SLOPE STABILITY ASESSMENT

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Slope Stability Asessment

- Introduction: Slope Failures
- Types of Slope
- Causes of Failures
- Types of Failures
- Method of Analysis
- Slope stabilization

Slope Failures

Slope Failure is the movement of mass on slope (falls, slides, flows)

Landslide: involves an extensive area, mild slope (<20^o), movement is slow and gradual.

Slope Failure: limited area, steep slope, movement is fast (sometimes with no signs)

The stability of a slope should be evaluated when slope movement due to additional load or loss of strength is identified to cause problems.

Slope Failures

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Problems related to slope failures

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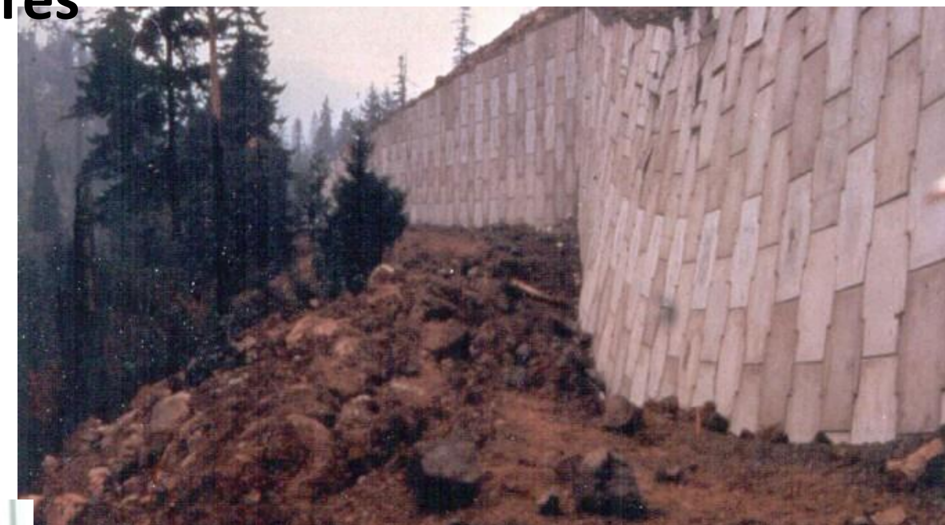

Types of Slope

Natural Slopes

- Long term process
- Short process

Man-made Slopes

- Excavated Slopes
- Slopes of Embankment and Earth Dam

Man-made slopes

embankment slope

cut slope

Causes of Slope Failure

Some factors have been identified to cause slope failures i.e.:

- Geometrical factors: slope inclination, additional load or fill height,
- excessive pore water pressure,
- loss of shear strength due to weathering,
- Liquefaction (earthquake),
- water (infiltration, seepage, ground water table).

Man made slopes

Most failures of man-made slope are caused by design errors (60%), construction error (8%) while design and construction errors take 20%

These include geometric design i.e. slope inclination, slope height and inability to estimate load or fill height including pore-water and seepage pressure.

Other cause of slope failure include geology (6%) and maintenance (6%)

Natural & Man made slopes

Natural slopes are not safe either.

Both man-made and natural slopes that have been standing for years can fail due to loss of shear strength due to weathering, liquefaction, and water (rainfall infiltration and seepage) as well as erosion process.

The presence of tension crack in slope surface plays a major contribution to slope failure. Furthermore, lack of maintenance, utilities etc. can cause slope failures.

Types of Failures

Wedge Failure is the soil mass movement due to external force. This type of failure usually occur on a weak plane or weak joint

Translational Failures occur where the form of failure is influenced by the presence of weak layer. The failure surface tends to be plane and roughly parallel to the slope surface

Circular Failure or non circular failure,

Circular failure are associated with homogeneous soil conditions

Non-circular slips are associated with non- homogeneous conditions

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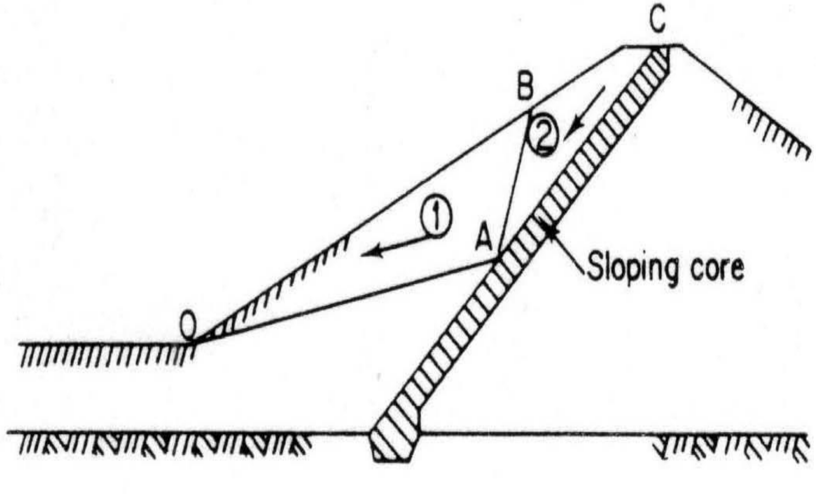

