Introduction

- Landslide and other ground failures posting substantial damage and loss of life
- In U.S., average 25 deaths; damage more than $1 billion
- For convenience, definitions of ***landslide*** includes all forms of mass-wasting movements
- Landslide and subsidence: naturally occurred and affected by human activities

Role of Gravity and Slope Angle

- Gravitational force acts to hold objects in place by pulling on them in a direction perpendicular to the surface

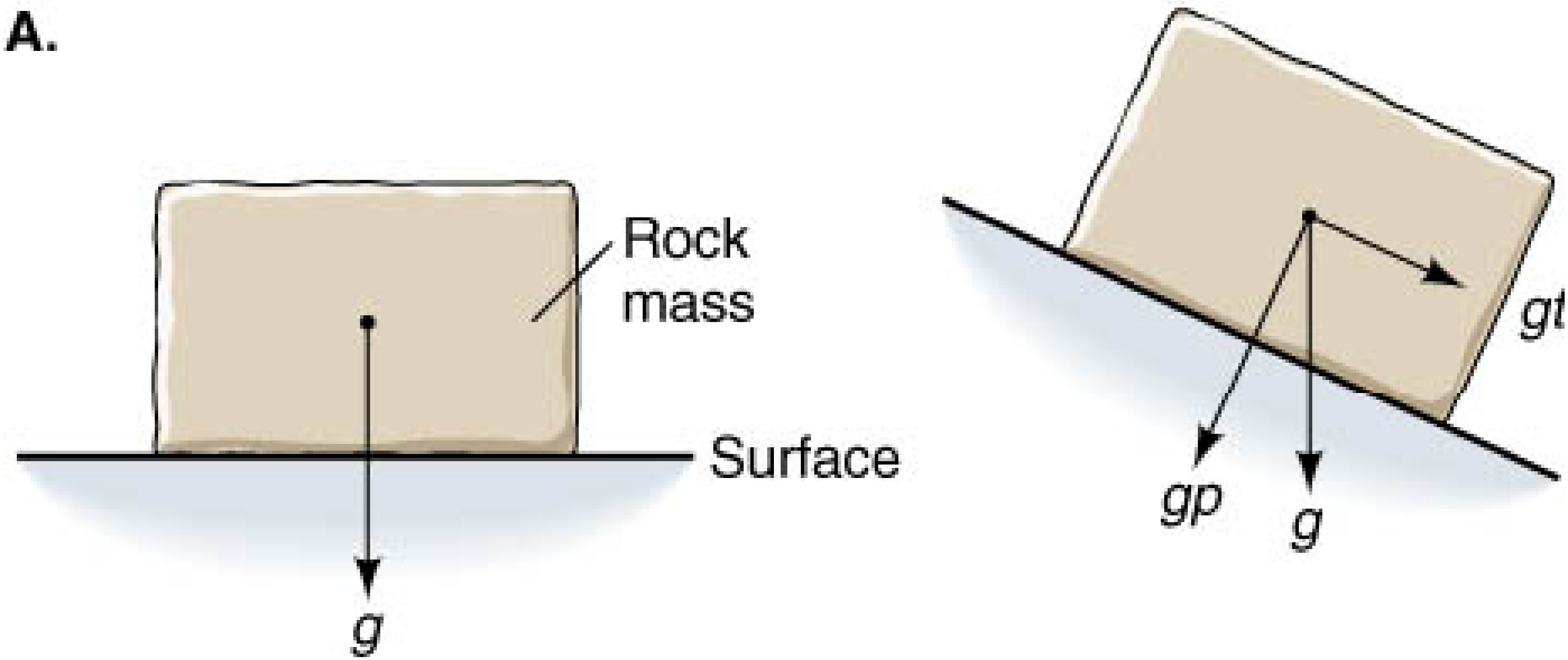
- The tangential component of gravity acts down a slope: it causes objects to move downhill

Role of Gravity and Slope Angle

- **Shear stress** is the downslope component of the total stress involved
  - Steepening a slope by erosion, jolting it by earthquake, or shaking it by blasting, can cause an increase in shear stress

- **Normal stress** is the perpendicular component

A.



The Role of Water (1)

- Water is almost always present within rock and regolith near the Earth's surface
- Unconsolidated sediments behave in different ways depending on whether they are dry or wet
- **Capillary attraction** is the attraction that results from surface tension
  – This force tends to hold the wet sand together as a cohesive mass

The Role of Water

- If sand, silt, or clay becomes saturated with water, and the fluid pressure of this water rises above a critical limit, the fine-grained sediment will lose strength and begin to flow

- If the voids along a contact between two rock masses of low permeability are filled with water, the water pressure bears part of the weight of the overlying rock mass, thereby reducing friction along the contact

The Role of Water

- **Failure** is the collapse of a rock mass due to reduced friction
  - An analogous situation is **hydroplaning**, in which a vehicle driven on extremely wet pavements loses control.

Types of Landslides (1)

- Slow or rapid failure of slope:
  - **Slope gradient**
  - **type of slope materials**
  - **amount of water present**
  - **rate of movement**

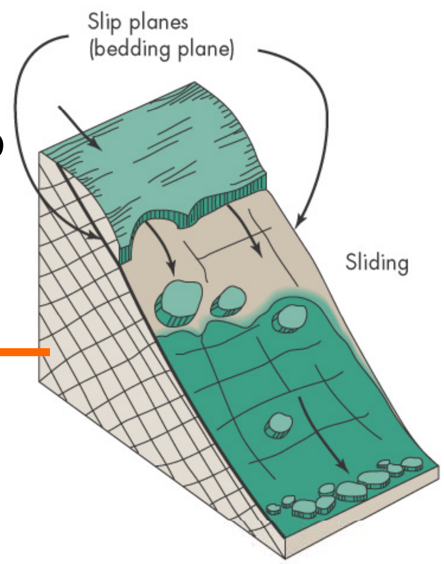
- **Rate of movement**: Imperceptible creep to thundering avalanches

- **Types**: Creep, sliding, slumping, falling, flowage or flow, and complex movement (sliding and flowage)

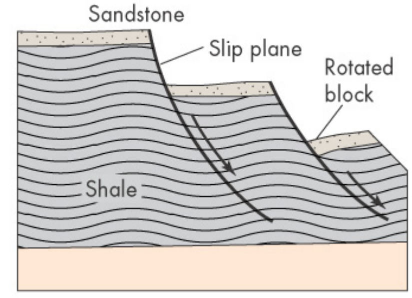
Types of Landslides (2)

Classification of landslides and other downslope movements

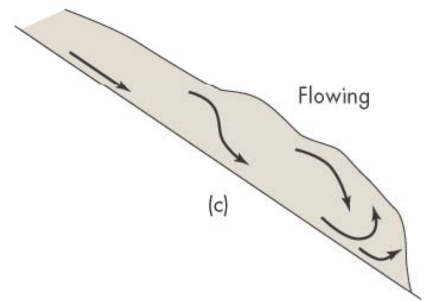
Type of Movement	Materials	
	Rock	Soil
Slides (a) (variable water content and rate of movement)	Slump blocks (b)	Slump blocks
Falls	Rock fall (d)	Soil fall
Flows (c) Slow → Rapid	Rock creep	Soil creep
	Unconsolidated materials (saturated)	
	Earthflow Mudflow Debris flow Debris avalanche	
Subsidence (e)	Rock or soil	
Complex (f)	Combinations of slides, slumps, and flows	



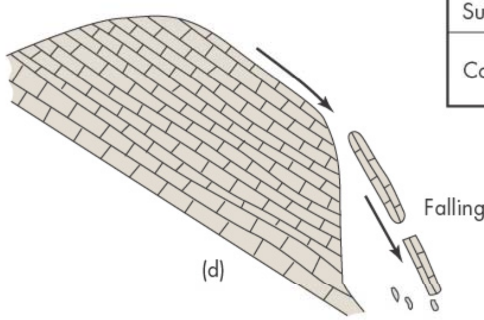
(a)



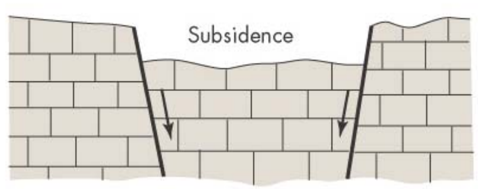
(b)



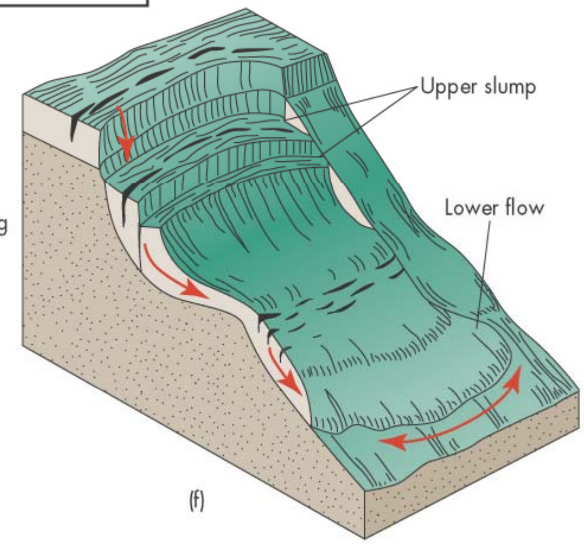
(c)



(d)

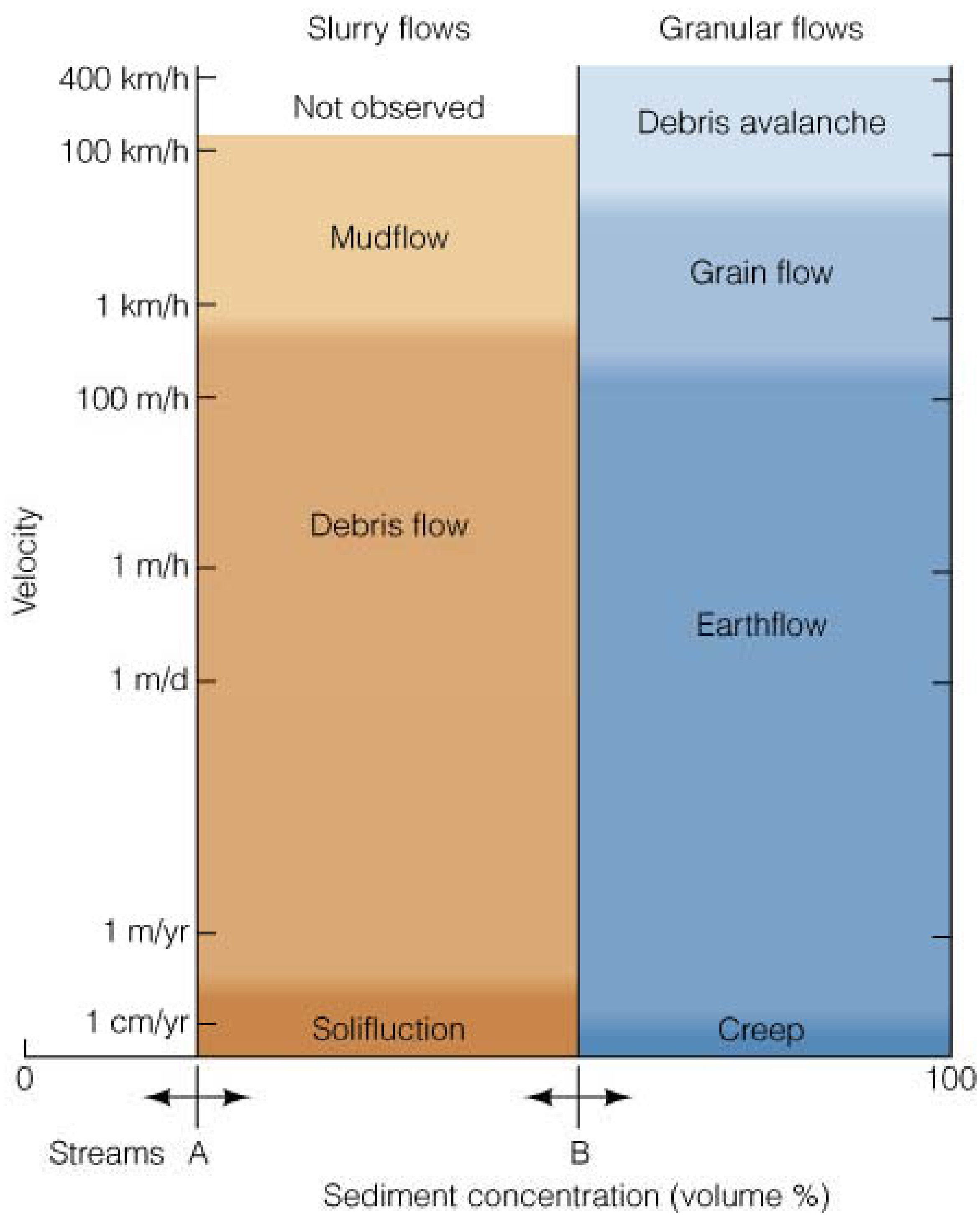


(e)



(f)

Figure 8.4



Slurry flows
Granular flows
400 km/h
100 km/h
1 km/h
100 m/h
1 m/h
1 m/d
1 m/yr
1 cm/yr
Velocity
Not observed
Mudflow
Debris flow
Solifluction
Debris avalanche
Grain flow
Earthflow
Creep
0
100
Streams
A
B
Sediment concentration (volume %)

Earthflows (2)

- A special type of earthflow called **liquefaction** occurs in wet, highly porous sediment consisting of clay to sand-size particles weakened by an earthquake
  - **An abrupt shock increases shear stress and may cause a momentary buildup of water pressure in pore spaces which decreases the shear strength**
  - A rapid fluidization of the sediment causes abrupt failure

Slope Stability

- **Safety Factor**

  SF = Resisting Forces/Driving Forces

  If SF > 1, Then safe or stable slope

  If SF < 1, Then unsafe or unstable slope

- **Driving and resisting forces determined by the interrelationships of the following variables**:
  - Type of Earth materials
  - Slope angle and topography
  - Climate
  - Vegetation and water
  - Time

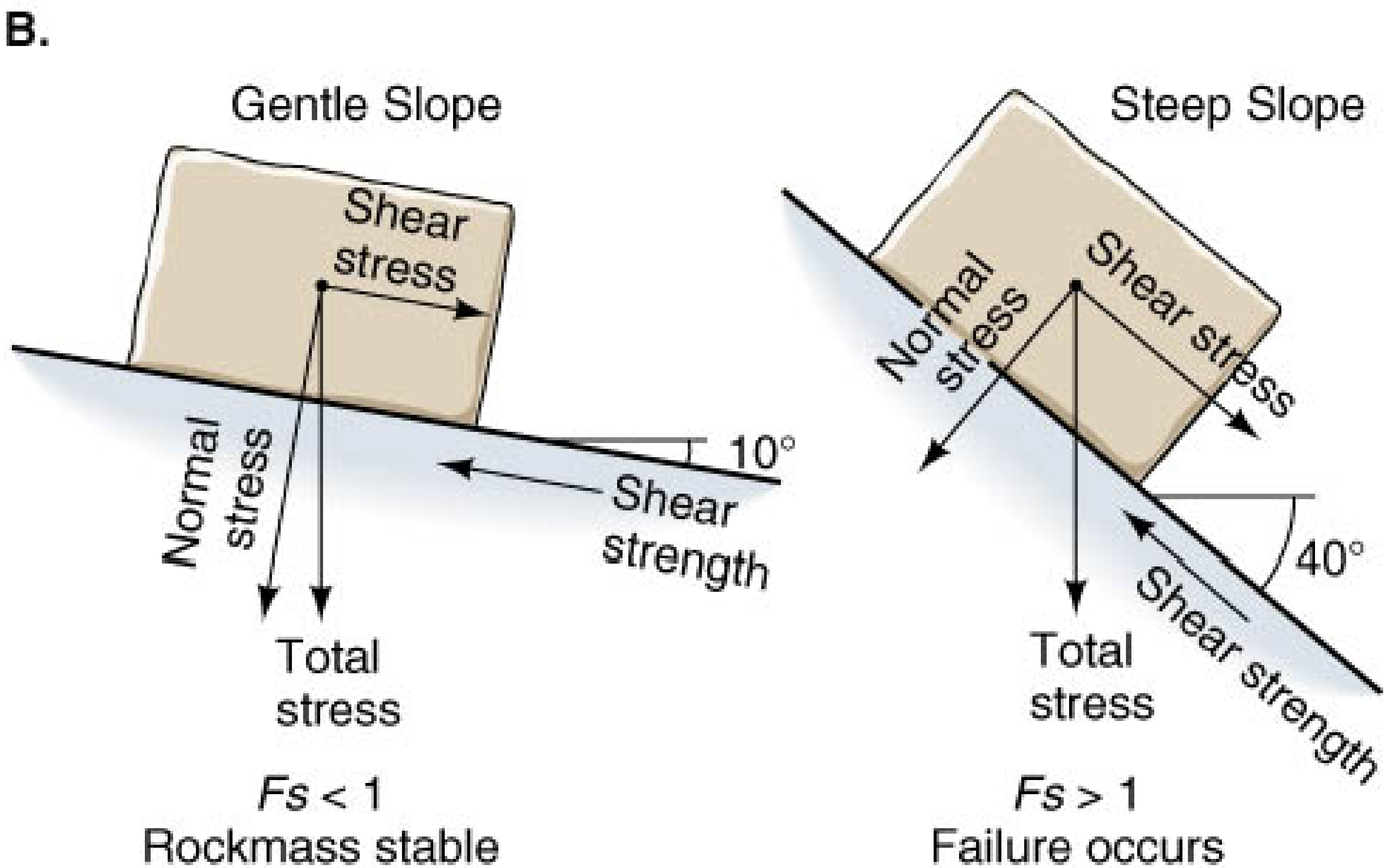

B.
Gentle Slope
Shear stress
Normal stress
Total stress
10°
Shear strength
Fs < 1
Rockmass stable
Steep Slope
Normal stress
Shear stress
Total stress
40°
Shear strength
Fs > 1
Failure occurs

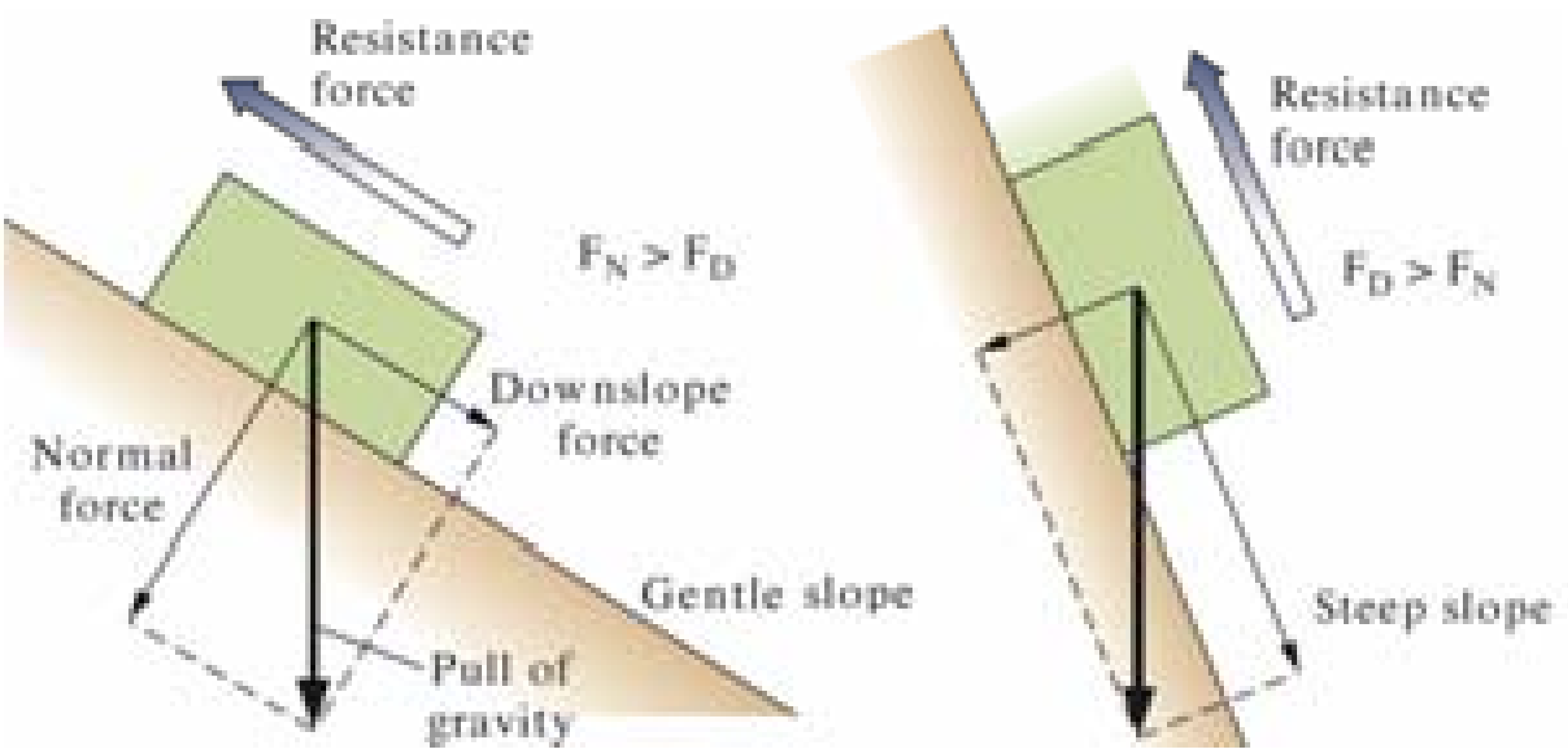
Figure B 13.1

Human Land Use and Landslide

- Urbanization, irrigation
- Timber harvesting in weak, relatively unstable areas
- Artificial fillings of loose materials
- Modification of landscape
- Dam construction

The Role of Gravity

- **Power** behind agents of erosion: rainfall, water flow, ice gliding, wind blowing, waves breaking
- **Geologic time: all slopes are inherently unstable**
- Can measure **pull of gravity**, using trigonometry to measure downhill force



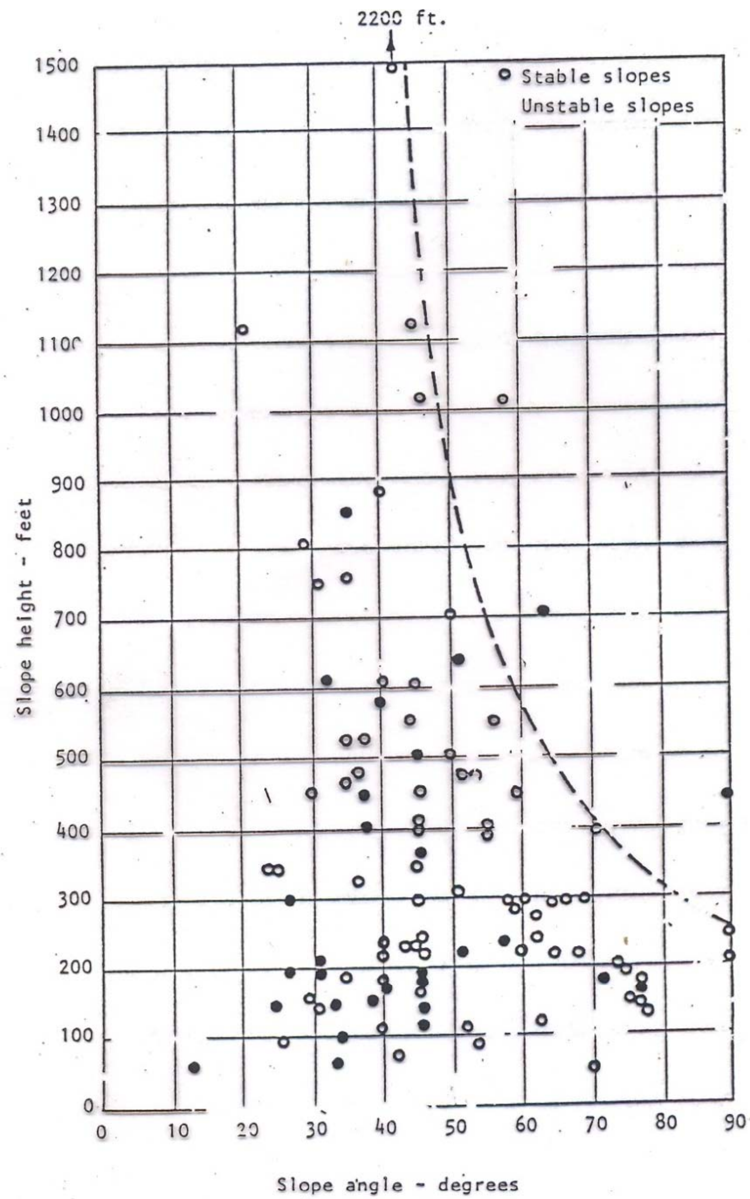


Figure 7 : Slope height versus slope angle relationships for hard rock slopes, including data collected by Kley and Lutton [21] and Ross-Brown [22].

