SLOPE STABILITY

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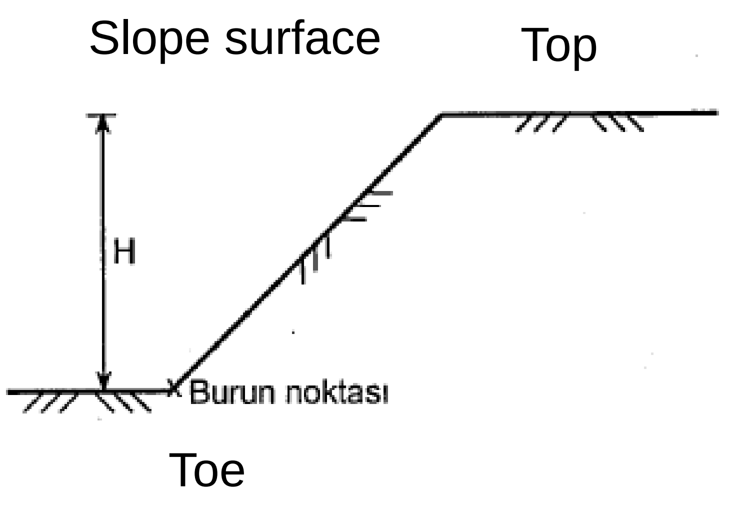
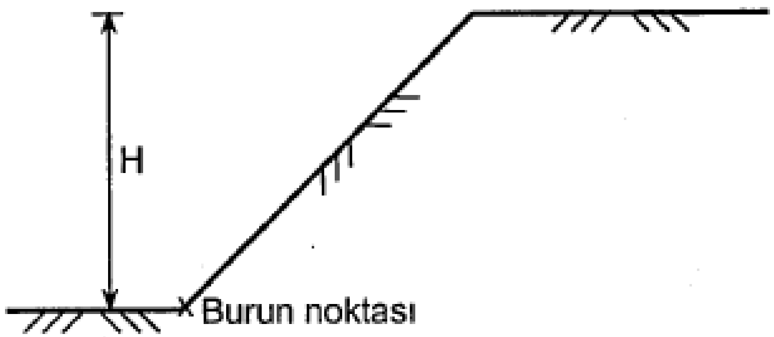
- An exposed ground surface that stands at an angle with the horizontal is called a *slope.*
- The slope can be natural or constructed.
- Natural: Formation due to geological features of the earth
- Man made: Construction activity like cutting, filling etc.



Geometric features of slope

Infinite slopes: They have two dimensions that extend over great distances and the soil mass is inclined to the horizontal.

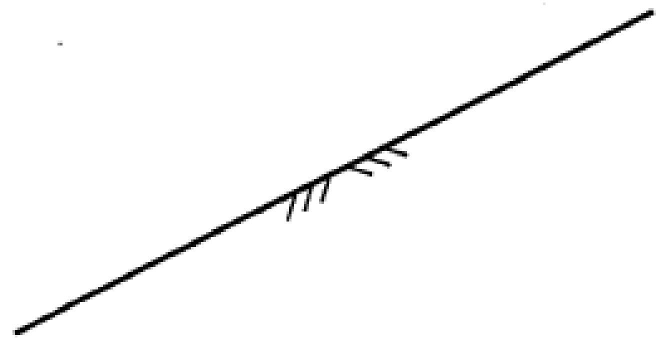
Finite Slopes: A finite slope is one with a base and top surface, the height being limited.



