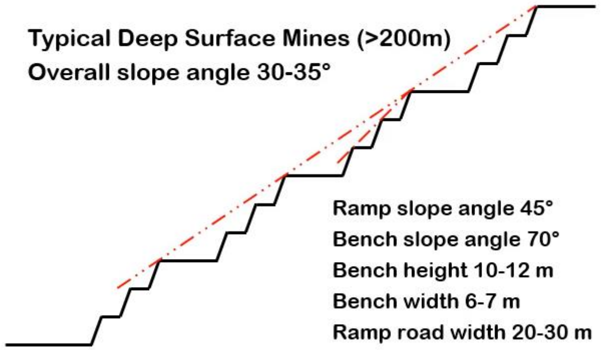
Learning objectives

- Develop an understanding of rock failure modes and their identification with stereonets
- Learn how to determine the factor of safety for slopes

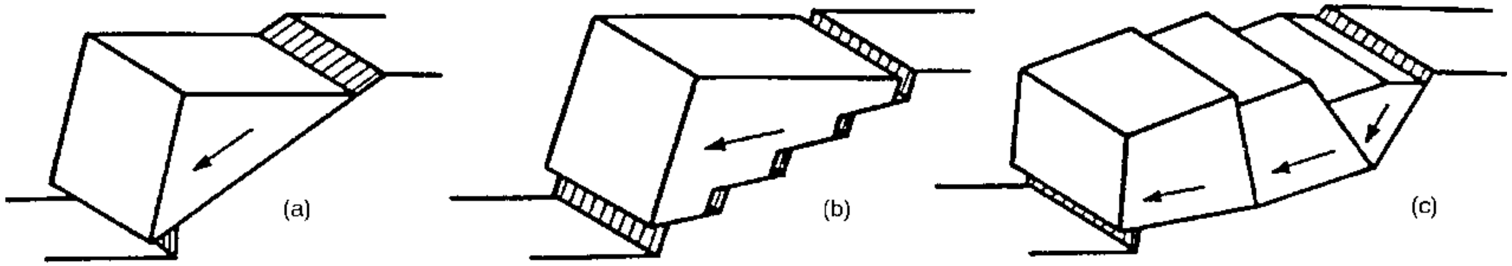
Rock slopes

- Natural slopes typically in hillsides; mostly stable but some at critical states; difficult to support;
- Excavated slopes when roads/rails need slope cutting; normally single steep bench and often with reinforcement
- Surface mining in rocks to access the ore materials; bench slope can be 70° and overall angle of 30-45°; slope typically not supported
- Focuses on rock slope stability analysis and rock support design

