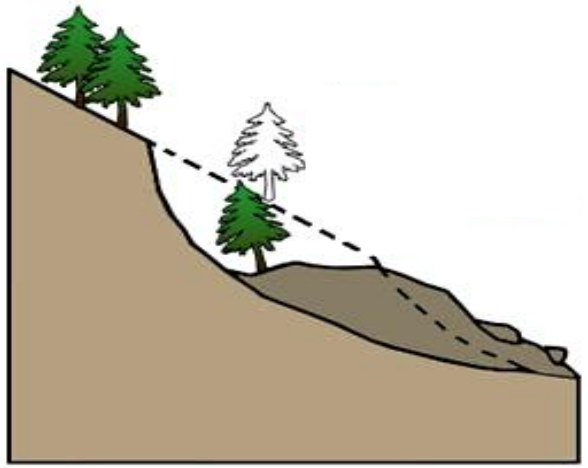
SLOPE STABILITY

Chapter 15

Omitted parts:

Sections 15.9, 15.13, 15.14,15.15



TOPICS

- Introduction
- Types of slope movements
- Concepts of Slope Stability Analysis
- Factor of Safety
- Stability of Infinite Slopes
- Stability of Finite Slopes with Plane Failure Surface
  - Culmann's Method
- Stability of Finite Slopes with Circular Failure Surface
  - Mass Method
  - Method of Slices

TOPICS

- **Introduction**
- Types of slope movements
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SLOPE STABILITY

What is a Slope?

An exposed ground surface that stands at an angle with the horizontal.

Why do we need slope stability?

In geotechnical engineering, the topic stability of slopes deals with:

1. **The engineering design of slopes of man-made slopes in advance**

   (a) Earth dams and embankments,
   (b) Excavated slopes,
   (c) Deep-seated failure of foundations and retaining walls.

2. **The study of the stability of existing or natural slopes of earthworks and natural slopes.**

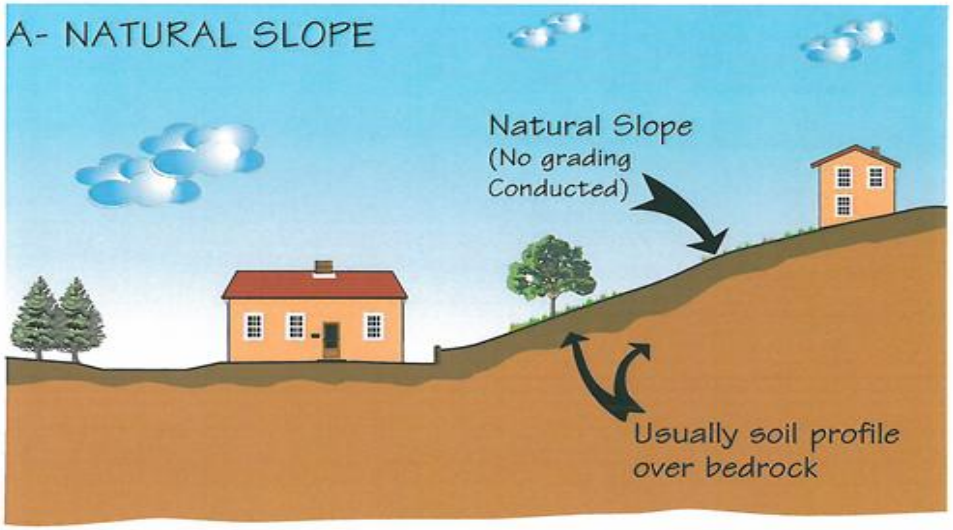
- **In any case the ground not being level results in gravity components of the weight tending to move the soil from the high point to a lower level. When the component of gravity is large enough, slope failure can occur, i.e. the soil mass slide downward.**
- **The stability of any soil slope depends on the shear strength of the soil typically expressed by friction angle (ϕ) and cohesion (c).**

TYPES OF SLOPE

Slopes can be categorized into two groups:

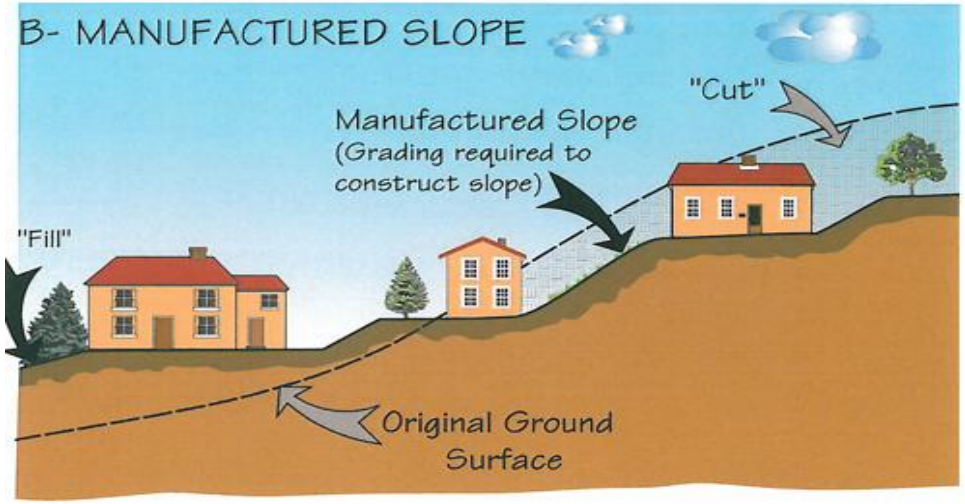
A. Natural slope

- Hill sides
- Mountains
- River banks



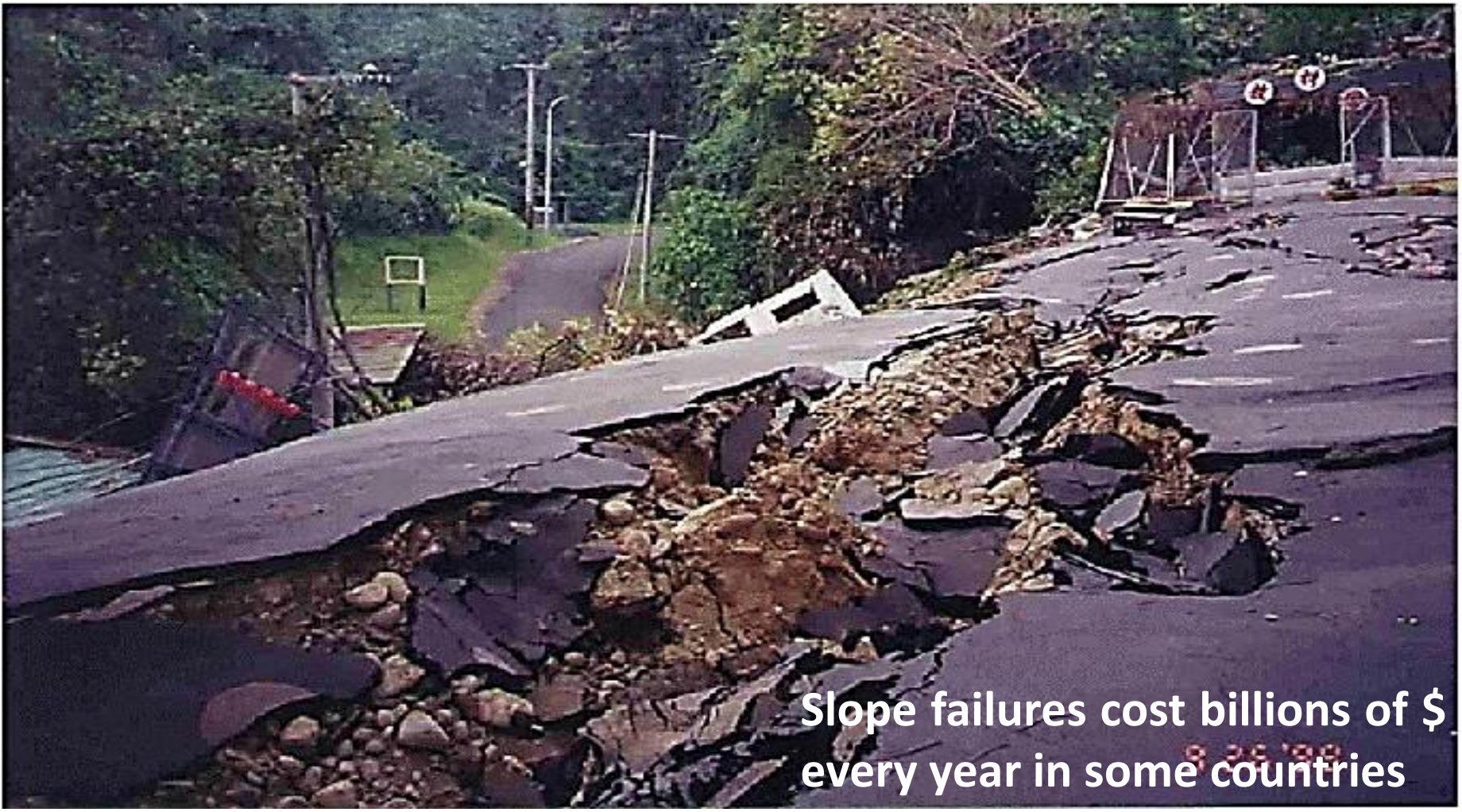
B. Man-made slope

- Fill (Embankment)
- Earth dams
- Canal banks
- Excavation sides
- Trenches
- Highway Embankments



Case histories of slope failure

- Some of these failure can cause dramatic impact on lives and environment.



