FOUNDATIONS AND EARTH STRUCTURES

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Table of contents

I CHAPTER 2: STABILITY OF SLOPES AND EMBANKMENTS

1. Specific Objectives for Chapter II

Fundamental

- Classify the main types of slope movements based on their mechanisms.
- Apply the Fellenius' and Bishop's methods to calculate safety factors (F) for circular failure surfaces.
- Differentiate between failure types and soil conditions.
- Compare the accuracy and limitations of the Fellenius and Bishop methods.
- Evaluate the stability of natural and artificial slopes by interpreting safety factor results.

2. Introduction

The stability of slopes is a concern for both natural slopes and artificial embankments. Failures can result in major hazards.

Definition

The failure mechanisms of natural slopes can be categorized as follows:

- ***Collapse***
- ***Planar, rotational, or complex sliding***
- ***Mudflows or clay flows***
- ***Creep***

Artificial embankments are primarily affected by sliding and sometimes by creep. They can be classified based on the type of structure:

- ***Cut or fill slopes***
- ***Retaining structures against deep-seated sliding***
- ***Earth dams and levees***

Reminder

Any stability study must be preceded by a detailed geological and geotechnical investigation to identify factors favoring instability, such as:

- Local heterogeneities
- Favorable dip for sliding
- Cracks
- Water circulation

Since these factors are not always quantifiable, estimating the actual safety factor against the risk of failure is challenging, regardless of the approach used.

However, extensive experience has been gained in both calculation methods and stabilization techniques, allowing slope stability problems to be resolved with reasonable reliability today.

This chapter highlights the mechanisms leading to the failure of certain slopes or embankments. The most common calculation methods for assessing slope and embankment stability are described using the concept of a global safety factor.

3. Description of the Main Types of Land Movements

Land movements vary widely in nature (landslides, rockfalls, mudflows, underground collapses, subsidence, soil swelling/shrinkage, etc.) and scale (some slides can involve tens of millions of cubic meters).

Their spatial distribution is influenced by:

- Topography
- Geology (rock type, fracturing, hydrogeology)
- External loading (physical environment)

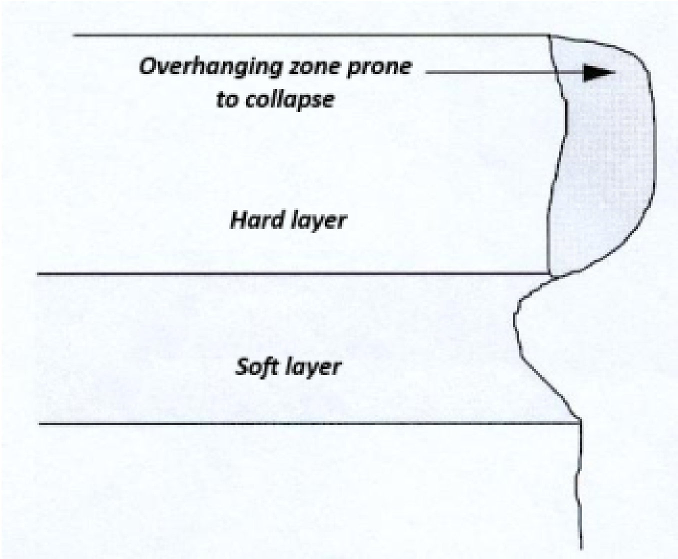
They occur not only in mountainous and coastal regions but also in areas with high densities of underground voids (natural or mined) and in clay soils sensitive to moisture changes. Their occurrence is strongly linked to climatic variations (heavy rainfall, snow melt, drought) but can also be triggered by seismic activity or human actions

3.1. Collapses (Rockfalls)

Definition

Collapses involve the sudden fall of rock masses. A typical example is the collapse of a cliff section, which can result from:

- Erosion of underlying layers
- Evolution of pre-existing discontinuities (e.g., cracks)



Collapse due to erosion of underlying layers

Example

As an example, the photo shows the rockfall at El Kantara cliffs, triggered by the widening of fissures.

