# What causes landslides to occur?

# Learning Objectives

- Identify key factors that drive landslides.
- Identify factors that contribute to shear strength.
- Identify factors that contribute shear stress.

# What Drives Landslides to Occur?

- Geologic (i.e., weak materials, joints, water, etc.)
- Morphological (i.e., erosion, tectonic uplift, etc.)
- Physical (i.e., rainfall, rapid snow melt, etc.)
- Anthropogenic (i.e., excavation, etc.)

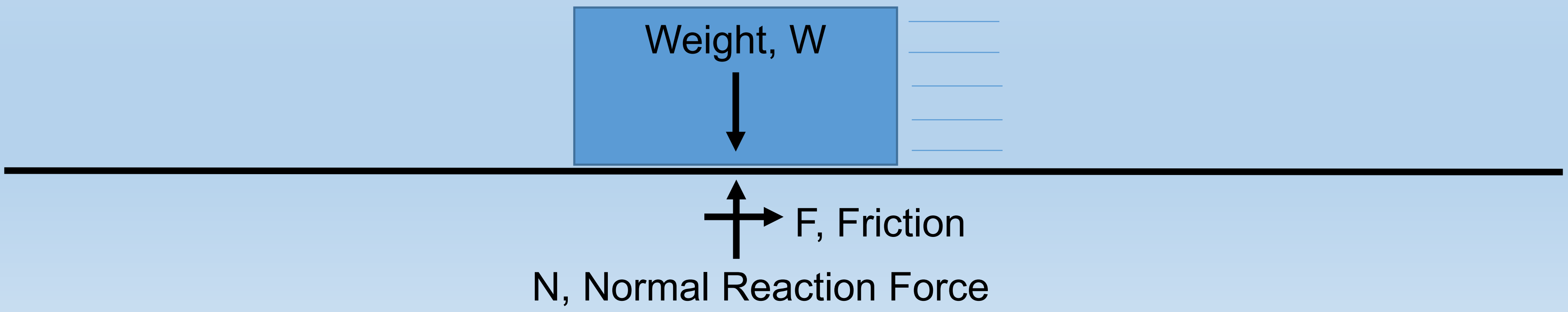
- Some processes increase shear stresses.
- Others decrease shear strength.
- Generally, FS is defined as ratio of shear strength to shear stress.

# Some of the Typical Culprits…

- Geology.
- Soil Conditions.
- Excavation and Loading (oversteepening/overloading).
- Freeze/Thaw.
- Moisture Cycling.
- Seismicity.
- Water.
- Water.
- Water.

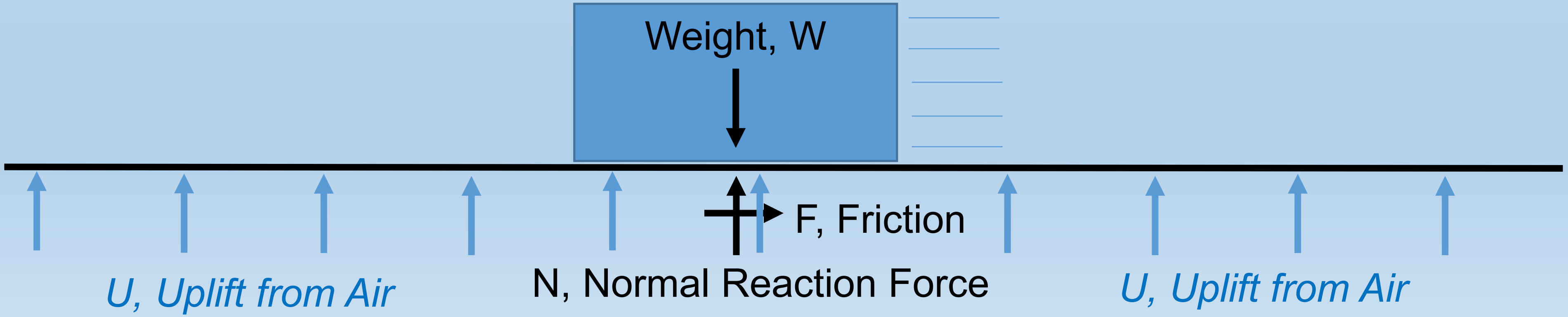
# Why does water cause landslides?

- Let's take an example that we all remember from childhood: air hockey.
- When the air is off, the puck doesn't slide as well.
- The reaction force, N, is equal to the weight of the puck.
- Friction is N multiplied by a friction coefficient.



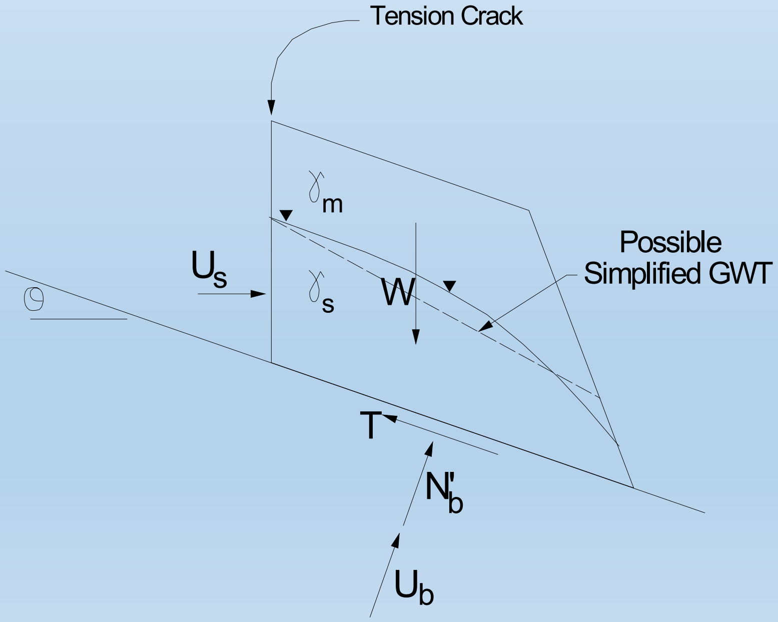
# Why does water cause landslides?

- If we turn on air on the table, the reaction force is no longer equal to the weight.
- The normal decreases the by uplift force from air.
- Thus, friction decreases and the puck slides easily.
- This is conceptually the same as “buoyancy.”



# What about soil and rock?

- The same concepts hold – except the puck is a mass of rock/soil at a slope, and instead of air, water is internally causing buoyancy.
- Many slopes are held in place by frictional shear strength. An increase in water levels causes reduced mobilization of frictional strength.
- This can induce failure.



1. *Let’s list the factors that affect the performance of soil slopes and embankments.*

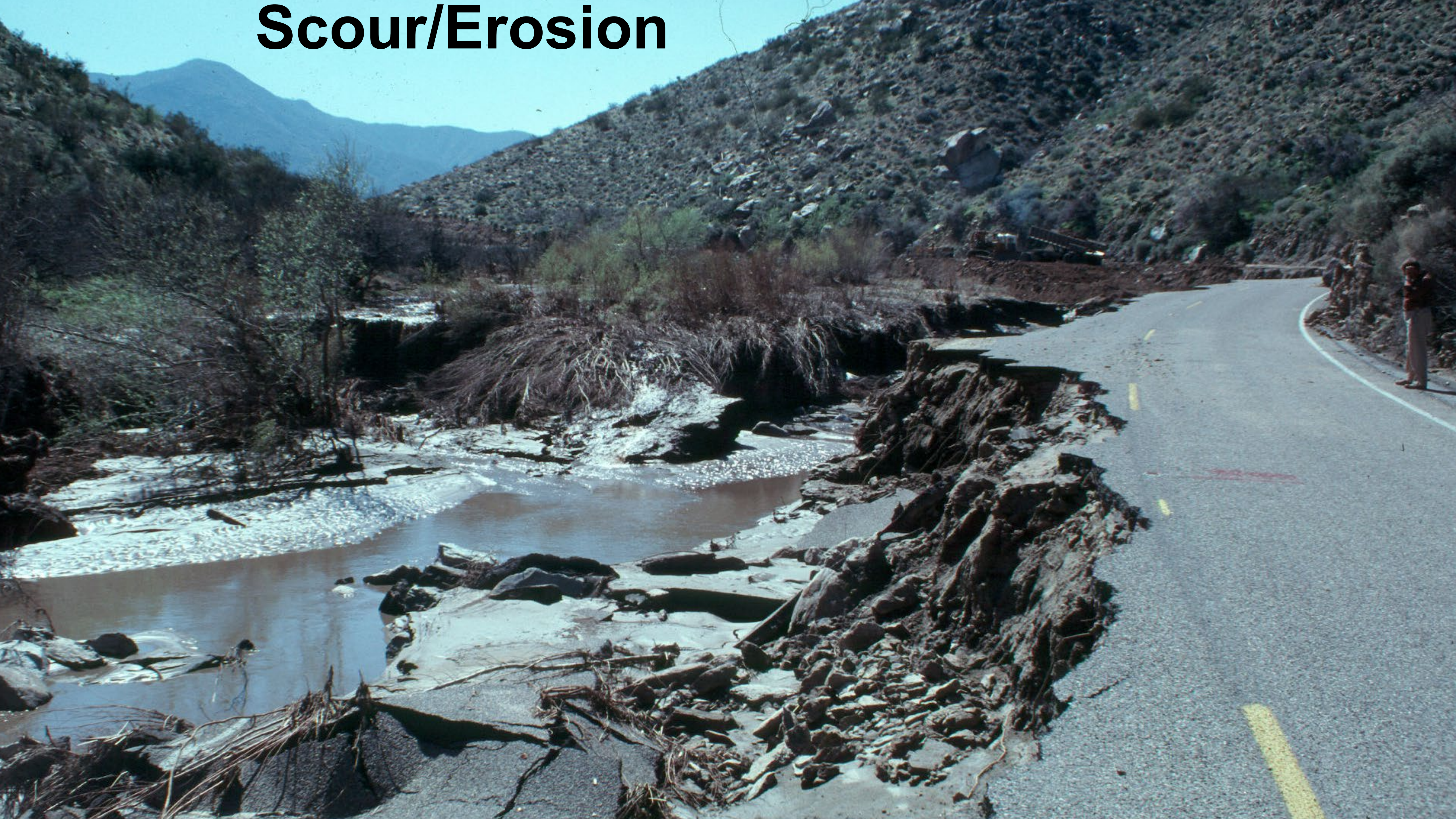
# What processes increase the shear stress in the ground?

- Removal of Support
  - Erosion
  - Falls, Slides Etc.
  - Human Activity
- Increase in Vertical Stress (Overloading)
  - Snow
  - Lower groundwater
  - Material from Slides
  - Construction Fill
  - Waves

# Construction – Removal of Support

- Common for cutslopes.
- Toe is arguably the most critical component of slope for stability (buttressing effect).
- Shear stresses increase in rest of slide plane from removal of support.
- Can stem from erosion/undercutting as well.
- Need to consider short term stability for cuts and construction!