Case histories of slope failure

Bolivia, 4 March 2003, 14 people killed, 400 houses buried



Case histories of slope failure

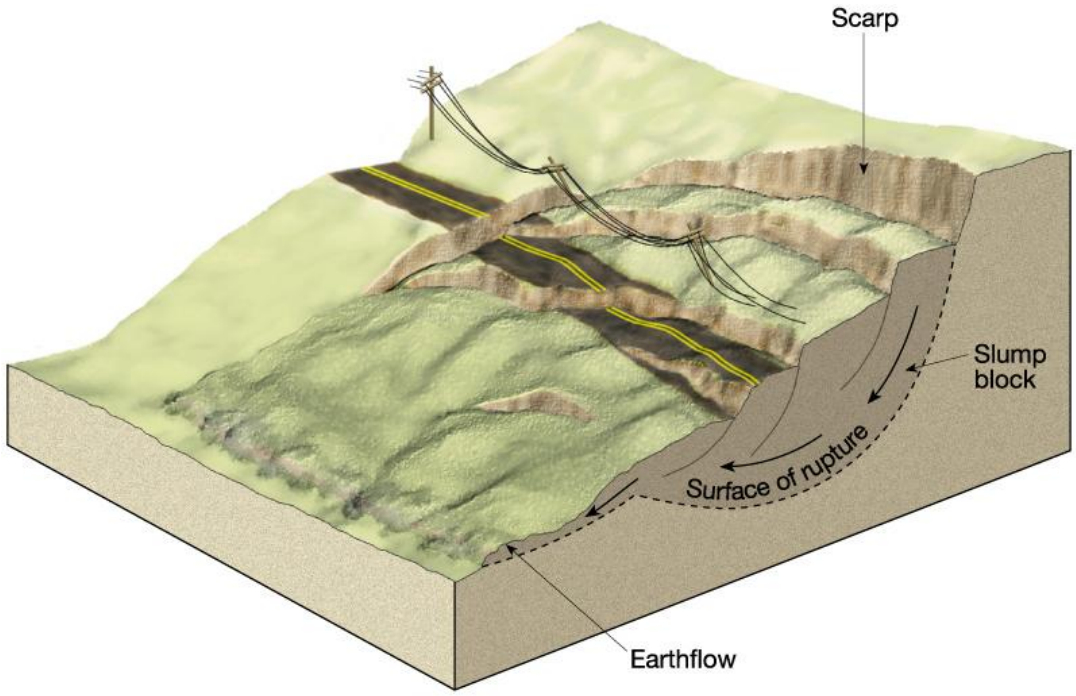
Brazil, January 2003, 8 people killed



Case histories of slope failure



LaConchita California Slump



Case histories of slope failure





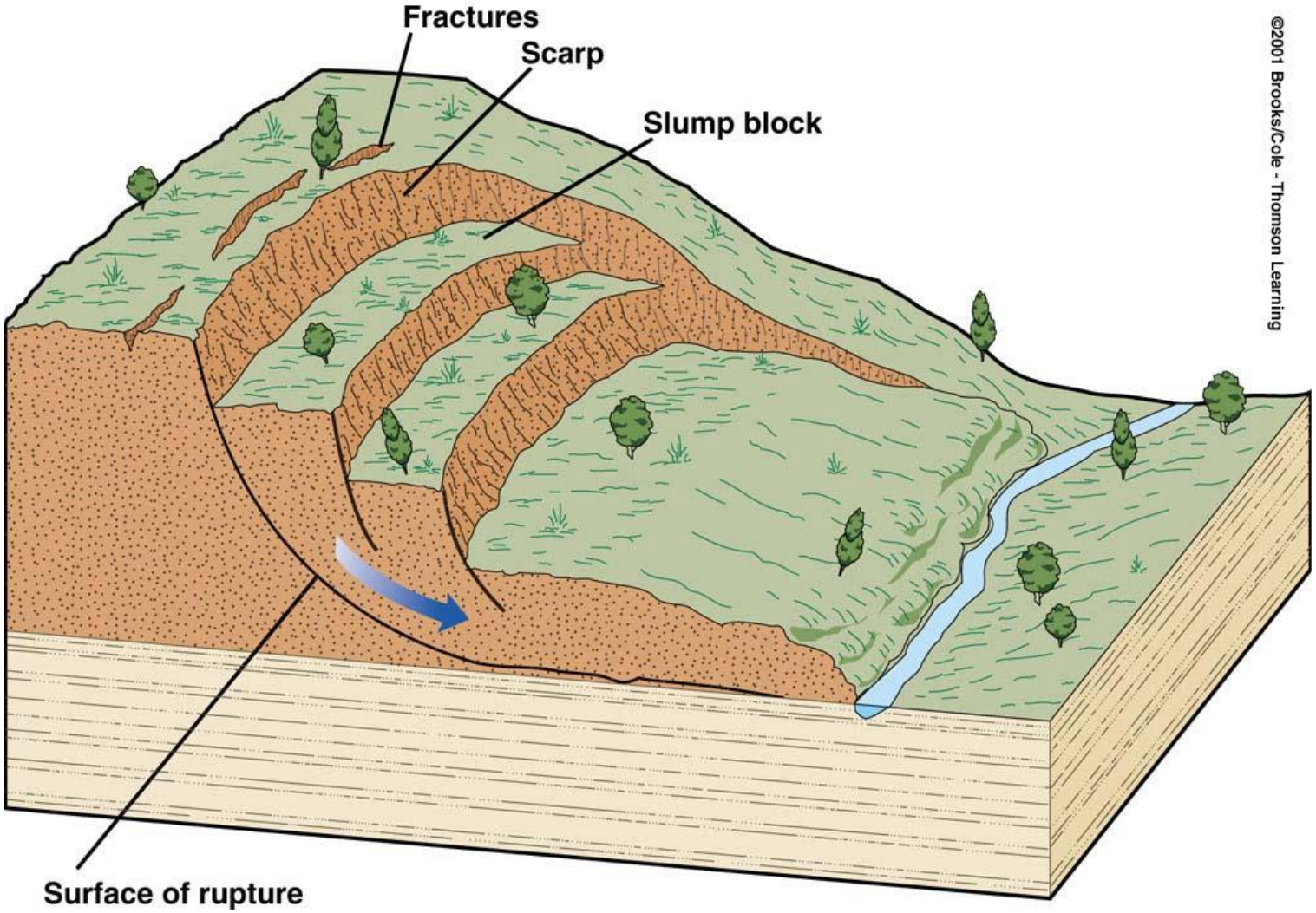
Case histories of slope failure





Case histories of slope failure

Slides: Rotational (slump)



Case histories of slope failure

Major slope-instability related catastrophes of the 20th century

Kansu (China)	1920	Loess flow	200,000 killed
Gros Ventre (Wyoming)	1925	Rockslide	~40 killed
Madison (Montana)	1959	Rockslide	>100 killed
Vaiont (Italy)	1963	Rockslide	2,600 killed
Aberfan (Wales)	1966	Debris-slide	144 killed
Huascaran (Peru)	1970	Complex	25,000 killed
Nevado del Ruiz (Colombia)	1985	Debris flow	23,000 killed
Casitas (Nicaragua)	1998	Debris flow	+2,000 killed
Venezuela	1999	Complex	+20,000 killed
Swiss/Italian Alps	2000	Debris flow	38 killed

- Injury & loss of life
- Property damage & communication problems
- Social & economic disruption
- Loss of productive land
- Annual economic losses
  - USA >2 billion US$
  - Japan ~4 billion US$
- 1999 Venezuela debris flows ~ 50,000 dead
  - 10 billion US$
  - 10.2% of GDP
- 2000 Swiss & Italian landslides and debris flows ~ 8. 5 billion US$

