Chapter 11
Analysis and Design

11-1. General

This chapter addresses the criteria, procedures, and parameters necessary for the analysis and design of the foundation system and the dam structure. Design of the project involves in-depth study of soil/structure interaction, stability analysis, and structural analysis.

11-2. Structural Analysis

a. General. A dam typically consists of a series of 3-D concrete structures (monoliths) surrounded by soil/silt, rock, and water. These structures are founded on either rock, soil, or piles and are subjected to a variety of external and internal soil and water loads.

b. Two-dimensional (2-D) analysis. An analysis of a 2-D slice through a monolith can reliably indicate the behavior of the monolith under the following conditions:

(1) When the cross-section geometry of the structure, the soil and water conditions, the support conditions, and the other loading effects are constant throughout an extended length of the monolith.

(2) When a 2-D slice, obtained by passing parallel planes perpendicular to the longitudinal axis of the monolith, typifies adjacent slices and is sufficiently remote from any discontinuities in geometry and loading (i.e., the slice is in a state of plane strain).

c. Two-dimensional (2-D) frame analysis. Structural analysis of the dam component is based on the assumption that the various slabs, walls, etc., of the structure interact as elements (members) of a 2-D plane frame. Establishment of a plane frame representation of the structure requires designation of parts of the structure as flexible members connected at their ends to joints. While some regions of the structure may lend themselves to treatment as flexible members (i.e., beam bending elements), there are significant zones of mass concrete that cannot be assigned bending characteristics. For analysis purposes, these zones are assumed to be rigid. The location and extent of these rigid zones will depend on the type of monolith being analyzed. The size of these zones must be determined to obtain reliable indications of the behavior of the 3-D monolith using a frame model. The frame should be calibrated by determining rigid zone sizes to agree with the stress results from a finite element analysis using plane strain elements for a section with similar geometry.

d. Three-dimensional (3-D) analysis. If the dam monolith geometry and/or loading does not meet the above requirements for a 2-D frame analysis, a 3-D finite element computer model should be used to analyze the monolith. Guidance on modeling of structure for linear elastic finite element analysis is provided in other Corps documents.

e. Seismic. Earthquake-induced ground motion effects must be considered in the analysis and design of navigation dam structures. The structures must be designed for the inertial forces from the structure mass combined with hydrodynamic pressures. These forces should be combined with any dynamic soil pressures generated within the backfill. Linearly elastic procedures used in design include the response spectrum analysis and the time history analysis.

(1) Seismic coefficient method. Traditional design practice based on the seismic coefficient method failed to account for the dynamic response characteristics of the soil-structure-water system. Dams designed by the seismic coefficient methods may not be adequately proportioned or reinforced to resist forces generated during a major earthquake. Therefore, this approach should be used only as a simple, preliminary means of checking a new design or an existing structure for seismic susceptibility. It should not be used as a final analysis procedure for controlling member proportions or for remedial design (with the exception of those cases where extensive results or comparisons of previously designed or evaluated structures are available).

(2) Response spectrum analysis. A response spectrum is a plot of the maximum response of a series of single-degree-of-freedom (SDOF) systems with varying periods or frequencies. A response spectrum analysis can provide an analysis procedure that partially accounts for the dynamic structural properties of the system. The response spectrum analysis can be accomplished by either a finite element procedure or a frame analysis. Results from these procedures provide only the *absolute* maximum stresses and forces due to the methods of combining modal responses.

(3) Time history analysis. The exact time history of a response quantity can be produced using this technique; therefore, an exact sign-dependent stress distribution can be found at any given time. However, a digitized design earthquake record for the site is needed, and a significant

computing effort is required for the numerical integration of the differential equation of motion using small time steps.

(4) Guidance. A detailed description of the response spectrum and the time history analysis is provided in ETL 1110-2-365.

f. Nonlinear incremental structural analysis (NISA). A NISA should be conducted on massive concrete structures if it will help achieve cost savings, develop more reliable designs for structures that have exhibited unsatisfactory behavior in the past, or predict behavior in structures for which a precedent has not been set. A NISA first requires that a time-dependent heat transfer analysis be performed. Further discussion on NISA is included in Chapter 12.

11-3. Foundation Design and Soil/Structure Interaction

a. Type of foundation. Another critical aspect in the design of navigation dams involves determining the appropriate foundation type. The foundation conditions often influence the site selection for a navigation lock project. The foundation characteristics should therefore be determined for each tentative site at an early stage of the investigation. These characteristics are usually determined by using available data and a minimum of foundation exploration. Sites chosen for further investigation should have foundation characteristics that would allow the dam structures to be constructed at a reasonable cost. The possible sites selected for study from a review of topography and hydraulics can thus be reduced to one or two after reviewing the site from a foundation and navigation standpoint. Final site selection requires extensive foundation exploration of the remaining sites under consideration. Before a pile foundation is selected, the foundation characteristics must be well-defined and a sufficient analysis of them must be made.

b. Foundation pressures (compatible deformations). Foundation pressures depend on the type of foundation material, the nature of the loading, and the size and shape of the monolith. For gravity-type monoliths (due to their rigidity), a linear distribution of base pressure can be assumed. However, for structural monoliths with a flexible base, the distribution of base pressure should be based on a soil/structure interaction analysis.

c. Bearing strength of soils. The bearing strength of soils and methods for its determination based on field and laboratory test data are described in EM 1110-1-1905. Another good reference for the calculation of bearing capacities is the program documentation for the CASE computer program CBEAR.

d. Earth pressures settlement. For a gravity structure, settlement analyses can be performed by following the principles set forth in EM 1110-1-1904.

e. Pile foundations.

(1) Determination of type of foundation--soil or pile.

(a) Determining the foundation type is probably the most critical aspect in the design of a dam. Because this decision will affect the project cost, the foundation type should be determined at the feasibility report stage of the project. This analysis should involve the use of a thorough subsurface investigation and testing program to define the soil strengths and parameters. For major structures an in-situ pile load test will normally be required.

(b) The criteria for selecting a soil or pile foundation are based on economic considerations and site-specific characteristics. Usually, a soil foundation is more economical if special measures (deeper excavation, elaborate pressure relief system, etc.) are not required. In addition, the structure on a soil foundation must satisfy stability requirements for sliding and overturning, as well as resisting uplift (flotation) and earthquake forces. At some sites, liquefaction of the foundation in the event of an earthquake becomes a determining factor in selecting the foundation type. Differential settlements between monoliths should also be considered in determining whether a soil or pile foundation will be used. If expensive special measures are required to make a soil foundation suitable for use, then a pile foundation should be studied and its cost compared to the cost of a soil foundation. The piling selection process should consider all reasonable types of piling, the site's geotechnical conditions, availability of material, construction limitations, and economics. The estimated quantities of piling can be based on minimum spacing and approximate lateral and vertical capacities for one or two typical monoliths. The most cost-effective type of pile foundation that satisfies engineering requirements is thus determined for comparison to the soil foundation. Computer programs such as CPGA (rigid base) or CWFRAME (flexible base) or other finite-element programs are useful for designing pile foundations. The final decision between a soil and a pile foundation is then based on a cost comparison using these refined pile quantities.

(2) Design guidance. Detailed design guidance for pile foundations is contained in EM 1110-2-2906.

f. Design considerations. Dowels or reinforcing bars can be used to prevent differential movement between monoliths. These may be bonded, bonded on one side, or greased on each side of the joint, and they may be post-tensioned. The reinforcing should be detailed to facilitate construction and so that it is not exposed to water in the joint. See paragraph 9-16*b* for a discussion of joint loads.