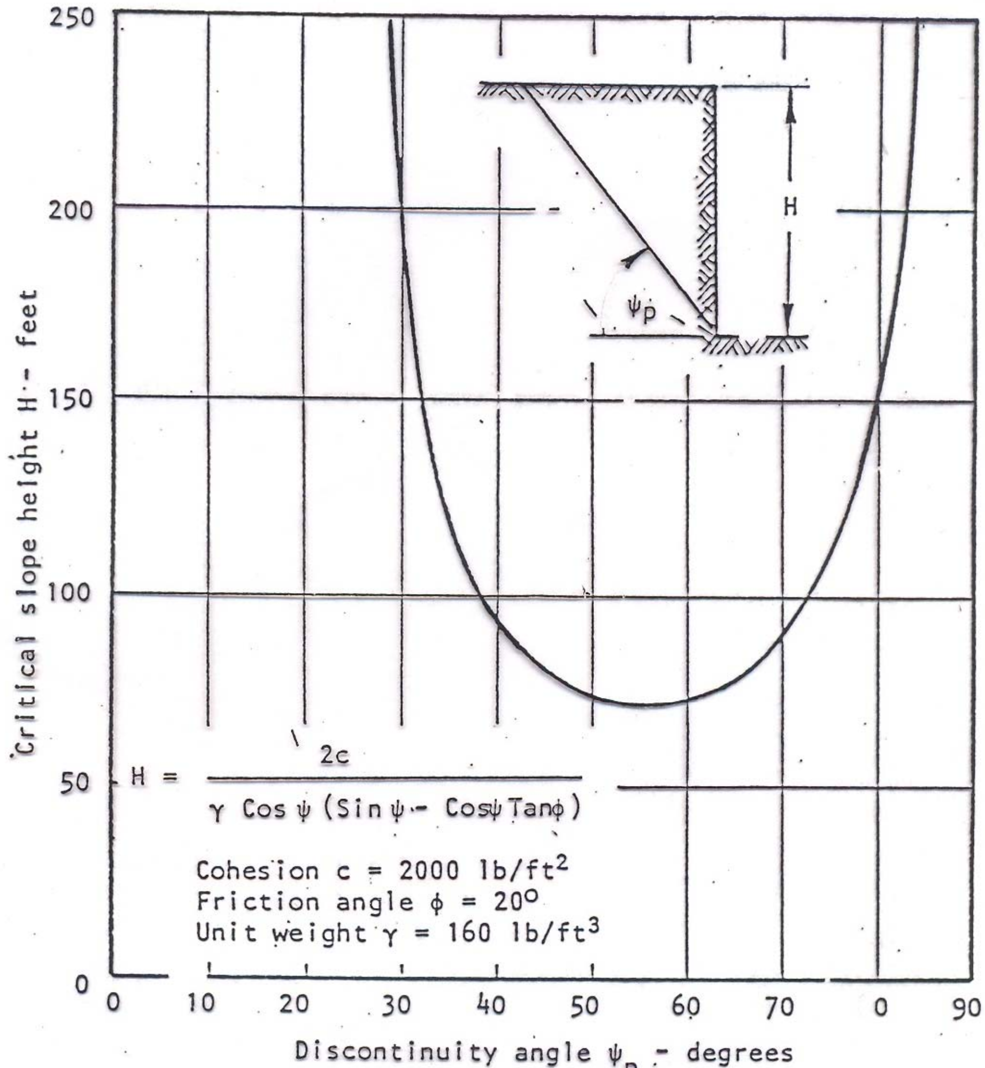
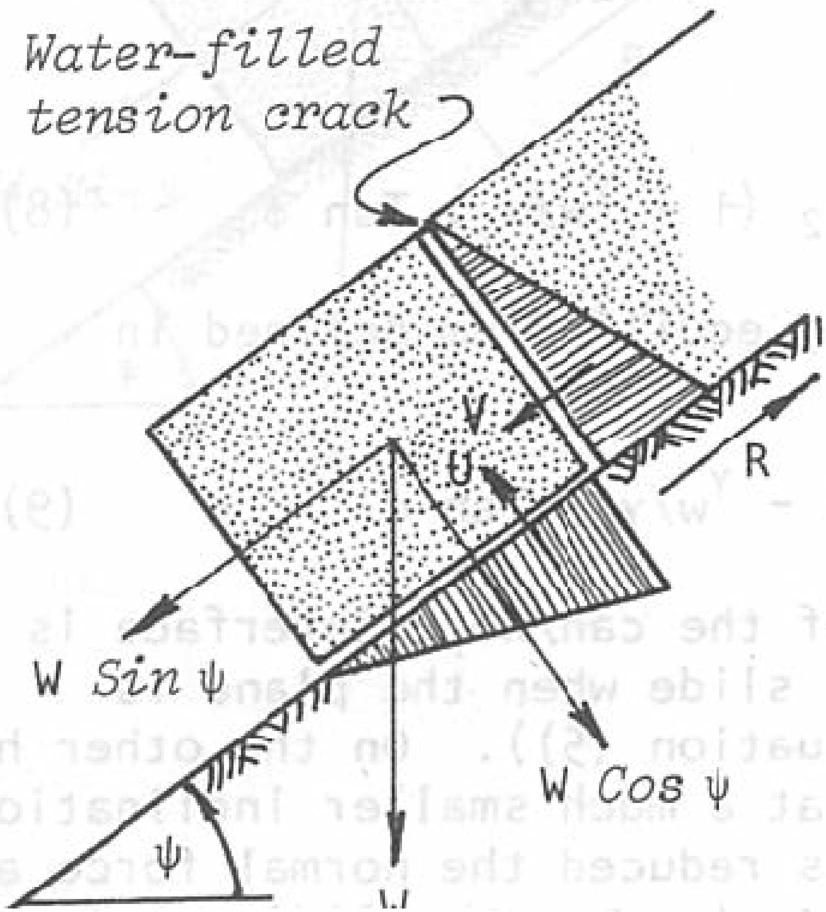
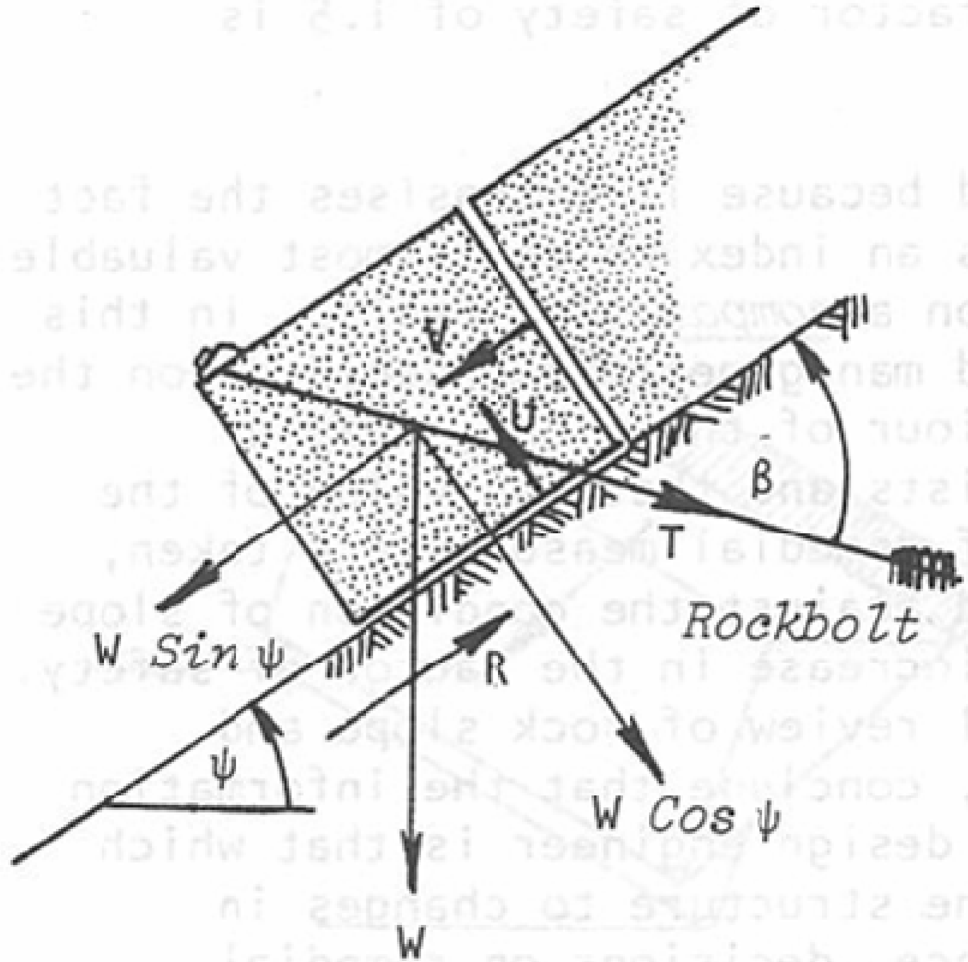


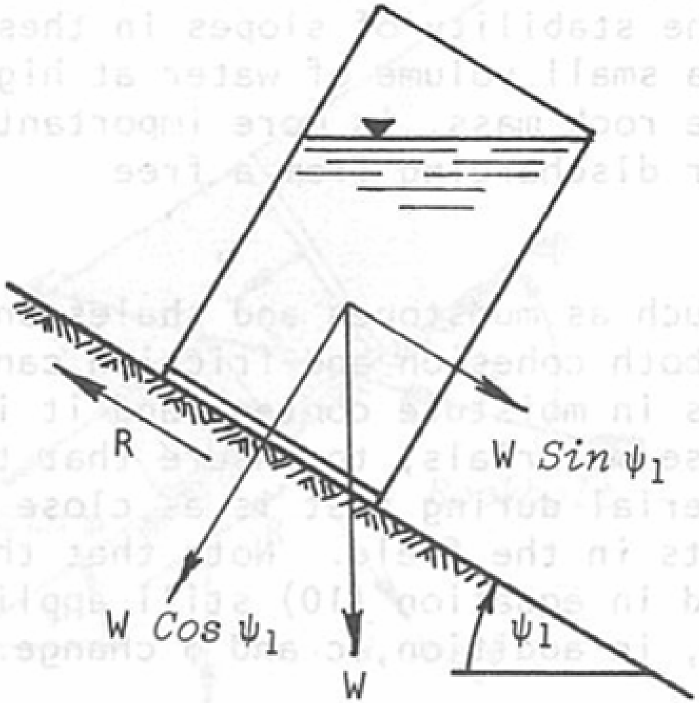
Figure 8 : Critical height of a drained vertical slope containing a planar disconti uity dipping at an angle ψ_p .

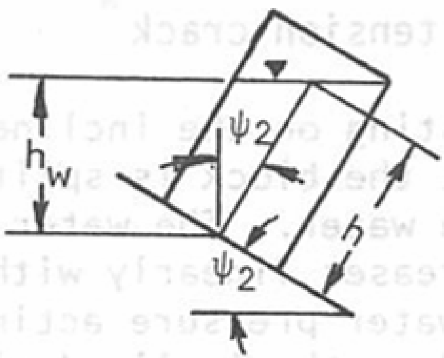


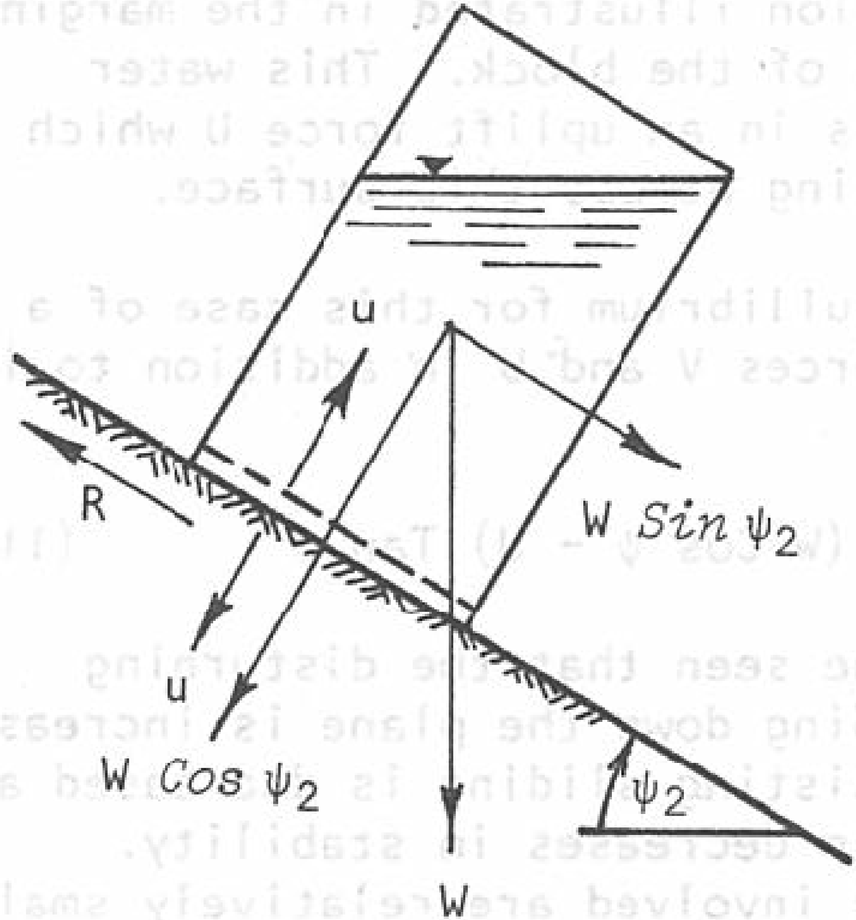
$$W \sin \psi + V = cA + (W \cos \psi - U) \tan \phi$$



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


R
W Sin ψ1
W Cos ψ1
W
ψ1


hw
ψ2
ψ2
h


u
R
W Sin ψ2
u
W Cos ψ2
W
ψ2

$$W \sin \psi = cA + W \cos \psi \, . \, \tan \phi \qquad (4)$$

$$R = (W \cos \psi_2 - U) \tan \phi$$

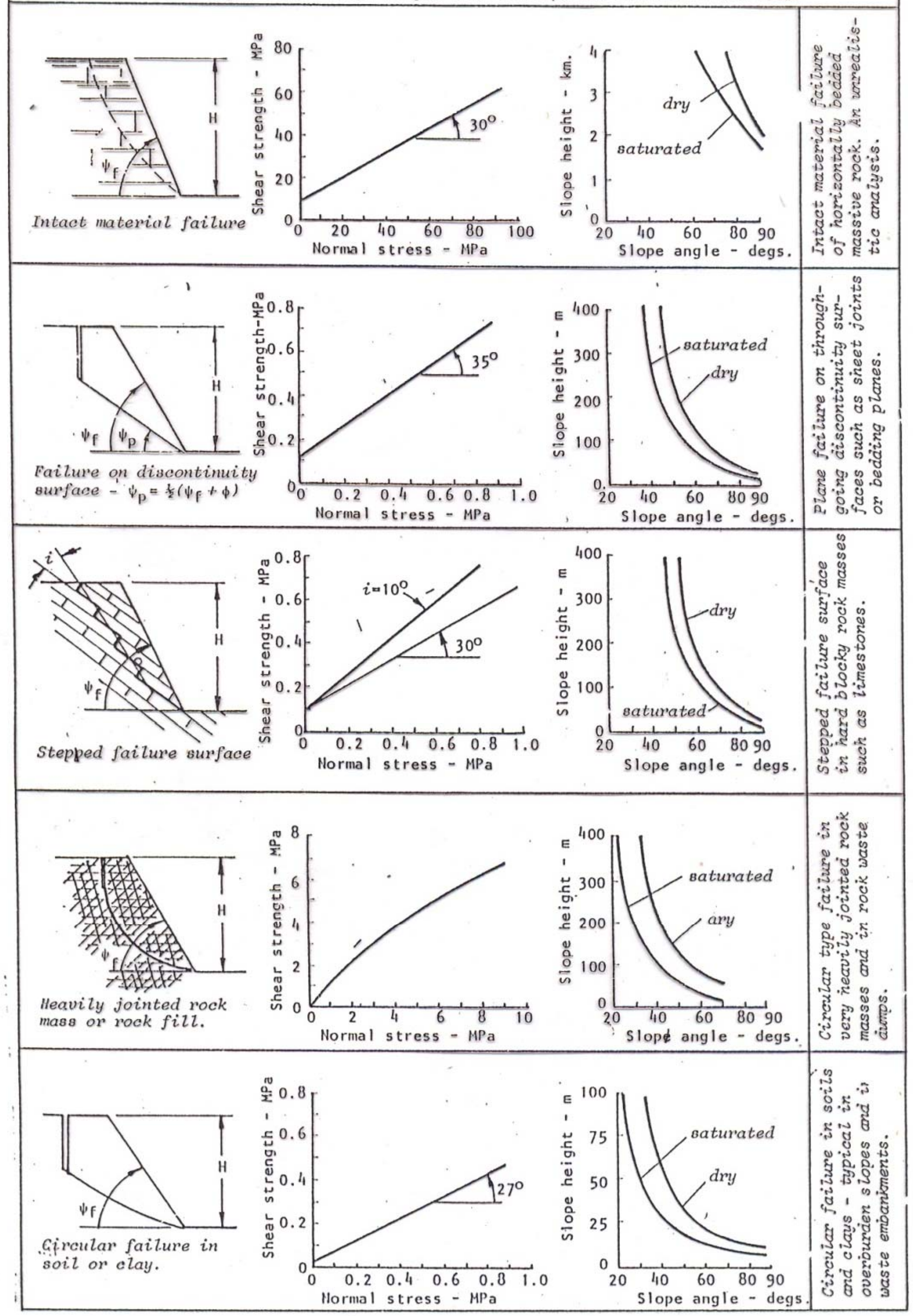
$$U = \gamma_w/\gamma_t \, . \, W \cos \psi_2$$

$$R = W \cos \psi_2 \, (1 - \gamma_w/\gamma_t) \tan \phi$$

and the condition for limiting equilibrium defined in equation (4) becomes

$$\tan \psi_2 = (1 - \gamma_w/\gamma_t) \tan \phi$$

Figure 10 : Slope angle versus slope height relationships for different materials.



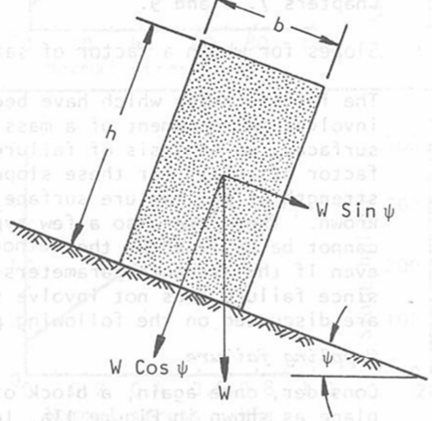


Figure 11a : Geometry of block on inclined plane.

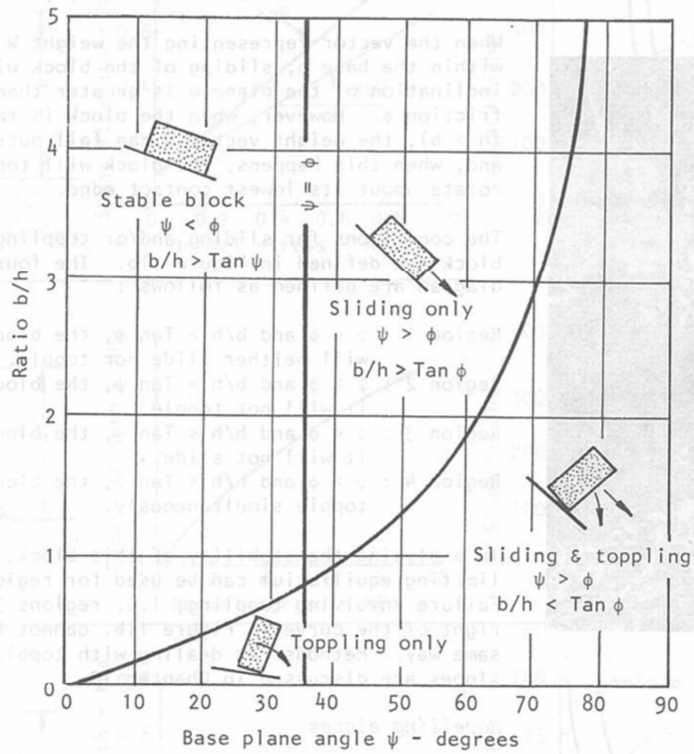
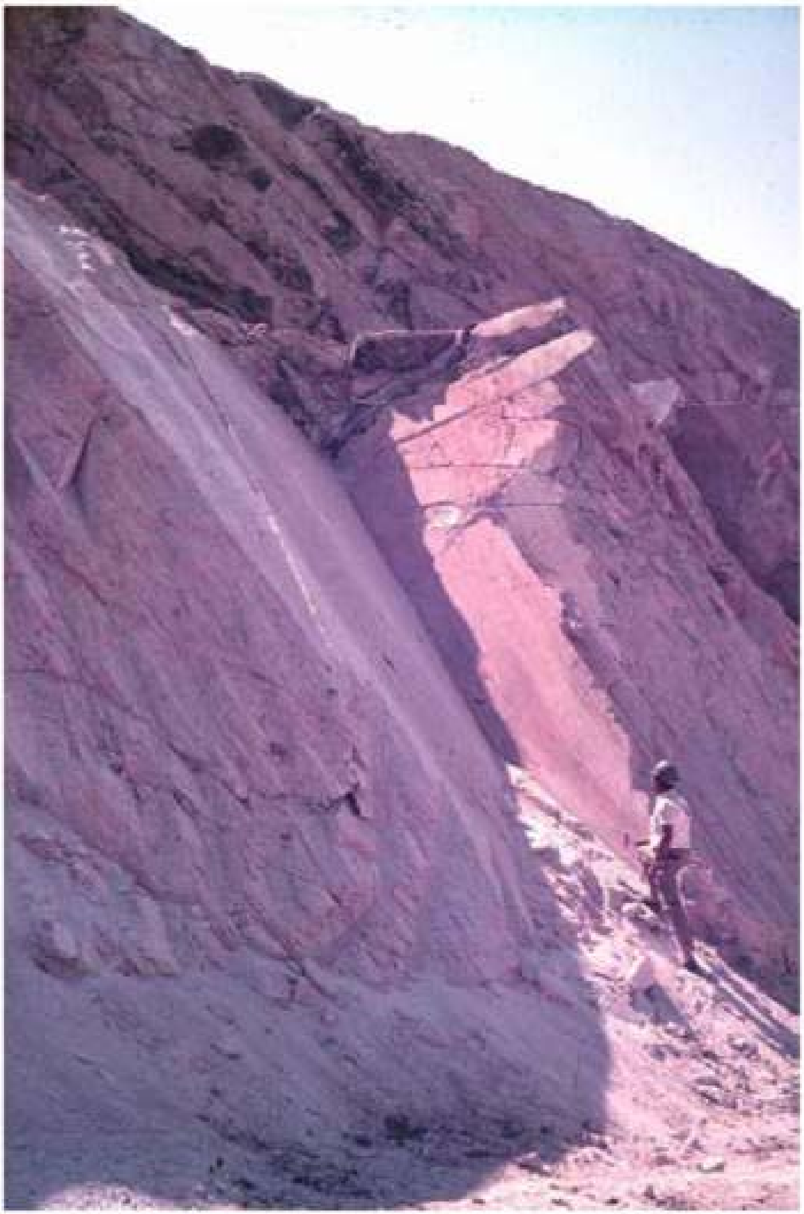
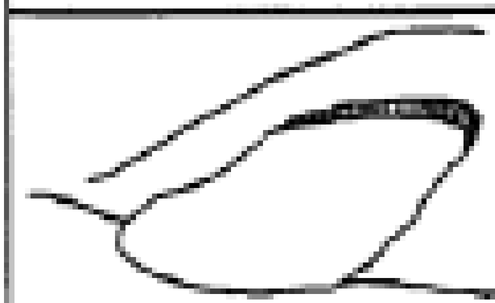


Figure 11b : Conditions for sliding and toppling of a block on an inclined plane.

Small and Large Scale Failures



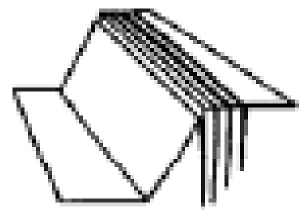
Mode of Failure



Landslides.

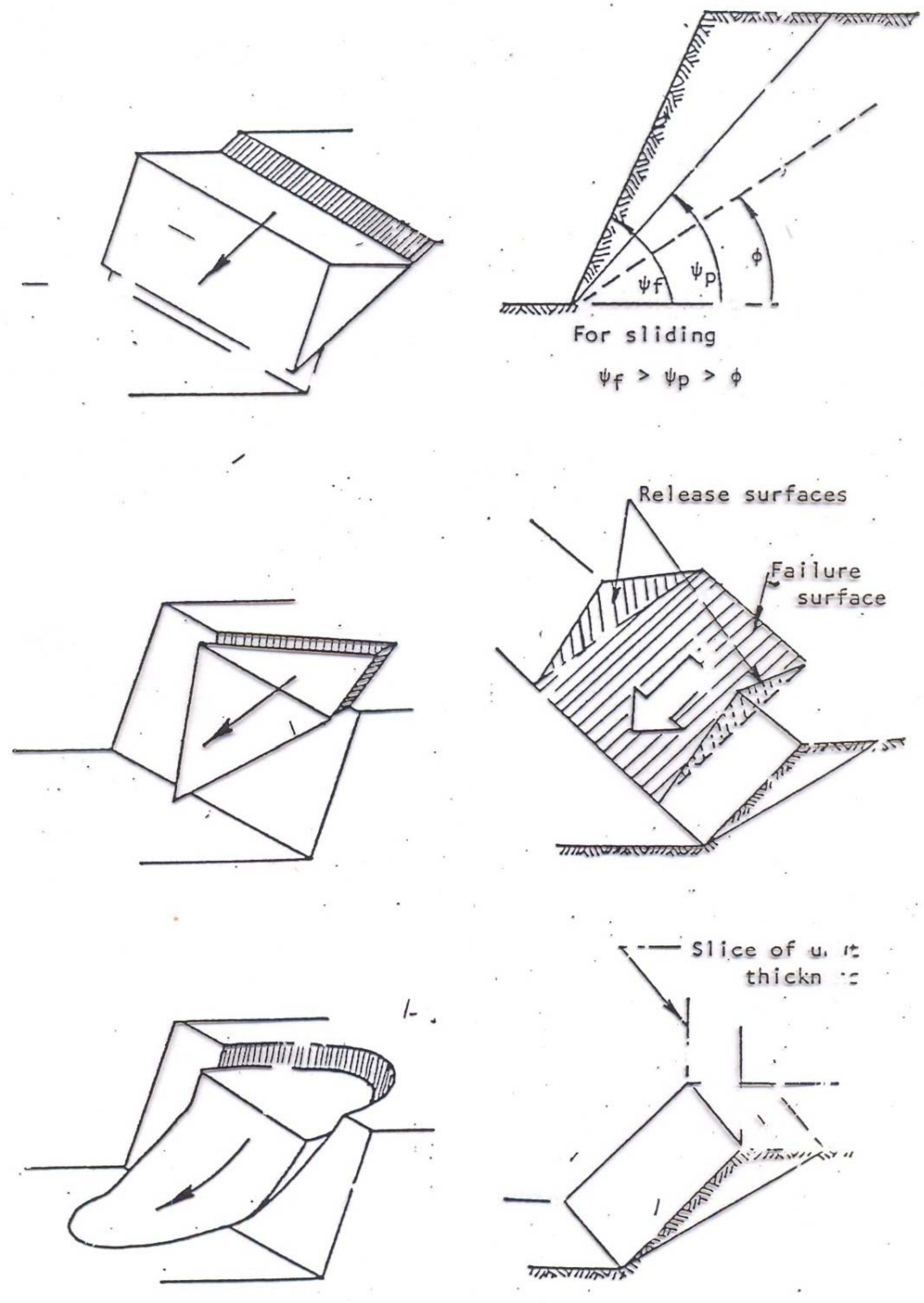
Soil or heavily jointed rock slopes.

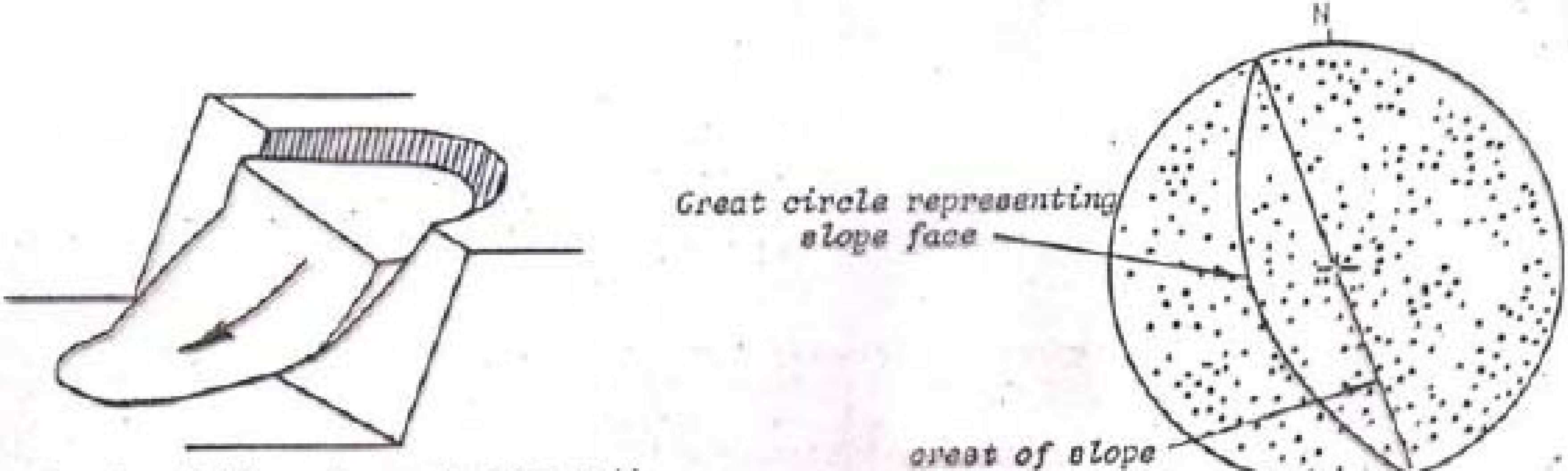
Jointed rock slopes.



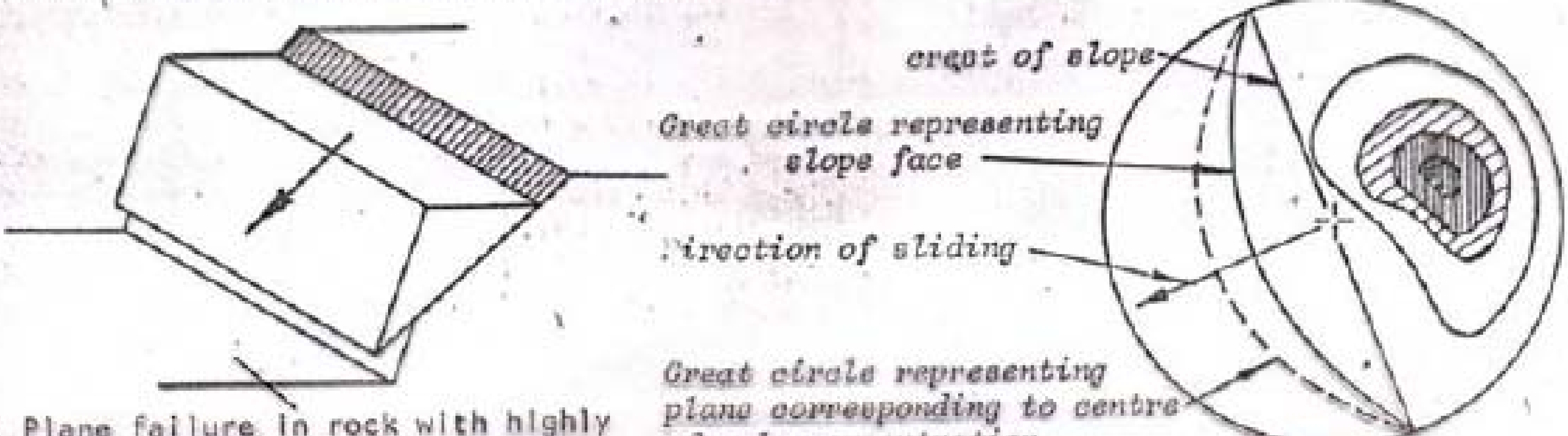
Vertically jointed rock slopes .

