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GEOTEKNIK TAMBANG

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Subjects

1. Rock slope design methods
2. Identification of modes of slope instability
3. Stabilization of rock slopes
4. Movement monitoring
5. Mining applications

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Identification of Modes of Slope Instability

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Identification of Modes of Slope Instability

1) Kinematic analysis
2) Plane failure
3) Wedge failure
4) Toppling failure
5) Friction cone
6) Applications of kinematic analysis

Identification of Modes of Slope Instability

- **Different types of slope failure** are associated with different geological structures and it is important that the slope designer be able to recognize potential stability problems during the early stages of a project.

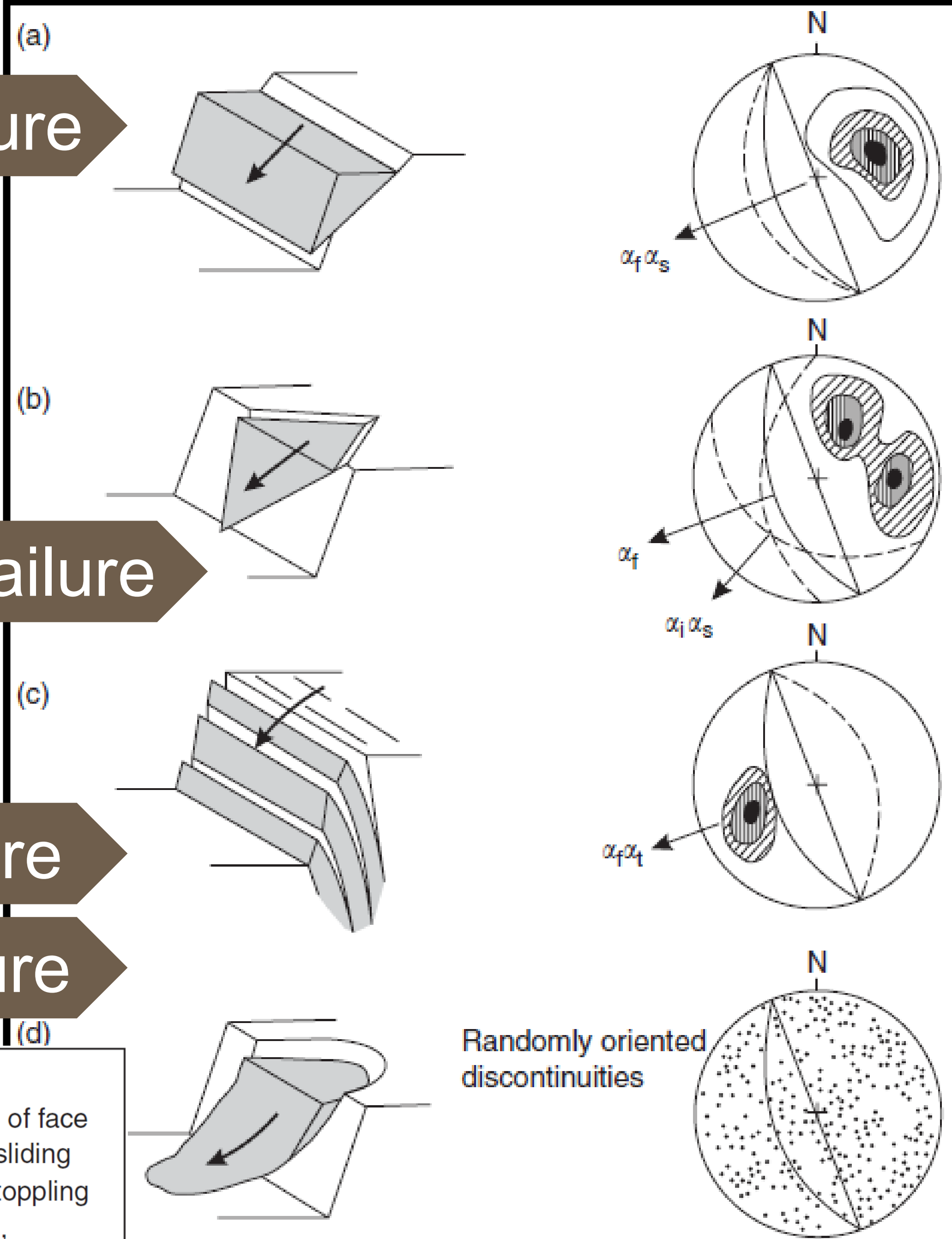
Main types of block failures in slopes and structural geology conditions likely to cause failure.

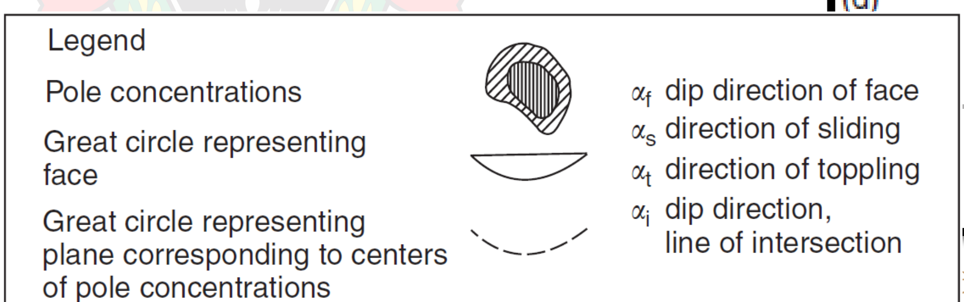
Plane failure

Wedge failure

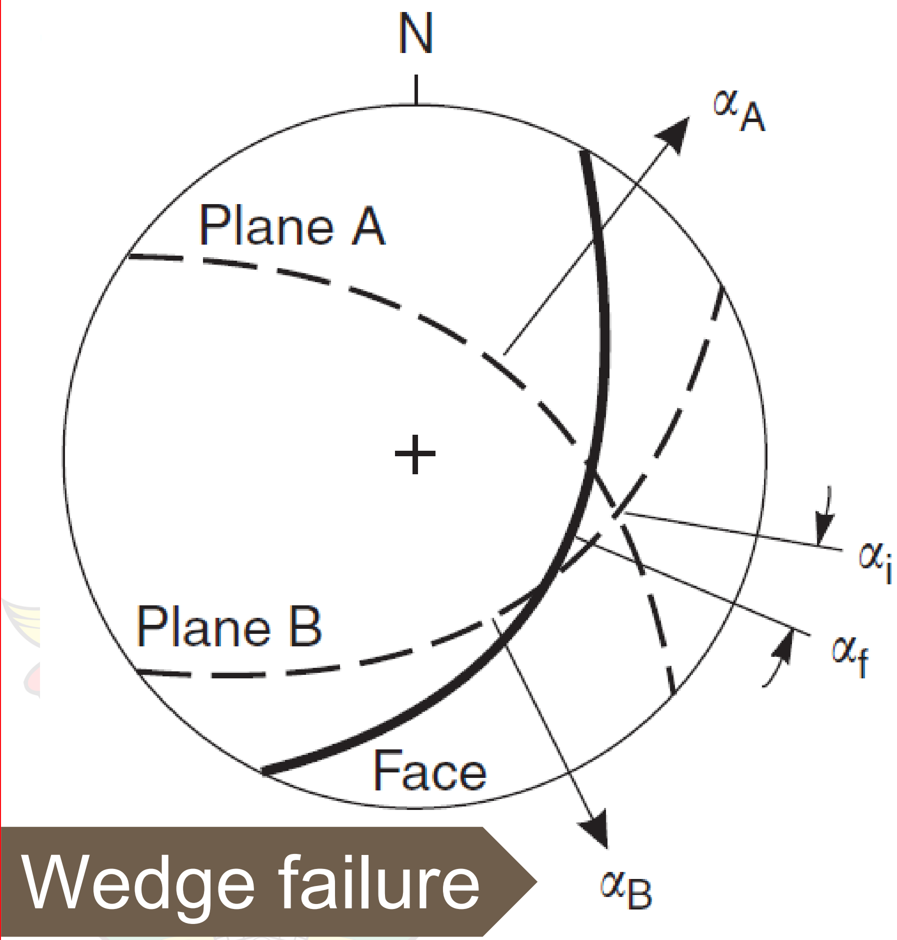
Toppling failure

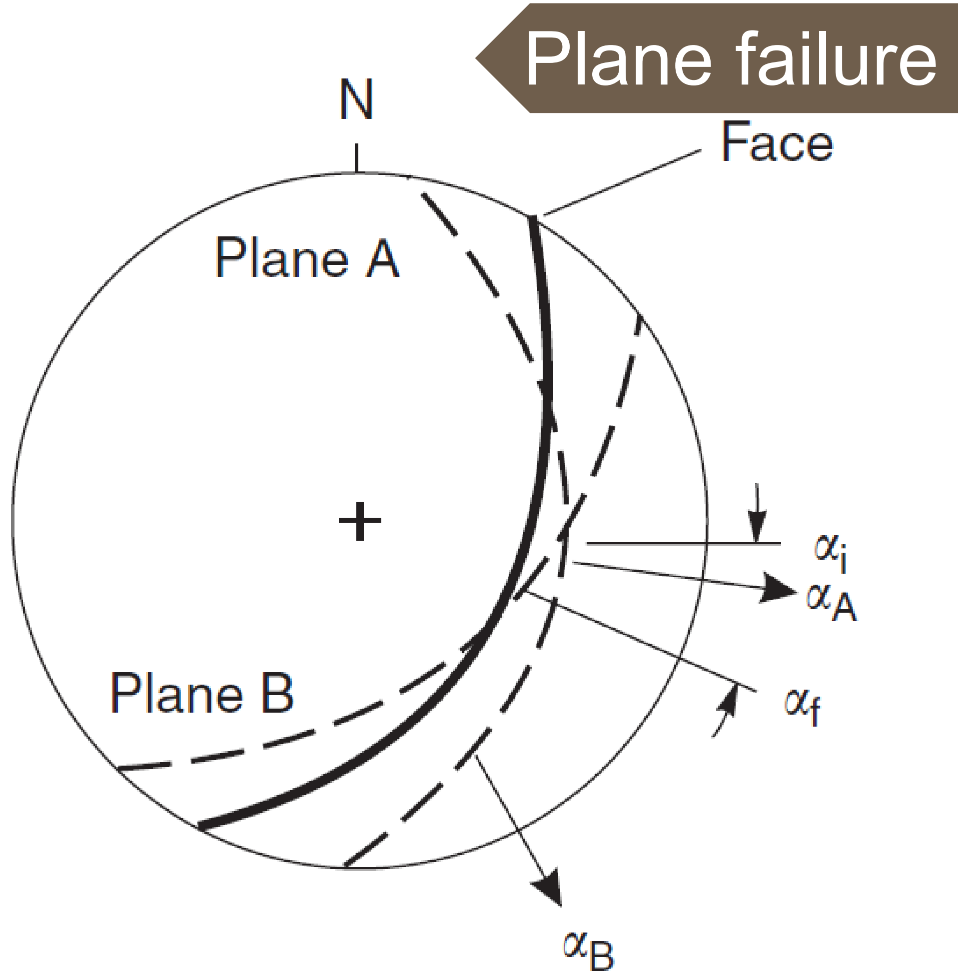
Circular failure





Identification of Plane and Wedge Failures On Stereonet





1) Kinematic Analysis

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Kinematic Analysis

Once the type of block failure has been identified on the stereonet, the same diagram can also be used **to examine the direction** in which a block will slide and give an indication of stability conditions.

The relationship between the direction in which the block of rock will slide and the orientation of the face is readily apparent on the stereonet.

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Kinematic Analysis

It does not account for external forces such as water pressures or reinforcement comprising tensioned rock bolts, which can have a significant effect on stability.

The usual design procedure is to use kinematic analysis to identify potentially unstable blocks.

2) Plane Failure

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Plane Failure

- A plane failure is a comparatively rare sight in rock slopes because it is only occasionally that all the geometric conditions required to produce such a failure occur in an actual slope.

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General Conditions for Plane Failure

- ✓ The plane on which sliding occurs must **strike parallel or nearly parallel** (within approximately ±20°) to the slope face.
- ✓ The dip of the plane must be less than the dip of the slope face, that is, $\psi_p < \psi_f$.

General Conditions for Plane Failure

- ✓ The dip of the sliding plane must be greater than the angle of friction of this plane, that is, $\psi_p > \emptyset$.
- ✓ The upper end of the sliding surface either intersects the upper slope, or terminates in a tension crack.

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General Conditions for Plane Failure

- ✓ **Release surfaces** that provide negligible resistance to sliding must be present in the rock mass to define the lateral boundaries of the slide. Alternatively, failure can occur on a sliding plane passing through the convex "nose" of a slope.