Collapse of the El Kantara cliffs caused by crack evolution

3.2. Landslides

Definition

Landslides affect soils and typically involve large masses of terrain detaching and sliding down a slope or embankment. They can be triggered by:

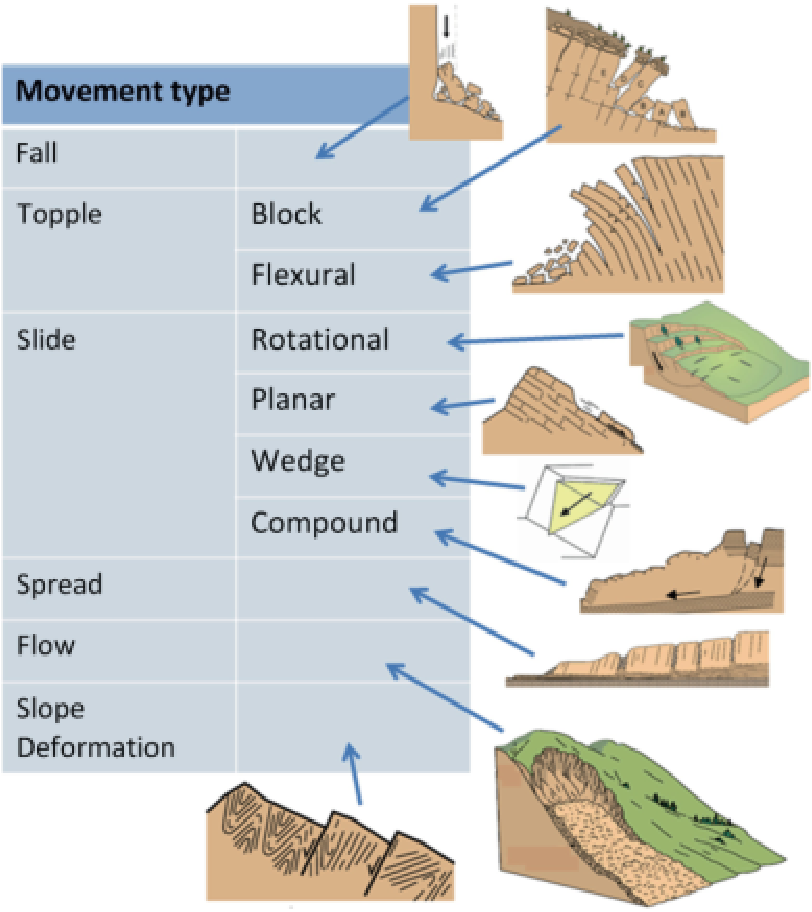
- Natural events (heavy rain, bank erosion, mechanical degradation, earthquakes)
- Human actions (earthworks, deforestation, dam/levee construction)

The speed of failure can vary greatly. Sometimes, the collapse is preceded by warning signs (e.g., cracks forming, bulging ground), but it can also occur suddenly (within seconds to minutes). The slip surface is often planar or circular.

Slide caused by earthworks (Jijel Bypass, 2008)

a. Planar Slides

The failure surface is mostly planar, following a thin layer with poor mechanical properties, often prone to water seepage (e.g., a permeable loose surface layer overlying an inclined bedrock stratum).



Schematic Representation of Different Types of Landslides

b. Rotational Slides (Single)

This is the most common type of landslide. The failure surface has a simple shape and can be approximated as a cylindrical section.

Example

The first photo shows a landslide that occurred in 2009 on the national road RN 29 in Boumerdes Province. Additionally, the second photo illustrates an embankment slope failure that occurred in 2006 during fill repair works on a section of the RN 79A roadway in Mila Province.

Rotational slide on RN 29 (Boumerdes, 2009)

Embankment slide during RN 79A repair works (Mila, 2006)

Definition: c. Complex Rotational Landslide

This type involves multiple nested rotational slide. The initial failure at the slope toe removes lateral support for upslope material, triggering a retrogressive succession of rotational failures that progress uphill through a "domino effect."

