Chapter 4
General Design Considerations

4-1. General

a. Embankment dams. Dams have become an integral part of the Nation's infrastructure and play a significant and beneficial role in the development and management of water in river basins. Because of the wide variations in geologic settings in river basins, embankment dams will continue to provide the economic solutions for multipurpose projects. The design of an embankment dam is complex because of the unknowns of the foundation and materials available for construction. Past experience confirms that embankment dams can easily be "tailor-made" to fit the geologic site conditions and operational requirements for a project. There have been significant improvements in the design and construction practices and procedures for embankment dams. This trend will continue as more experience is gained from the actual performance of embankment dams under the full range of loading. Experience and judgment have always played a significant role in the design of embankment dams. The detailed analyses should be performed using a range of variables to allow an understanding of the sensitivity of the particular analysis to the material properties and the geometric configuration. Comparisons of actual versus predicted performance related to the most likely failure modes of a dam give the designers information to validate their experience and judgment.

b. Causes of failure.

(1) Since the failure of the Buffalo Creek Dam in West Virginia in 1972, there has been a considerable effort in the area of dam safety that created the inventory and developed a comprehensive dam safety program that included guidelines for inspection and evaluation and inspections to provide the governors with the status and condition of dams within their state. This effort was strengthened in 1996, when Public Law 104-303 established the National Dam Safety Program under the coordination of the Federal Emergency Management Agency (FEMA).

(2) An understanding of the causes of failure is a critical element in the design and construction process for new dams and for the evaluation of existing dams. The primary cause of failure of embankment dams in the United States is overtopping as a result of inadequate spillway capacity. The next most frequent cause is seepage and piping. Seepage through the foundation and abutments is a greater problem than through the dam. Therefore, instrumentation in the abutments and foundation as well as observation and surveillance is the best method of detection. Other causes are slides (in the foundation and/or the embankment and abutments) and leakage from the outlet works conduit. In recent years, improved methods of stability analyses and better tools for site characterization and obtaining an understanding of material properties have reduced the frequency of failures from sliding stability.

c. Failure mode analysis.

(1) New projects. The project requirements, geologic assessment and site characterization, unique project features, loading conditions, and the design criteria for the dam and appurtenant structures are the basis for the detailed project design. As the design progresses, an assessment of the materials distribution is made and a preliminary embankment section is established. The next step is to conduct a preliminary failure mode analysis. This consists of identifying the most likely modes of failure for the dam, foundation, abutments, and appurtenant structures as designed. It is important to have a thorough understanding of the historic causes of failure and their respective probabilities of occurrence. The failure modes should then be listed in the order of their likelihood of occurrence. During the final design, the failure modes are reviewed and updated. The results will be used to establish expected performance; identify the key parameters, measurements, and observations (performance parameters) needed to monitor performance of the dam; and establish the threshold

of unsatisfactory performance. The results of this failure mode analysis will also provide input to the identification and notification subplan of the project Emergency Action Plan. During the final design, the performance parameters that will be used to measure and monitor the performance of the dam, foundation, abutments, and appurtenant structures are established. These performance criteria, generally expressed in terms of design limits and threshold performance limits, are refined as the project proceeds through more detailed levels of design, including design changes necessitated by site conditions more fully revealed during construction.

(2) Existing projects. A similar failure mode analysis should be performed on all existing dams. The input is the original design criteria that were used, the loading and performance history, previous modifications, and current design criteria.

d. Critical information for flood control operation. The successful operation of multipurpose projects during the flood control mission requires an understanding of the project features, their past performance, anticipated performance, and the ability to unload should indications of unsatisfactory performance develop. The critical information needed by the designer, operator, and dam safety officer is as follows:

(1) Critical project information.

(a) Results of the failure mode analysis.

(b) Performance parameters.

(c) Threshold for increased monitoring.

(d) Threshold for any potential changes in reservoir operation to ensure safety.

- Return period of the event.

- Corresponding storage available.

(e) Drawdown capabilities.

- Full bank discharge (the discharge from the project that remains within the downstream riverbank. This is controlled by the lowest elevation of the top of river bank).

- Full discharge (the maximum discharge from the project with the reservoir at spillway crest. Generally corresponds to minimum tailwater).

(2) Information needed prior to and during an event.

(a) Projected inflow.

(b) Corresponding reservoir levels and storage.

(c) Predicted performance for the projected reservoir levels.

(d) Reports from onsite monitoring.

