Chapter 6
Stability Considerations and Analytical Methods

6-1. General

Both new and existing structures are constantly being examined to determine if they meet stability criteria. The traditional procedure is to evaluate sliding stability of these structures using the limit equilibrium method of analysis and to evaluate rotational stability using rigid body assumptions and bearing pressure distributions that vary linearly across the base. Soil and uplift loads on the structure are often based on simplifying assumptions. In the limit equilibrium method, only the stress state at failure is considered, usually as represented by the Mohr-Coulomb limit-state criterion. The simplified loads and the Mohr-Coulomb limit-state criterion are then used to obtain a single overall factor of safety against a sliding stability failure. This traditional approach is appropriate for many structures where it is difficult to predict just how a particular failure mechanism may develop. However, for existing structures where more is known about service state conditions and uplift pressures, it is possible to more precisely predict what stress changes must occur to develop a failure condition. The margin of safety can be more accurately determined when the path to failure, from initial stress conditions to limit state conditions, is known. This path to failure can be investigated using linear elastic and nonlinear finite-element numerical solutions and fracture mechanics concepts. Because the deformation of the structure and its foundation is considered in finite element analyses, and because the path to failure can be more realistically characterized through fracture mechanics, a more accurate assessment of safety can often be made using advanced analytical methods.

6-2. Traditional Methods

Traditional two-dimensional and three-dimensional, simplified, conservative stability analyses are used as the first step of a stability evaluation. Advanced analytical methods may be used to further investigate stability when the traditional methods indicate the structure is inadequate or marginal with respect to sliding stability or rotational stability.

a. *Two-dimensional analysis.* Two-dimensional stability analyses using traditional methods are suitable for the intermediate monoliths of structures that have uniform geometry and loading for their entire length and where the loads and resistance due to end effects are not transmitted across monolith joints. Many walls have variable height or loads along their length. Each monolith of such walls should be proportioned for stability at the low-end monolith joint, at the midpoint between monolith joints, and at the high-end monolith joint; the dimensions at different points along the wall should vary linearly between the sections for which the stability is checked.

b. *Three-dimensional analysis*. Some structures can not be suitably idealized as a two-dimensional structural system and therefore require a three-dimensional analysis. Examples of such structures include: nonoverflow monoliths at the ends of gravity dams, navigation-lock miter-gate monoliths, arch dams, and other structures having nonuniform geometry and/or loading. These types of structures, however, may still be analyzed using traditional methods with the following additional considerations.

(1) End effects. Figure 6-1 shows a plan and elevation of a short wall and the earth wedges that would be associated with sliding failure. However, frictional drag forces will exist on the active (driving) wedge faces abc and a'b'c', and on the passive (resisting) wedge faces edf and e'd'f' as well on the embedded end areas of the wall. These forces are generated by at-rest soil pressure on the end faces of the wedges and the wall, acting in conjunction with the internal soil friction. The frictional drag forces may be added to the numerator of Equation 5-1. When this resistance is used in conjunction with a multiple-wedge sliding analysis, as discussed in Chapter 2, $Ø_d$ (the developed value) should be used in lieu of Ø in calculations.

(2) Arch dams. Unlike a gravity dam, where stability is provided by the weight of the structural wedge, an arch dam's stability depends, not only on weight but to a much larger extent, upon arch action that transmits the imposed loads to the valley walls. Therefore, an evaluation of the foundation characteristics is required prior to laying out the dam. Following this procedure, the dam is designed so that the loads transmitted to the foundation will be within acceptable limits. In special instances artificial abutments (thrust blocks) may be used to increase the ability of the valley walls to resist these thrusts. Arch dams are constructed using monoliths in the same manner as

for gravity dams. The construction blocks or monoliths of double curvature arch dams may have a tendency to rotate upstream prior to completion. This tendency should be evaluated and a system of support should be evaluated, designed and included in the construction documents. The stability of these vertically cantilevered monoliths must be maintained at all stages of construction. EM 1110-2-2201 provides detailed information on site selection, stability requirements, design and construction criteria and procedures, methods of static and dynamic analysis, temperature studies, concrete testing requirements, foundation investigation, and instrumentation for use in the design of arch dams.