# Scour/Erosion



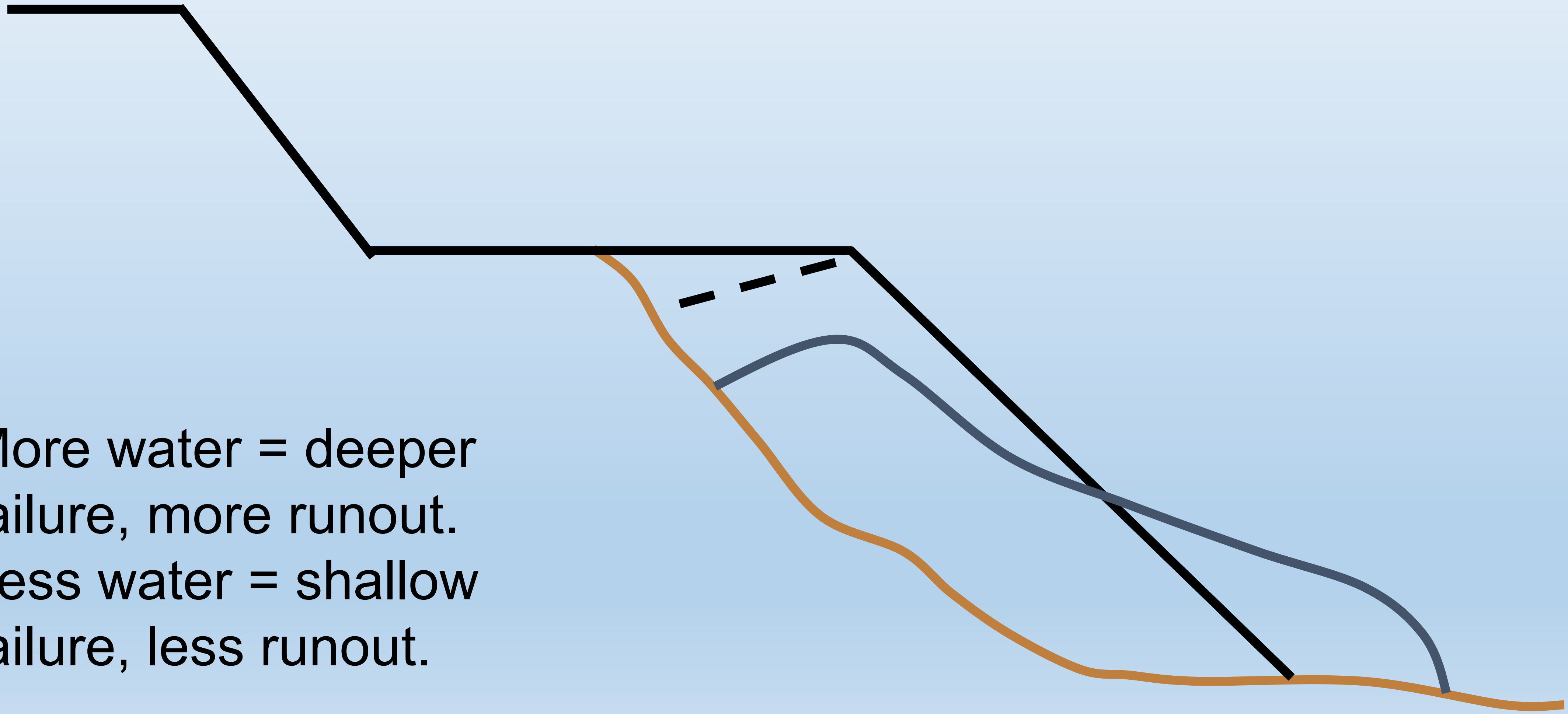
# Erosion, Rilling and Ravel

# What processes increase the shear stress in the ground?

- Increase in Lateral Pressure

- Rise in the groundwater table
- Water in Cracks
- Freezing of Water in Cracks
- Expansive Soils
- Earthquakes

# Alteration of Hydrology and Water



- More water = deeper failure, more runout.
- Less water = shallow failure, less runout.

# Earthquakes

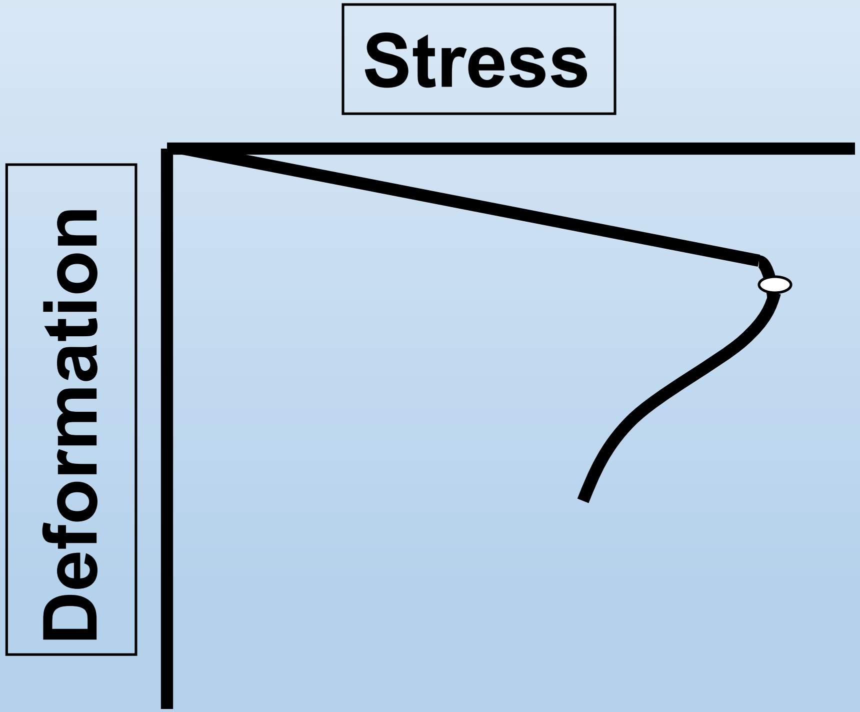

What processes reduce the shear strength in the ground?
Weathering

# What processes reduce the shear strength in the ground?


- Pore Pressure Increase

# Seismic Liquefaction

# What processes reduce the shear strength in the ground? Post-peak creep.



# Geologic Considerations

- Groundwater
- Soil Properties and Depositional Processes
- Weathering Processes

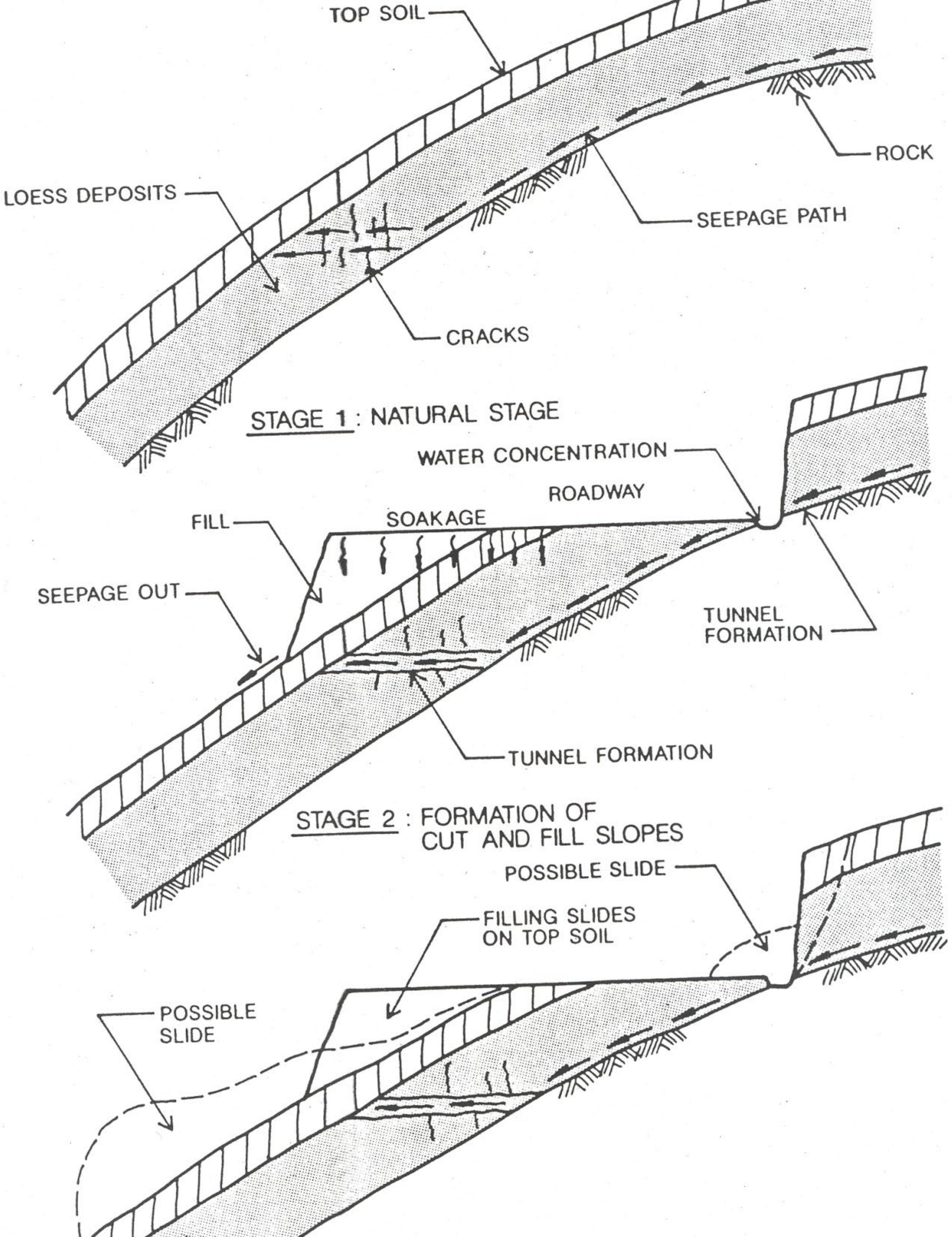
# Soil Deposition – Alluvial

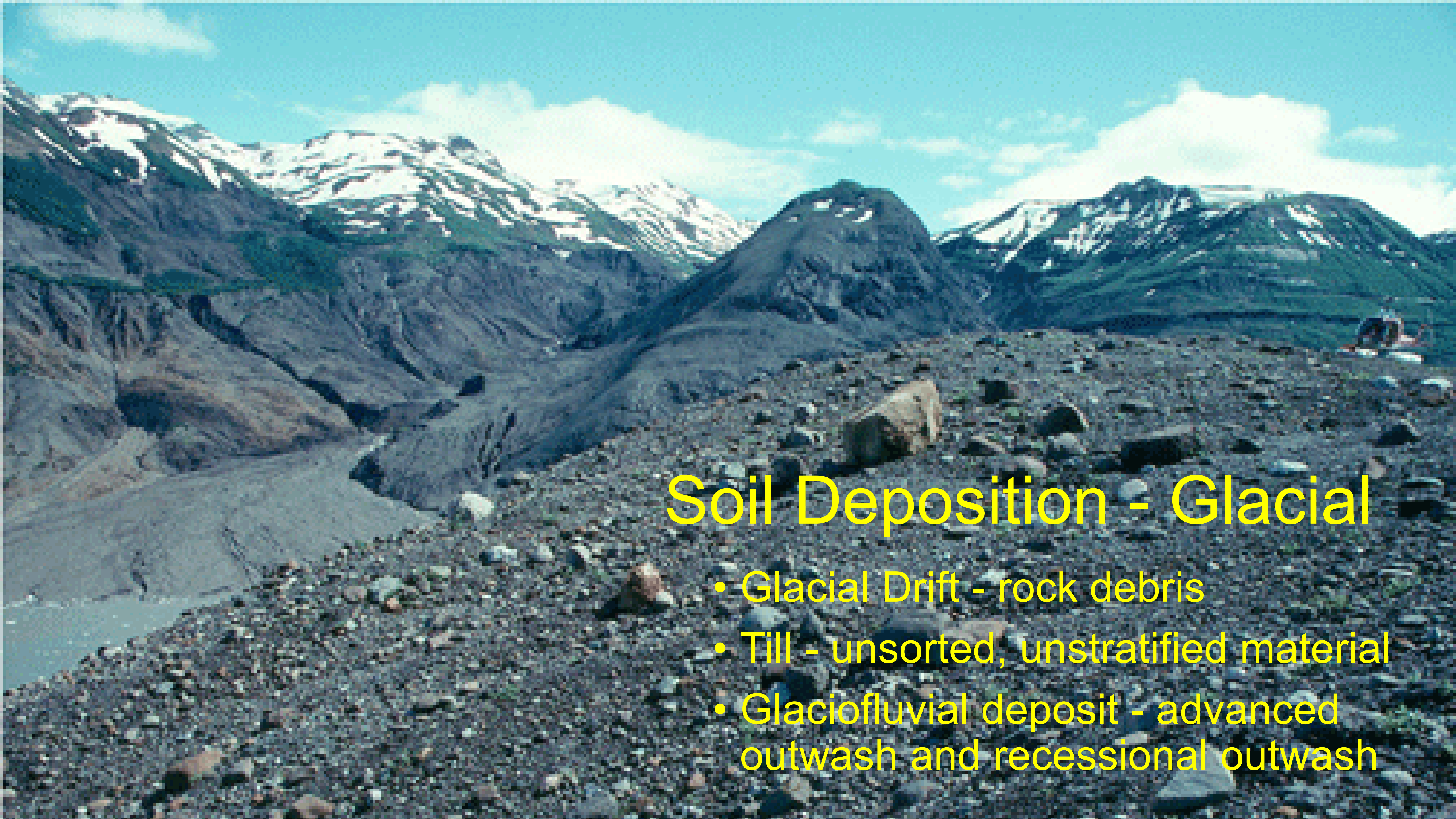
- Alluvial Deposits - transported by running water
- No distinct horizontal strata, unconsolidated, favorable conditions for embankment/slope instability and landslides.