Loose boulders on rock slopes.

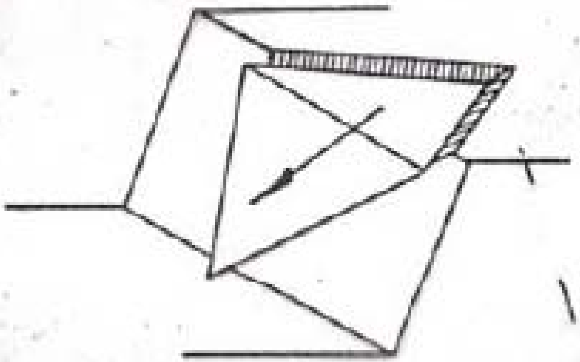

ψf
ψp
ϕ
For sliding
ψf > ψp > ϕ
Release surfaces
Failure surface
Slice of
thickn

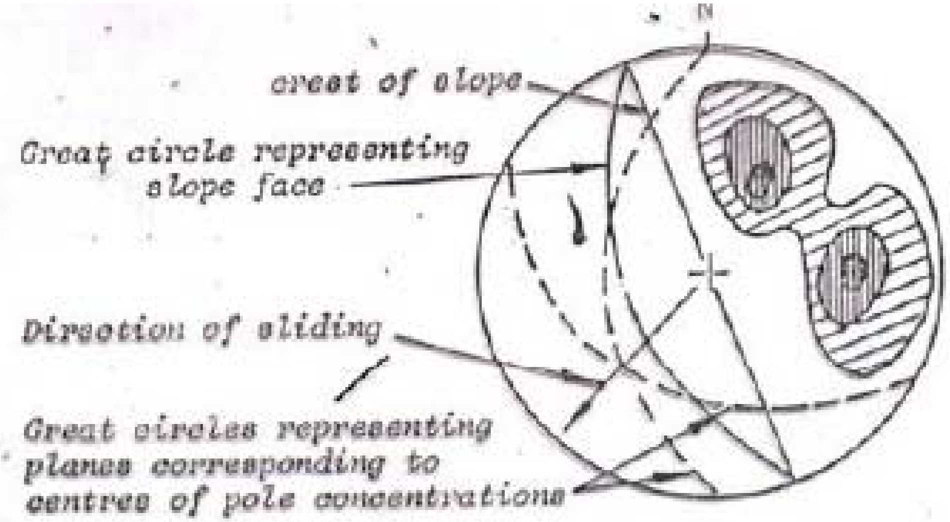


a. Circular failure in overburden soil, waste rock or heavily fractured rock with no identifiable structural pattern.

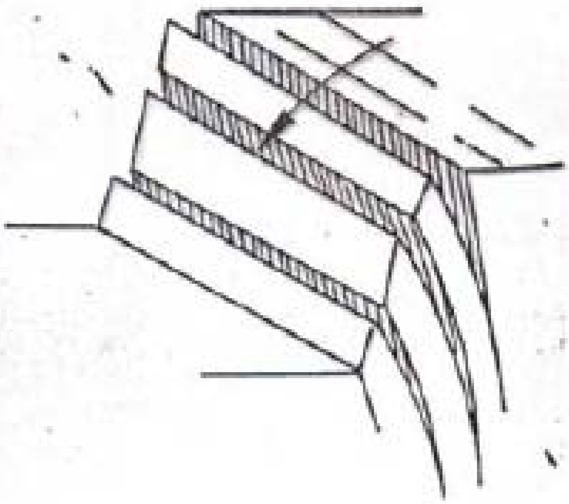


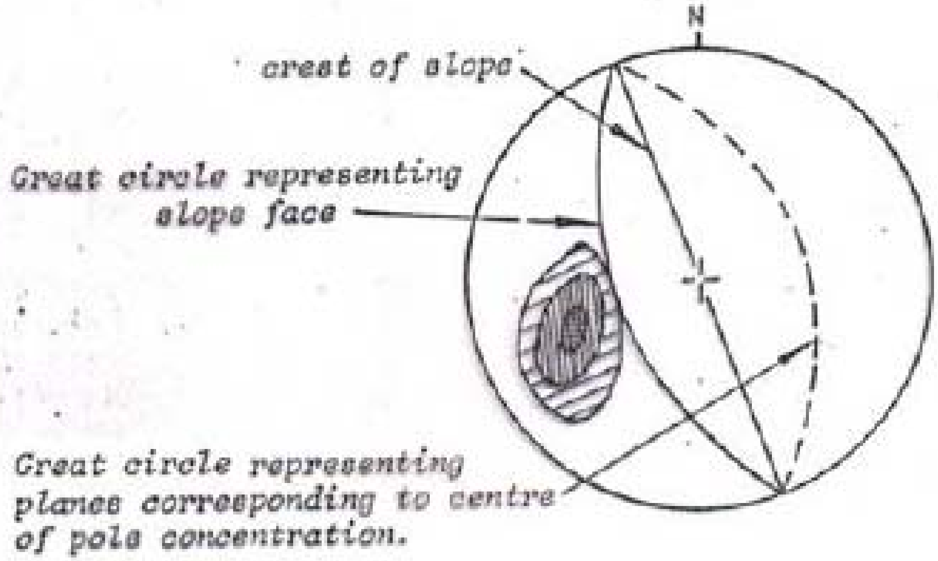
b. Plane failure in rock with highly ordered structure such as slate.





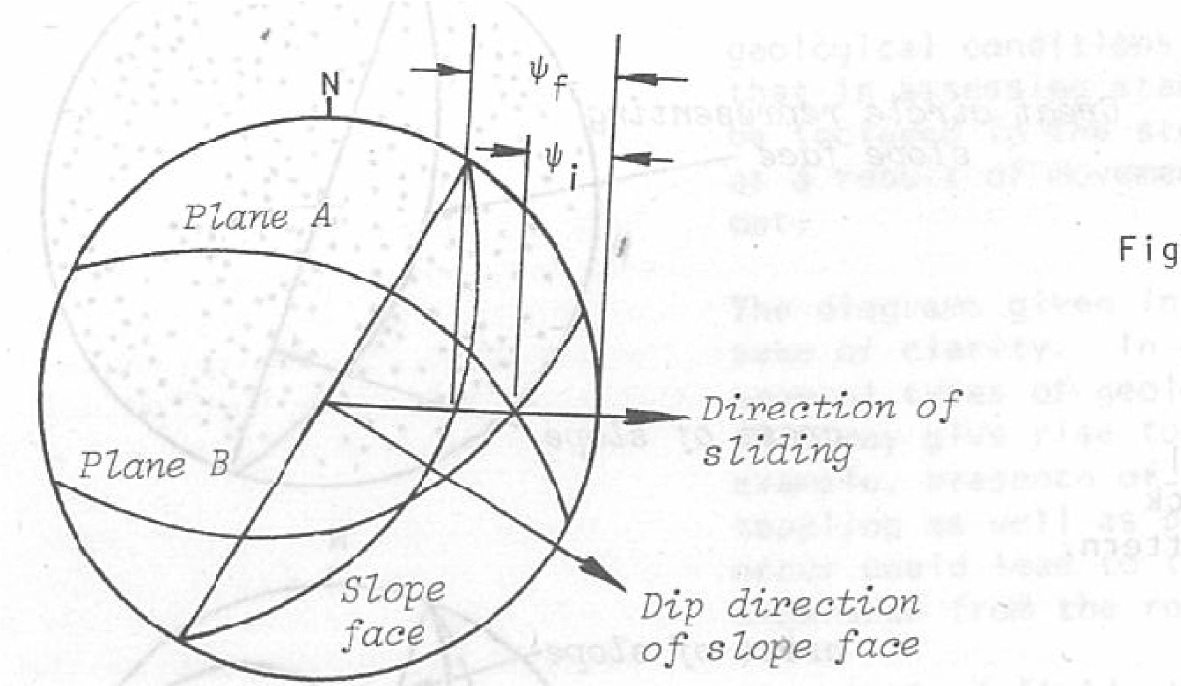
c. Wedge failure on two intersecting discontinuities.





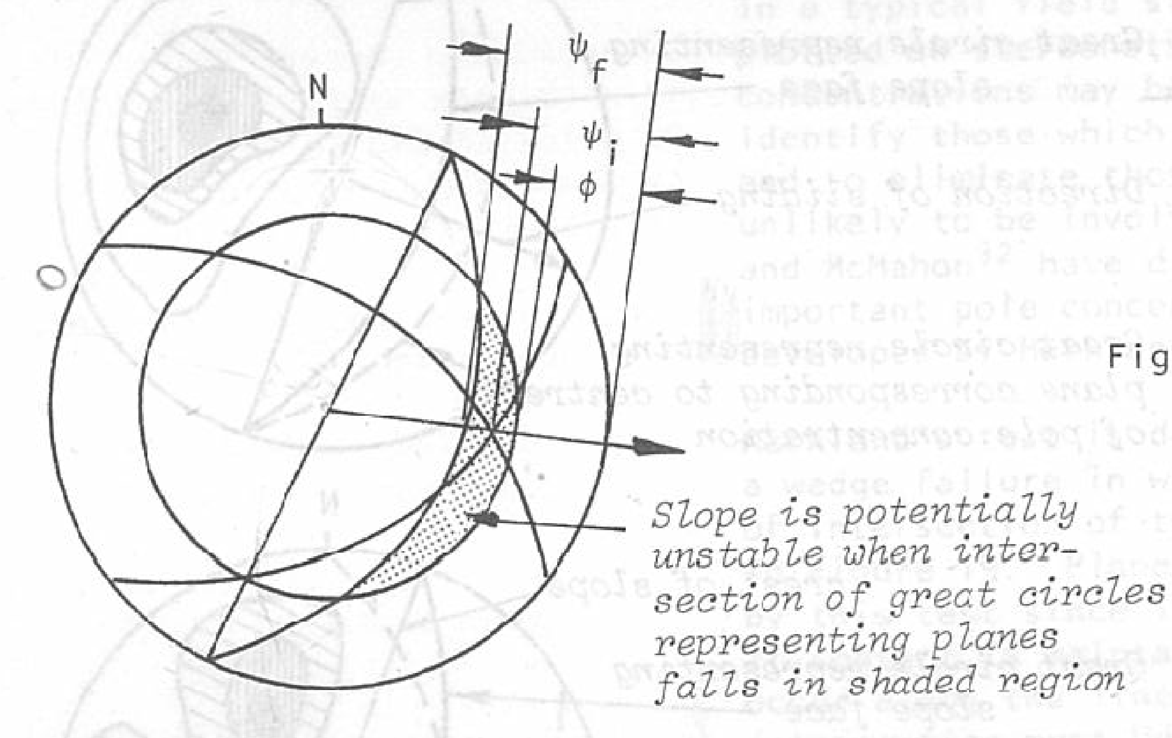
d. Toppling failure in hard rock which can form columnar structure separated by steeply dipping discontinuities.

Main types of slope failure and stereoplots of structural conditions likely to give rise to these failures.



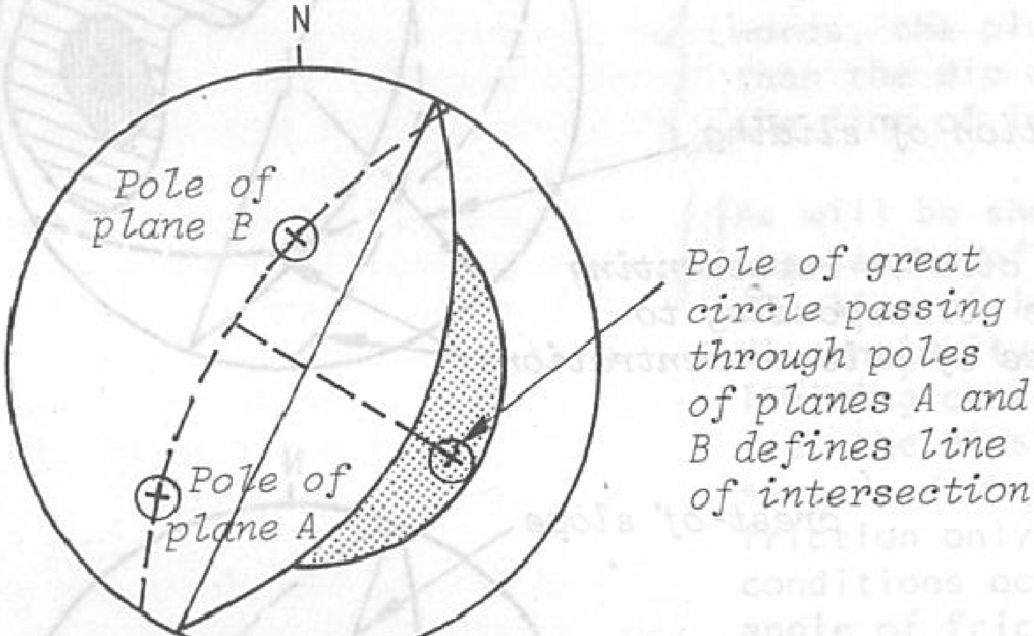
Sliding along the line of intersections of plane A and B is possible when the plunge of this line is less than the dip of the slope face in the direction of sliding.

$\Psi_f > \Psi_i$

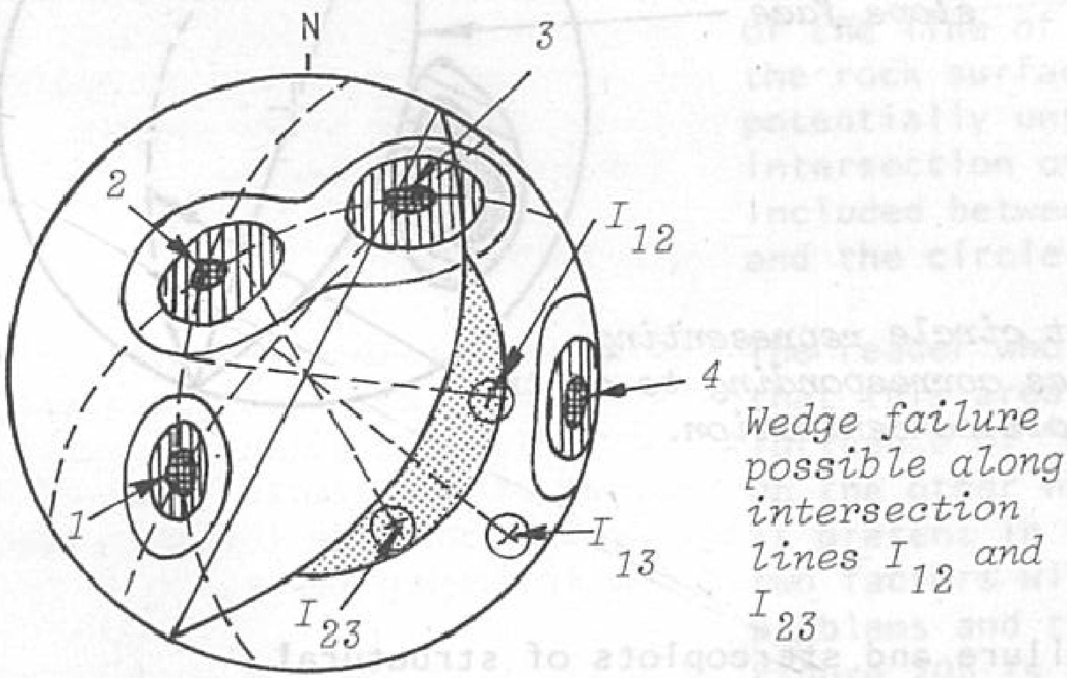


Sliding is assumed to occur when the plunge of the line of intersection exceeds the angle of friction.

$\Psi f > \Psi i > \Phi$



Representation of planes by their poles and determination of the line of intersection of the planes by the pole of the great circle which passes through their poles.

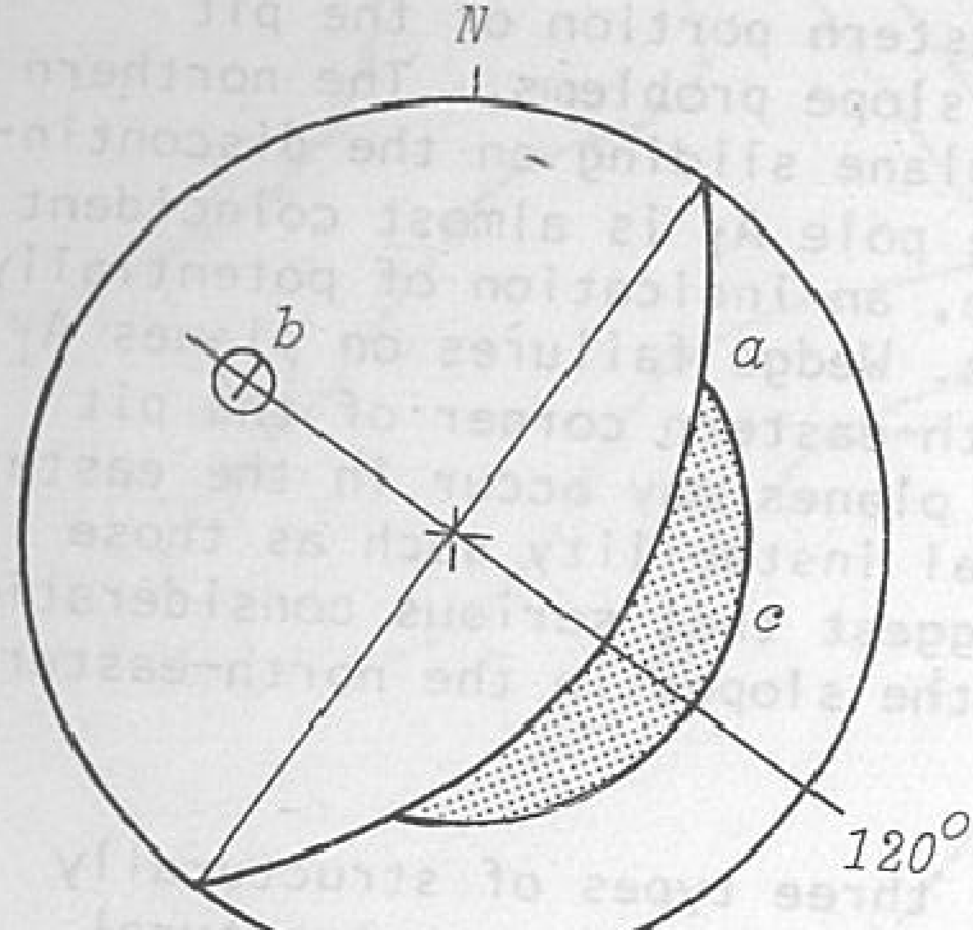


Preliminary evaluation of the stability of a 50^0 slope in a rock mass with 4 set of joints.

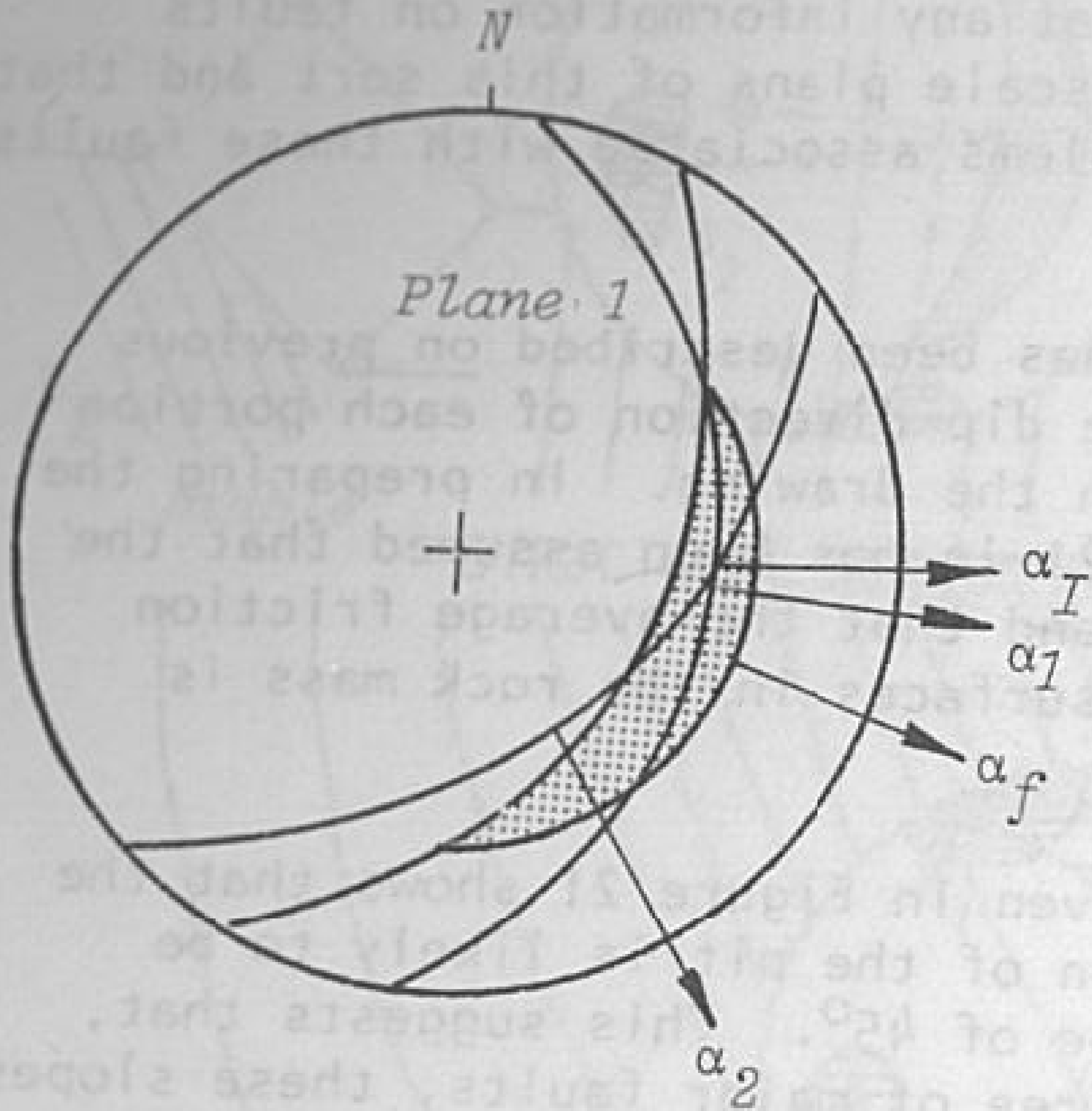
Marklands Test

- To establish the possibility of wedge failure. Plane failure is a special case of wedge failure.

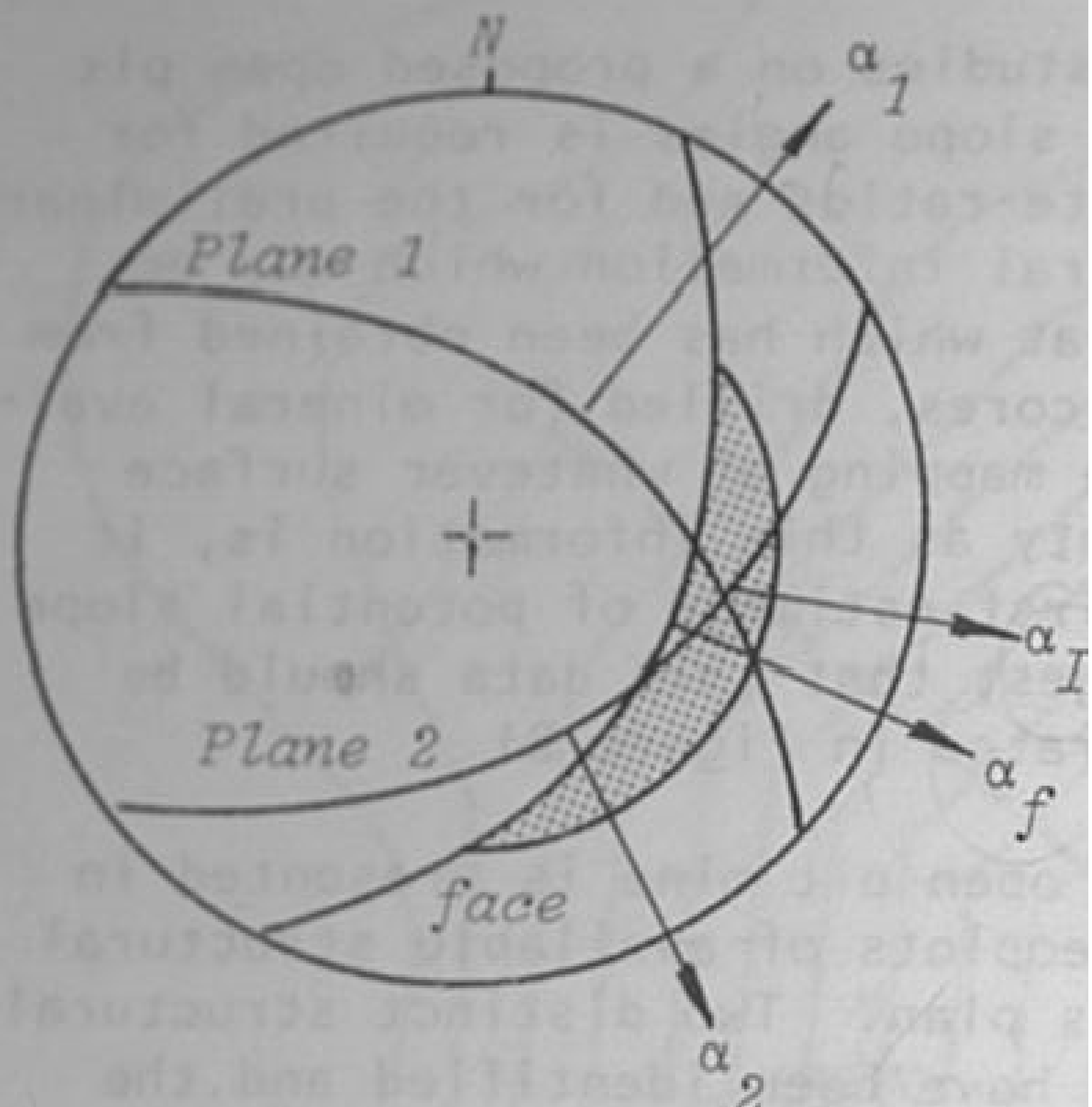
- The most dangerous combination of discontinuities are represented by pole concentrations no. 1,2 and 3.
- I_{13} falls outside the shaded region. Pole concentration 4 will not have sliding and may have overturning.
- The poles of plane 1 and 2 lie outside the angle included between the dip direction of the slope face and the line of intersection I_{12}, hence the wedge failure is possible.
- In case of planes 2 and 3, failure will be sliding on plane 2. This is most critical.



Overlay for checking wedge failure potential



Sliding on plane 1 only



Wedge failure along α_I

Plane Failure

Plane failure occurs due to sliding along a single discontinuity. The conditions for sliding are that:

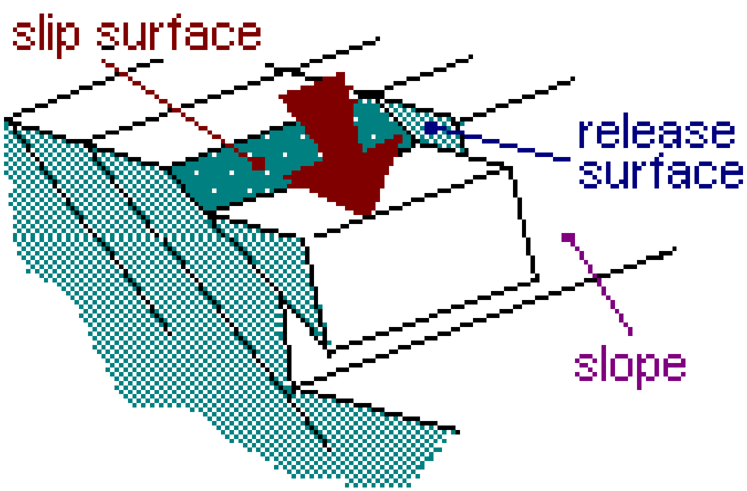
· the strikes of both the sliding plane and the slope face lie parallel (±20°) to each other.

