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Slope Stability Analysis Of Earth And Rockfill Dams

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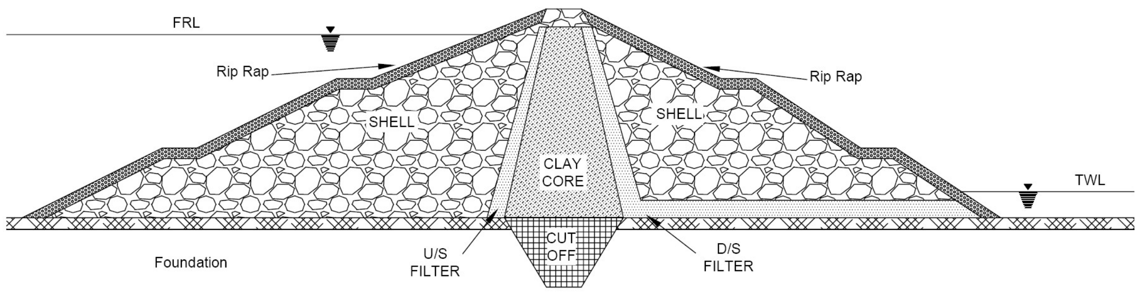
I. INTRODUCTION

The developments in geotechnical engineering and the advancement in the earth moving machineries enabled the construction of high earth and rockfill dams to store huge quantities of water for irrigation, power generation and other public uses. The constructions of earth and rockfill dams are preferred mostly for many construction sites in comparison with the concrete or masonry dams because of its economic considerations as it is constructed using the cheap locally available materials. But the lack of appropriate construction methodology such as compaction equipment, maintenance of appropriate density, moisture content etc. may lead to the construction of unstable structure. Therefore, the construction with the natural materials needs good quality control. Zoned dams, specifically earth and rockfill dams have become more popular as they allow the use of available soils of different gradations in appropriate zones of the dam cross section. Moreover the flexibility of the materials provides excellent seismic stability to the structure. An earth and rockfill dam should be stable under various conditions. The stability of an earth slope subjected to changing water levels depends on many factors. Though the strength envelope of almost all geomaterials has the nature of nonlinearity, linear failure criterion is widely used in slope stability analyses. The dams located in active seismic prone areas need to be analyzed extensively for the safety of the structure.

II. STABILITY ANALYSIS

The purpose of slope stability analysis is to provide a quantitative measure of the stability of a slope or part of a slope. Traditionally, it is expressed as the factor of safety against failure of that slope, where the factor of safety is defined as the ratio of the restoring forces to the disturbing forces, such that a factor of safety greater than unity denotes stability but a factor of safety less than one denotes failure. It may be more valuable to have a measure of the probability of failure and the traditional analysis does not provide this. With modern computer power it is possible, however, to carry out a probabilistic analysis that would give a figure for the likelihood of failure.

Earth dams, in general, should have seepage control measures, such as interior drainage trenches, downstream pervious zones, or drainage blankets in order to keep the line of seepage from emerging on the downstream slope, and to control foundation seepage. In zoned embankments, consideration should be given to the relative permeability and gradation of embankment materials. No particle greater in size than six inches in maximum dimension should be allowed to be placed in the impervious zone of the dam.



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Typical Earth and Rockfill Dam

GENERAL PRINCIPLES

The critical issues in the analysis of the stability of dam embankments are:

- The potential mechanism and geometry of sliding
- Pore pressures
- Shear strength (Effective cohesion and effective friction angle)

For dam embankments, there are generally three potential failure mechanisms which have to be assessed.