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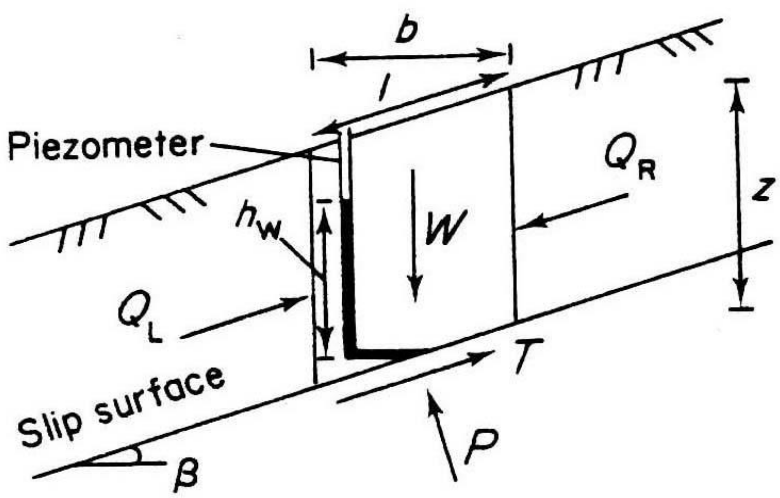
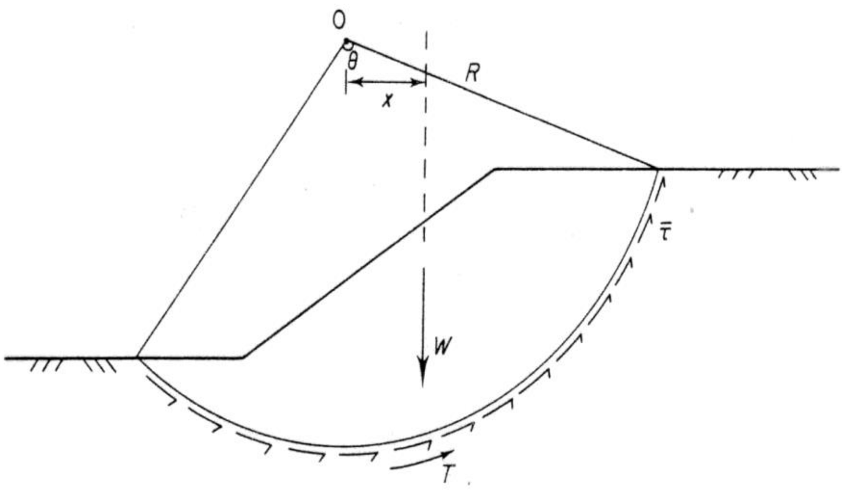


Circular Failure or non circular failure

the shape of failure plane maybe circular or non-circular. In general, circular slips are associated with homogeneous soil conditions while non-circular slips are associated with non-homogeneous conditions