a) Sonlu şev

Toe of the slope

Finite slope

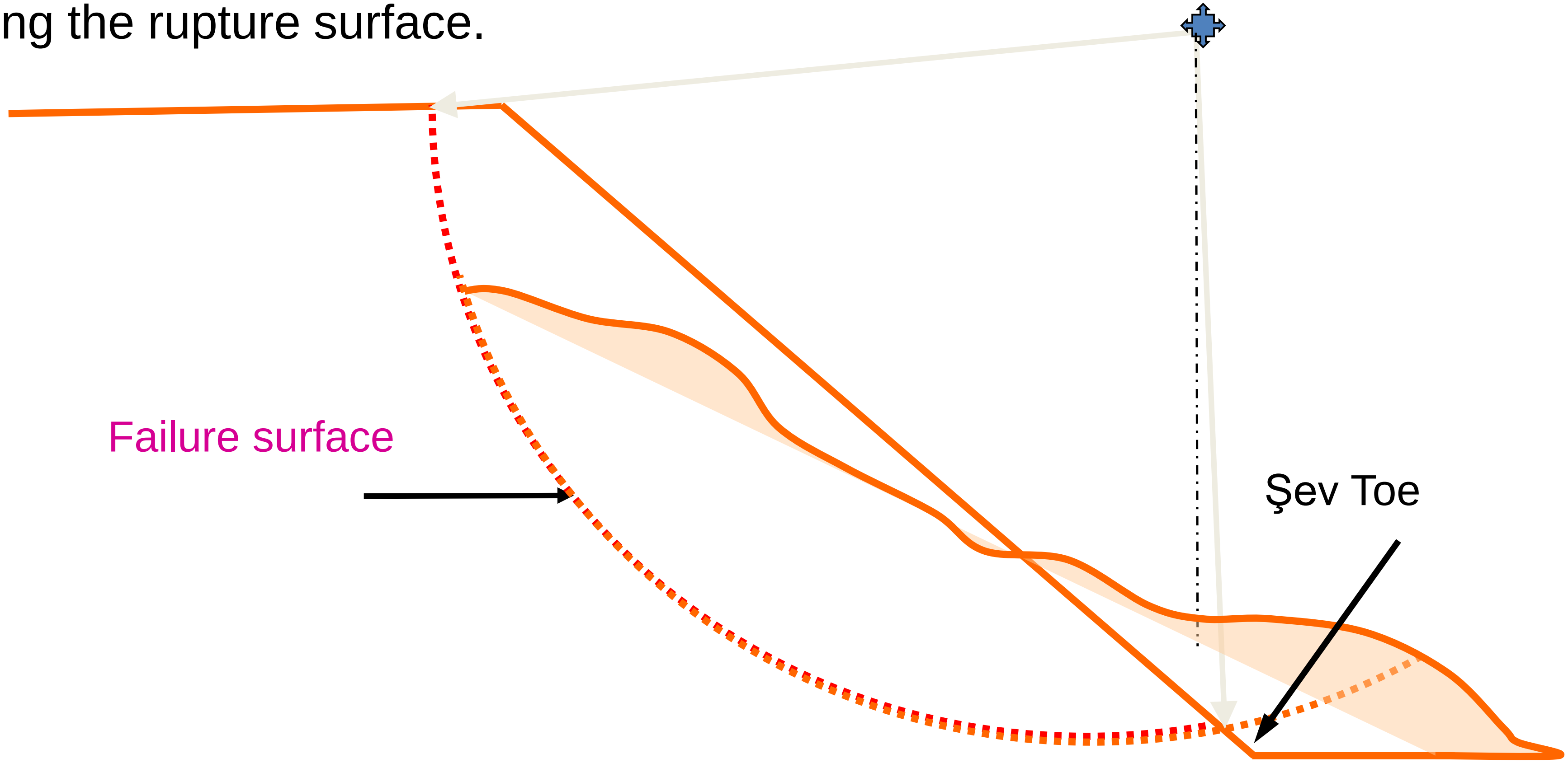


b) Sonsuz şev

Infinite slope

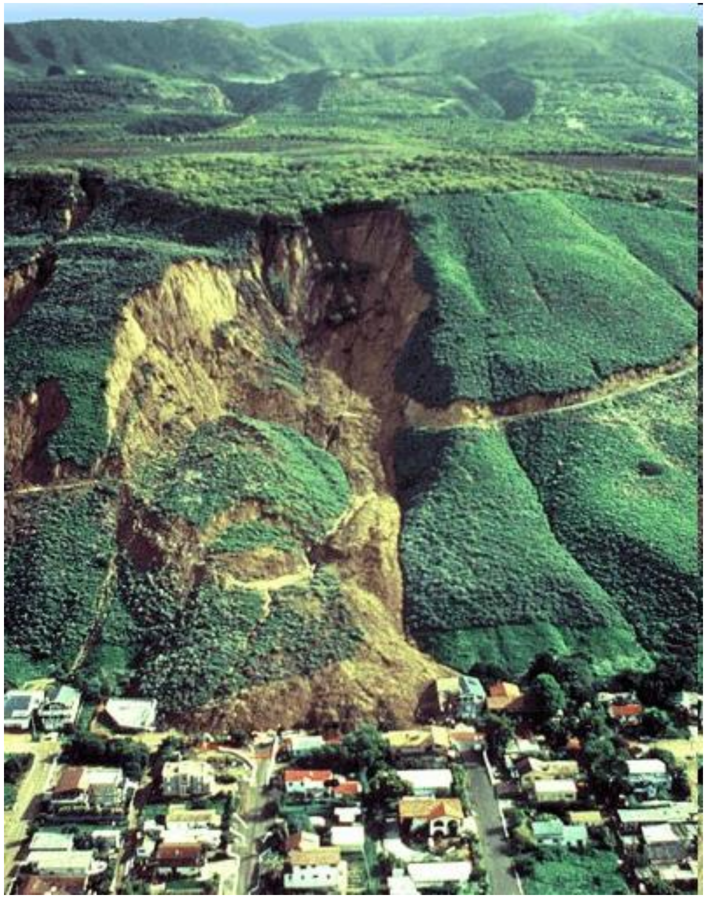
Slope Failure

If the ground surface is not horizontal, a component of gravity will cause the soil to move downward. If the component of gravity is large enough, slope failure can occur; that is, the soil mass can slide downward. The driving force overcomes the resistance from the shear strength of the soil along the rupture surface.



Slope failure

La Conchita, CA Landslide



Classification of slope movements

Slope movements (e.g. landslides) are dynamic systems that are complex in time and space and closely linked to both inherited and current preparatory and triggering controls.