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Plane failure on smooth, persistent bedding planes in shale (Interstate 40, near Newport, Tennessee)

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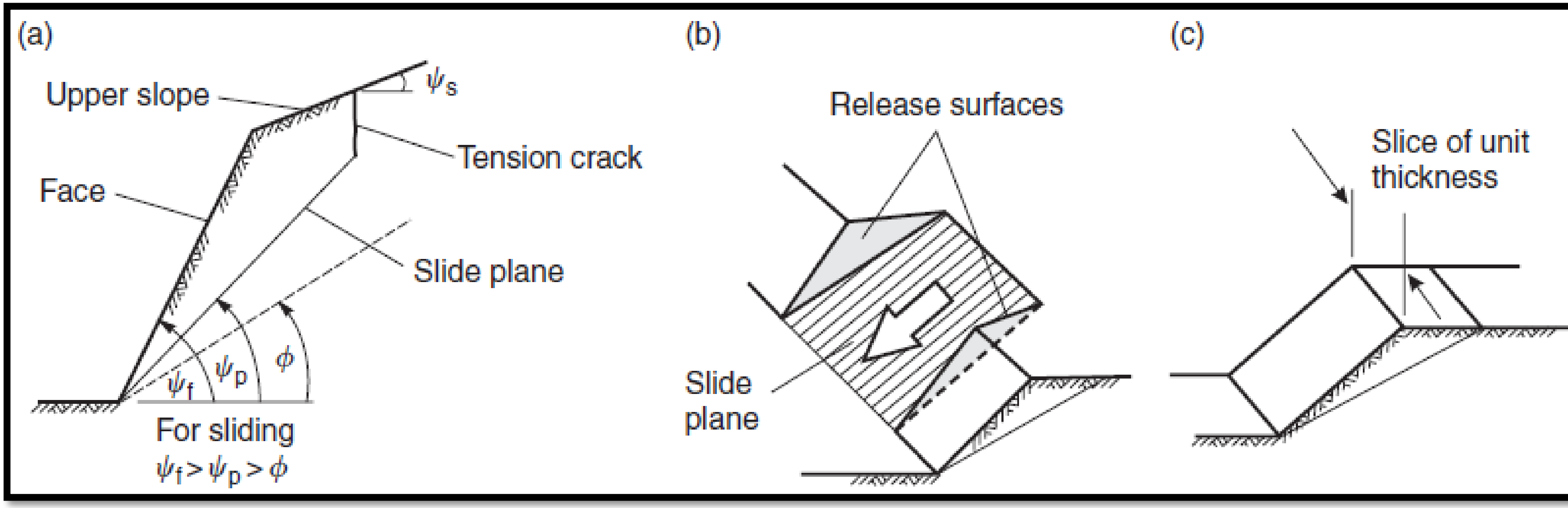


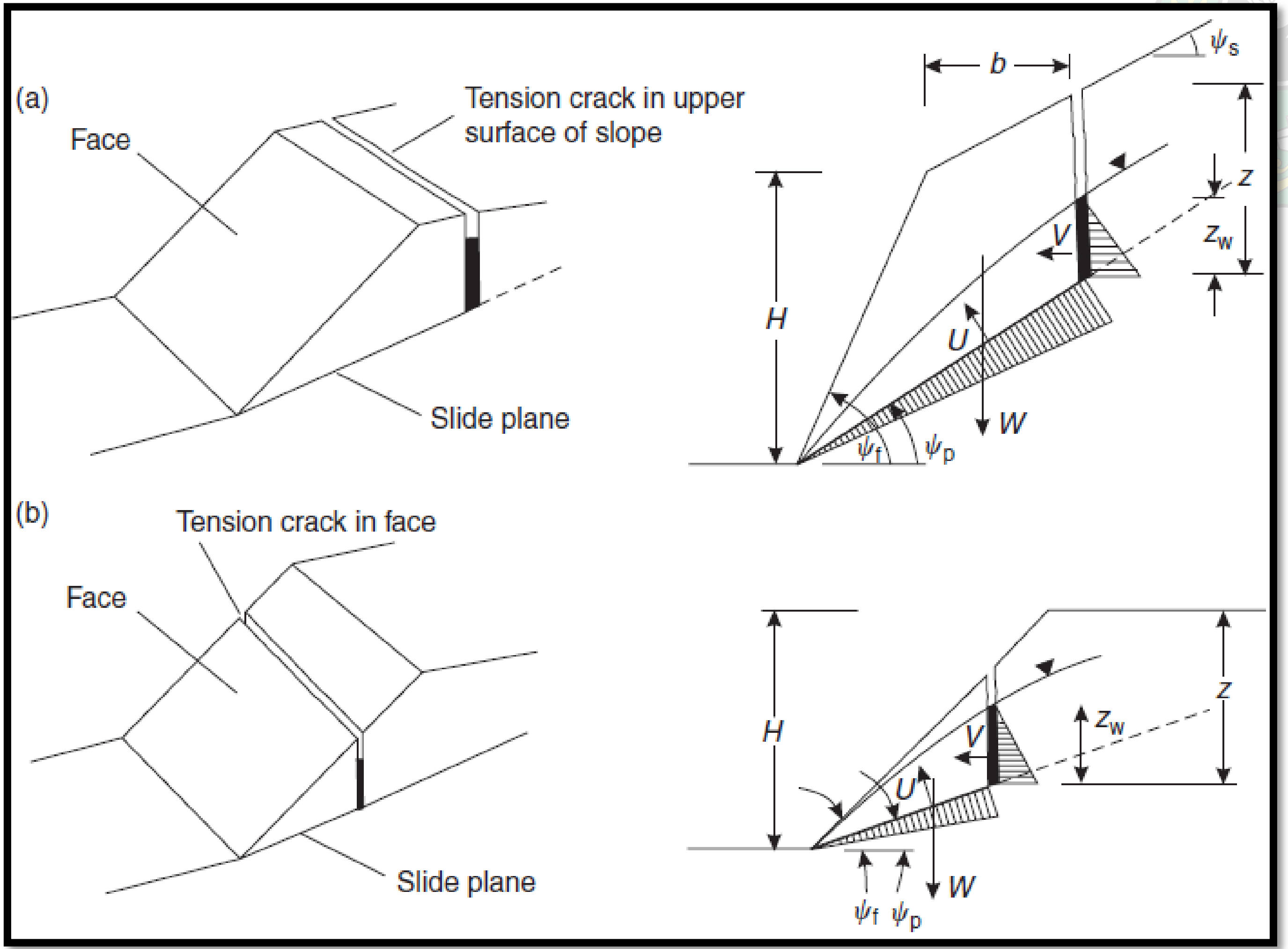
Geometry of slope exhibiting plane failure: (a) cross-section showing planes forming a plane failure; (b) release surfaces at ends of plane failure; (c) unit thickness slide used in stability analysis.

ψ_f = slope face angle (°)

ψ_p = dip of the sliding plane (°)

ϕ = internal friction angle (°)

Geometries of plane slope failure: (a) tension crack in the upper slope; (b) tension crack in the face.



The following assumptions are made in plane failure analysis

- ✓ Both sliding surface and tension crack strike parallel to the slope.
- ✓ The tension crack is vertical and is filled with water to a depth z_w.
- ✓ Water enters the sliding surface along the base of the tension crack and seeps along the sliding surface.

The following assumptions are made in plane failure analysis

- ✓ The forces W (the weight of the sliding block), U (uplift force due to water pressure on the sliding surface), and V (force due to water pressure in the tension crack) all act through the centroid of the sliding mass. In other words, it is assumed that there are no moments that would tend to cause rotation of the block, and hence failure is by sliding only.

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The following assumptions are made in plane failure analysis

- ✓ It is assumed that release surfaces are present so that there is no resistance to sliding at the lateral boundaries of the failing rock mass.

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The following assumptions are made in plane failure analysis

- ✓ In analyzing two-dimensional slope problems, it is usual to consider a slice of unit thickness taken at right angles to the slope face. This means that on a vertical section through the slope, the area of the sliding surface can be represented by the length of the surface, and the volume of the sliding block is represented by the cross-section area of the block.

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Factor of Safety

$$FS = \frac{cA + (W\cos\psi_p - U - V\sin\psi_p)\tan\emptyset}{W\sin\psi_p + V\cos\psi_p}$$

where A is given by

$$A = (H + b\tan\psi_s - z)\csc\psi_p$$

The slope height is H, the tension crack depth is z and it is located a distance b behind the slope crest. The dip of the slope above the crest is ψ_s.

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Factor of Safety

When the depth of the water in the tension crack is z_w, the water forces acting on the sliding plane U and in the tension crack V are given by

$$U = \frac{1}{2}\gamma_w z_w (H + b\tan\psi_s - z)\csc\psi_p$$

$$V = \frac{1}{2}\gamma_w {z_w}^2$$

where γ_w is the unit weight of water.

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Factor of Safety

The weights of the sliding block W for the two geometries are given by following equations.

For the **tension crack in the inclined upper slope surface**:

$$W = \gamma_r \left[(1 - \cot \psi_f \tan \psi_p) \left(bH + \frac{1}{2} H^2 \cot \psi_f \right) + \frac{1}{2} b^2 (\tan \psi_s - \tan \psi_p) \right]$$

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Factor of Safety

And **for the tension crack in the slope face:**

$$W = \frac{1}{2}\gamma_r \cdot H^2 \left[\left(1 - \frac{z}{H}\right)^2 \cdot \cot \psi_p \left(\cot \psi_p \cdot \tan \psi_f - 1\right) \right]$$

where γ_r is the unit weight of rock.

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Critical tension crack depth and location

The critical tension crack depth z_c for a **dry slope** can be found as

$$\frac{z_c}{H} = 1 - \sqrt{\cot \psi_f \tan \psi_p}$$

and the corresponding position of the critical tension crack b_c behind the crest is

$$\frac{b_c}{H} = \sqrt{\cot \psi_f \cot \psi_p} - \cot \psi_f$$

Critical slide plan inclination

For **dry slopes** this gives the critical slide plane inclination ψ_{pc}.

$$\psi_{pc} = \frac{1}{2}\left(\psi_f + \emptyset\right)$$

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Seismic Analysis of Rock Slopes

It has been found that the following five slope parameters have the greatest influence on stability during earthquakes:

1) **Slope angle**

   Rock falls and slides rarely occur on slopes with angles less than about 25°.

Seismic Analysis of Rock Slopes

2) **Weathering**

Highly weathered rock comprising core stones in a fine soil matrix, and residual soil are more likely to fail than fresh rock.

3) **Induration**

Poorly indurated rock in which the particles are weakly bonded is more likely to fail than stronger, well-indurated rock.

Seismic Analysis of Rock Slopes

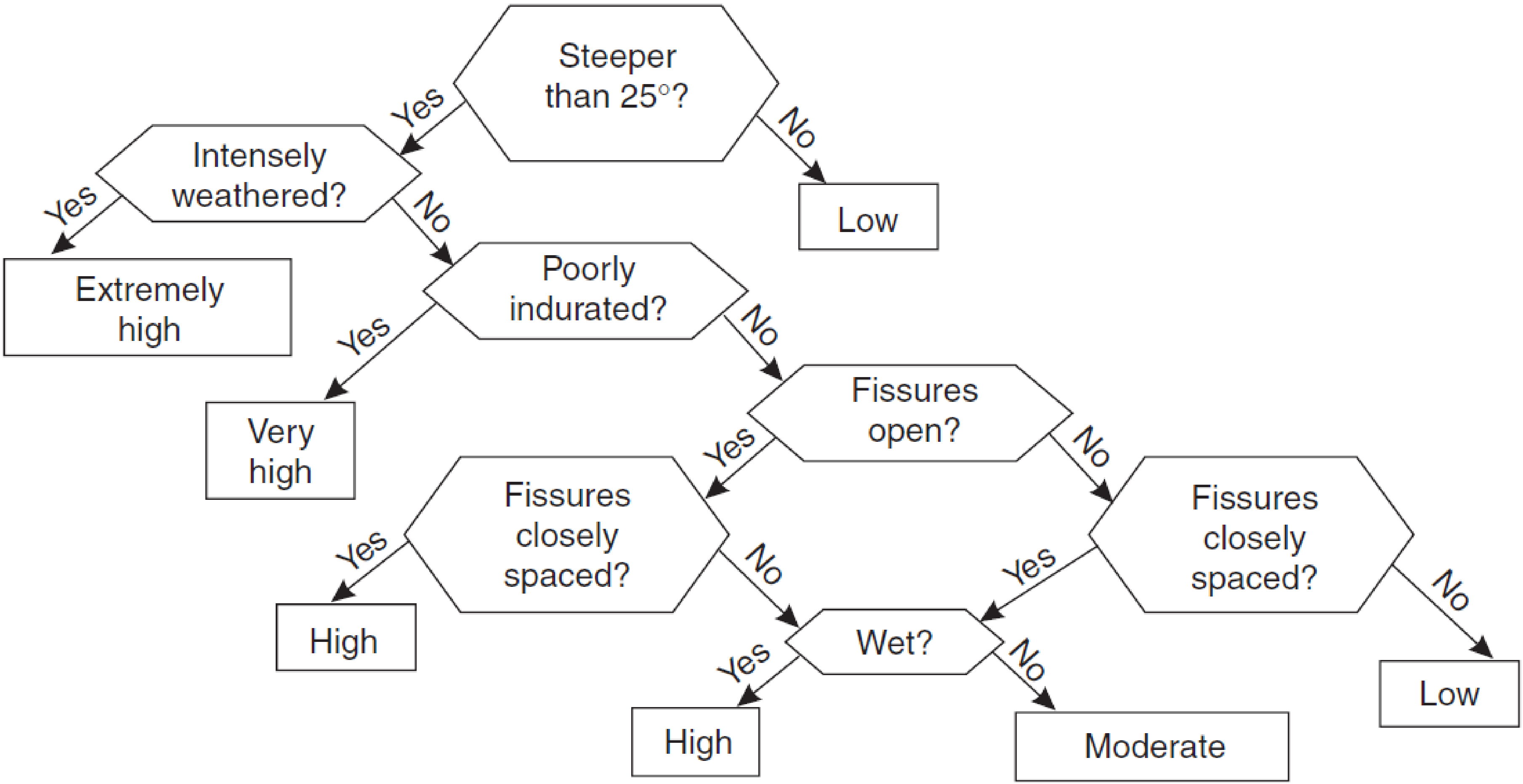
4) **Discontinuity characteristics**

   Rock containing closely spaced, open discontinuities are more susceptible to failure than massive rock in which the discontinuities are closed and healed.