# Soil Deposition – Aeolian

- Aeolian Deposits - transported by wind
  - Loess - angular silt size particles

  - Engineering properties - low density, high strength prior to wetting


TOP SOIL
ROCK
LOESS DEPOSITS
SEEPAGE PATH
CRACKS
STAGE 1 : NATURAL STAGE
WATER CONCENTRATION
ROADWAY
FILL
SOAKAGE
SEEPAGE OUT
TUNNEL FORMATION
TUNNEL FORMATION
STAGE 2 : FORMATION OF CUT AND FILL SLOPES
POSSIBLE SLIDE
FILLING SLIDES ON TOP SOIL
POSSIBLE SLIDE


Soil Deposition - Glacial
• Glacial Drift - rock debris
• Till - unsorted, unstratified material
• Glaciofluvial deposit - advanced outwash and recessional outwash

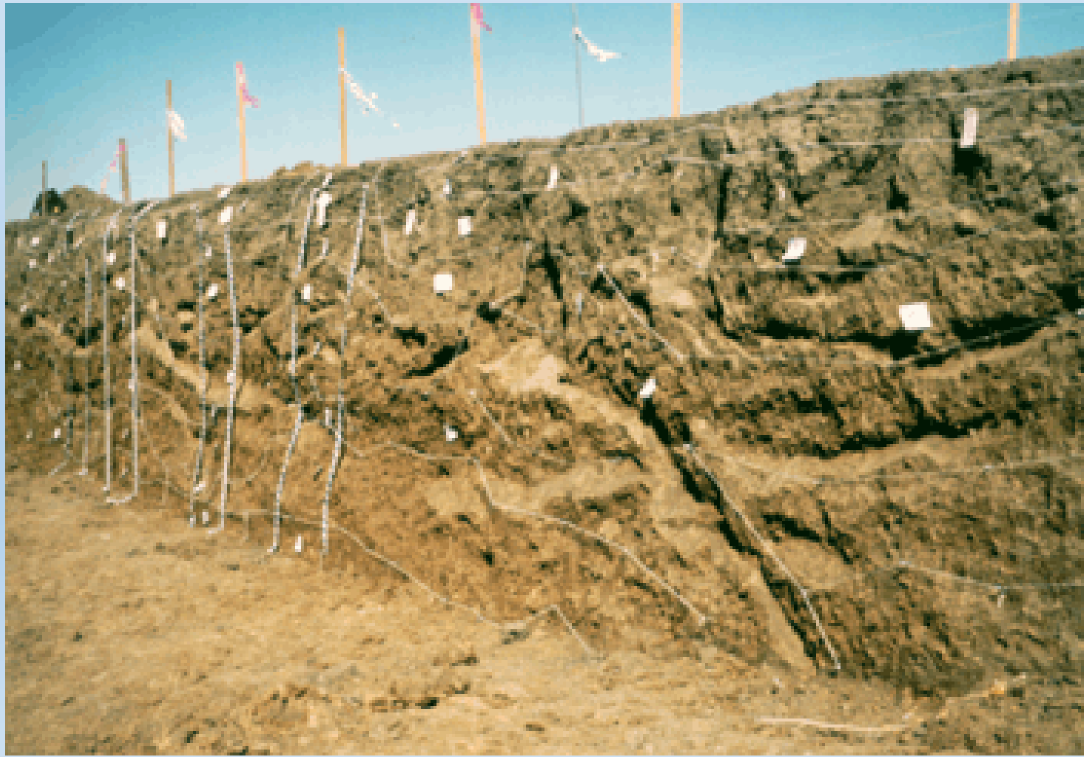
# Soil Deposition - Marine

- Marine Deposits - sands, silts and clays, stratified.
  - Marine Clays - flocculated
  - Glacio-Marine Clays - from leaching of the salt out of deposit become highly sensitive.

# Sensitive Clay Failure

# Slickensides

- Typical to clays, especially marine clays
- Historical shear zones from prior slope failures
- Predisposed to failure

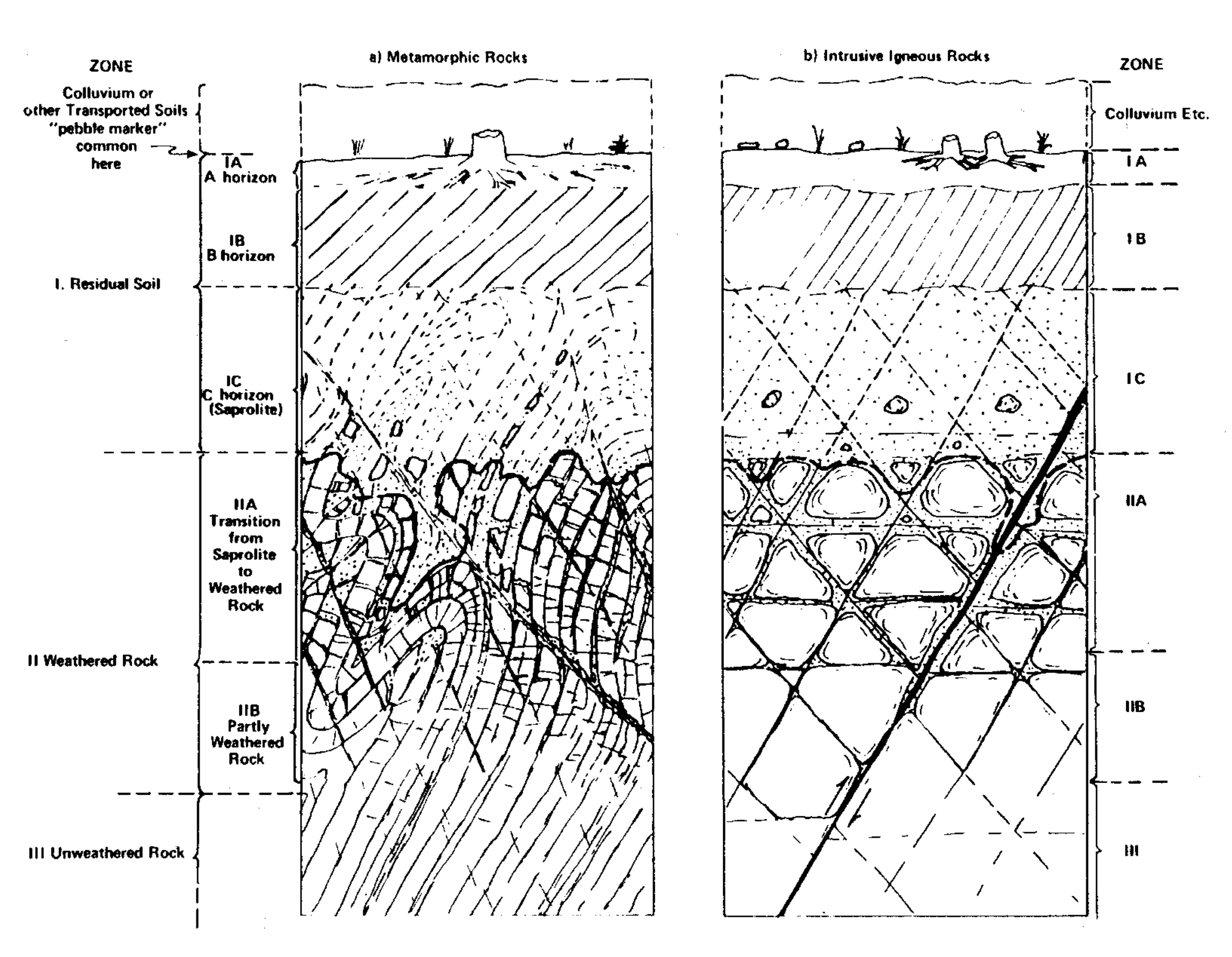


# Faults/Joints

- Typical to rocks, extremely overconsolidated clays
- Macropores tend to store and transport fine materials
- Prime suspect in rockfalls/topples/rockslides

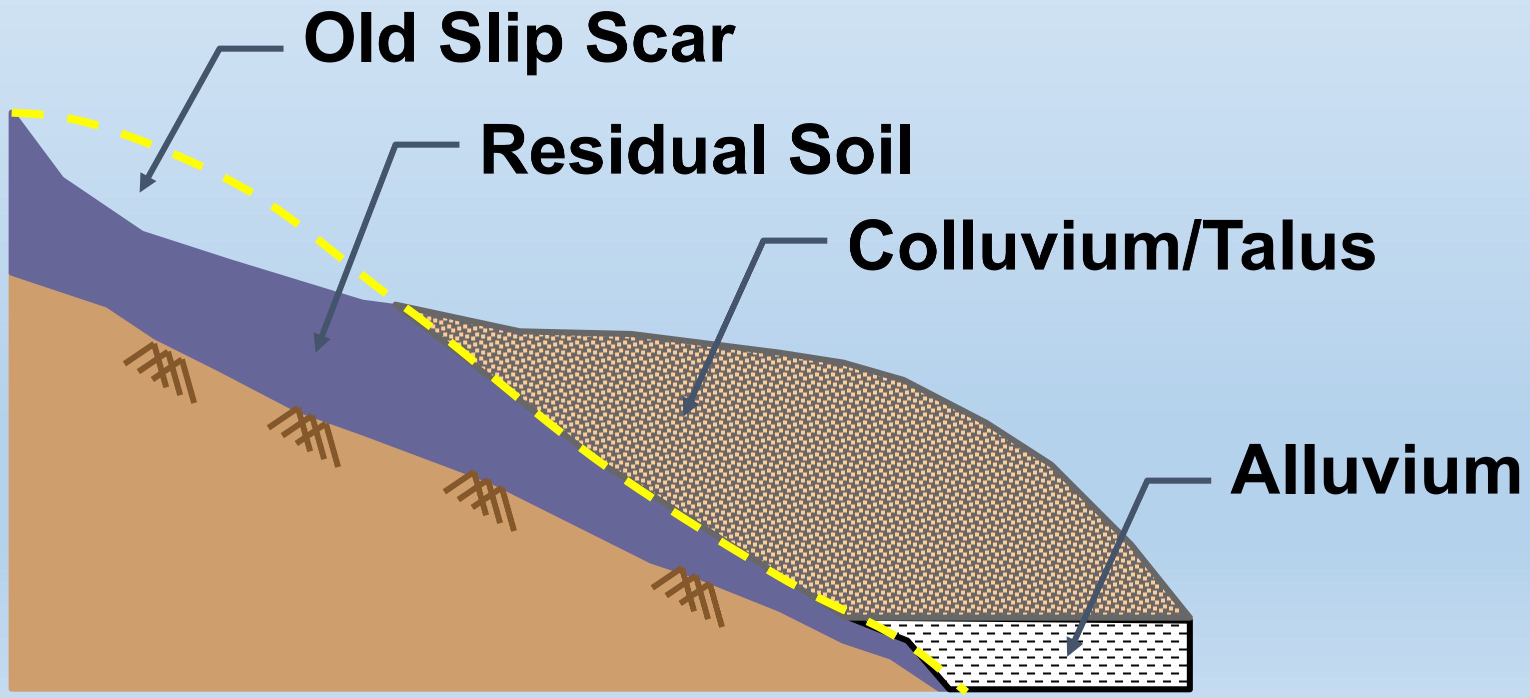
# Soil Deposition - Residual

- Residual Deposits



# Soil Deposition – Colluvial

- Colluvial Deposits - transported downslope by gravity



# Standard Approach to Slope Stability

# Learning Objectives

- Identify the process for which slope stability analysis is performed.
- Understand the influence of soil properties on slope stability.
- Understand the influence of slope geometry on slope stability.