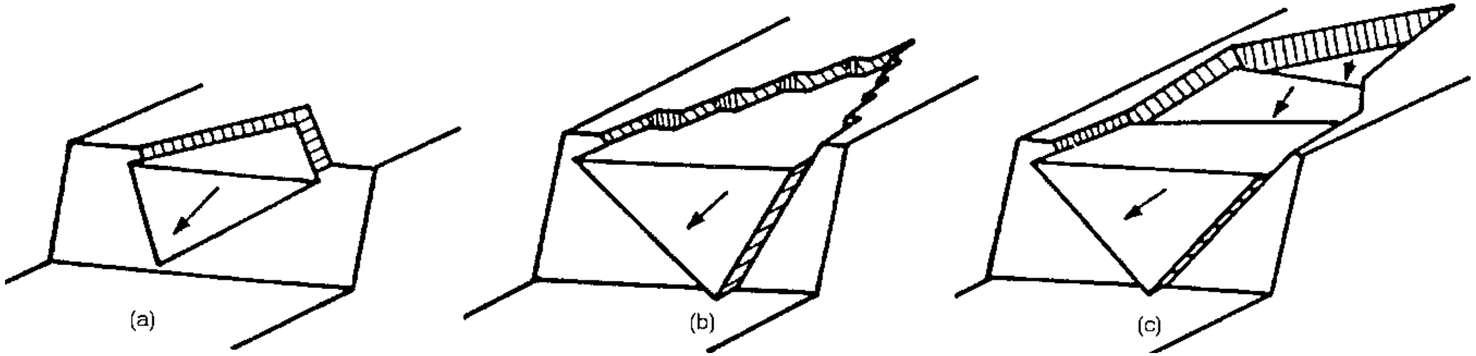


Rock slope failure modes

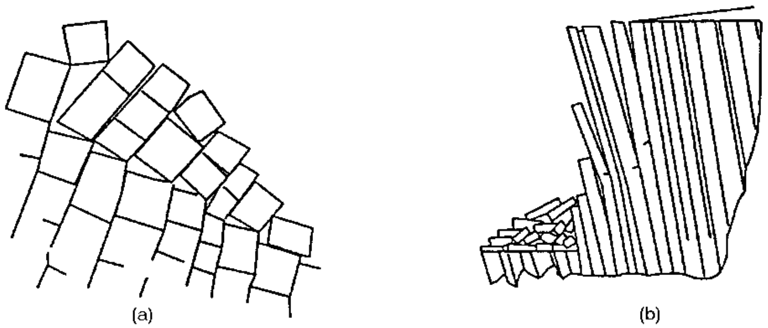
Planar



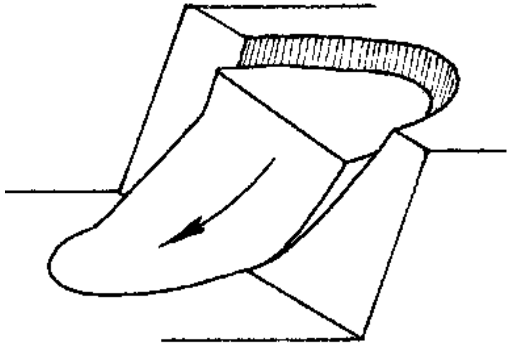
Wedge



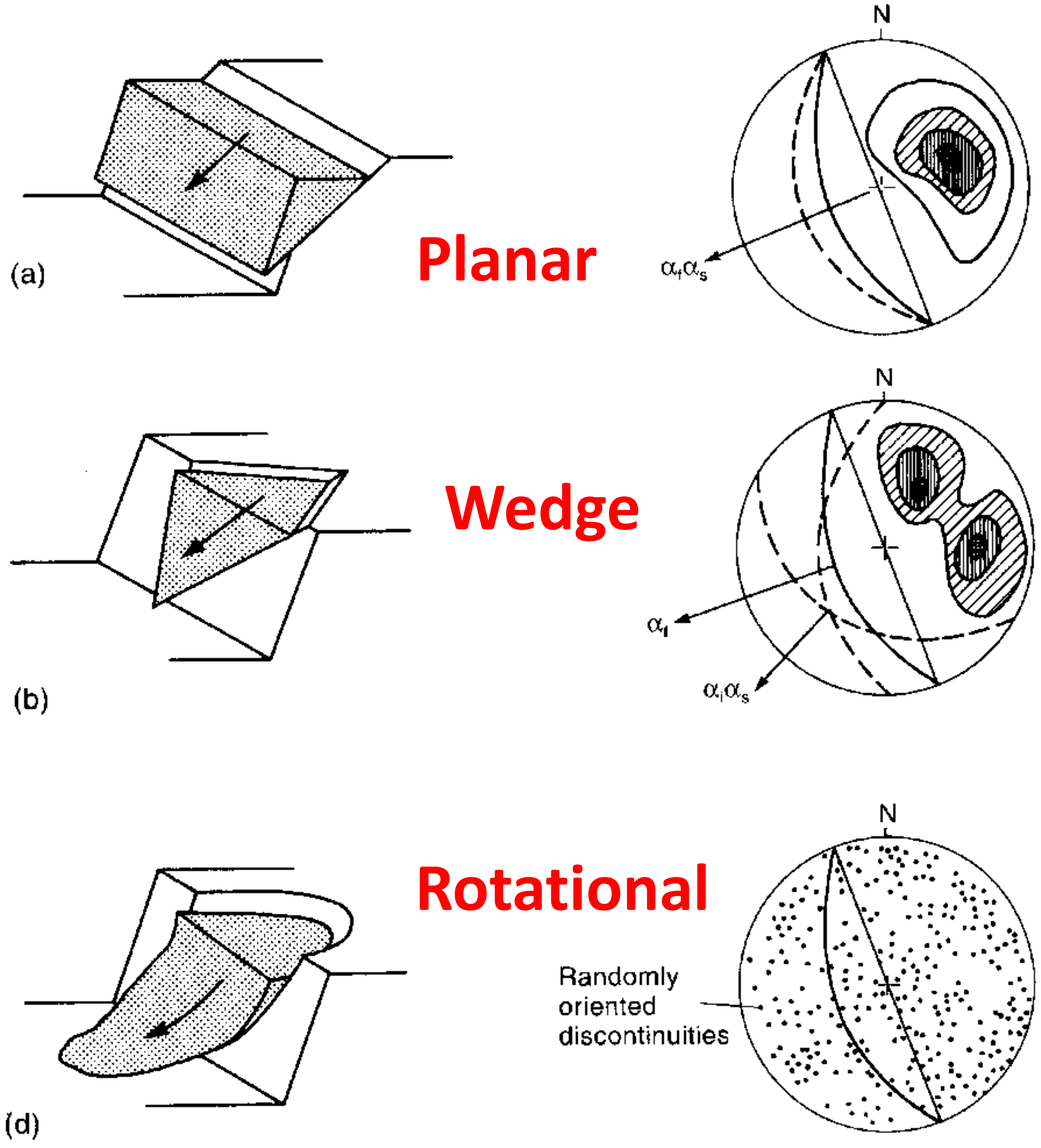
Toppling

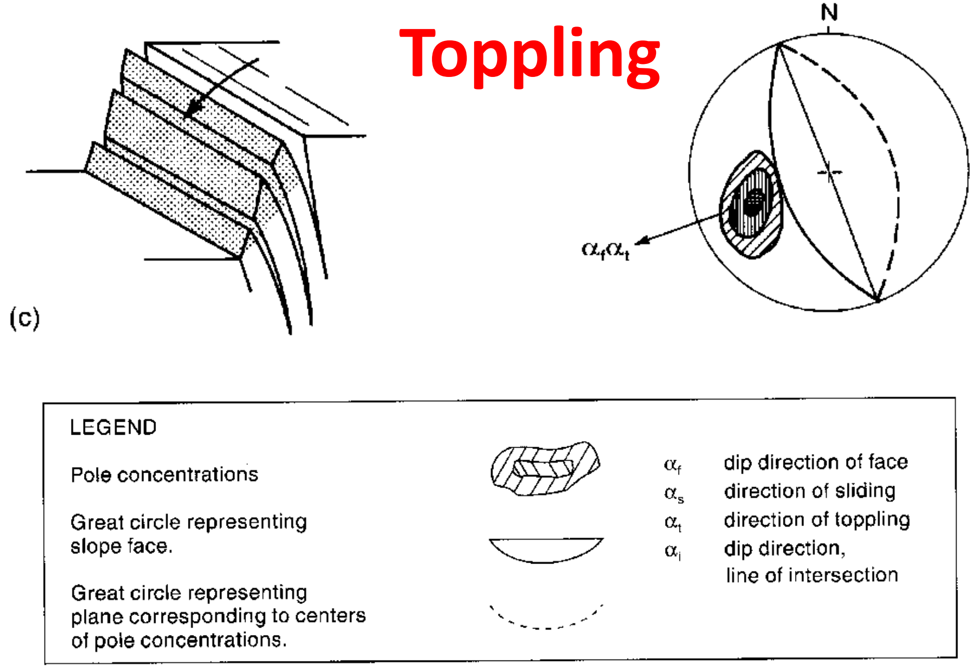


Rotational



Stereonet identification of failure mechanisms



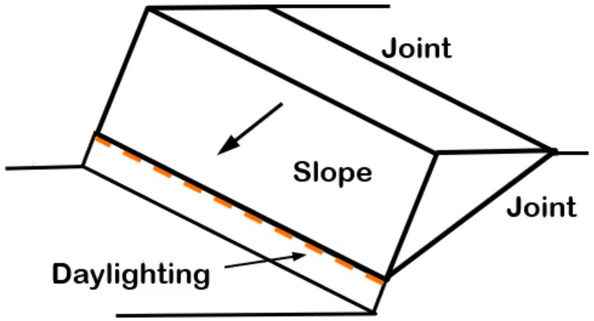


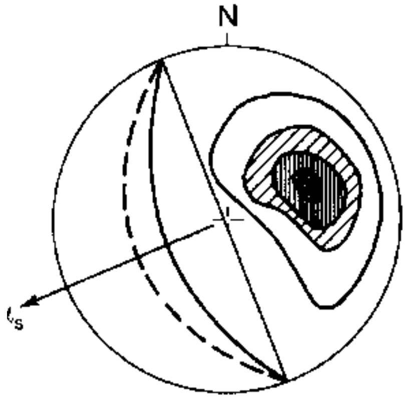
Planar failure

- Through going discontinuity exists, e.g. faults
- Discontinuity strikes parallel to the slope face (±20°)
- Sides of block are free to move
- If $\psi_p > \psi_{slope\ face}$, then the discontinuity does not daylight in the slope face, and therefore no planar failures
- For dry conditions

$$\phi < \psi_p < \psi_{slope\ face}$$

- For wet conditions ψ_p is not necessarily greater than ϕ



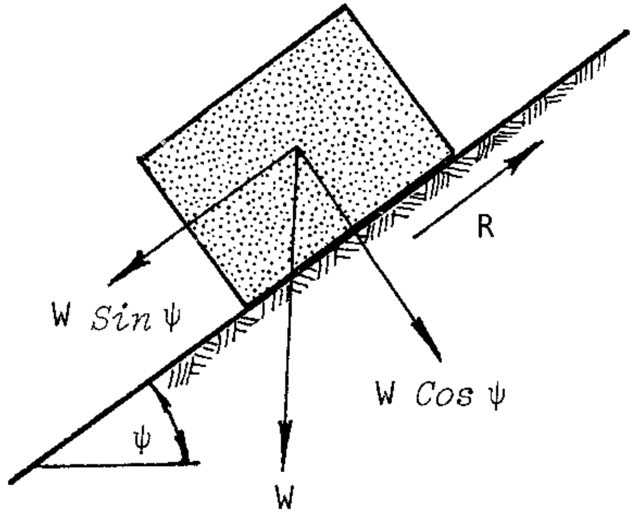


Limit equilibrium of a sliding block

- Gravity force W can be divided into two components: parallel and normal to the inclined surface
- $W\cos\psi$ is the normal contact force causing normal stress and their shear resistant strength
- $W\sin\psi$ drives the block to slide downward
- Factor of safety is the ratio of resisting force by the disturbing force

$$\sigma_n = \frac{W\cos\psi}{A}$$

$$\tau = c + \left(\frac{W\cos\psi}{A}\right)\tan\phi$$



$$R = \tau A = cA + W\cos\psi\tan\phi$$

$$F = \frac{\sum \text{resisting forces}}{\sum \text{disturbing forces}} \qquad F = \frac{cA + W\cos\psi\tan\phi}{W\sin\psi}$$

If cohesion = 0, $F = \dfrac{\cos\psi\tan\phi}{\sin\psi} = \dfrac{\tan\phi}{\tan\psi}$

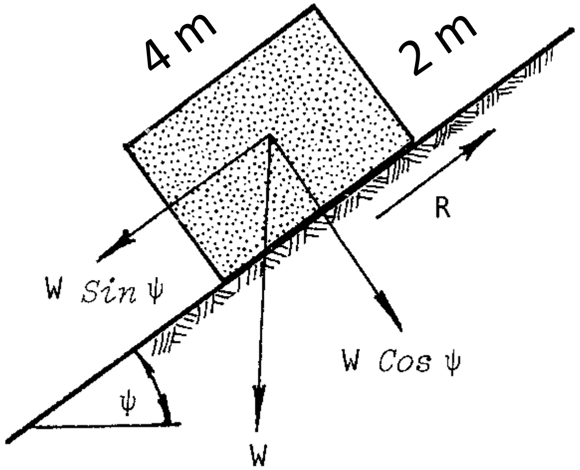
Limit equilibrium of a sliding block - example