5) **Water**

   Slopes in which the water table is high, or where there has been recent rainfall, are susceptible to failure.

Seismic Analysis of Rock Slopes (Keefer, 1992)



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Seismic Analysis of Rock Slopes

$$FS = \frac{cA + \{W(\cos\psi_p - \alpha\sin\psi_p) - U - V\sin\psi_p\}\tan\emptyset}{W(\sin\psi_p + \alpha\cos\psi_p) + V\cos\psi_p}$$

where α is seismic factor.

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Plane Failure

A 12-m high rock slope has been excavated at a face angle of 60°. The rock in which this cut has been made contains persistent bedding planes that dip at an angle of 35° into the excavation. The 4.35-m deep tension crack is 4 m behind the crest, and is filled with water to a height of 3 m above the sliding surface. The strength parameters of the sliding surface are as follows:

cohesion, c = 25 kPa, and

friction angle, $\phi = 37°$.

The unit weight of the rock is 26 kN/m^3, and the unit weight of the water is 9.81 kN/m^3.

EXERCISE

Plane Failure

Assuming that a plane slope failure is the most likely type of instability, analyze the following stability conditions.

1) Calculate the factor of safety of the slope for that conditions.

2) Determine the factor of safety if the tension crack were completely filled with water due to run-off collecting on the crest of the slope.

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Plane Failure

EXERCISE

3) Determine the factor of safety if the slope were completely drained.
4) Determine the factor of safety if the cohesion were to be reduced to zero and the slope was still completely drained.
5) Determine whether the 4.35-m deep tension crack is the critical depth.

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3) Wedge Failure

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Wedge Failure

In this case the pole of the line of intersection of the two discontinuities is plotted on the stereonet and sliding is possible if the pole daylights on the face, that is $\psi_i < \psi_f$.

The failure of slopes containing discontinuities striking obliquely to the slope face where sliding of a wedge of rock takes place along the line of intersection of two such planes.

Wedge Failure (strong, volcanic rock on Interstate 5, near Grants Pass, Oregon)

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Wedge Failure

Wedge failures can occur over a much wider range of geologic and geometric conditions than plane failures, so the study of wedge stability is an important component of rock slope engineering.

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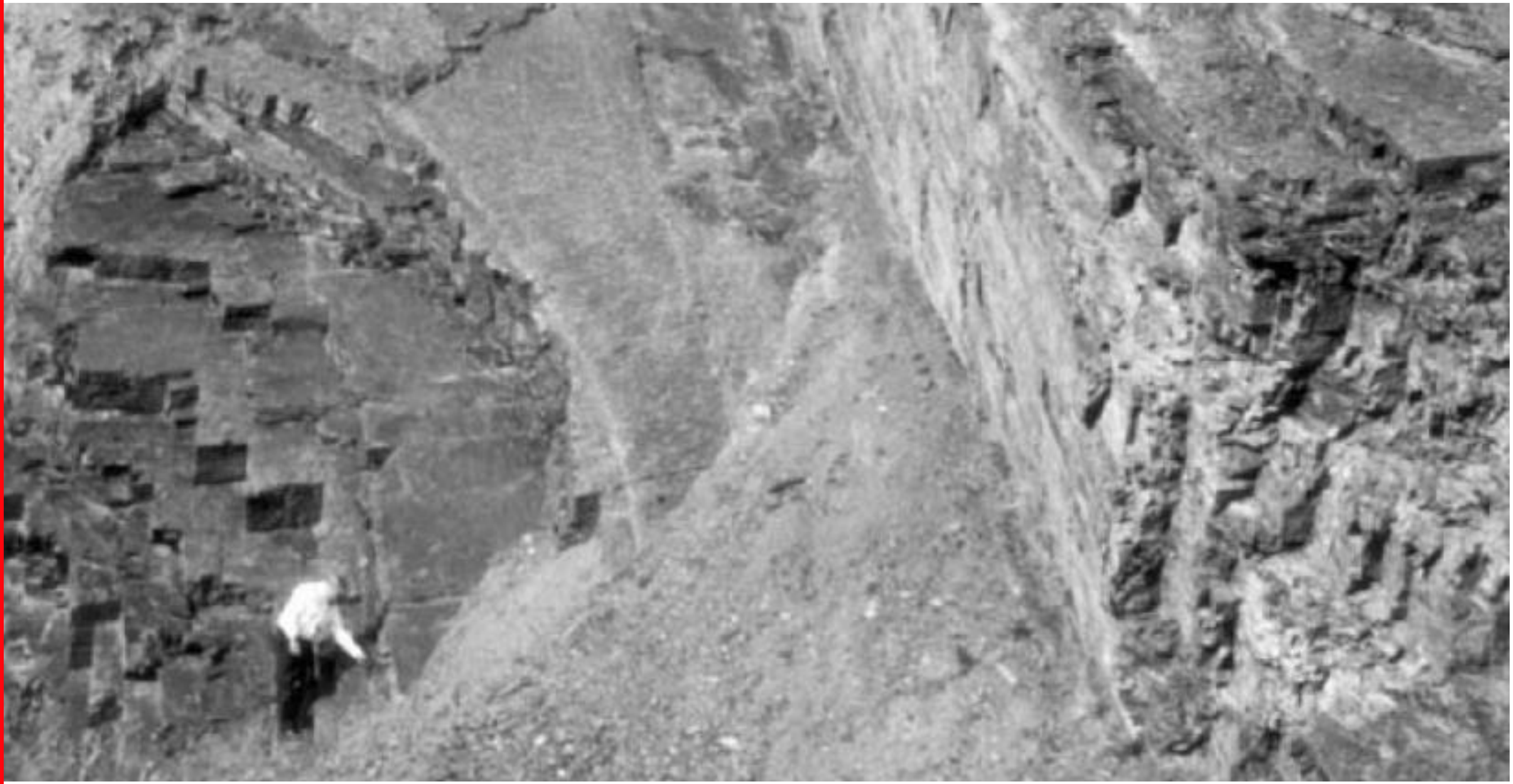

Wedge formed by bedding (left) and a conjugate joint set (right); sliding occurred on bedding with joints acting as a release surface (bedded shale, near Helena, Montana)

General Conditions for Wedge Failure

- ✓ **Two planes will always intersect in a line**. On the stereonet, the line of intersection is represented by the point where the two great circles of the planes intersect, and the orientation of the line is defined by its trend (α_i) and its plunge (ψ_i).

General Conditions for Wedge Failure

- ✓ The plunge of the line of intersection must be flatter than the dip of the face, and steeper than the average friction angle of the two slide planes, that is $\boldsymbol{\psi_{fi}} > \boldsymbol{\psi_i} > \emptyset$. Note the ψ_{fi} would only be the same as ψ_f, the true dip of the slope face, if the dip direction of the line of intersection were the same as the dip direction of the slope face.

General Conditions for Wedge Failure

- ✓ The line of intersection must dip in a direction out of the face for sliding to be feasible; the possible range in the trend of the line of intersection is between α_i and α_i'.

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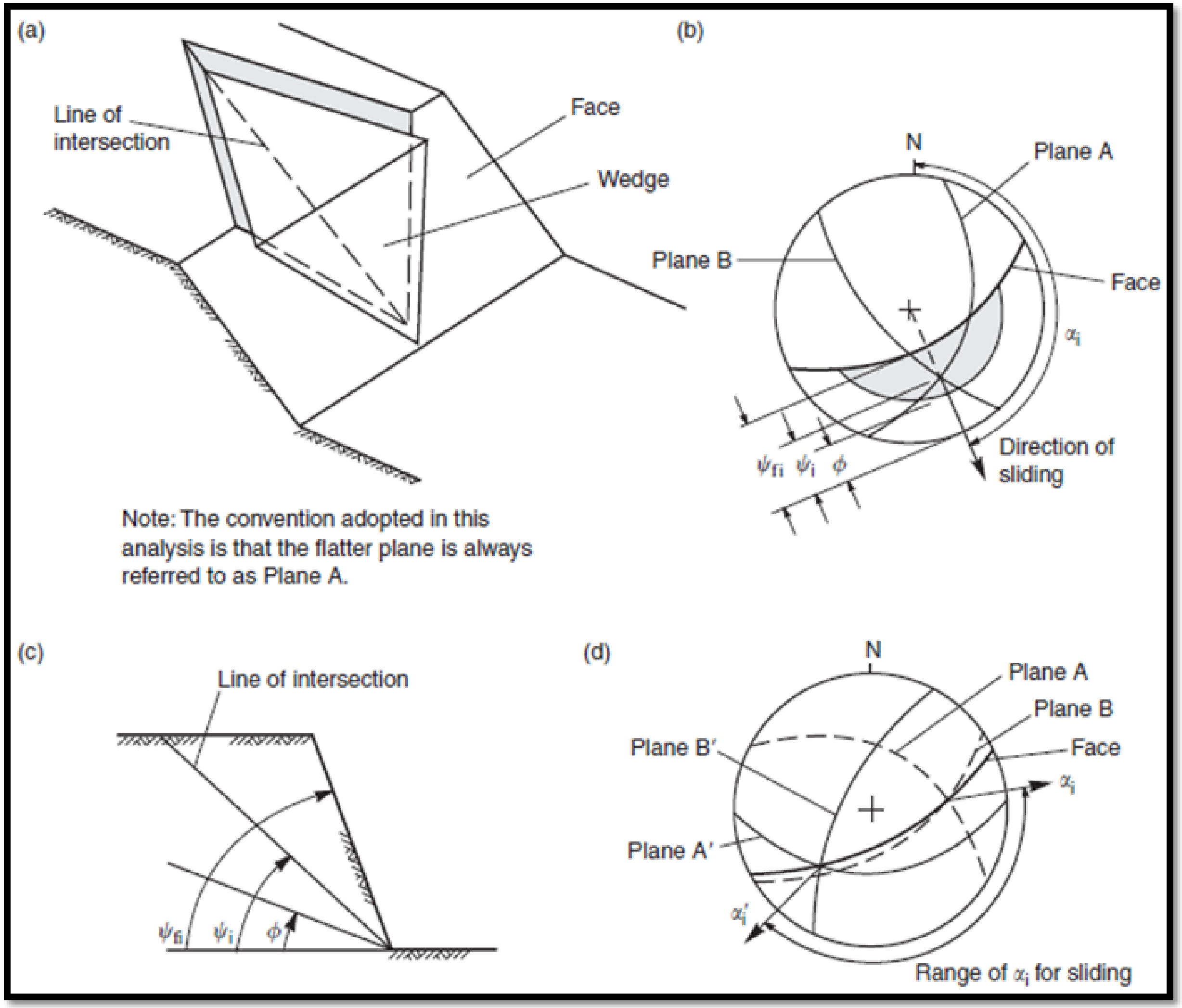
Geometric conditions for weidge failure: (a) pictorial view of wedge failure; (b) stereoplot showing the orientation of the line of intersection, and the range of the plunge of the line of intersection ψ_i where failure is feasible; (c) view of slope at right angles to the line of intersection; (d) stereonet showing the range in the trend of the line of intersection α_i where wedge failure is feasible



Factor of Safety

The actual factor of safety of the wedge cannot be determined from the stereonet because it depends on the details of the geometry of the wedge, the shear strength of each plane and water pressure.