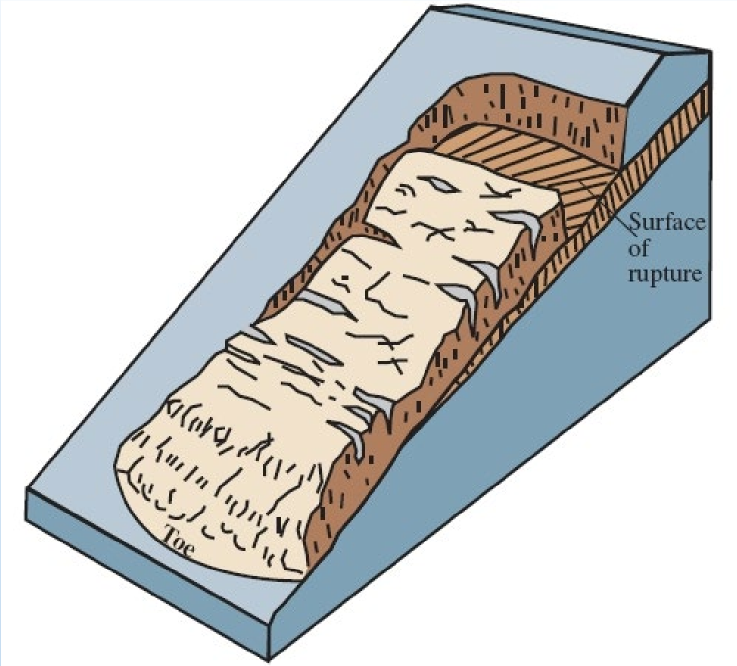
# Concepts of Slope Stability

- Slope stability is the primary means of quantitatively assessing the level of stability of a slope, done using a Factor of Safety.
- Soil tends to fail in shear, these concepts directly govern slope failures.
- Soil has shear strength, conventionally defined as friction and cohesion.
- At a given shear surface, there is shear stress, induced by:
  - The gravitational mass of the soil.
  - Water pressures.
  - Overloading, seismicity, etc.
- Generally, slope stability is a comparison of available shear strength to shear stress:

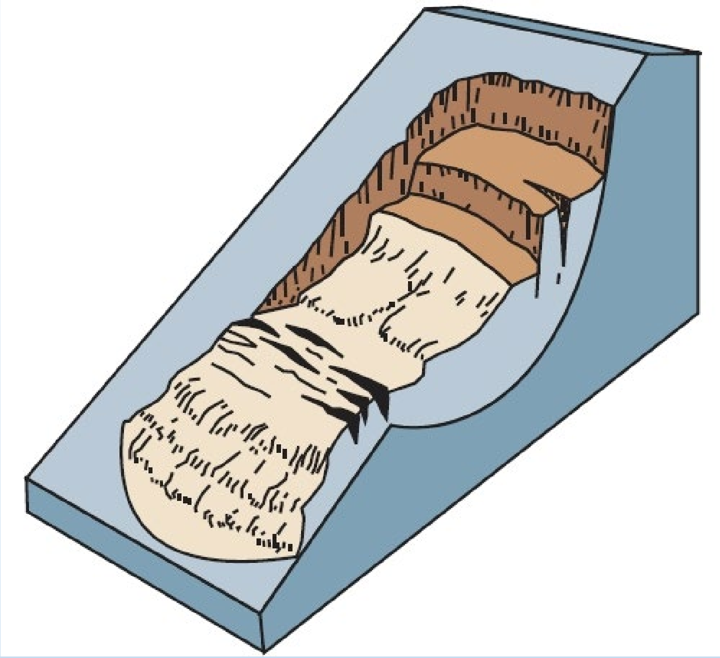
Factor of Safety = $FS = \frac{Available\ Shear\ Strength}{Mobilized\ Shear\ Stress}$

1. Identify the kinematics of the problem

- Kinematics – the study of the geometry of motion without regard for what caused it.
- For slope stability, the question is:
  - What is the likely initial geometry of motion that a potential slope failure would exhibit?
  - We may want to consider more than one possible failure.




Translational

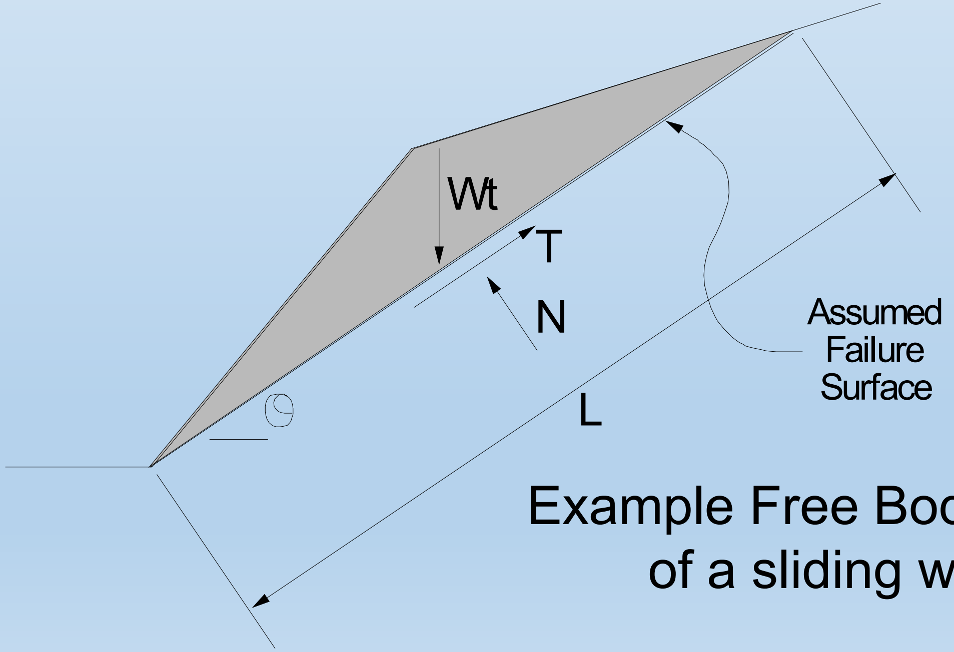


Rotational

Combination??

2. Construct a free body diagram of the rigid body of concern

- Isolate the Slide Mass.
- Indentify and show all external forces.
- Include body forces (weight and if an earthquake force is to be included, inertia).




Example Free Body Diagram of a sliding wedge.

## 3. Evaluate the forces on the free body diagram

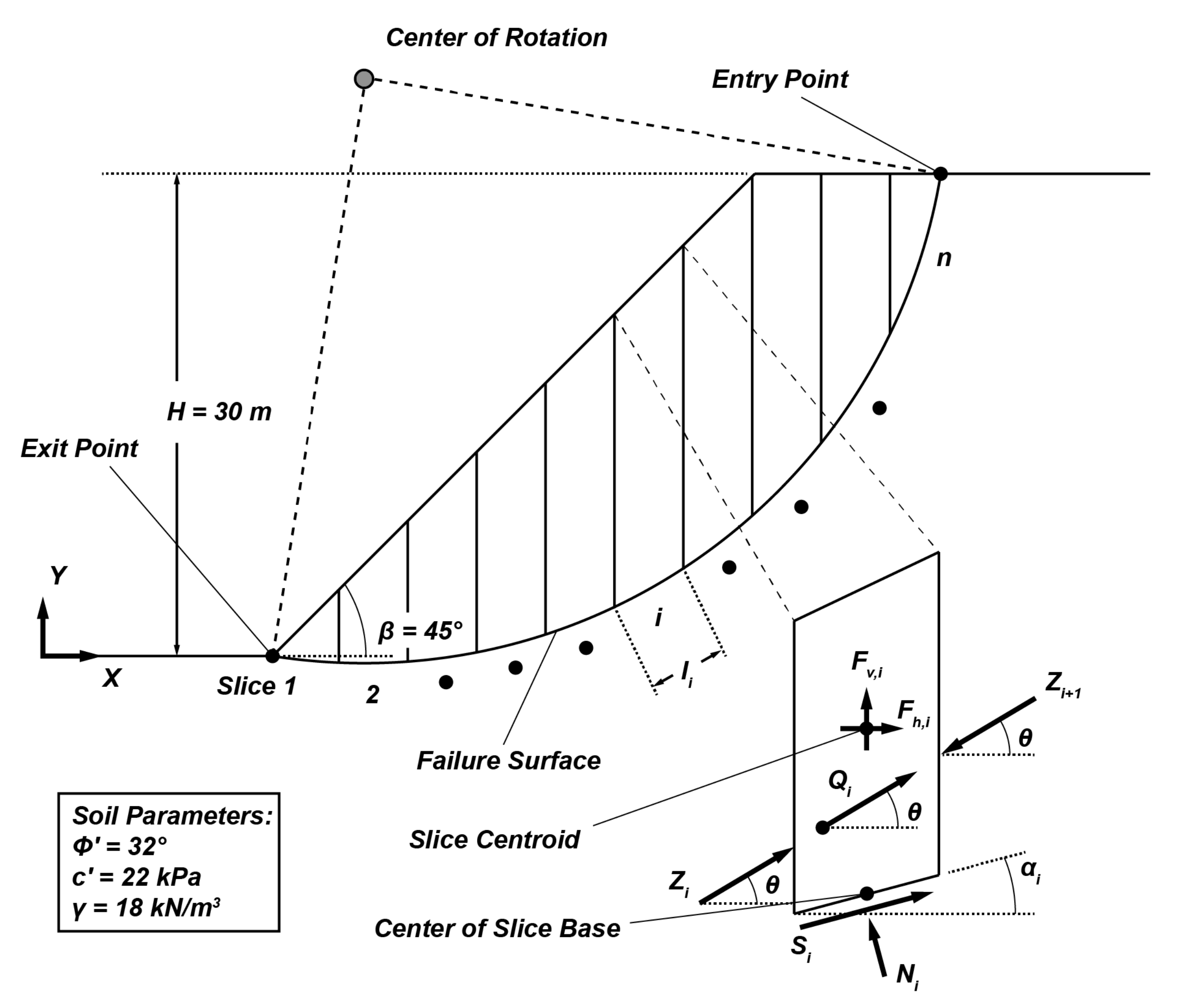
- ***Be Careful – some forces cannot be evaluated directly.***
- Weight of the body – in 2-dimensions, this will be the area times the appropriate unit weight.
- Boundary Neutral Forces – only present if a portion of the body is below the local GWT.
  - Compute the boundary pore pressure distribution.
  - Integrate the distribution to obtain a resultant force.
- Solve for other forces using equilibrium equations.
  - Usually requires simplifying assumptions.
  - Usually requires solution of simultaneous equations.

4. Incorporate a Factor of Safety to address cases where the slide mass is not in a state of limit equilibrium with soil strength fully mobilized.

