design ground motions should be based on deterministic and probabilistic assessments of ground motions. These design ground motions should be reviewed and approved by the principal design engineer.

c. Establishment of analysis procedures.

(1) Basic entities of analysis procedures. The establishment of analysis procedures is an important aspect of the structural design and safety evaluation of hydraulic structures subjected to earthquake excitation. The choice of analysis procedures may influence the scope and nature of the seismic input characterization, design procedures, specification of material properties, and evaluation procedures of the results. The basic entities of analysis procedures described in this manual are as follows: specification of the form and point of application of seismic input for structural analysis, selection of method of analysis and design, specification of material properties and damping, and establishment of evaluation procedures.

(2) Formulation of analysis procedures. The analysis procedures and the degree of sophistication required in the related topics should be established by the principal design engineer. In formulating rational structural analysis procedures, the principal design engineer must consult with experienced seismic structural, materials, and geotechnical specialists to specify the various design and analysis parameters as well as the type of seismic analysis required. The seismic structural specialist should review the completed design criteria for adequacy and in the case of major projects may work directly with the engineering seismologists and the geotechnical engineers in developing the seismic input. The physical properties of the construction materials and the foundation supporting the structure are determined in consultation with the materials, geotechnical engineer, and the engineering geologist (for the rock foundation).

d. Development of structural models. The task of structural modeling should be undertaken by an engineer (seismic structural analyst) who is familiar with the basic theory of structural dynamics as well as the finite element structural analysis. The structural analyst should work closely with the principal design engineer in order to develop an understanding of the basic functions and the dynamic interactions among the various components of the structure. In particular, interaction effects of the foundation supporting the hydraulic structure and of the impounded, surrounding, or contained water should be accounted for. However, the structural model selected should be consistent with the level of refinement used in specifying the earthquake ground motion, and should always start with the simplest model possible. Classifications, unit weights, and dynamic modulus and damping properties of the backfill soils and the soil or rock foundation are provided by the geotechnical engineer or engineering geologist member of the project team. Various aspects of the structural modeling and the way seismic input is applied to the structure are discussed in Chapter 2.

e. Prediction of earthquake response of structure. After constructing the structural models, the seismic structural analyst should perform appropriate analyses to predict the earthquake response of the structure. Prediction of the earthquake response includes the selection of a method of analysis covered in paragraph 1-7, formulation of structural mass and stiffness to obtain vibration properties, specification of damping, definition of earthquake loading and combination with static loads, and the computation of response quantities of interest. The analysis should start with the simplest method available and progress to more refined types as needed. It may begin with a pseudo-static analysis performed by hand or spreadsheet calculations, and end with more refined linear elastic response-spectrum and time-history analyses carried out using appropriate computer programs. The required material parameters are formulated initially based on preliminary values from the available data and past experience, but may need adjustment if the analysis shows strong sensitivity to certain parameters, or new test data become available. Damping values for the linear analysis should be selected consistent with the induced level of strains and the amount of joint opening or cracking and yielding that might be expected. Seismic loads should be combined with the most probable static loads, and should include multiple components of the ground motion when the structure is treated as a two-dimensional (2-D) or three-dimensional (3-D) model. In the modal superposition method of dynamic analysis, the number of vibration modes should be selected according to the guidelines discussed in Chapter 2, and response quantities of interest should be determined based on the types of information needed for the design or the safety evaluation. In simplified procedures, the earthquake loading is represented by the equivalent lateral forces associated with the fundamental mode of vibration, where the resultant forces are computed from the equations of equilibrium.

f. Interpretation and evaluation of results.

(1) Responsibilities. The seismic structural analyst and the principal design engineer are the primary personnel responsible for the interpretation and evaluation of the results. The final evaluation of seismic

performance for damaging earthquakes should include participation by experienced structural earthquake engineers.

(2) Interpretation and evaluation. The interpretation of analysis results should start with the effects of static loads on the structure. The application of static loads and the resulting deflections and stresses (or forces) should be thoroughly examined to validate the initial stress conditions. The earthquake performance of the structure is then evaluated by combining the initial static stresses (or forces) with the dynamic stresses (or forces) due to the earthquake. The evaluation for the linear elastic analysis is carried out by comparing computed stresses for unreinforced concrete (URC) or section forces and deformations for reinforced concrete (RC) with the allowable stress values or the supplied capacities, in accordance with the performance goals set forth in Chapter 2. However, in view of the fact that the predicted earthquake response of the structure is based on numerous assumptions, each of which has a limited range of validity, the evaluation procedure should not be regarded as absolute. The final evaluation therefore should consider the uncertainties associated with the earthquake ground motions, accuracy of the analysis techniques, level of foundation exploration, testing, and confidence in material properties, as well as limitations of the linear analysis and engineering judgment to predict nonlinear behavior.