The trend α_i and plunge ψ_i

The trend α_i and plunge ψ_i of the line of intersection of planes A and B can be determined on the stereonet, or calculated using equations as follows:

$$\alpha_i = \tan^{-1}\left(\frac{\tan\psi_A\cos\alpha_A - \tan\psi_B\cos\alpha_B}{\tan\psi_B\sin\alpha_B - \tan\psi_A\sin\alpha_A}\right)$$

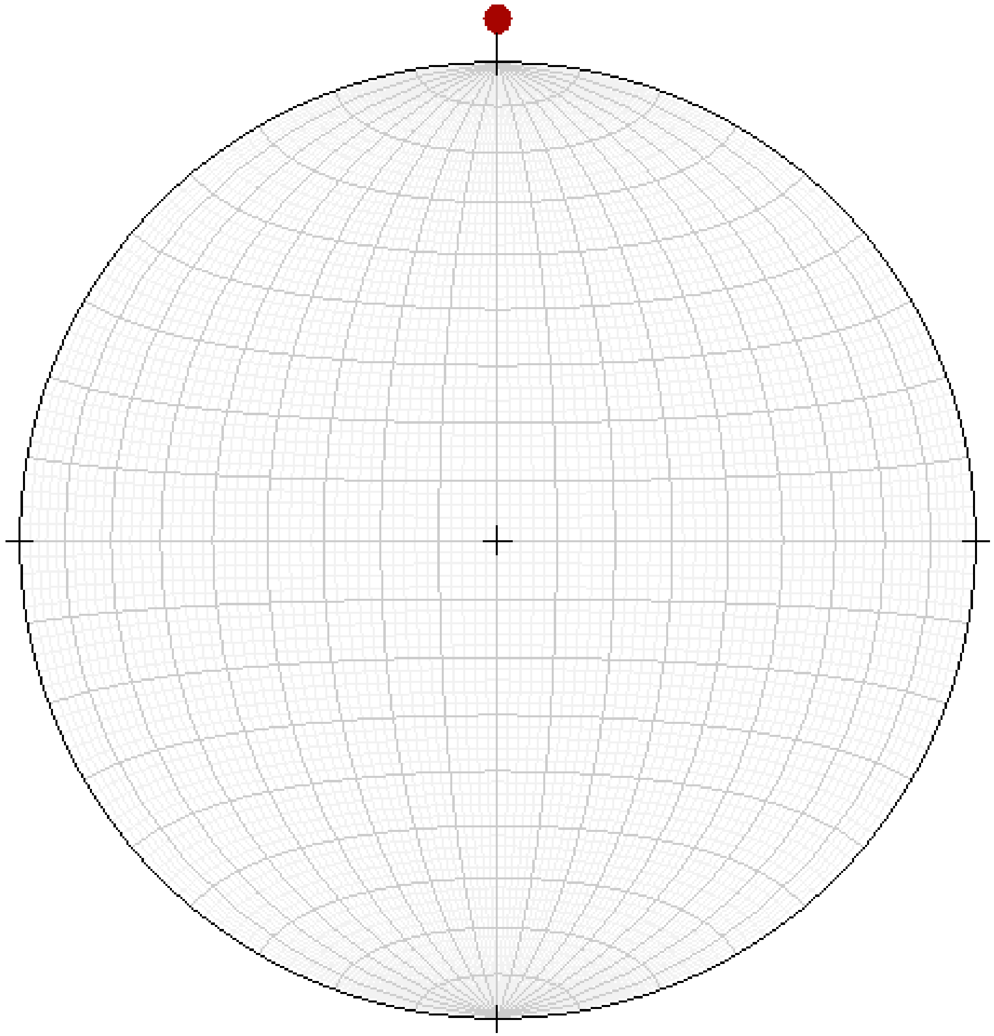
This equation gives two solutions 180° apart; <u>the correct value</u> lies between α_A and α_B.

The trend α_i and plunge ψ_i

$$\psi_i = \tan\psi_A \cos(\alpha_A - \alpha_i) = \tan\psi_B \cos(\alpha_B - \alpha_i)$$

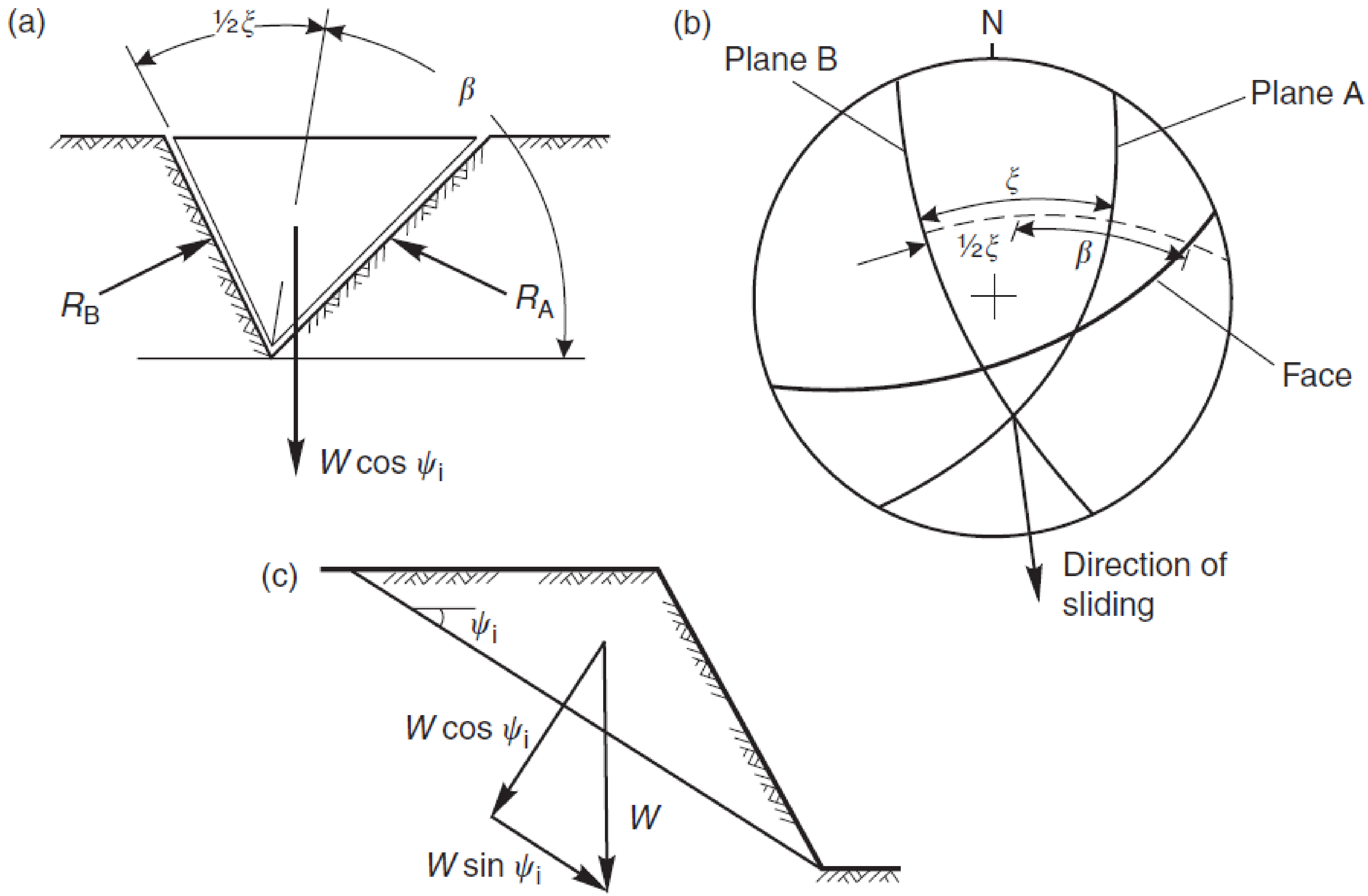
where α_A and α_B are the dip directions, and ψ_A and ψ_B are the dips of the two planes.

Analysis of Wedge Failure



Please kindly remember the Geological Structure Course.

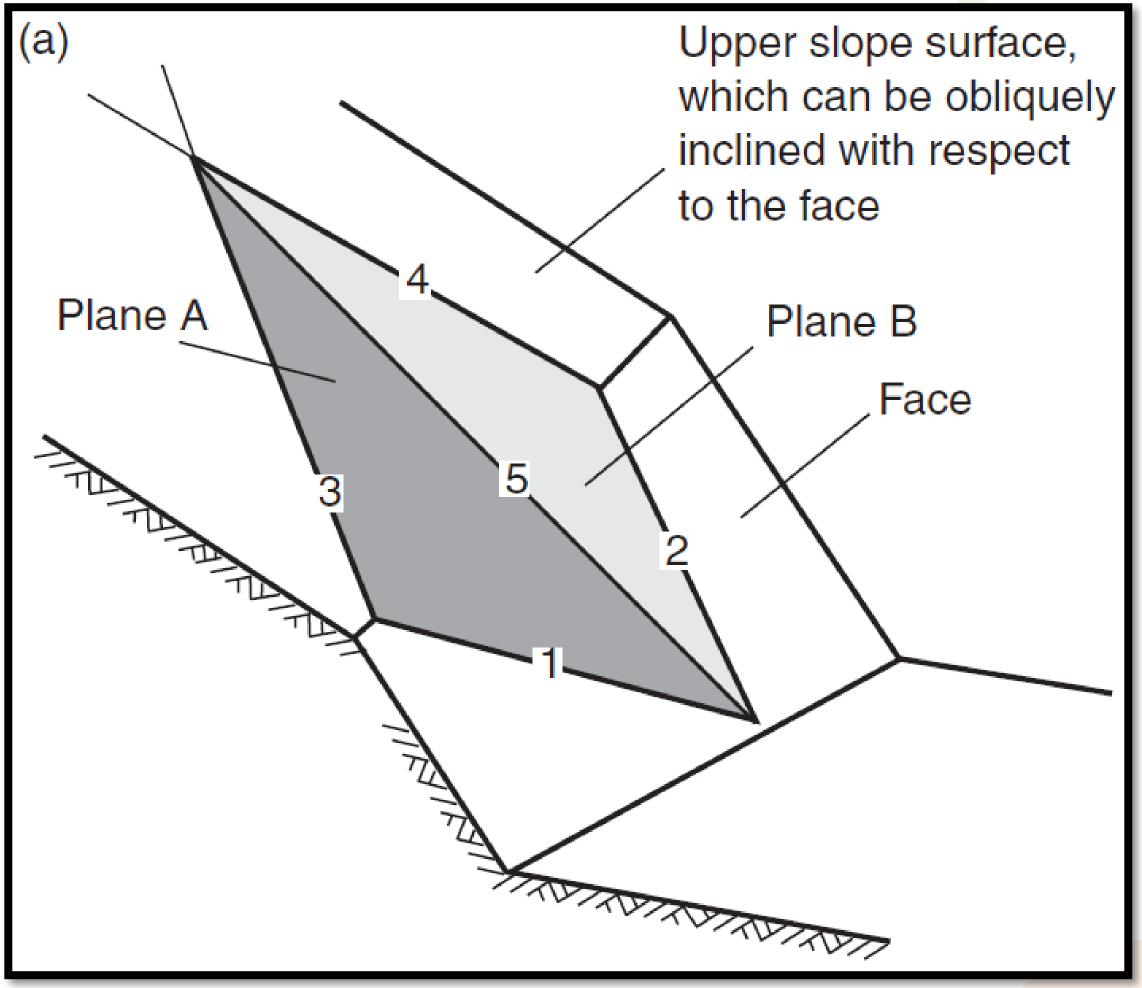
(a) View of wedge looking at face
(b) Stereonet
(c) Cross-section of wedge



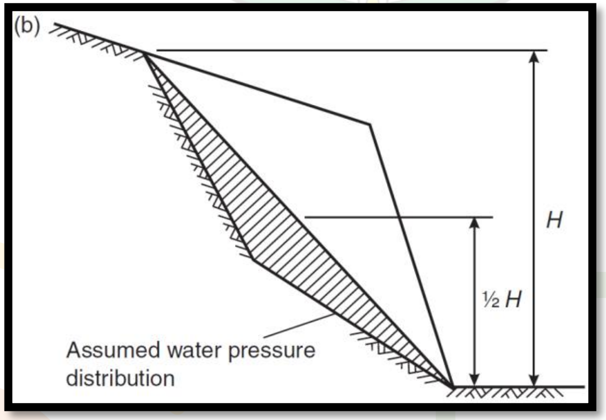
Wedge Analysis Including Cohesion, Friction, and Water Pressure

This is a method to calculate the factor of safety of a wedge that incorporates the slope geometry, different shear strengths of the two slide planes, and ground water (Hoek et al., 1973). However, the limitations of this analysis are that there is no tension crack and no external forces such as bolting can be included.