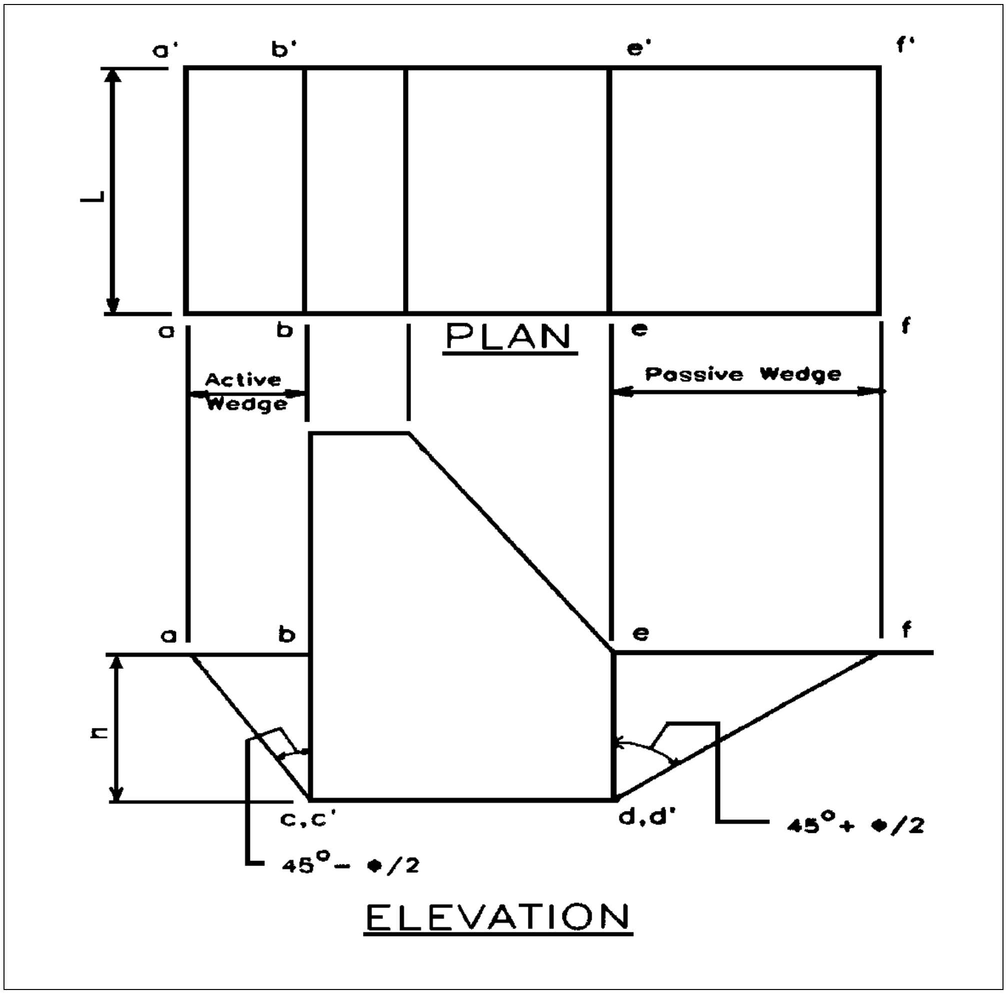

Figure 6-1. End effects on short wall

6-3. Advanced Analytical Analyses

Advanced analytical analyses can be used to gain a better understanding of structural behavior. However, the results obtained from such an analysis must be used in conjunction with the traditional analysis methods. The advanced analytical methods briefly described in this manual can be extremely difficult to perform and evaluate. Therefore, advanced analytical analyses should be conducted in conjunction with experts who can oversee the numerical modeling and can help with the interpretation of the results.

a. Stress/strain compatibility. Foundations may contain more than one material or may be made up of a combination of intact rock, jointed rock, or sheared rock. The stress-strain characteristics of these materials may be quite different. They might exhibit elastic-plastic behavior where peak shear strengths will occur simultaneously (Figure 6-2) or one or more might exhibit strain-softening behavior where only the residual strength of that material will be available at the strain level associated with peak shear in the other material (Figure 6-3). The overall strength of the foundation will depend on the stress-strain characteristics and compatibility of the various materials.