Concept of Stability Analysis

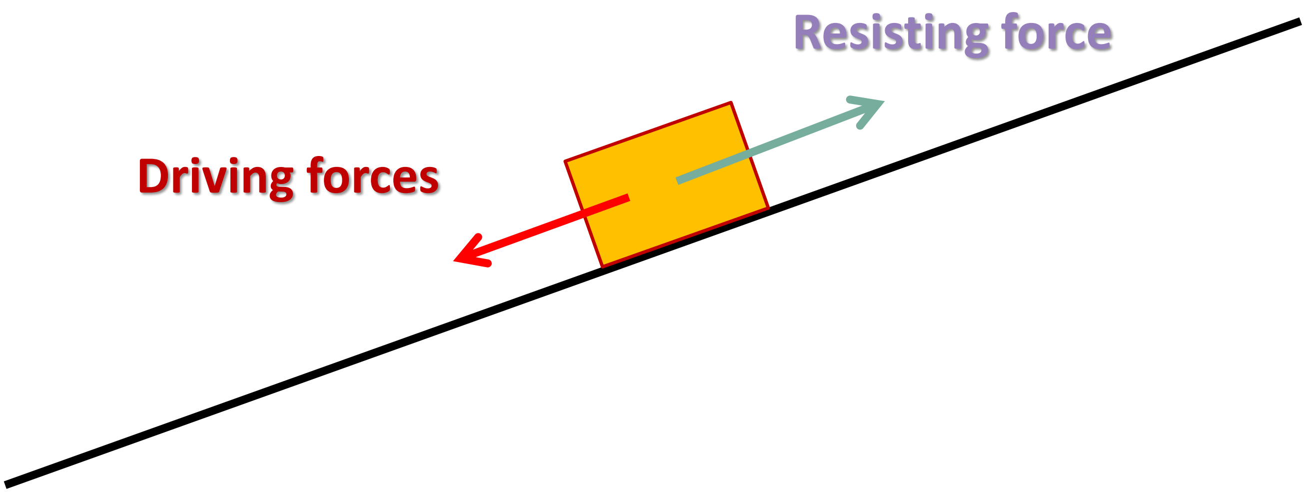
Slope failure occurs when the driving force is larger than the resisting force

LIMIT EQUILIBRIUM CONCEPT

Driving forces move material down the slope (Most common = weight of slope material and structures on slope)

Resisting forces oppose downward movement (Most common = strength of slope material)

Read Chapter 7 Duncan and Wright
Method of analyzing slope stability



Slope Stability

- Slope stability is evaluated by computing Factor of Safety
- **Factor of Safety = ratio of resisting forces to driving forces**
- FOS = 1.0 → Threshold of failure

LIMIT EQUILIBRIUM ANALYSIS

Calculation of factor of safety

SIMPLE

As long as we can obtain the soil properties and type of analysis (Undrained vs Drained)

Searching for Critical Failure Plane

QUITE DIFFICULT

With the advantage of computer program. You can create a simple program based on Slices Methods or use available program

Critical Failure Plane

The first thing to do in the slope stability analysis is to find the most dangerous or the most critical surface (location & shape). Then, impose several assumptions i.e:

- the failure occurs in two-dimension,
- rigid block movement taking place on the failure surface itself, and
- uniform shear stress is mobilized over the whole length of the failure surface.

Factor of Safety

Factor of safety is the shear strength at the time of failure τ_f compared to the stress acting at that plane τ_m.

$$FS = \frac{\tau_f}{\tau_m} > 1$$

If *FS = 1*, then the slope is in critical condition.

At the time of failure, the shear strength of the soil is fully mobilized along the failure plane. The shear strength is represented by the Mohr-Coulomb criteria:

$\tau = c_u$ (Total stress analysis)

$\tau = c' + \sigma' \tan \phi'$ (Effective stress analysis)

Limit Equilibrium Analysis

In general, there are two methods of limit equilibrium analysis i.e.:

Linear methods for relatively simple situation

- Slope in dry cohesionless soil
- Slope in cohesive soil (undrained condition)
- Infinite slope analysis for surface failure

Non-linear methods or Method of Slices which is necessary for complex situation involving irregular slope geometry, non-uniform soil condition, and slope analyses involving the consideration of seepage in soil.

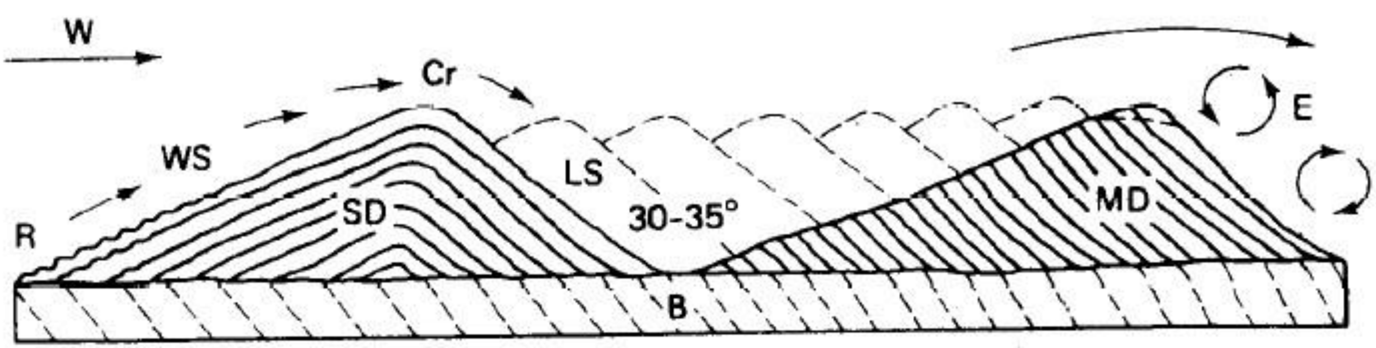
Read: Duncan and Wright (2005) *Soil Strength and Slope Stability chapter 6*