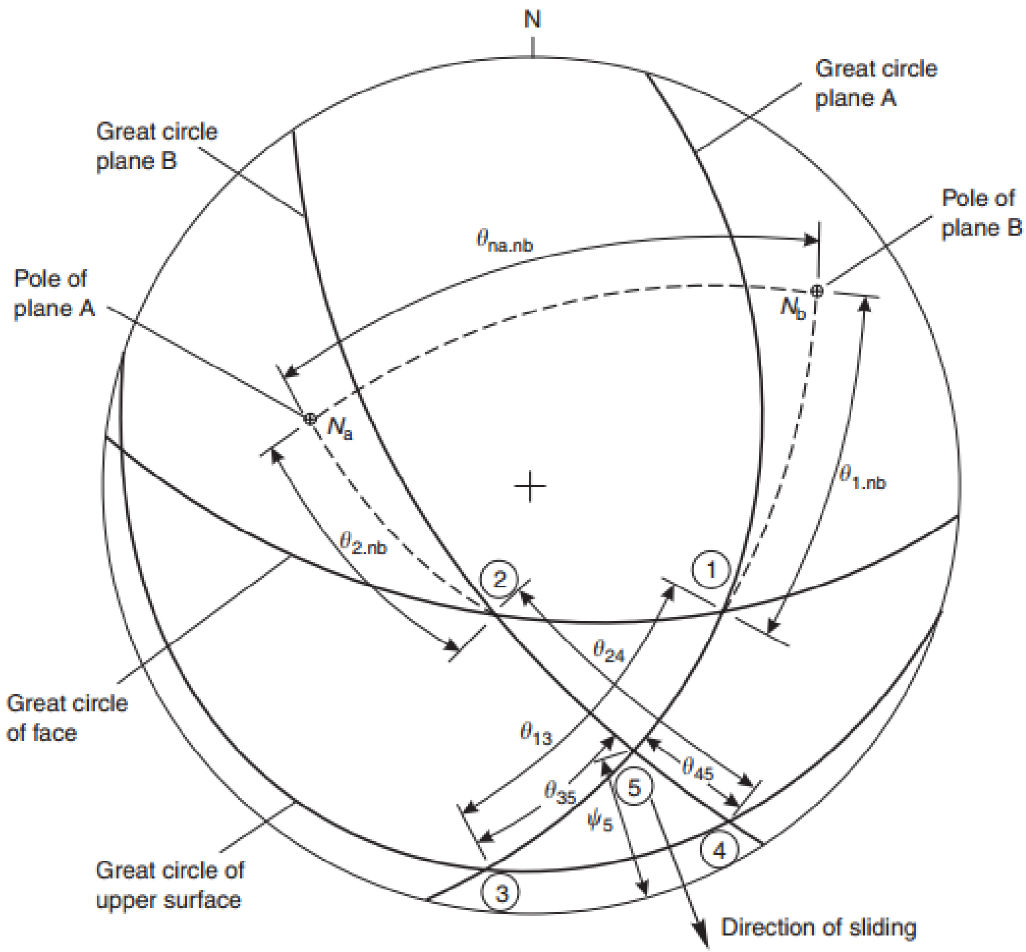
Wedge Analysis Including Cohesion, Friction, and Water Pressure



Geometry of wedge used for stability analysis including the influence of friction and cohesion, and of water pressure on the slide surfaces



Wedge Analysis Including Cohesion, Friction, and Water Pressure



1 = intersection of plane A with the slope face

2 = intersection of plane B with the slope face

3 = intersection of plane A with upper slope surface

4 = intersection of plane B with upper slope surface

5 = intersection of planes A and B

Wedge Analysis Including Cohesion, Friction, and Water Pressure

$$F = \frac{3}{\gamma_r \cdot H}(c_A X + c_B Y) + \left(A - \frac{\gamma_w}{2\gamma_r}X\right)\tan\emptyset_A + \left(B - \frac{\gamma_w}{2\gamma_r}Y\right)\tan\emptyset_B$$

c_A, c_B = the cohesive strengths on planes A and B

$\emptyset_A, \emptyset_B$ = the angles of friction on planes A and B

X = $\frac{\sin\theta_{2,4}}{(\sin\theta_{4,5}\cos\theta_{2,na})}$

Y = $\frac{\sin\theta_{1,3}}{(\sin\theta_{3,5}\cos\theta_{1,nb})}$

A = $\frac{\cos\psi_a - \cos\psi_b\cos\theta_{na,nb}}{\sin\psi_5 sin^2\theta_{na,nb}}$

B = $\frac{\cos\psi_b - \cos\psi_a\cos\theta_{na,nb}}{\sin\psi_5 sin^2\theta_{na,nb}}$

ψ_a, ψ_b = the dips of planes A and B

ψ_5 = the dip of the line of intersection, line 5

θ = the angles can be measured most conveniently on a stereoplot

Wedge Analysis Including Cohesion, Friction, and Water Pressure

EXERCISE

Assuming that a wedge failure is the most likely type of the slope instability, determine the factor of safety by using the stereoplot and carrying out the calculation. The parameters shown in the following table.

Plane	Dip (°)	Dip Direction (°)	Properties
A	45	105	$\emptyset_A = 20°, c_A = 24\ kPa$
B	70	235	$\emptyset_B = 30°, c_B = 48\ kPa$
Slope face	65	185	
Upper surface	12	195	

EXERCISE

Wedge Analysis Including Cohesion, Friction, and Water Pressure (cont.)

The total height of the wedge *H* is 40 m, the unit weight of the rock is 25 kN/m^3, and the unit weight of the water 9.81 kN/m^3.

Instruction:

The stereoplot can be carried out either by using stereonet manually on a paper or using stereonet digitally on application/online.

4) Toppling Failure

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Toppling Failure

For a toppling failure to occur, the dip direction of the discontinuities dipping into the face must be within about 10° of the dip direction of the face so that a series of slabs are formed parallel to the face. This failure mode is different because it involves rotation of columns or blocks of rock about a fixed base.

The direction of the major principal stress in the cut is parallel to the face of the cut (dip angle ψ_f), so interlayer slip and toppling failure will occur on planes with dip ψ_p when the following conditions are met (Goodman and Bray, 1976):

$$(90° - \psi_f) + \emptyset_j < \psi_p$$

Toppling Failure

Kinematic Analysis

Carrying out a kinematic analysis of the structural geology to identify potential toppling conditions.

Stability Analysis

Performing a stability analysis specific to toppling failures.

Types of Toppling Failure

- Block Toppling
- Flexural Toppling
- Block-flexure Toppling
- Secondary Toppling

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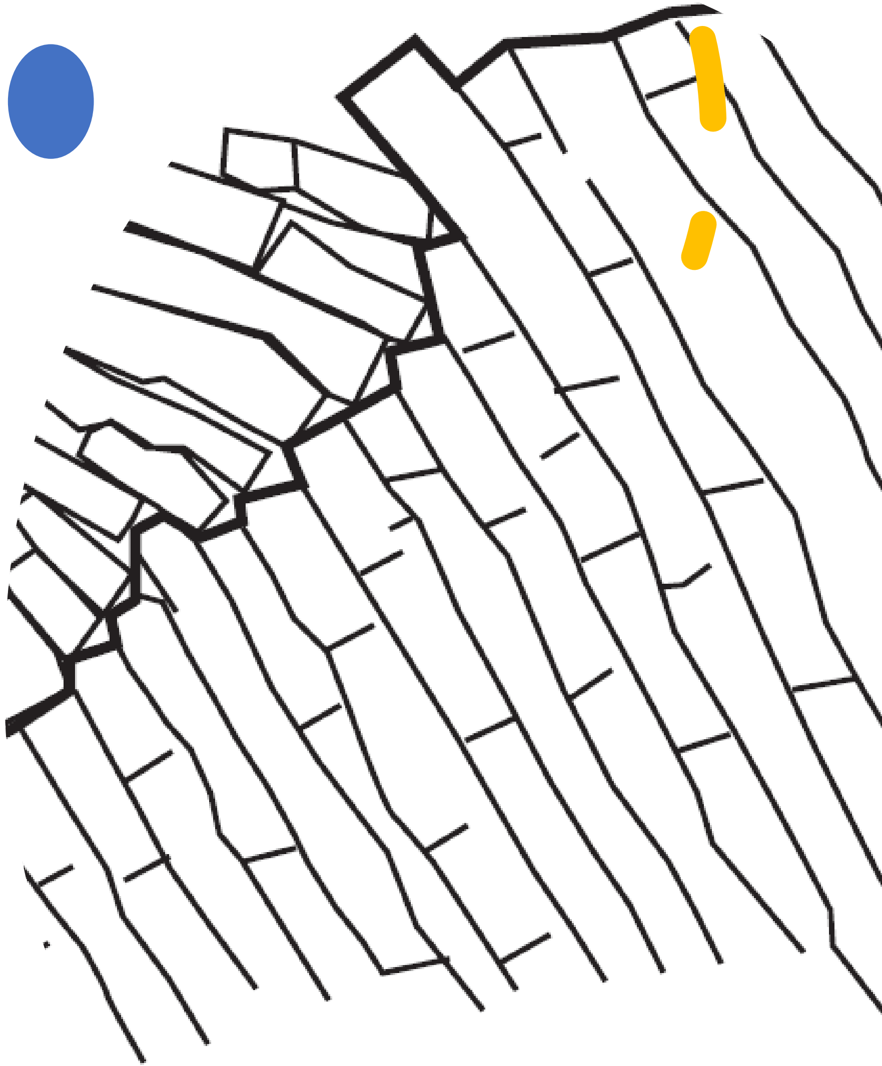
Block Toppling

Block toppling occurs when, in strong rock, individual columns are formed by a set of discontinuities dipping steeply into the face, and a second set of widely spaced orthogonal joints defines the column height.

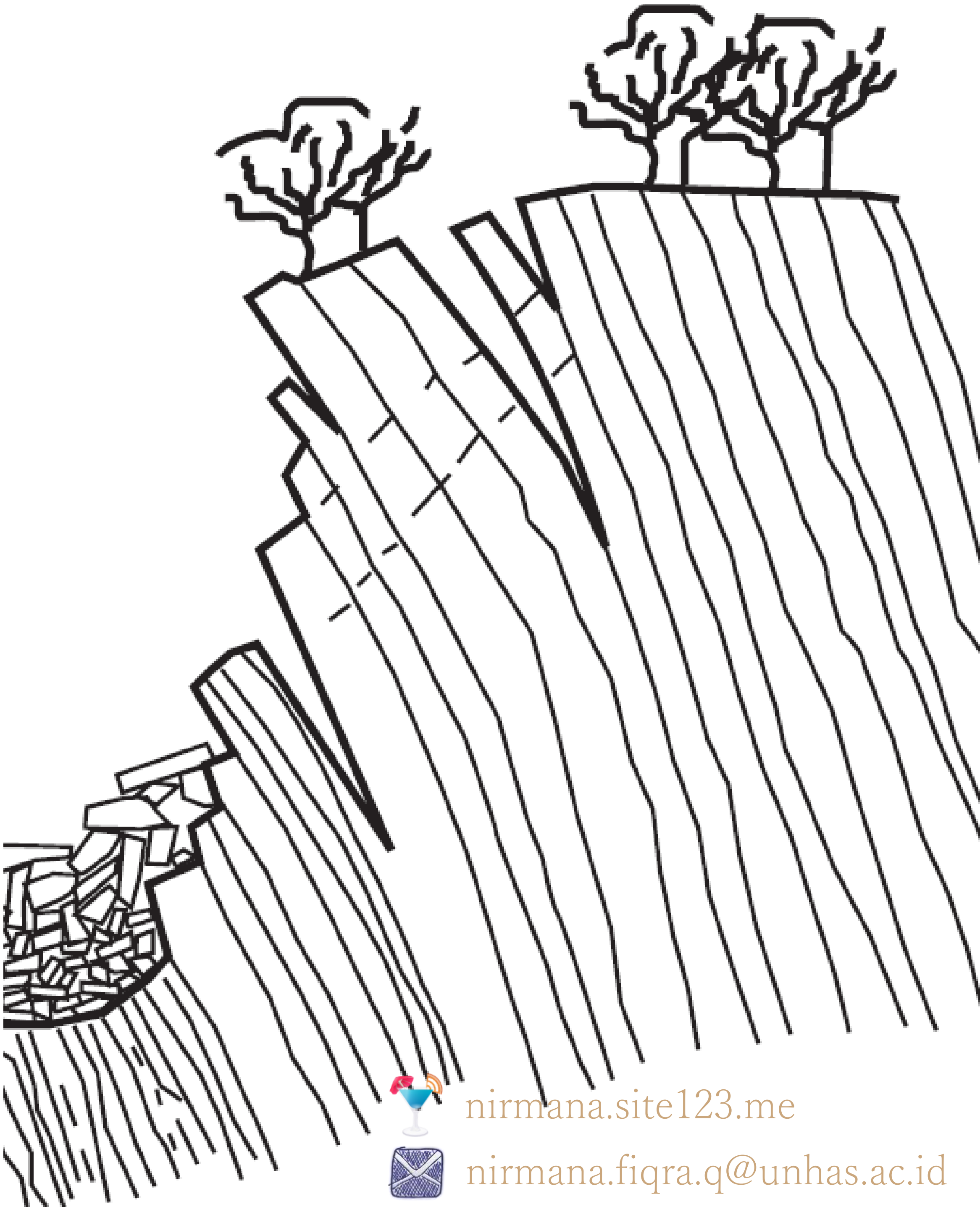
Typical geological conditions in which this type of failure may occur are bedded sandstone and columnar basalt in which orthogonal jointing is well developed.