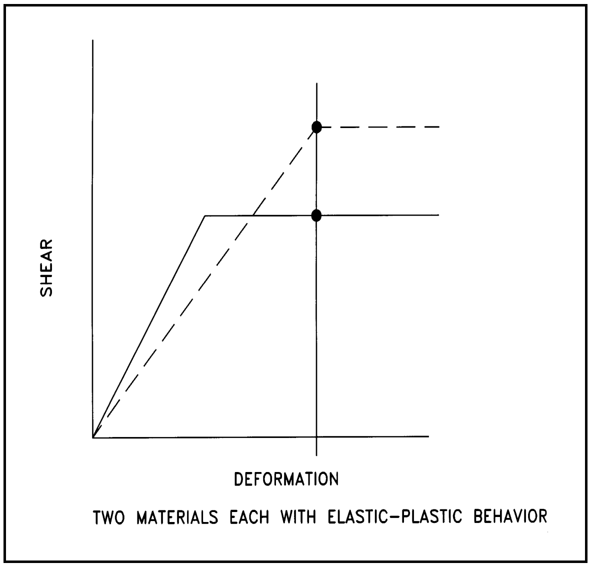

Figure 6-2

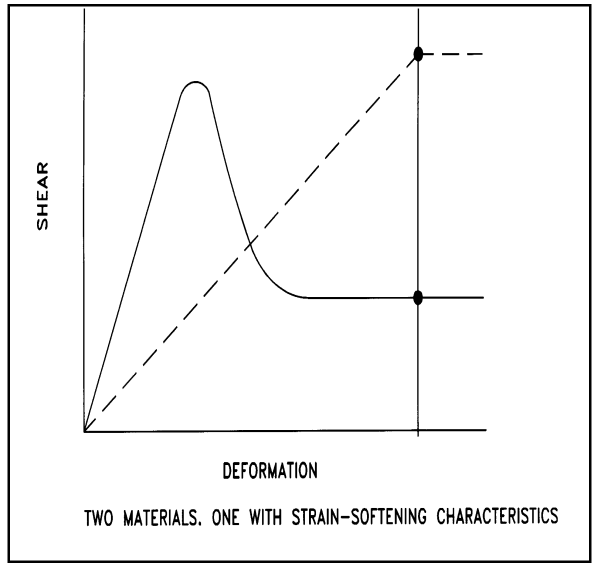

Figure 6-3

b. Deformations. The sliding stability analysis procedures described in Chapter 2 are based on a limit state approach, which satisfies only some of the equilibrium conditions and only accounts for deformations indirectly. No attempt has been made in this approach to relate shear stresses to displacements. The magnitude of displacement required to reach a limit state needs to be considered when selecting strength parameters. It is not possible, for instance, to develop peak shear and cohesive strength as well as passive resistance, all at the same strain level. Therefore, the analysis may require the use of residual shear strengths rather than peak shear strength values. In addition, the deformations associated with shear resistance may be unacceptable for reasons of serviceability. Controls on maximum displacement, needed to ensure proper function and safety, may govern over factor of safety requirements.

c. Special Circumstances. The minimum factors of safety for sliding stability are based on Mohr-Coulomb limit-state failure criterion without consideration of the deformations that occur in the structure and its foundation, or of the type of failure path the structure will experience in moving from a service-state from a limit-state condition. In many cases, it can be demonstrated by the use of finite element analysis and fracture mechanics methods that the factor of safety is substantially different from that predicted by the limit equilibrium method. Under special circumstances, such as in the case of an existing structure where the limit equilibrium method indicates that remedial action is required to improve stability, additional stability analyses may be performed using finite element and fracture mechanics procedures to verify whether stability remediation is actually required.