Linear method, dry cohesionless soil

$$FS = \frac{\tan \phi'}{\tan \beta}$$

where ϕ' = internal friction angle,

β = slope angle/angle of repose



When slope angle (β) of a sand slope > ϕ, the sand slope tends to fail by sliding in a downhill direction parallel to the slope

The greatest slope for free-standing cohesionless soil = ϕ

The slope angle at which a loose sand fails may be estimated by its angle of repose, the angle formed by sand as it forms a pile below a funnel through which it passes

Linear method,
Slope in Homogeneous Cohesive soil
(ϕ= 0 analysis)

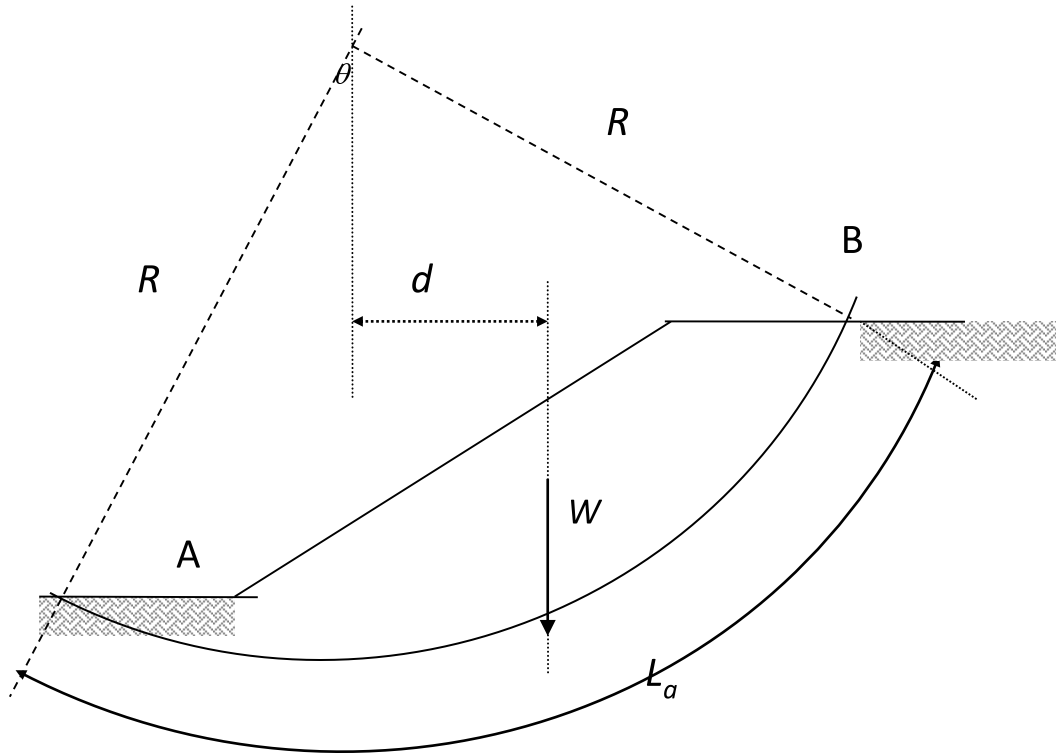
In homogeneous cohesive soils relatively unaffected by faults or bedding, deep seated shear failure surfaces tend to form in a circular, rotational manner.

This failure plane sometimes reached interface between the soil and the stronger layer underneath the soil.

The slope with larger inclination will have a shallow failure plane as compared to those with small slope angle.