Flexural Toppling

Continuous columns of rock, separated by well developed, steeply dipping discontinuities, breaking in flexure as they bend forward.

Typical geological conditions in which this type of failure may occur are thinly bedded shale and slate in which orthogonal jointing is not well developed.



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Flexural Toppling

Sliding, excavation, or erosion of the toe of the slope

The toppling process to start and it retrogresses back into the rock mass with the formation of deep tension cracks

The outward movement of each cantilevered column produces an interlayer slip

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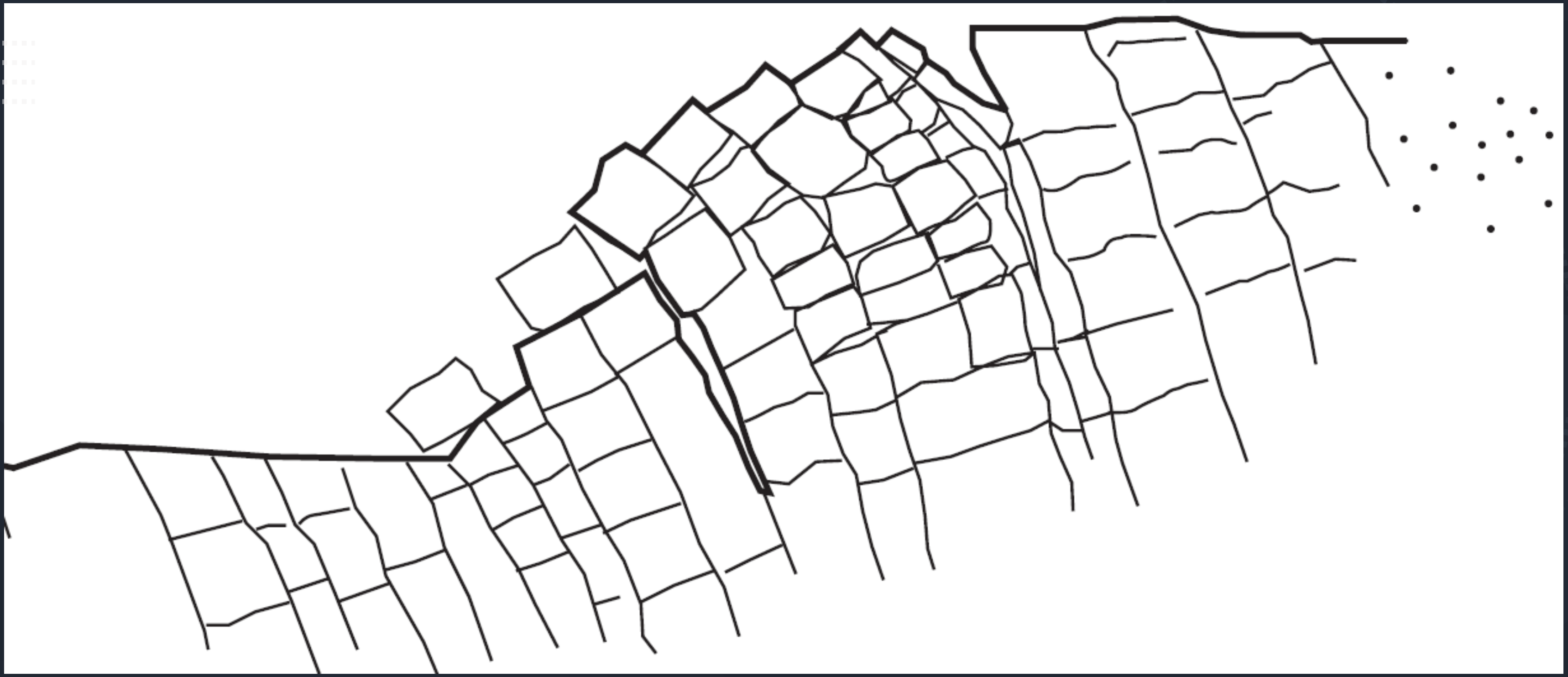
Block-flexure Toppling

Block-flexure toppling is characterized by pseudo-continuous flexure along long columns that are divided by numerous cross joints.

Toppling of columns in this case results from accumulated displacements on the cross-joints.



Block-flexure Toppling

The large number of small movements in this type of topple

Fewer tension cracks than in flexural toppling

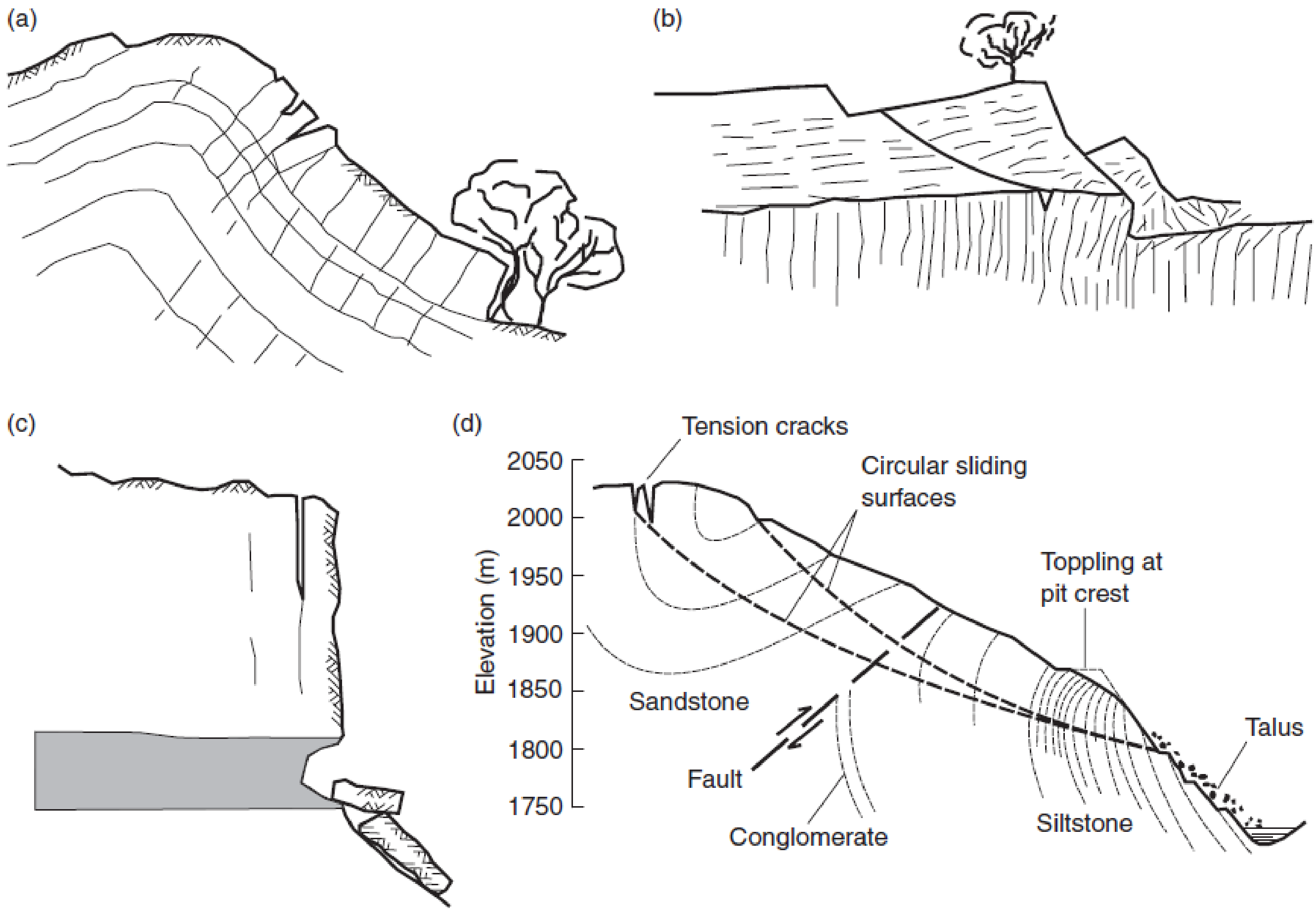
Fewer edge-to-face contacts and voids than in block toppling

Secondary Toppling Modes

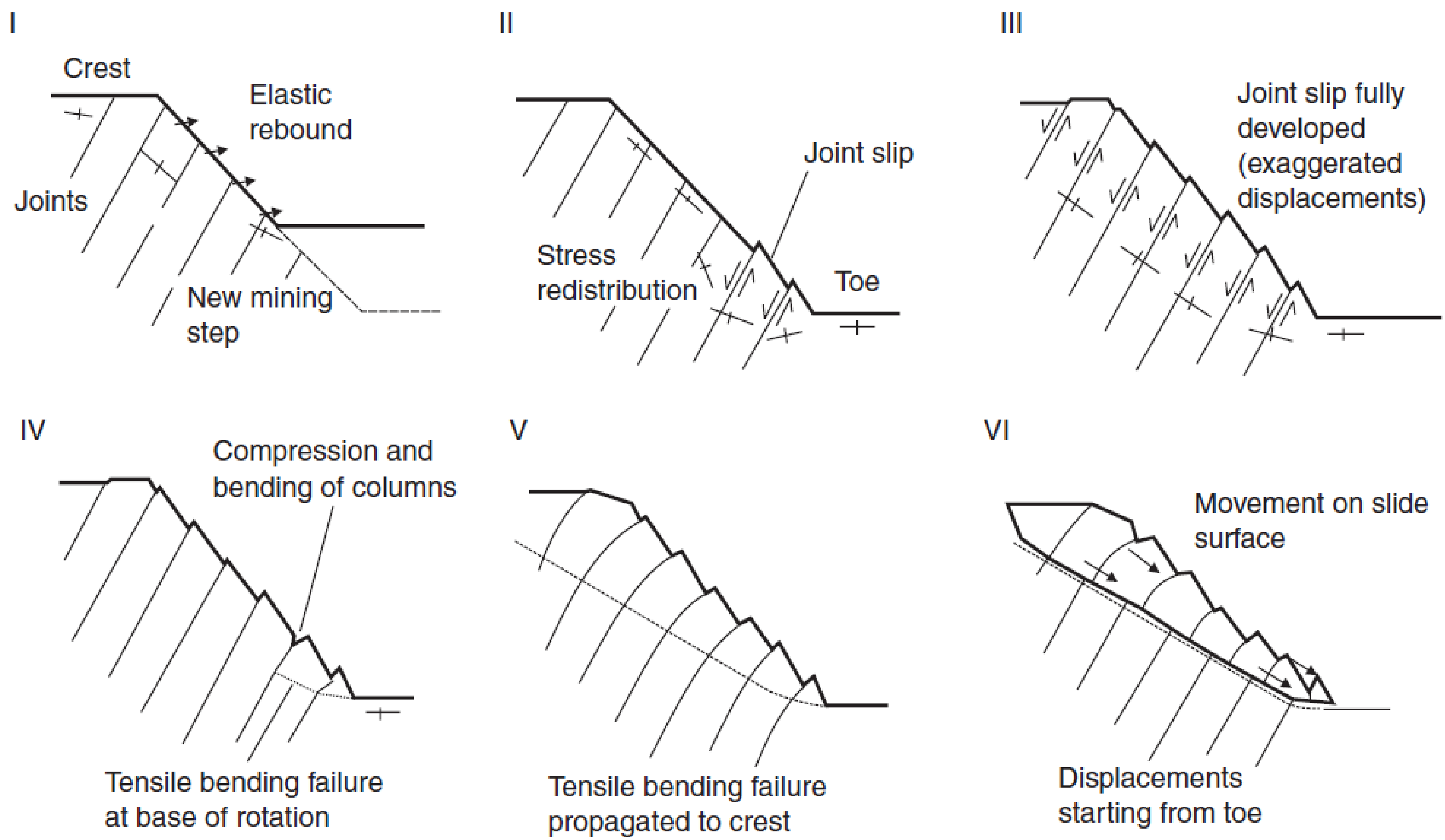
In general, these failures are initiated by some undercutting of the toe of the slope, either by natural agencies such as scour or weathering, or by human activities.