3.3. Mudflows

Definition

Mudflows behave more like fluid-transported materials than slides. They often result from slide materials mixing with large amounts of water (e.g., from rivers or heavy rain). Characteristics:

- Loose, heterogeneous clay-rich materials

- Triggered by exceeding a critical water content, creating semi-fluid behavior
- Long travel distances and potentially high velocities

Example

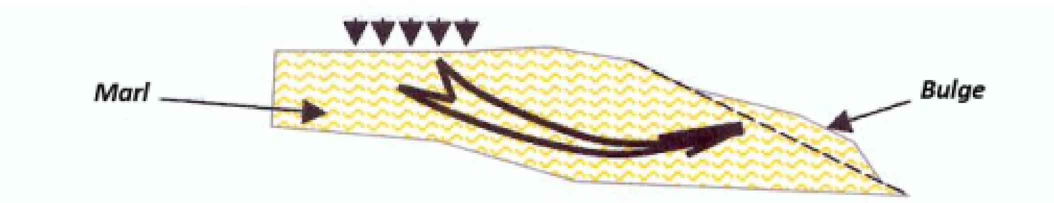
The Photo shows the 2005 clay-rich mudflow on National Road RN 52 in Mila Province. The catastrophic 2003 Beb El-Oued mudflow remains unforgettable, destroying multiple homes and claiming numerous lives.

Mudflow on RN 52 (Mila, 2005)

3.4. Creep

Definition

Creep is characterized by slow, continuous ground movement occurring at very low velocities. In cases of creep, identifying a distinct failure surface is typically difficult. Unlike landslides, this movement occurs without changes in applied stresses - the material is essentially in a near-failure state. This type of movement may either stabilize or progress to complete failure (As shown in the figure).



Example of Creep

Example

The photo illustrates the creep of a large land area toward Ben Haroune Dam, resulting in the collapse and loss of numerous structures.

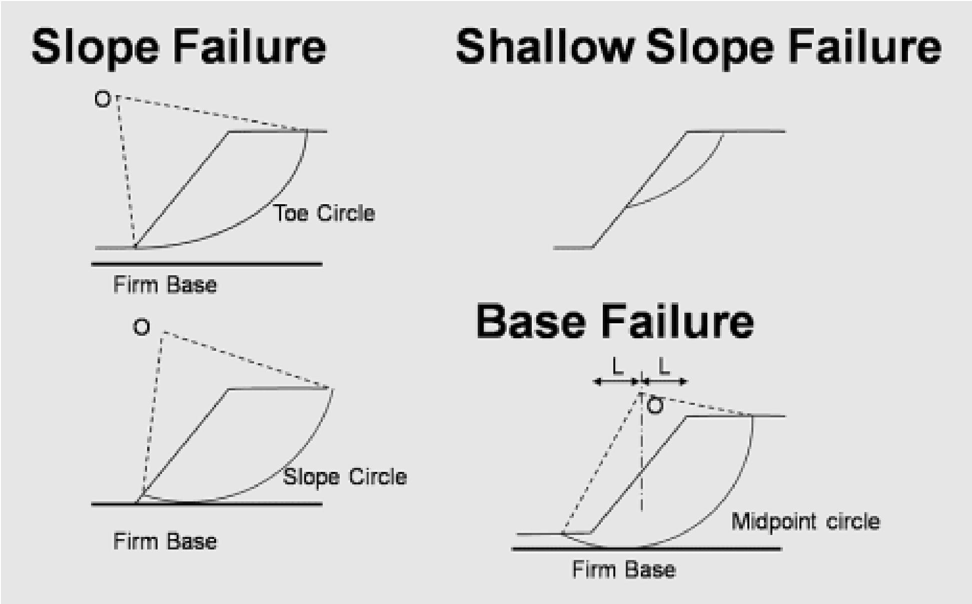
Creep of Chigara village toward Ben Haroune Dam

3.5. Cut Slopes and Fill Slopes on Non-Compressible Soils

Definition

Failure typically occurs as rotational slips with circular failure surfaces, categorized as follows:

- ***Slope circles:*** Occur in heterogeneous soils, with the circle base at a stronger layer.
- ***Toe circles:*** Most common.
- ***Deep circles:*** Occur when weak soil lies below the toe.