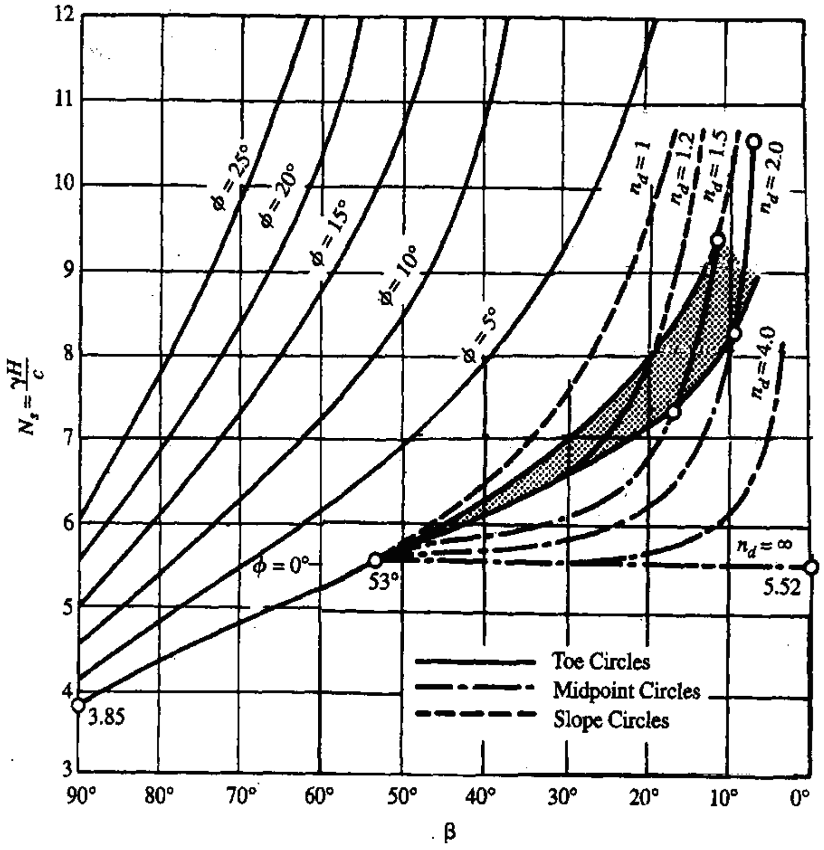
Factor of safety

$$FS = \frac{c_u \, L_a \, R}{W \, d}$$

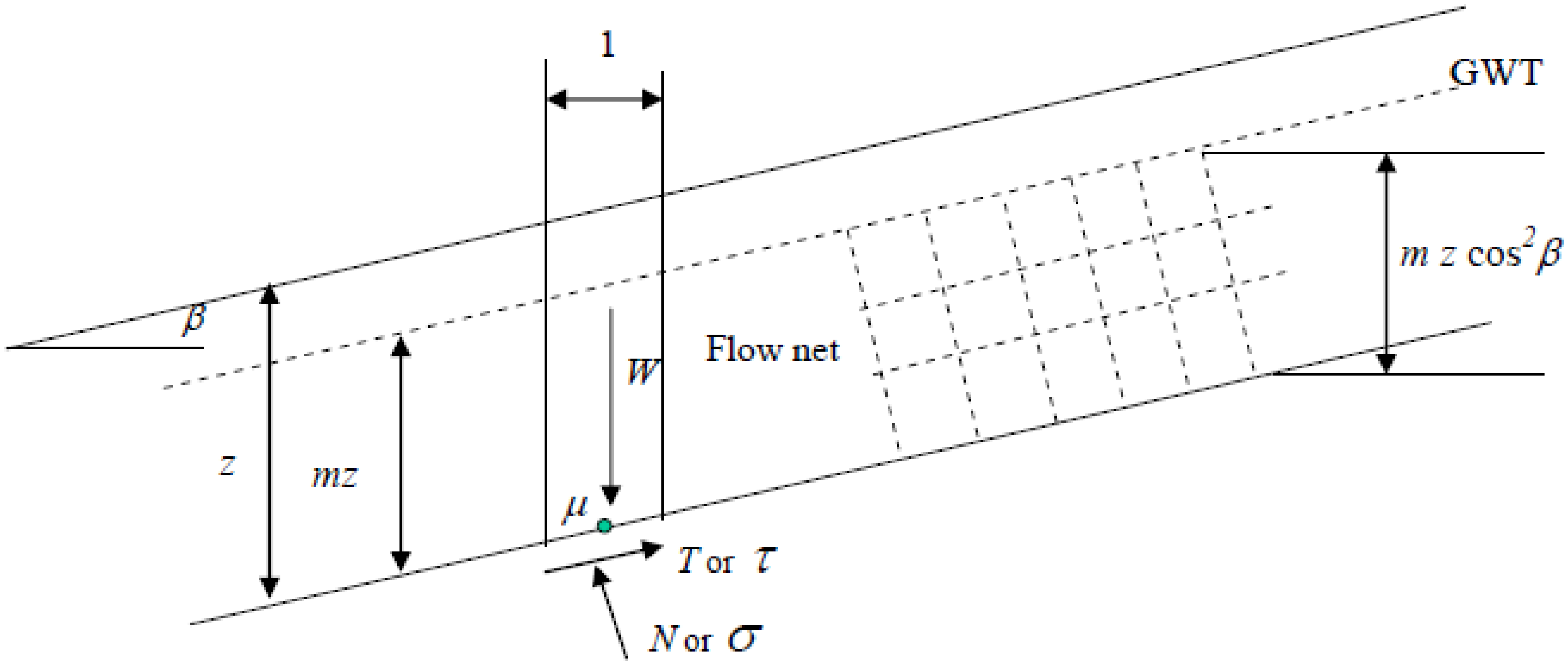


Stability number method (Taylor's chart)

$$FS = \frac{N_s \ c_u}{\gamma H}$$



Linear Method: Infinite Slope Analysis



failure surface is parallel to the ground surface

factor of safety is assumed constant along the failure plane.

