Current U.S. Army Corps of Engineers' Policy and Guidance for Seismic Design of Dams

by

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ABSTRACT

The seismic design of concrete hydraulic structures (concrete dams, locks, retaining walls, and other massive navigation or water control structures) constitutes a complex and time-consuming process that involves a variety of engineering disciplines. Procedures for seismic design or evaluation of these massive hydraulic structures need to account for the dynamic characteristics governing the response of the soil-structure-water system. Typically, this types of problems require a multidisciplinary team of structural, materials, geotechnical, and hydraulic engineers, engineering geologists, and seismologists to ensure the appropriate and successful completion of the design or evaluation process. This process, that typically requires extensive engineering judgment and experience, must be facilitated by a consistent framework of technical guidelines and recommendations. The purpose of this paper is to present a brief description of some of the most relevant guidance documents that provide the technical framework for seismic design or evaluation of dams under the responsibility of the U.S. Army Corps of Engineers.

KEYWORDS: Seismic Design and Evaluation; Embankment Dams; Concrete Dams; Gravity Dams; Intake Towers.

1. INTRODUCTION

The seismic design and evaluation of civil works projects under the responsibility of the U.S. Army Corps of Engineers (USACE) must be performed in accordance with the technical policy established in Engineer Regulation No. 1110-2-1806 (HQUSACE, 1995a). The purpose of this document is to provide general criteria for seismic design of new projects and seismic evaluation of existing projects. It applies to all projects which have the potential to malfunction or fail during major seismic events and cause hazardous conditions related to loss of human life, appreciable property damage, disruption of lifeline services, or unacceptable environmental consequences. According to this regulation, any seismic design and evaluation process should focus on assessing the ground motions, site characterization, structural response, functional consequences, and potential hazards within a consistent, well-integrated, and cost-effective framework. Furthermore, this regulation explicitly indicates that the overall analysis should be performed in various phases in order of increasing complexity, an approach that should provide higher degree of confidence in the resulting conclusions.

ER 1110-2-1806 also establishes the different ground motion levels to be considered in design and evaluation studies. The Maximum Design Earthquake (MDE) is defined as the maximum level of ground motion for which the structure is designed or analyzed. The structure should be able to withstand the MDE without catastrophic failure, although severe damage may be tolerated (i.e., the system may suffer serious damage but retain the project pool). The severity of the MDE selected for design or evaluation depends not only on the local seismic hazard but also on the "criticality" of the project. As established in ER 1110-2-1806, a critical project (or project feature) is that whose failure during or immediately after an earthquake could directly result in loss of life due to flooding. For design or analysis of projects deemed critical, the MDE must be set equal to the Maximum Credible Earthquake (MCE), which represents an estimation of the greatest earthquake that

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could be generated by a specific source. For other features (i.e., not linked to potential loss-of-life consequences), the MDE could be selected as a lesser earthquake than the MCE in order to provide a more economical design.

The MCE is determined by means of a deterministic seismic hazard analysis, and a common approach to define the corresponding earthquake loading at the site is based on the use of response spectral attenuation relationships. Using an attenuation relationship (appropriately selected for the corresponding site conditions and tectonic environment), it is possible to generate estimates of spectral ordinates based on the design earthquake magnitude and distance. These attenuation relationships are typically developed based on statistical regression analyses of relevant ground motion data, and the resulting spectral ordinates are associated to the corresponding parameters (mean value, variance, etc.) that define their statistical distribution. Therefore, the definition of the earthquake loading using this approach requires the selection of a specific spectral level (commonly defined as the mean spectrum, mean plus one standard deviation spectrum, etc). This constitutes an extremely important decision that significantly affects the design and evaluation of critical projects.

This document also addresses the sequence of analysis procedures to be followed during the design and evaluation process. In this regard, the recommendations provided in ER 1110-2-1806 are that the overall analysis should be performed in various phases in order of increasing complexity. This type of progressive analysis is summarized in Table 1, which shows that the recommended analysis progression is a function of the seismic hazard at the site and if the seismic response is controlling the design or evaluation.