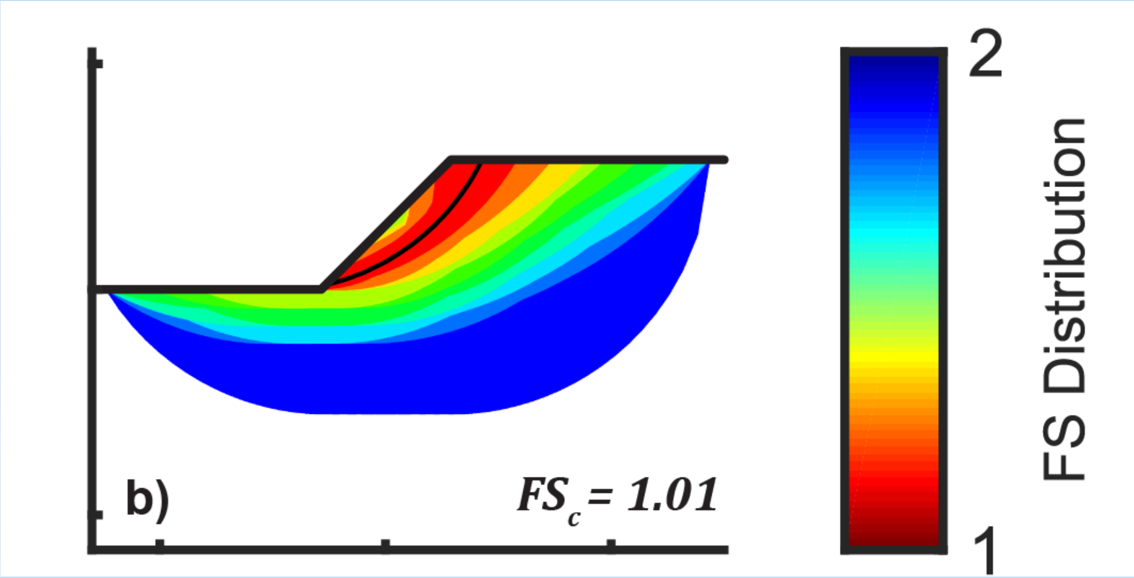
$$FS = \frac{Available\ Shear\ Strength}{Mobilized\ Shear\ Stress}$$

$$FS = \frac{Forces\ Resisting}{Forces\ Driving}$$

$$FS = \frac{Moments\ Resisting}{Moments\ Driving}$$



5. Analyze other similar free bodies in order to determine the worst case situation.
   - If failure surface is absolutely known this will not be required.
   - Failure surface is rarely “absolutely known”.
   - The exception is for existing landslides (forensics).
   - **To find the failure geometry of an existing landslide, we need to perform a field investigation and monitoring.**



# BASIC CONCEPTS OF SLOPE STABILITY ANALYSIS

1. Identify when total stress or effective stress should be used in a slope stability analysis
2. Define the factor of safety in limit equilibrium analysis

# Process Responsible for Slope Failures

- External effects: Driving forces increase while shearing resistance is unaltered

- Internal effects: Failure occurs without any change in external conditions or earthquake

# Recall: Examples of causes of instability

- ***External effects:***

  *Steepening or heightening of slope by man-made excavation, river erosion*

- ***Internal effects:***

  *Increase in PWP within the slope*

# Implications to Engineered Slopes

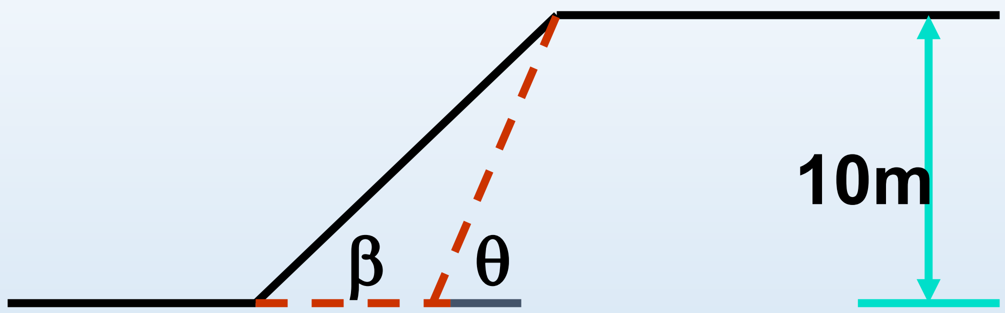
To increase stability:

- Reduce driving forces (e.g., use lightweight fill, flatter slopes)

- Increase shear resistance (e.g., reinforce fill material; preload soft foundation)

- Provide adequate long-term drainage to minimize potential decrease in shear strength

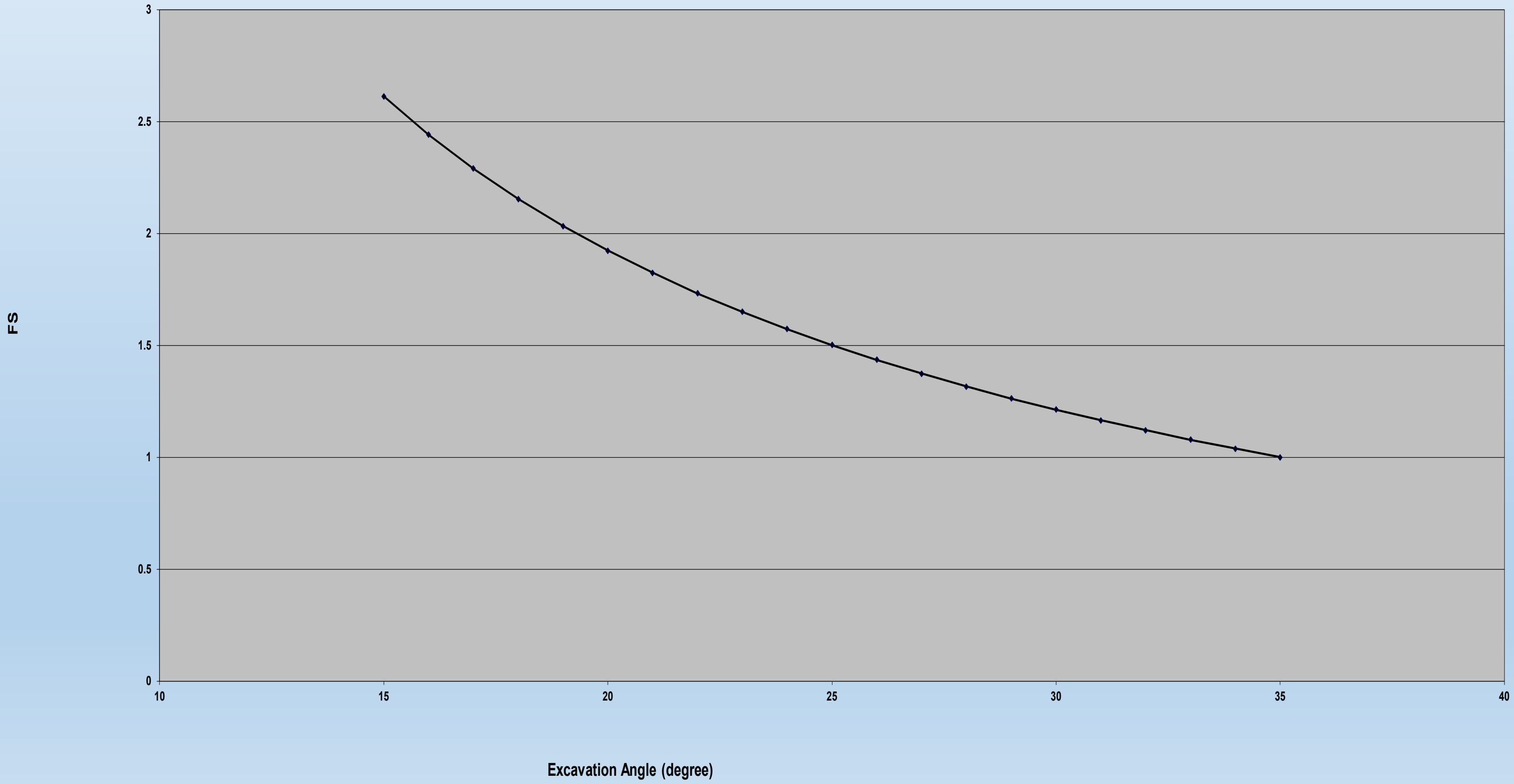
# Angle of Slope vs. Safety Factor



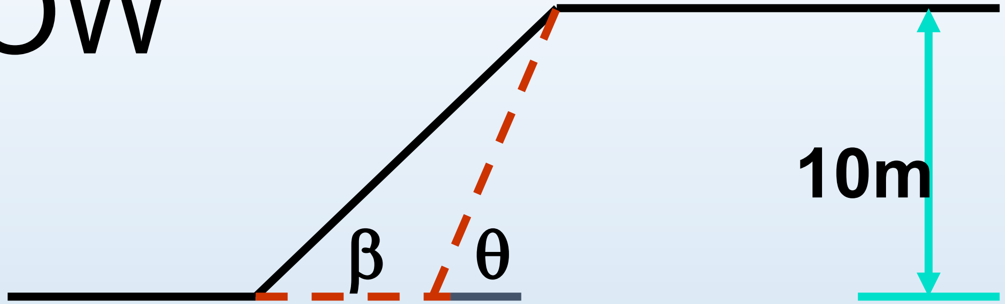

$\phi = 35°$

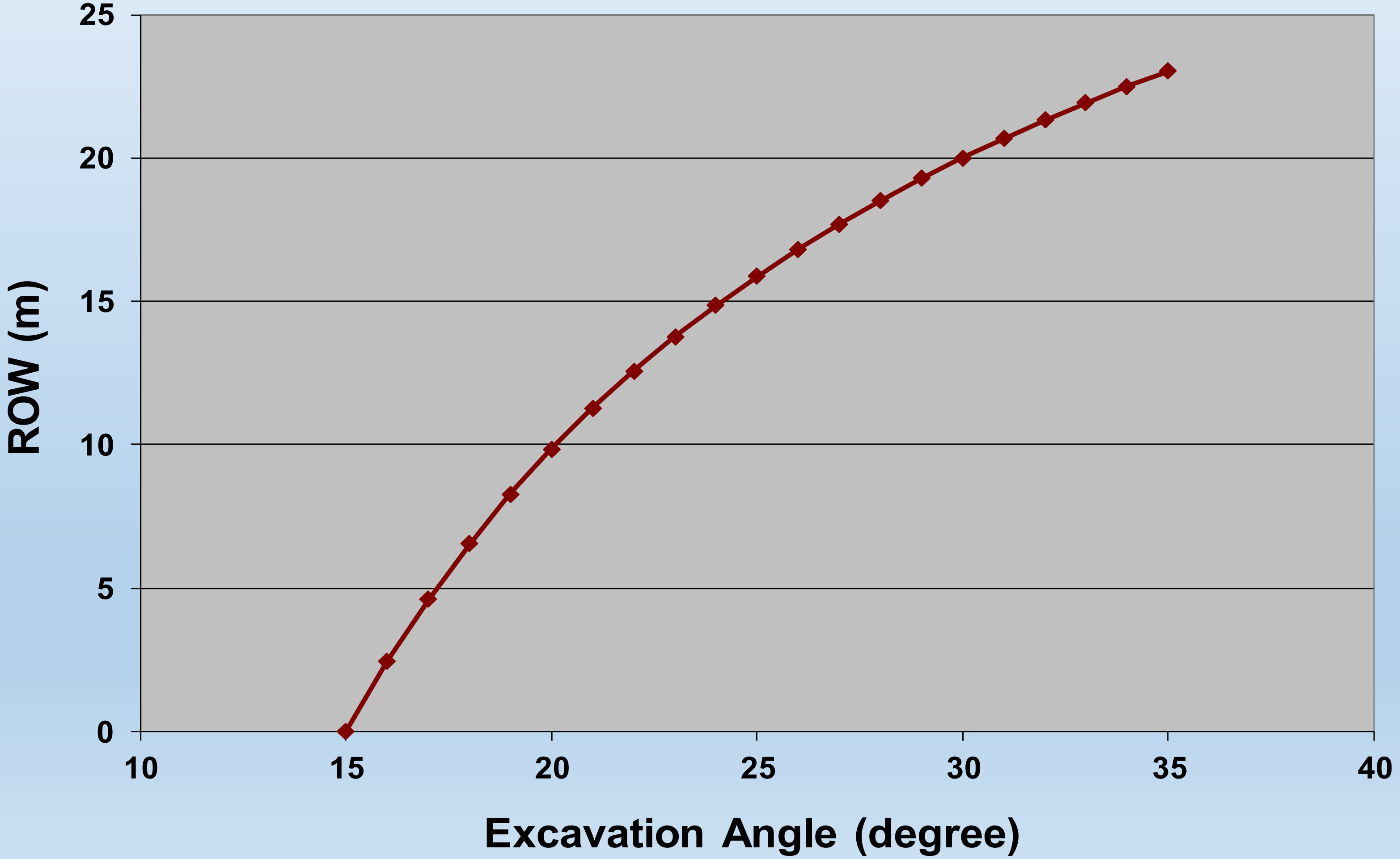
$\beta = 15°$

$15° < \theta < 35°$



# Slopes vs. Gained ROW




$\phi = 35°$

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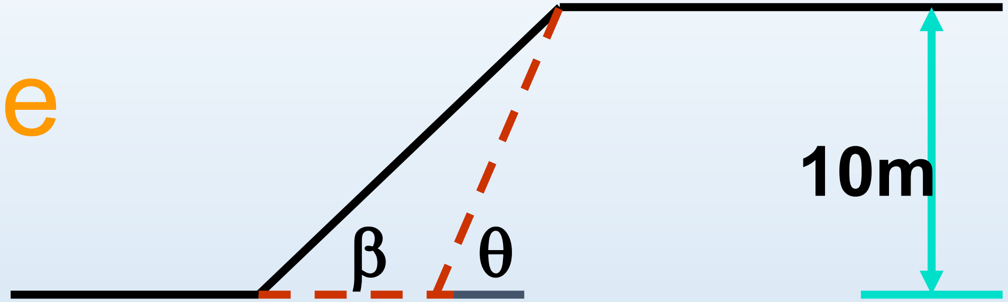
$15° < \theta < 35°$