1-7. Summary of Seismic Analysis of Concrete Hydraulic Structures

a. General. Hydraulic structures traditionally have been designed based on the seismic coefficient method. This simple method is now considered inadequate because it fails to recognize dynamic behavior of the structures during earthquake loading. The seismic coefficient method should be used only in the preliminary design and evaluation of hydraulic structures for which an equivalent static force procedure based on the vibration properties of the structure has not yet been formulated. The final design and evaluation of hydraulic structures governed by seismic loading should include response spectra and, if needed, acceleration time-histories as the seismic input and response spectrum or time-history method of analysis for predicting the dynamic response of the structure to this input. With recent advances in the estimation of site-specific ground motions and in structural dynamic computer analysis techniques, the ability to perform satisfactory and realistic analyses has increased. This manual presents improved guidelines for the estimation of site-specific ground motions and the prediction of dynamic response for the design and seismic safety evaluation of hydraulic structures.

b. Types of hydraulic structures. The general guidelines provided in this manual apply to concrete hydraulic structures including locks, intake towers, earth retaining structures, arch dams, conventional and Roller Compacted Concrete (RCC) gravity dams, powerhouses, and critical appurtenant structures.

c. Design criteria. The design and evaluation of hydraulic structures for earthquake loading must be based on appropriate criteria that reflect both the desired level of safety and the nature of the design and evaluation procedures (ER 1110-2-1806). The first requirement is to establish earthquake ground motions to be used as the seismic input by considering safety, economics, and the designated operational functions. The second involves evaluating the earthquake performance of the structure to this input by performing a linear elastic dynamic analysis based on a realistic idealization of the structure, foundation, and water.

d. Design earthquakes. The design earthquakes for hydraulic structures are the OBE and the MDE. The actual levels of ground motions for these earthquakes depend on the type of hydraulic structure under consideration, and are specified in the seismic design guidance provided for a particular structure in conjunction with ER 1110-2-1806.

(1) 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 exceedance during the

service life. The associated performance requirement is that the project function with little or no damage, and without interruption of function.

(2) Maximum design earthquake (MDE). The MDE is the maximum level of ground motion for which the structure is designed or evaluated. The associated performance requirement is that the project performs without catastrophic failure, such as uncontrolled release of a reservoir, although severe damage or economic loss may be tolerated. The MDE is set equal to the maximum credible earthquake (MCE) or to a lesser earthquake, depending on the critical nature of the structure (see ER 1110-2-1806 and paragraph 2-4b).

(3) The MCE 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.

e. Earthquake ground motion(s). The ground motions for the design earthquakes are defined in terms of smoothed elastic response spectra and, if required, also in terms of acceleration time-histories. Standard ground motions selected from published ground motion maps can be used in preliminary and screening studies, and for final design or evaluation in areas of low to moderate seismicity where the earthquake loading does not control the design. Site-specific ground motions, as described in Chapter 3, are required for projects with high to significant hazard potential in case of failure and located in areas of high seismicity, and in areas of moderate seismicity where the earthquake loading controls the design (ER 1110-2-1806).

f. Structural idealization. The structural idealization should start with the simplest model possible and, if required, progress to a 2-D or a more comprehensive 3-D model. The structural model should represent the important features of the dynamic behavior of the structure including its interaction with the foundation and the water. It should also be consistent with the design and evaluation objectives, that is, to reflect the relative accuracy suitable for the type of seismic input used as well as the type of studies performed, i.e., feasibility, preliminary, or final study. For example, one-dimensional (1-D) models are used for the preliminary design and evaluation, whereas depending on geometry of the structure, 2-D or 3-D models are used in the final phase of the study.

(1) Simplified models. Simplified models are based on the equivalent lateral force procedures, where the earthquake response of the structure is obtained directly from the response spectra. In most cases only the fundamental mode of vibration, but sometimes the second mode as well, is considered. However, only the fundamental mode is adjusted to account for the effects of structure-foundation and structure-water interaction.

(2) Two-dimensional models. 2-D models including the structure-foundation and structure-water interaction effects are developed using the finite element (FE) procedures. They are employed in the final or preliminary study of structures for which simplified models have not yet been formulated. The seismic input consists of response spectra (or acceleration time-histories) for the vertical and one horizontal components of ground motion. The seismic input is applied either at the base of the composite structure-foundation model or at the base of the structure if the substructure method of analysis is used.