- Downstream slope for steady state seepage
- Upstream slope for rapid drawdown
- Downstream and upstream slope for the construction condition

The actual geometry of potential sliding for those cases will be determined by trial and error, but must allow for zones of lower strength in the embankment, and particularly for lower strength zones in the foundation including:

- Fissured soils for an embankment constructed on a soil foundation
- Existing landslide planes
- Bedding plane shears in a rock foundation
- Joint bedding surfaces in the dam abutment which may combine to make a portion of the embankment potentially unstable
- High pore pressure zones in the foundation, giving a reduction in strength and hence stability

Most failures which have occurred in dam embankments have been due to not recognizing the presence of these lower strength zones, or attributing the wrong strength to them, e.g. peak strength being used when residual was more appropriate, or residual strength being overestimated.

The use of total stress methods of analysis is not recommended because

- The total strength (i.e. Undrained shear strength Su) for a material is difficult to determine accurately, with the potential error being much greater than that for effective shear stress parameters c',ϕ' e.g. for a compacted clay, Su is affected by the degree of compaction and in particular by compaction water content. The strength can be changed by an order of magnitude by these factors, as shown in Figure 1.

- It is difficult to monitor and check the Undrained strength in the embankment, but it is relatively easy to monitor pore pressures and compare these to those predicted. Since pore pressure is the most sensitive variable in effective stress analysis it means that monitoring is relatively straightforward if effective stress methods are being used.

- Total stress methods have often been used for analysis of the construction condition.

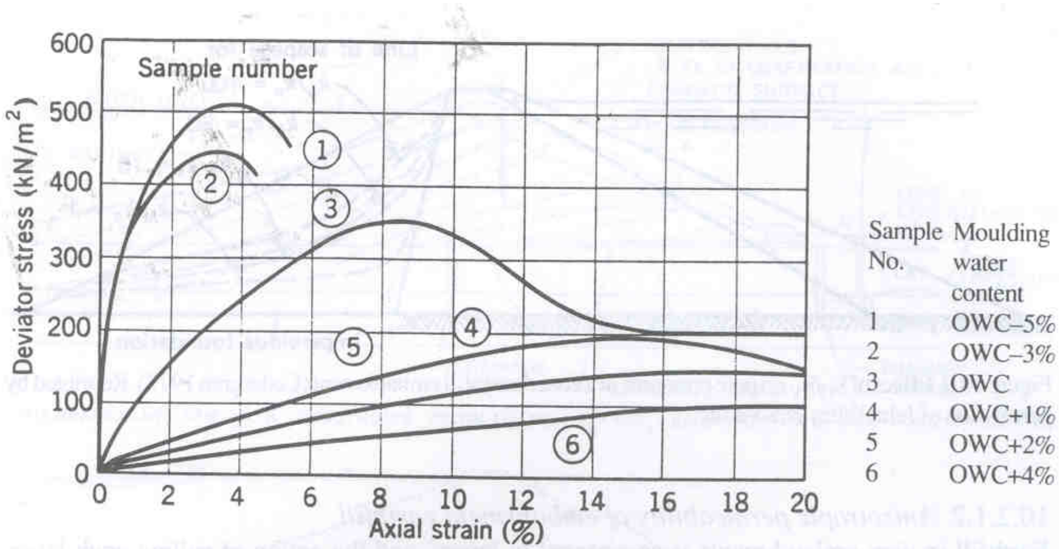

Figure 1 Dependence of Undrained Strength of Compacted Clay on Compaction Density and Water Content

III. METHODS FOR SLOPE STABILITY ANALYSIS

There are numerous methods currently available for performing the slope stability analysis. The majority of these methods may be categorized as limit equilibrium method. The limit equilibrium method is widely used at present time due to its simplicity.

The basic assumption on the limit equilibrium approach is that Coulomb's failure criterion is satisfied along the assumed failure surface, which may be a straight line, circular arc, logarithmic spiral, or other irregular surface. A free body is taken from the slope and starting from known or assumed values of the forces acting upon the free body, the shear resistance of the soil necessary for equilibrium is calculated. The calculated shear resistance is then compared to the estimated or available shear strength of the soil to give an indication of the factor of safety.