# Angle of Slope vs Excavation Volume




$\phi = 35°$

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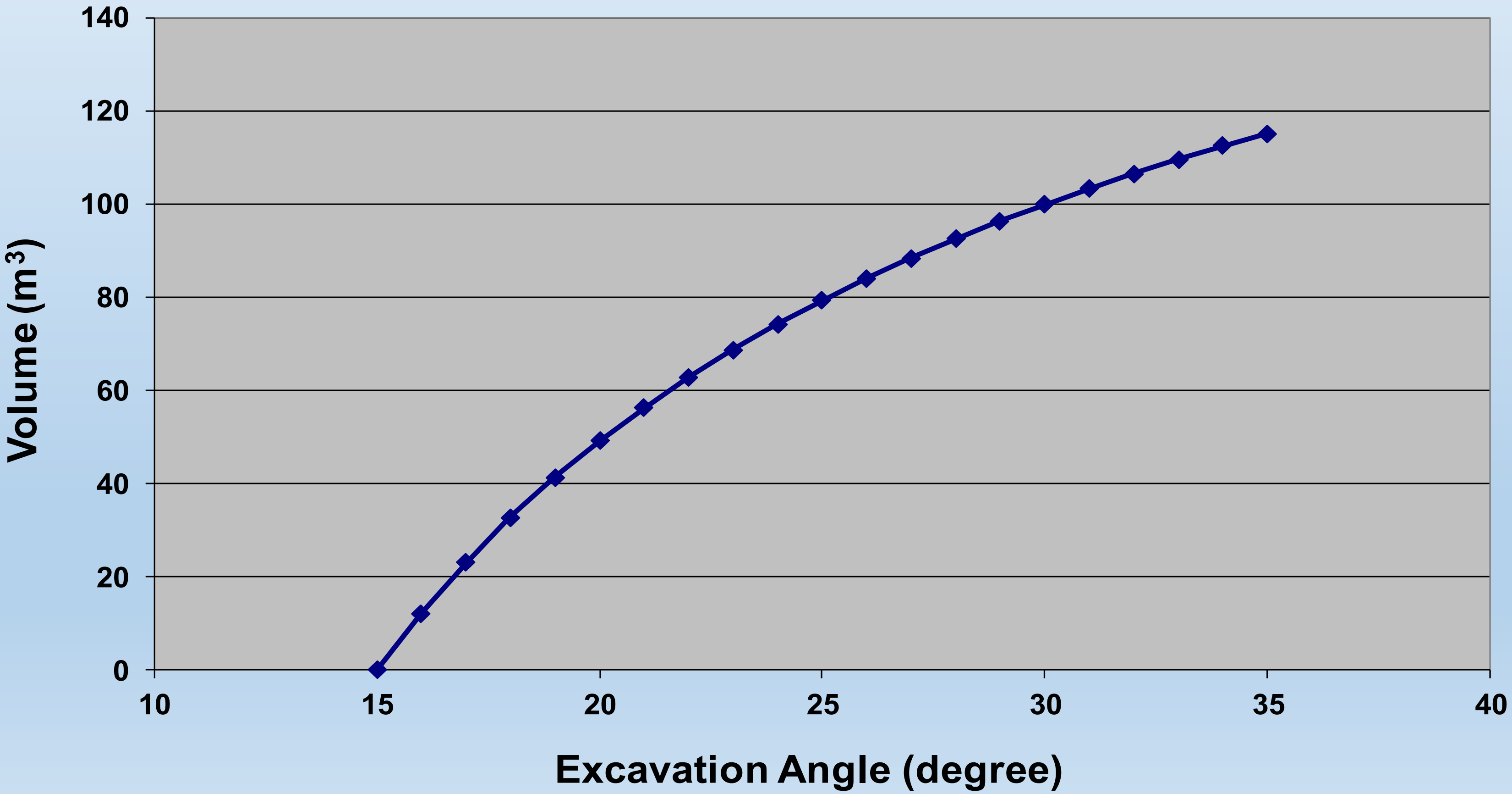
$15° < \theta < 35°$



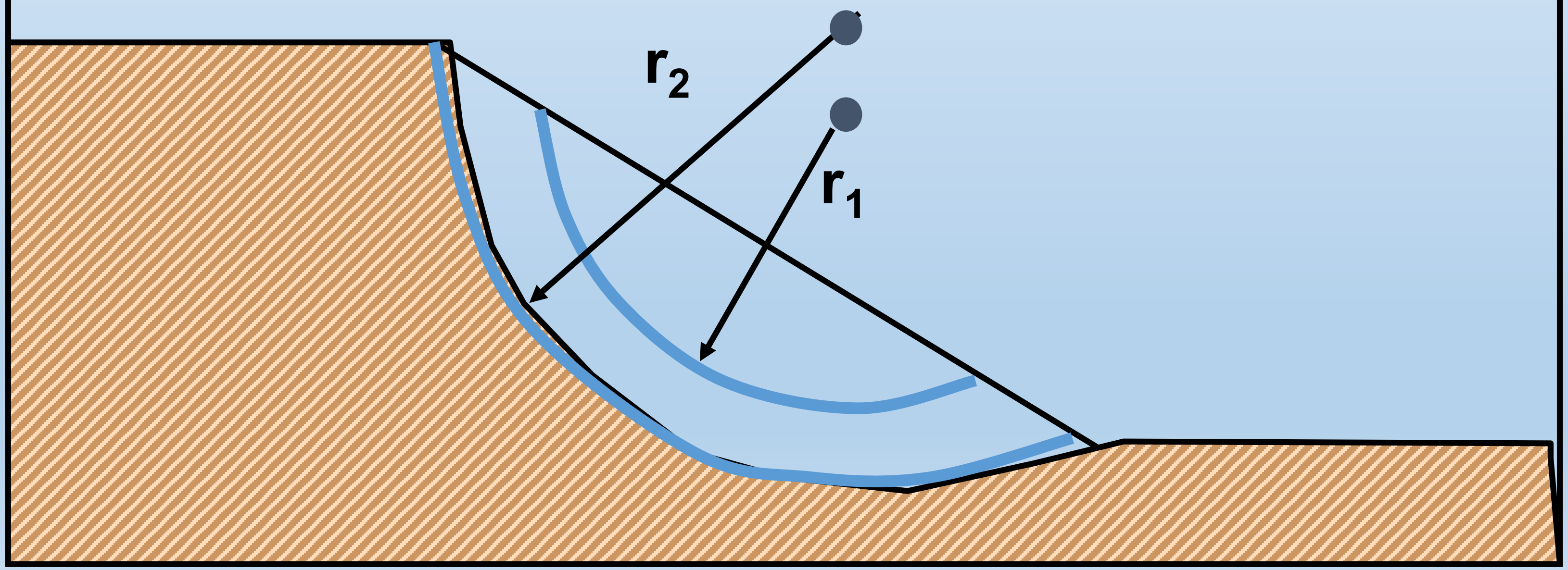
# Tips and Intuition When Running Slope Stability Analysis

# Slide in Homogeneous Soil

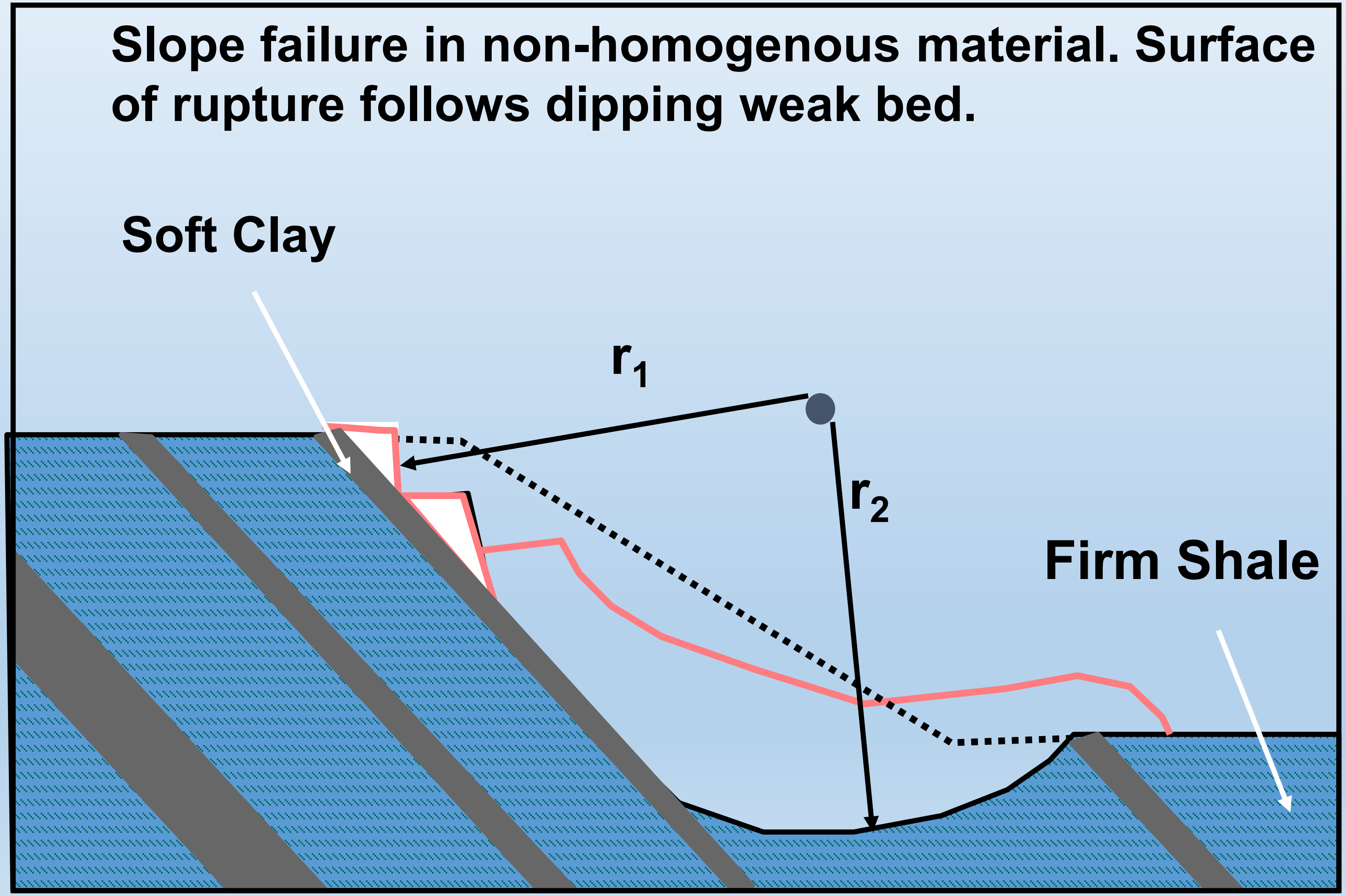
**Slope failures in homogenous material tends be circular:**