TOPICS

- Introduction
- **Types of slope movements**
- Concepts of Slope Stability Analysis
- Factor of Safety
- Stability of Infinite Slopes
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  - Culmann's Method
- Stability of Finite Slopes with Circular Failure Surface
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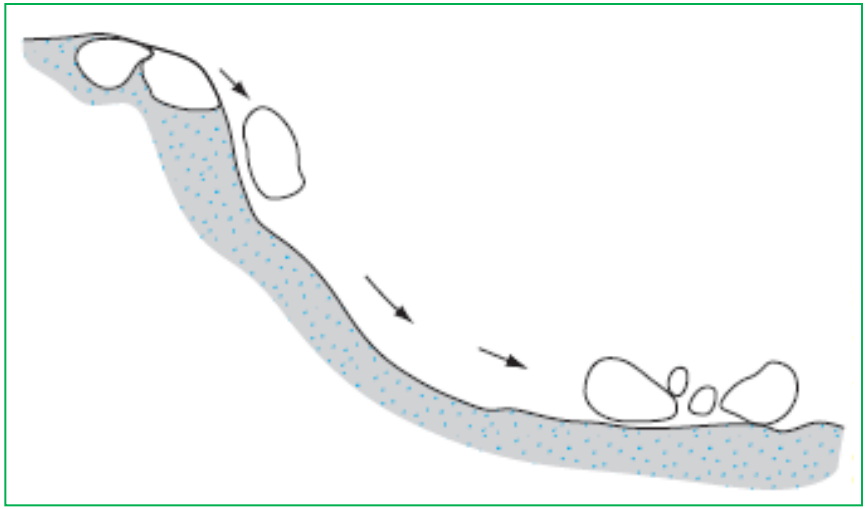
Types of Slope Movements

- Slope instability (movement) can be classified into six different types:
  - Falls
  - Topples
  - Slides
  - Flows
  - Creep
  - Lateral spreads
  - Complex

Falls

- **Rapidly moving mass of material (rock or soil) that travels mostly through the air with little or no interaction between moving unit and another.**
- **As they fall, the mass will roll and bounce into the air with great force and thus shatter the material into smaller fragments.**
- **It typically occurs for rock faces and usually does not provide warning.**
- **Analysis of this type of failure is very complex and rarely done.**





Falls

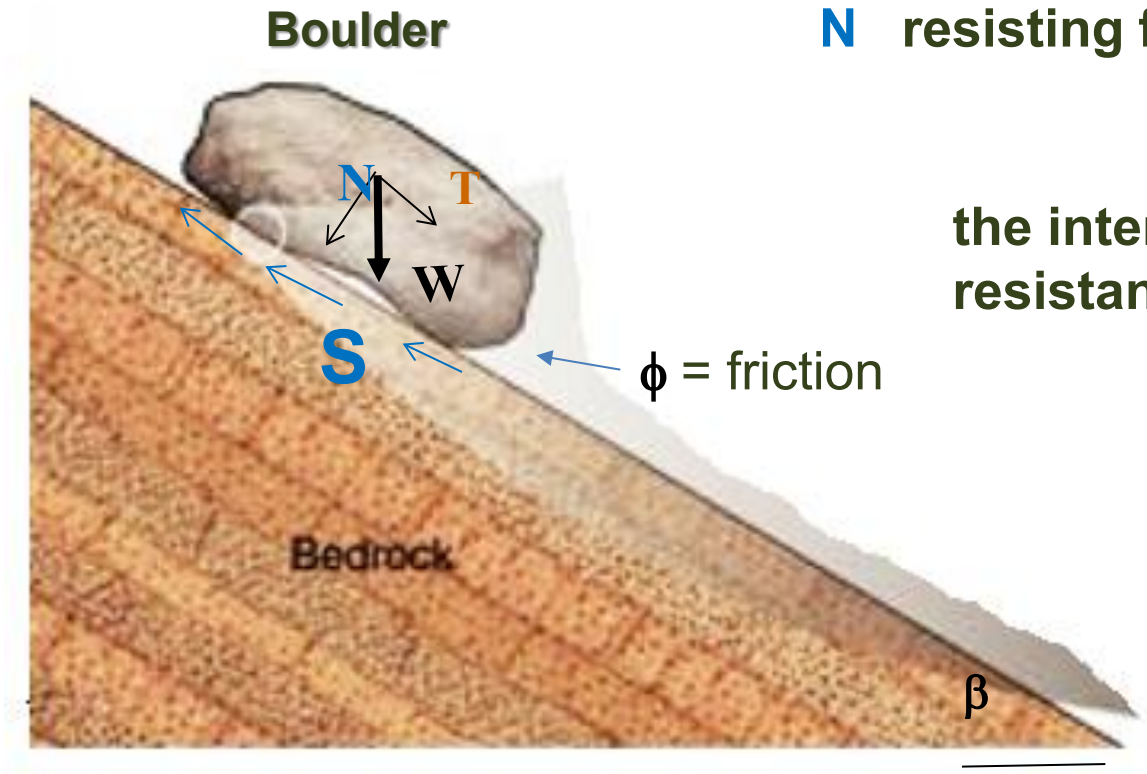
- **Gravitational effect and shear strength**

Gravity has two components of forces:

T driving forces: $T = W . \sin \beta$

N resisting forces (because of friction)

$N = W . \cos \beta$



the interface develop its resistance from friction (ϕ):

$S = N \tan \phi$

In terms of stresses:

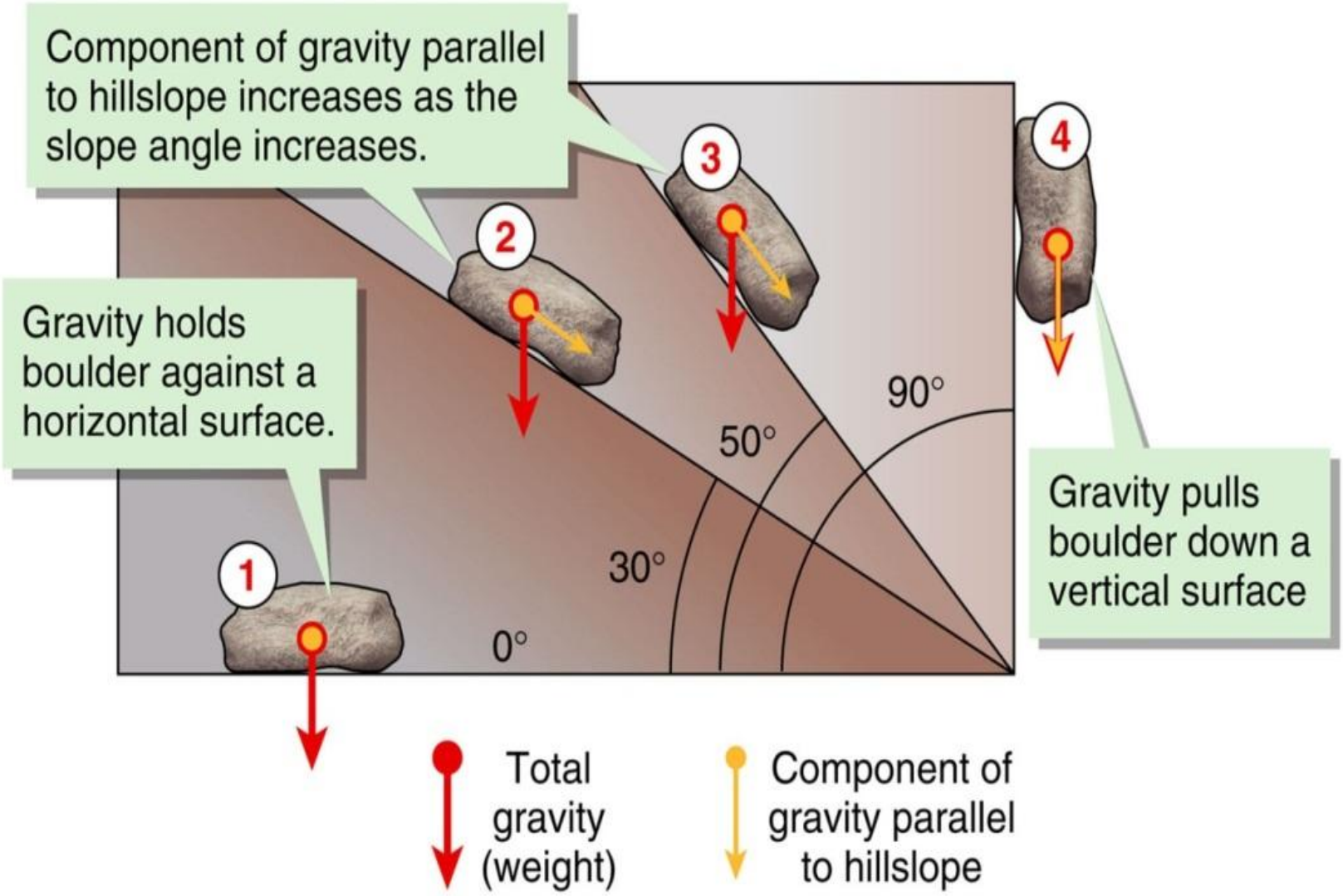
$S/A = N/A \tan \phi$

or

$\tau_f = \sigma \tan \phi$

A = effective Base Area of sliding block

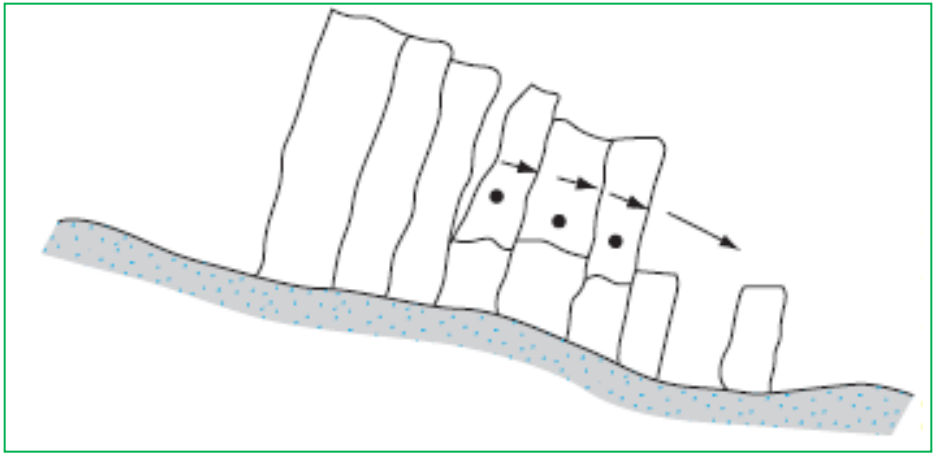
Falls


Component of gravity parallel to hillslope increases as the slope angle increases.
Gravity holds boulder against a horizontal surface.
Gravity pulls boulder down a vertical surface
1
2
3
4
0°
30°
50°
90°
Total gravity (weight)
Component of gravity parallel to hillslope

Topples

This is a forward rotation of soil and/or rock mass about an axis below the center of gravity of mass being displaced.



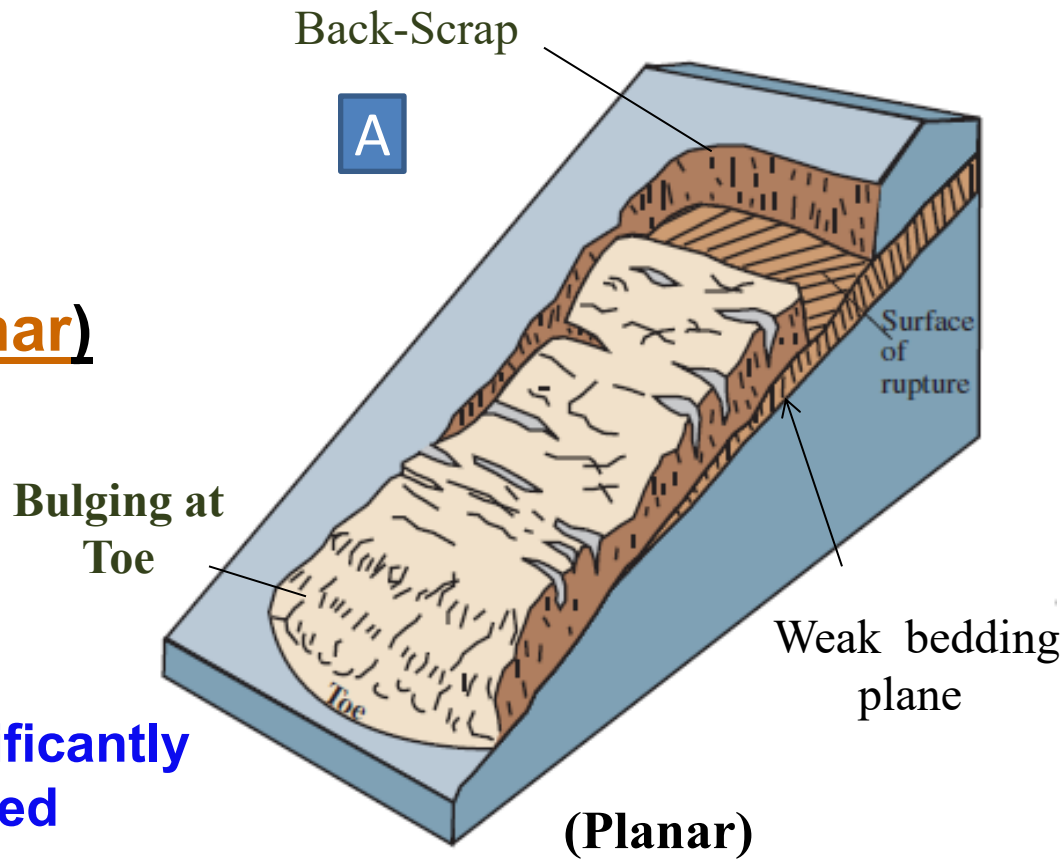


Slides

- Movements occur along planar failure surfaces that may run more-or less parallel to the slope. Movement is controlled by discontinuities or weak bedded planes.

Slides

A. Translational (planar)



(Planar)

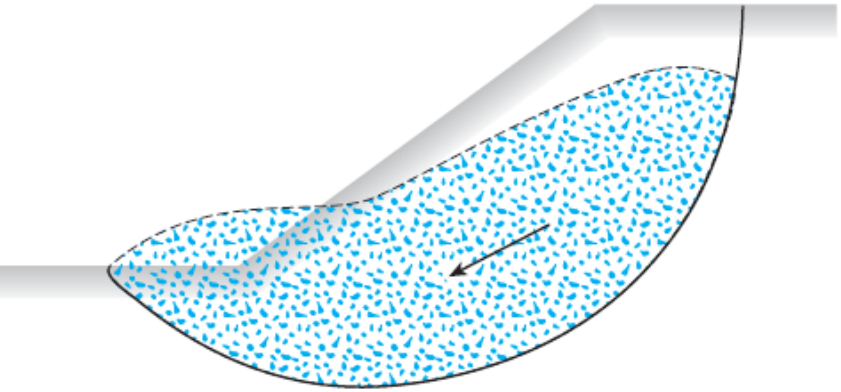
Translational landslide

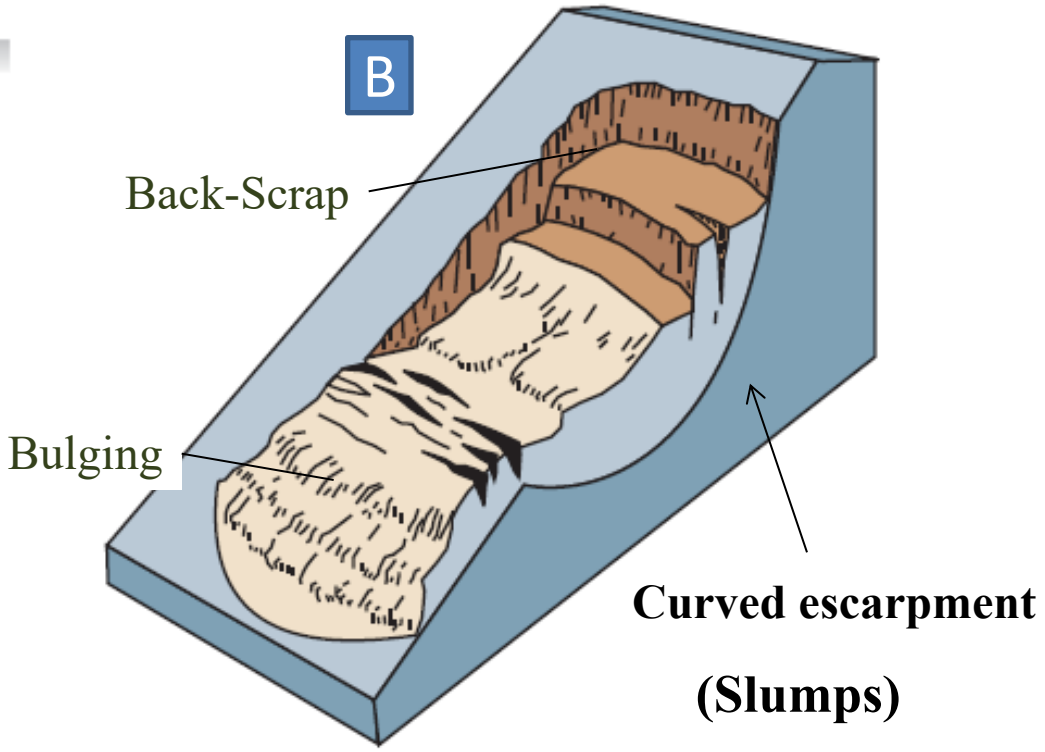
Occur when soil of significantly different strength is presented

Slides

B. Rotational (curved)

This is the downward movement of a soil mass occurring on an almost circular surface of rupture.