There are numerous limit equilibrium methods available for evaluation of slope stability, such as

- Ordinary or Swedish circle method,
- Bishop's simplified method,
- Spencer method
- Morgenstern and Price method
- Janbu's rigorous Method and
- GLE Method

IV. GENERAL ASSUMPTION OF LIMIT EQUILIBRIUM

The soil mass must be safe against slope failure on anyconceivable surface across the slope. In this method using thetheory of elasticity or plasticity are also being increasinglyused, the most common method based on limit equilibriumin which it is assumed soil is at verge of failure. The limitequilibrium is statically indeterminate analysis. As the stressstrain relationship along assume surface are not known, sonecessary that system becomes statically determinant and itcan be analyzed easily using the equation of equilibrium.

Following assumption are generally made,

- The stress system is assumed to be two-dimensional.The stresses in the third direction (perpendicular tothe section of the soil mass) are taken as zero.
- It is assumed that the column equation for shearstrength is applicable and the strength parameters cand f are known.
- It is further assumed that the seepage conditions andwater level are known, and the corresponding porewater pressure can be estimated.
- The condition of plastic failure as assumed to besatisfied along the critical surface in other wordshearing strains at all points of the critical surfaceare large enough to mobilize all the available shearstrength.
- Depending upon the method of analysis someadditional assumption are made regarding themagnitude and distribution of forces along variousplanes.

V. CONDITIONS FOR SLOPE STABILITY ANALYSIS

The stability of an embankment is analyzed for several sliding planes in various dam cross-sections under various conditions. In practice, computations are made for three design situations.

- End of construction
- Steady state seepage at full reservoir and
- Rapid drawdown of the reservoir level

The end of construction and first impoundment is characterized by the transient pore pressures in the core not being adjusted to the impounded water regime. Pore pressure will rise with the increase in overburden load during construction of the embankment. In the case end of construction condition, the stability analysis of the downstream slope is carried out.

The condition of steady state seepage is said to exist when pore pressures at all locations are fully adjusted to the maximum water level regime. As it takes considerable time for the steady seepage condition to establish itself in an embankment during which period the oil becomes sufficiently consolidated, the stability analysis of the downstream slope is carried out.

The condition of rapid drawdown is characterized by the transient pore pressure which results from a sudden drawdown of the reservoir from a maximum water level to a lower critical water level. This may give a critical stability situation. The stability analysis of the upstream slope is carried out in the case of rapid drawdown condition.

During Construction

Slides of embankment dam during construction have not occurred as frequently as slides during the operation of reservoir and have not resulted in failures of the catastrophic type. Nevertheless the pore pressures which develop in the embankment or foundation during construction may be higher than at any subsequent time and it is usually recommended to analyze the stability of the embankment for this condition. The construction condition is especially likely to be critical for dams on soft foundation. The materials of dam in this case are simulated unconsolidated and undrained
Full Reservoir

Since a shear slide when the reservoir is full can be loaded to a disastrous failure, the stability analysis should be treated more conservatively then during construction and reservoir draw down condition for the full reservoir state only the downstream portion of the dam need to be analyzed since an upstream slope slide during full reservoir is theoretically conceivable only if the strength of the foundation were to be reduced very greatly by wetting. The materials of dam in this case are simulated drained. The minimum tolerable safety factor

Rapid Draw Down

Rapid draw-down in every reservoir is possible because of war or flood situation or every other accident. Because of this the stability analyses in this case must be done. The dams' materials in this case are simulated consolidated and undrained.

The effects of stochastic hydraulic conductivity on the slope stability of an embankment dam are investigated using a combination of random field simulation, seepage analysis, and slope stability analysis.

VI. CHOICE OF METHODS FOR STABILITY ANALYSIS OF EARTH DAM

The method to be chosen in the stability analysis of earth dam slopes depends on the situation as explained below.

- If the stability analysis of the slope is to be analyzed at the end of construction where the soil is saturated and the period of construction is relatively short so that there is no pore water pressure dissipation during construction, total stress method must be used. In such situations stability at the end of construction is critical.