Density = 2500 kg/m3

cohesion = 5 kPa

$\varphi=30^\circ$

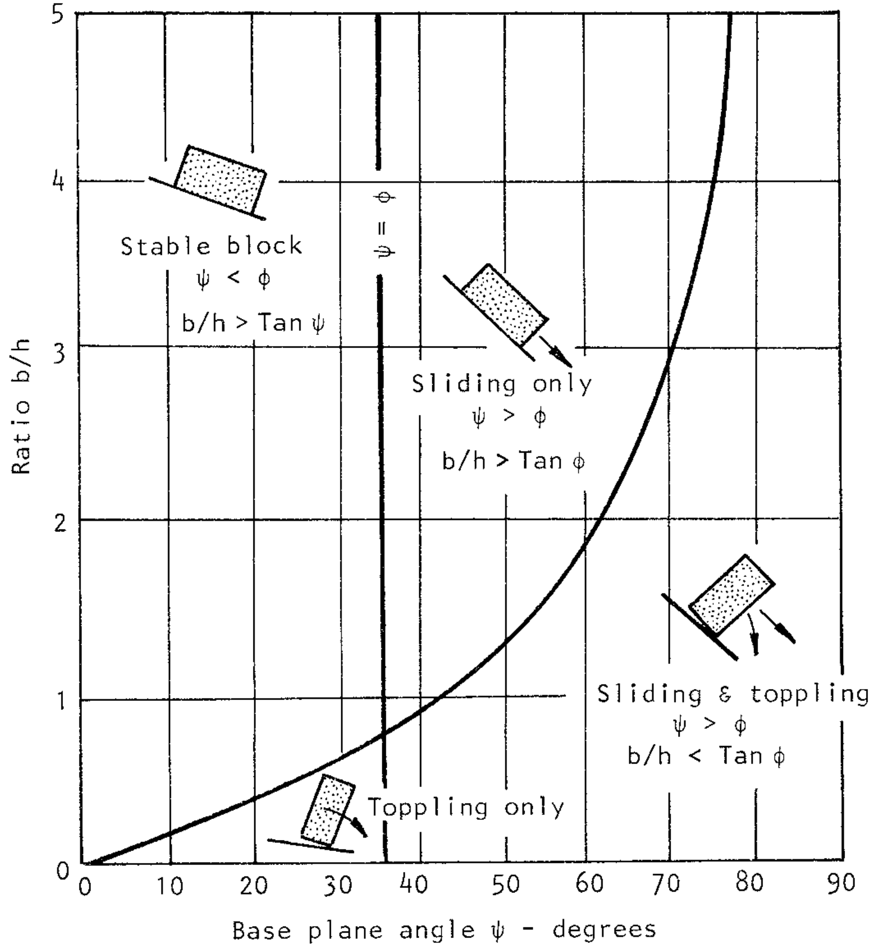
$\psi=30^\circ$

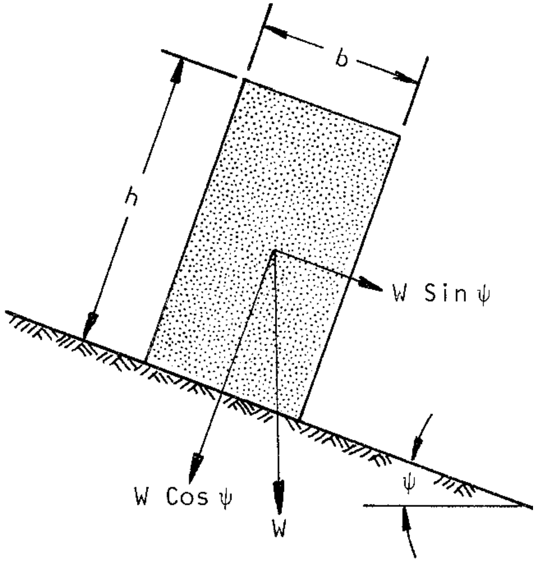


$$F = \frac{\sum \text{resisting forces}}{\sum \text{disturbing forces}}$$

$$F = \frac{cA + (W\cos\psi - U)\tan\phi}{W\sin\psi + V}$$

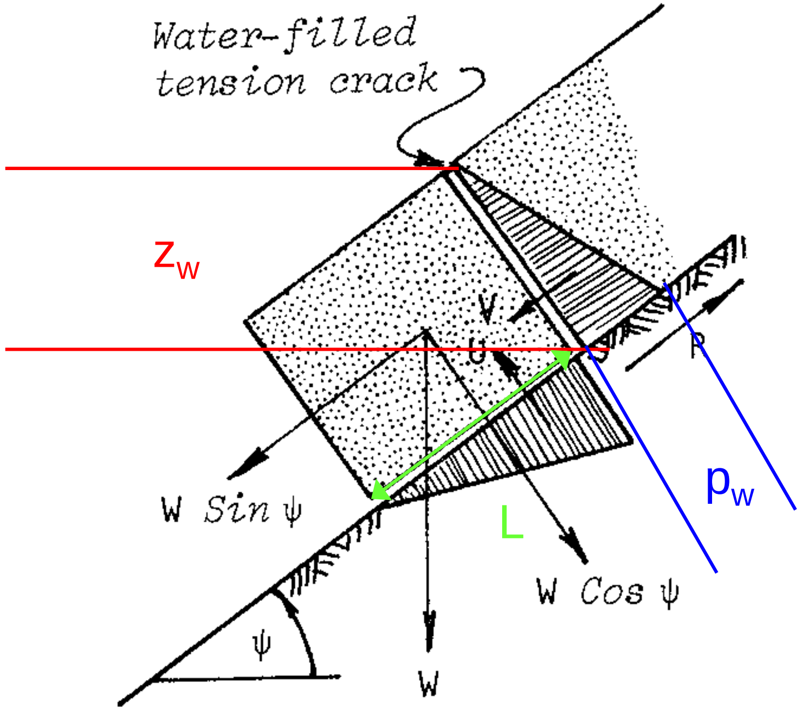
Conditions for block sliding and toppling





Tension crack with water

- A tension crack may occur at the crest (conservative), in the slope face, or behind the crest
- Plot of factor of safety versus crack position, find the minimum SF