4-2. Freeboard

a. Vertical distance. The term freeboard is applied to the vertical distance of a dam crest above the maximum reservoir water elevation adopted for the spillway design flood. The freeboard must be sufficient to prevent overtopping of the dam by wind setup, wave action, or earthquake effects. Initial freeboard must allow for subsequent loss in height due to consolidation of embankment and/or foundation. The crest of the dam will generally include overbuild to allow for postconstruction settlements. The top of the core should also be overbuilt to ensure that it does not settle below its intended elevation. Net freeboard requirements (exclusive of earthquake considerations) can be determined using the procedures described in Saville, McClendon, and Cochran (1962).

b. Elevation. In seismic zones 2, 3, and 4, as delineated in Figures A-1 through A-4 of ER 1110-2-1806, the elevation of the top of the dam should be the maximum determined by either maximum water surface plus conventional freeboard or flood control pool plus 3 percent of the height of the dam above streambed. This requirement applies regardless of the type of spillway.

4-3. Top Width

The top width of an earth or rock-fill dam within conventional limits has little effect on stability and is governed by whatever functional purpose the top of the dam must serve. Depending upon the height of the dam, the minimum top width should be between 25 and 40 ft. Where the top of the dam is to carry a public highway, road and shoulder widths should conform to highway requirements in the locality with consideration given to requirements for future needs. The embankment zoning near the top is sometimes simplified to reduce the number of zones, each of which requires a minimum width to accommodate hauling and compaction equipment.

4-4. Alignment

Axes of embankments that are long with respect to their heights may be straight or of the most economical alignment fitting the topography and foundation conditions. Sharp changes in alignment should be avoided because downstream deformation at these locations would tend to produce tension zones which could cause concentration of seepage and possibly cracking and internal erosion. The axes of high dams in narrow, steep-sided valleys should be curved upstream so that downstream deflection under water loads will tend to compress the impervious zones longitudinally, providing additional protection against the formation of transverse cracks in the impervious zones. The radius of curvature forming the upstream arching of the dam in narrow valleys generally ranges from 1,000 to 3,000 ft.

4-5. Embankment

Embankment sections adjacent to abutments may be flared to increase stability of sections founded on weak soils. Also, by flaring the core, a longer seepage path is developed beneath and around the embankment.

4-6. Abutments

a. Alignments. Alignments should be avoided that tie into narrow ridges formed by hairpin bends in the river or that tie into abutments that diverge in the downstream direction. Grouting may be required to decrease seepage through the abutment (see paragraph 3-1*c*). Zones of structurally weak materials in abutments, such as weathered overburden and talus deposits, are not uncommon. It may be more economical to flatten embankment slopes to attain the desired stability than to excavate weak materials to a firm foundation. The horizontal permeability of undisturbed strata in the abutment may be much greater than the permeability of the compacted fill in the embankment; therefore, it may be possible to derive considerable benefit in seepage control from the blanketing effects of flared upstream embankment slopes. The design of a transition from the normal embankment slopes to flattened slopes is influenced by stability of sections founded on the weaker foundation materials, drainage provisions on the slopes and within the embankment, and the desirability of making a gradual transition without abrupt changes of section. Adequate surface drainage to avoid erosion should be provided at the juncture between the dam slope and the abutment.

b. Abutment slopes. Where abutment slopes are steep, the core, filter, and transition zones of an embankment should be widened at locations of possible tension zones resulting from different settlements. Widening of the core may not be especially effective unless cracks developing in it tend to close. Even if cracks remain open, a wider core may tend to promote clogging. However, materials in the filter and transition zones are usually more self-healing, and increased widths of these zones are beneficial. Whenever possible, construction of the top 25 ft of an embankment adjacent to steep abutments should be delayed until significant embankment and foundation settlement have occurred.

c. Settlement. Because large differential settlement near abutments may result in transverse cracking within the embankment, it may be desirable to use higher placement water contents (see paragraph 7-8*a*) combined with flared sections.

4-7. Performance Parameters

a. Performance parameters are defined as those key indicators that are used to monitor and predict the response of the dam and foundation to the full range of loading for the critical conditions at a project. They document the performance history beginning with predictions made during design and construction through the actual performance based on observations and instrumentation. They also provide the historical data, quantitative values for specified limits, and complete records of performance for use in conventional evaluations and risk assessments. Performance parameters are characterized as follows:

- Optimizes and refines existing practices and procedures (not a new requirement).
- Establishes threshold limits for increased surveillance.
- Provides continuity over project life.
- Provides basis for emergency identification and response subplan of the project Emergency Action Plan.
- Provides the basic information and input for the justification of any required structural modifications or operational changes to the project.

b. Project requirements, loading conditions, unique project features, the initial geologic assessment and site characterization along with the design criteria for the dam and appurtenant structures are the basis for establishing project performance criteria on a preliminary level during the earliest phases of design. These performance criteria, generally expressed in terms of design limits and threshold performance limits, are refined as the project proceeds through more detailed levels of design, including design changes necessitated by site conditions more fully revealed during construction. Performance parameters continue to be refined and updated throughout the operational life of the project as information acquired from instrumentation, visual observation, and surveillance is evaluated.

c. In summary, this process is a comprehensive and simple summarization of the existing USACE philosophy for design, construction, and operation of civil works projects. It represents a systematic approach to the evaluation and assessment of project performance based on historical data and loading, and the projected performance for the remaining range of loading. This process provides an insight into the actual behavior of the dam and appurtenant structures to the designer, operator, and regulator. When documented and updated in the periodic inspection report, it provides continuity over the project life for routine evaluations and proposed modifications to project purposes. This process is an important part of the project turnover plan, which is prepared for projects formulated and constructed as a result of the Water Resources Development Act of 1986. Guidance on the development and use of performance parameters is provided in Appendix E.