- If the stability of the slope is to be analyzed at the end of construction where the soil is saturated but the period of construction is relatively long so that there occurs some pore water pressure dissipation during construction, the use of total stress method of analysis will give conservative and expensive solutions. Realistic assumptions must be made for pore water pressure development and dissipation for various stages of construction. With this, the stability analysis must be carried out by effective stress method. During construction, pore water pressure must be measured using piezometric installation to check the adequacy of design. If pore water pressures develop far in excess of the assumed values the rate and phases of construction must be suitably regulated or the slope must be redesigned.

- If the stability is to be analyzed at the end of construction where the soil is unsaturated, again assumptions for pore water pressure can be made and effective stress method can be used. Observations for pore water pressure must be made during construction. Alternatively total stress method can be used using total stress parameters, c_u andϕ_u , determined from UU tests.

- For long term stability of the slopes, effective stress method must be used. Pore pressure for steady stage seepage conditions can be estimated by constructing flow net.

- The stability of upstream slope is to be analyzed for rapid drawdown condition. Due to rapid lowering of water level pore water pressure changes and reaches the new equilibrium depending on the type of soil.

- If the drawdown is fast and time taken to reach new equilibrium is long, effective stress method can be used with pore water pressures calculated according to Bishop's equations.

- If the drawdown is slow and time to reach new equilibrium is small then the condition immediately after drawdown is critical. Effective stress method must be used for stability analysis using pore water pressure determined from flow net for transient conditions.

VII. STABILITY ANALYSIS SOFTWARE – SLIDE (Rocscience):

Numerous slope stability programs are available. Virtually all have facilities for both circular and non-circular analyses by various limit equilibrium methods, and can handle applied external forces and distributed loads, multiple soil layers, specification of groundwater conditions by watertable, pore pressures or Ru values, seismic loading coefficients and tension cracks. In most cases the circular slip surfaces may be defined as a grid of circle centres, a tangent to a common surface or as passing through a common point. Non-circular slip surfaces are individually defined by the user. The various programs are distinguished mainly by the limit equilibrium methods that they employ and the user interface. With the more modern programs the geometry can also be input graphically in a CAD style interface.

SLIDE is a 2D slope stability program for evaluating the safety factor or probability of failure, of circular or non-circular failure surfaces in soil or rock slopes. External loading, groundwater and support can all be modelled in a variety of ways.

SLIDE analyzes the stability of slip surfaces using vertical slice limit equilibrium methods (eg. Bishop, Janbu, Spencer etc). Individual slip surfaces can be analyzed, or search methods can be applied to locate the critical slip surface for a given slope. Deterministic (safety factor) or probabilistic (probability of failure) analyses can be carried out.

Some of the important features of the program are:

- Critical surface search methods for circular or non-circular slip surfaces
- Analysis methods include Bishop, Janbu, Spencer, GLE / Morgenstern-Price
- Multiple materials
- Anisotropic, non-linear Mohr-Coulomb materials
- Probabilistic analysis – calculate probability of failure, reliability index (see below)
- Sensitivity Analysis
- Groundwater – piezo surfaces, Ru factors, pore pressure grids, finite element seepage analysis (see below), excess pore pressure (B-bar method)
- Finite element groundwater seepage for steady state or transient conditions
- Rapid drawdown analysis
- Tension crack (dry or water filled)
- External loading – line, distributed or seismic
- Support – soil nails, tiebacks, geotextiles, piles. Infinite strength (slip surface exclusion) zones
- Back analysis of required support force for a given safety factor
- Back analysis of material strength using sensitivity or probabilistic analysis
- View any or all surfaces generated by search
- Detailed analysis results can be plotted for individual slip surfaces

The software package consists of 3 separate programs:

MODEL – the pre-processing program used for entering and editing the model boundaries, loads, material properties, and slip surface definition, and saving the input file

COMPUTE – the limit equilibrium analysis engine

INTERPRET – the post-processing program, used for viewing the results of the analysis

MODEL, COMPUTE and *INTERPRET* will each run as standalone programs. However, they are fully integrated, and interact with each other as illustrated in the schematic below.