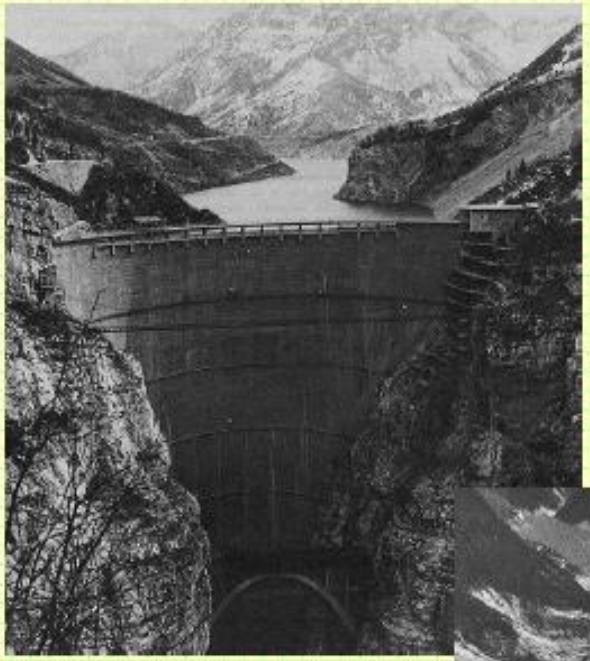




Rotational landslide

C. Compound (curved)

Slides



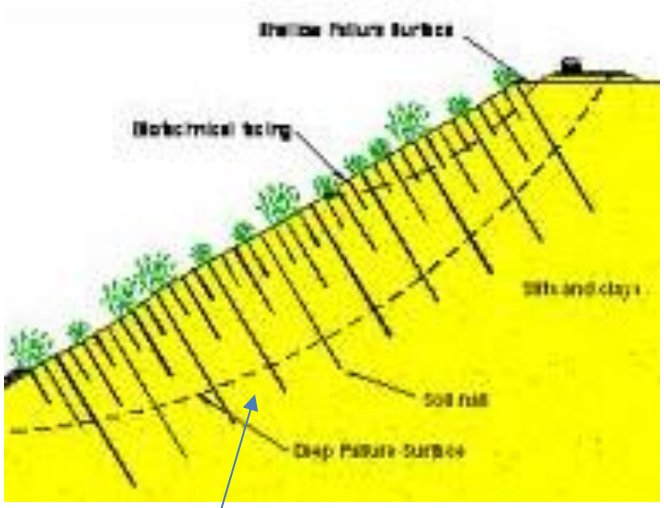


Vaiont dam disaster 1963

- Dam constructed 1957-60
- 276 m high. World's 2nd highest dam
- Slope started to creep as lake filled
- Accelerated to 80cm/day
- 9.10.63 275 millions tons of rock slid into lake
- 25 millions m^3 of water displaced over dam
- Three towns destroyed
- 2000+ killed

Slides

Reinforcement

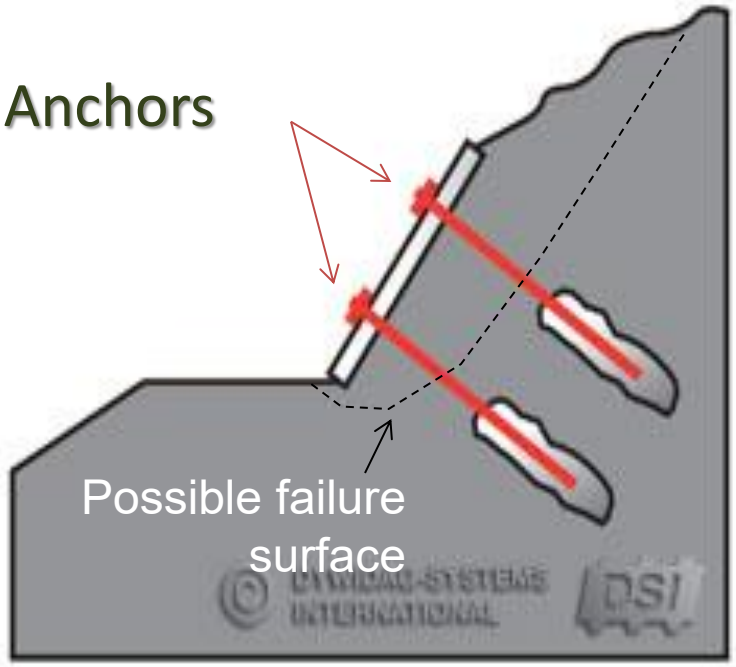


Soil nails



Slides

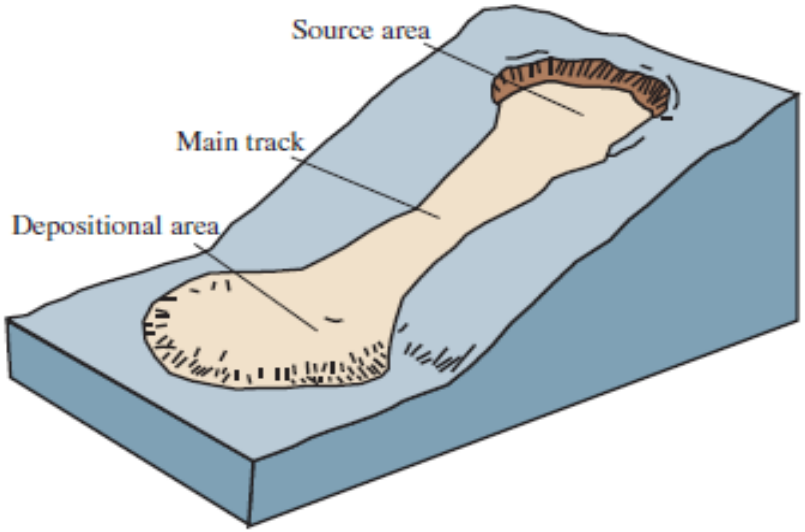
Reinforcement



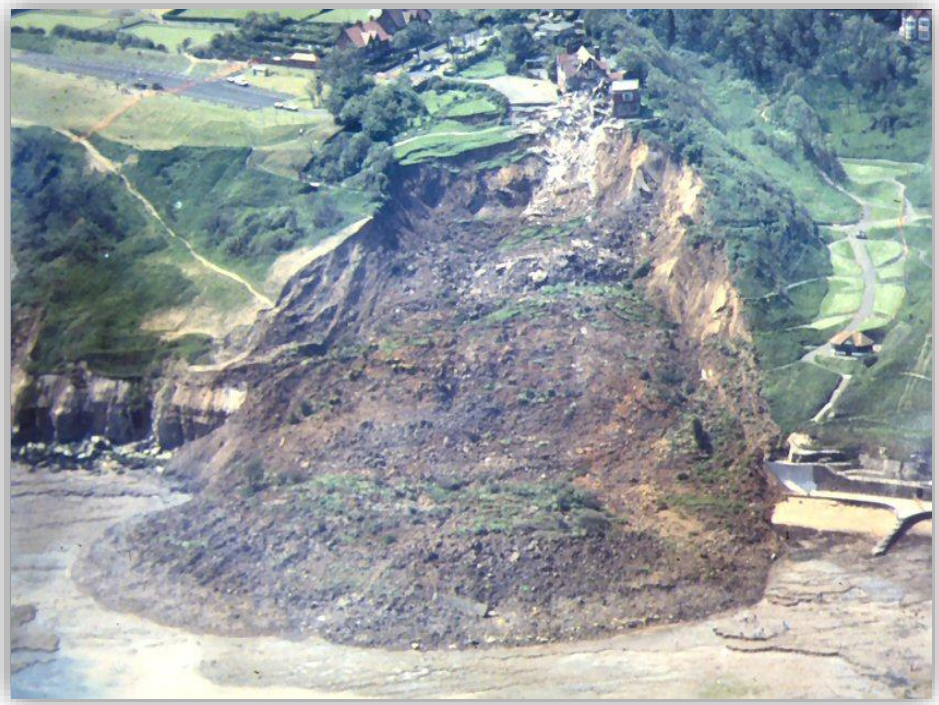


Flows

- The materials moves like a viscous fluid. The failure plane here does not have a specific shape.