$$F = \frac{\sum \text{resisting forces}}{\sum \text{disturbing forces}}$$

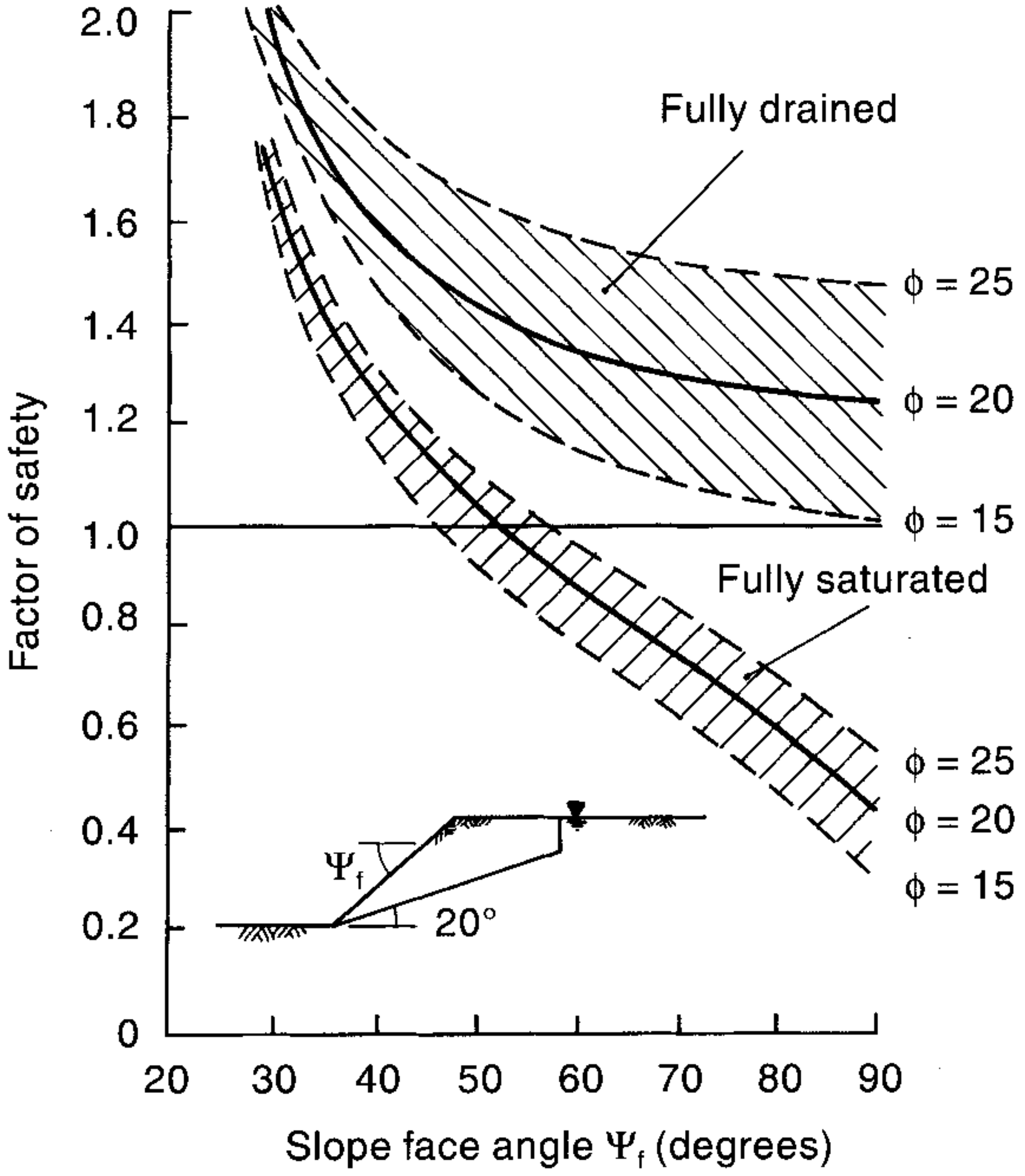
$$F = \frac{cA + (W\cos\psi - U)\tan\phi}{W\sin\psi + V}$$

$$V = 0.5 \cdot \rho_w g z_w \cdot \frac{z_w}{\cos\psi}$$

$$U = 0.5 \cdot \rho_w g z_w \cdot L$$

Role of water pressure

- Presence of water increase the sliding force and reduce the normal stress and hence lower the shear resistance
- Water can also soften rock materials (especially with clays) and can reduce the cohesion/friction angle of rocks which reduce the shear resistance



Bolt reinforcement

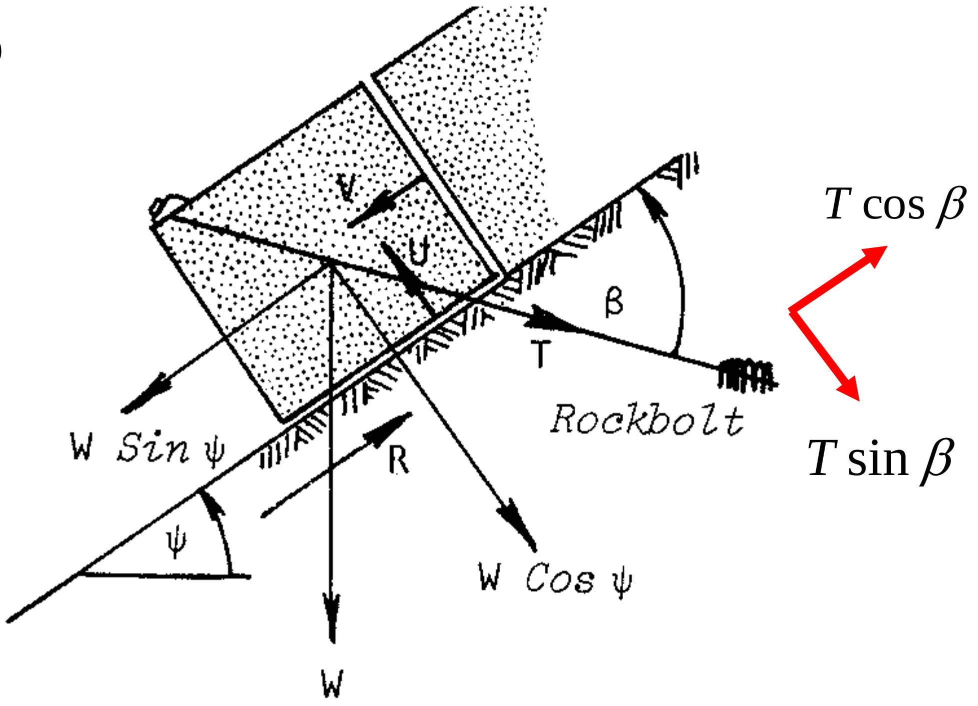
- Dewatering, or changing W, or bolt can be used to reinforce the slope
- Bolts can pre-stressed by applying a tension to stretch the bolt, which is termed as active bolts
- Bolts can also be untensioned, which is passive
- For passive bolts, force coming from the bolt will be mobilized once the slope moves

$$F = \frac{cA + (W\cos\psi - U + T\sin\beta)\tan\phi + T\cos\beta}{W\sin\psi + V}$$

component increases the resisting force

- For active bolts, tension force T is already applied to the slope

$$F = \frac{cA + (W\cos\psi - U + T\sin\beta)\tan\phi}{W\sin\psi + V - T\cos\beta}$$



$T\cos\beta$ reduces the sliding force

$T\sin\beta$ increases the resistant force

Bolt reinforcement for active bolts

$$F = \frac{cA + (W\cos\psi - U + T\sin\beta)\tan\phi}{W\sin\psi + V - T\cos\beta}$$

To optimize *b*, differentiate

$$\frac{\delta T}{\delta\beta} = 0$$

to find the maximum

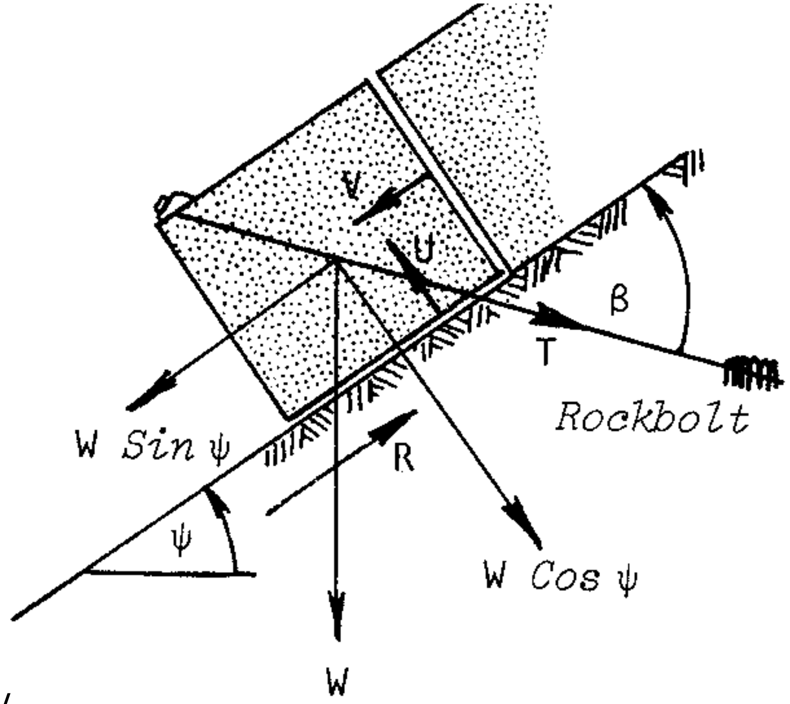
$$F(W\sin\psi + V - T\cos\beta) = cA + (W\cos\psi - U + T\sin\beta)\tan\phi$$

