CHAPTER 4

Stability Conditions for Analyses

Variations of the loads acting on slopes, and variations of shear strengths with time, result in changes in the factors of safety of slopes. As a consequence, it is often necessary to perform stability analyses corresponding to several different conditions, reflecting different stages in the life of a slope.

When an embankment is constructed on a clay foundation, the embankment load causes the pore pressures in the foundation clay to increase. Over a period of time the excess pore pressures will dissipate, and eventually, the pore pressures will return to values governed by the groundwater conditions. As the excess pore pressures dissipate, the effective stresses in the foundation clay increase, the strength of the clay will increase, and the factor of safety of the embankment will also increase. Figure 4.1 illustrates these relationships. If, as shown, the embankment height stays constant and there is no external loading, the most critical condition occurs at the end of construction. In this case, therefore, it is only necessary to analyze the end-of-construction condition.

When a slope in clay is created by excavation, the pore pressures in the clay decrease in response to removal of the excavated material. Over time, the negative excess pore pressures dissipate and the pore pressures eventually return to values governed by the groundwater conditions. As the pore pressures increase, the effective stresses in the clay around the excavation decrease, and the factor of safety of the slope decreases with time. Figure 4.2 shows these relationships. If the depth of excavation is constant and there are no external loads, the factor of safety continually decreases, and its minimum value is reached when the pore pressures reach equilibrium with the groundwater seepage condition. In this case, therefore, the long-term condition is more critical than the end-of-construction condition.

In the case of a natural slope, not altered by either fill placement or excavation, there is no end-of-construction condition. The critical condition for a natural slope corresponds to whatever combination of seepage and external loading results in the lowest factor of safety. The higher the phreatic surface within the slope and the more severe the external loading condition, the lower is the factor of safety.

In the case of an embankment dam, several different factors affect stability. Positive pore pressures may develop during construction of clay embankments, particularly if the material is compacted on the wet side of optimum. The same is true of clay cores in zoned embankments. Over time, when water is impounded and seepage develops through the embankment, the pore pressures may increase or decrease as they come to equilibrium with steady seepage conditions. Reservoir levels may vary with time during operation of the dam. A rapid drop in reservoir level may create a critical loading condition on the upstream slope. A rise from normal pool level to maximum pool level may result in a new state of seepage through the embankment and a more severe loading condition on the downstream slope.

Earthquakes subject slopes to cyclic variations in load over a period of seconds or minutes that can cause instability or permanent deformations of the slope, depending on the severity of the shaking and its effect on the strength of the soil. As noted in Chapter 10, loose sands may liquefy and lose almost all shearing resistance as a result of cyclic loading. Other, more resistant soils may deform during shaking but remain stable.

END-OF-CONSTRUCTION STABILITY

Slope stability during and at the end of construction is analyzed using either drained or undrained strengths,

Copyrighted Material

Copyright © 2005 John Wiley & Sons Retrieved from: www.knovel.com

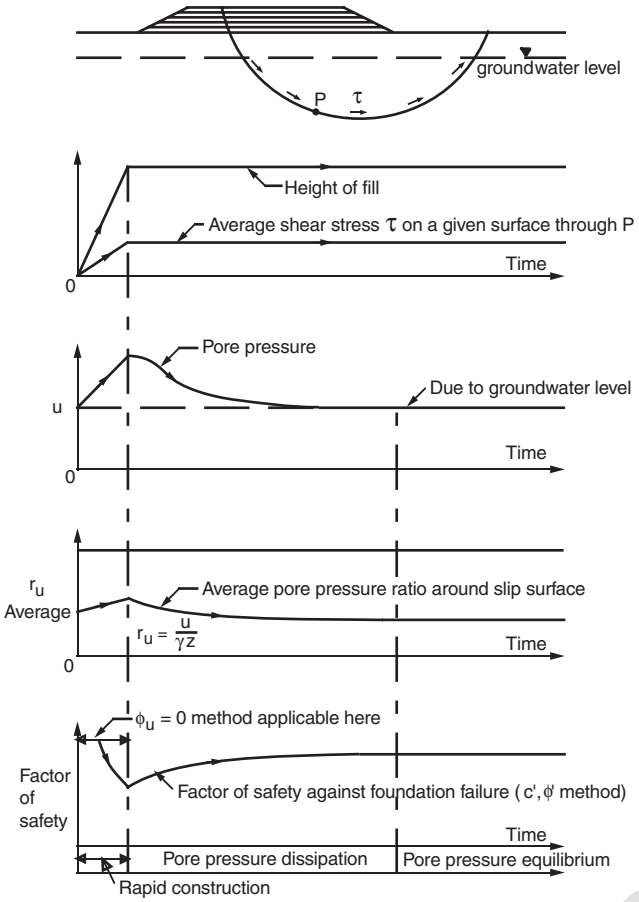


Figure 4.1 Variations with time of shear stress, pore pressure, and factor of safety for an embankment on saturated clay. (After Bishop and Bjerrum, 1960.)