As the factors that cause slope failure and the results of movements are very complex, several methods are used for the classification of slope movements.

Slope movements can be classified on the basis of the mode and rate of movement, the shape of the slide surface, the type of material involved and number of other criteria.

Classification of slope movement (Skempton – Hutchinson 1969)

D/L(%)	**Tanım**
5-10	Translational slide
0.5-3	Flow
15-30	Rotational slide

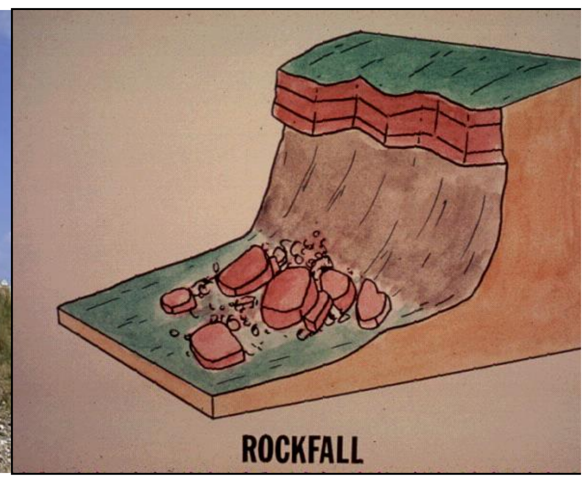
D=Height of slip surface L=Length of slip surface

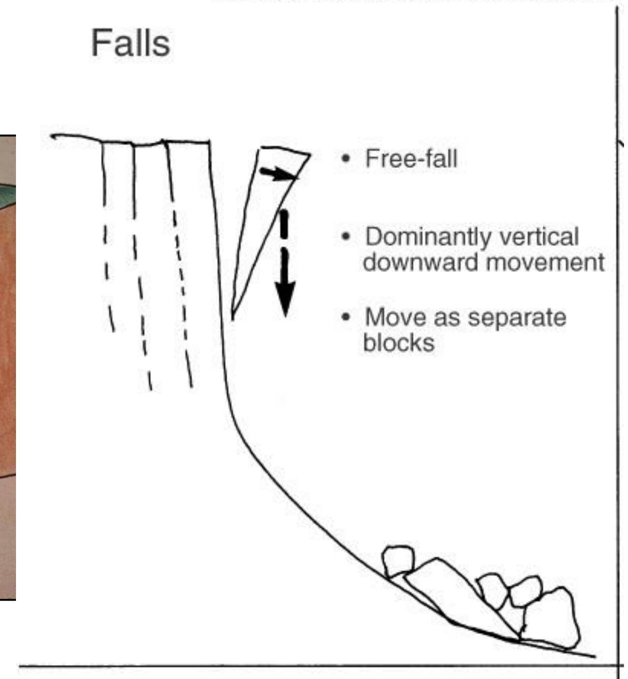
Classification of Slope Movements(Varnes, TSE)