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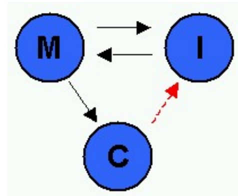

Modelling Features in Slide

The stability of a slope is influenced by factors such as geological conditions (soil and rock layers, discontinuities, groundwater conditions, etc.), material properties, and geometry. As a rule many of these factors cannot be defined with much certainty. This uncertainty means that engineers must analyze various possible scenarios in order to avoid surprises and unexpected behaviour. For Slide to be a beneficial program for routine practical design, it was necessary to equip the program with a wide range of analysis methods and strength models, and with tools that facilitate quick creation of models, and easy and fast modification of model input parameters/ assumptions.

Analysis Methods

Slide incorporates the most widely used and accepted limit-equilibrium approaches based on the method of slices. The methods implemented in the program are the:

- Ordinary / Fellenius
- Bishop Simplified
- Janbu Simplified
- Janbu Corrected
- Spencer
- Army Corps of Engineers #1
- Army Corps of Engineers #2
- Lowe-Karafiath
- GLE / Morgenstern-Price
- Sarma (vertical or non-vertical)

Because the formulation of the stability of a slope in limit equilibrium terms is a statically indeterminate problem (the number of equations is less than the number of unknowns), all approaches based on the method of slices use simplifying assumptions. These assumptions limit the range of application of the different methods. The limit equilibrium methods implemented in Slide falls into three main categories:

- Methods that satisfy force equilibrium equations
- Methods that satisfy moment equilibrium equations, and
- Methods that satisfy both force and moment equilibrium equations.

Table below provides a summary of the groupings of the methods in Slide.

Table Limit equilibrium slope stability methods and the equilibrium equations they satisfy

Method	Satisfaction of Force Equilibrium		Satisfaction of Moment Equilibrium
	Horizontal	Vertical	
Ordinary Method	No	No	Yes

Bishop Simplified	No	Yes	Yes
Janbu Simplified	Yes	Yes	No
Janbu Corrected	Yes	Yes	No
Corps of Engineers 1 & 2	Yes	Yes	No
Lowe and Karafiath	Yes	Yes	No
GLE	Yes	Yes	Yes
Spencer	Yes	Yes	Yes

The method selected for analyzing a specified slope problem must be suitable for the slope conditions being analyzed. Table below is a summary of the conditions under which the various methods are most suitable.

Strength Models

The shear strengths of the materials that form a slope have significant impact on stability and are required for all limit equilibrium methods. The following strength models are found in Slide:

- Mohr-Coulomb
- Hoek-Brown
- Generalized Hoek-Brown
- Anisotropic strength
- Non-Linear shear-normal functions
- Undrained
- Zero strength
- Infinite strength
- Vertical Stress Ratio
- Barton-Bandis
- Power Curve, and
- Hyperbolic

Methods of Analysis and their Limitations

Analysis Method	Shape of Slip Surfaces	Limitations and Applications
Ordinary	Only circular slip surfaces	Highly inaccurate for effective stress analysis of fl at slopes with high pore pressures. Quite accurate for total stress analysis for circular slip surfaces. Method does not have numerical stability problems.

Bishop Simplified	Only circular slip surfaces	Except when numerical instabilities arise, accurate for all conditions (gives practically the same answers as the methods that satisfy all equations of equilibrium). Method is numerical unstable under certain conditions. If for a specific slip circle the factor of safety obtained from the method is smaller than the factor of safety from the Ordinary method, then it can be concluded the Bishop method experienced numerical difficulties. In that case the result from the Ordinary method is the more accurate.
Force Equilibrium Methods: Lowe and Karafiath Corps of Engineers 1 & 2 Janbu Simplified Janbu Corrected	Any shape of slip surface	Computed factor of safety values are sensitive to the assumed inclinations of side forces. Can experience numerical instabilities. For slopes in cohesive soils, when side forces are improperly chosen, these methods may yield factor of safety values that are about a third larger than the 'correct' value.
Force and Moment Equilibrium Methods: Morgenstern and Price Spencer	Any shape of slip surface	Can be deemed to provide the correct answers to most practical problems. Accurate for any conditions except when numerical instabilities occur. Give about the same answers. Variation in answers is slightly increased in problems involving non-homogeneous materials.