2. EMBANKMENT DAMS

Technical guidelines for evaluating the seismic safety of existing embankment dams and foundations is provided in the USACE guidance document "Dam Safety Assurance Program," designated as Engineer Regulation 1110-2-1155 (HQUSACE, 1997). The stages of the evaluation process are designated as (1) Seismic Safety Review (SSR), (2) Phase I Special Study, (3) Phase II Special Study. The SSR is essentially a screening stage, using simple preliminary analysis with existing available data to determine whether seismic safety issues exist which require a Phase I Special Study. The Phase I study is to develop site specific ground motion, to perform site characterization with limited field investigations and laboratory studies, to evaluate liquefaction potential using 1-D analyses combined with simplified procedure for liquefaction evaluation, to assess post earthquake stability and post earthquake deformed shape. The Phase II study is detailed and sufficiently comprehensive such that the resulting conclusions should be definitive, and constitute the basis for detailed design and construction for project modifications or remediation. The Phase II study is to compute the site response using appropriate and validated dynamic finite element program with input ground motion time history developed in Phase I, to perform detailed field investigation and laboratory testing for defining the input parameters and the extent of potential problem zones, to perform post earthquake stability analysis, to estimate the deformation response of the embankment dam and the post earthquake shape using an appropriate 2-D and/or 3-D finite element program, to evaluate various remediation alternatives if remedial measures are recommended, and to develop detailed scope, cost, and schedule for pre-construction engineering and design. More detailed numerical procedures and tools used for seismic analysis in geotechnical engineering will be contained in the upcoming guidance document "Seismic Stability Evaluation of Embankment Dams," (EM 1110-2-6001) which is currently being reviewed.

3. GRAVITY DAMS

Recommendations for seismic design and evaluation of concrete gravity dams are provided in the USACE guidance document entitled "Gravity Dam Design" and designated as

Engineer Manual 1110-2-2200 (HQUSACE, 1995b). The purpose of this manual is to provide general criteria and guidance for the planning, design or evaluation of both conventional concrete and roller compacted concrete dams. Concrete gravity sections within an embankment dam should also be designed in accordance with these guidelines. Some of the specific topics covered include design considerations (Chapter 2), determination of concrete and foundation material properties, and definition of load conditions (Chapter 3), stability requirements (Chapter 4), static and dynamic stress analysis (Chapter 5), temperature control of mass concrete (Chapter 6), structural design considerations (Chapter 7), re-evaluation of existing dams (Chapter 8), and roller-compacted gravity sections (Chapter 9).

As an example of the information provided in these guidelines, the performance criteria for stability analysis are shown in Table 2. This table includes the criteria to be used for stability evaluation of concrete gravity dams using the seismic coefficient method. This method provides a simple and direct approach for stability evaluations. Depending on the loading scenario, different limit conditions have been established for sliding factor of safety and resultant location. In particular, for the extreme loading condition (seismic loads corresponding to the MCE level), the minimum sliding factor of safety is 1.3 and the resultant is required to be within the base.

It must be highlighted, however, that these sliding stability criteria has been mainly developed for evaluation of structures subject to moderate seismic forces. The factor of safety against sliding required by these conservative criteria may not be practically attainable for larger seismic forces representative of severe earthquake ground motions. Furthermore, it is necessary to take into account that even if consideration of the seismic actions results in a factor of safety of less than one (indicating the potential for sliding), this condition would be implicitly transient. Due to the oscillatory nature of the earthquake, instantaneous sliding may occur only during very short intervals, thus limiting the resulting displacement. An update/revision of the values specified for the corresponding factors of safety is currently under consideration, as indicated in a later section.

4. ARCH DAMS

Comprehensive information on design and evaluation criteria for arch dams is available in Engineer Manual 1110-2-2201, entitled "Arch Dam Design" (HQUSACE, 1994). The purpose and scope of this document is stated in its first chapter, which also provides a set of standard technical definitions. General design recommendations with special consideration of abutment and foundation conditions are addressed in Chapter 2, whereas technical aspects related to spillways (both attached and detached configurations), outlet works (intake structures, conduits, control house) and appurtenances (elevator tower, access bridges, galleries) are discussed in Chapter 3. Load definitions, loading combinations are presented in Chapter 4, which also discusses the problem of selection of load cases for each phase of the design process. Chapter 5 focuses on some specific aspects related to the design problem (initial geometric design, preliminary stress analyses, design optimization). The application of finite-element procedures for static stress analysis as well as recommendations for interpretation of the corresponding results are discussed in Chapter 6.

