# Embankment Dam Slope Stability 101

## Introduction

Design of new embankment dams, and the more common scenario of reviewing the conditions of existing dams, should, as general practice, include evaluating the stability of the embankment structure. Stability, in the simplest definition, refers to the ability of a slope to resist the driving forces tending to move earth materials downslope. The stability of an embankment can be adversely affected by excessive stresses on the crest or slopes, sudden addition or loss of water in the reservoir, changes in internal water pressures, or loss of materials due to erosion (both internal, such as piping, and external, such as surface erosion). Stability conditions of a dam can be assessed using both visual and analytical methods.

Recently, the central Front Range and surrounding areas in Colorado experienced historic rainfall that led to extensive flooding in the region. The rainfall and flood imposed loading conditions that many dams, both large and small, had never experienced. These events may have created changes of conditions, internally, in embankment dams. The Colorado State Engineer's Office recently completed emergency inspection reports for affected dams, some of which will require quantitative slope stability analyses to further assess their conditions and levels of safety.

The purpose of this article is to describe visual inspections of stability performance and identify triggers that may indicate the need for a more quantitative or analytical approach. This article is not intended to be prescriptive and provides only a general overview of assessing embankment stability. Future articles will provide more details in terms of strength characterization and specific analysis methodology for different loading cases.

## Visual Inspection and Monitoring for Stability

For many western states, State Engineers have waived the requirements of performing stability analyses for low hazard dams if it can be demonstrated that the dams have conservative slopes and were constructed of competent materials. Generally, upstream earth embankment slopes should be no steeper than 3H:1V (horizontal to vertical), and downstream earth embankment slopes no steeper than 2H:1V. Regular visual inspections are always required, even if stability analyses have been waived, and such inspections can provide efficient means of monitoring embankment performance with respect to stability.

Regular visual inspection is the best tool an Owner can use to assess the safety of an embankment dam. Benchmarking photographs (those taken of the same feature from the same perspective, inspection to inspection) are invaluable to the monitoring process. Photos can be compared across multiple inspections to identify subtle changes in conditions, which may be an indication of a developing adverse condition that affects the stability and safety of the dam.

Visual indicators of developing instability may include:

- Longitudinal cracks on the dam crest or slope (see **Photo 1**).
- Wet areas on the downstream slope or toe (see **Photo 2**) indicating an adverse internal phreatic level within the embankment. The relationship between reservoir level and seepage quantity and quality should also be established and used to compare successive observations.
- An apparent slope failure or slump (see **Photo 3**).
- Erosion or sloughing of the downstream slope which results in oversteepening of the overall slope.
- Displaced riprap, crest station markers, or fence lines indicating movement.
- Bulges at or downstream of the toe.
- Depressions or sinkholes in the dam crest or slopes.
- Changes in the appearance of the normal waterline against the upstream slope at multiple water levels.