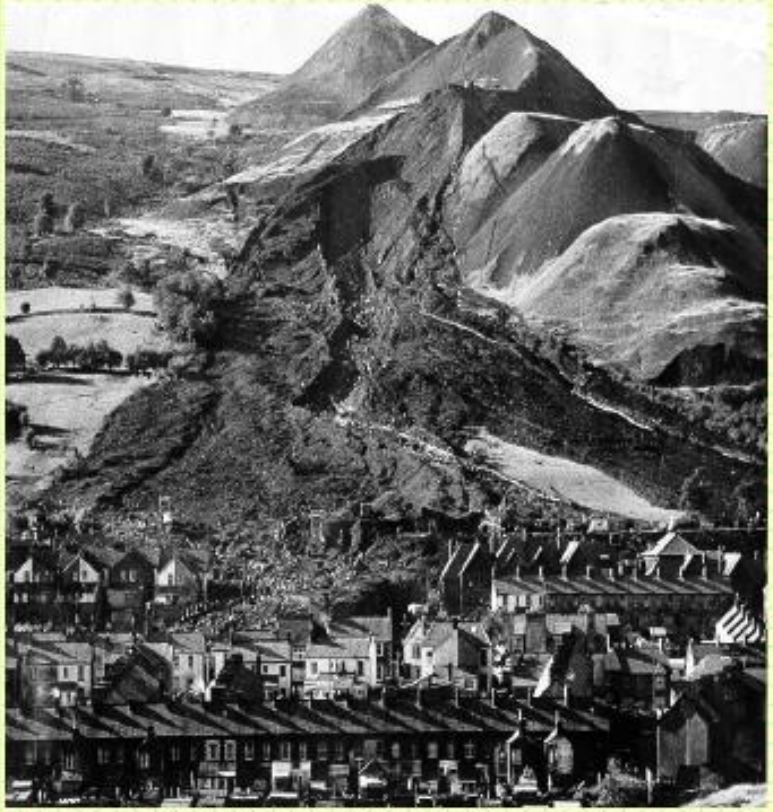
Earthflow



It can take place in soil with high water content or in dry soils. However, this type of failure is common in the QUICK CLAYS, like in Norway.

Flows

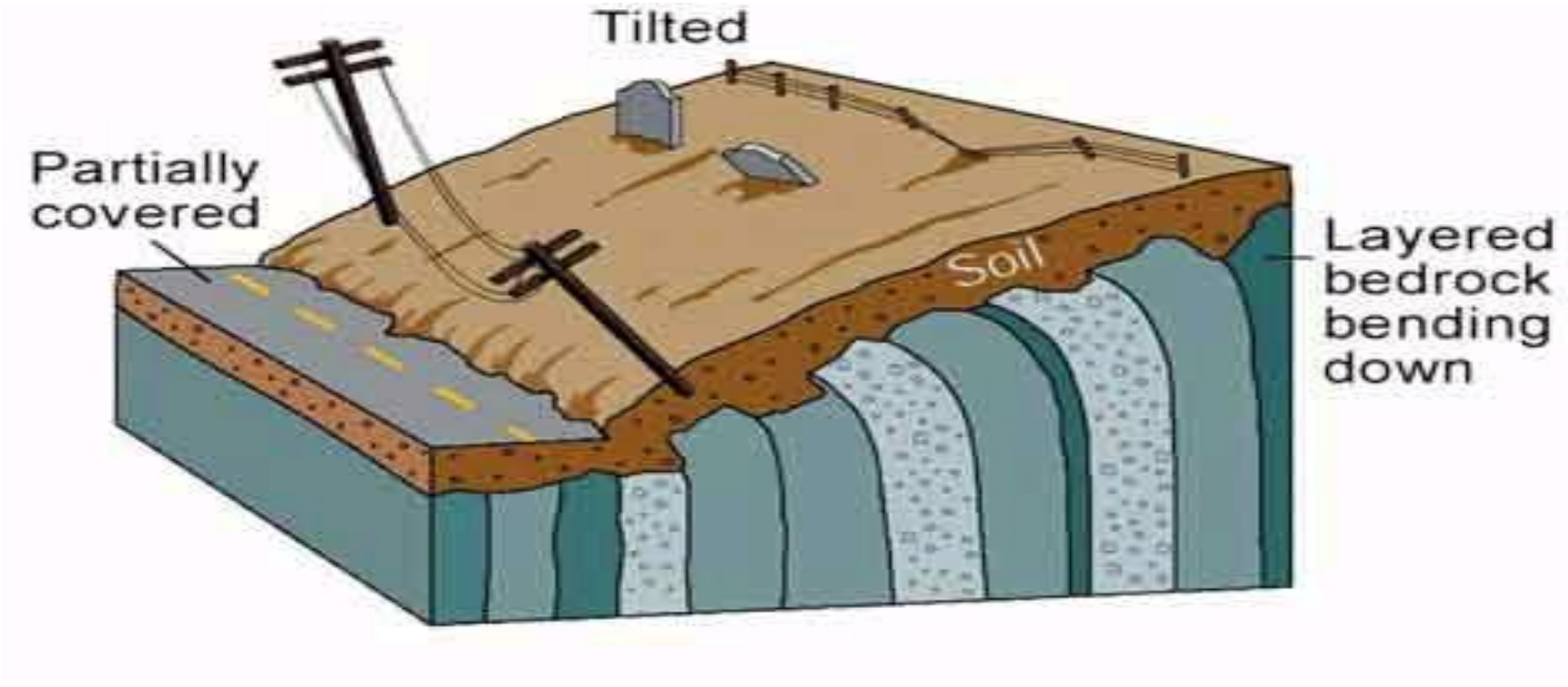
Aberfan debris flow (South Wales) 1966



- Occurred at overloaded & unmonitored coal tip
- Early morning on 21.10.66 upper part of tip subsided by up to 6m
- 9.15am ~150,000 m^3 of debris broke away
- Flow of super-saturated rock waste moved downslope as high velocity viscous surges
- Cottages & school buried up to 10m deep
- 144 killed (116 children)

Creep

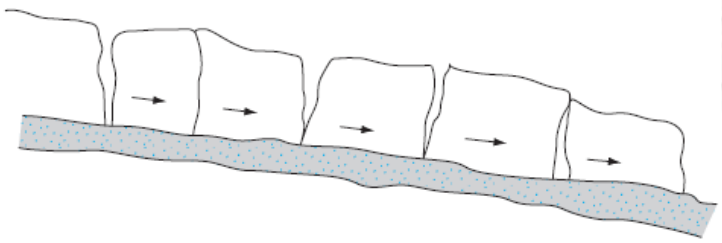
- It is the very slow movement of slope material that occur over a long period of time
- It is identified by bent post or trees.

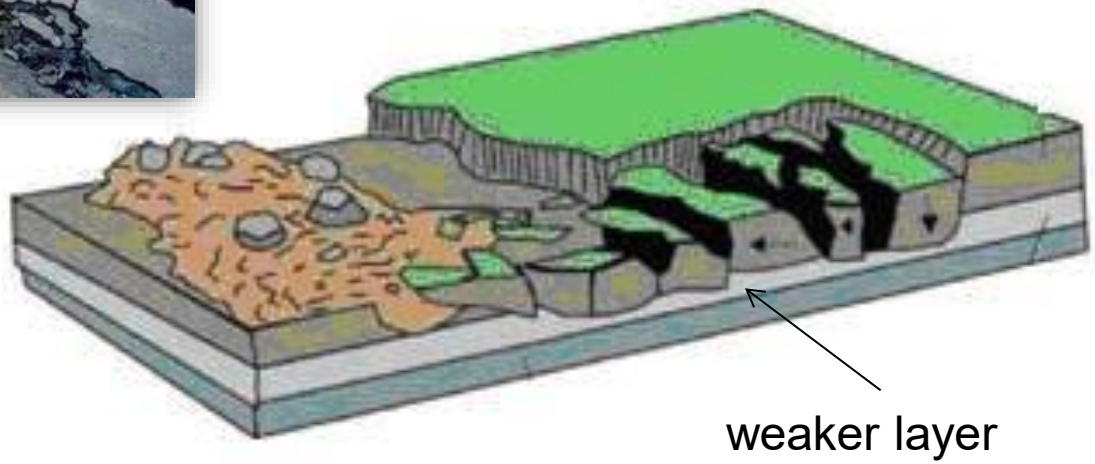


Lateral spreads

- **Lateral spreads usually occur on very gentle slopes or essentially flat terrain, especially where a stronger upper layer of rock or soil undergoes extension and moves above an underlying softer, weaker layer.**



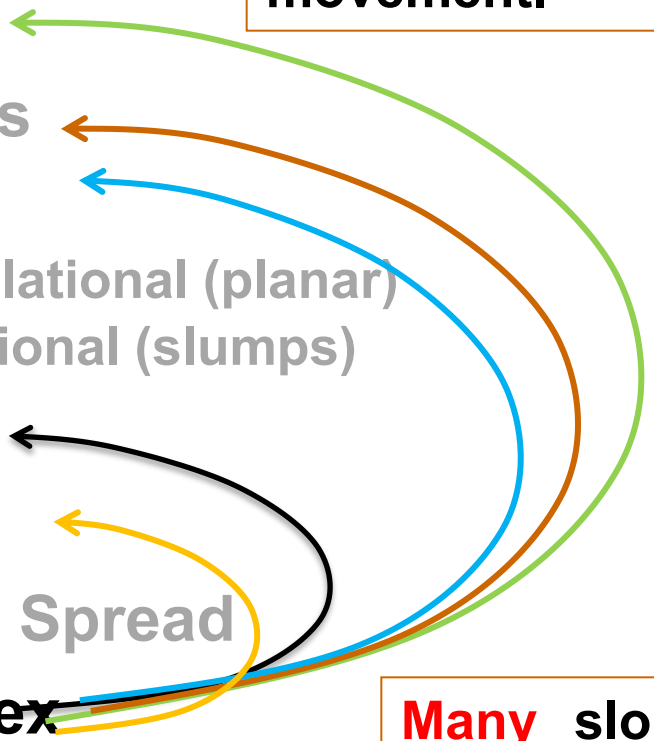




Complex

Complex movement is by a **combination** of one or more of the other principal types of movement.