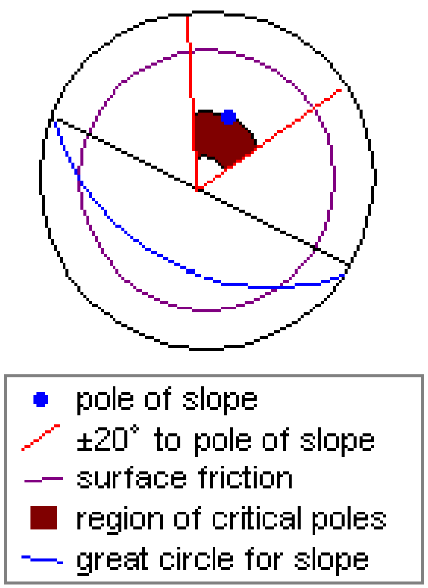
· the failure plane "daylights" on the slope face.

· the dip of the sliding plane is greater than ϕ'.

· the sliding mass is bound by release surfaces of negligible resistance.

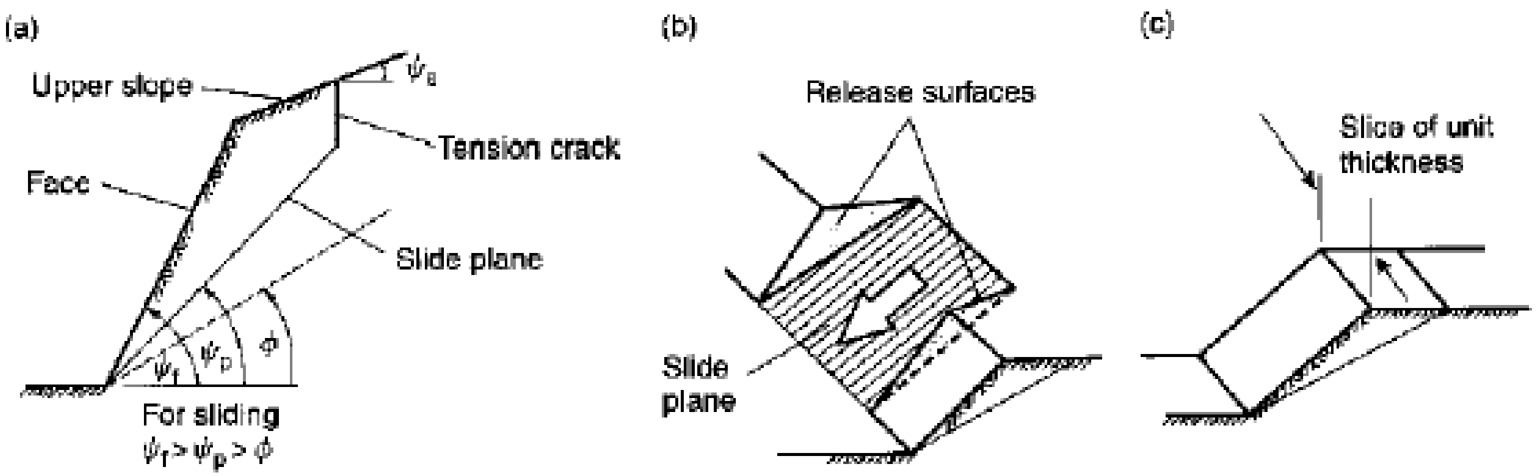
Possible plane failure is suggested by a stereonet plot, if a pole concentration lies close to the pole of the slope surface and in the shaded area corresponding to the above rules.





Planar Failure

(After Hoek & Bray)



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

Concept of FoS

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

$$D = W\sin\beta + V\cos\beta$$

F>D => Wedge in Equilibrium

Factor of Safety FoS=F/D

Planar Failure

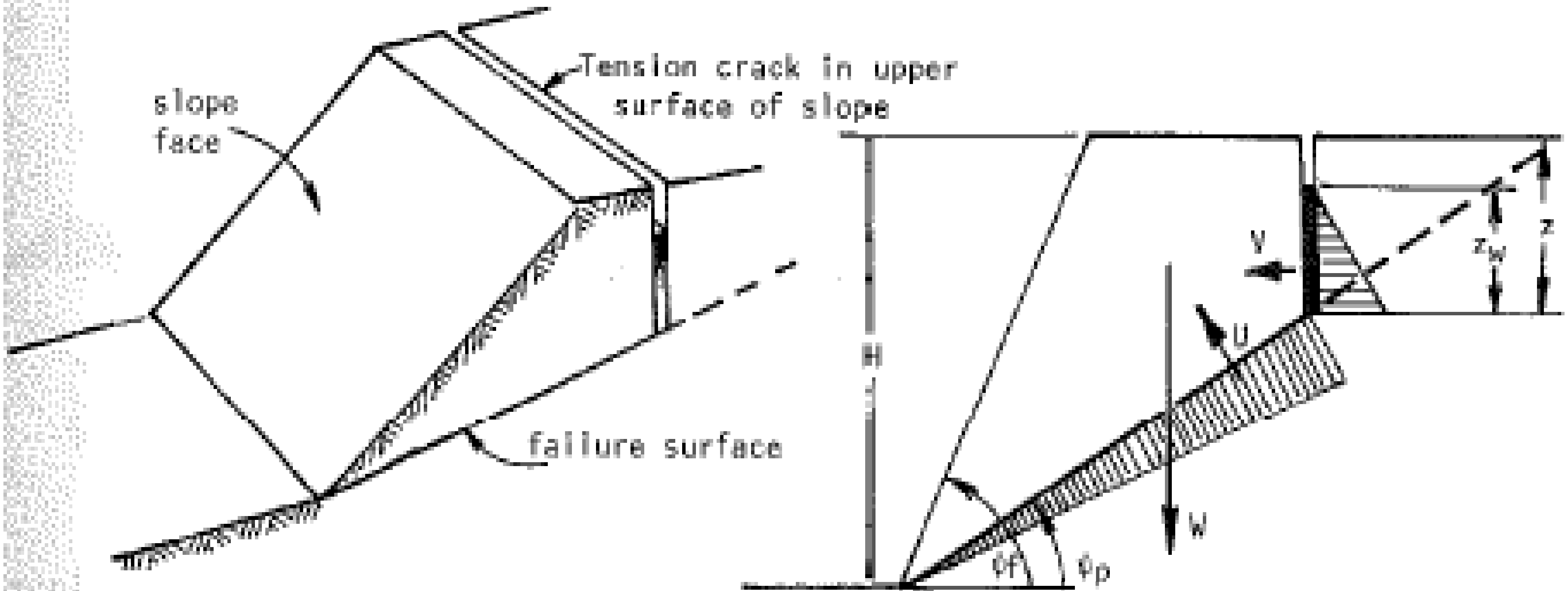


Figure 62a : Geometry of slope with tension crack in upper slope surface.

Planar Failure

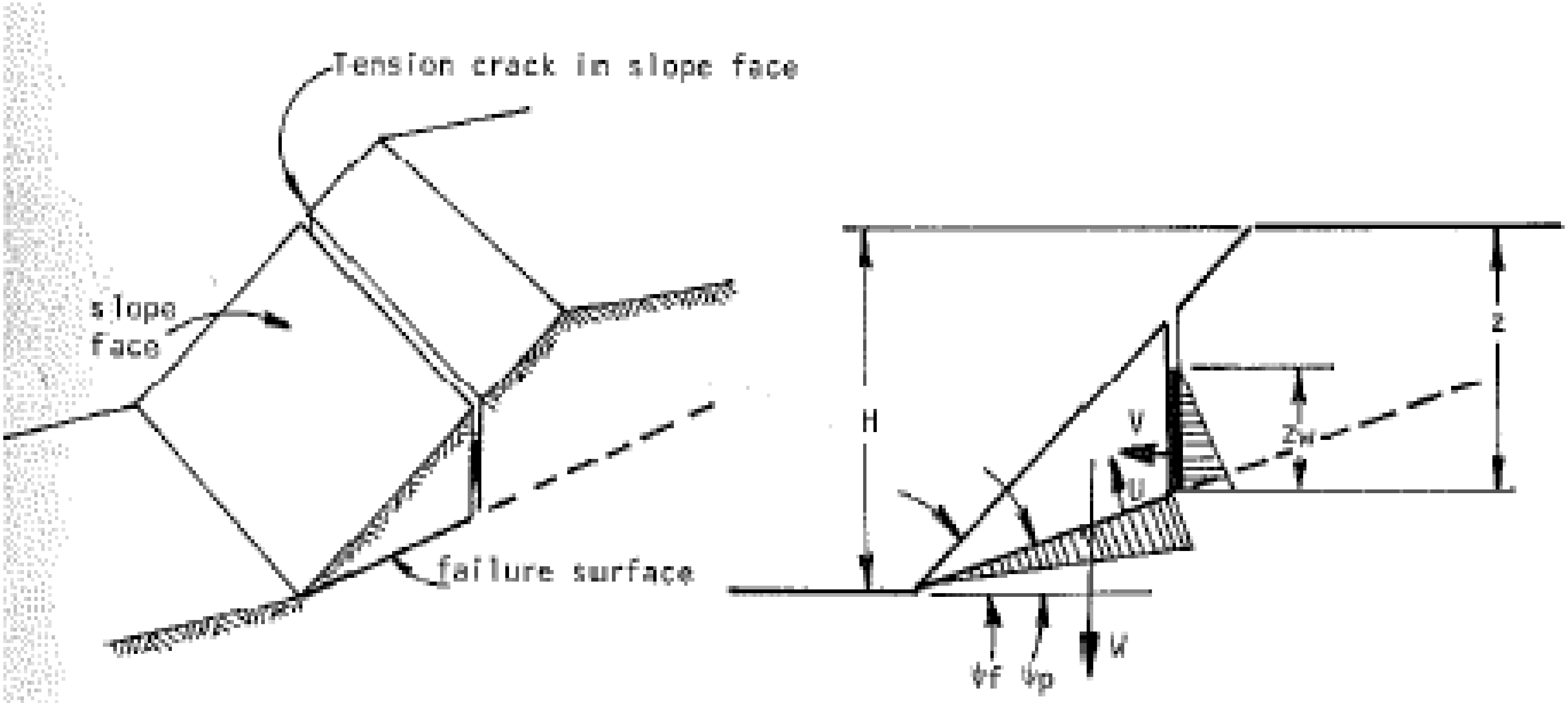
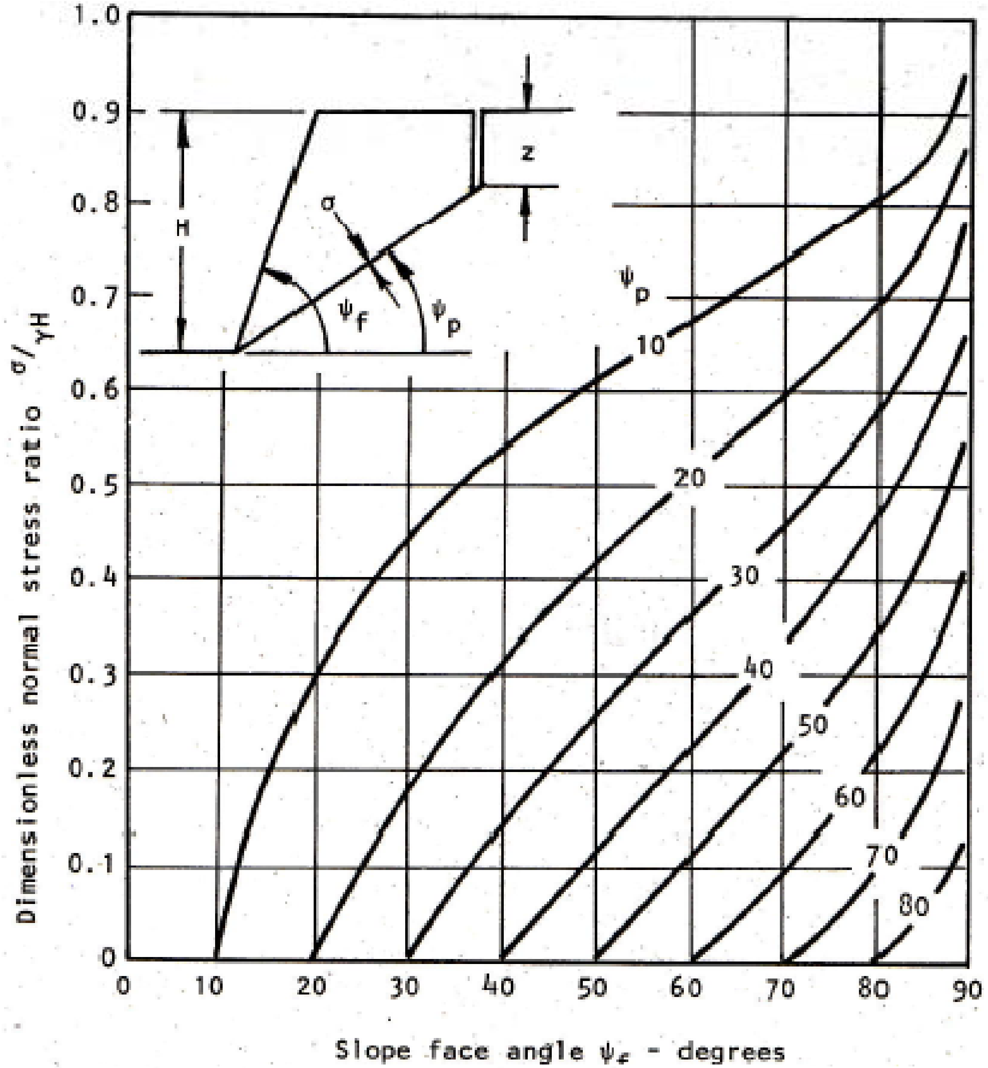


Figure 62b : Geometry of slope with tension crack in slope face.



$$\frac{\sigma}{\gamma H} = \frac{\left((1 - (z/H)^2)\text{Cot}\psi_p - \text{Cot}\psi f\right)\text{Sin}\psi_p}{2(1 - z/H)}$$

where $z/H = 1 - \sqrt{\text{Cot}\psi f.\text{Tan}\psi_p}$ (see page 161)

Figure 63: Normal stress acting on the failure plane in a rock slope.

where, from Figure 62 :

$$A = (H - z).\mathrm{Cosec}\psi_p \tag{43}$$

$$U = \tfrac{1}{2}\gamma_w.\ z_w(H - z).\mathrm{Cosec}\psi_p \tag{44}$$

$$V = \tfrac{1}{2}\gamma_w.z^2_w \tag{45}$$

For the tension crack in the upper slope surface (Figure 62a)

$$W = \tfrac{1}{2}\gamma H^2\left((1 - (z/H)^2)\mathrm{Cot}\psi_p - \mathrm{Cot}\psi_f\right) \tag{46}$$

and, for the tension crack in the slope face (Figure 62b)

$$W = \tfrac{1}{2}\gamma H^2\left((1 - z/H)^2\mathrm{Cot}\psi_p(\mathrm{Cot}\psi_p.\mathrm{Tan}\psi_f - 1)\right) \tag{47}$$

$$F = \frac{(2c/\gamma H).P + \{Q.Cot\psi_p - R(P + S)\}Tan\phi}{Q + R.SCot\psi_p} \qquad (48)$$

where

$$P = (1 - z/H).Cosec\psi_p \qquad (49)$$

When the tension crack is in the upper slope surface :

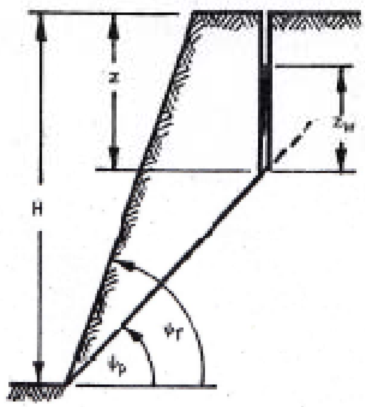
$$Q = \{(1 - (z/H)^2)Cot\psi_p - Cot\psi_f\}Sin\psi_p \qquad (50)$$

When the tension crack is in the slope face :

$$Q = \{(1 - z/H)^2 Cos\psi_p(Cot\psi_p.Tan\psi_f - 1)\} \qquad (51)$$

$$R = \frac{\gamma_w}{\gamma}.\frac{z_w}{z}.\frac{z}{H} \qquad (52)$$

$$S = \frac{z_w}{z}.\frac{z}{H}\,Sin\psi_p \qquad (53)$$



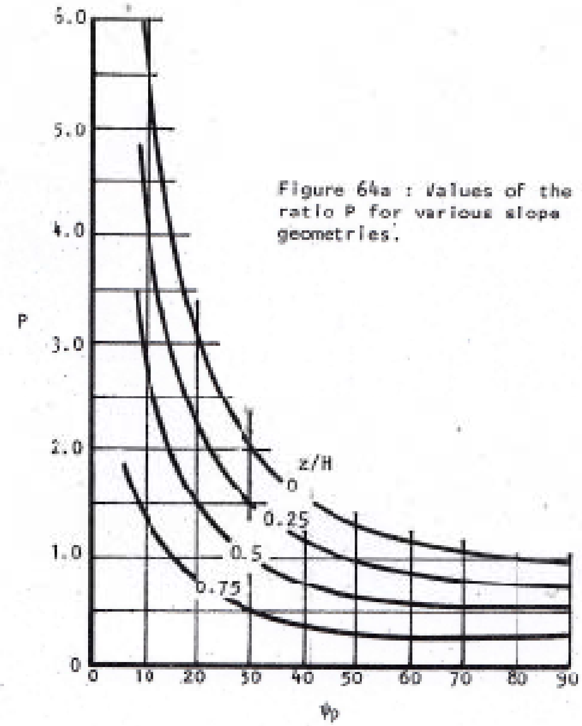


Figure 64a : Values of the ratio P for various slope geometries.

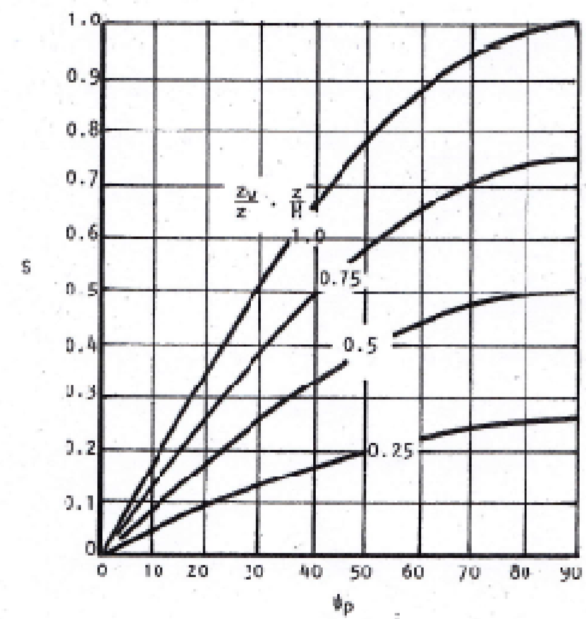


Figure 64b: Values of the ratio S for various geometries

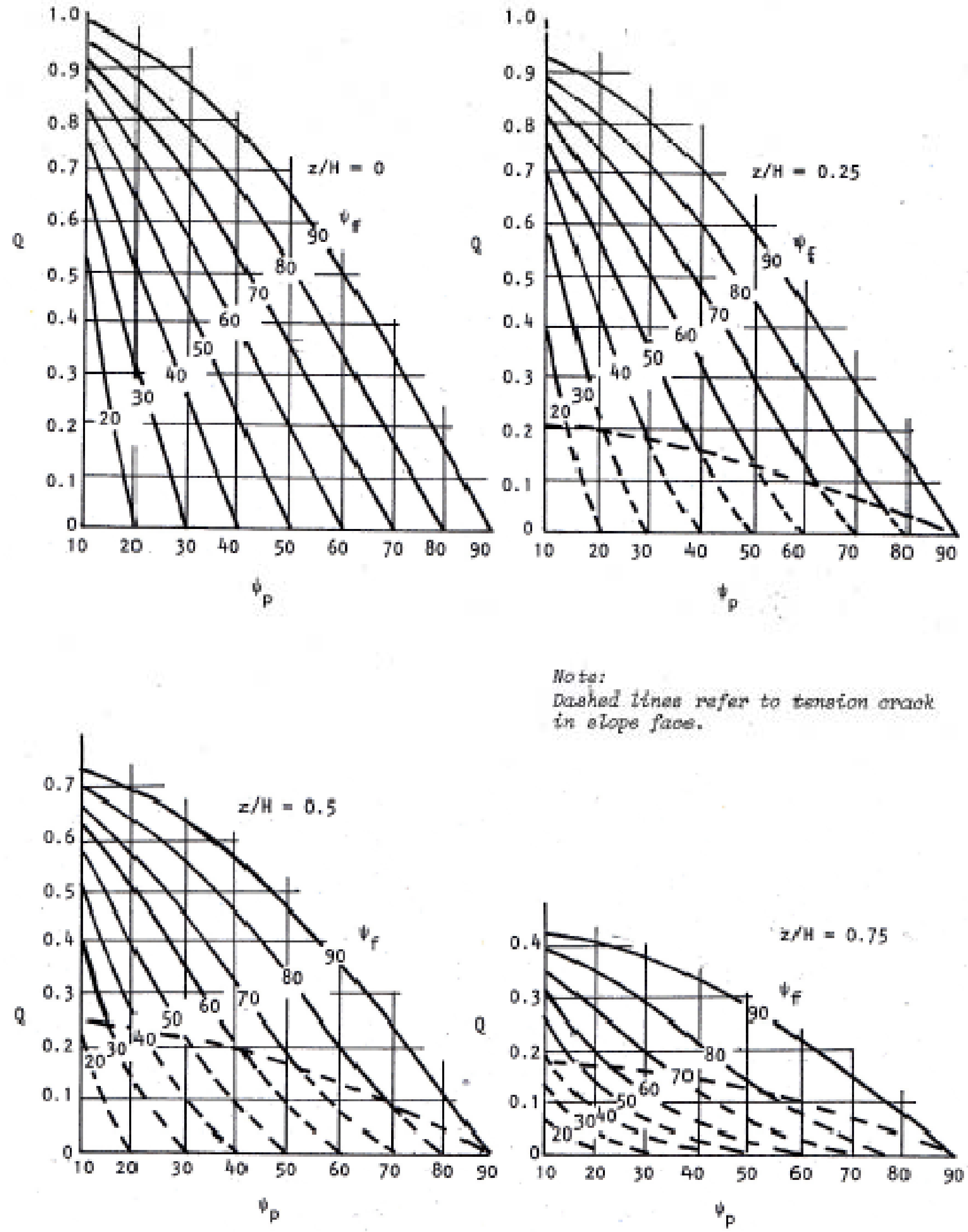
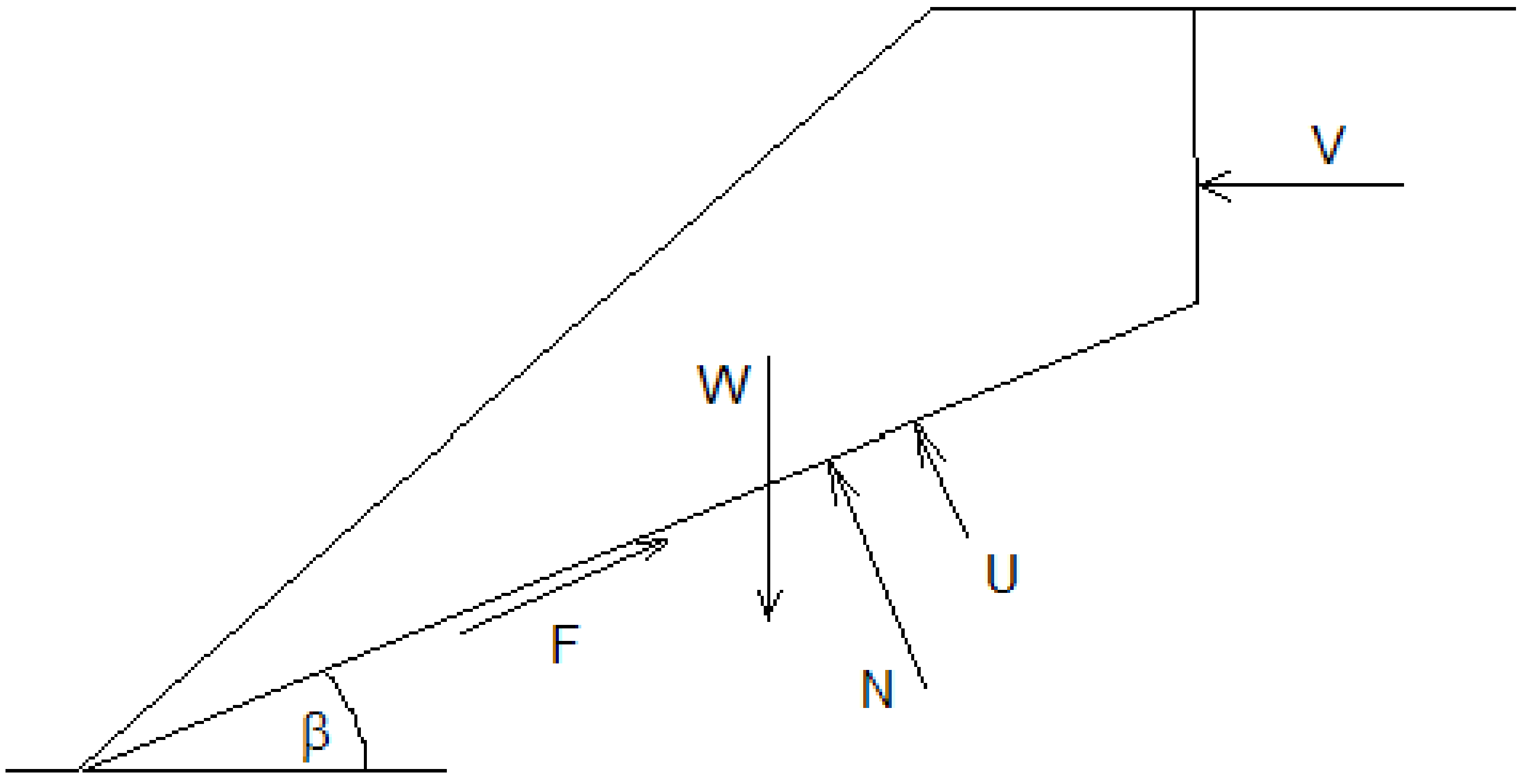
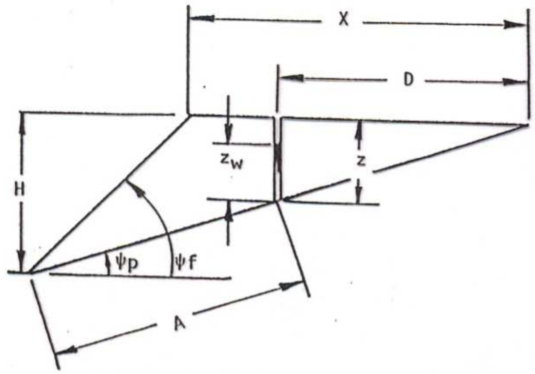


Figure 64c : Value of the ratio Q for various slope geometries.

Equilibrium



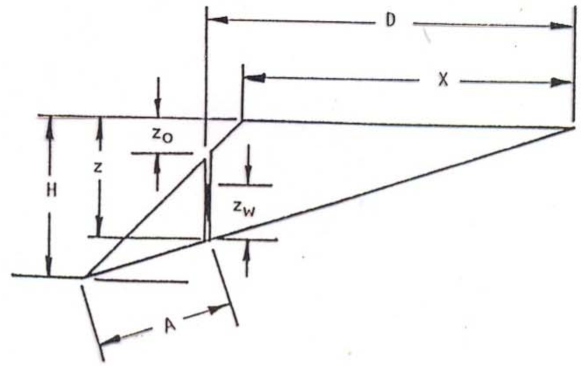


Weight of sliding wedge :

$W = \frac{1}{2}\gamma(HX - Dz)$

Horizontal water force : $V = \frac{1}{2}\gamma_w . z_w^2$

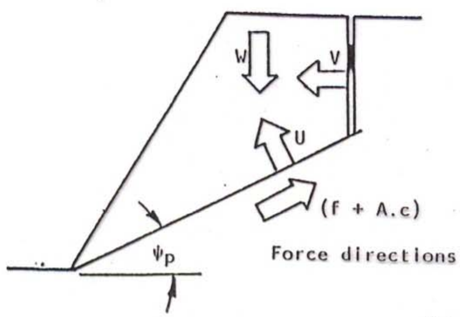
Uplift water force : $U = \frac{1}{2}\gamma_w . z_w . A$



Weight of sliding wedge :

$W = \frac{1}{2}\gamma\left(HX - Dz + z_o(D - X)\right)$

Figure 65a : Slope geometry and equations for calculating forces acting on slope.



$$\text{Factor of safety } F = \frac{f + A.c}{S}$$

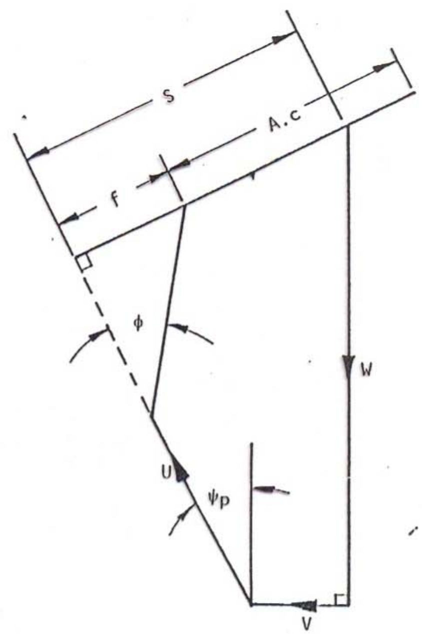


Figure 65b : Force diagram for two-dimensional slope stability analysis.