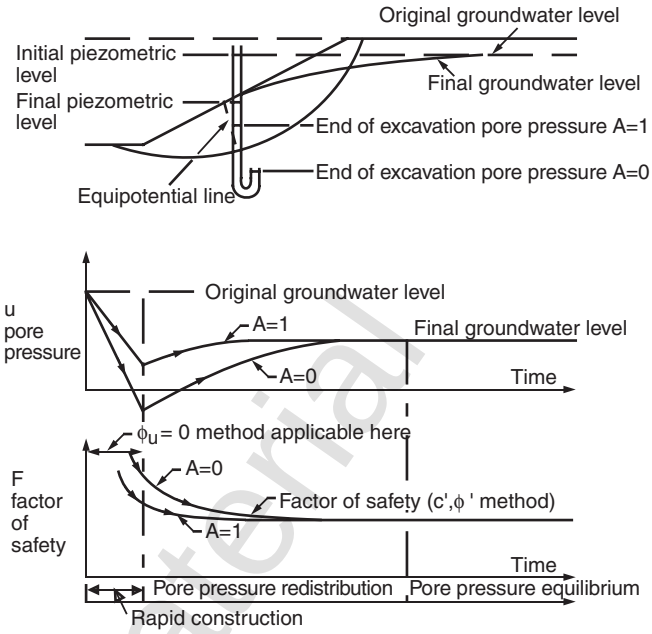


Figure 4.2 Variation with time of pore pressure and factor of safety during and after excavation of a slope in clay. (After Bishop and Bjerrum, 1960.)

depending on the permeability of the soil. Many fine-grained soils are sufficiently impermeable that little drainage occurs during construction. This is particularly true for clays. For these fine-grained soils, undrained shear strengths are used, and the shear strength is characterized using total stresses. For soils that drain freely, drained strengths are used; shear strengths are expressed in terms of effective stresses, and pore water pressures are defined based on either water table information or an appropriate seepage analysis. Undrained strengths for some soils and drained strengths for others can be used in the same analysis.

For many embankment slopes the most critical condition is the end of construction. In some cases, however, there may be intermediate conditions during construction that might be more critical and should therefore be analyzed. In some fill placement operations, including some waste fills, the fill may be placed with a slope geometry such that the stability conditions during construction are more adverse than at the conclusion of construction. As discussed later, if an embankment is constructed in stages, and significant consolidation occurs between stages, each construction stage should be analyzed.

LONG-TERM STABILITY

Over time after construction the soil in slopes may either swell (with increase in water content) or consolidate (with decrease in water content). Long-term stability analyses are performed to reflect the conditions after these changes have occurred. Shear strengths are expressed in terms of effective stresses and the pore water pressures are estimated from the most adverse groundwater and seepage conditions anticipated during the life of the slope. Seepage analyses can be performed using either graphical techniques (flow nets) or numerical analyses (finite element, finite difference), depending on the complexity of the cross section.

RAPID (SUDDEN) DRAWDOWN

Rapid or *sudden drawdown* is caused by a lowering of the water level adjacent to a slope, at a rate so fast that the soil does not have sufficient time to drain signifi-

Copyrighted Material

Copyright © 2005 John Wiley & Sons Retrieved from: www.knovel.com

cantly. Undrained shear strengths are assumed to apply for all but the coarsest free-draining materials ($k > 10^{-3}$ cm/s). If drawdown occurs during or immediately after construction, the undrained shear strength used in the drawdown analysis is the same as the undrained shear strength that applies to the end-of-construction condition. If drawdown occurs after steady seepage conditions have developed, the undrained strengths used in the drawdown analysis are different from those used in the end-of-construction analyses. For soils that expand when wetted, the undrained shear strength will be lower if drawdown occurs some time after construction than if it occurs immediately after construction. Rapid drawdown is discussed in Chapter 9.