The primary failure mode involves sliding or physical breakdown of the rock.

Toppling is induced in the upper part of the slope as a result.



Secondary toppling modes: (a) toppling at head of slide; (b) toppling at toe of slide with shear movement of upper slope (Goodman and Bray, 1976); (c) toppling of columns in strong upper material due to weathering of underlying weak material; (d) toppling at pit crest resulting in circular failure of upper slope (Wyllie and Munn, 1978).



Failure stages for large-scale toppling failure in a slope (Sjoberg, 2000)

Kinematics of Block Toppling Failure

- The shape of the block
- The relationship between the dip of the planes forming the slabs and the face angle

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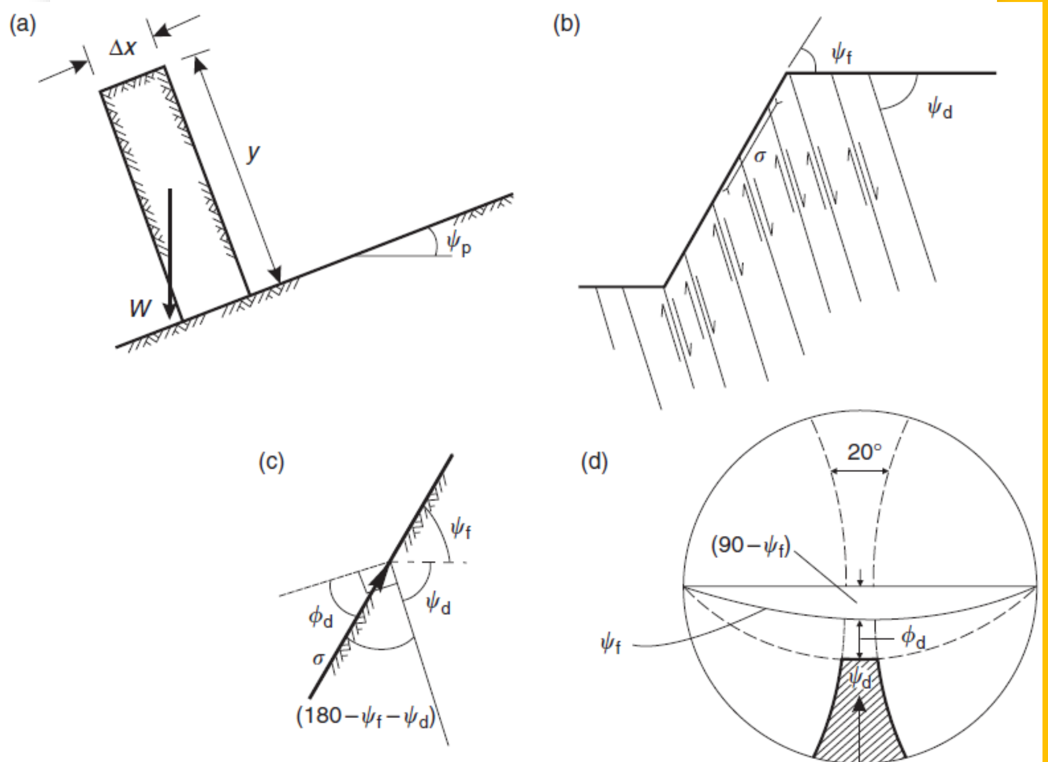
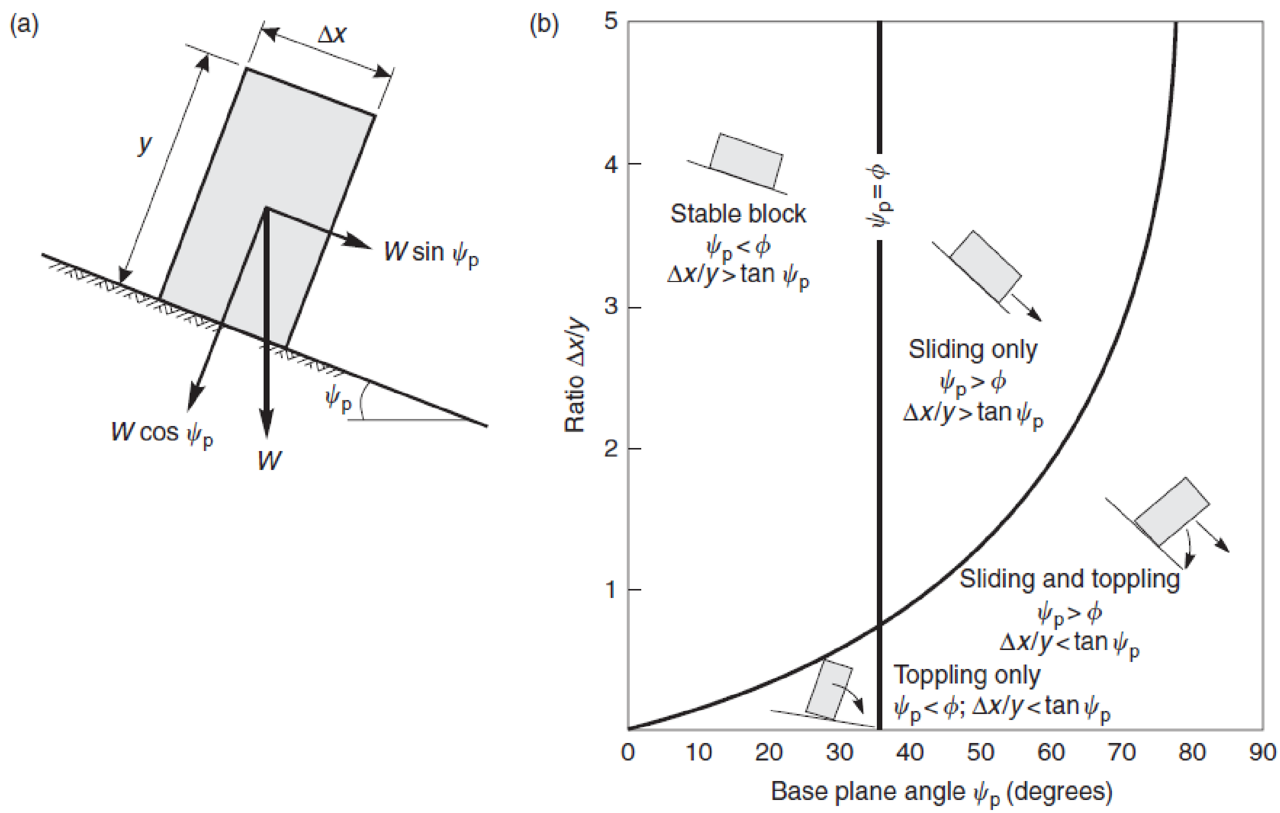
Block Shape Test

$\psi_p < \phi_p$
(Stable)

$\Delta x / y < \tan \psi_p$
(Topple)





Identification of sliding and toppling blocks: (a) geometry of block on inclined plane; (b) conditions for sliding and toppling of block on an inclined plane

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Inter-layer Slip Test

$$\left(180° - \psi_f - \psi_d\right) \geq \left(90° - \phi_d\right)$$

$$\psi_d \geq \left(90° - \psi_f\right) + \phi_d$$

Block Alignment Test

- Instability is possible where the dip direction of the planes forming sides of the blocks, α_d is within about $10°$ of the dip direction of the slope face α_f, or

$$\left|\left(\alpha_f - \alpha_d\right)\right| < 10°$$

- On the stereonet, toppling is possible for planes for which the poles lie within the shaded area.

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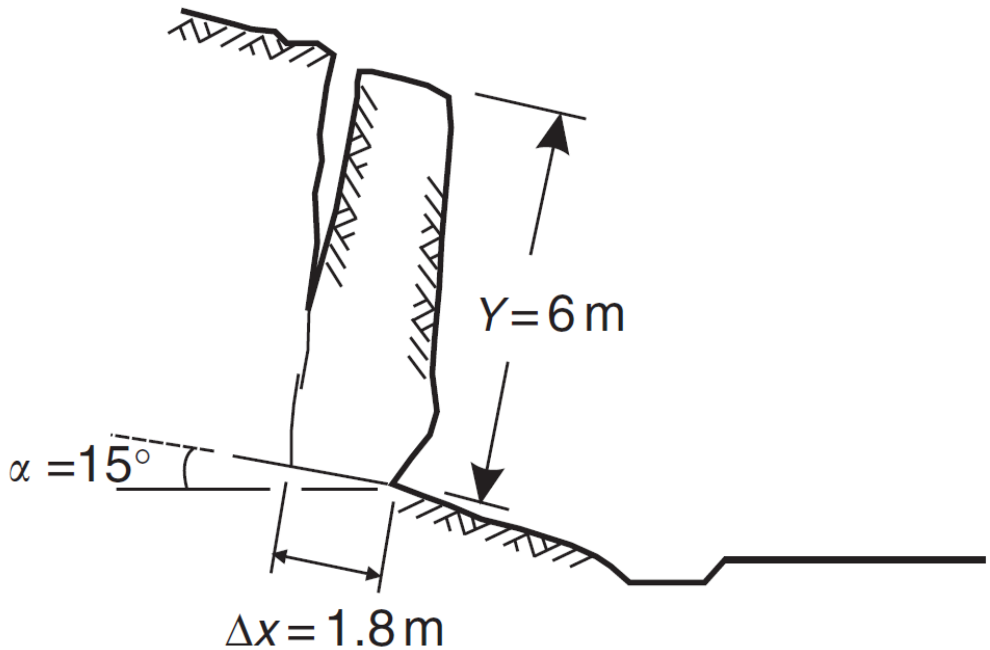
Toppling Failure Analysis

EXERCISE

Consider a 6 m high slope with an overhanging face at an angle of 75°. There is a fault, dipping at an angle of 15° out of the face, at the toe of the slope that is weathering and undercutting the face. A tension crack, which is wider at the top than at the bottom, has developed 1.8 m behind the crest of the slope indicating that the face is marginally stable. The friction angle ϕ of the fault is 20° and the cohesion c is 25 kPa. The slope is dry.



EXERCISE

Required

a) Calculate the factor of safety of the block against sliding if the density of the rock is 23.5 kN/m^3.

b) Is the block stable against toppling?

c) What stabilization measures would be appropriate for this slope?

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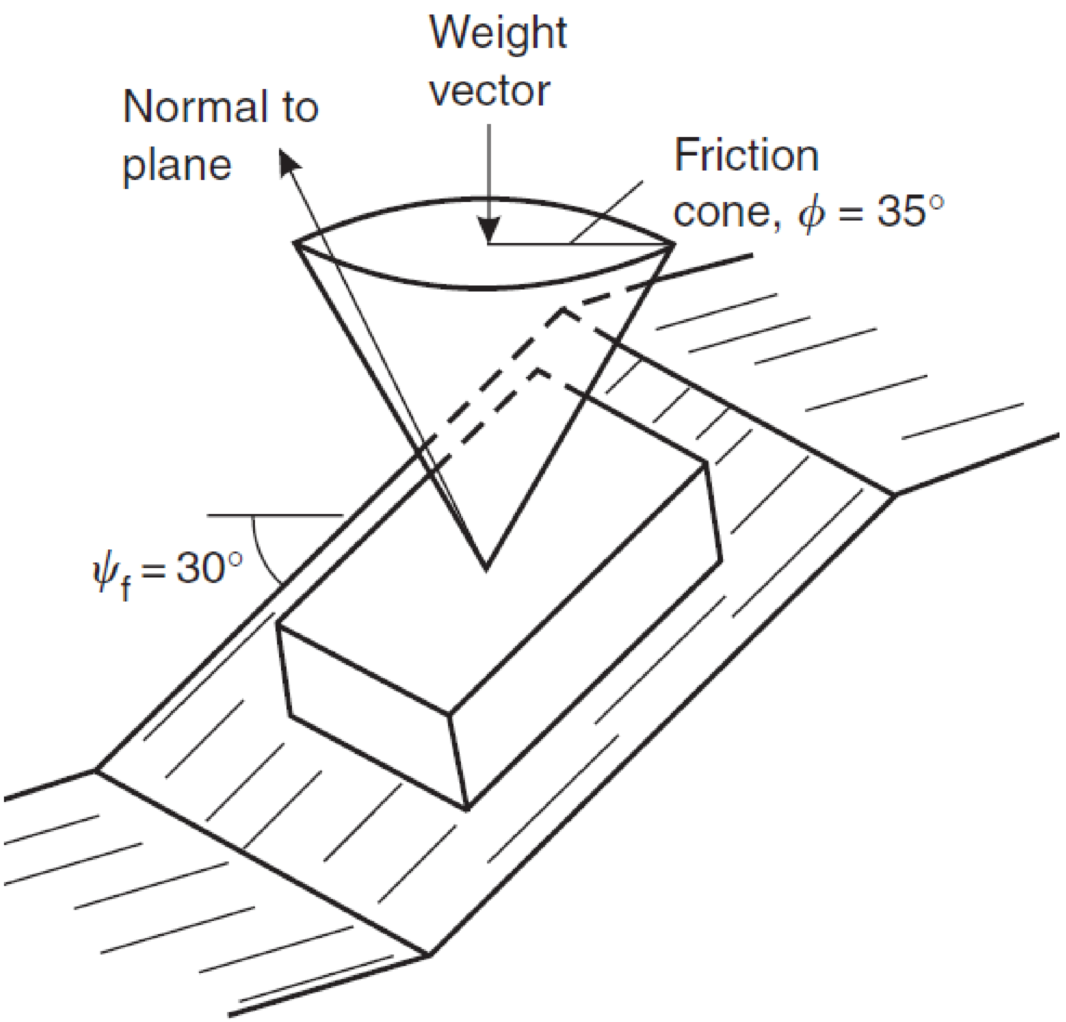
Friction Cone

Friction Cone

It is also possible to examine stability conditions on the same stereonet.