1. Falls
2. Topples
3. Slides
   - A. Translational (planar)
   - B. Rotational (slumps)
4. Flow
5. Creep
6. Lateral Spread
7. **Complex**



Many slope movements are **complex**, although **one** type of movement generally **dominates** over the others at certain areas or at a particular time.

Types of Slope Failures

In general, there are six types of slope failures:

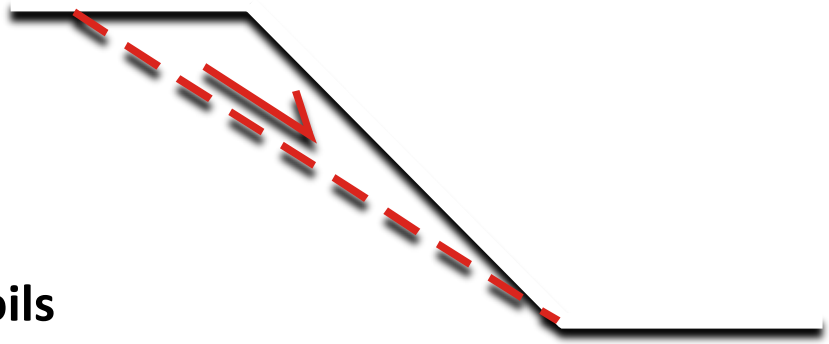
1. Falls
2. Topples
3. **Slides**
   - **Translational (planar)**
   - **Rotational (curved)**
4. Flows
5. Creep
6. Lateral spreads
7. Complex

Slide is the most common mode of slope failure, and it will be our main focus in this course

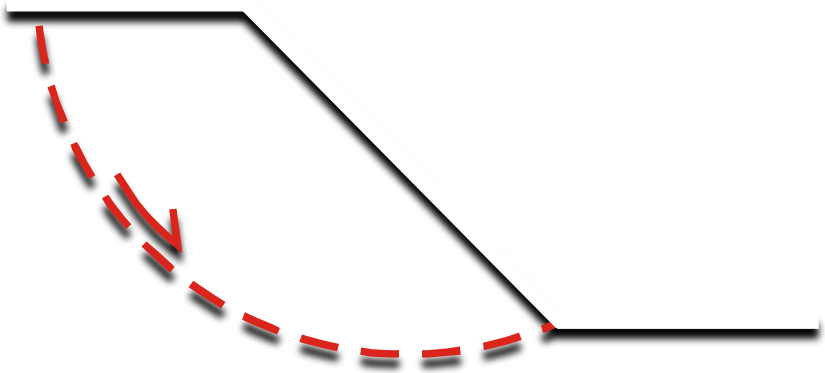
Types of Slide Failure Surfaces

- Failure of slopes generally occur along surfaces known as failure surfaces. The main types of surfaces are:

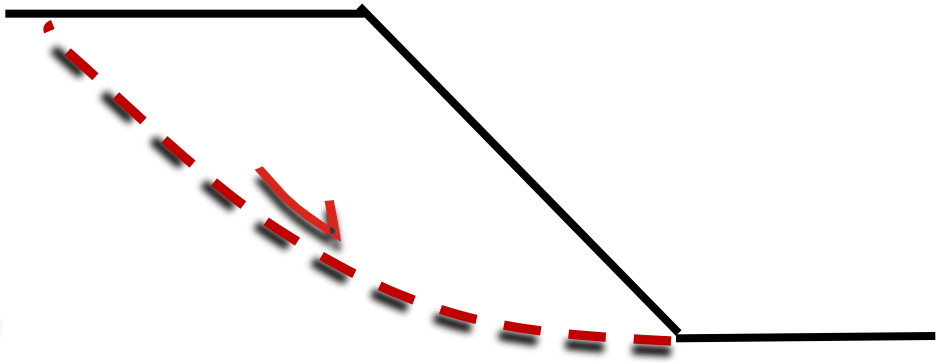
  - **Planar Surfaces:** Occurs in frictional, non cohesive soils



  - **Rotational surfaces:** Occurs in cohesive soils



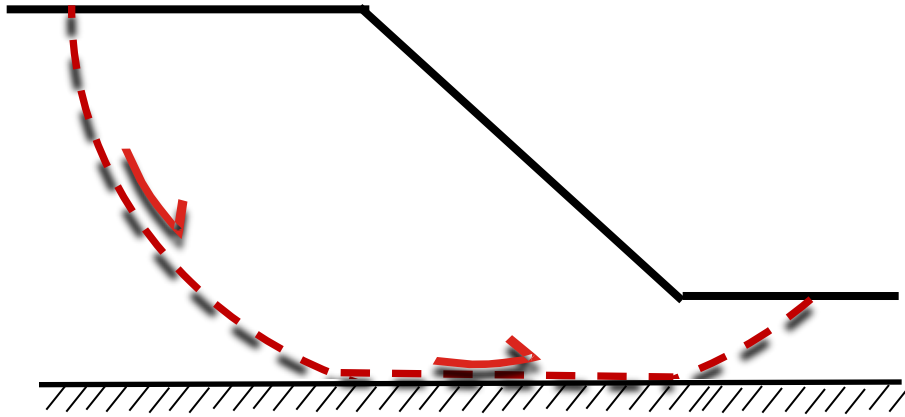
Circular surface (homogeneous soil)



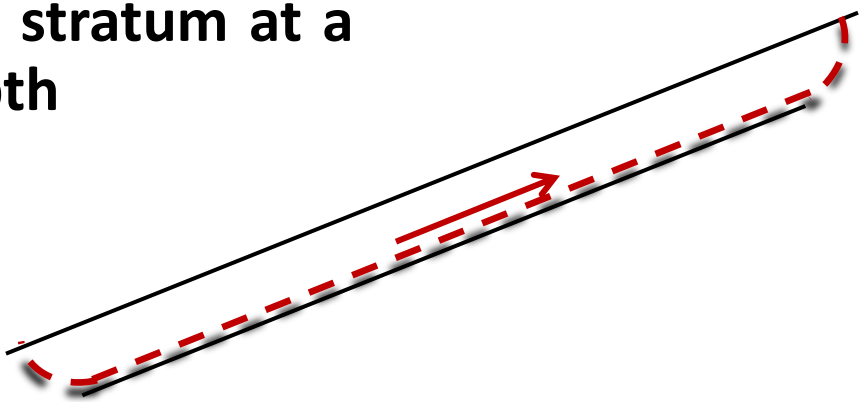
Non-circular surface (non-homogeneous soil)

Types of Slide Failure Surfaces

- **Compound Slip Surfaces:**
  When there is hard stratum at some depth that intersects with the failure plane



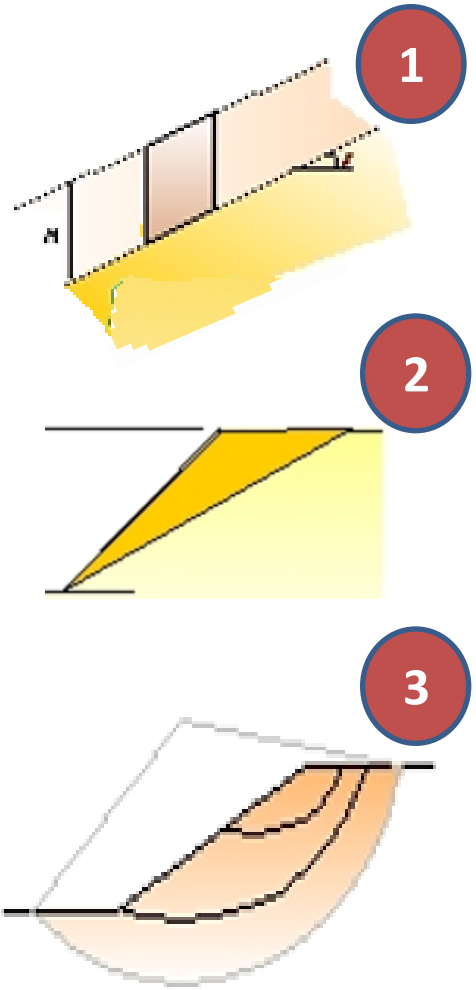
- **Transitional Slip Surfaces:**
  When there is a **hard** stratum at a relatively **shallow** depth