d. Finite element method (FEM). Finite element methods can be used to determine the manner in which loads and resistance are developed as a function of the stiffness of the foundation, stiffness of the structure, and the structure-to-foundation interface. They can also be used to calculate displacements and stresses due to incremental construction and/or load applications, and can model nonlinear stress-strain material behavior. The FEM program SOILSTRUCT, a two-dimensional plane strain-analysis program, is commonly used for soil-structure interaction problems and has been modified for use in evaluating the loss of contact along a crack, or along the structure-foundation interface. The modified version uses a procedure called the Alpha Method (Ebeling et. a1 1992) in an incremental analysis to determine the extent of cracking that might occur at the structure-foundation interface. Finite element analyses can also be used to capture soil-structure interaction effects and to investigate crack propagation using fracture mechanics techniques. Soil-structure interaction. When a structure is supported by rock or soil, a finite element analysis can provide lateral pressures and bearing pressures that are realistic since the elastic and plastic properties of the structure, foundation, and soil are all considered.

e. Linear elastic fracture mechanics (LEFM) analysis. LEFM methods are FEM-based procedures for modeling crack development in a structure or along the base of a structure. The analysis can be performed using discrete crack analysis theory, or smeared crack analysis theory. The use of LEFM analysis in the evaluation of stability is described in various engineering papers (Dewey, Reich, and Saouma 1994), (Saouma, Bruhwiler, and Boggs 1990), (Bazant 1990) and (Ebeling, Morrison, and Mosher 1996).

6-4. Computer Programs

Following is a listing and brief description of computer programs that may serve as aids when determining the stability requirements for new or existing structures. Other commercially available computer programs which are not included in the following list, such as ADINA, ANSYS, CRISP, NASTRAN, or PLAXIS may also help when performing complex stability analysis.

- 3DSAD is a U.S. Army Corps of Engineers developed program (library number X8100) that allows the user to describe the geometry of a three-dimensional structure, interactively plot the described structure, and compute weight and centroid information for individual pieces or the sum total of the structure.

- CFRAG is a U.S. Army Corps of Engineers developed program (I0018) that allows the user to analyze groundwater flow using the method of fragments. The program can be used to compute: (a) seepage through soil mediums that can be modeled using fragment, (b) head losses, (c) exit gradients, and (d) resultant uplift and lateral forces.

- CSLIDE is a U.S. Army Corps of Engineers developed program (X0075) that allows the user to assess the sliding stability of concrete structures using the limit equilibrium method described in Chapter 2.

- CSEEP is a U.S. Army Corps of Engineers developed program (X8202) that allows the user to (a) interactively generate a finite element grid, (b) perform a finite element method seepage analysis, and (c) to plot the results.

- MERLIN is an Electric Power Research Institute (EPRI) developed program that allows the user to solve problems in elasticity, plasticity, linear and nonlinear fracture mechanics, steady-state and linear-transient heat transfer, and transient seepage flow. This program includes numerous capabilities for performing fracture mechanics analyses using the discrete crack approach. Pre- and post-processing capabilities are contained in PreMERLIN and PostMERLIN, respectively.

- SOILSTRUCT is a U.S. Army Corps of Engineers developed program that allows the user to perform a two-dimensional plane-strain finite element analysis of incremental construction, soil-to-structure interaction analysis of earth-retaining structures. The program is capable of simulating incremental construction including embankment construction or backfilling, the placement of layer(s) of a reinforcement material during backfilling, dewatering, excavation, installation of a strut or tie-back anchor support system, removal of the same system, and the placement of concrete or other construction materials. The program is also capable of modeling the interface region between the soil backfill and the structure using interface elements.

- CG-DAMS is an EPRI developed program that is a specialized nonlinear, finite element, concrete gravity-dam stability code that predicts cracking potential under all types of loads including extreme flood and earthquake loads. The code has library models of typical dam and foundation cross-sections that can be customized by entering elevations and slopes of the actual dam. Uniquely shaped dam profiles are modeled by user input. Output routines provide the sliding stability factor of safety, structural deformations, stress and pressure profiles in the dam foundation, and crack length.

6-5 Mandatory Requirements

There are no mandatory requirements in this chapter.