This analysis is carried out assuming that the shear strength of the sliding surface comprises only friction and the cohesion is zero.



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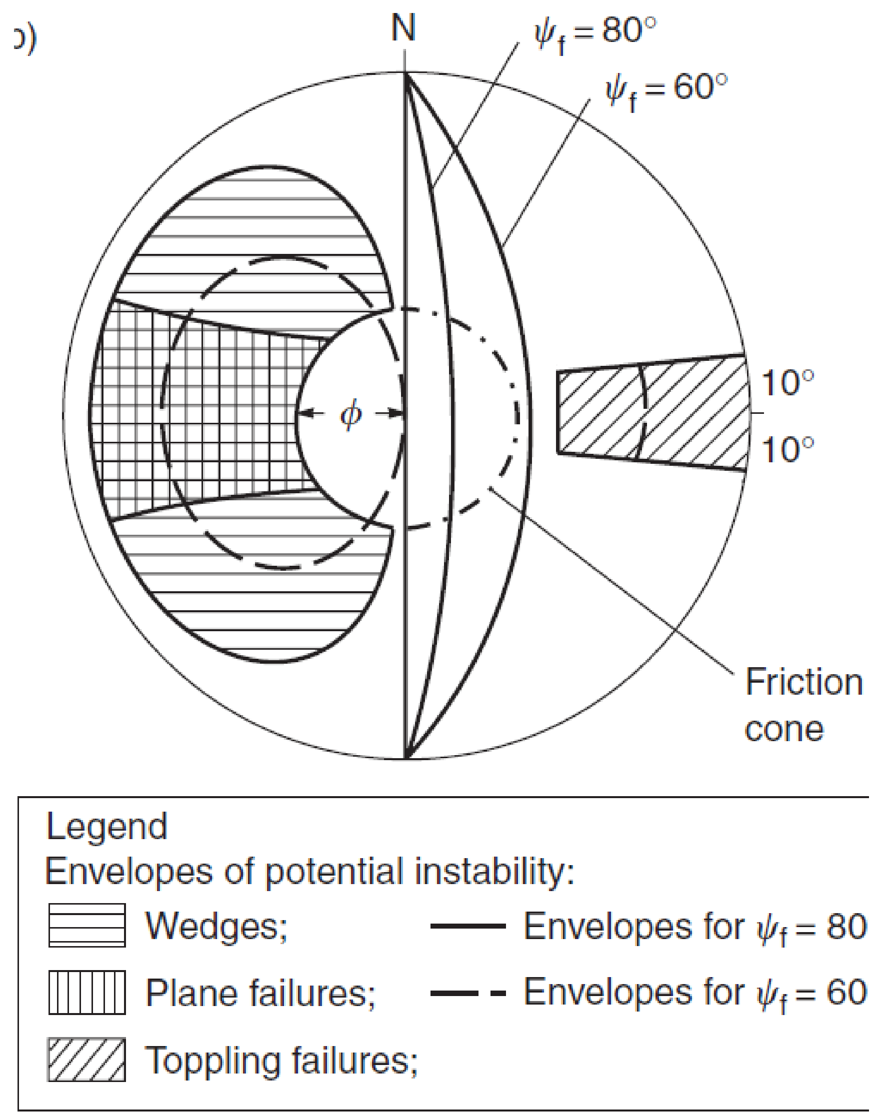
Friction Cone

When the only force acting on the block is gravity, the pole to the plane is in the same direction as the normal force, so the block will be stable when the pole lies within the friction circle.



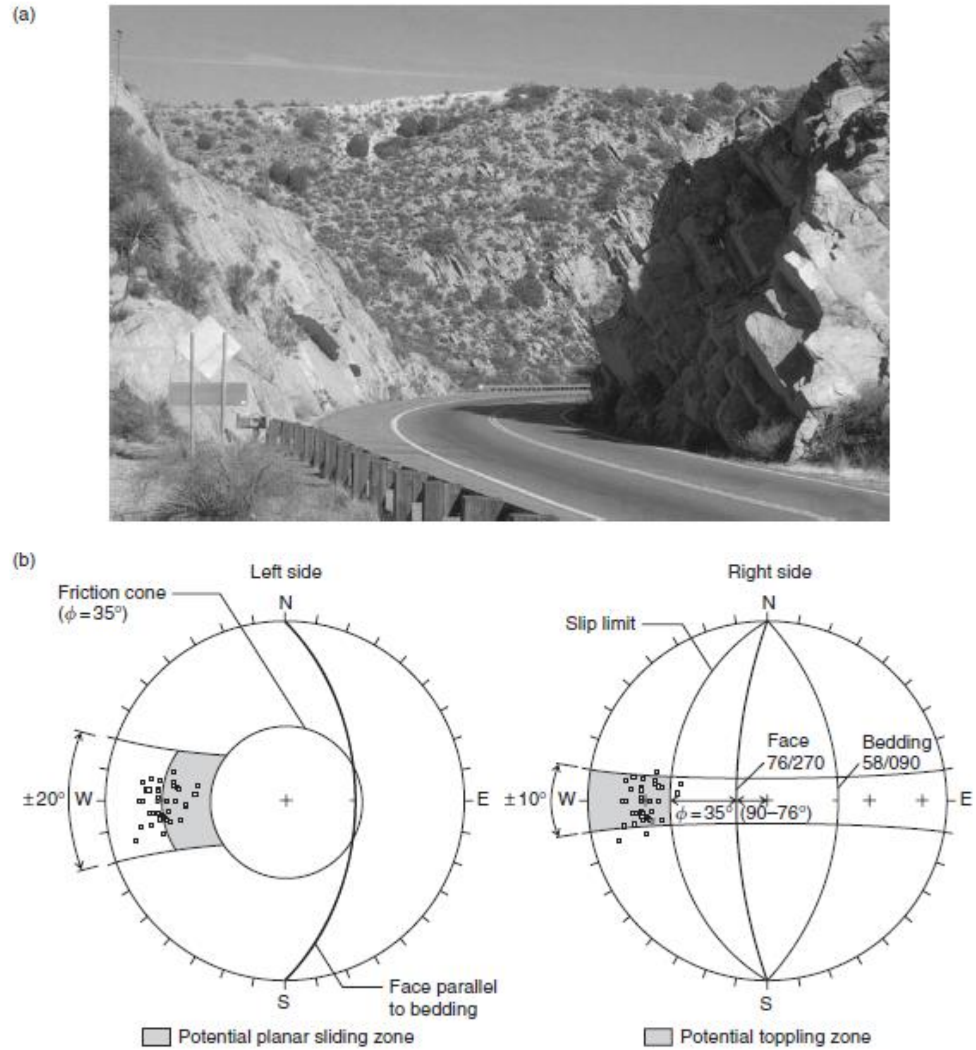
Applications of Kinematic Analysis

1. Highway
2. Open Pit Slopes

Highway

- A proposed highway on a north-south alignment passes through a ridge of rock in which a through-cut is required to keep the highway on grade.
- The predominant geological structure is the bedding that strikes north-south, parallel to the highway alignment and dips to the east at angles of between 70° and 80°.

Highway


(a)
(b)
Left side
Right side
Friction cone
(φ = 35°)
Slip limit
N
S
W
E
±20°
±10°
Face
76/270
Bedding
58/090
φ = 35° (90–76°)
Face parallel
to bedding
Potential planar sliding zone
Potential toppling zone

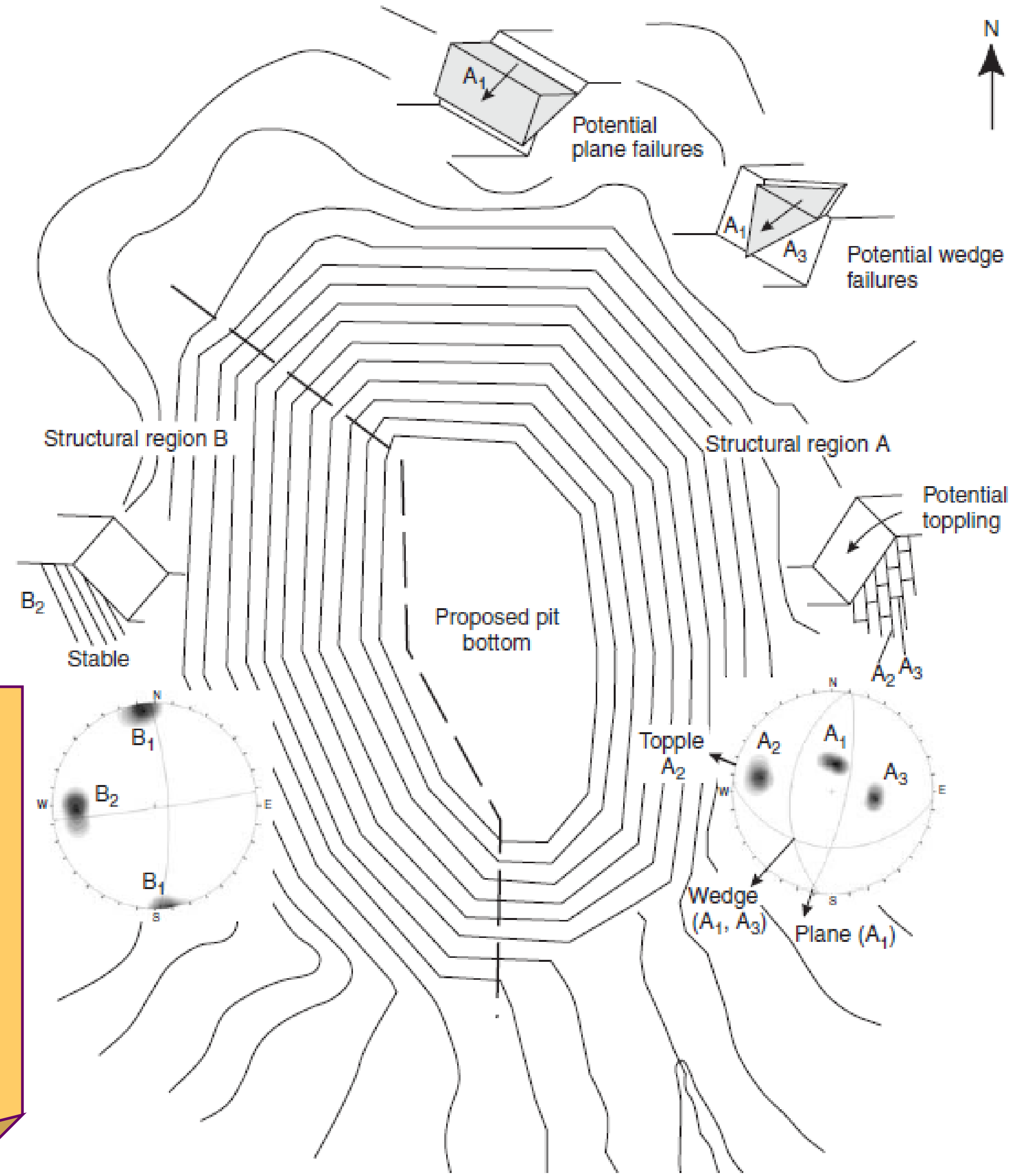
Open Pit Slopes

During the feasibility studies on a proposed open pit mine, an estimate of the safe slope is required for the calculation of ore-to-waste ratios and the preliminary pit layout.

- ✓ Drill cores
- ✓ Mapping of surface outcrops

It does provide a basis for preliminary slope design.

Presentation of Structural Geology on Stereonets, and Preliminary Evaluation of Slope Stability of Proposed Open Pit Mine



Note that three types of structurally controlled slope failure can occur in the same structural region, depending upon the orientation of the slope face.

THANK YOU

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