Support

A variety of support measures are employed by geotechnical engineers to stabilize slopes. The distribution of loads along reinforcement elements differs from one support type to the other. To enable engineers to design support systems by modelling them and comparing their effectiveness, the following commonly used reinforcement types are incorporated into Slide:

- End Anchored support (e.g. Mechanically end anchored rock bolts)
- GeoTextiles (also GeoGrids or Strip reinforcement)
- Grouted Tiebacks / Ground Anchors
- Piles / Micro Piles
- Soil Nails
- RSPile (pile support capacity computed with RSPile)
- Launched Soil Nails
- User Defined support

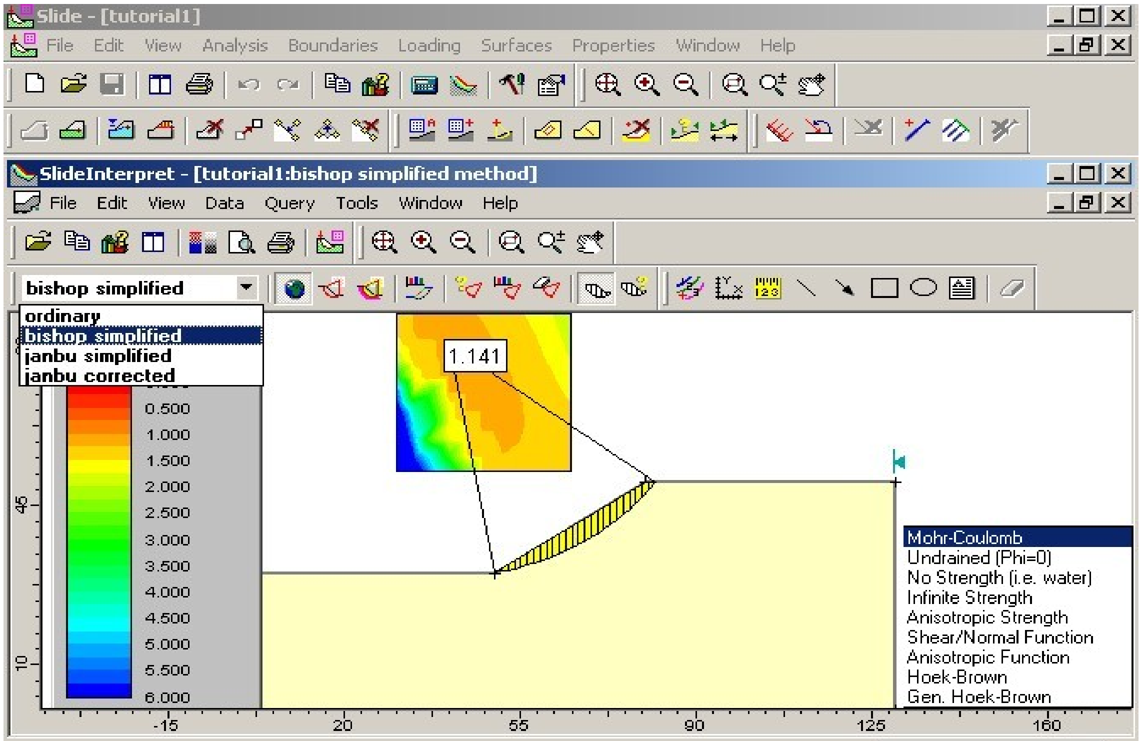

Figure 2 Screen shot of SLIDE

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