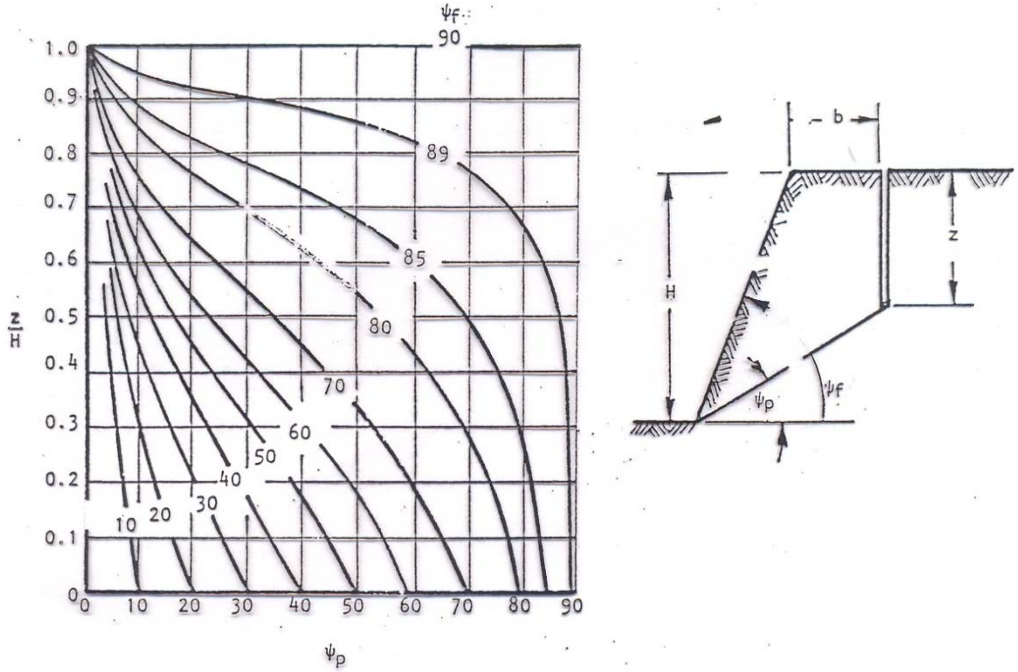


Figure 67a: Critical tension crack depth for a dry slope.

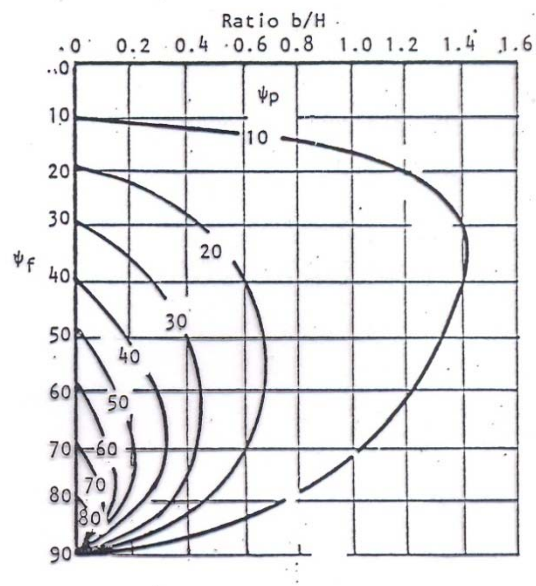
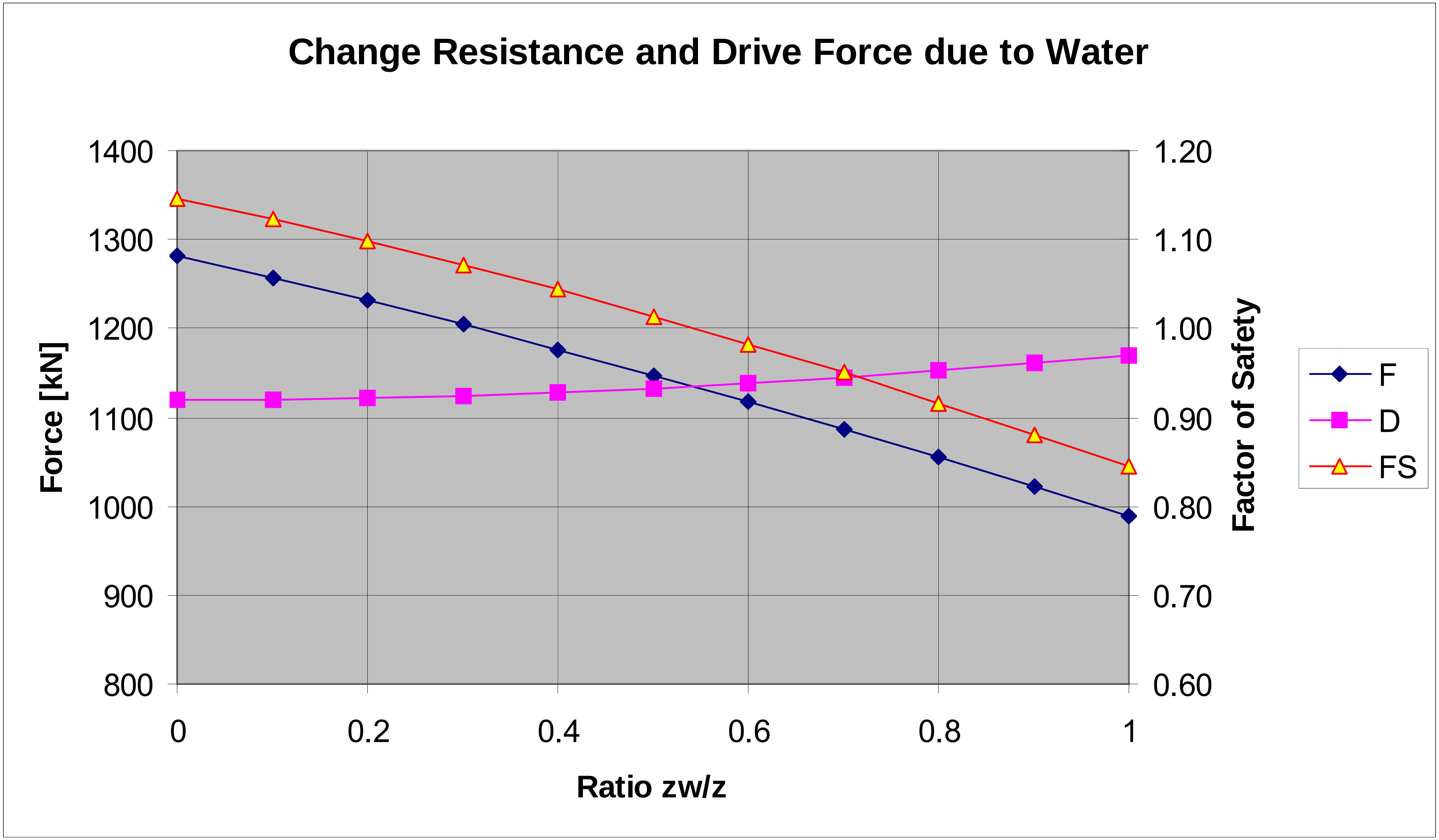


Figure 67b; Critical tension crack location for a dry slope.

Effect of Water on Tension Crack



Example Problem

- A 60 m high slope has an overall face angle of 50^0, made up from three 20 benches with 70^0 faces. The slope is in reasonably fresh granite but several sets of steeply dipping joints are visible and sheet jointing is evident. The rainfall is high and the area is in low seismicity zone (acceleration = 0.08g)

Structural Mapping Details

Features	dip ^{0}	dip direction ^{0}
Overall slope face	50	200
Individual benches	70	200
Sheet Joint	35	190
Joint set 1	80	233
Joint set 2	80	040
Joint set 3	70	325

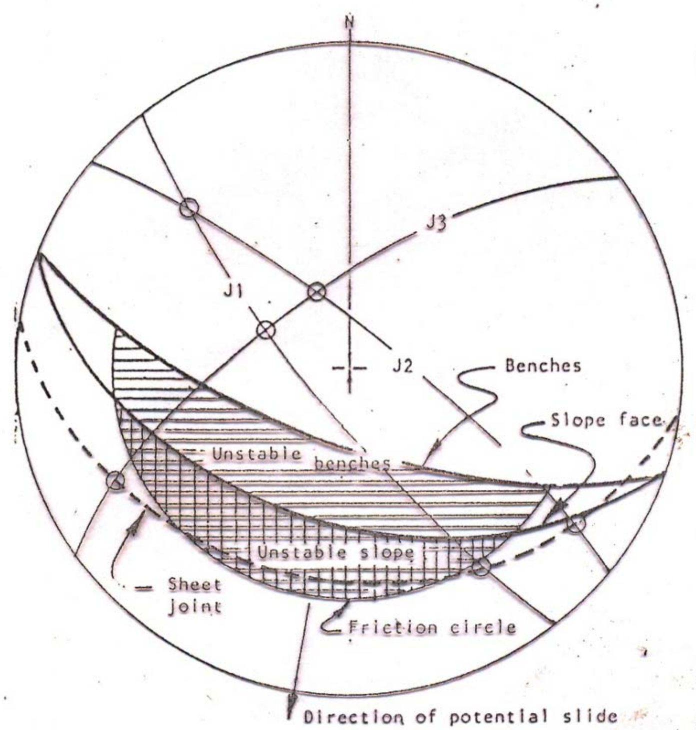
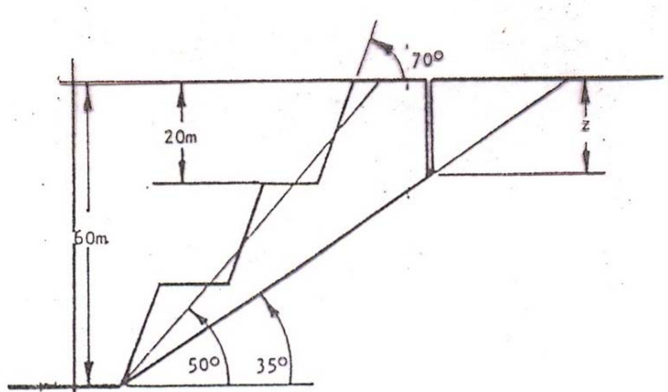
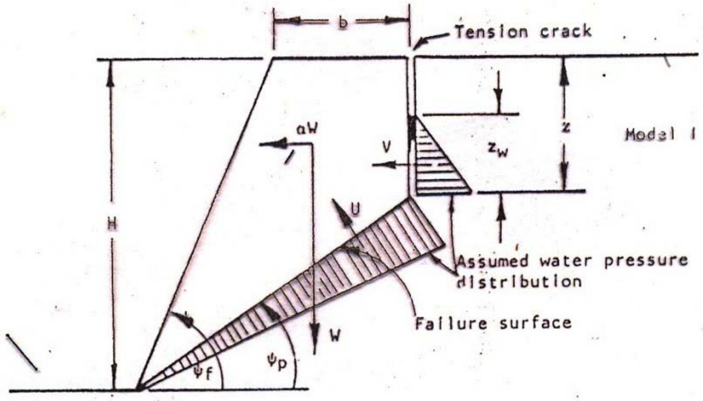


Figure 82 : Stereoplot of geometrical and geological data for example number 3



Typing instructions l:

Figure 83 : Geometry assumed for two-dimensional analysis of the slope defined in Figure 82.



$$F = \frac{cA + (W(\cos\psi_p - \alpha\sin\psi_p) - U - V\sin\psi_p)\tan\phi}{W(\sin\psi_p + \alpha\cos\psi_p) + V\cos\psi_p} \quad (71)$$

Where

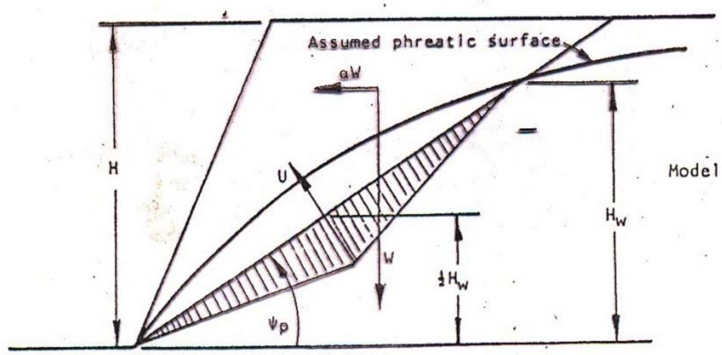
$$z = H(1 - \sqrt{\cot\psi_f . \tan\psi_p}) \quad (58)$$

$$A = (H - z)\ \text{Cosec}\psi_p \quad (43)$$

$$W = \tfrac{1}{2}\gamma H^2((1 - (z/H)^2)\cot\psi_p - \cot\psi_f) \quad (46)$$

$$U = \tfrac{1}{2}\gamma_w . z_w . A \quad (44)$$

$$V = \tfrac{1}{2}\gamma_w . z_w^2 \quad (45)$$



$$F = \frac{cA + (W(\cos\psi_p - \alpha\sin\psi_p) - U)\tan\phi}{W(\sin\psi_p + \alpha\cos\psi_p)} \quad (72)$$

Where

$$U = \tfrac{1}{4}\gamma_w . H_w^2 \text{Cosec}\ \psi_p \quad (73)$$

Figure 84 : Theoretical models for example number 3.

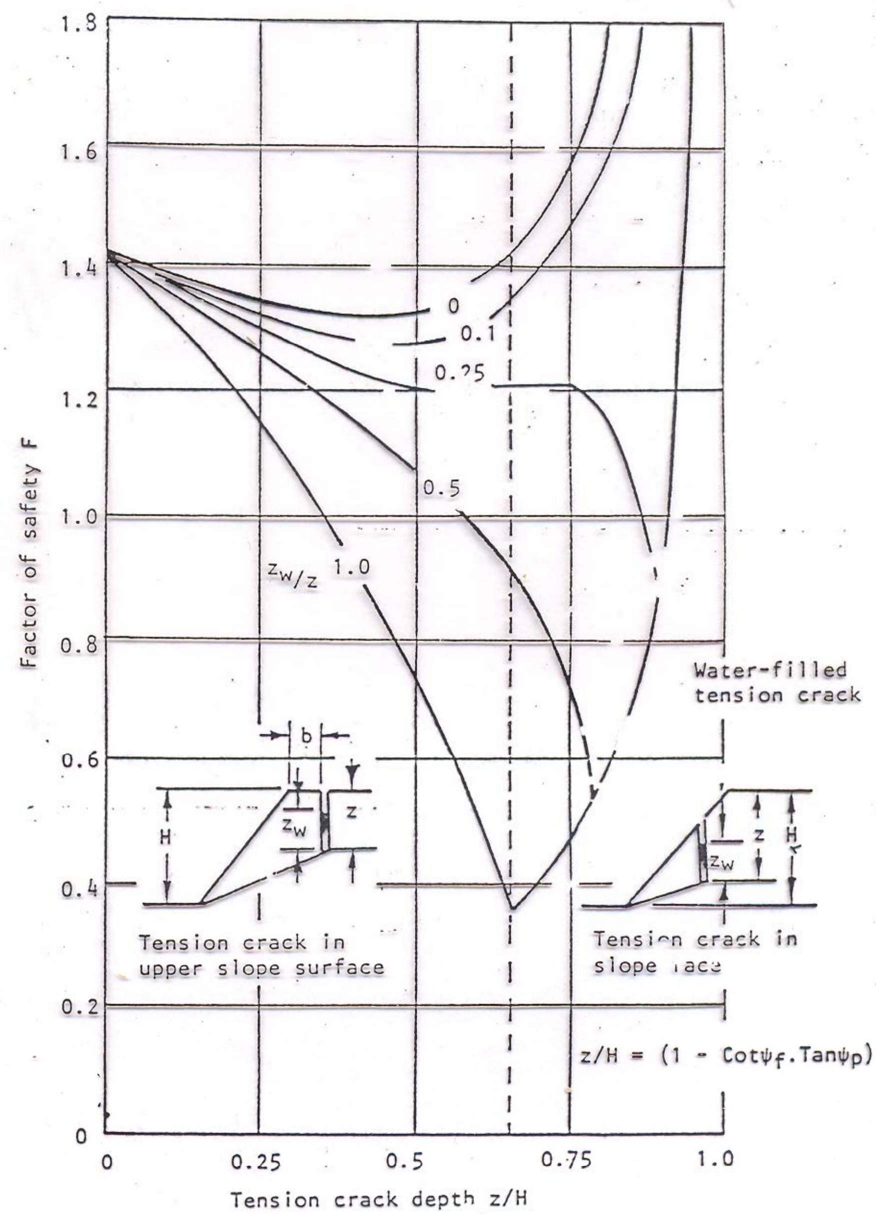


Figure 66 : Influence of tension crack depth and of depth of water in the tension crack upon the factor of safety of a slope. (Slope geometry and material properties as for example on page 154).

Summary of Input data available

• Slope Height	$H = 60$ m
• Overall slope angle	$\psi_f = 50^o$
• Bench face angle	$\psi_f = 70^o$
• Bench height	$H = 20$ m
• Failure plane angle	$\psi_p = 35^o$
• Rock Density	$\gamma = 2.6\ t/m^3$
• Water Density	$\gamma = 1.0\ t/m^3$
• Earthquake acceleration	$\alpha = 0.08g$

Conditions of analysis

- 1- Overall slope, Model I, dry z_w =0.
- 2- Overall slope, Model I, saturated, z_w = z = 14 m.
- 3- Overall slope Model II, dry, H_w=0
- 4- Overall slope, Model II, saturated, H_w= H = 60 m.

- 5- Individual bench, Model I, dry z_w =0.
- 6- Individual bench, Model I, saturated, z_w = z = 9.9 m.
- 7- Individual bench Model II, dry, H_w=0
- 8- Individual bench, Model II, saturated, H_w= H = 20 m.

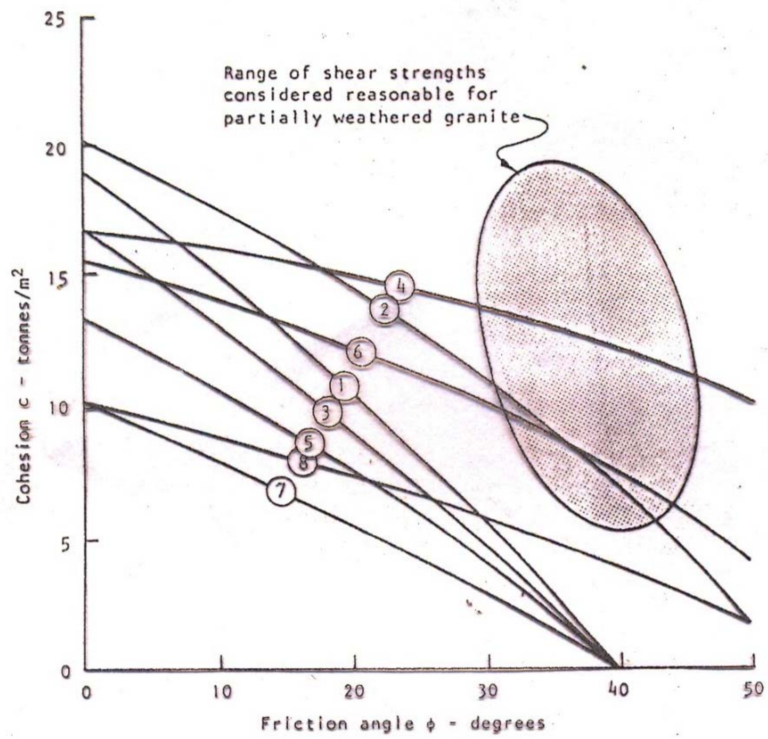


Figure 85 : Shear strength mobilised for failure of slope considered in practical example number 3.

its stability.

Four basic methods for improving the stability of the slope can be considered. These methods are the following :

a. Reduction of slope height.
b. Reduction of slope face inclination.
c. Drainage of slope.
d. Reinforcement of slope with bolts and cables.

In order to compare the effectiveness of these different methods, it is assumed that the sheet joint surface has a cohesive strength of 10 tonnes/m^2 and a friction angle of 35°. The increase in factor of safety for a reduction in slope height, slope angle and water level can be found by altering one of these variables at a time in equations 71 and 72. The influence of reinforcing the slope is obtained by modifying these equations as in equations 78 and 79 on page 188.

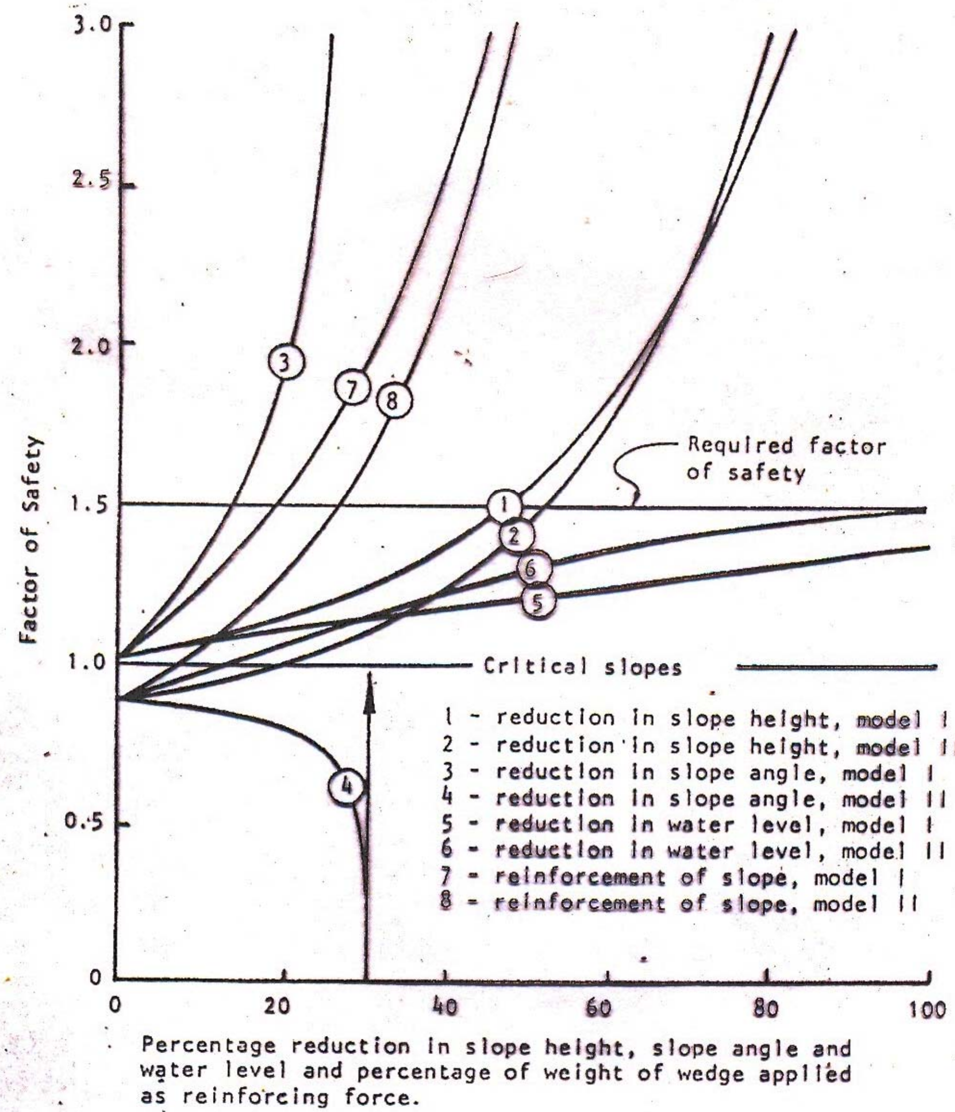


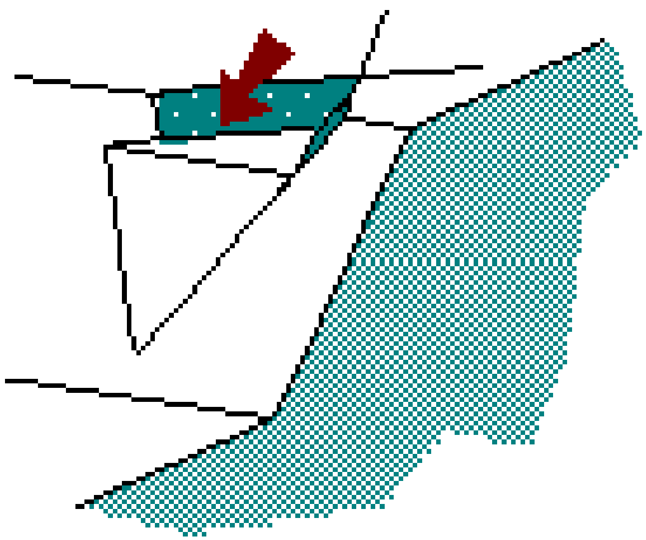
Figure 86 : Comparison between alternative methods of increasing stability of overall slope considered in example 3.

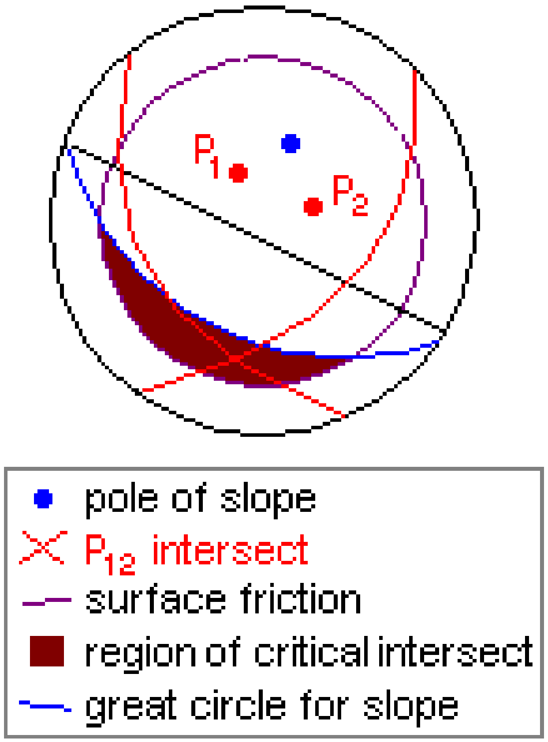
Wedge Analysis

- Similar to planar failure
- Wedge considered as a rigid block
- Resistance forces controlled by joint strength
- Actual orientation of the joints is included in the analysis
- Actual location is not considered at bench scale (maximum possible wedge)

Wedge

Wedge failure occurs due to sliding along a combination of discontinuities. The conditions for sliding require that ϕ is overcome,
and that the intersection of the discontinuities "daylights" on the slope surface. On the stereonet plot these conditions are indicated by the intersection of two discontinuity great circles within the shaded crescent formed by the friction angle and the slope's great circle. Note that this intersection can also be located by finding the pole P_{12} of the great circle which passes through the pole concentrations P_1 and P_2.