differentiating gives:

$$FT\sin\beta = T\cos\beta\tan\phi$$

Hence, *b* is optimized when $\beta = \tan^{-1}\left(\frac{\tan\phi}{F}\right)$

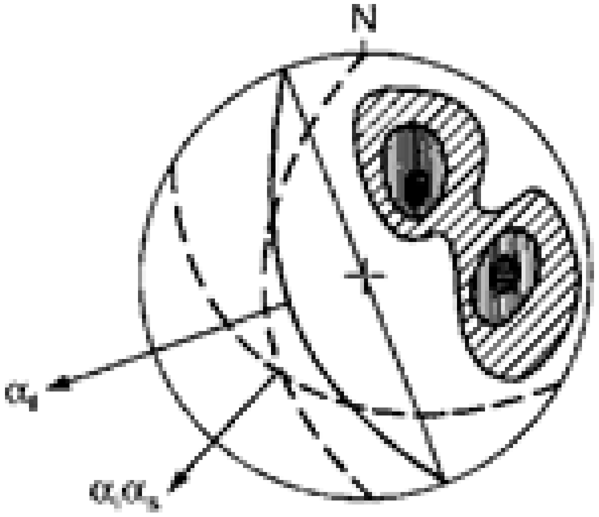
(for active bolts only)



Wedge failure

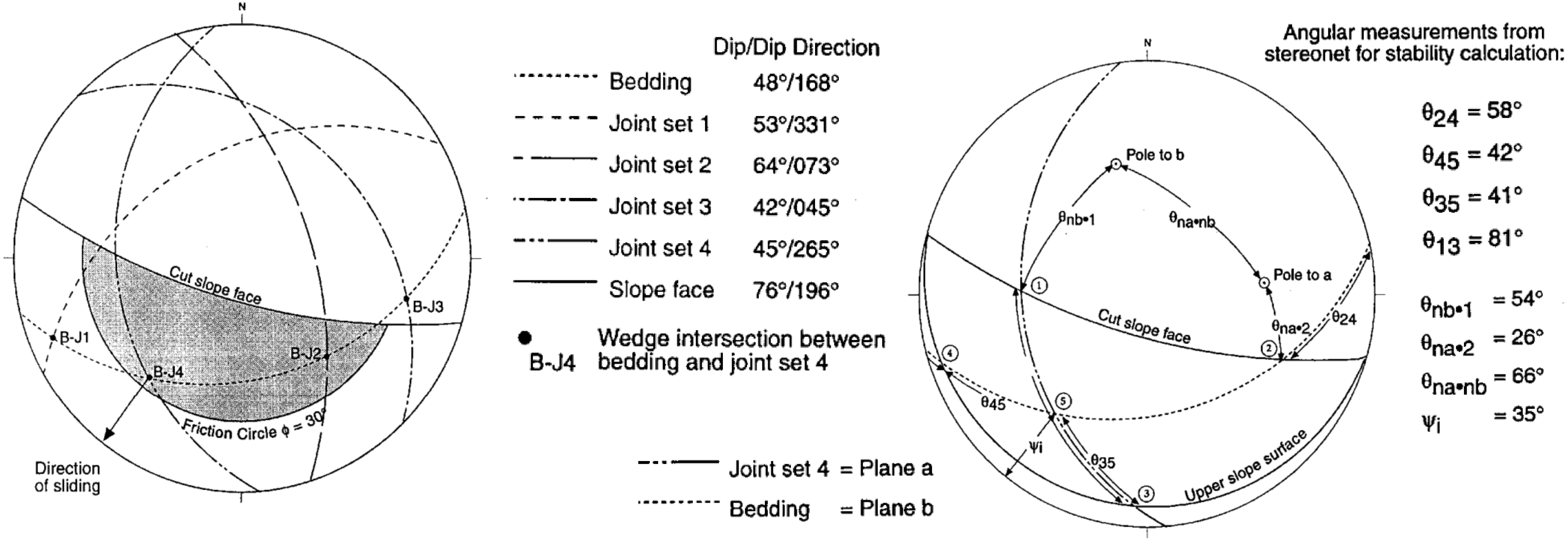
- 2 (or more) discontinuities exist
- Intersection trends perpendicular to the slope face (±20°)
- If $\psi_i > \psi_{slope\ face}$, then the discontinuity does not daylight in the slope face, and therefore no wedge failure
- For dry conditions

$$\phi < \psi_i < \psi_{slope\ face}$$



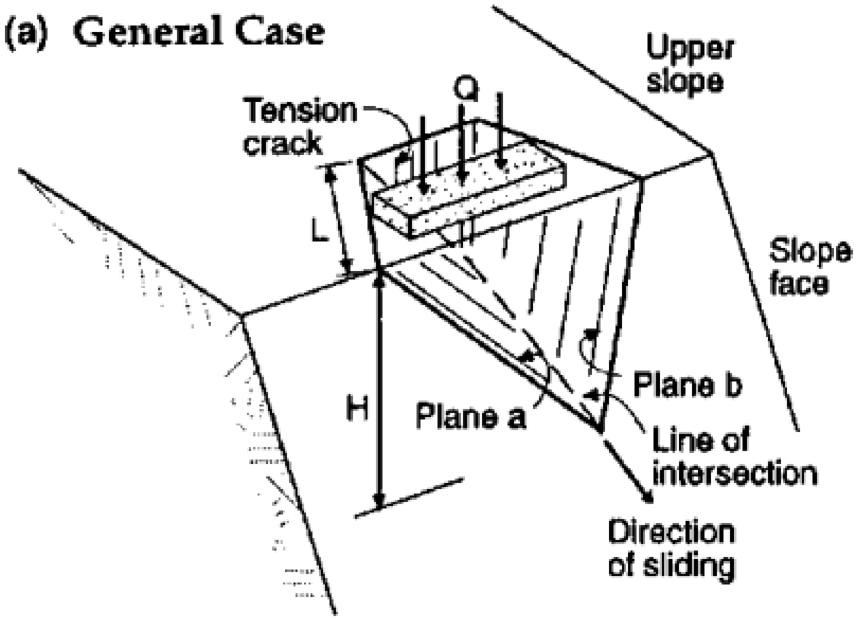
Wedge failure

- Perform kinematical analysis to see if potential wedge failures are likely
- If so, further calculate the factor of safety using analytical equations



Factor of safety for wedge failure

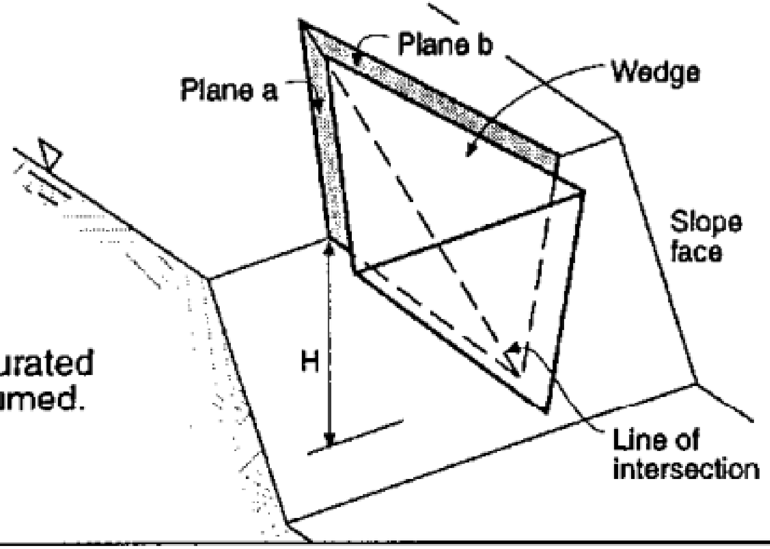
(a) General Case



Use comprehensive solution by Hoek and Bray (1981)

Note: This solution required if external loads to be included.
Typically solved using computer program.

