Chapter 3
Design Criteria

3-1. General

a. Applicability. This chapter provides guidance for analysis conditions and factors of safety for the design of slopes. Required factors of safety for embankment dams are based on design practice developed and successfully employed by the USACE over several decades. It is imperative that all phases of design be carried out in accord with established USACE methods and procedures to ensure results consistent with successful past practice.

(1) Because of the large number of existing USACE dams and the fact that somewhat different considerations must be applied to existing dams as opposed to new construction, appropriate stability conditions and factors of safety for the analysis of existing dam slopes are discussed as well.

(2) The analysis procedures recommended in this manual are also appropriate for analysis and design of slopes other than earth and rock-fill dams. Guidance is provided for appropriate factors of safety for slopes of other types of embankments, excavated slopes, and natural slopes.

b. Factor of safety guidance. Appropriate factors of safety are required to ensure adequate performance of slopes throughout their design lives. Two of the most important considerations that determine appropriate magnitudes for factor of safety are uncertainties in the conditions being analyzed, including shear strengths and consequences of failure or unacceptable performance.

(1) What is considered an acceptable factor of safety should reflect the differences between new slopes, where stability must be forecast, and existing slopes, where information regarding past slope performance is available. A history free of signs of slope movements provides firm evidence that a slope has been stable under the conditions it has experienced. Conversely, signs of significant movement indicate marginally stable or unstable conditions. In either case, the degree of uncertainty regarding shear strength and piezometric levels can be reduced through back analysis. Therefore, values of factors of safety that are lower than those required for new slopes can often be justified for existing slopes.

(2) Historically, geotechnical engineers have relied upon judgment, precedent, experience, and regulations to select suitable factors of safety for slopes. Reliability analyses can provide important insight into the effects of uncertainties on the results of stability analyses and appropriate factors of safety. However, for design and construction of earth and rock-fill dams, required factors of safety continue to be based on experience. Factors of safety for various types of slopes and analysis conditions are summarized in Table 3-1. These are minimum required factors of safety for new embankment dams. They are advisory for existing dams and other types of slopes.

c. Shear strengths. Shear strengths of fill materials for new construction should be based on tests performed on laboratory compacted specimens. The specimens should be compacted at the highest water content and the lowest density consistent with specifications. Shear strengths of existing fills should be based on the laboratory tests performed for the original design studies if they appear to be reliable, on laboratory tests performed on undisturbed specimens retrieved from the fill, and/or on the results of in situ tests performed in the fill. Shear strengths of natural materials should be based on the results of tests performed on undisturbed specimens, or on the results of in situ tests. Principles of shear strength characterization are summarized in Appendix D.

Table 3-1
Minimum Required Factors of Safety: New Earth and Rock-Fill Dams

Analysis Condition[1]	Required Minimum Factor of Safety	Slope
End-of-Construction (including staged construction)[2]	1.3	Upstream and Downstream
Long-term (Steady seepage, maximum storage pool, spillway crest or top of gates)	1.5	Downstream
Maximum surcharge pool[3]	1.4	Downstream
Rapid drawdown	1.1-1.3[4,5]	Upstream

[1] For earthquake loading, see ER 1110-2-1806 for guidance. An Engineer Circular, “Dynamic Analysis of Embankment Dams,” is still in preparation.

[2] For embankments over 50 feet high on soft foundations and for embankments that will be subjected to pool loading during construction, a higher minimum end-of-construction factor of safety may be appropriate.

[3] Pool thrust from maximum surcharge level. Pore pressures are usually taken as those developed under steady-state seepage at maximum storage pool. However, for pervious foundations with no positive cutoff steady-state seepage may develop under maximum surcharge pool.

[4] Factor of safety (FS) to be used with improved method of analysis described in Appendix G.

[5] FS = 1.1 applies to drawdown from maximum surcharge pool; FS = 1.3 applies to drawdown from maximum storage pool.

For dams used in pump storage schemes or similar applications where rapid drawdown is a routine operating condition, higher factors of safety, e.g., 1.4-1.5, are appropriate. If consequences of an upstream failure are great, such as blockage of the outlet works resulting in a potential catastrophic failure, higher factors of safety should be considered.

(1) During construction of embankments, materials should be examined to ensure that they are consistent with the materials on which the design was based. Records of compaction, moisture, and density for fill materials should be compared with the compaction conditions on which the undrained shear strengths used in stability analyses were based.