**1. Slide wholly on slope.**

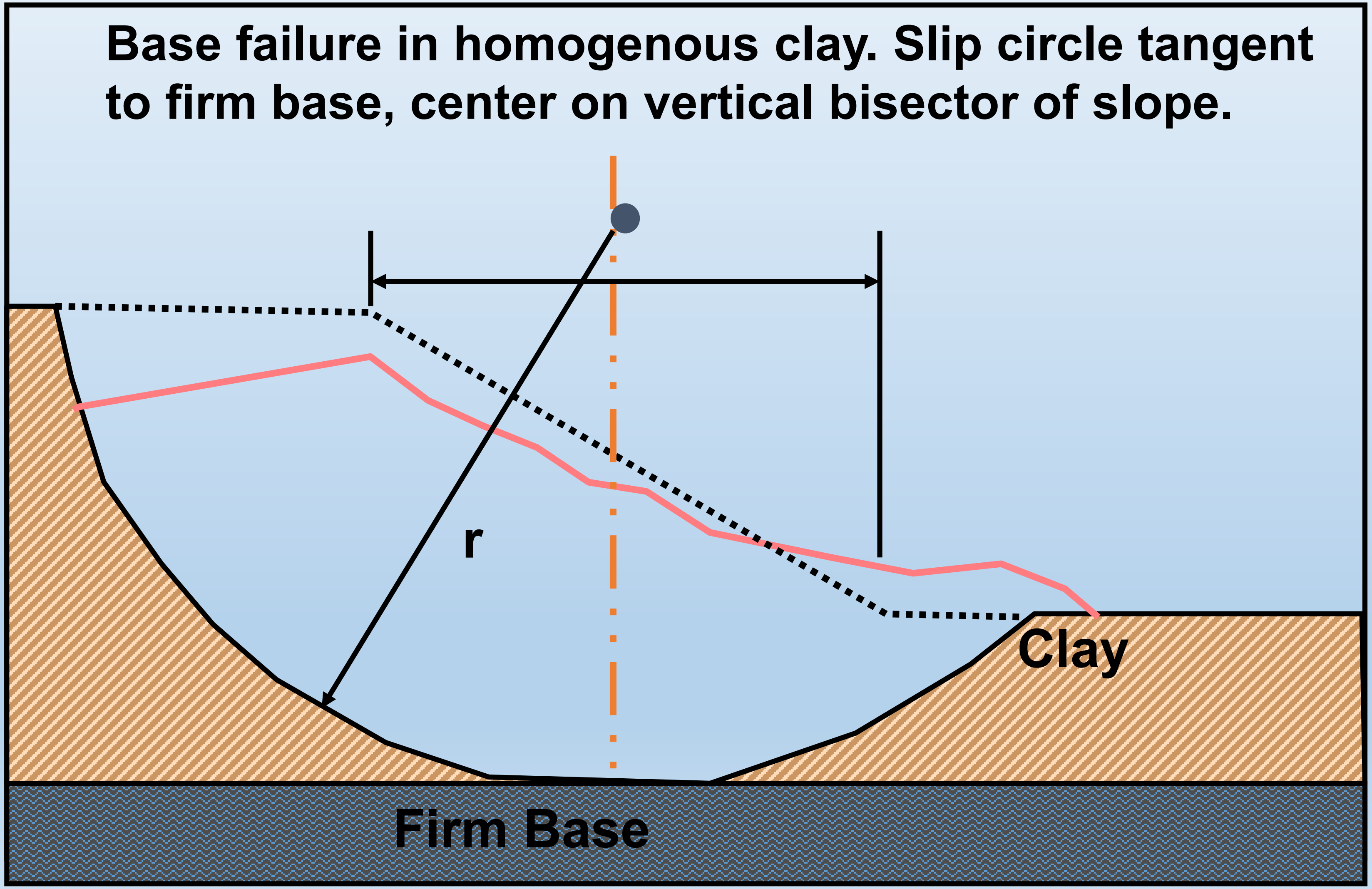
**2. Surface of rupture intersects toe of slope when steep.**