Details pertaining to dynamic stress analysis are presented in detail in Chapter 7. This chapter also discusses some of the modeling factors affecting the results from the dynamic response analysis. In particular, it is recommended that the analysis should be based on a 3-D idealization of the dam-water-foundation system which accounts for the interaction effects of the foundation rock and the impounded water. Arch dams are designed to resist most of the applied loads by transmitting them through arch action to the canyon walls. Consequently, the effects of foundation rock on the earthquake response of arch dams are expected to be significant. However, it is highlighted the fact that a

complete solution of the dam foundation interaction effects is very complicated and such procedures have not yet reach a development stage conducive to their wide application.
Issues related to temperature effects and determination of material properties are addressed in Chapters 8 and 9 of this document, respectively. The important topic of foundation investigations is discussed in Chapter 10. 10-1. Introduction. Foundation investigations for arch dams generally must be accomplished in more exacting detail than for other dam types because of the critical relationship of the dam to its foundation and to its abutments. The foundation investigation effort should be accomplished in phases with each leading to the succeeding one and building upon the previous one, and it is very important that the latest state-of-the-art techniques in geological and rock mechanics are employed in these investigations. Criteria for static and dynamic performance evaluation are proposed in Chapter 11. The final sections of the document (Chapters 12 and 13) address instrumentation and construction considerations.

5. OUTLET WORKS

Comprehensive information of design and evaluation for intake tower is available in Engineering Manual 1110-2-2400, entitled "Structural Design and Evaluation of Outlet Works" (HQUSACE, 2003a). The purpose and scope of the document is stated in its first chapter. Seismic criteria for design and evaluation are addressed in Chapter 4. The objectives of design and evaluation, structural stability analysis, seismic design and evaluation of intake towers and access bridges are included in this chapter. Also this chapter provides guidance on an alternative displacement-based analysis procedure for evaluation of existing rectangular and circular towers. Information on seismic analysis for preliminary design or screening evaluation of free standing intake tower are also provided in this document. The application of a two-mode approximate procedure is recommended to account for the dynamic characteristics of the tower structure. Additional guidance is provided to determine hydrodynamic added masses reflecting the influence of the water inside and outside the tower. This document also contains guidelines for investigating the rotational stability of intake towers.

6. RESPONSE-SPECTRUM ANALYSIS

Comprehensive technical guidelines regarding the application of response-spectrum procedures for seismic analysis of concrete hydraulic structures are presented in Engineer Manual 1110-2-6050, "Response Spectra and Seismic Analysis for Concrete Hydraulic Structures" (HQUSACE, 1999). This 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. 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.

7. TIME-HISTORY ANALYSIS

Recommendations for seismic evaluation using time-history procedures are provided in the USACE guidance document entitled "Time-History Dynamic Analysis of Concrete Hydraulic Structures" (HQUSACE, 2000). This document is the final stages of review and it is currently designated as Engineer Circular 1110-2-6051. These guidelines describe general procedures for the linear-elastic time-history dynamic analysis of concrete hydraulic structures. These structures present distinctive response characteristics when compared to other civil engineering structures, and the evaluation of their dynamic response is usually complicated by structure-foundation and structure-water interaction phenomena. The first chapter of this manual provides an overview of the seismic performance evaluation process for concrete hydraulic structures. Chapter 2 discusses the general methodology for their time-history dynamic analysis, including a general description of structural types, modeling aspects, water and foundation-rock interaction, energy absorption effects, and the ground acceleration time-histories required for each structural type. Chapter 3 focuses on the computational aspects regarding the solution of the equations of motion in both time and frequency domains. A general methodology for performance evaluation and qualitative estimation of the probable level of seismically induced damage is presented in Chapter 4, whereas Chapter 5 describes the procedures for development of earthquake input acceleration time-histories. The final chapter provides practical examples of time-history evaluation for major concrete hydraulic structures including a gravity dam, a concrete arch dam, an inclined intake tower, and a W-frame lock structure.

A main objective behind these guidelines was the development of a systematic methodology for seismic performance evaluation and qualitative damage estimation using the results from linear time-history analyses. A systematic interpretation of linear time-history results is presented in terms of local and global performance indices: demand-capacity ratio, cumulative inelastic duration, and spatial extent of overstressed regions. Several empirical performance criteria are defined in terms of these indices and they form the basis for the qualitative estimation of the level of damage. If the predicted performance falls within the specified limits, the seismically induced damage is expected to be minor or negligible and the results of the linear time-history analysis will be sufficient to characterize the performance. Otherwise, the structural damage is expected to be severe, and the accurate estimation of its extent and consequences should be carried out using an appropriate nonlinear model. As an example, Figure 1 shows the performance curve for concrete gravity dams. The USACE guidelines therefore provide the analyst with standard criteria that, along with the proper engineering judgment, allow him/her to ascertain whether a nonlinear dynamic analysis is needed.