(2) Particular attention should be given to determining if field compaction moisture contents of cohesive materials are significantly higher or dry unit weights are significantly lower than values on which design strengths were based. If so, undrained (UU, Q) shear strengths may be lower than the values used for design, and end-of-construction stability should be reevaluated. Undisturbed samples of cohesive materials should be taken during construction and unconsolidated-undrained (UU, Q) tests should be performed to verify end-of-construction stability.

d. Pore water pressure. Seepage analyses (flow nets or numerical analyses) should be performed to estimate pore water pressures for use in long-term stability computations. During operation of the reservoir, especially during initial filling and as each new record pool is experienced, an appropriate monitoring and evaluation program must be carried out. This is imperative to identify unexpected seepage conditions, abnormally high piezometric levels, and unexpected deformations or rates of deformations. As the reservoir is brought up and as higher pools are experienced, trends of piezometric levels versus reservoir stage can be used to project piezometric levels for maximum storage and maximum surcharge pool levels. This allows comparison of anticipated actual performance to the piezometric levels assumed during original design studies and analysis. These projections provide a firm basis to assess the stability of the downstream slope of the dam for future maximum loading conditions. If this process indicates that pore water pressures will be higher than those used in design stability analyses, additional analyses should be performed to verify long-term stability.

e. Loads on slopes. Loads imposed on slopes, such as those resulting from structures, vehicles, stored materials, etc. should be accounted for in stability analyses.

3-2. New Embankment Dams

a. Earth and rock-fill dams. Minimum required factors of safety for design of new earth and rock-fill dams are given in Table 3-1. Criteria and procedures for conducting each analysis condition are found in Chapter 2 and the appendices. The factors of safety in Table 3-1 are based on USACE practice, which includes established methodology with regard to subsurface investigations, drilling and sampling, laboratory testing, field testing, and data interpretation.

b. Embankment cofferdams. Cofferdams are usually temporary structures, but may also be incorporated into a final earth dam cross section. For temporary structures, stability computations only must be performed when the consequences of failure are serious. For cofferdams that become part of the final cross section of a new embankment dam, stability computations should be performed in the same manner as for new embankment dams.

3-3. Existing Embankment Dams

a. Need for reevaluation of stability. While the purpose of this manual is to provide guidance for correct use of analysis procedures, the use of slope stability analysis must be held in proper perspective. There is danger in relying too heavily on slope stability analyses for existing dams. Appropriate emphasis must be placed on the often difficult task of establishing the true nature of the behavior of the dam through field investigations and research into the historical design, construction records, and observed performance of the embankment. In many instances monitoring and evaluation of instrumentation are the keys to meaningful assessment of stability. Nevertheless, stability analyses do provide a useful tool for assessing the stability of existing dams. Stability analyses are essential for evaluating remedial measures that involve changes in dam cross sections.

(1) New stability analysis may be necessary for existing dams, particularly for older structures that did not have full advantage of modern state-of-the-art design methods. Where stability is in question, stability should be reevaluated using analysis procedures such as Spencer's method, which satisfy all conditions of equilibrium.

(2) With the force equilibrium procedures used for design analyses of many older dams, the calculated factor of safety is affected by the assumed side force inclination. The calculated factor of safety from these procedures may be in error, too high or too low, depending upon the assumptions made.

b. Analysis conditions. It is not necessary to analyze end-of-construction stability for existing dams unless the cross section is modified. Long-term stability under steady-state seepage conditions (maximum storage pool and maximum surcharge pool), and rapid drawdown should be evaluated if the analyses performed for design appear questionable. The potential for slides in the embankment or abutment slope that could block the outlet works should also be evaluated. Guidance for earthquake loading is provided in ER 1110-2-1806, and an Engineer Circular, "Dynamic Analysis of Embankment Dams," is in draft form.

c. Factors of safety. Acceptable values of factors of safety for existing dams may be less than those for design of new dams, considering the benefits of being able to observe the actual performance of the embankment over a period of time. In selecting appropriate factors of safety for existing dam slopes, the considerations discussed in Section 3-1 should be taken into account. The factor of safety required will have an effect on determining whether or not remediation of the dam slope is necessary. Reliability analysis techniques can be used to provide additional insight into appropriate factors of safety and the necessity for remediation.