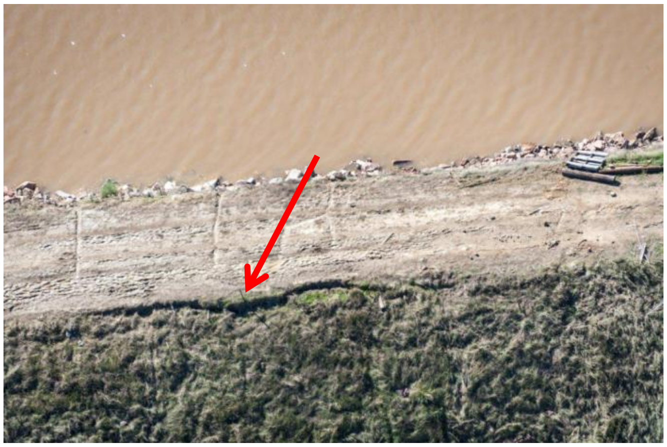

**Photo 1.** Severe longitudinal cracks in downstream slope

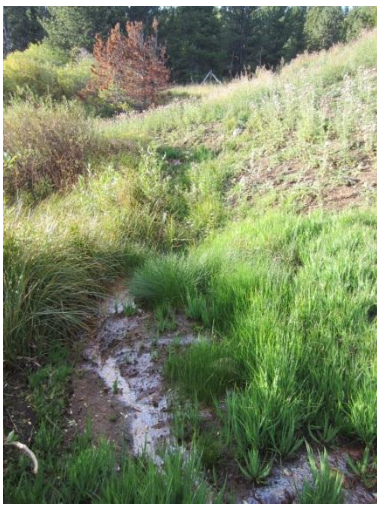

**Photo 2.** Seepage exiting dam face

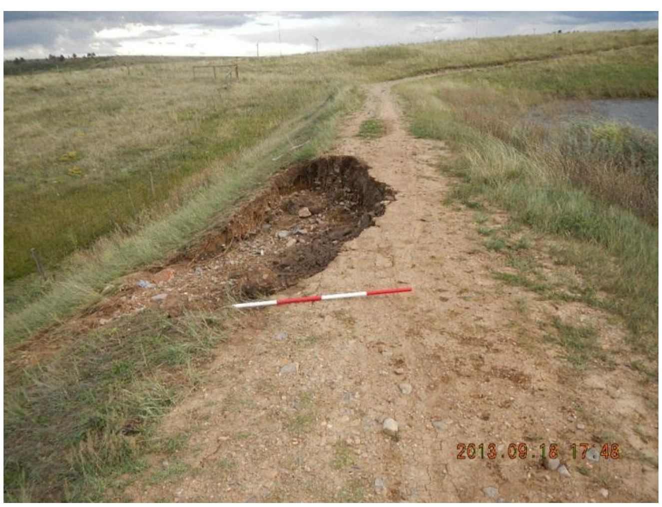

**Photo 3.** Slope failure on downstream slope

## Triggers for More Quantitative Analyses

Besides a change in conditions resulting from rainfall/flooding or other events, triggers requiring stability analysis be performed may include:

- Designing a new dam.
- Raising an existing dam.
- Construction of a berm.
- Potential reclassification of a dam to high hazard.
- Deterioration of existing conditions, i.e. oversteepening of embankment slopes for any reason.
- Reassurance that a latent, undetected issue has not developed – indicators of such an issue may include embankments with steep slopes (greater than 2H:1V), soft foundation conditions, high phreatic surface within the dam and/or foundation, seepage at the face or toe, depression/sinkhole formation or observed scarp or bulge.
- Indications from field observations that instability may be developing – i.e. observed scarps, toe bulges, longitudinal cracking along crest or slope.

## Slope Stability Analysis Requirements

The analyzed stability of a slope is expressed as a Factor of Safety (FS). FS values greater than 1 indicate the estimated driving forces are less than the resistance forces. However, due to inherent uncertainties in the behavior and characterization of earth materials, regulations and good practice require FSs greater than 1 for most loading conditions. Each regulatory agency has its own FS requirements; however, the following table provides some commonly adopted values:

| Loading Condition | Min. Factor of Safety |
|---|---|
| Steady State Drained | 1.5 |
| End of Construction | 1.3 |
| Rapid Drawdown | 1.2 |
| Post-Seismic | 1.2 |
| Pseudo-Static (where applicable) | 1.0 |

To prepare a slope stability analysis, a model or sectional view of the slope is developed for the most vulnerable section, typically the maximum section of the dam, or where signs of distress are observed. The phreatic surface is included in the model and can be identified through piezometer readings, when available, by accurately located observations of wetness or free water on the embankment, or by estimating a typical phreatic surface shape. References such as Cedergren (1989) can be used to estimate the phreatic surface for various embankment zoning scenarios. Each material or soil type within the embankment and the foundation should be assigned appropriate properties for use in the analysis.

Slope stability is primarily a tool for comparing the relative stability of various possible designs at a site and benchmarking them against historically successful practice. It should not be relied upon as an absolute indicator of the safety of a particular design.