(b) Tension Crack Not Present



Note: Saturated slope assumed.

$$FS = \frac{3}{\gamma_r H}(c_a \cdot X + c_b \cdot Y) + (A - \frac{\gamma_w}{2\gamma_r}X)\tan\phi_a + (B - \frac{\gamma_w}{2\gamma_r}Y)\tan\phi_b$$

PARAMETERS:

c_a and c_b are the cohesive strengths of planes a and b

ϕ_a and ϕ_b are the angles of friction on planes a and b

γ_r is the unit weight of the rock

γ_w is the unit weight of water

H is the total height of the wedge

X, Y, A, and B are dimensionless factors which depend upon the geometry of the wedge

ψ_a and ψ_b are the dips of planes a and b

ψ_i is the plunge of the line of intersection

$$B = \frac{\cos\psi_b - \cos\psi_a \cdot \cos\theta_{na \cdot nb}}{\sin\psi_i \cdot \sin^2\theta_{na \cdot nb}}$$

$$X = \frac{\sin\theta_{24}}{\sin\theta_{45} \cdot \cos\theta_{na \cdot 2}} \qquad A = \frac{\cos\psi_a - \cos\psi_b \cdot \cos\theta_{na \cdot nb}}{\sin\psi_i \cdot \sin^2\theta_{na \cdot nb}} \qquad Y = \frac{\sin\theta_{13}}{\sin\theta_{35} \cdot \cos\theta_{nb \cdot 1}}$$

Factor of safety for wedge failure

(c) Fully Drained Slope

$$FS = \frac{3}{\gamma_r H}(c_a X + c_b Y) + A \tan \phi_a + B \tan \phi_b$$

PARAMETERS:

c_a and c_b are the cohesive strengths of planes a and b

ϕ_a and ϕ_b are the angles of friction on planes a and b

γ_r is the unit weight of the rock

H is the total height of the wedge

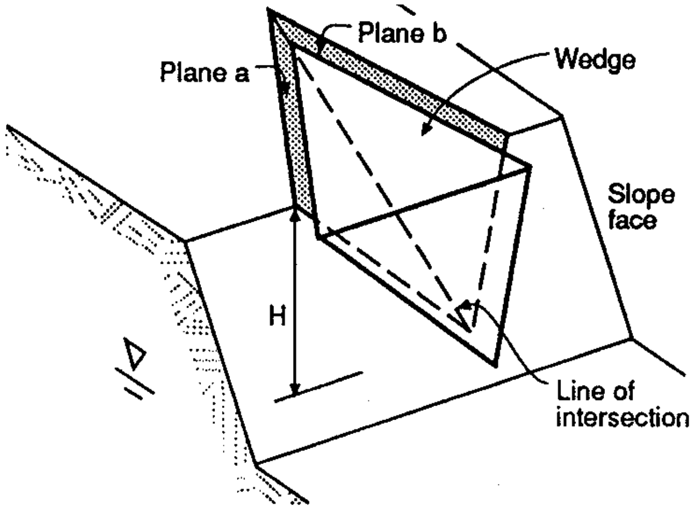
X, Y, A, and B are dimensionless factors which depend upon the geometry of the wedge

ψ_a and ψ_b are the dips of planes a and b

ψ_i is the plunge of the line of intersection

$$X = \frac{\sin\theta_{24}}{\sin\theta_{45} \cdot \cos\theta_{na \cdot 2}} \qquad Y = \frac{\sin\theta_{13}}{\sin\theta_{35} \cdot \cos\theta_{nb \cdot 1}}$$

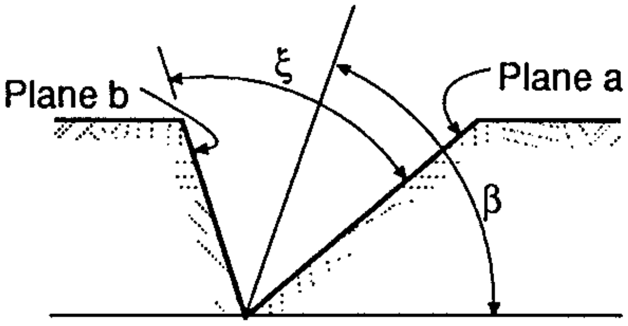
$$A = \frac{\cos\psi_a - \cos\psi_b \cdot \cos\theta_{na \cdot nb}}{\sin\psi_i \cdot \sin^2\theta_{na \cdot nb}} \qquad B = \frac{\cos\psi_b - \cos\psi_a \cdot \cos\theta_{na \cdot nb}}{\sin\psi_i \cdot \sin^2\theta_{na \cdot nb}}$$



(d) Friction Only Shear Strengths

$$FS = A \tan \phi_a + B \tan \phi_b$$

(e) Friction Angle Same for Both Planes



View along line of intersection

$$FS = \frac{\sin \beta}{\sin(\xi/2)} \cdot \frac{\tan \phi}{\tan \psi_i}$$

PARAMETERS:

ϕ = friction angle

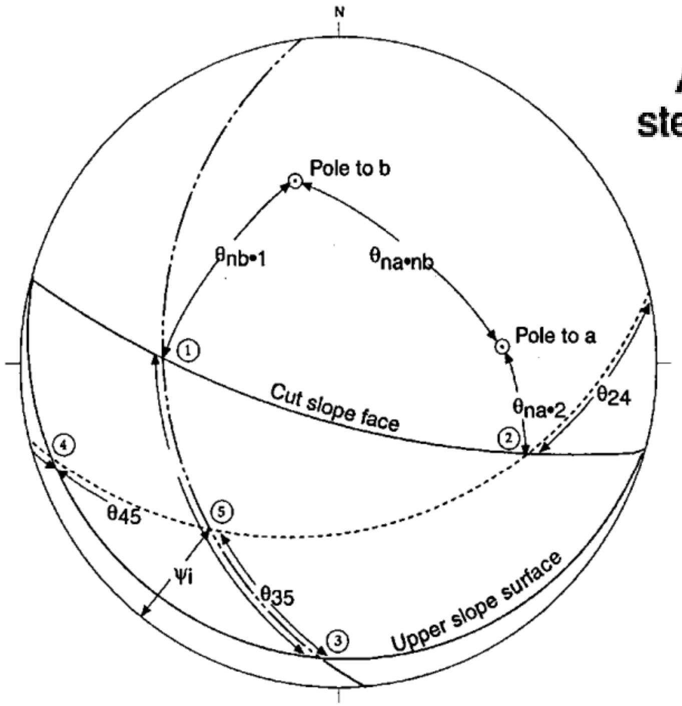
ψ_i = plunge of line of intersection

β = see sketch

ξ = angle between wedge - forming planes

Wedge failure calculation

- Potential wedge failure formed by bedding and joint set 4
- Slope is fully drained; slope cut has a dip of 76° an dip direction of 196 degrees. Friction angle of Joint set 4 and bedding are 35° and 25°, respectively. Cohesions are 20 kPa and 10 kPa, respectively. H is 30 m. Unit weight of rock is 25 kN/m3



Angular measurements from stereonet for stability calculation:

$\theta_{24} = 58°$ $\theta_{nb\bullet 1} = 54°$

$\theta_{45} = 42°$ $\theta_{na\bullet 2} = 26°$

$\theta_{35} = 41°$ $\theta_{na\bullet nb} = 66°$

$\theta_{13} = 81°$ $\psi_i = 35°$

Joint set 4 = Plane a

Bedding = Plane b

$$FS = \frac{3}{\gamma_r H}(c_a X + c_b Y) + A \tan \phi_a + B \tan \phi_b$$

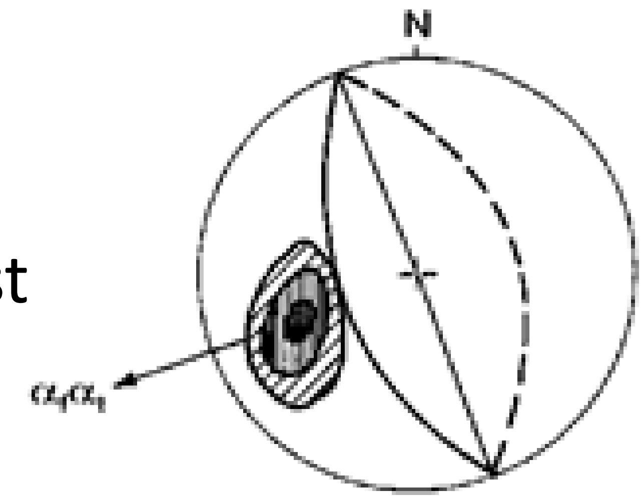
X=1.41, Y=2.56, A = 0.91, B = 0.8

$$FS = \frac{\{3[(20)(1.41) + (10)(2.56)]\}}{[(25)(30)]} + (0.91)\tan 35° + (0.80)\tan 25°$$

$$FS = 0.22 + 0.64 + 0.37 = 1.23$$

Toppling failure

- Steeply dipping (normally > 60°) discontinuities exist
- Discontinuities strike parallel to slope face (±20°)
- Discontinuities dip oppositely to the slope face
- Rock beams/blocks bend under its own weight out of slope face; erosion starts from the toe

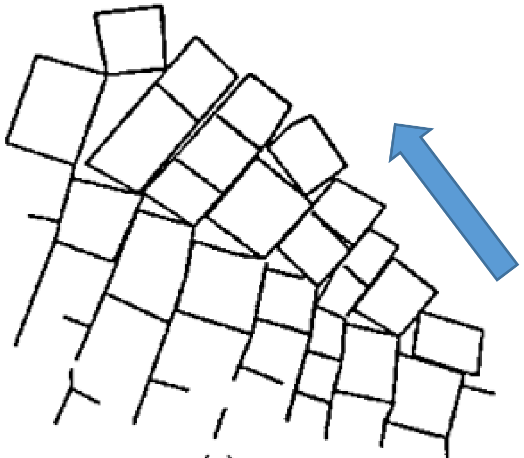


$$(90° - \Psi_p) \leq (\Psi_f - \phi_p)$$

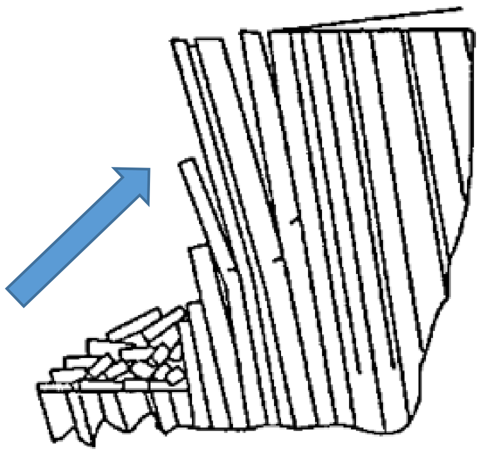
where

Ψ_p = dip of geologic layers (planes),
Ψ_f = dip of slope face, and
ϕ_p = friction angle along planes.

Block toppling with three orthogonal joints



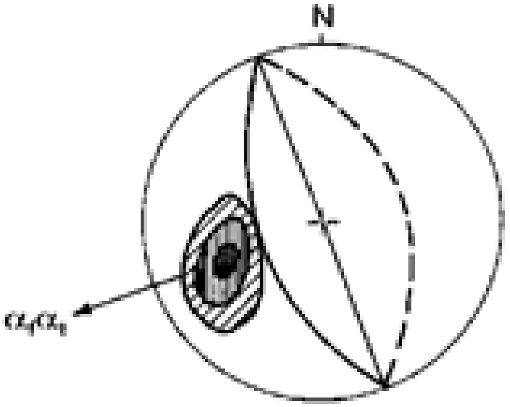
(a)



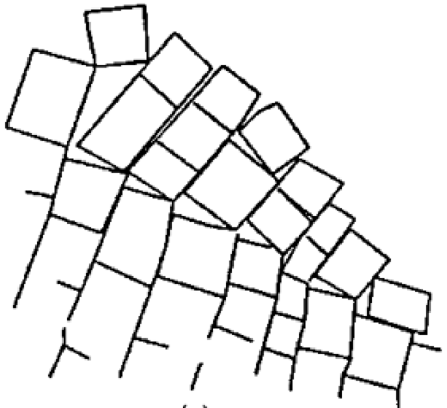
(b)

Flexural toppling of continuous columns of joints

Toppling failure



Conditions for toppling



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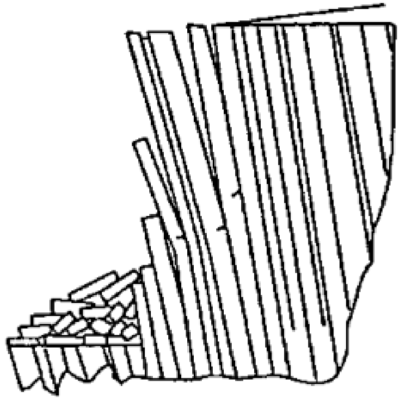
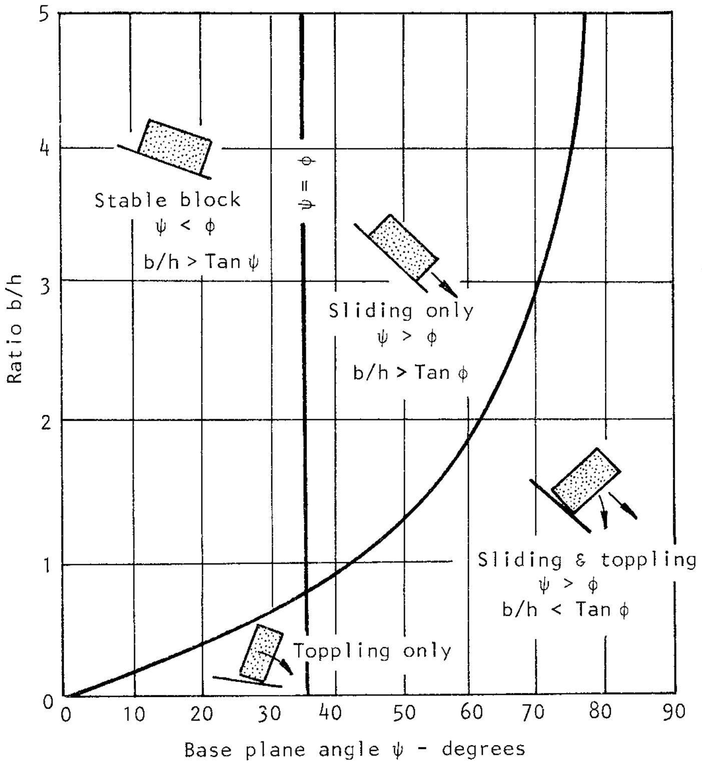
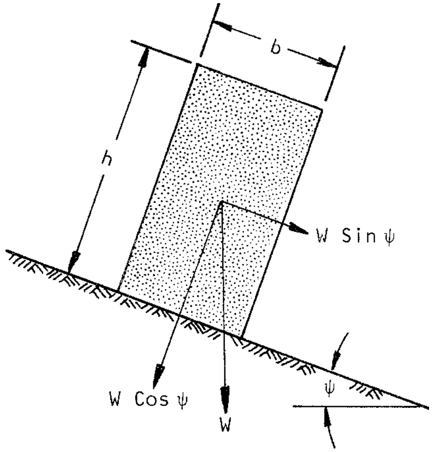