Different types of rotational slides

3.6. Embankment Slopes on Compressible Soils

Definition

Failures in compacted earth embankments (e.g., road fills) overlying soft clay, silt, or peat deposits typically exhibit the following characteristics:

Failure Mechanism:

- Rotational slip surfaces tangent to the base of the compressible layer when relatively thin
- Critical dependence on the underlying weak stratum thickness

Long-Term Stability Concerns:

Failures in compacted soil embankments (e.g., road fills) overlying soft clay, silt, or peat deposits typically exhibit the following characteristics:

Failure Mechanism:

Rotational slip surfaces tangent to the base of the soft layer when relatively thin

Potential creep-induced foundation deformation when the safety factor is marginally above 1.0, leading to:

- Excessive embankment settlement
- Lateral heaving of the soft stratum
- Strength reduction in the embankment material

Example

Case Example:

The current road embankment construction across Chott El Hodna's sebkha demonstrates these challenges. The firsrt photo shows significant sub-grade deformations during low-water periods. Despite surface water presence (second photo)), construction was enabled through:

- Filtration geotextiles

- Reinforcement geogrids (visible in photo)

Embankment on compressible soil (Chott El Hodna)

Junction of embankment sections during construction

3.7. Earth Dams and Embankments

Definition

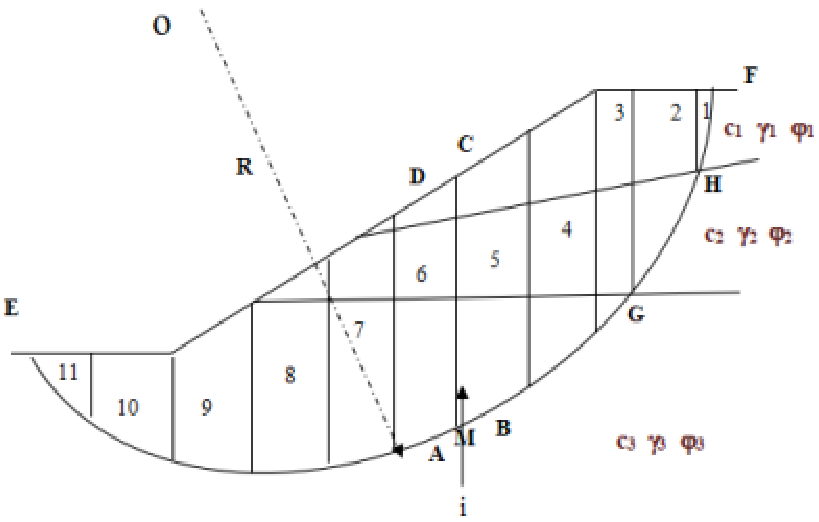
The stability analysis of upstream and downstream slopes constitutes a critical component in the design of earth dams. The structural integrity of these constructions must be verified under various loading conditions, with particular consideration given to the pore water pressure distribution within the dam body.

4. Circular Failure Stability with Global Safety Factor

4.1. Fellenius' Slice Method

Method:a. Stability for a Given Circle

A slope intersecting multiple soil layers (properties: C_i, γ_i, φ_i). The stability analysis assumes plane strain conditions (two-dimensional problem).



Division of a slope into elementary slices.

For an arbitrary slip circle with center O and radius R, we evaluate the safety factor against sliding. The method involves dividing the potentially unstable soil mass above the arc EMF into vertical slices.

Key Observations:

- The slicing should ensure that any intersection between the slip circle and layer boundaries coincides with slice boundaries
- Field experience demonstrates that satisfactory accuracy can be achieved with a limited number of slices

For any given slice ABCD with total weight W_i, the acting forces include:

Weight components:

Normal component (N_i) perpendicular to the circular arc AB

Tangential component (T_i) parallel to AB

Boundary forces:

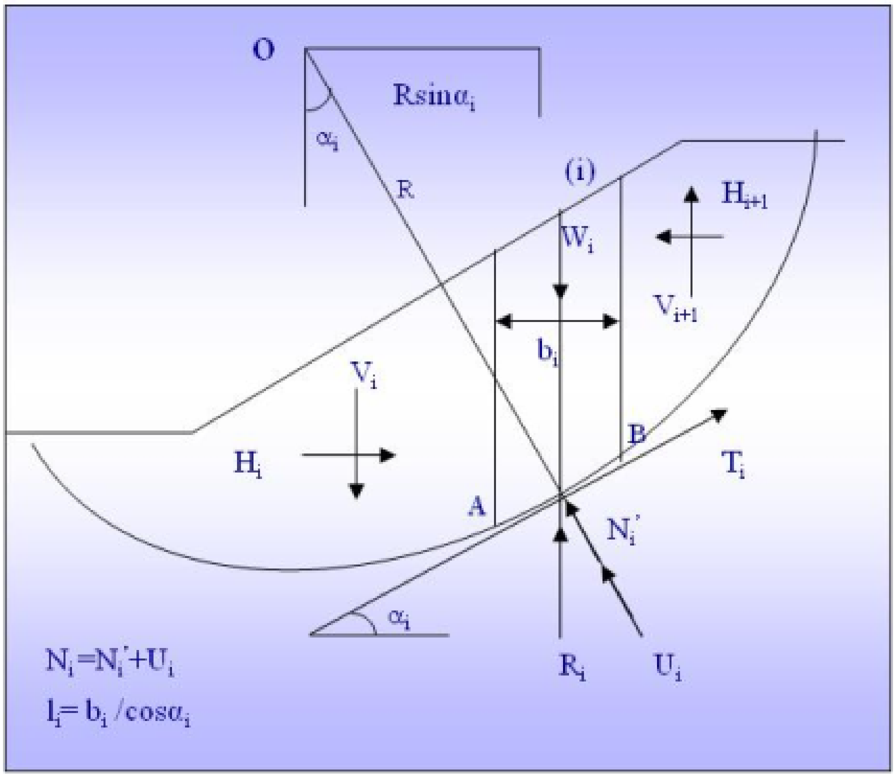
Subgrade reaction (R_i) along arc AB

Neighboring slice reactions:

Horizontal components (H_i , H_{i+1})

Vertical components (V_i , V_{i+1})

Pore water pressure force (U_i) acting along AB



Forces acting on a typical slice ABCD.

Fellenius introduced a key hypothesis that significantly simplifies calculations by considering that the internal forces H_i, H_{i+1}, V_i, and V_{i+1} become self-balancing when analyzing the complete slice system. Their moment contributions are neglected, yielding:

$$H_i - H_{i+i} = 0$$

$$V_i - V_{i+i} = 0$$

Consequently, only two forces remain active on arc AB:

The soil weight W_i

The resultant reaction R_i (where $W_i = R_i$)

leaving only $W_i = R_i$

Driving moment, Generated solely by tangential component T_i is equal to $T_i . R$ (Normal component N_i passes through center O, producing zero moment).

Resisting moment: Maximum available shear resistance along AB

According to Coulomb's failure criterion:

$$(R_i)_t = C_i \cdot AB + N_i \cdot \tan \varphi_i$$

Sum of moments for all slices:

$$\sum_{i=1}^{I=m} R(C_i \cdot AB + N_i \cdot \tan \varphi_i)$$

Where:

m: Total number of slices, c_i' and ϕ_i': Effective shear strength parameters (cohesion and friction angle) of the layer containing arc AB.

The failure surface being bounded by points E and F, the global safety factor F is defined by the ratio:

$$F_s = \frac{\sum_{EF} Maximum\ Resisting\ Moments}{\sum_{EF} Driving\ Moments}$$

The factor of safety (F) is then defined as:

$$F_s = \frac{\sum_{i=1}^{i=m} (C_i \cdot AB + N_i \cdot \tan\varphi_i)}{\sum_{i=1}^{i=m} T_i} = \frac{\sum_{i=1}^{i=m} (C_i \cdot (\frac{b}{\cos\alpha}) + W_i \cdot \cos\alpha \tan\varphi_i)}{\sum_{i=1}^{i=m} W_i \cdot \sin\alpha}$$

Important Notes:

In the safety factor (F_s) formula, $\sum_{i=1}^{i=m} T_i$ represents an algebraic sum.