TYPE OF MOVEMENT		TYPE OF MATERIAL		
		BEDROCK	ENGINEERING SOILS	
			Predominantly coarse	Predominantly fine
FALLS		Rock fall	Debris fall	Earth fall
TOPPLES		Rock topple	Debris topple	Earth topple
SLIDES	ROTATIONAL	Rock slide	Debris slide	Earth slide
	TRANSLATIONAL			
LATERAL SPREADS		Rock spread	Debris spread	Earth spread
FLOWS		Rock flow (deep creep)	Debris flow (soil creep)	Earth flow
COMPLEX		Combination of two or more principal types of movement		

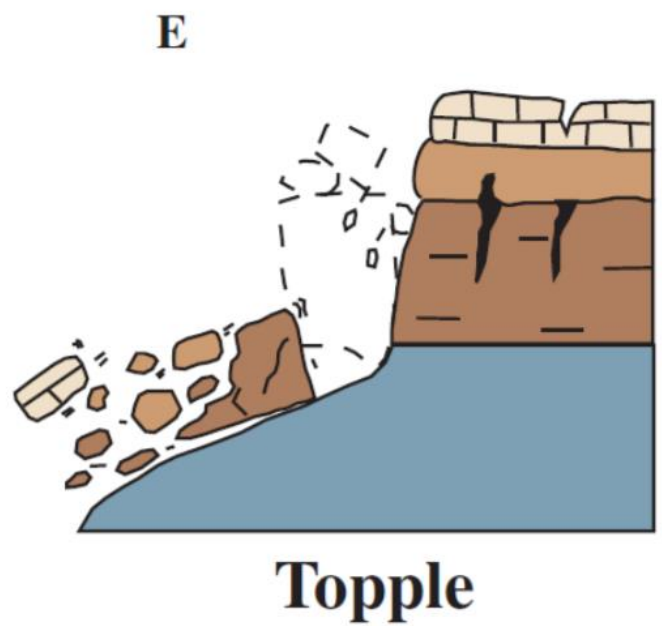
Abbreviated version of Varnes´ classification of slope movements (Varnes 1978)

Falls are abrupt movements of masses of geologic materials, such as rocks and boulders, that become detached from steep slopes or cliffs. Separation occurs along discontinuities such as fractures, joints, and bedding planes, and movement occurs by free-fall, bouncing, and rolling. Falls are strongly influenced by gravity, mechanical weathering, and the presence of interstitial water.

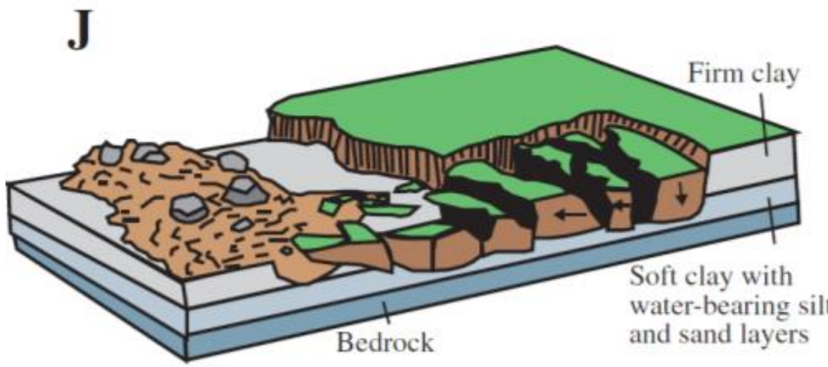




TOPPLES: Toppling failures are distinguished by the forward rotation of a unit or units about some pivotal point, below or low in the unit, under the actions of gravity and forces exerted by adjacent units or by fluids in cracks.