4-8. Earthquake Effects

a. General. The embankment and critical appurtenant structures should be evaluated for seismic stability. The method of analysis is a function of the seismic zone as outlined in ER 1110-2-1806. Damsites over active faults should be avoided if at all possible. For projects located near or over faults in earthquake areas, special geological and seismological studies should be performed. Defensive design features for the embankment and structures as outlined in ER 1110-2-1806 should be used, regardless of the type of analyses performed. For projects in locations of strong seismicity, it is desirable to locate the spillway and outlet works on rock rather than in the embankment or foundation overburden.

b. Defensive design measures. Defensive design measures to protect against earthquake effects are also used for locations where strong earthquakes are likely, and include the following to increase the safety of the embankment:

- Ensuring that foundation sands have adequate densities (at least 70 percent relative density).
- Making the impervious zone more plastic.
- Enlarging the impervious zone.
- Widening the dam crest.
- Flattening the embankment slopes.
- Increasing the freeboard.
- Increasing the width of filter and transition zones adjacent to the core.
- Compacting shell sections to higher densities.
- Flaring the dam at the abutments

4-9. Coordination Between Design and Construction

a. Introduction. Close coordination between design and construction personnel is necessary to thoroughly orient the construction personnel as to the project design intent, ensure that new field information acquired during construction is assimilated into the design, and ensure that the project is constructed according to the intent of the design. This is accomplished through the report on engineering considerations and instructions to field personnel, preconstruction orientation for the construction engineers by the designers, and required visits to the site by the designers.

b. Report on engineering considerations and instructions to field personnel. To ensure that the field personnel are aware of the design assumptions regarding field conditions, design personnel (geologists, geotechnical engineers, structural engineers, etc.) will prepare a report entitled, "Engineering Considerations and Instructions for Field Personnel." This report should explain the concepts, assumptions, and special details of the embankment design as well as detailed explanations of critical sections of the contract documents. Instruction for the field inspection force should include the necessary guidance to provide adequate Government Quality Assurance Testing. This report should be augmented by appropriate briefings, instructional sessions, and laboratory testing sessions (ER 1110-2-1150).

c. Preconstruction orientation. Preconstruction orientation for the construction engineers by the designers is necessary for the construction engineers to be aware of the design philosophies and assumptions regarding site conditions and function of project structures, and understand the design engineers' intent concerning technical provisions in the P&S.

d. Construction milestones which require visit by designers. Visits to the site by design personnel are required to ensure the following (ER 1110-2-112, ER 1110-2-1150):

(1) Site conditions throughout the construction period are in conformance with design assumptions and principles as well as contract P&S.

(2) Project personnel are given assistance in adapting project designs to actual site conditions as they are revealed during construction.

(3) Any engineering problems not fully assessed in the original design are observed, evaluated, and appropriate action taken.

e. Specific visits. Specifically, site visits are required when the following occur (ER 1110-2-112):

(1) Excavation of cutoff trenches, foundations, and abutments for dams and appurtenant structures.

(2) Excavation of tunnels.

(3) Excavation of borrow areas and placement of embankment dam materials early in the construction period.

(4) Observation of field conditions that are significantly different from those assumed during design.

4-10. Value Engineering Proposals

The Corps of Engineers has several cost-saving programs. One of these programs, Value Engineering (VE), provides for a multidiscipline team of engineers to develop alternative designs for some portion of the project. The construction contractor can also submit VE proposals. Any VE proposal affecting the design is to be evaluated by design personnel prior to implementation to determine the technical adequacy of the proposal. VE proposals must not adversely affect the long-term performance or condition of the dam.

4-11. Partnering Between the Owner and Contractor

Partnering is the creation of an owner-contractor relationship that promotes achievement of mutually beneficial goals. By taking steps before construction begins to change the adversarial mindset, to recognize common interests, and to establish an atmosphere of trust and candor in communications, partnering helps to develop a cooperative management team. Partnering is not a contractual agreement and does not create any legally enforceable rights or duties. There are three basic steps involved in establishing the partnering relationship:

a. Establish a new relationship through personal contact.

b. Craft a joint statement of goals and establish common objectives in specific detail for reaching the goals.

c. Identify specific disputes and prevention processes designed to head off problems, evaluate performance, and promote cooperation.