3-4. Other Slopes

a. Factors of safety. Factors of safety for slopes other than the slopes of dams should be selected consistent with the uncertainty involved in the parameters such as shear strength and pore water pressures that affect the calculated value of factor of safety and the consequences of failure. When the uncertainty and the consequences of failure are both small, it is acceptable to use small factors of safety, on the order of 1.3 or even smaller in some circumstances. When the uncertainties or the consequences of failure increase, larger factors of safety are necessary. Large uncertainties coupled with large consequences of failure represent an unacceptable condition, no matter what the calculated value of the factor of safety. The values of factor of safety listed in Table 3-1 provide guidance but are not prescribed for slopes other than the slopes of new embankment dams. Typical minimum acceptable values of factor of safety are about 1.3 for end of construction and multistage loading, 1.5 for normal long-term loading conditions, and 1.1 to 1.3 for rapid drawdown in cases where rapid drawdown represents an infrequent loading condition. In cases where rapid drawdown represents a frequent loading condition, as in pumped storage projects, the factor of safety should be higher.

b. Levees. Design of levees is governed by EM 1110-2-1913. Stability analyses of levees and their foundations should be performed following the principles set forth in this manual. The factors of safety listed in Table 3-1 provide guidance for levee slope stability, but the values listed are not required.

c. Other embankment slopes. The analysis procedures described in this manual are applicable to other types of embankments, including highway embankments, railway embankments, retention dikes, stockpiles, fill slopes of navigation channels, river banks in fill, breakwaters, jetties, and sea walls.

(1) The factor of safety of an embankment slope generally decreases as the embankment is raised, the slopes become higher, and the load on the foundation increases. As a result, the end of construction usually represents the critical short-term (undrained) loading condition for embankments, unless the embankment is built in stages. For embankments built in stages, the end of any stage may represent the most critical short-term condition. With time following completion of the embankment, the factor of safety against undrained failure will increase because of the consolidation of foundation soils and dissipation of construction pore pressures in the embankment fill.

(2) Water ponded against a submerged or partially submerged slope provides a stabilizing load on the slope. The possibility of low water events and rapid drawdown should be considered.

d. Excavated slopes. The analysis procedures described in this manual are applicable to excavated slopes, including foundation excavations, excavated navigation and river channel slopes, and sea walls.

(1) In principle, the stability of excavation slopes should be evaluated for both the end-of-construction and the long-term conditions. The long-term condition is usually critical. The stability of an excavated slope decreases with time after construction as pore water pressures increase and the soils within the slope swell and become weaker. As a result, the critical condition for stability of excavated slopes is normally the long-term condition, when increase in pore water pressure and swelling and weakening of soils is complete. If the materials in which the excavation is made are so highly permeable that these changes occur completely as construction proceeds, the end-of-construction and the long-term conditions are the same. These considerations lead to the conclusion that an excavation that would be stable in the long-term condition would also be stable at the end of construction.

(2) In the case of soils with very low permeability and an excavation that will only be open temporarily, the long-term (fully drained) condition may never be established. In such cases, it may be possible to excavate a slope that would be stable temporarily but would not be stable in the long term. Design for such a

condition may be possible if sufficiently detailed studies are made for design, if construction delays are unlikely, and if the observational method is used to confirm the design in the field. Such a condition, where the long-term condition is unstable, is inherently dangerous and should only be allowed where careful studies are done, where the benefits justify the risk of instability, and where failures are not life-threatening.

(3) Instability of excavated slopes is often related to high internal water pressures associated with wet weather periods. It is appropriate to analyze such conditions as long-term steady-state seepage conditions, using drained strengths and the highest probable position of the piezometric surface within the slope. For submerged and partially submerged slopes, the possibility of low water events and rapid drawdown should be considered.

e. Natural slopes. The analysis procedures in this manual are applicable to natural slopes, including valley slopes and natural river banks. They are also applicable to back-analysis of landslides in soil and soft rock for the purpose of evaluating shear strengths and/or piezometric levels, and analysis of landslide stabilization measures.

(1) Instability of natural slopes is often related to high internal water pressures associated with wet weather periods. It is appropriate to analyze such conditions as long-term, steady-state seepage conditions, using drained strengths and the highest probable position of the piezometric surface within the slope. For submerged and partially submerged slopes, the possibility of low water events and rapid drawdown should be considered.

(2) Riverbanks are subject to fluctuations in water level, and consideration of rapid drawdown is therefore of prime importance. In many cases, river bank slopes are marginally stable as a result of bank seepage, drawdown, or river current erosion removing or undercutting the toe of the slope.