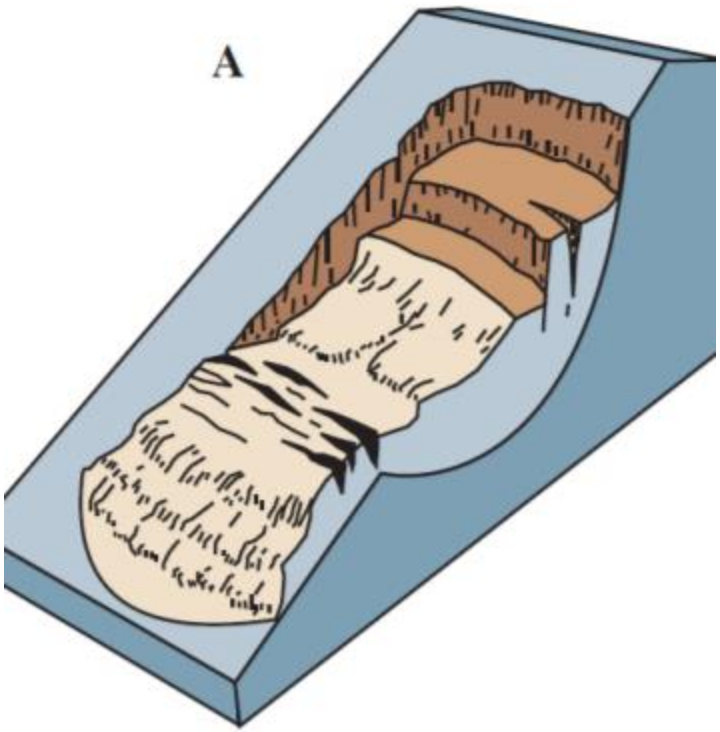


LATERAL SPREADS: Lateral spreads are distinctive because they usually occur on very gentle slopes or flat terrain. The dominant mode of movement is lateral extension accompanied by shear or tensile fractures. The failure is caused by liquefaction, the process whereby saturated, loose, cohesionless sediments (usually sands and silts) are transformed from a solid into a liquefied state.

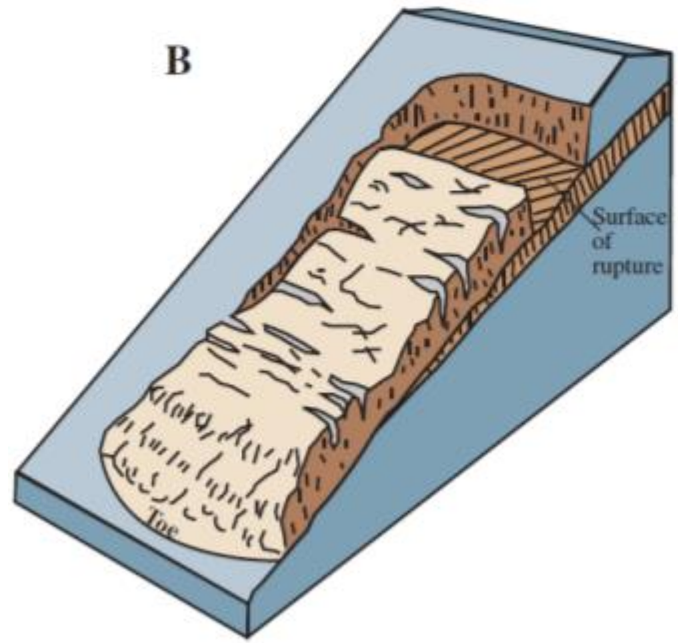


Lateral spread

SLIDES: Although many types of mass movements are included in the general term "landslide," the more restrictive use of the term refers only to mass movements, where there is a distinct zone of weakness that separates the slide material from more stable underlying material. The two major types of slides are rotational slides and translational slides.