Partnering has been used by the Mobile District on Oliver Lock and Dam replacement and by the Portland District on Bonneville Dam navigation lock. Detailed instructions concerning the partnering process are available in Edelman, Carr, and Lancaster (1991).

4-12. Modifications to Embankment Dams to Accommodate New or Revised Inflow Design Floods or to Provide Additional Storage for Water Supply or Other Purposes

a. General. As part of the continuing inspection, review, and evaluation of a dam, the inflow design flood (IDF) must be reviewed every 5 years and updated as appropriate. This can also be done as part of a watershed or river basin study or program. The increased development and expanding population in the Nation's watersheds have created a definite need to develop additional water supply. In many areas the current infrastructure cannot meet these needs. The increase in urban development has also had a negative impact on water quality. As a result, a customer or sponsor may request that additional storage for water supply or other purposes be provided at existing USACE projects.

b. Accommodating a new or revised IDF. The first step in this process is to review and update the existing IDF and then compare it with current hydrometeorological criteria. The hazard potential of the dam should also be reviewed and updated at this time. Once this is done, the risk of failure from spillway erosion and/or overtopping of the embankment can be assessed. This is best accomplished by examination of several reservoir levels from spillway crest to several feet over the top of dam. If the project cannot safely pass the IDF, a modification in accordance with State and/or Federal regulations is required. Typically, these are significant modifications in terms of cost and impacts on the environment.

c. Providing additional storage for water supply or other purposes. The simplest and most cost-effective method to obtain the quantities needed in a region is to add additional storage at existing dams. The first step in this process is to review the authorized project purposes and the plan of reservoir regulation. The requested change in active storage must then be reviewed and the project discharge capability evaluated. This will result in a new top of flood control pool. The next step is to perform a technical evaluation and environmental assessment of the alternatives that increase discharge capacity for events to the IDF for the new active storage.

d. Alternatives for modifying embankment dams for an IDF and providing additional storage. With the new or updated inflow and/or request for additional active storage and regulatory guidance, the following alternative plans to increase spillway discharge capacity are normally considered:

(1) An auxiliary spillway.

(2) Lined overflow section of the dam.

(3) Raising of the dam.

(4) Modification to the existing spillway.

(5) Combinations of an auxiliary spillway, a modification to the existing spillway, and raising the top of dam.

e. Environmental considerations. Evaluating these alternatives presents the design engineer with real challenges and opportunities. The goal is to select the most cost-effective technical and environmentally responsible alternative for the modification. The cost estimates for each alternative must reflect realistic costs to mitigate the impacts on the natural environment. The environmental considerations attempt to minimize damage to the environment by

(1) Minimal or no construction outside of the footprint of the dam and spillway.

(2) Minimal or no disturbance to ground cover and erosion during and after construction.

(3) Minimization of erosion during construction.

(4) Provision of adequate control of sedimentation.

(5) Minimization of impact on water quality during construction.

(6) Minimal or no impact during future operation.

f. Technical evaluation and environmental assessment of the alternatives.

(1) While an auxiliary spillway provides flexibility to obtain maximum discharge capacities, it requires significant construction and disturbance to the environment. A lined overflow section offers considerable discharge, but requires excavation in the embankment and loss of vegetation and ground cover. Raising any dam over about 3 ft results in a higher upstream water surface and requires borrow excavation for the required embankment fill. A modification to the existing spillway is usually the most cost effective and results in minimal disturbance to the surrounding environment. Where additional freeboard is needed, the combination of a 3-ft raising of the dam along with a modification to the existing spillway is also a cost-effective solution. Each of these alternatives should be evaluated and compared by cost and environmental consequences. Guidance on raising embankment dams is given in Appendix F.

(2) Recent hydraulic model tests on labyrinth fusegates have verified that a "fusegate system" installed in an existing spillway is a cost-effective and reliable solution to accommodate the IDF or to provide additional storage to the project. This system provides a leveraged discharge for a given width and allows the designer to select the operating reservoir levels. This system can be used for both embankment and concrete dam projects. It is also environmentally responsible since it does not require construction outside the footprint of the existing spillway.

(3) A comprehensive environmental assessment must be made for all of the alternatives considered. This assessment evaluates the conditions and impacts for both the "with" and "without" modification at the dam, and is accomplished in accordance with State and Federal regulations. The extent and permanence of any detrimental effects of the modification on the project and watershed are critical parts of this assessment. Public involvement in the proposed modification is also part of this process. Each alternative should be assessed with the following environmental criteria:

- Avoids adverse impacts to the environment.

- Mitigates any unavoidable environmental impacts.

- Maintains water quality and the ecosystem during and after the modification.

- Achieves no net loss in environmental values and functions.