### *Drained or Undrained*

It is important to understand whether the embankment or foundation soils have high permeability (e.g., can drain during a change in loading condition; drained behavior) or if they are a low permeability material (e.g. cohesive materials in which excess pore pressures due to loading takes longer to dissipate; undrained behavior). Duncan et al (1996) provides a logical base to estimate the degree of drainage to evaluate whether a material will behave in a drained or undrained manner during rapid drawdown. This basis can be extended to other possible loading conditions to evaluate whether undrained strengths would be induced.  This is done by using the dimensionless time factor, T which is expressed as:

$$T = C_v t/D^2$$

in which $C_v$ = coefficient of consolidation ($ft^2$/day or $m^2$/day); t= construction or loading time (days); and D = length of drainage path (feet or meters). Typical values of $C_v$ for various soils are given in Duncan, Wright, and Wong (1992), and are summarized in the following table:

| Type of Soil | Values of $C_v$ |
|---|---|
| Coarse sand | >10,000 $ft^2$/day |
| Fine sand | 100 to 10,000 $ft^2$/day |
| Silty sand | 10 to 1,000 $ft^2$/day |
| Silt | 0.5 to 100 $ft^2$/day |
| Compacted clay | 0.05 to 5 $ft^2$/day |
| Soft clay | <0.2 $ft^2$/day |

If the value T exceeds 3.0, it is reasonable to treat the material as drained. If the value T is less than than 0.01, it is reasonable to treat the material as undrained. If the value T is between these two limits, both possibilities should be considered. If the data required to calculate T are not available, it is usually assumed for problems that involve normal rates of loading, that soils with permeabilities (hydraulic conductivities) greater than $10^{-4}$ cm/sec will be drained, and soils with permeabilities less than $10^{-7}$ cm/sec will be undrained. If hydraulic conductivity falls between these two limits, it would be conservative to assume that the material is undrained.

### *Typical Soil Parameters*

If available, investigation records including geologic assessments, drill logs, laboratory test data, in situ test data, or even construction specifications should be reviewed to identify material characterization properties (such as gradation, density, Atterberg limits) and ideally, if available, shear strength parameters (undrained and drained) for the embankment and foundation materials.

If strength parameters are not available from test data, index properties and blow counts can be used with published correlations to estimate strength parameter ranges for each type of soil. If index properties or blow count data are not available, only a screening level of analysis can be performed. For screening level analyses, published reference strength parameter values can be used. Reference and correlation values for engineering properties of gravels, sands, silts, and clays of varying plasticity can be found in the following manuals and papers (hyperlinks provided where available):

- NAVFAC Department of the Navy, NAVFAC DM-7.01, Soil Mechanics, US Department of Defense, Alexandria 2005.

- Lambe and Whitman, *Soils Mechanics, SI Version,* 1979.
- Hunt, *Geotechnical Engineering Investigation Manual,* McGraw-Hill, New York, 1984.
- Bell, *Engineering Properties of Soils and Rocks,* Butterworth-Heinemann, Oxford, UK, 1992.
- Duncan and Wright, *Soil Strength and Slope Stability,* John Wiley & Sons, 2005.
- U.S. Dept. of the Interior, Bureau of Reclamation, Design of Small Dams, Third Edition, 1987. Table 5-1 in this reference provides typical values for compacted embankment soils.
- USSD, Materials for Embankment Dams, January 2011.


### *Typical Loading Conditions*

After the slope geometry, phreatic surface, and material properties estimates have been established, the potential loading conditions of the embankment should be evaluated. Typical loading conditions include:

- Steady-state Drained – This condition represents the stability of the dam under normal operating conditions with steady-state seepage conditions and is one of the fundamental analyses performed in any quantitative analysis. Drained parameters should be used. Laboratory tests to evaluate the drained shear strength could include consolidated undrained triaxial tests with pore pressure measurement (CU'), drained triaxial tests (CD), or direct shear tests. Pore pressures can be estimated using flow nets, empirical relationships, or other types of seepage analyses. Both internal pore pressures (downstream slope) and external water pressures (upstream slope) should be included in the analysis. In case of noncohesive, drained embankment shell materials, infinite slope formulations ("angle of repose analysis") could be used to analyze shallow failure surfaces.
- End of Construction – This case should be analyzed when either embankment or foundation soils (or both) are predicted to develop significant pore pressures during embankment construction (undrained conditions) and undrained strengths are estimated to be less than drained strengths. Factors determining the likelihood of this occurring include the height of the planned embankment, the speed of construction, the saturated consistency of foundation soils, and others. If the materials are free-draining, the drained shear strengths should be considered. If the soils are cohesive, then undrained shear strengths should be considered. The total stress undrained shear strength should be evaluated, and laboratory tests to evaluate this could include undrained unconsolidated triaxial shear tests (UU). In the case of soft clay foundation, this loading case should be analyzed first, since it will likely control the embankment design.
- Rapid Drawdown – Analyze the stability of the upstream embankment slope for the condition created by a rapid drawdown of the water level in the reservoir from the normal full reservoir level. Although there are several methods of analyses, each having a different method of modeling the phreatic pressures during a rapid drawdown condition, the three-stage method presented by Duncan et al for developing appropriate phreatic and pore pressure parameters is the authors' recommended approach. Different agencies also have different requirements for the assumed drawdown elevations of the pool. For rapid drawdown analysis, undrained shear strengths should be used for both noncohesive (if material is judge to behave undrained as discussed above) and for cohesive embankment soils. Laboratory test to estimate undrained strengths could include the isotropically undrained triaxial tests with pore pressure measurement (CU').
- Seismic – Dams requiring seismic analysis should be designed to withstand at least the predicted earthquake loads with a full reservoir under steady-state seepage conditions. This is often referred to as a "pseudo-static" or post-earthquake analysis. Typically, this loading condition applies to high hazard structures. Refer to the applicable state

regulations for additional guidance. This condition should be evaluated when estimated local seismicity is anticipated to generate ground motions greater than about 0.10g, or as otherwise required by applicable regulations. For example, current NRCS practice is that no seismic analysis would be required for: 1) design ground accelerations less than 0.07g, and 2) well-constructed embankment dams on competent clay foundations or bedrock, where the design earthquake is less than 0.35g. If seismic analysis is deemed warranted, then the selection of the appropriate method and strengths can be complex and very case specific. This issue is outside the scope of this article and will be discussed in future publications.

### *Analysis Results*

Resulting FS values higher than the minimum required values indicate the embankment is expected to be stable under the applied loading conditions. If FS values are lower than the required values, a more detailed investigation may be warranted to further characterize the embankment and foundation materials to better represent the site conditions. FS values lower than one generally indicate potential instability.

If obtaining site-specific data is justified, consider excavating test pits, advancing drill holes, performing in situ testing (e.g. blow counts, torvane, pocket penetrometer, etc.), and installing piezometers. Useful laboratory tests include gradation, density, Atterberg limits, consolidation, and triaxial shear strength testing.

## Conclusions

This article presented embankment slope stability with a focus on smaller structures that may have limited data. The reader is further encouraged to read the references. Future articles will provide more in depth discussion on topics such as:

- Strength characterization with respect to laboratory testing and evaluation of drained and undrained shear strengths.
- Specific analysis methodology for different loading cases (i.e. rapid drawdown and seismic analysis).
- Sensitivity of selected shear strengths for the various loading cases.
- Applicability of various available methods of slope stability analysis; limit equilibrium, i.e. Bishop, Janbu, Spencer; Finite Element Method (FEM), etc.

## References

Cedergren, H.R., 1989, Seepage, Drainage and Flow Nets, Third Edition, John Wiley and Sons, Inc., 465 pgs.

Duncan, J.M., S.G. Wright, and K.S. Wong, 1992, "Slope Stability During Rapid Drawdown," Proceedings of the H. Bolton Seed Memorial Symposium, Volume 2, No. 4, p. 253-272, B-Tech Publishers, Vancouver, B.C.

Duncan, J.M. 1996. "State of the Art: Limit Equilibrium and Finite-Element Analysis of Slopes". Journal of Geotechnical Engineering. Vol. 122, No. 7. July.

Duncan, J.M. and S.G. Wright, 2005, Soil Strength and Slope Stability, John Wiley and Sons, Inc., 297 pgs.

TR-210-60: Earth Dams and Reservoirs (Revised July 2005) (7/2005), Natural Resource Conservation Service.