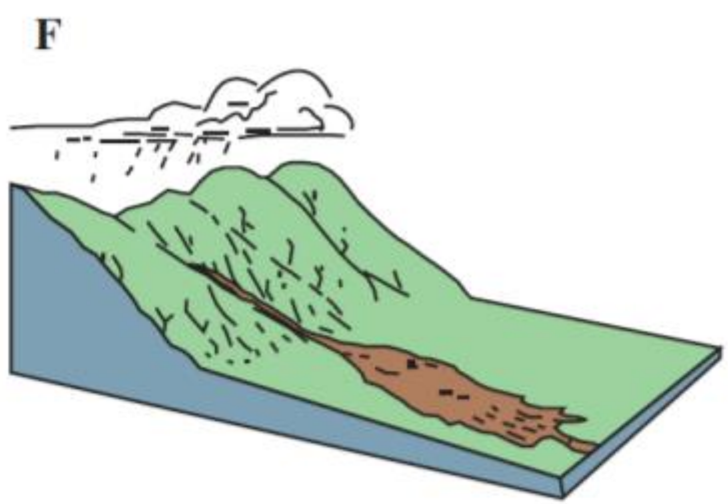
Rotational landslide



Translational landslide

FLOWS: There are five basic categories of flows that differ from one another in fundamental ways.

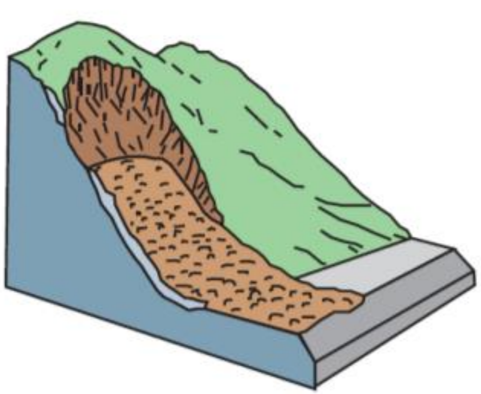
a. Debris flow: A debris flow is a form of rapid mass movement in which a combination of loose soil, rock, organic matter, air, and water mobilize as a slurry
that flows downslope. Debris flows include <50% fines. Debris flows are commonly caused by intense surface-water flow, due to heavy precipitation or rapid snowmelt, that erodes and mobilizes loose soil or rock on steep slopes.



Debris flow

- **b. Debris avalanche:** This is a variety of very rapid to extremely rapid debris flow.
- **c. Earth flow:** Earth flows have a characteristic “hourglass” shape. The slope material liquefies and runs out, forming a bowl or depression at the head. The flow itself is elongate and usually occurs in fine-grained materials or clay-bearing rocks on moderate slopes and under saturated conditions. However, dry flows of granular material are also possible.
- **d. Mud flow**: A mudflow is an earth flow consisting of material that is wet enough to flow rapidly and that contains at least 50 percent sand-, silt-, and clay-sized particles.

G



Debris avalanche

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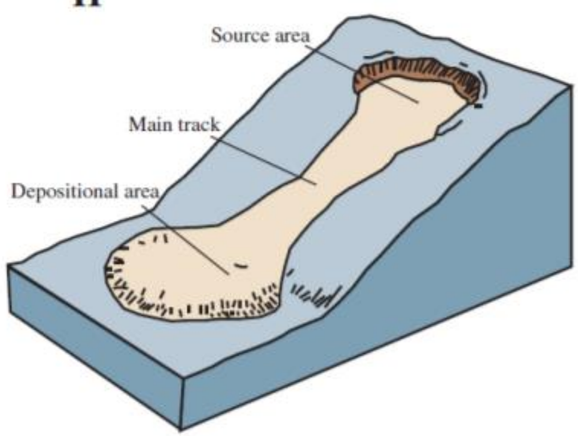
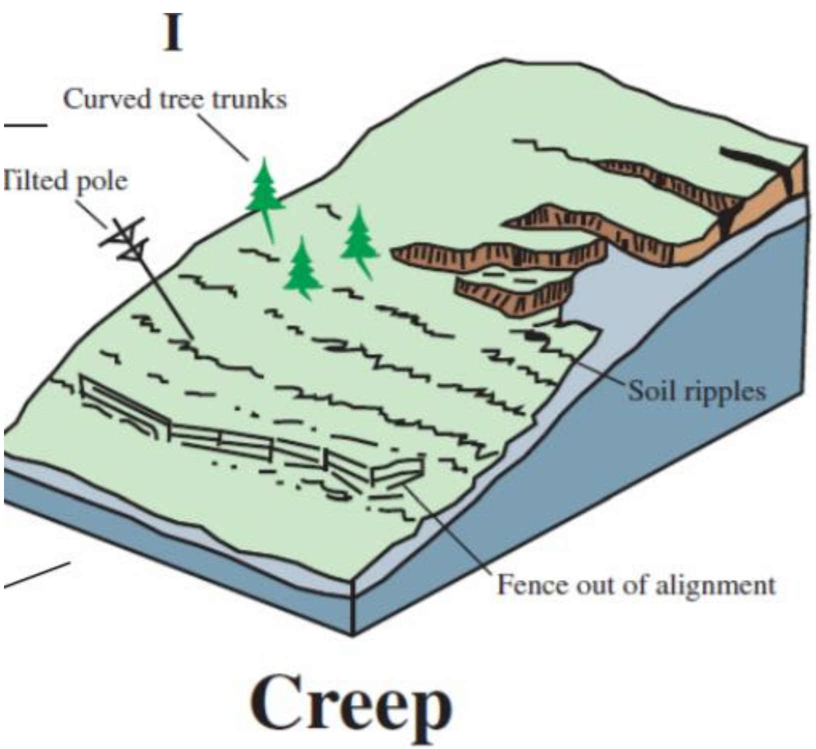