Wedge Stability Analysis

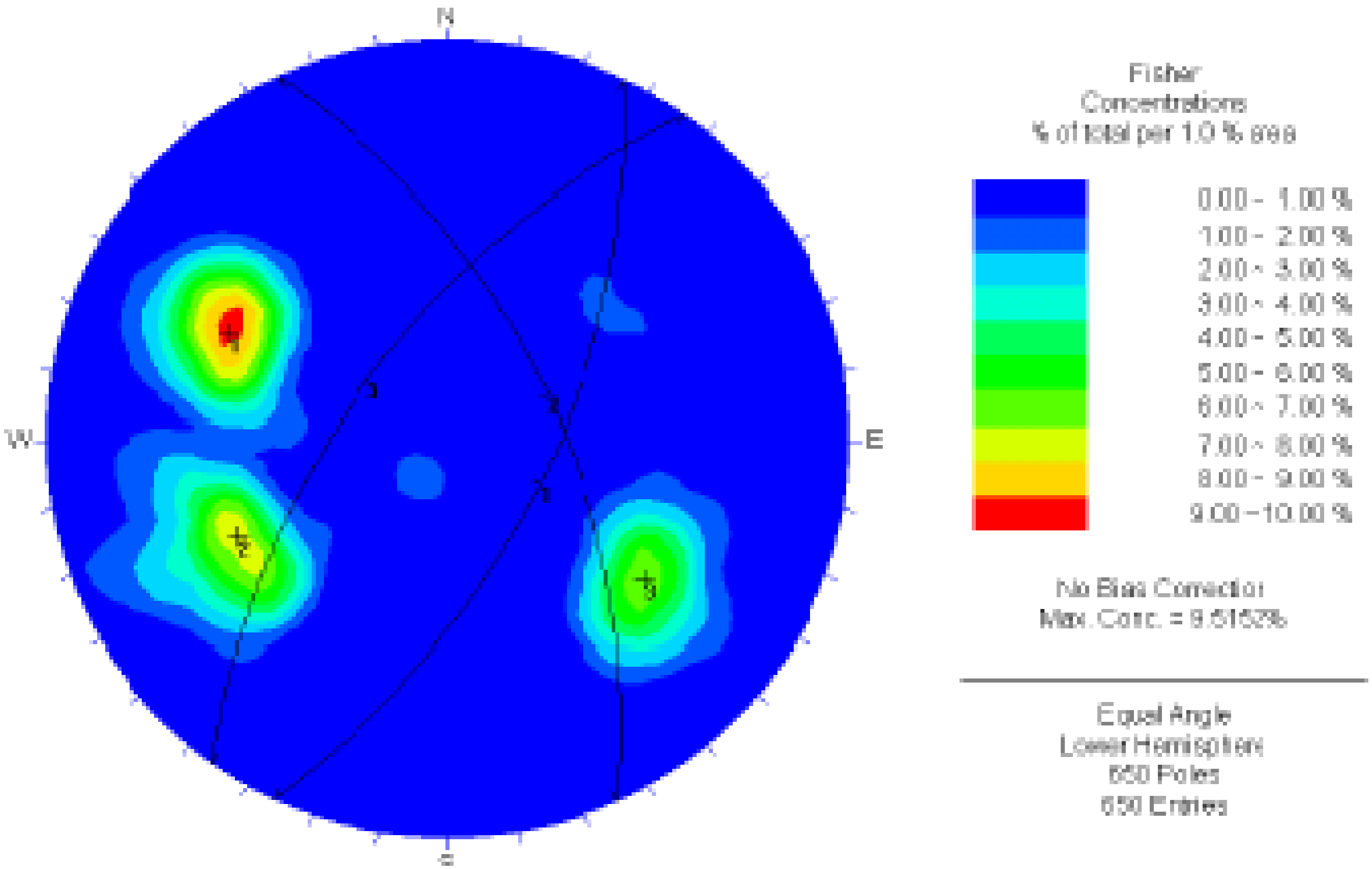
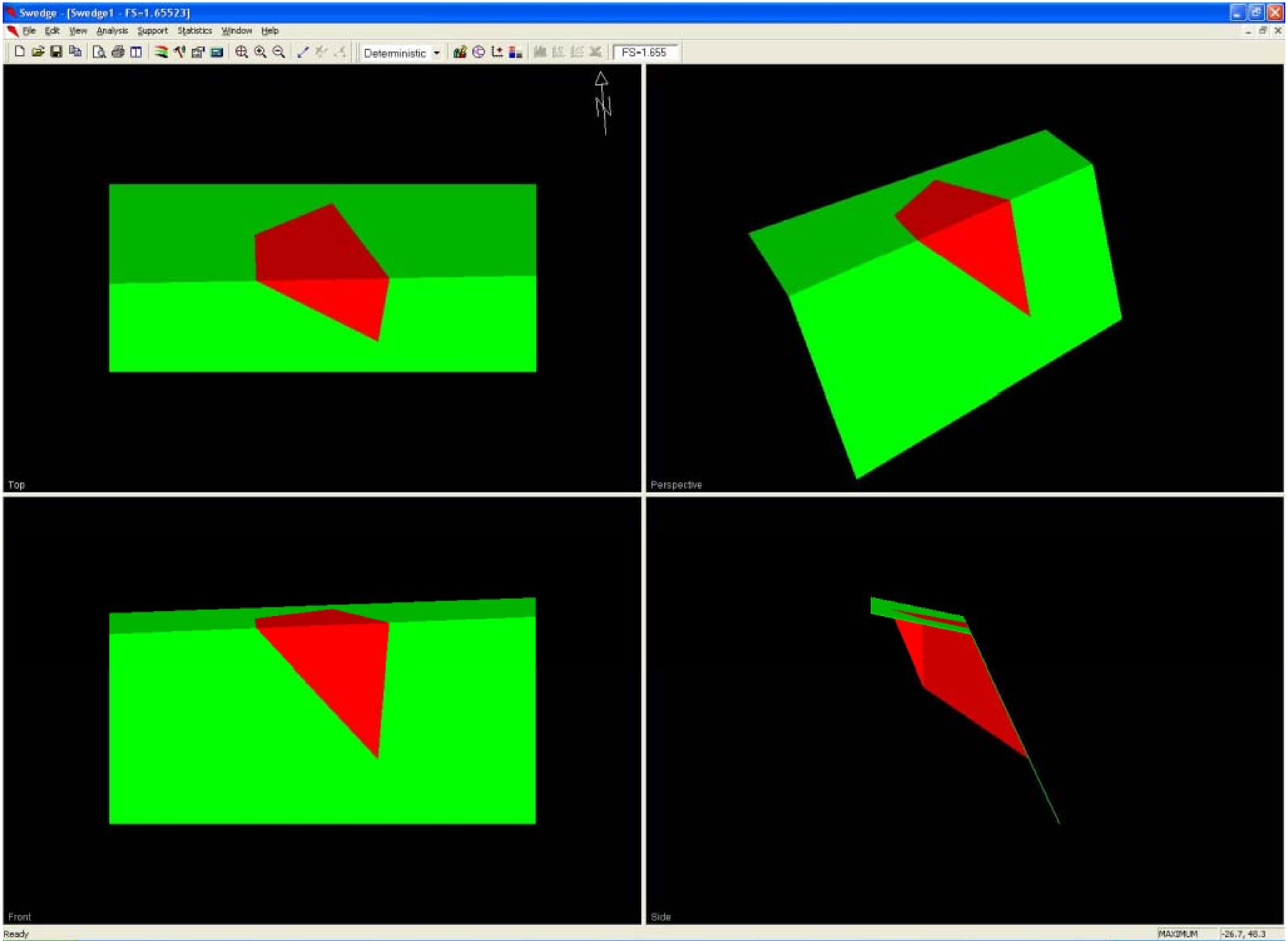


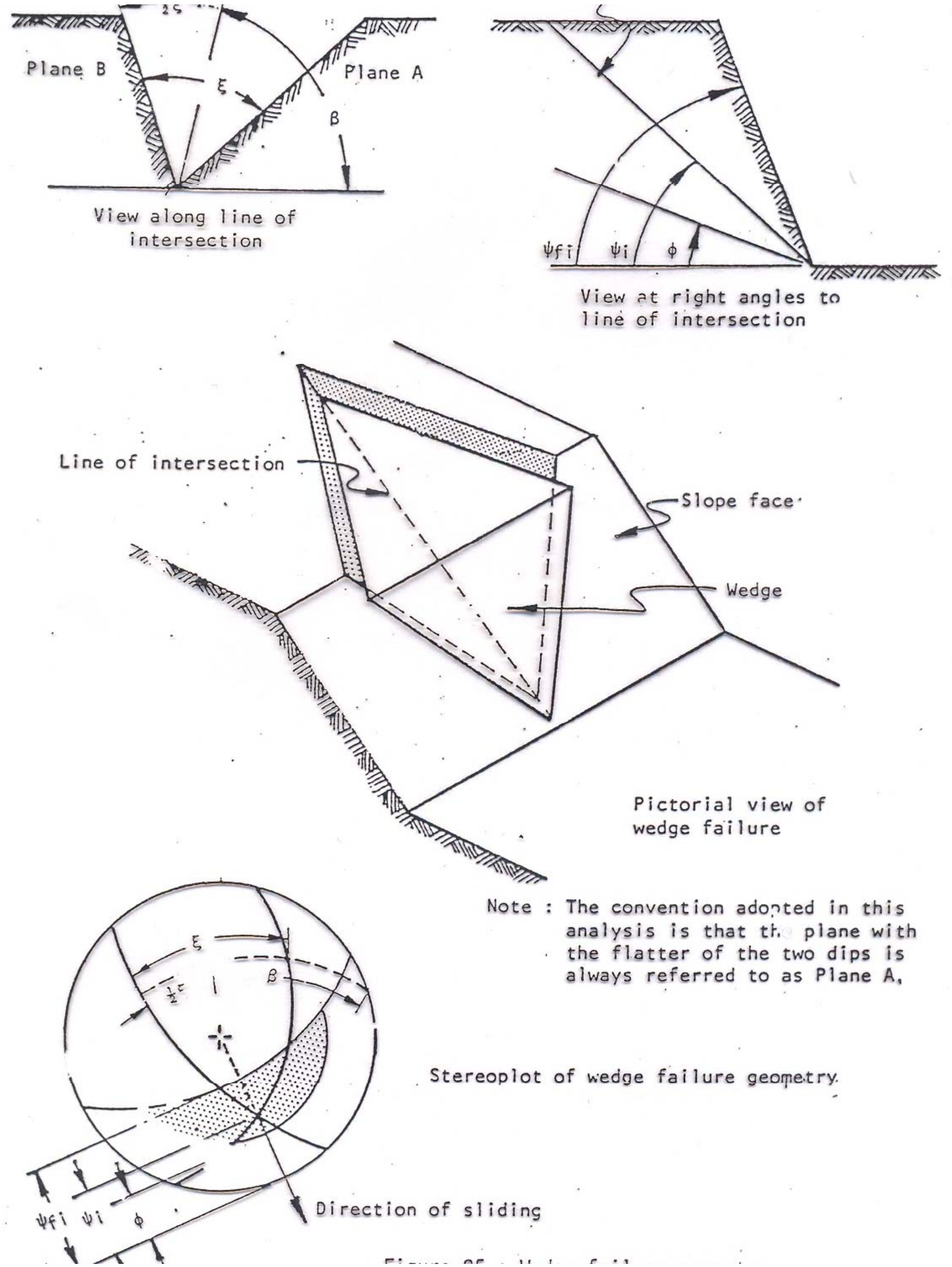
Figure 1.5: Plot of structural features using the program DIPS.



Swedge - [Swedge1 - FS=1.65523]
File Edit View Analysis Support Statistics Window Help
Deterministic
FS=1.655
N
Top
Perspective
Front
Side
Ready
MAXIMUM
-26.7, 48.3

Wedge Analysis

- In general applied to small scale
- Some times applied to large scale where faults define a wedge
- In mining the main objective is define the spill berm width (SBW) for falling rocks and small failures
- In civil slope design the main objective is identify the unstable wedge and support it



Plane B
ξ
Plane A
β
View along line of intersection
ψfi
ψi
φ
View at right angles to line of intersection
Line of intersection
Slope face
Wedge
Pictorial view of wedge failure
Note : The convention adopted in this analysis is that the plane with the flatter of the two dips is always referred to as Plane A,
ξ
β
Stereoplot of wedge failure geometry
ψfi ψi φ
Direction of sliding

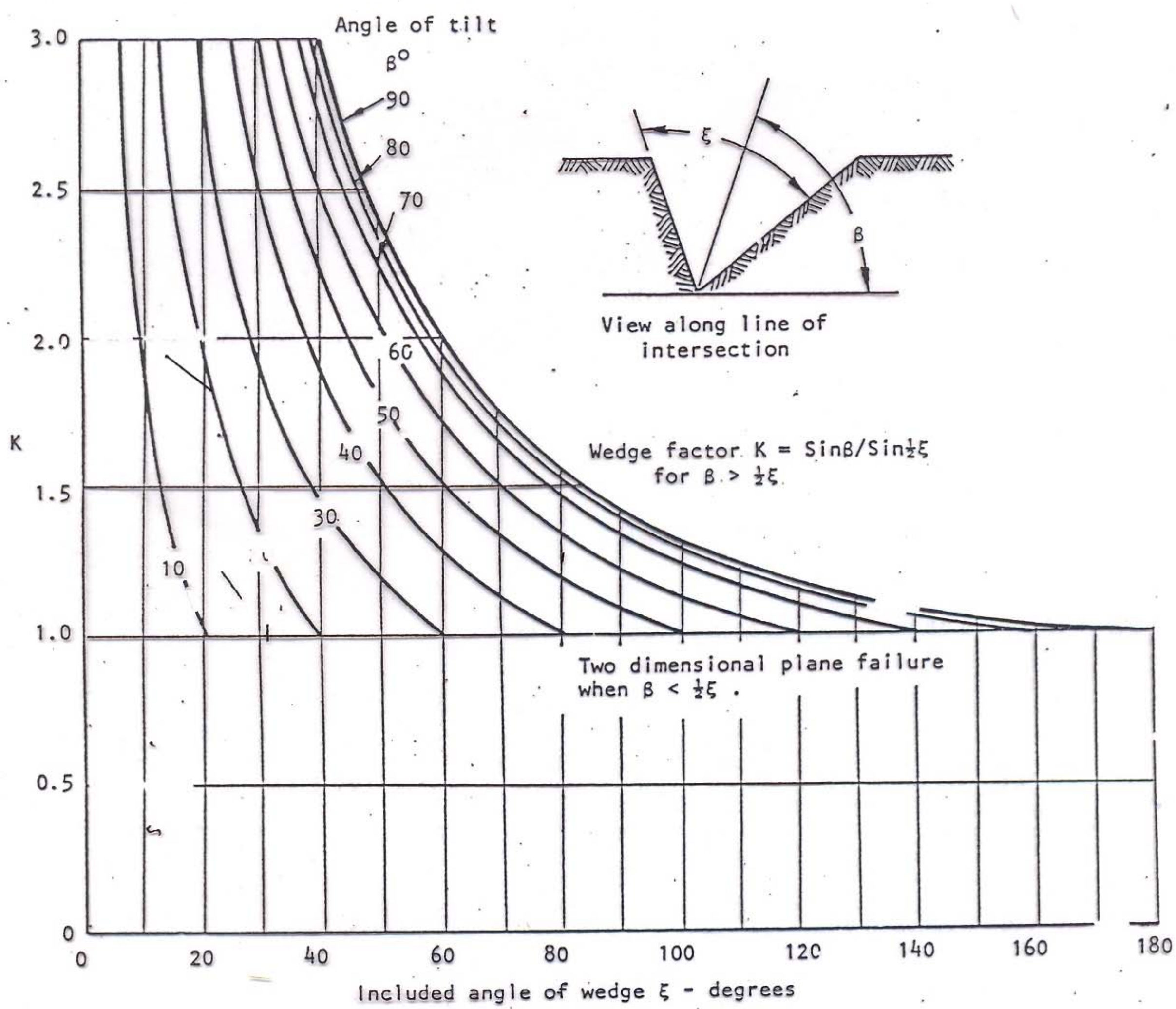
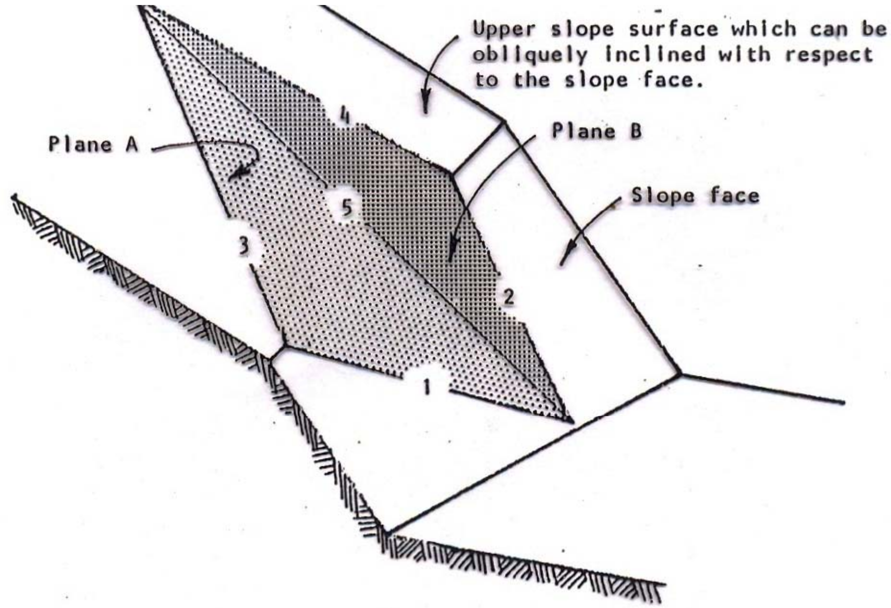
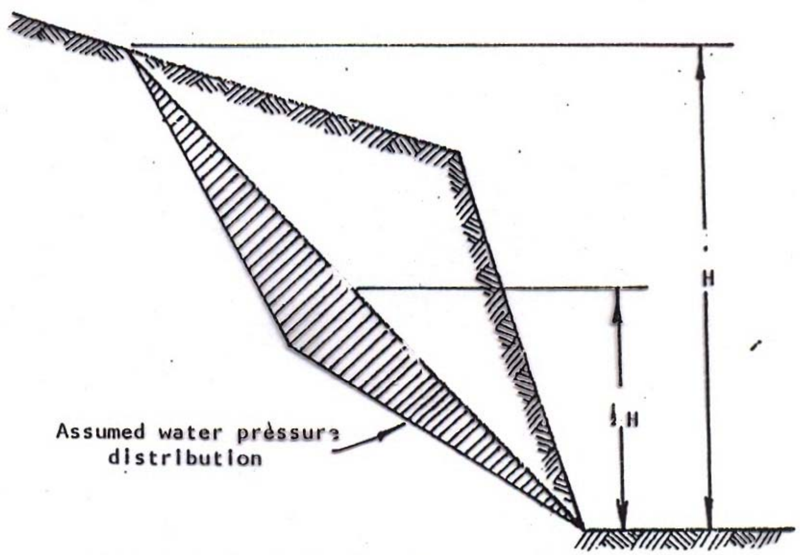


Figure 96 : Wedge factor K as a function of wedge geometry.



a. Pictorial view of wedge showing the numbering of intersection lines and planes.

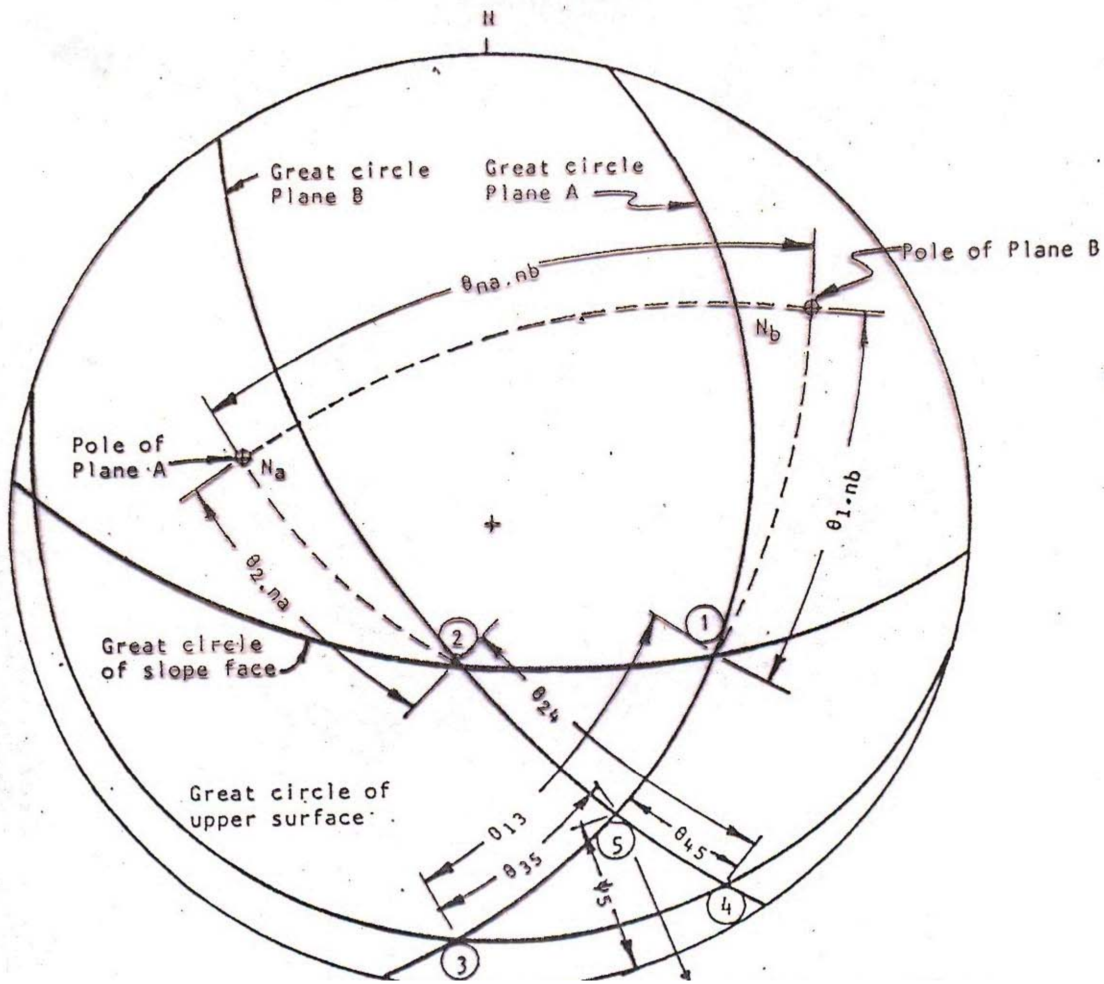


b. View normal to the line of intersection 5 showing the

Plane	dip°	dip direction	Properties
A	45	105	$\phi_A=20^o$, $c_A= 500 lb/ft^2$
B	70	235	$\phi_B=30^o$, $c_B= 1000 lb/ft^2$
Slope face	65	185	$\gamma=160 lb/ft^3$
Upper surface	12	195	$\gamma_w= 62.5 lb/ft^3$

The total height of the wedge H = 130 feet.

The stereoplot of the great circles representing the four planes involved in this problem is presented in Figure 98 and all the angles required for the solution of equations 92 to 95 are marked in this figure.



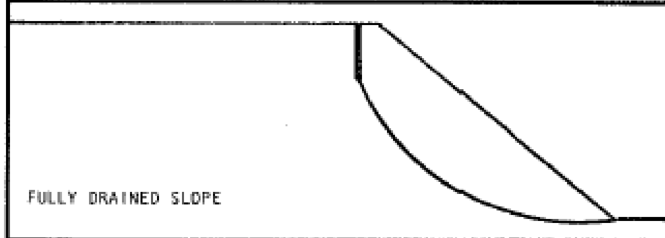
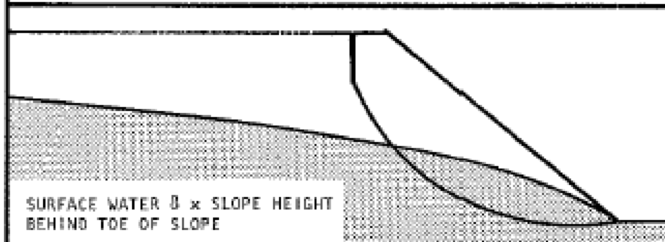
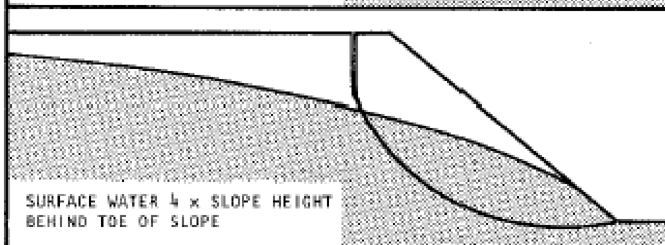
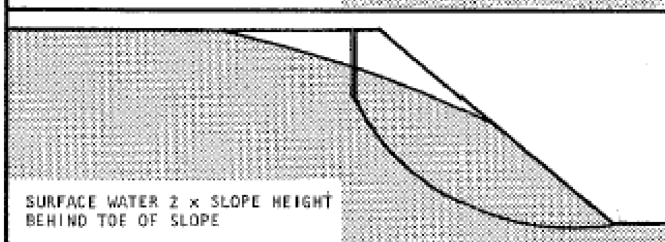
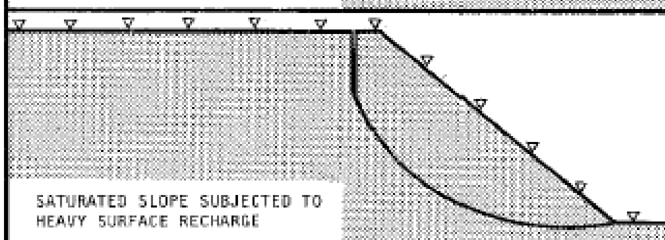
WEDGE STABILITY CALCULATION SHEET

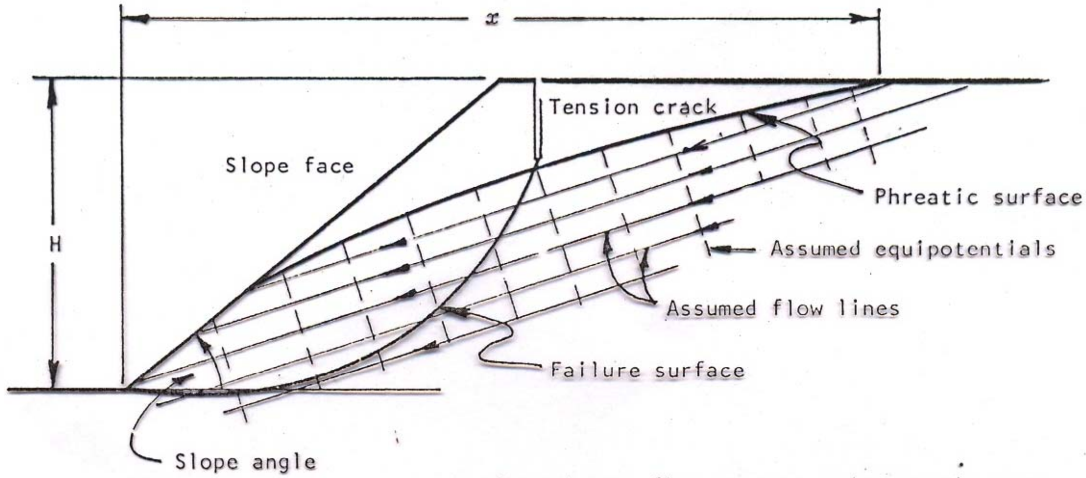
INPUT DATA	FUNCTION VALUE	CALCULATED ANSWER
$\psi_a = 45^o$ $\psi_b = 70^o$ $\psi_5 = 31.2^o$ $\theta_{na.nb} = 101^o$	$\text{Cos } \psi_a = 0.7071$ $\text{Cos } \psi_b = 0.3420$ $\text{Sin } \psi_5 = 0.5180$ $\text{Cos } \theta_{na.nb} = -0.191$ $\text{Sin } \theta_{na.nb} = 0.982$	$A = \dfrac{\text{Cos}\psi_a - \text{Cos}\psi_b.\text{Cos}\theta_{na.nb}}{\text{Sin}\psi_5.\text{Sin}^2\theta_{na.nb}} = \dfrac{0.7071 + 0.342 \times 0.191}{0.5180 \times 0.9636} = 1.5475$ $B = \dfrac{\text{Cos}\psi_b - \text{Cos}\psi_a.\text{Cos}\theta_{na.nb}}{\text{Sin}\psi_5.\text{Sin}^2\theta_{na.nb}} = \dfrac{0.3420 + 0.7071 \times 0.191}{0.5180 \times 0.9636} = 0.9557$
$\theta_{24} = 65^o$ $\theta_{45} = 25^o$ $\theta_{2.na} = 50^o$	$\text{Sin } \theta_{24} = 0.9063$ $\text{Sin } \theta_{45} = 0.4226$ $\text{Cos } \theta_{2.na} = 0.6428$	$X = \dfrac{\text{Sin}\theta_{24}}{\text{Sin}\theta_{45}.\text{Cos}\theta_{2.na}} = \dfrac{0.9063}{0.4226 \times 0.6428} = 3.3363$
$\theta_{13} = 62^o$ $\theta_{35} = 31^o$ $\theta_{1.nb} = 60^o$	$\text{Sin } \theta_{13} = 0.8829$ $\text{Sin } \theta_{35} = 0.5150$ $\text{Cos } \theta_{1.nb} = 0.5000$	$Y = \dfrac{\text{Sin}\theta_{13}}{\text{Sin}\theta_{35}.\text{Cos}\theta_{1.nb}} = \dfrac{0.8829}{0.5150 \times 0.500} = 3.4287$
$\phi_A = 30^o$ $\phi_B = 20^o$ $\gamma = 160 \text{ lb/ft}^3$ $\gamma_w = 62.5 \text{ lb/ft}^3$ $c_A = 500 \text{ lb/ft}^2$ $c_B = 1000 \text{ lb/ft}^2$ $H = 130 \text{ ft}$	$\text{Tan } \phi_A = 0.5773$ $\text{Tan } \phi_B = 0.3640$ $\gamma_w/2\gamma = 0.1953$ $3c_A/\gamma H = 0.0721$ $3c_B/\gamma H = 0.1442$	$F = \dfrac{3c_A}{\gamma H}.X + \dfrac{3c_B}{\gamma H}.Y + (A - \dfrac{\gamma_w}{2\gamma} \cdot X)\text{Tan}\phi_A + (B - \dfrac{\gamma_w}{2\gamma} \cdot Y)\text{Tan}\phi_B$ $F = 0.2405 + 0.4944 + 0.8934 - 0.3762 + 0.3478 - 0.2437 = 1.3562$

Circular Failure

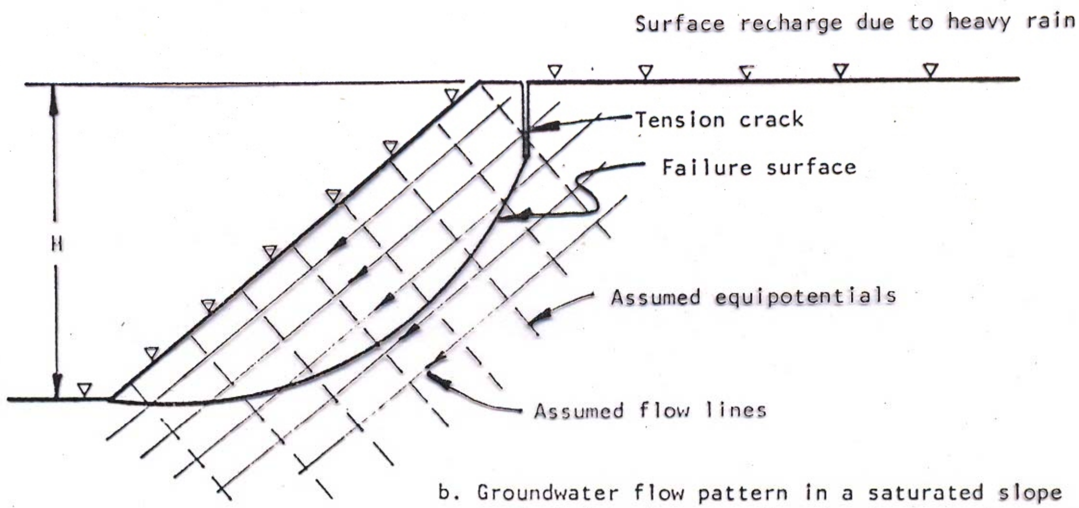
- The mechanical properties of the slope material is assumed to be homogeneous.
- The shear strength is given by Mohr Coulomb Equation.
- Failure surface is circular passing through the toe.
- A vertical tension crack is present.
- The location of tension crack and failure surface is critical and gives least FOS.
- The ground water conditions are as assumed.