The equation for factor of safety (*FS*) of infinite slope with failure plane of depth *D* can be used to determine the stability of a slope against surface failure.

$$FS = \frac{c' + \gamma' D \cos^2 \beta \tan \phi'}{\gamma_b D \cos \beta \sin \beta}$$

where ϕ' is the effective friction angle, c' is the effective cohesion, γ_b is the wet density and γ' is the buoyant density of the soil. The slope forms an inclination β.

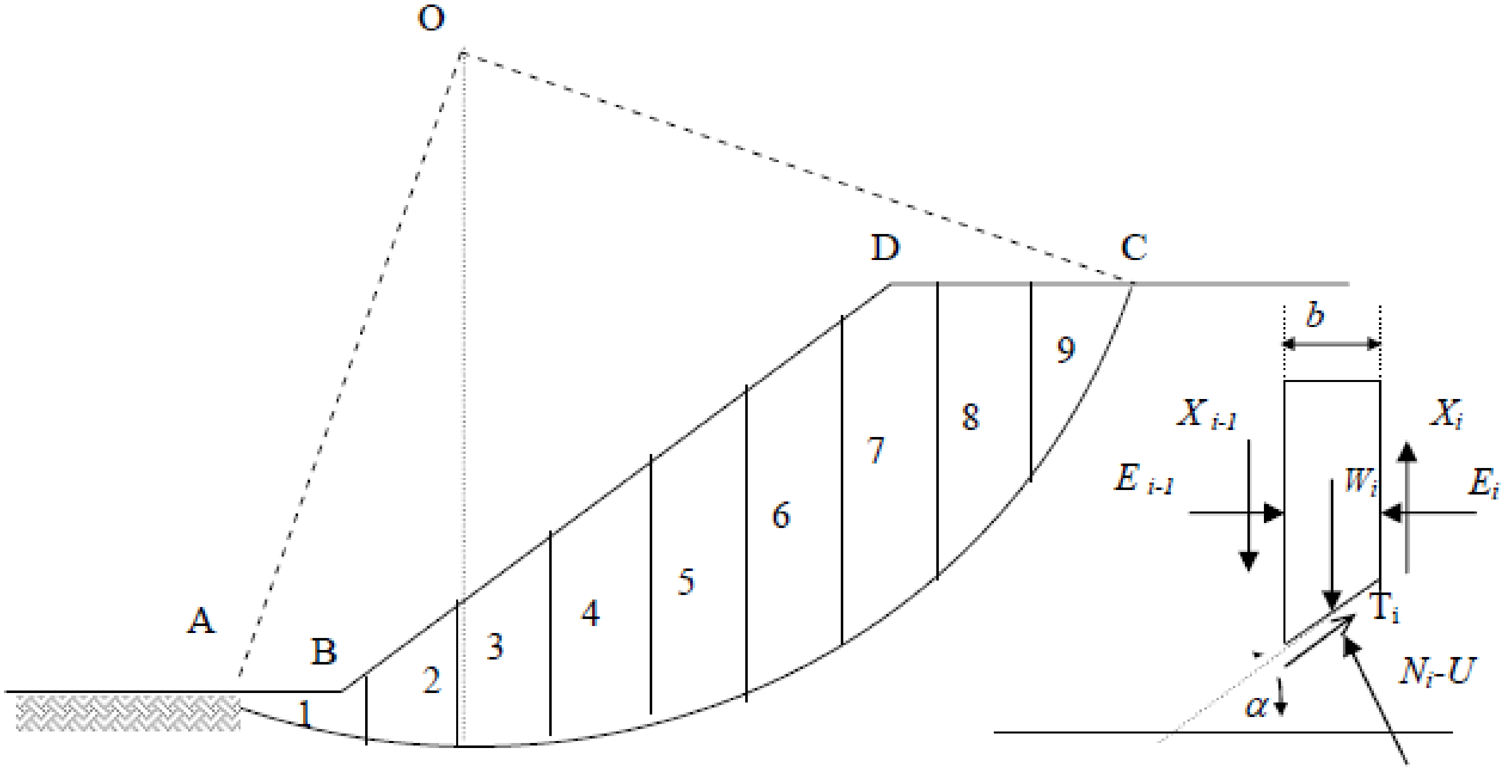
Non-linear Method: Method of Slices

Most of the times, the slope stability cannot be analyzed using the simple methods presented earlier especially for slope with both cohesion and internal friction angle $\phi > 0$.