(3) Three-dimensional models. Hydraulic structures with complicated 3-D geometry should be idealized as 3-D models and analyzed for all three components of the earthquake ground motion. The model should be developed using FE procedures and account for the effects of structure-foundation and structure-water interaction. The seismic input in the form of response spectra or acceleration time-histories is applied along three principal axes of the structure either at the base of the composite structure-foundation model or at the base of the structure if the foundation region is analyzed separately.

g. Dynamic analysis procedures. Linear dynamic analysis procedures are presently used for earthquake-resistant design and safety evaluation of hydraulic structures. The linear dynamic analysis is performed using the response spectrum or the time-history modal superposition method. The primary feature of the modal analysis is that the total response of a structure is obtained by combining the response of its individual modes of vibration, calculated separately. The response spectrum analysis is adequate for structures whose responses to earthquakes are within the linear elastic range. But for structures for which the cracking strength of the concrete and yield strength of the reinforcing steels may be exceeded under a major earthquake, a linear time-history analysis provides additional information that is essential to approximating the damage or expected level of inelastic response behavior.

(1) Response spectrum analysis. In the response spectrum analysis, the maximum response of the structure to earthquake excitation is evaluated by combining the maximum responses from individual modes and multicomponent input. All response quantities computed in this manner are positive and require careful examination and interpretation. The accuracy of the results depends on the number of vibration modes considered and the methods of combination used for the modal and multicomponent earthquake responses.

(2) Time-history analysis. Linear time-history analysis involves computation of the complete response history of the structure to earthquakes, and not just the maximum values. The results of such analysis serve to demonstrate the general behavior of the seismic response, and combined with rational interpretation and judgment can provide a reasonable estimate of the expected inelastic behavior or damage, when the cracking or other form of nonlinearity is considered to be slight to moderate. Prediction of the actual damage that could occur during major earthquakes can only be estimated using more complicated nonlinear analyses, but approximate assessment can still be made using the analysis discussed in paragraph 2-4b(3)(a) and (b). The complete nonlinear analysis of hydraulic structures is not currently practical; only limited aspects of the nonlinear response behavior such as joint opening and sliding of blocks can be considered.

h. Interpretation and evaluation of results. The evaluation of earthquake performance of hydraulic structures is currently based on the numerical results of linear dynamic analyses, in which the calculated stresses for URC or section forces and deformations for RC are compared with the allowable stress values or the supplied moment and shear capacities. New hydraulic structures should resist the OBE excitation within the elastic range of the element stresses (or section forces) to avoid structural damage or yielding. However, existing hydraulic structures in high seismic hazard regions may be allowed to respond to the OBE excitation within the *nearly elastic* range; that is, minor local damage or yielding is permitted if retrofit to preclude damage is deemed uneconomical. The evaluation for the severe MDE excitation is more complicated because the dynamic response is expected to exceed the linear elastic limits, resulting in damage and inelastic behavior. In such cases, the extent of damage for URC hydraulic structures is normally estimated based on the results of linear response history analysis together with engineering judgment and other considerations discussed in paragraph 2-8a(4). For RC hydraulic structures undergoing inelastic deformations, approximate postelastic dynamic analyses are performed to ensure that the inelastic demands of the severe MDE excitation can be resisted by the available capacity of the structure. The postelastic analysis discussed in paragraph 2-4b(3)(b) is a step-by-step linear analysis with revised stiffness or resistance characteristics of all structural members that have reached their yielding capacities. The stiffness modification and analysis of the modified structure are repeated until no further yielding will occur or the structure reaches a limit state with excessive distortions, mechanism, or instability.

1-8. Summary of Development of Site-Specific Response Spectra for Seismic Analysis of Structures

a. Factors affecting earthquake ground motion. It has been well recognized that earthquake ground motions are affected by earthquake source conditions, source-to-site transmission path properties, and site conditions. The source conditions include stress conditions, source depth, size of rupture area, amount of rupture displacement, rise time, style of faulting, and rupture directivity. The transmission path properties include the crustal structure and the shear wave velocity and damping characteristics of the crustal rock. The site conditions include the rock properties beneath the site to depths of up to 2 km, the local soil conditions at the site for depths of up to several hundred feet, and the topography of the site. In current ground motion estimation relationships, the effects of source, path, and site are commonly represented in a simplified manner by earthquake magnitude, source-to-site distance, and local subsurface conditions. Due to regional differences in some of the factors affecting earthquake ground motions, different ground motion attenuation relationships have been developed for western United States (WUS) shallow crustal earthquakes, eastern United States (EUS) earthquakes, and subduction zone earthquakes (which, in the United States, can occur in portions of Alaska, northwest California, Oregon, and Washington). It is also recognized that ground motions in the near-source region of earthquakes may have certain characteristics not found in ground motions at more distant sites, especially a high-energy intermediate-to-long-period pulse that occurs when fault rupture propagates toward a site.