F_s can be directly applied to mechanical properties through strength reduction:

$$C_i^* = \frac{C_i}{F_{sa}}$$

$$\tan\varphi_i^* = \tan\frac{\varphi_i}{F_{sa}}$$

Where:

C_i, φ_i : Design cohesion and friction angle

F_{sa} : Required minimum safety factor

The slope stability condition then simplifies to:

$$\frac{\sum_{i=1}^{i=m} (C_i^* \cdot AB + N_i \cdot \tan\varphi_i^*)}{\sum_{i=1}^{i=m} T_i} > 1$$

✎ *Note*

Suitable for rapid assessments; used to find critical slip circle with lowest safety factor (F_s).

b. Determining the Minimum Safety Factor

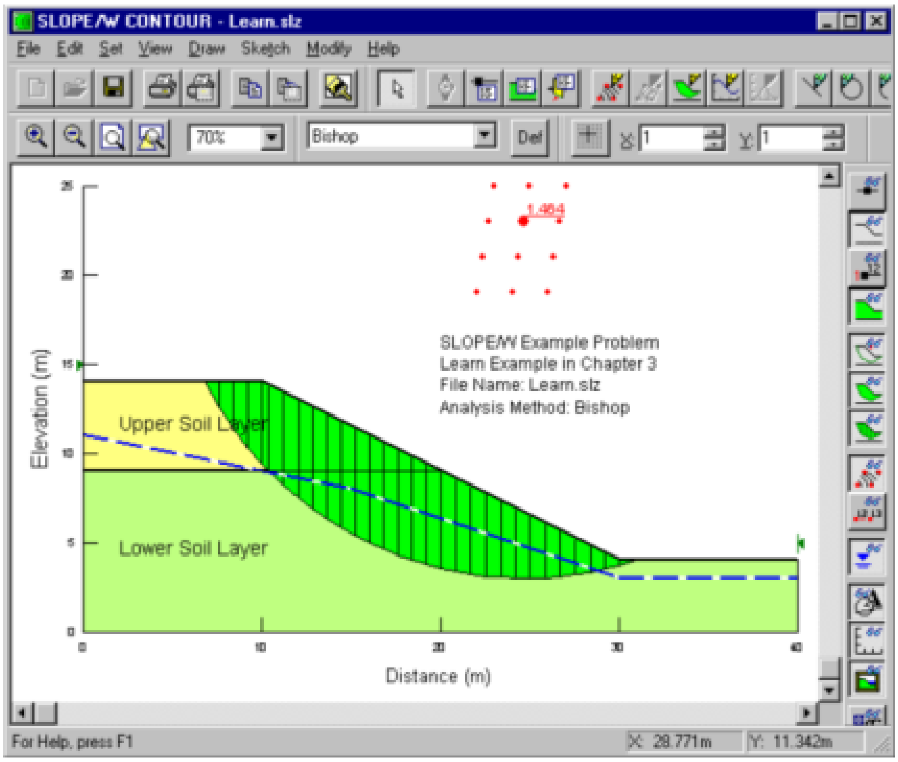
To identify the true safety factor (F_s) of a slope, the critical slip circle yielding the lowest F_s must be found, as failure is most likely to occur along this surface. There is no exact analytical method to predict the position of this critical circle a prior analysis.

Simulation

Industry-Standard Approach:

Most commercial software (e.g., Geo-Slope, shown in the figure below) uses an iterative trial-and-error process:

1. Grid Search: Computes F_s for numerous slip circles
2. Geometric Constraints: Tests only topographically plausible failure surfaces
3. Optimization: Identifies the circle with the minimal F_s as critical



Sample slope stability analysis output from Geo-Slope software.

4.2. BISHOP'S METHOD OF SLICES

Method

The components V_n , V_{n+1} , H_n , H_{n+i} contribute to the forces acting on slice (i) .