8. STABILITY EVALUATION

Starting in 1997, USACE began to revise and consolidate their guidance on stability criteria with the goal of establishing standard criteria for use in the design and evaluation of the many various types of concrete structures common to Corps of Engineers civil works projects. This will achieved by a new guidance document "Stability Analysis of Concrete Structures", currently under technical review (HQUSACE, 2003b). In this context, "stability" refers to external global stability (sliding, overturning, and bearing).

This manual will consolidate and verify the types and combination of applied loads and the corresponding safety factors that will govern stability requirements for all concrete hydraulic structures. The process used to standardize factors of safety will be based on the premise that the traditional factors of safety specified for USACE concrete hydraulic structures, for the most part, provide adequate protection against stability failure. However, the standardization process will recognize that lower factors of safety can be assigned to those loads and loading conditions designated as unusual, or extreme because the probabilities of those loads and load conditions occurring during the life of the structure are significantly less than the probabilities for usual loading conditions. In addition, this guidance will incorporate the practice of assigning lower factors of safety to normal structures, as compared to those traditionally used for critical structures. The goal will be to generate a consistent set of safety factors that will account for loading probability, criticality of the structure, and availability of site information

In particular, this guidance document will recognize that evaluation of sliding stability represents a difficult aspect of the analysis, especially in those instances where the foundation is jointed, and where the strength properties vary throughout the foundation. The approach to evaluating sliding stability is based on the limit equilibrium method with the linear Mohr-Coulomb failure criterion as a basis for estimating maximum available shear strength. Because of the uncertainties associated with shear strength determination, uplift and ground motions a combination of experience and judgment is always necessary to appropriately determine the corresponding strength, drainage and seismic parameters.

As mentioned before, the analyses should be a performed in phases in accordance with requirements of ER 1110-2-1806. The seismic coefficient method, although it fails to account for the true dynamic characteristics of the structure-water-soil system, is convenient as the initial empirical method for estimating structural stability, and is often used as a tool to decide if dynamic analyses should be undertaken. Structures that meet stability requirements when evaluated by the seismic coefficient method are considered safe and no additional seismic stability analyses are required. Structures that fail to meet stability requirements when evaluated using this empirical procedure should not be necessarily regarded as unsafe or in need of stability retrofit. The failure to meet these requirements should justify the need for other dynamic analyses to realistically assess the demands placed on the structure and foundation during a major earthquake. From these advanced analyses, engineers can determine if the displacements and stresses experienced by the structure and foundation will place the structure at risk of a stability failure. In many instances, it is acceptable for sliding and rocking to occur at the base of the structure during extreme earthquake load conditions. Stability in such cases should be evaluated using dynamic analysis methods, and performance is ensured by limiting permanent displacements to acceptable levels.

9. ASSOCIATED R&D EFFORTS

In spite of continual major advances, serious gaps in the current knowledge base still exist in the areas of earthquake hazard estimation; site characterization; constitutive behavior and determination of material parameters for dynamic loads; behavior and strength characteristics of lift joints and dam-foundation interfaces. Improved procedures are also need to accomplish the appropriate calibration of fast advancing numerical methods based on actual field performance. These technical gaps might result in costly conservatism and less effective design and evaluation procedures. In order to address some of these issues, the recent update of USACE technical guidelines has been supported by the products from a multi-disciplinary research program. This research effort has also served to develop the in-house expertise required by the continuous advances in the field of dam earthquake engineering.

The accomplishments of the research program included the development of improved analysis procedures for the seismic evaluation of existing lightly reinforced concrete intake towers. A displacement-based procedure was developed that takes into account the characteristics of the main failure mode associated with these structures. The research involved extensive experimental efforts in the form of cyclic loading and shake-table tests performed on reduced-scale models of a typical intake tower. Other research efforts focused on the quantification of the available ductility in typical reinforced concrete hydraulic structures designed according to USACE guidance. These efforts also included experimental studies on reduced-scale models of structures such as a tainter gate pier and a typical retaining wall. The research work also focused on the development of numerical tools for the analysis and design of cantilever retaining walls based on Newmark analysis procedures.