This analysis is generally done by using slices methods.

In this method, the potential failure surface is assumed to be circular or non-circular.

Method of Slices



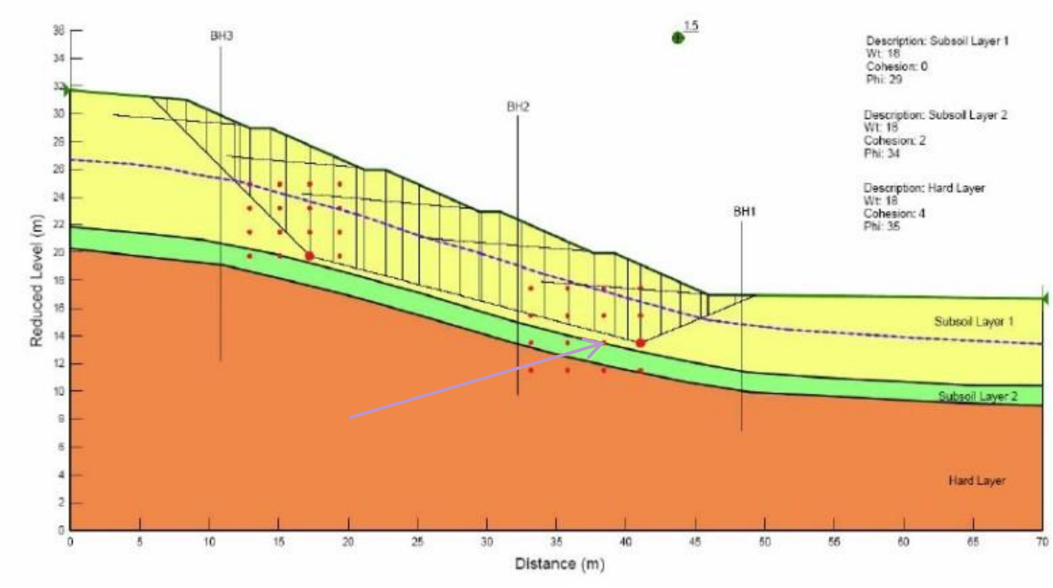
forces acting on a slice

Common Methods of slices

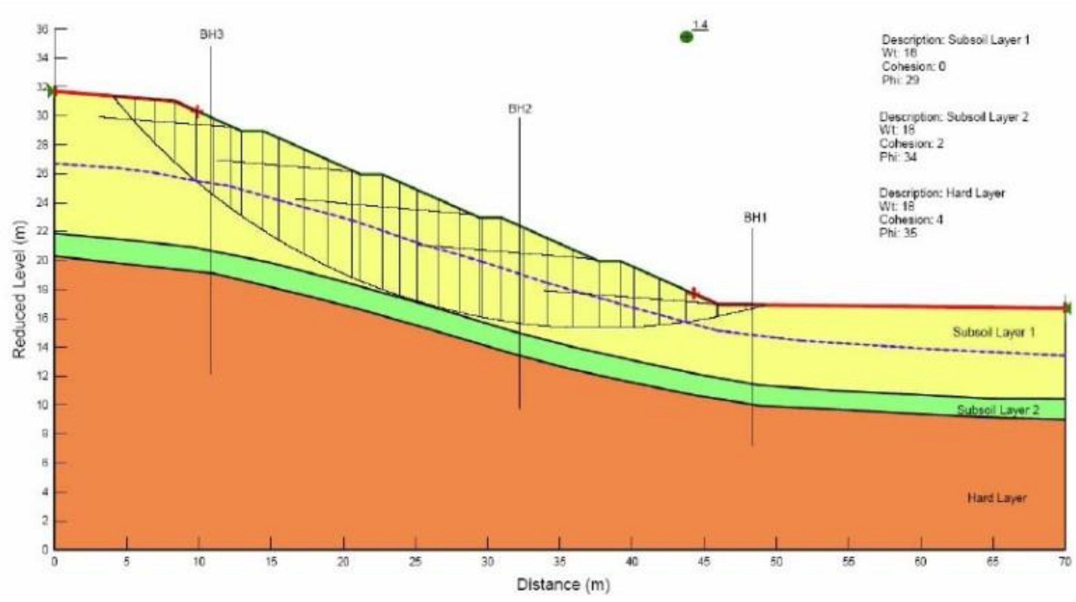
Method	Force equilibrium	Moment equilibrium	Shape of slip surface
Ordinary method of slices (Fellenius, 1927)	Does not satisfy horizontal or vertical forces equilibrium	Yes.	Circular
Bishops Modified (Bishop, 1955)	Satisfy vertical force but not horizontal force equilibrium	Yes.	Circular only. Non circular may have numerical problems.
Janbu's simplified method (Janbu, 1956)	Yes	No	Any shape. More frequent numerical problems than other methods
Morgenstern and Price (Morgenstern and Price, 1965)	Yes. Permits side forces to be varied	Yes.	Any shape.
Spencer's Method (Spencer, 1967)	Yes. Side forces are assumed to be parallel	Yes.	Any shape.