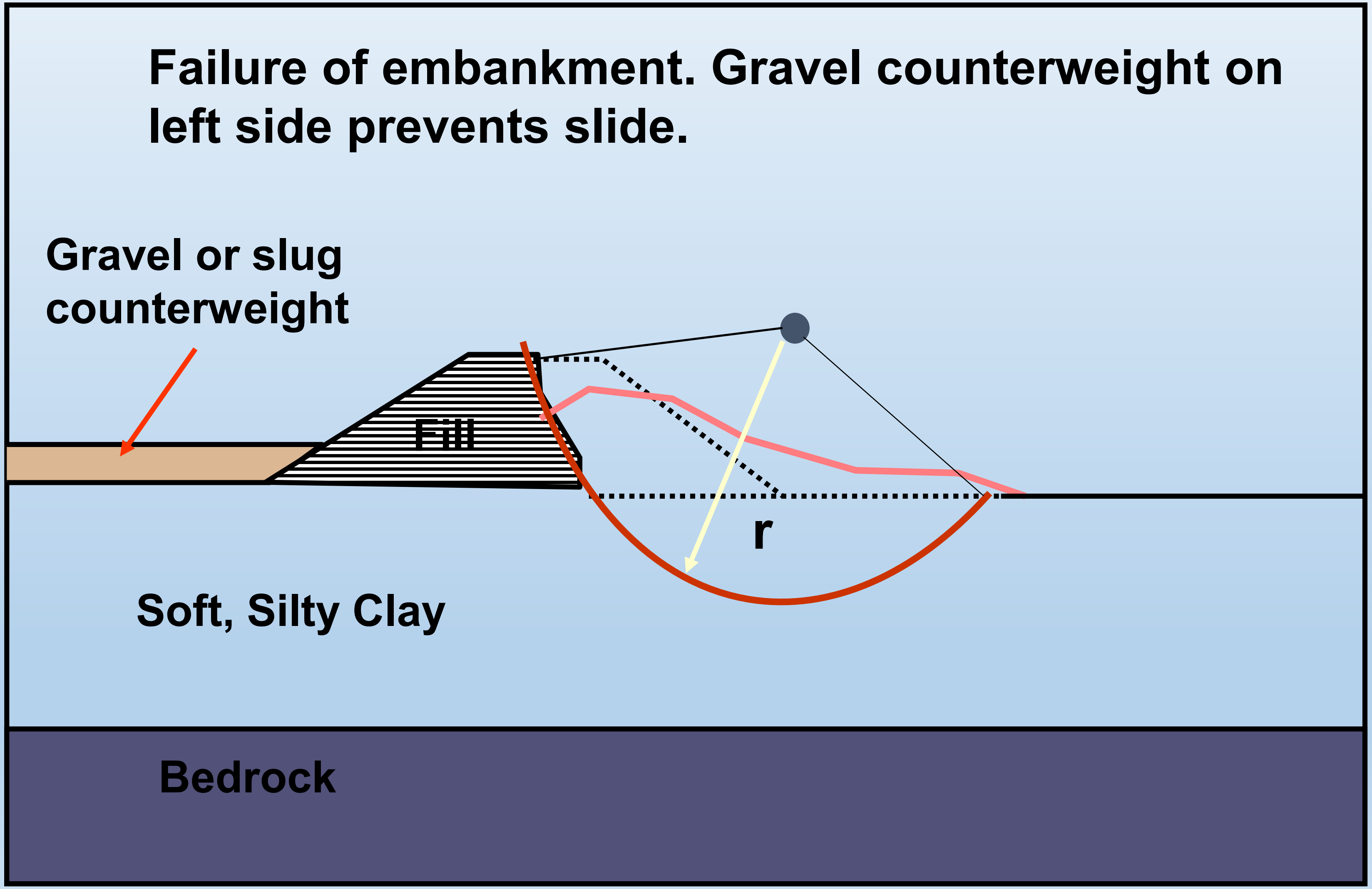
# Slide Controlled by Dipping Seams



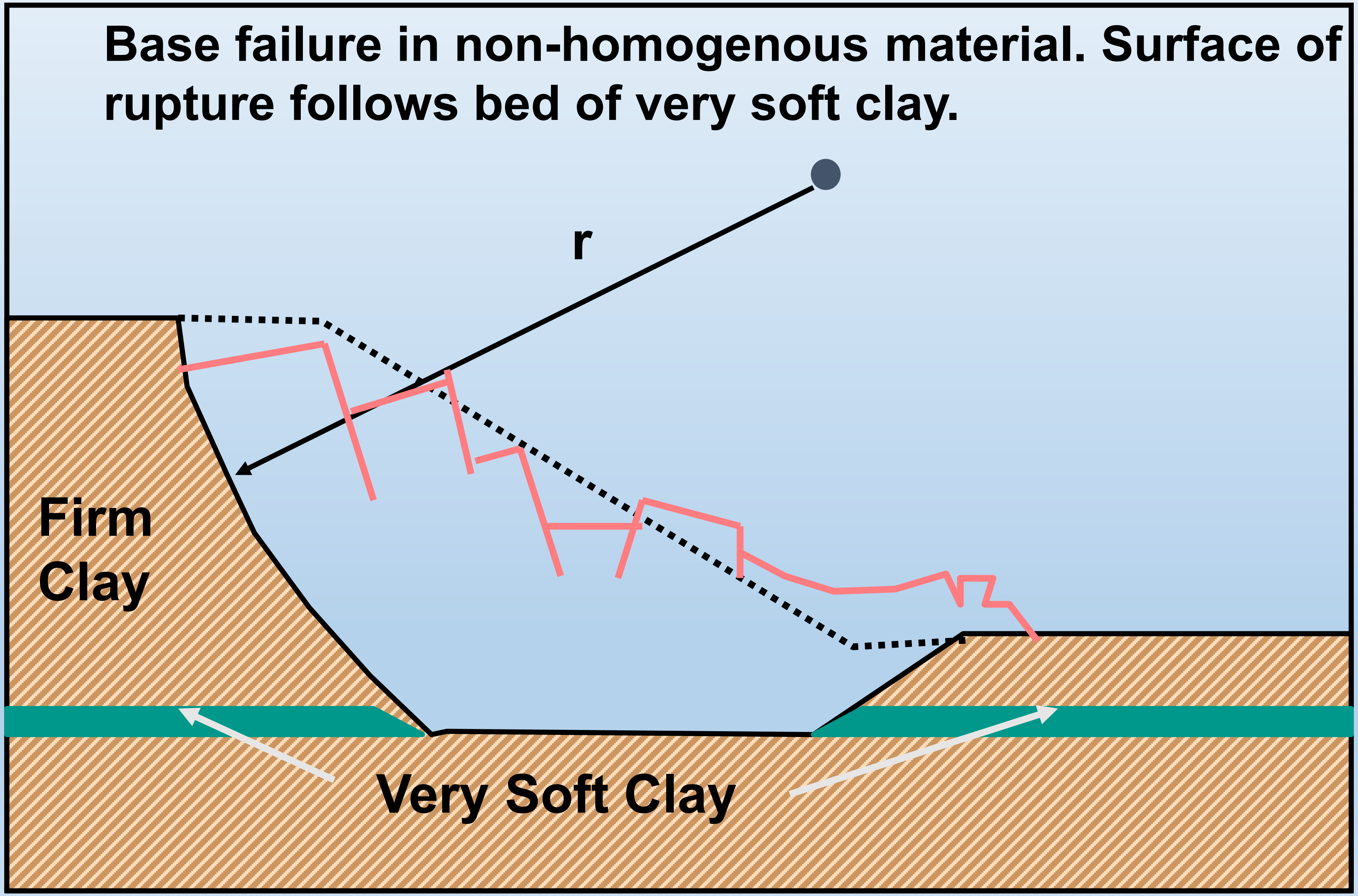
# Deepseated Failure Limited by Bedrock



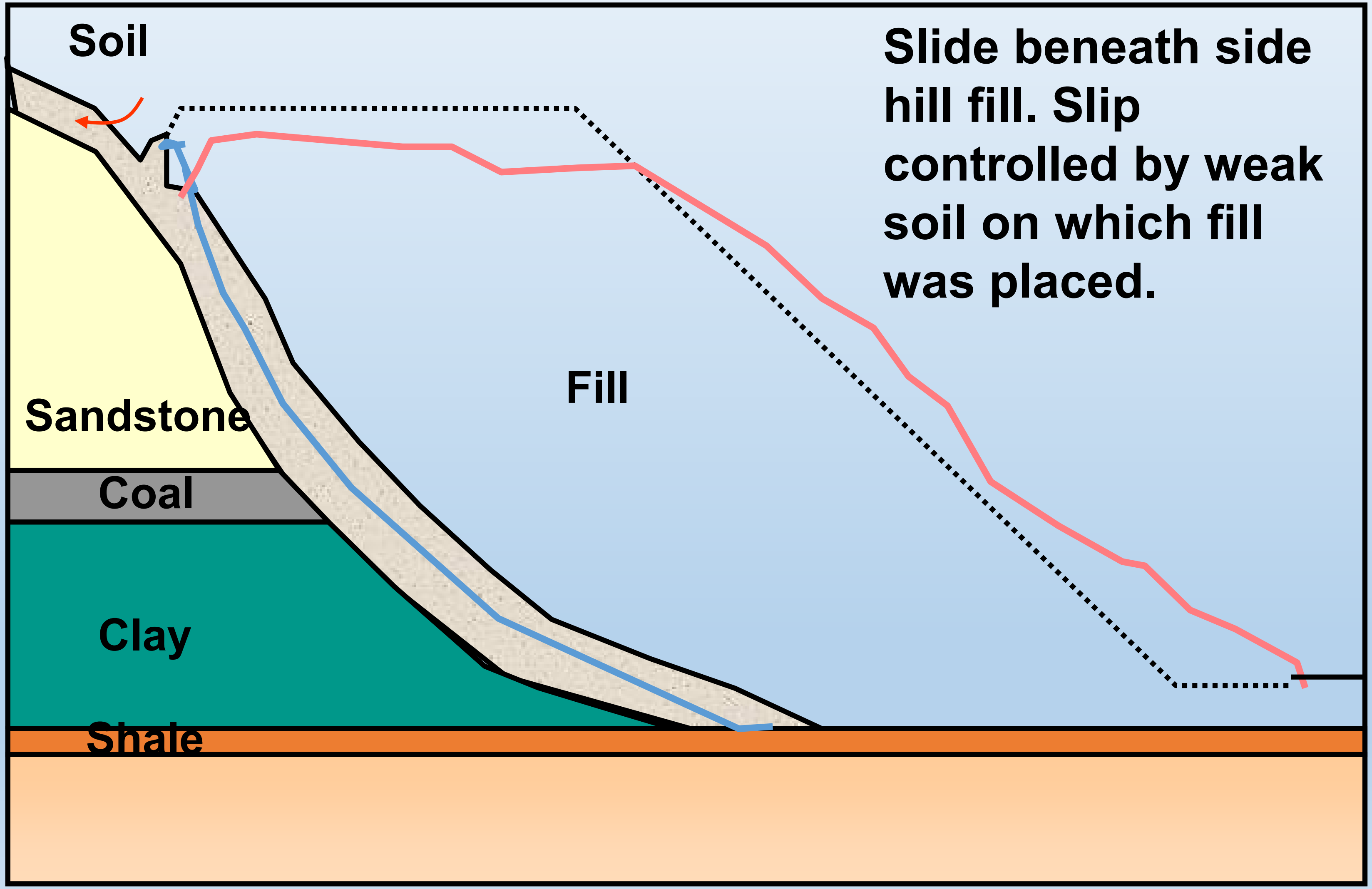
# Deepseated Failure Partially Controlled by Berm



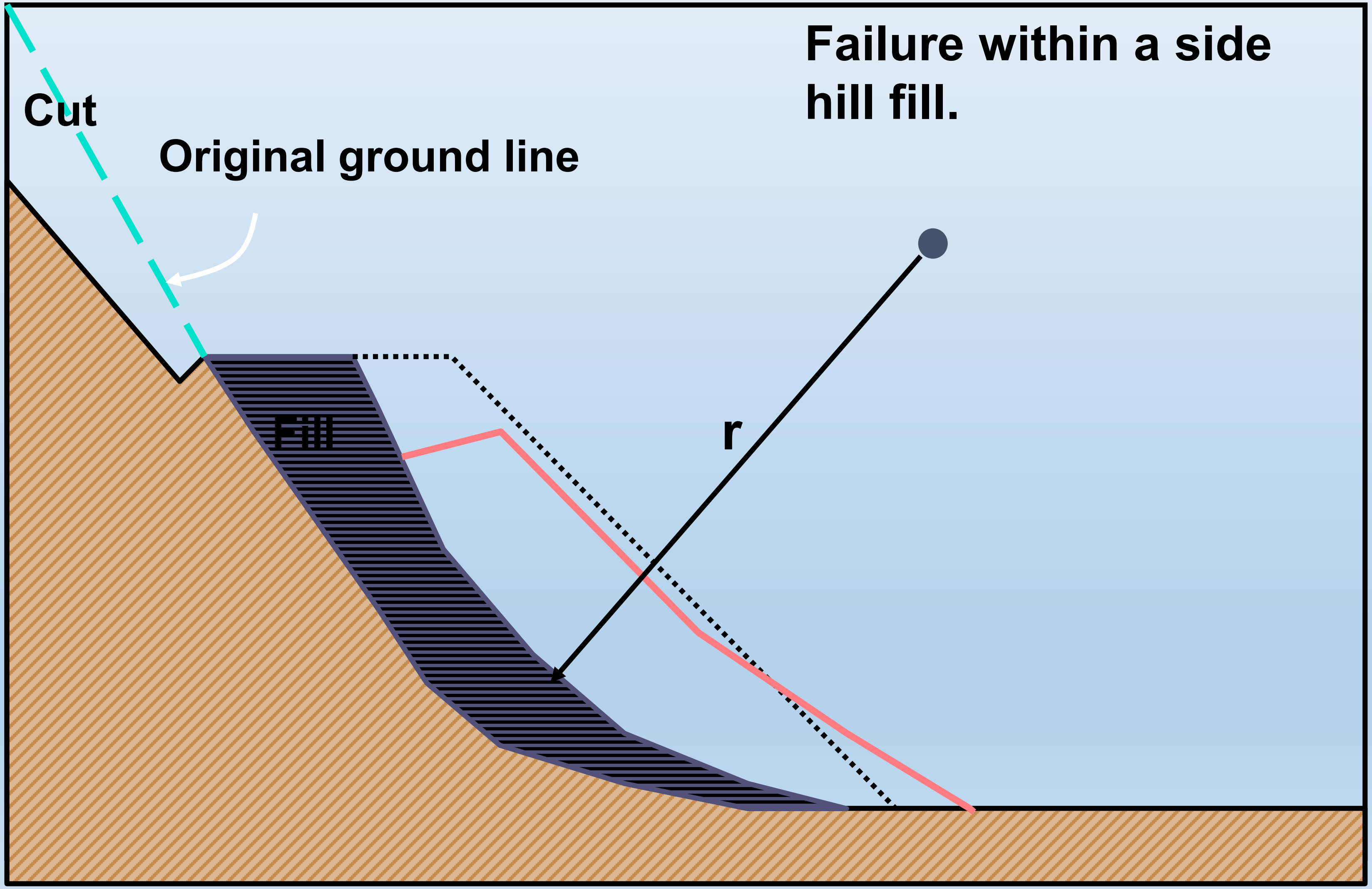
# Composite Failure Controlled by Soft Seam of Clay



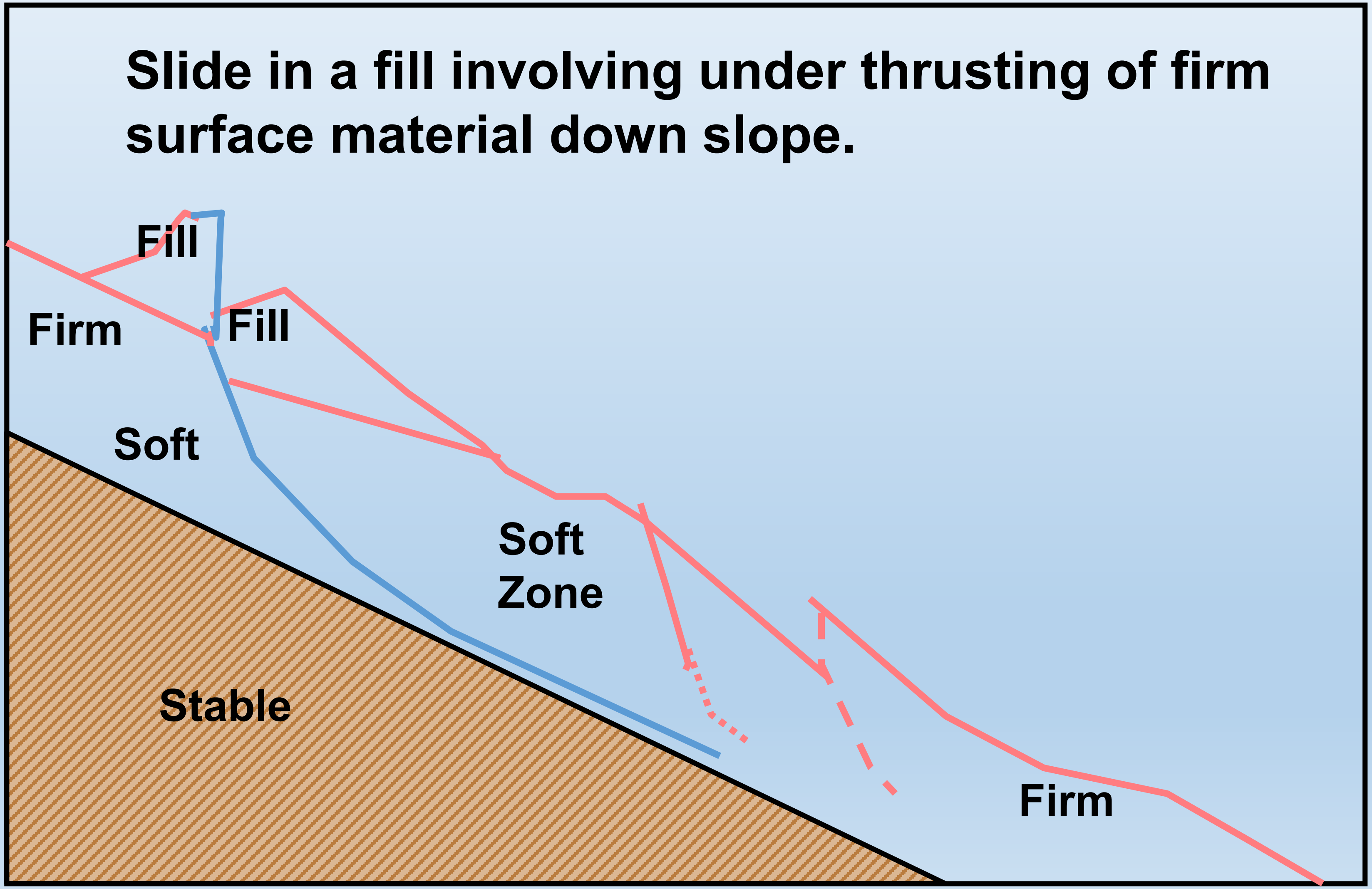
# Slide Along Interface of Fill and Sloping Natural Soil



# Slide within Fill in a Cut and Fill Operation



# Retrogressive Failure of Fill from Bottom Up



# Sliding Geometry: Tips

- If changes in strength of soil layers is gradual, circular failure is likely

- Large changes in strength of soil layers tend to cause composite or non-circular failure surfaces (e.g. bedrock, strong strata).

- Identification of potential failure mechanisms requires careful evaluation

# Questions?