Additional research studies were performed to generate benchmark experimental data to be used in calibration of numerical models predicting the seismic response of concrete gravity dams. These studies included a series of shake-table experiments conducted on a 1/20-scale model of the Koyna Dam that highlighted the non-linear characteristics of the observed response. The research program also addressed the important problem of the characterization of the energy absorption phenomena that occur at the bottom of the reservoir. These interaction phenomena have a significant effect on the predicted behavior of concrete dams. The research included collaboration and participation in several experimental efforts in the US and China.

10. CONCLUSIONS

Current USACE policy and guidance documents for seismic design and analysis of dams are less than ten years old and subject to periodic review and update. A significant number of comprehensive documents have been developed that provide the necessary framework for the technical work carried out at the different USACE districts and divisions. The available technical guidelines address the different types of dams and appurtenant structures under USACE responsibility. Ongoing research and development efforts performed at the USACE research facilities provide the necessary input for guidance development and update and stay abreast with the state-of-the art in seismic design.

11. ACKNOWLEDGEMENTS

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Table 1. Recommended analysis progression

Table E-1
Seismic Analysis Progression

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

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

[1] If the project proceeds directly from feasibility to plans and specifications stage, a seismic design memorandum will be required for all projects in zones 3 and 4, and projects for which a TH analysis is required.
[2] Seismic loading condition controls design of an unprecedented structure, or unusual configuration or adverse foundation conditions.
[3] Seismic loading controls the design requiring linear or nonlinear time-history analysis.
[4] RS may be used in seismic zones 3 and 4 for the feasibility and design memorandum phases of project development only if it can be demonstrated that phenomena sensitive to frequency content (such as soil-structure interaction and structure-reservoir interaction) can be adequately modeled in an RS.

Table 2. Stability and stress criteria for concrete gravity dams

Table 4-1
Stability and stress criteria

Load Condition	Resultant Location at Base	Minimum Sliding FS	Foundation Bearing Pressure	Concrete Stress: Compressive	Concrete Stress: Tensile
Usual	Middle 1/3	2.0	≤ allowable	$0.3\ f'_c$	0
Unusual	Middle 1/2	1.7	≤ allowable	$0.5\ f'_c$	$0.6\ f_c'^{2/3}$
Extreme	Within base	1.3	≤ 1.33 × allowable	$0.9\ f'_c$	$1.5\ f_c'^{2/3}$

Note: f'_c is 1-year unconfined compressive strength of concrete. The sliding factors of safety (*FS*) are based on a comprehensive field investigation and testing program. Concrete allowable stresses are for static loading conditions.

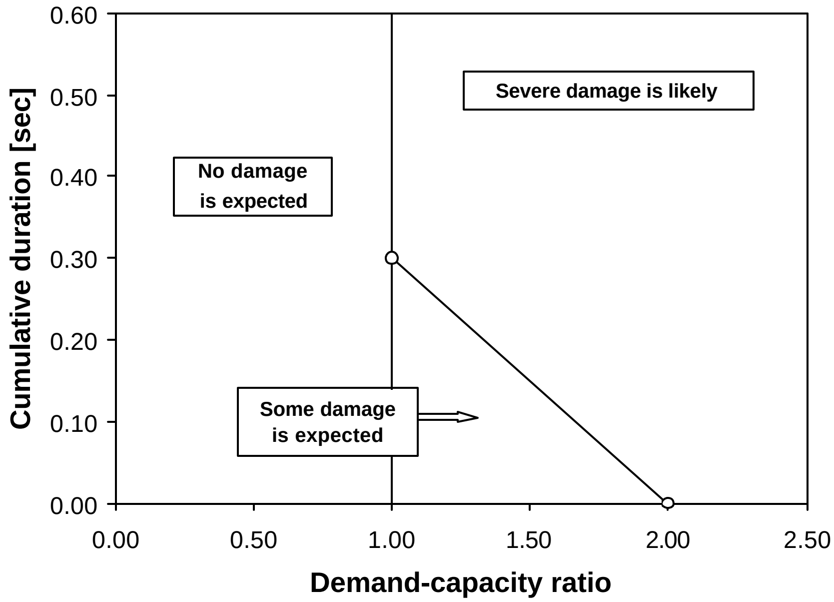

Figure 1. Performance curve for concrete gravity dams