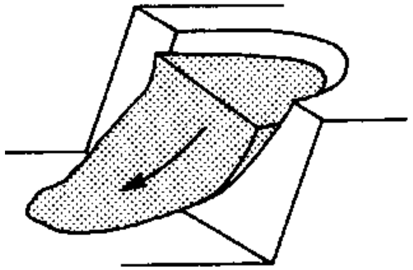
(b)

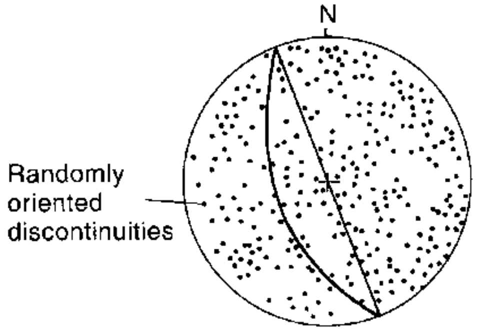




Rotational/circular failure

- Usually occurs in heavily fractured rock mass and/or weak rocks, forming a circular slide plane that is similar to soil slopes
- Rock mass slides on a similar-to-circular failure surface of least resistance through the slope $\psi_p > \psi_{slope\ face}$
- Slide is governed by shear strength of rock mass – can use GSI to estimate the value
- Can be analyzed using soil mechanics slope analysis methods, e.g. limit equilibrium slice methods (e.g. Rocscience Slide) or numerical modelling (e.g. Rocscience RS)

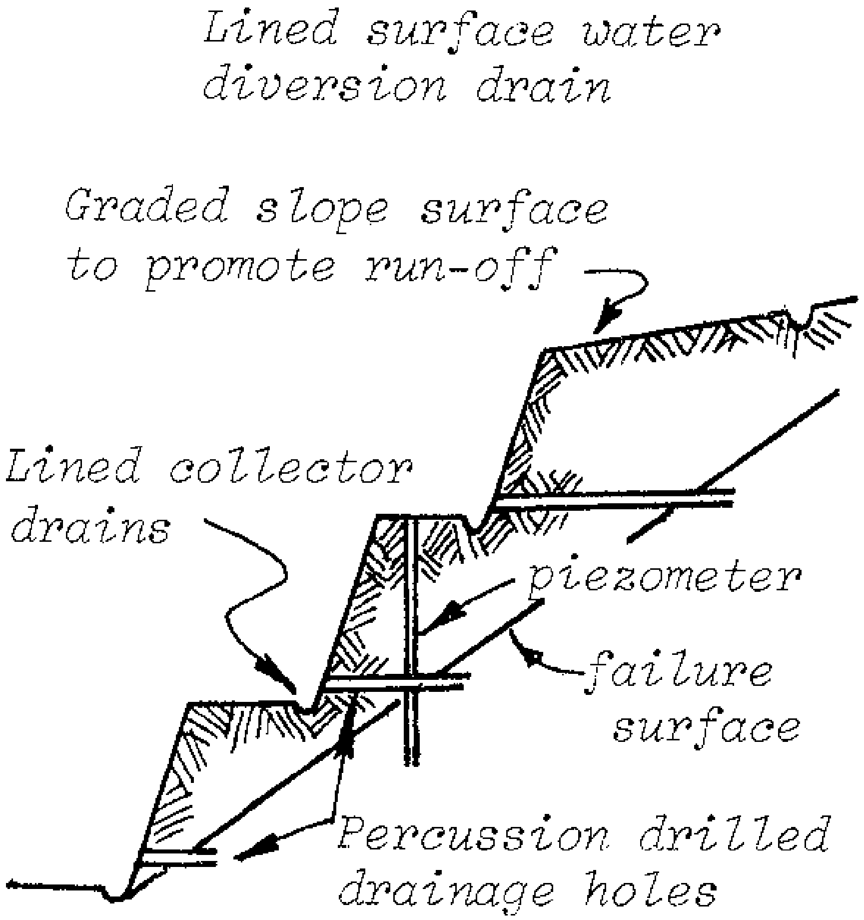




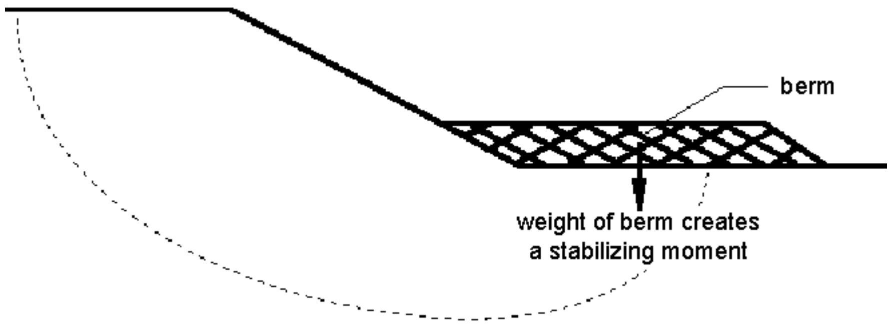
(Norrish and Fisher 2007)

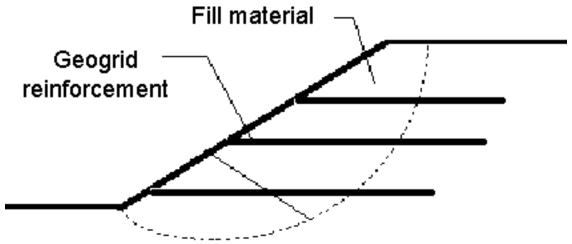
Remedial or stabilizing measures

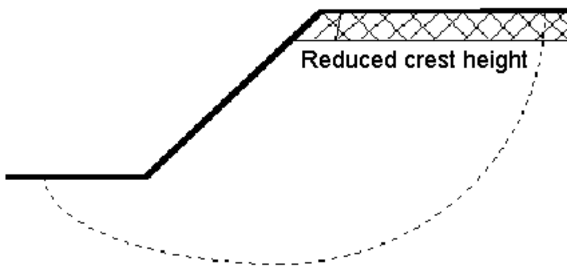
- Drainage
- Careful blasting practices
- Toe berms
- Regrading the slope
- Anchors
- Piles or retaining walls
- Geotextiles
- Vegetation

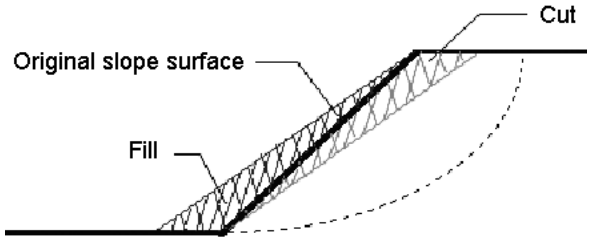


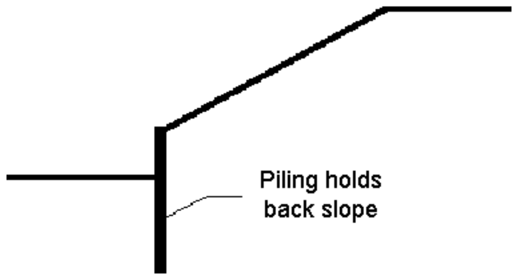
Remedial or stabilizing measures

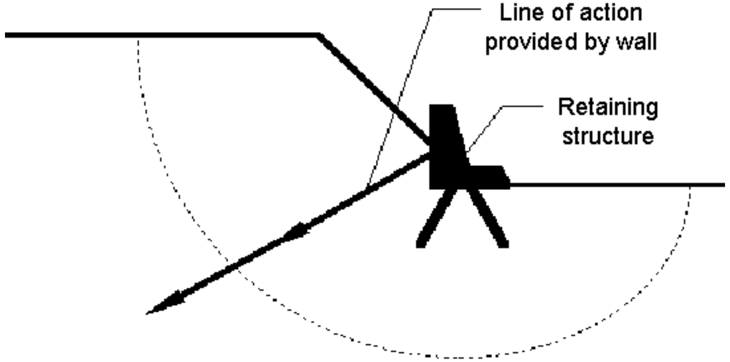












North Beach Rock Slide, Summerland, BC