- ***Vertical Force Equilibrium:***

$$W_i + \Delta V_i - (N_i' + u_i \cdot l_i)\cos\alpha_i - \left(\frac{C_i'}{F_s} l_i + N_i' \frac{\tan\varphi_i'}{F_s}\right)\sin\alpha_i = 0$$

$$N_i'\left(\cos\alpha_i + \frac{\tan\varphi_i' \sin\alpha_i}{F_s}\right) = W_i + \Delta V_i - u_i l_i \cos\alpha_i - \frac{C_i' l_i}{F_s}\sin\alpha_i$$

$$N_i' = \frac{W_i + \Delta V_i - u_i l_i \cos\alpha_i - \frac{C_i' l_i}{F_s}\sin\alpha_i}{\cos\alpha_i + \frac{\tan\varphi_i' \cdot \sin\alpha_i}{F_s}}$$

- ***Moment Equilibrium:***

Driving moment:

$$\sum_1^n W_i R \sin\alpha_i$$

Resisting moment (opposing movement):

$$\sum_{1}^{n} R\left(\frac{C_i' l_i}{F_s} + N_i' \frac{\tan \varphi_i'}{F_s}\right)$$

By equating moments, substituting (N_i'), and simplifying by R:

$$F_s\left(\sum_{1}^{n} W_i \sin \alpha_i\right) = \sum_{1}^{n} C_i' l_i + \frac{W_i + \Delta V_i - u_i l_i \cos \alpha_i - \frac{C_i' l_i}{F_s} \sin \alpha_i}{\cos \alpha_i + \frac{\tan \alpha_i'}{F_s}}$$

The numerator terms can be rewritten with common denominator:

$$C_i' l_i \cos\alpha + \frac{1}{F_s} C_i' l_i \tan \varphi_i' \sin \alpha_i + (W_i + \Delta V_i - u_i l_i \cos \alpha_i - \frac{1}{F_s} C_i' l_i \sin \alpha_i) \tan \varphi_i'$$

Safety factor formula is given by:

$$F_s = \frac{1}{\sum_{1}^{n} \sin \alpha_i} \sum \frac{C_i' l_i \cos \alpha_i + (W_i + \Delta V_i - u_i l_i \cos \alpha_i) \tan \varphi_i'}{\cos \alpha_i + \frac{1}{F_s} \tan \varphi_i' \sin \alpha_i}$$

This is called the exact Bishop formula.

Solution Procedure:

- Requires iterative calculations since Fs appears on both sides
- Requires additional assumptions to define V_i

Simplified Bishop Method

Assuming $\Delta V_i = V_i - V_{i+1} = 0$, the equation becomes:

$$F_s = \frac{1}{\sum_{1}^{n} \sin \alpha_i} \sum \frac{C_i' l_i \cos \alpha_i + (W_i - u_i l_i \cos \alpha_i) \tan \varphi_i'}{\cos \alpha_i + \frac{1}{F_s} \tan \varphi_i' \sin \alpha_i}$$

Or $$F_s = \frac{1}{\sum_{1}^{n} W_i \sin \alpha_i} \sum_{1}^{n} \frac{C_i' b_i + (W_i - u_i b_i) \tan \varphi_i'}{\cos \alpha_i + \frac{1}{F_s} \tan \varphi_i' \sin \alpha_i}$$

The expression for F_s is not explicit. Therefore, F_s cannot be calculated directly. An implicit method will be used in the form $F_{m+1} = f(F_m)$.

The initial value of F_s can be taken as F_{s0} , the value obtained using the Fellenius method. Convergence is generally quite fast. The process is stopped when $(F_{m+1} - F_m)$ is less than a pre-defined threshold.

✎ *Note*

The Bishop method is more accurate than the Fellenius method, but it requires three to four times more computation (three iterations); the safety factors obtained are generally slightly higher.

🔔 *Reminder*

Most often, to avoid excessively increasing the amount of calculation, the most critical slip circle is first determined using the Fellenius method, and then it is verified that the safety factor calculated using the Bishop method is greater than that calculated using the Fellenius method.

If this is not the case, the search for the critical circle must be redone using the Bishop method. (Philipponnat G. & Hubert B, 2000)

4.3. Choosing the Safety Factor

Fundamental

A probabilistic value must be associated with the global safety factor F_s. Experience has shown that, barring major errors in the calculation assumptions:

Slopes always remain stable if F_s >1.5

Sliding is almost inevitable if F_s <1

There is an increasing risk of sliding as F_s decreases, when 1< F_s <1.51