Hoek Chart

GROUNDWATER FLOW CONDITIONS	CHART NUMBER
 FULLY DRAINED SLOPE	1
 SURFACE WATER 8 x SLOPE HEIGHT BEHIND TOE OF SLOPE	2
 SURFACE WATER 4 x SLOPE HEIGHT BEHIND TOE OF SLOPE	3
 SURFACE WATER 2 x SLOPE HEIGHT BEHIND TOE OF SLOPE	4
 SATURATED SLOPE SUBJECTED TO HEAVY SURFACE RECHARGE	5



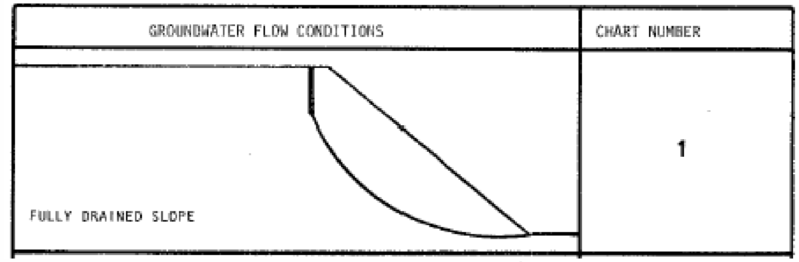
a. Groundwater flow pattern under steady state drawdown conditions where the phreatic surface coincides with the ground surface at a distance x behind the toe of the slope. The distance x is measured in multiples of the slope height H.

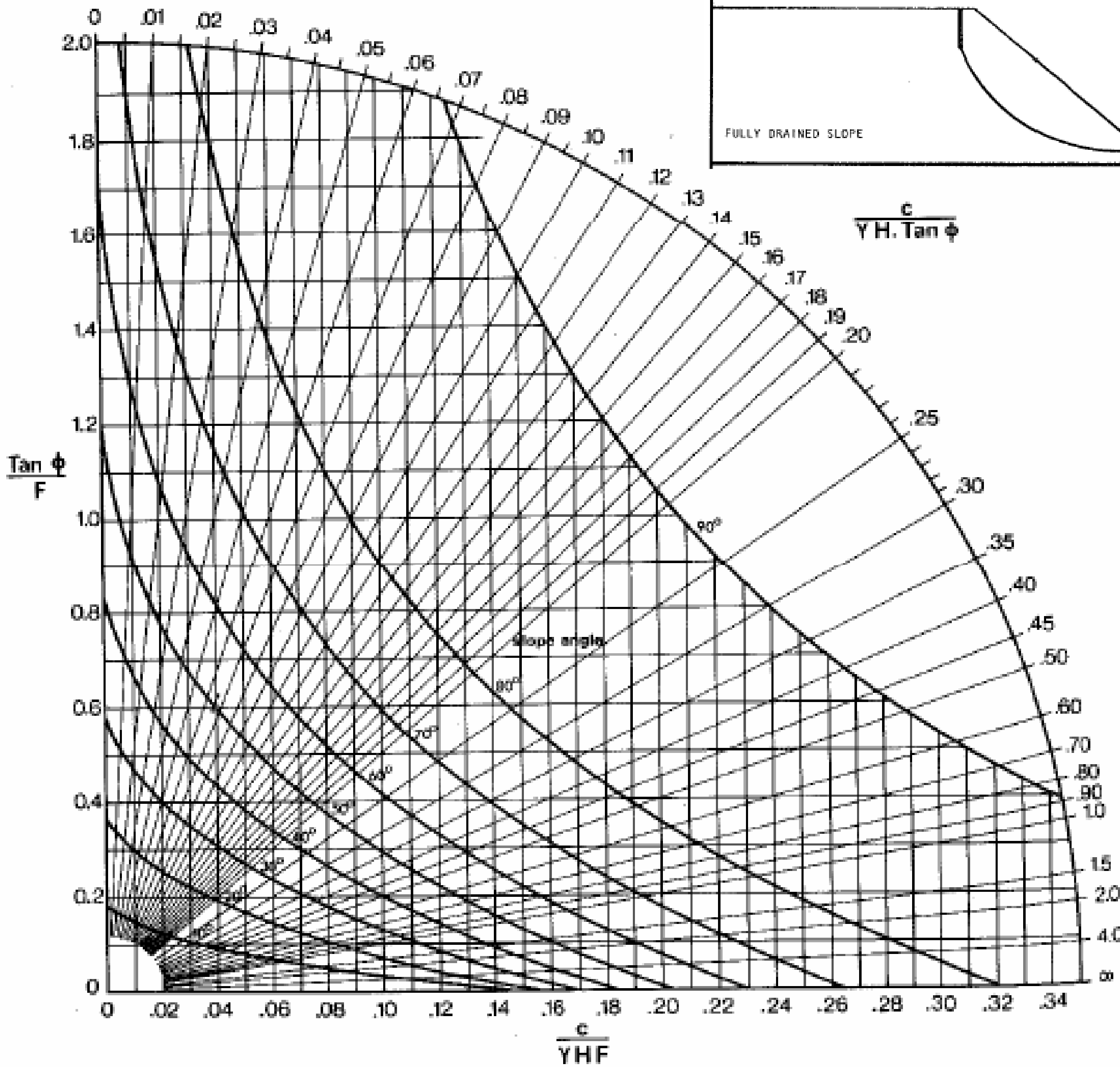


b. Groundwater flow pattern in a saturated slope subjected to heavy surface recharge by heavy rain.

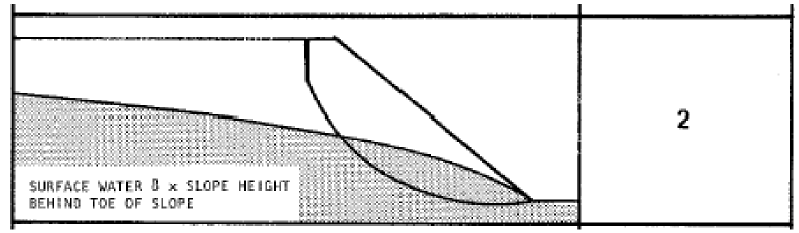
Figure 104 : Definition of groundwater flow patterns used in circular failure analysis of soil and waste rock slopes.

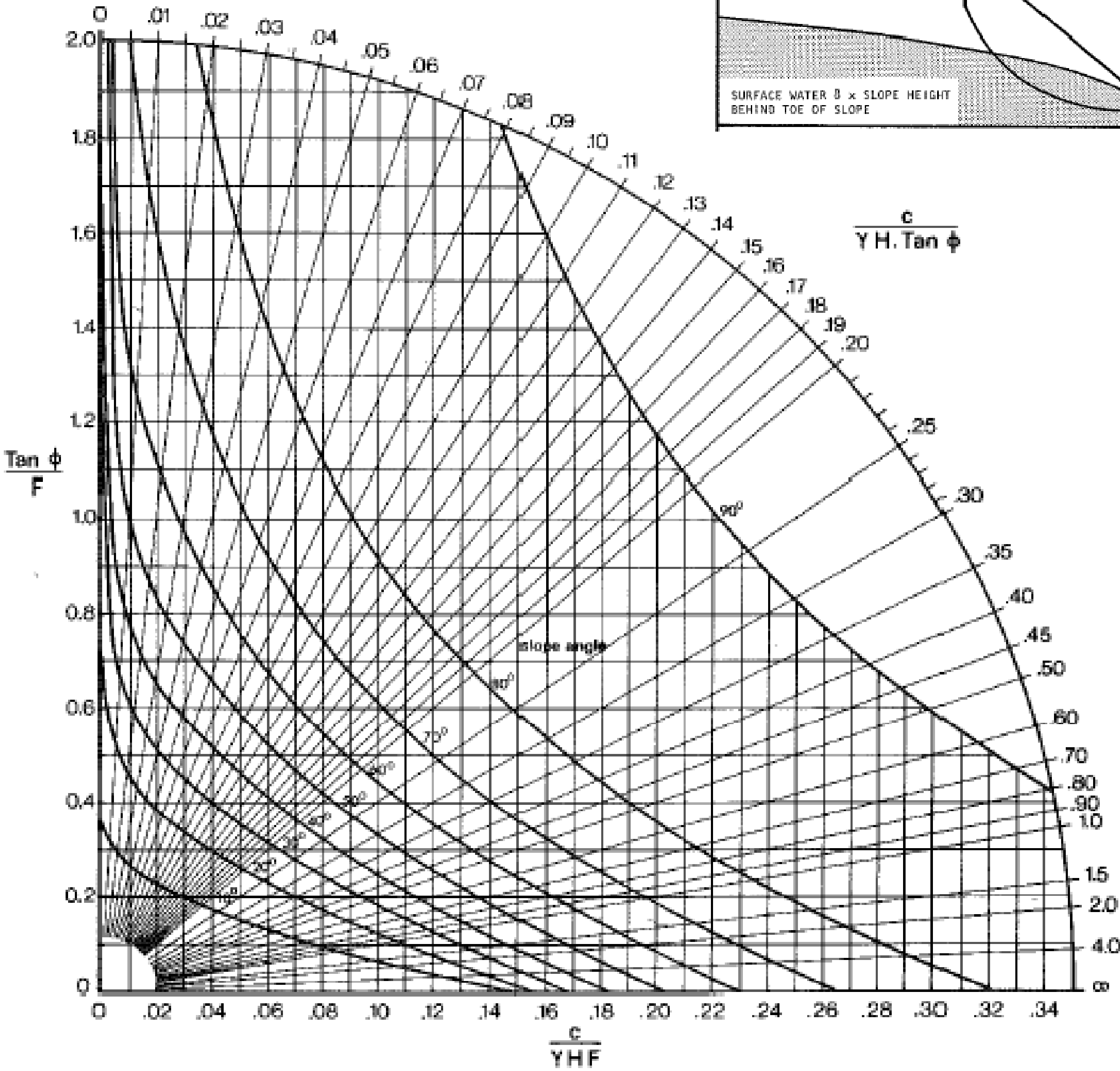
CIRCULAR FAILURE CHART NUMBER 1



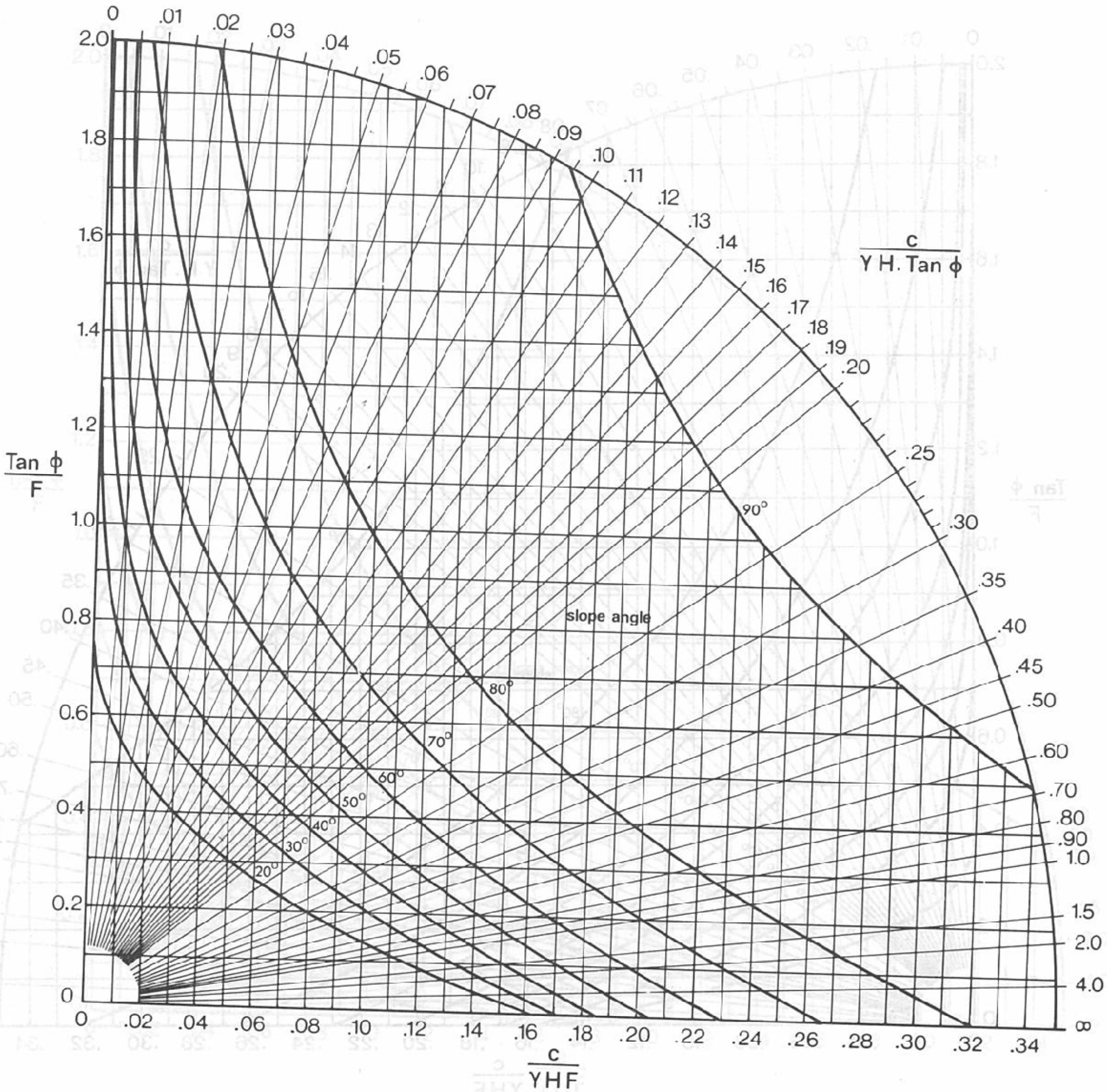


CIRCULAR FAILURE CHART NUMBER 2

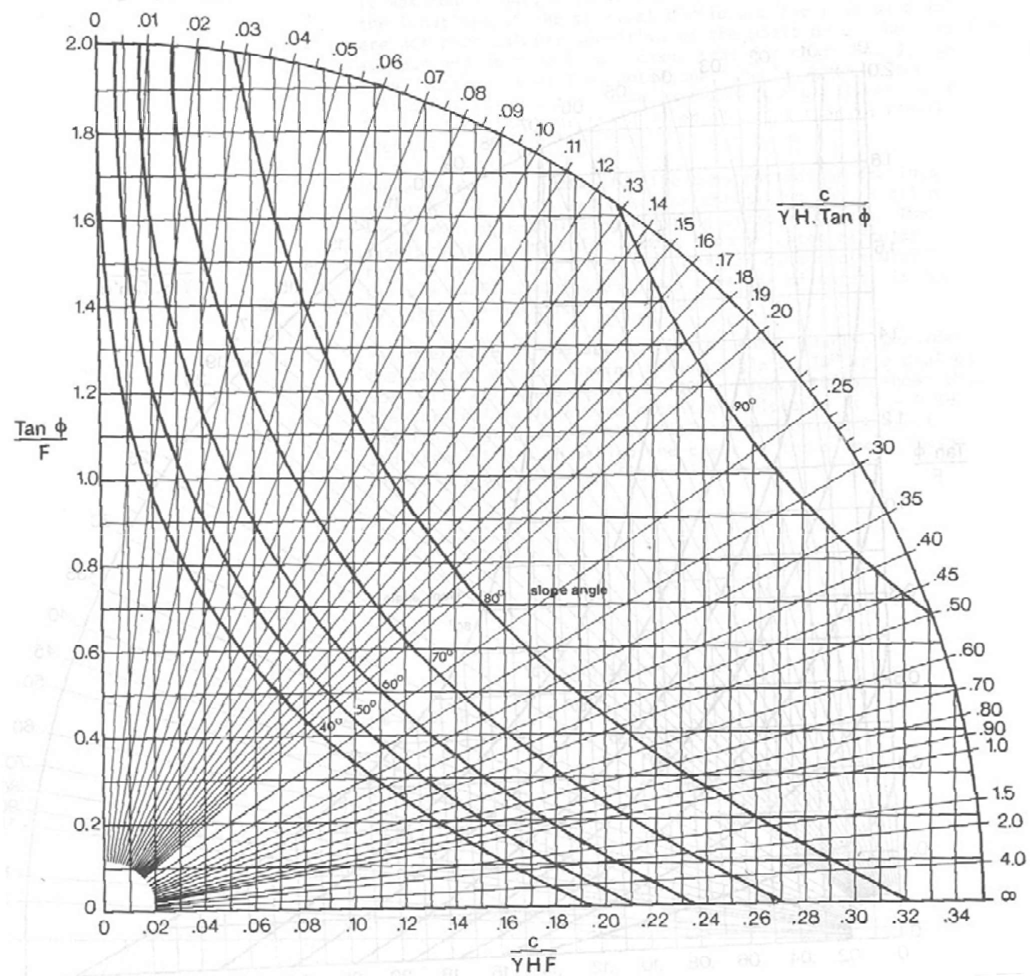




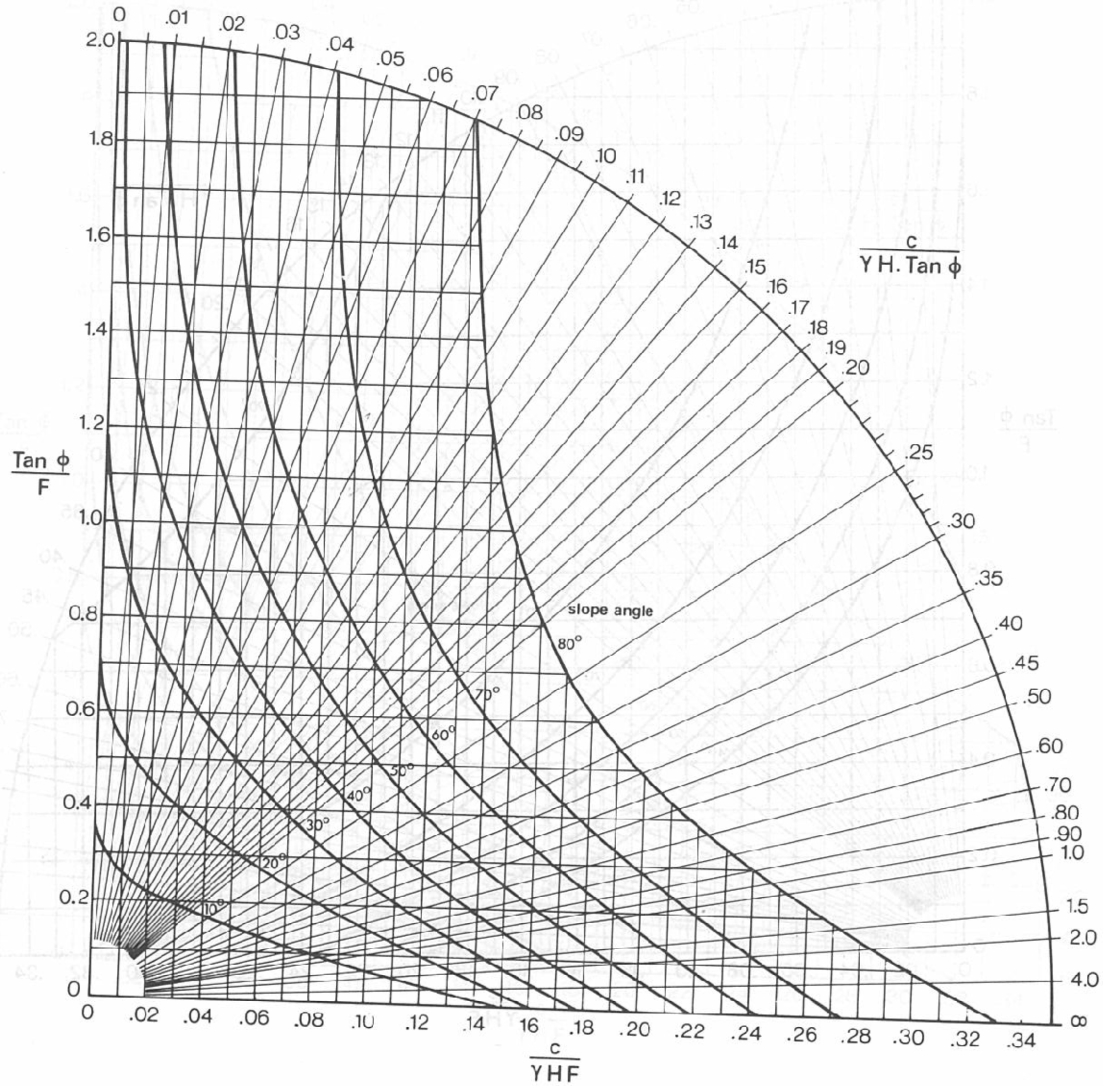
CIRCULAR FAILURE CHART NUMBER 3



CIRCULAR FAILURE CHART NUMBER 4



CIRCULAR FAILURE CHART NUMBER 5



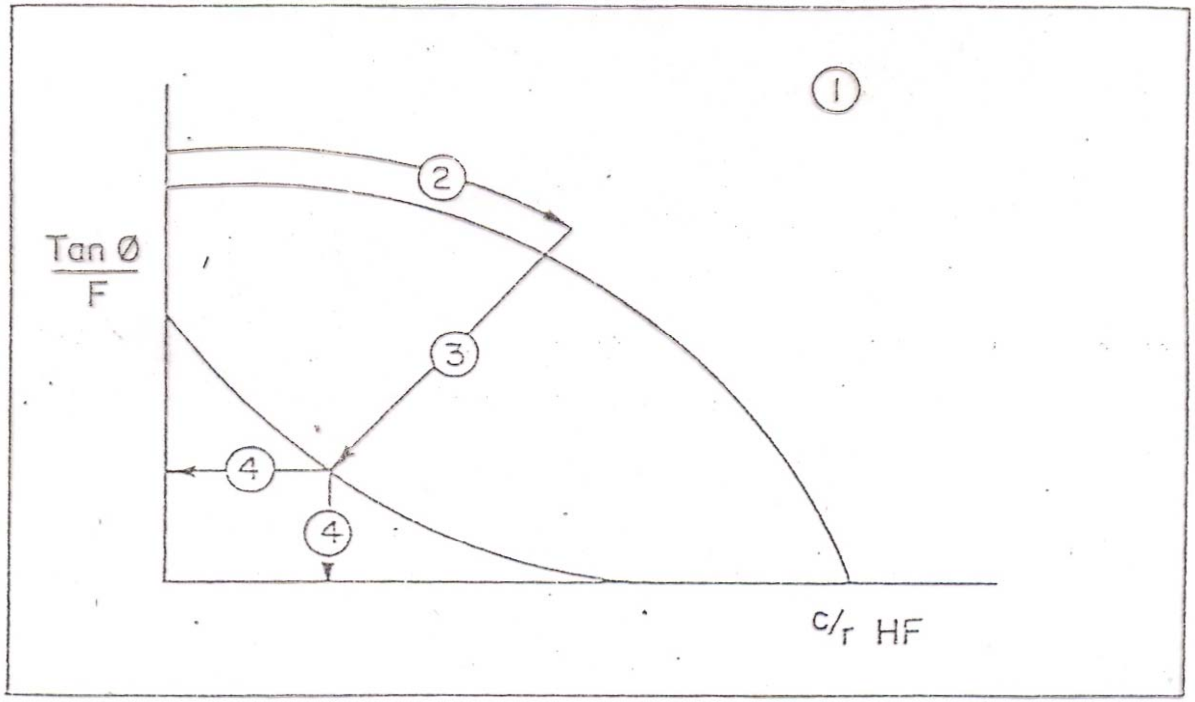
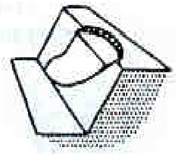
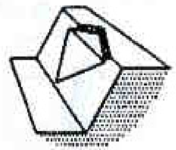
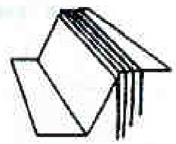
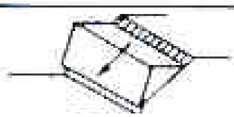
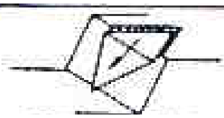
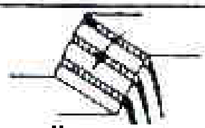


Fig. 8. Sequence of steps involved in using circular failure charts to find the factor of safety of a slope

STRUCTURE	TYPICAL PROBLEMS	CRITICAL PARAMETERS	ANALYSIS METHODS	ACCEPTABILITY CRITERIA
 Soil or heavily jointed rock slopes.	Circular failure along a spoon-shaped surface through soil or heavily jointed rock masses.	• Height and angle of slope face. • Shear strength of materials along failure surface. • Groundwater distribution in slope. • Potential surcharge or earthquake loading.	Two-dimensional limit equilibrium methods which include automatic searching for the critical failure surface are used for parametric studies of factor of safety. Probability analyses, three-dimensional limit equilibrium analyses or numerical stress analyses are occasionally used to investigate unusual slope problems.	Factor of safety > 1.3 for "temporary" slopes with minimal risk of damage. Factor of safety > 1.5 for "permanent" slopes with significant risk of damage. Where displacements are critical, numerical analyses of slope deformation may be required and higher factors of safety will generally apply in these cases.
 Jointed rock slopes.	Planar or wedge sliding on one structural feature or along the line of intersection of two structural features.	• Slope height, angle and orientation. • Dip and strike of structural features. • Groundwater distribution in slope. • Potential earthquake loading. • Sequence of excavation and support installation.	Limit equilibrium analyses which determine three-dimensional sliding modes are used for parametric studies on factor of safety. Failure probability analyses, based upon distribution of structural orientations and shear strengths, are useful for some applications.	Factor of safety > 1.3 for "temporary" slopes with minimal risk of damage. Factor of safety > 1.5 for "permanent" slopes with significant risk of damage. Probability of failure of 10 to 15% may be acceptable for open pit mine slopes where cost of clean up is less than cost of stabilization.
 Vertically jointed rock slopes.	Toppling of columns separated from the rock mass by steeply dipping structural features which are parallel or nearly parallel to the slope face.	• Slope height, angle and orientation. • Dip and strike of structural features. • Groundwater distribution in slope. • Potential earthquake loading.	Crude limit equilibrium analyses of simplified block models are useful for estimating potential for toppling and sliding. Discrete element models of simplified slope geometry can be used for exploring toppling failure mechanisms.	No generally acceptable criterion for toppling failure is available although potential for toppling is usually obvious. Monitoring of slope displacements is the only practical means of determining slope behaviour and effectiveness of remedial measures.
 Loose boulders on rock slopes.	Sliding, rolling, falling and bouncing of loose rocks and boulders on the slope.	• Geometry of slope. • Presence of loose boulders. • Coefficients of restitution of materials forming slope. • Presence of structures to arrest falling and bouncing rocks.	Calculation of trajectories of falling or bouncing rocks based upon velocity changes at each impact is generally adequate. Monte Carlo analyses of many trajectories based upon variation of slope geometry and surface properties give useful information on distribution of fallen rocks.	Location of fallen rock or distribution of a large number of fallen rocks will give an indication of the magnitude of the potential rockfall problem and of the effectiveness of remedial measures such as draped mesh, catch fences and ditches at the toe of the slope.