b. Basic approaches for developing site-specific response spectra. There are two basic approaches to developing site-specific response spectra: deterministic and probabilistic. In the deterministic approach, termed deterministic seismic hazard analysis, or DSHA, typically one or more earthquakes are specified by magnitude and location with respect to a site. Usually, the earthquake is taken as the MCE and assumed to occur on the portion of the source closest to the site. The site ground motions are then estimated deterministically, given the magnitude and source-to-site distance. In the probabilistic approach, termed probabilistic seismic hazard analysis, or PSHA, site ground motions are estimated for selected values of the probability of ground motion exceedance in a design time period or for selected values of return period of ground motion exceedance. A PSHA incorporates the frequency of occurrence of earthquakes of different magnitudes on the various seismic sources, the uncertainty of the earthquake locations on the sources, and the ground motion attenuation including its uncertainty. Guidance for using both of these approaches is presented in Chapter 3 and is briefly summarized below.

(1) Deterministic approach for developing site-specific response spectra. Deterministic estimates of response spectra can be obtained by either Approach 1, anchoring a response spectral shape to the estimated peak ground acceleration (PGA); or Approach 2, estimating the response spectrum directly. When Approach 1 is followed, it is important to consider the effects of various factors on spectral shape (e.g., regional tectonic environment, earthquake magnitude, distance, local soil or rock conditions). Because of the significant influence these factors have on spectral shape and because procedures, data, and relationships are now available to estimate response spectra directly, Approach 2 should be used. Approach 1 can be used for comparison. The implementation of Approach 2 involves the following:

(a) Using response spectral attenuation relationships of ground motions (attenuation relationships are now available for directly estimating response spectral values at specific periods of vibration).

(b) Performing statistical analyses of response spectra of ground motion records.

(c) Applying theoretical (numerical) ground motion modeling.

When soil deposits are present at a site and response spectra on top of the soil column are required (rather than or in addition to spectra on rock), then either empirically based approaches and/or analytical procedures can be used to assess the local soil amplification effects. Empirically based approaches rely on recorded ground motion data and resulting empirical relationships for similar soil conditions. Analytical procedures involve modeling the dynamic properties of the soils and using dynamic site response analysis techniques to propagate motions through the soils from the underlying rock.

(2) Probabilistic approach for developing site-specific response spectra. Similar to a deterministic analysis, a probabilistic development of a site-specific response spectrum can be made by either Approach 1, anchoring a spectral shape to a PGA value, or Approach 2, developing the spectrum directly. In Approach 1, PSHA is carried out for PGA, and an appropriate spectral shape must then be selected. The selection of the appropriate shape involves the analysis of earthquake sizes and distances contributing to the seismic hazard. In Approach 2, the PSHA is carried out using response spectral attenuation relationships for each of several periods of vibration. Drawing a curve connecting the response spectral values for the same probability of exceedance gives a response spectrum having an equal probability of exceedance at each period of vibration. The resulting spectrum is usually termed an equal-hazard spectrum. Approach 2 should be used because response spectral attenuation relationships are now available and the use of these relationships directly incorporates into the analysis the influence of different earthquake magnitudes and distances on the results for each period of vibration.

c. Developing acceleration time-histories. When acceleration time-histories are required for the structure dynamic analysis, they should be developed to be consistent with the design site-specific response spectrum. They should also have an appropriate duration of shaking (duration of shaking is strongly dependent on earthquake magnitude). The two general approaches to developing acceleration time-histories are selecting a suite of recorded motions that, in aggregate, have spectra that envelope the design spectrum; or synthetically modifying one or more recorded motions to produce motions having spectra that are a close match to the design spectrum ("spectrum matching" approach). For either approach, when near-source ground motions are modeled, it is desirable to include a strong intermediate-to-long-period pulse to model this characteristic that is observed in near-source ground motions.

1-9. Terminology

Appendix I contains defiinitions of terms that relate to Response Spectra and Seismic Analysis for Hydraulic Structures.