EARTHQUAKE

Earthquakes affect the stability of slopes in two ways, as discussed in Chapter 10: (1) The acceleration produced by the seismic ground motion during an earthquake subjects the soil to cyclically varying forces, and (2) the cyclic strains induced by the earthquake loads may cause reduction in the shear strength of the soil.

If the strength of the soil is reduced less than 15% by cyclic loading, pseudostatic analyses of the earthquake loading can be used. In pseudostatic analyses, the effect of the earthquake is represented crudely by applying a static horizontal force to the potential sliding mass. This type of analysis, which is discussed in Chapter 10, provides a semi-empirical means of determining whether deformations due to an earthquake will be acceptably small.

If the strength of the soil is reduced more than 15% as a result of cyclic loading, dynamic analysis are needed to estimate the deformations that would result from earthquakes. Some engineers perform this type of analysis for all slopes, even if the strength reduction due to earthquake loading is less than 15%. These more complex analyses are highly specialized and are beyond the scope of this book.

In addition to analyses to estimating the potential for earthquake-induced deformation, analyses are also needed to evaluate post-earthquake stability. Strengths for these analyses are discussed in Chapter 5, and analysis procedures are discussed in Chapter 10.

PARTIAL CONSOLIDATION AND STAGED CONSTRUCTION

In cases where a clay foundation is so weak that it is unable to support the loads imposed by an embankment, the stability of the embankment can be improved by placing only a portion of the planned fill and allowing the foundation clay to consolidate and gain strength before additional fill is placed. In these cases, consolidation analyses are needed to estimate the increase in effective stresses due to consolidation of the foundation under the weight of the fill. The calculated values of effective stress are used to estimate the undrained shear strengths for use in total stress (undrained strength) analyses or are used directly in effective stress analyses. Procedures for analyses of staged constructions are discussed in Chapter 11.

Recapitulation

- End-of-construction stability is analyzed using drained or undrained strengths, depending on the permeability of the soil.
- Long-term stability analyses, which reflect conditions after swelling and consolidation are complete, are analyzed using drained strengths and pore water pressures corresponding to steady seepage conditions.
- Sudden drawdown removes the stabilizing effect of external water pressures and subjects the slope to increased shear stress. Either drained or undrained strengths are used, depending on the permeability of the soil.
- Earthquakes subject slopes to cyclically varying stresses and may cause reduction in the shear strength of the soil as a result of cyclic loading. Shear strengths measured in cyclic loading tests are appropriate for analyses of stability during earthquakes.
- Stability analyses for staged construction of embankments require consolidation analyses to estimate the increase in effective stresses that results from partial consolidation of the foundation.

OTHER LOADING CONDITIONS

The five loading conditions described above are those most frequently considered for earth slopes. There are, however, other loading conditions that may occur and should be considered. Two of these involve placement of surcharge loads at the top of a slope, and intermediate water levels producing partial submergence of a slope.

Surcharge Loading

Loads may be imposed on slopes as a result of either construction activities or operational conditions. The

Copyrighted Material

Copyright © 2005 John Wiley & Sons Retrieved from: www.knovel.com

loads may be short term, such as passage of a heavy vehicle, or permanent, such as construction of a building. Depending on whether the load is temporary or permanent, and whether the soil drains quickly or slowly, undrained or drained strengths may be appropriate. If the surcharge loading occurs shortly after construction, the undrained strengths would be the same as those used for end-of-construction stability. However, if the load is imposed some time after construction, and the soil has had time to drain (consolidate or expand), the undrained strengths may be different and would be estimated using the same procedures as those used to estimate undrained strengths for rapid drawdown.

In many cases slopes will have a sufficiently high factor of safety that the effect of small surcharge loads is insignificant. Often, the loads imposed by even heavy vehicles and multistory buildings are negligible compared to the weight of the soil in the slope. For example, a typical one-story building will exert loads of about the same magnitude as an additional 1 ft of soil. If it is unclear whether a surcharge load will have a significant affect on stability, the condition should be analyzed.

Partial Submergence and Intermediate Water Levels

For the upstream slopes of dams and other slopes where the level of an adjacent body of water has an influence on stability, the lowest water level usually produces the most adverse conditions. In the case of slopes that contain zones of materials with different strength characteristics, the factor of safety of the upstream slope may be lower with a water level at some elevation between the top and the toe of the slope. The most critical water level for these conditions must be determined by repeated trials.

Copyrighted Material

Copyright © 2005 John Wiley & Sons Retrieved from: www.knovel.com