Types of Failure Surfaces

Failure surface

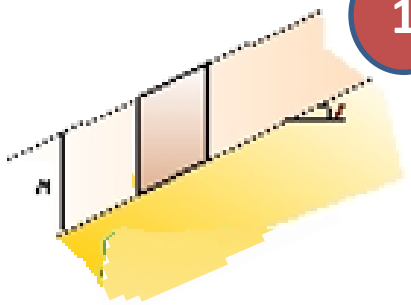
- **Slides**
  - **Translational (planar)**
    - **Infinite** — **Long plane failure surface**
    - **Finite** — **Plane failure surface**
  - **Rotational (curved)** — **Finite**
    - **Above the toe**
    - **Through the toe**
    - **Deep seated**



Types of Failure Surfaces

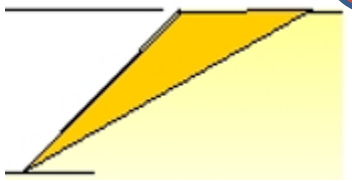
Types of Failure Surfaces Considered in this Course are

1



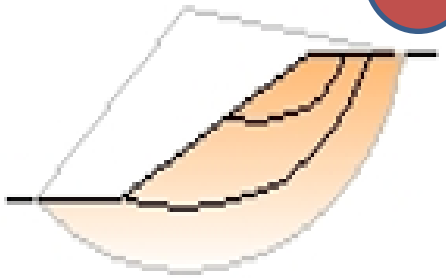
Stability of **infinite** slopes

2



Stability of **finite** slopes with **plane** failure surfaces

3



Stability of **finite** slopes with **circular** failure surfaces

TOPICS

- Introduction
- Types of slope movements
- **Concepts of Slope Stability Analysis**
- Factor of Safety
- Stability of Infinite Slopes
- Stability of Finite Slopes with Plane Failure Surface
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Concepts of Slope Stability Analysis

In general we need to check

- **The stability of a given existed slope**
- **Determine the inclination angle for a slope that we want to build with a given height**
- **The height for a slope that we want to build with a given inclination**

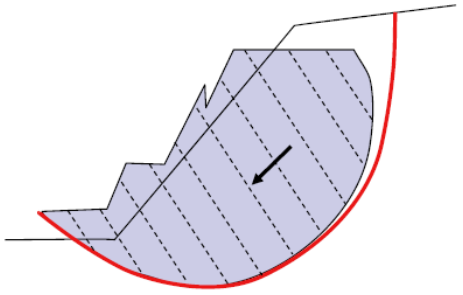
Methodology of Slope Stability Analysis

It is a method to expresses the relationship between resisting forces and driving forces

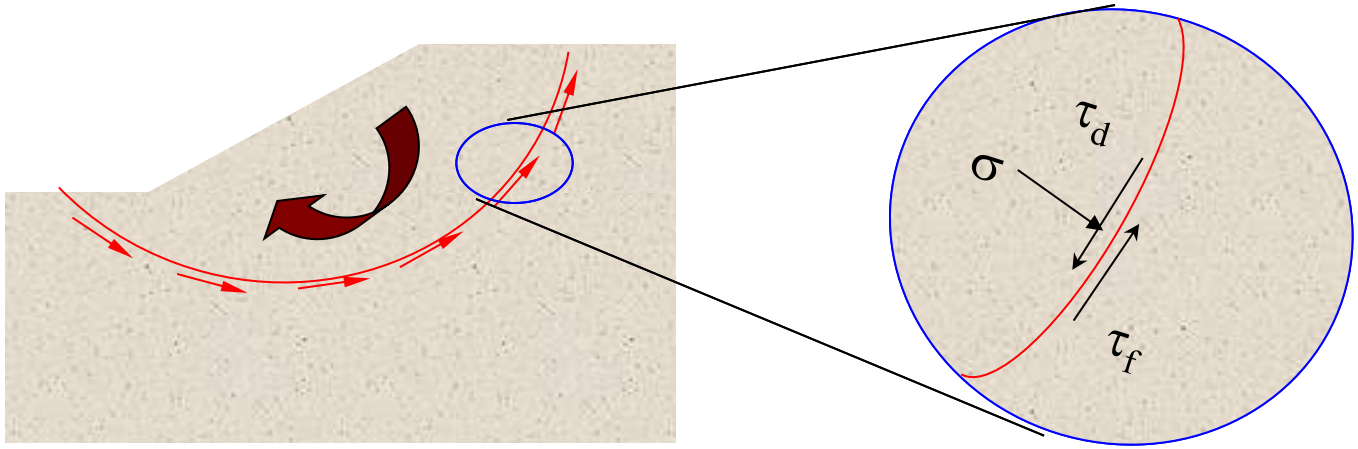
- Driving forces – forces which move earth materials downslope. Downslope component of weight of material including vegetation, fill material, or buildings.

- Resisting forces – forces which oppose movement. Resisting forces include strength of material

- Failure occurs when the driving forces (component of the gravity) overcomes the resistance derived from the shear strength of soil along the potential failure surface.



Methodology of Slope Stability Analysis



The analysis involves determining and comparing the *shear stress developed* along the most likely rupture surface to the *shear strength of soil.*

Slope Stability Analysis Procedure

1. Assume a probable failure surface.
2. Calculate the factor of safety by determining and comparing the shear stress developed along the most likely rupture surface to the shear strength of soil.
3. Repeat steps 1 and 2 to determine the most likely failure surface. The most likely failure surface is the critical surface that has a minimum factor of safety.
4. Based on the minimum F_S, determine whether the slope is safe or not.

Methods of Slope Stability Analysis

- Limit equilibrium method
- Limit analysis method
- Numerical methods

We will consider only the limit equilibrium method, since it is the oldest and the mostly used method in practice.

Assumptions of Stability Analysis

- The problem is considered in two-dimensions
- The failure mass moves as a rigid body
- The shear strength along the failure surface is isotropic
- The factor of safety is defined in terms of the average shear stress and average shear strength along the failure surface

TOPICS

- Introduction
- Types of slope movements
- Concepts of Slope Stability Analysis
- **Factor of Safety**
- Stability of Infinite Slopes
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Factor of Safety

$$\text{Factor of safety} = \frac{\text{Resisting Force}}{\text{Driving Force}}$$

$$= \frac{\text{Shear Strength}}{\text{Shear Stress}}$$

$$F_S = \frac{\tau_f}{\tau_d}$$

τ_f= Avg. Shear strength of soil

τ_d= Avg. Shear stress developed along the failure surface

Factor of Safety

- The most common analytical methods of slope stability use a factor of safety F_S with respect to the limit equilibrium condition,

F_s is the ratio of resisting forces to the driving forces, or

$$F_s = \frac{\tau_f}{\tau_d}$$

Shear strength (resisting movement) average shear strength of the soil.

$$\tau_f = c' + \sigma' \tan \phi' \text{ (Available)}$$

Shear stress (driving movement) average shear stress developed along the potential failure surface.

$$\tau_d = c'_d + \sigma' \tan \phi'_d \text{ (developed)}$$

$F_S < 1 \rightarrow$ unstable

$F_S \approx 1 \rightarrow$ marginal

$F_S >> 1 \rightarrow$ stable

Generally, FS ≥ 1.5 is acceptable for the design of a stable slope

If factor safety F_s equal to or less than 1, the slope is considered in a state of impending failure

Causes of slope failure

1. External causes

These which produce increase of shear stress, like steepening or heightening of a slope, building on the top of the slope

2. Internal causes

These which cause failure without any change in external conditions, like increase in pore water pressure.

Therefore, slopes fail due either to increase in stress or reduction in strength.

Factor of Safety

$$F_s = \frac{c' + \sigma' \tan \phi'}{c'_d + \sigma' \tan \phi'_d}$$

Where:

c' = cohesion

ϕ' = angle of internal friction

c'_d, ϕ'_d = cohesion and angle of friction that develop along the potential failure surface

Other aspects of factor of safety

Factor of safety with respect to cohesion

$$F_{c'} = \frac{c'}{c'_d}$$

Factor of safety with respect to friction

$$F_{\phi'} = \frac{\tan \phi'}{\tan \phi'_d}$$

When the factor of safety with respect to cohesion is equal to the factor of safety with respect to friction, it gives the factor of safety with respect to strength, or

When $F_{c'} = F_{\phi'}$ then $F_s = F_{c'} = F_{\phi'}$

The end