Non-circular

Failure Plane



Circular



Methods of Slices

Due to repetitive nature of the calculations and the need to select the most critical failure surface, the method of slices is particularly suitable for solution by computer program.

More complex geometry and soil strata can be introduced.

Many computer programs have been developed based on limit equilibrium methods and available for use.

However, it is quite easy to develop your own program for some simple problems

Types of analysis

The shear strength is represented by the Mohr-Coulomb criteria:

Total stress analysis: $\tau = c_u$

Effective stress analysis

$$\tau = c' + \sigma' \tan \phi'$$

Total stress vs. effective stress

The most critical condition for excavated slope is long term, while the most critical condition for embankment is short term.

total stress concept is more appropriate for slope made of low permeability soil such as clay

effective stress concept is to be applied for long term situation

Short term	**Total stress analysis**	**Undrained strength**
Long term	**Effective stress analysis**	**Drained strength**

Estimation of soil parameters & FOS

Accurate estimate of shear strength parameters is important in limit equilibrium analysis. It is therefore common in practice to impose a factor of safety in slope stability analysis. Conventionally,

FOS of 1.25 to 1.4 is considered appropriate for natural slope and routine cut and fills,

higher FOS is required for the design of dam.

Read Duncan and Wright (2005)
Soil Strength and Slope Stability
chap 3

Eurocode Design

EuroCode (EC) 7. Design Approach 3

applies for slope stability analysis:

Design Approach 3 deals with situations in which the values of ground properties are uncertain, therefore partial factors greater than unity are applied to the relevant soil parameters.

Factors are applied to actions or the effect of actions from the structure and to ground strength (materials parameter).

A single calculation is required for each part of the design, and the way in which the factors are applied is varied according to the calculation considered.

Estimation of Load and soil parameters

<u>Clause 2.4.7.3.4.4</u>

Use combination : (A1 or A2) + M2 + R3

For slope and overall stability analyses, action on the soil (eg structural action, traffic load) are treated as geotechnical actions by using A2

c' and tanϕ' should be divided by factors 1.60 and 1.25, respectively (MA: 1.35 for both c' and tanϕ').

Parameter c_u should be divided by 1.40 (MA: 1.50)

A factor of unity is appropriate for the self-weight of the soil and for pore water pressures.

However, variable loads on the soil surface adjacent to the slope should be multiplied by a factor of 1.30. (MA: 1.35 (Permanent unfavorable) or 1.50 (Variable Unfavorable).

Strength Reduction Technique

Slope failure occurs when the driving force is larger than the resisting force

STRENGTH REDUCTION

Driving forces assumed CONSTANT

Resisting forces DECREASE
Due to reduction in strength of the slope material)

Read Dawson et. al.,(1999). Slope stability analysis by strength reduction, Geotechnique 49 (6): 835-840

Finite Element Analysis with Strength reduction technique

"strength reduction factor" – gradually reduce shear strength until slope start to fail

$\tau = c'_F + \sigma \tan \phi'_F$

$c'_F = c' / SRF$

$\phi'_F = \tan^{-1} (\tan \phi' / SRF)$

where

c'_F and ϕ_F' – factored shear strength

SRF – strength reduction factor

Advantages of shear strength reduction technique in FEM:

No need to assume shape and location of slip surface, Predict progressive failure, Consider reduction in shear stress due to defomation

Assignments

Develop a spreadsheet program for limit equilibrium analysis of slope using Bischop routine method on Case 4 in Duncan & Wright book Chapter 7 (pg 120).

Note: you can check your results using SLOPE/W or other slope stability program.

Thanks for your attention