In rockfall problems the volume of a single rock is usually considered less than 10 m^3 and volume of rock masses less than 105 m^3.

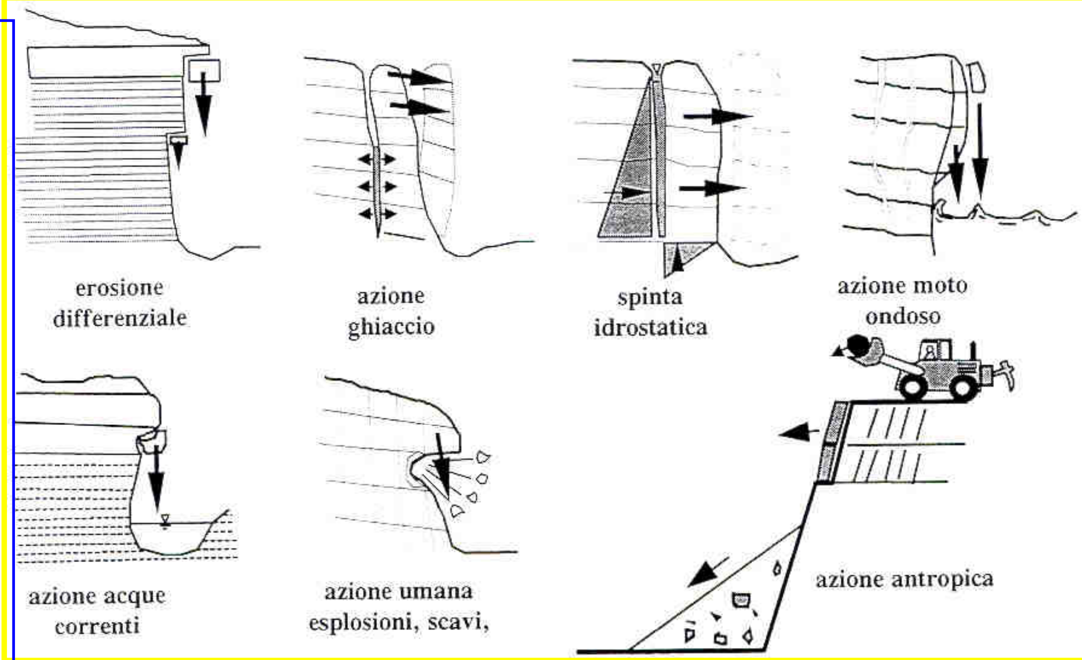
REMEDIAL MEASURES FOR ROCK SLOPES

	excavations				reinforcement methods										drainage					falling control				
Type of instability	slope	benches	trimming and scaling		spritz beton	support	local reiforcing		anchor walls	lacing	dowels	bolts	anchors		drainage ditches	surface protection	short drainholes	drainholes and gallary		reelocation	interception ditchies	catch fances and wall	netting	scaling
 planar sliding	*	*							*			*	*		*	*	*			*	*	*		
 wedge sliding	*								*		*	*	*		*	*		*		*				
 toppling	*											*	*		*	*		*			*			
 Small blocks and surface instability	*	*	*		*	*	*		*	*	*	*			*	*	*			*	*	*	*	*

CAUSES OF ROCKFALL

CAUSES	%
Rain	30
Frost	21
Discontinuities	12
Wind	12
Snow	8
Runoff	7
Discontinuities orientation	5
Animal dens	2
Differential erosion	1
Tree roots	0.6
Springs	0.6
Animal	0.6
Vehicles vibrations	0.3
Rock weathering	0.3

Percentage of observed causes which originated failures (Mac Cauley, 1985 - Caltrans)



Examples of combined triggering causes

REMEDIAL MEASURES FOR ROCK SLOPES

Stabilization methods → Reduction of the driving forces and increase of resisting forces. Stabilization measures reduce likelihood of rocks from moving out of place and also reduce the progressive deterioration.

Protection methods → Prevent rock materials which have moved out of place on the slope, from reaching vulnerable areas.
The initial cost is less then stabilization methods, but usually they require more maintenance.

Warning and instrumentation methods → These methods help predict when movement are going to occur or that a hazardous failure has occurred and further failures may be imminent

STABILIZATION METHODS

Stability of rock slopes shall be analyzed at different scales:

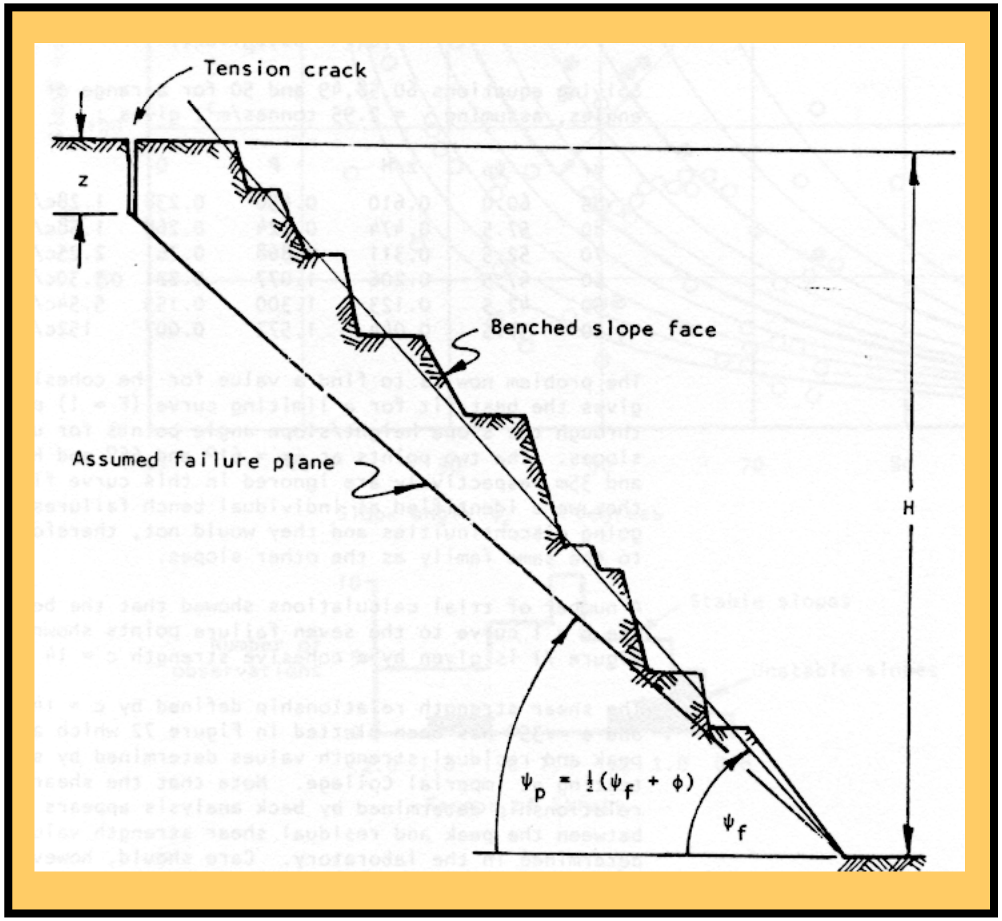
* global
* local
* surficial

The different scale problems will require different remediation methods.

When possible, the slope stability is improved by:

- removing unstable or potentially unstable material
- flattening the slope
- removing weight from the upper part of the slope
- incorporate benches in the slope

STABILIZATION METHODS - Benches



Benches are often protected with a rockfall netting which will prevent or limit rocks falling down the slope.

Benches also reduce effects due to rainfall runoff. They can be combined with ditches to prevent water infiltration. Bench width is usually dependant upon rock mass characteristics and on the size of equipment (usually not less than 7 m).

STABILIZATION METHODS – First assessment

If no excavation is made, before any remedial work, the size of loose overhanging or protruding blocks shall be estimated.

Surface and subsurface drainage.

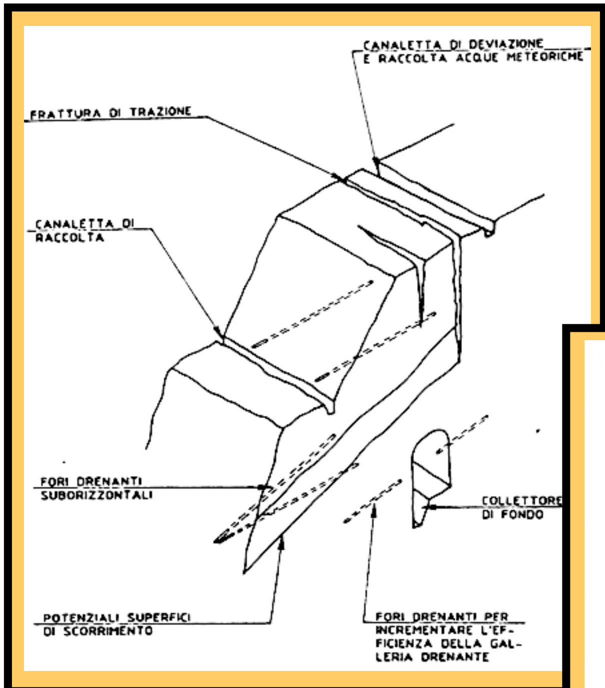
These methods can improve stability and substantial benefits can be obtained also on the case of large failure at relatively low cost.
Surface drainage cantral on the area behind the top of slope

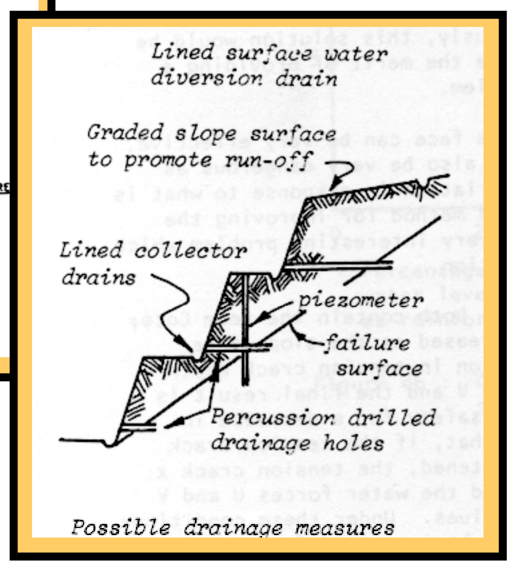
Surface drainage control on up-slope area

1. **Reshape the surface area**
2. **Seal and plug tension cracks**
3. **Provide lined or unlined ditches**
4. **Minimize vegetation removal**

STABILIZATION METHODS – Subsurface drainage

Include drainage galleries, pumped wells, trenches and drainholes





Possible drainage measures

Drainage holes are normally used for slope drainage

Characteristics:

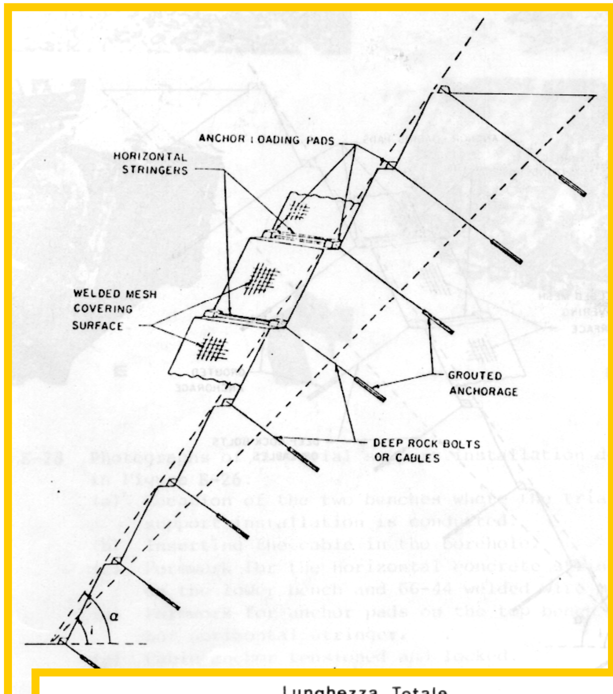
5° inclined upwards from horizontal

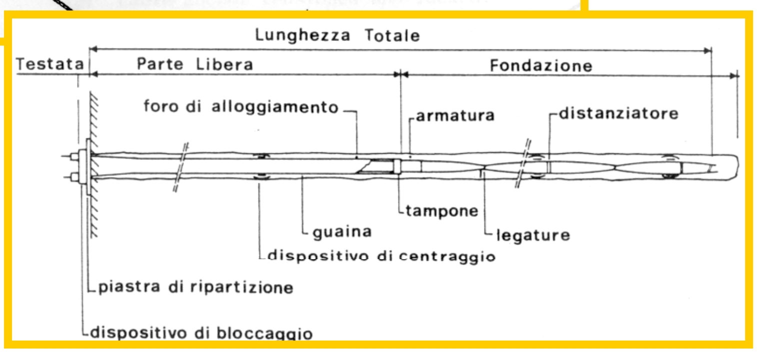
Spacing: ranging from 7 to 30 m(depending on nature of the problem)

Length: depend on geometry of failure and usually the drains must intersect the maximum number of significant discontinuities.

STABILIZATION METHODS – Anchors

Stabilizing systems for global and local stability





Anchors are used to stabilise large volumes of rock. Anchors are pre-stressed so movements are required to mobilise strength.

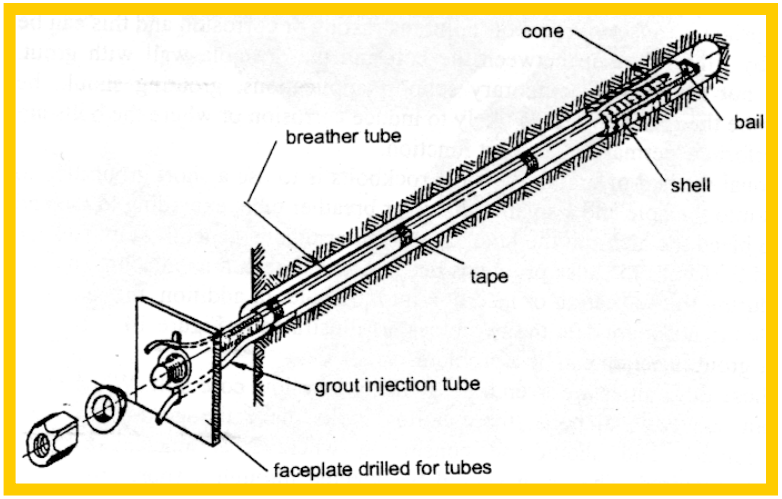
The required force of the single anchor (Nq) is defined by:

Nq $\leq$ Nfu / Fs
Nfu = ultimate strength of foundation

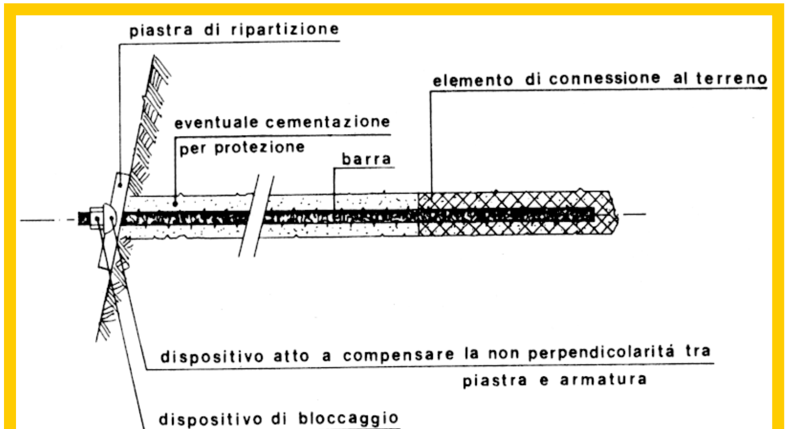
Fs = 2.0 for temporary works
Fs = 2.5 for permanent works

The anchor ultimate strength is applicable when the distance between anchors is :
$\geq$ 1 / 3 of length of foundation
> 10 times drilling diameter

STABILIZATION METHODS – Rock bolts



mechanic bolt



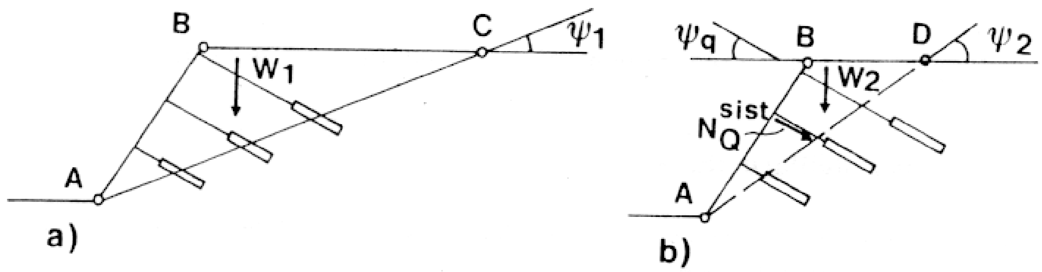
cement grouted bolt

Rock bolts are similar to anchors. Usually they are plain steel rods with a mechanical anchor or grouting at one end with a face plate and nut at the other. For permanent applications the free length is filled with grouting after tensioning in order to prevent corrosion.

Usually they are less than 12 m long and are used for local stability of single block or for surface stability to reinforce a loose external rock layers.

The length depends on the geometry of failure or thickness of loose rock. Spacing is usually 2 - 3 m; however in order to ensure that they can interact with each other the spacing must be less than 1 / 2 the length.

STABILIZATION METHODS – Design of anchors



$$F_a = \frac{W_1 \cos \psi_1 \, tg\, \varphi}{W_1 \sin \psi_1}$$

$$F_b = \frac{[W_2 \cos \psi_2 + N_Q^{sist} \sin(\psi_q + \psi_2)]\, tg\, \varphi}{W_2 \sin \psi_2 - N_Q^{sist} \cos(\psi_q + \psi_2)}$$

$$N_Q = 0$$

Reinforcement for rock slope with anchors and bolts is usually designed using equilibrium method of analysis.
There are many software programs which performing calculations of safety factors against plane, wedge and stepped surface failure which including reinforcement.

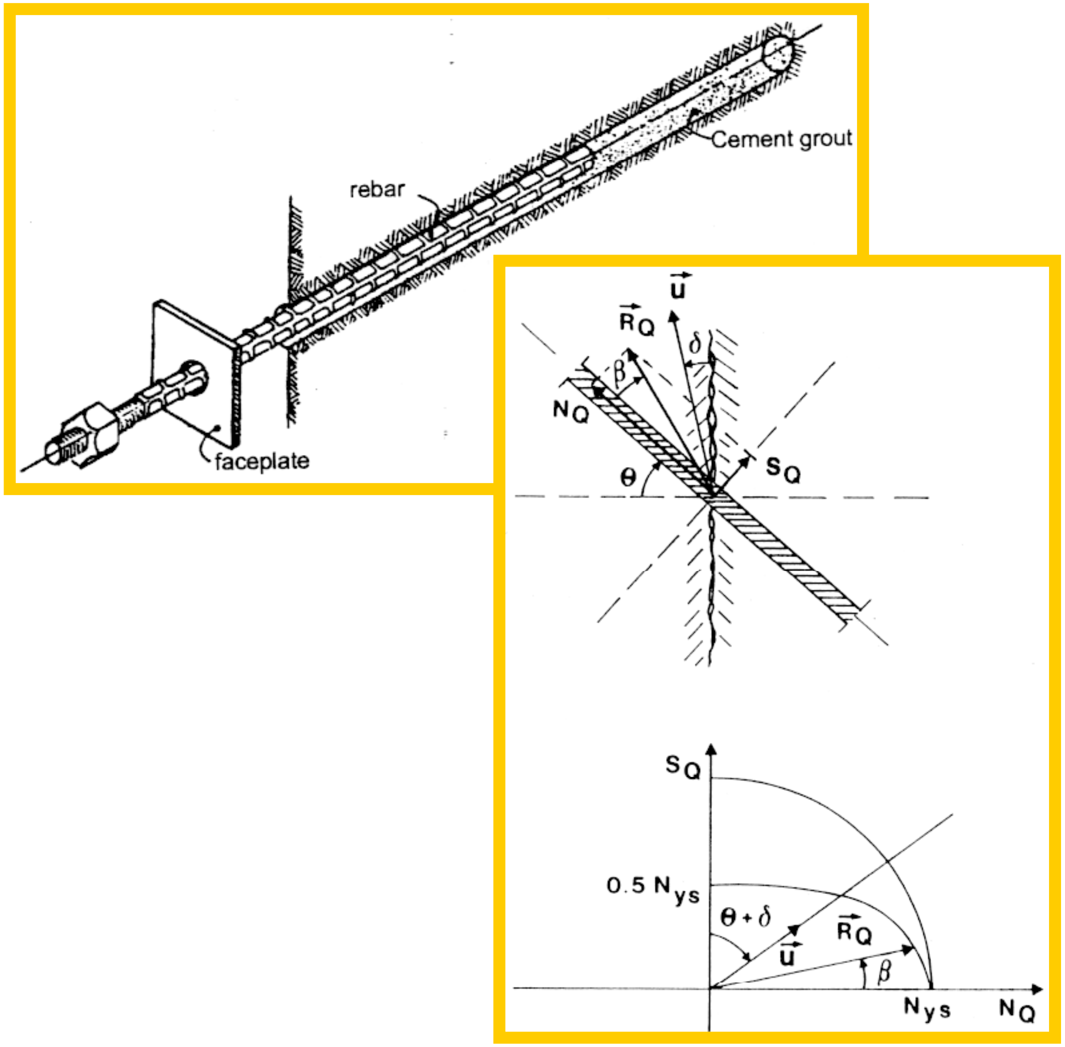
They apply normal and shear force along discontinuities (components of working load of anchor) .

Where complex situation of global stability are present the analysis can be performed by means of numeric methods such as finite elements or finite difference.

The reinforcing elements usually are tensioned at a working load which is less than their capacity (60-70% of elastic limit strength) in order to have a reserve in case of additional load induced by displacement.

STABILIZATION METHODS

DOWELS



Dowels are usually deformed steel bars cemented in grouted. When a more flexible element is needed instead of a bar a cable can be used. They are passive (mobilize strength with rock movement) elements and basically increase the shear resistance across failure planes. Their length usually is less than 4 - 5 m enabling placement by manual pneumatic equipment.

$$Tg\ \beta = \frac{1}{4\ tg\ (\Theta + \delta)}$$

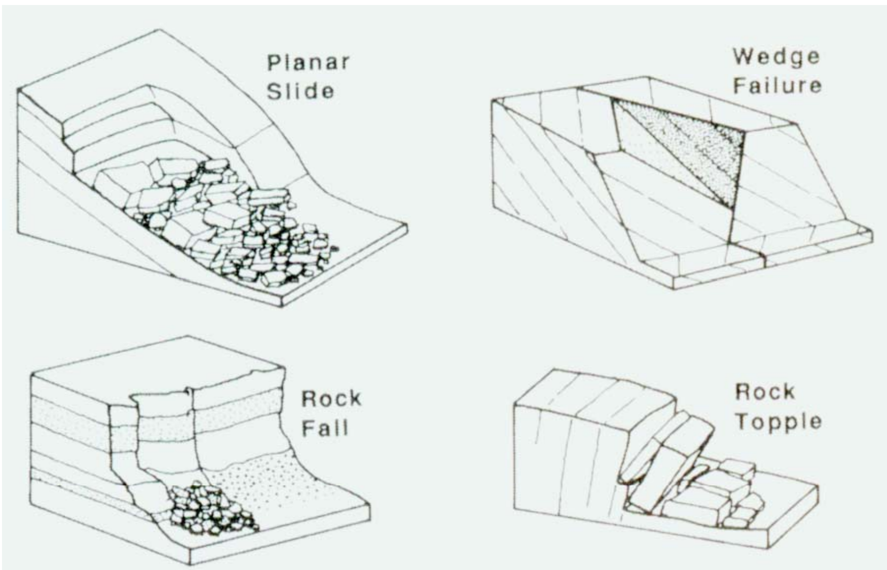
N'q= (Nq^2 + 4Sq^2)^0.5
Theoretic equivalent working load

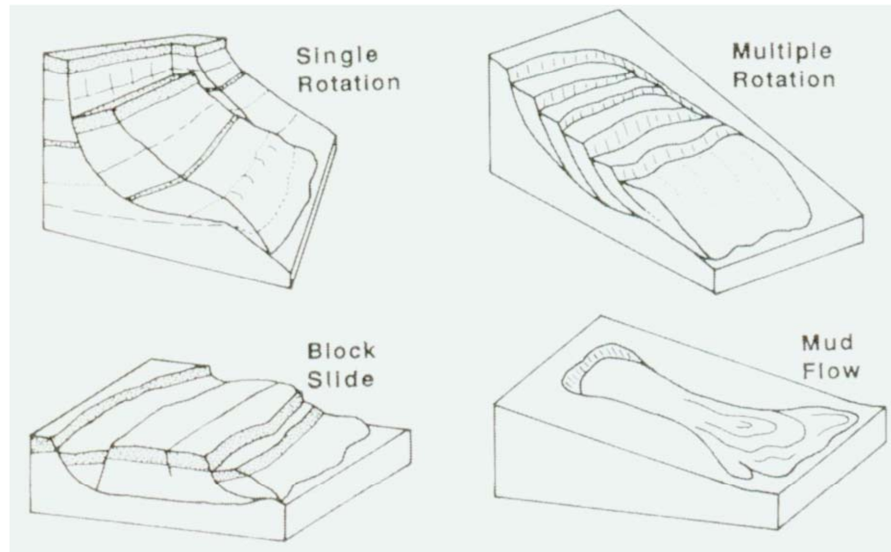
In case of very loosened rock

$$Sq < 1{,}87\ Nys\ \frac{(\sigma c)^{0.5}}{\sigma\ ys}$$

Nys = elastic limit load of steel

Types of landslide

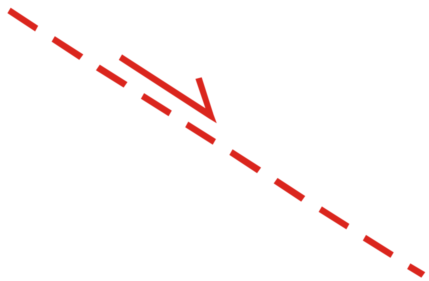


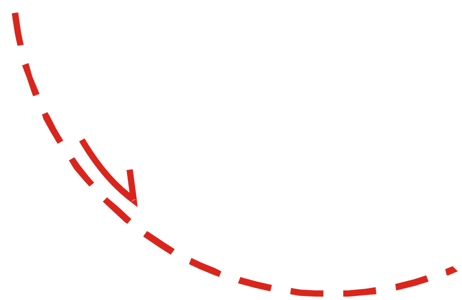


- Rock failure
  - failure plane pre-determined
- Soil failure
  - failure plane along line of max stress

Types of landslide

- Rock failure
  - failure along pre-determined planes of weakness
- Soil failure
  - failure along lines of max. stress
    - frictional, cohesive = rotational
    - frictional, incohesive = planar





Rock failure – remedial measures