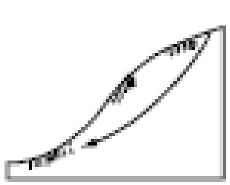
Earthflow

- **e. Creep:** Creep is the imperceptibly slow, steady, downward movement of slopeforming soil or rock. Movement is caused by shear stress sufficient to produce permanent deformation, but too small to produce shear failure. Creep is indicated by curved tree trunks, bent fences or retaining walls, tilted poles or fences, and small soil ripples or ridges.

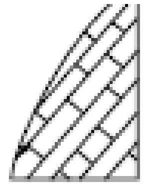


- **COMPLEX:** Combination of two or more of the above types is known as a complex landslide.

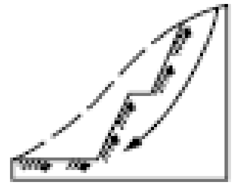
Slope Stability Problems



earth slope

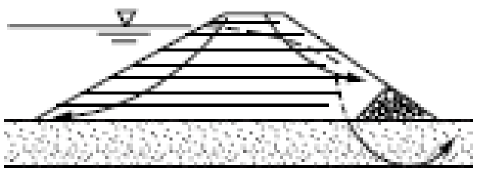


Rock slope

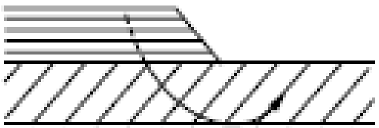


Slope with berm

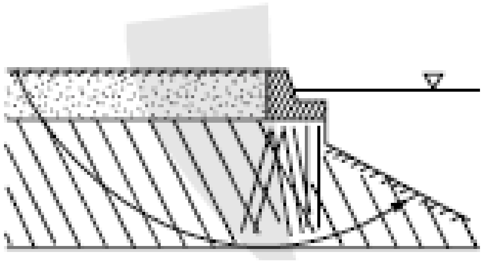
Cut slope



Earth fill dam



Embankments on soft soil



Water retaining structure

Embankment on slope

Natural and Man-made slopes

- Material type,
- Geological history,
- Stress,
- Seepage forces

are different for natural and man-made slopes.

Causes for slope failure;

1) Decrease in shear strenght of soil
2) Increase in shear stress of soil

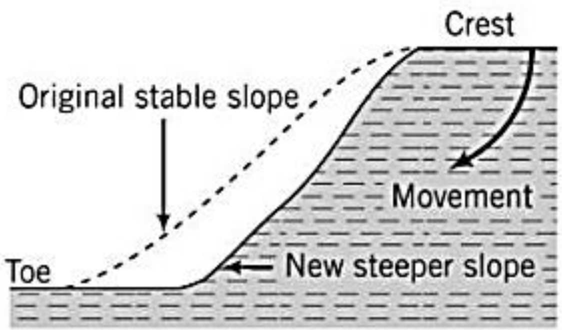
Decrease in shear strength;

1. Increase in pore water pressure
2. Occurance of cracks
3. Heave
4. Occurance of fracture
5. Weathering of rock
6. Creep
7. Chemical decomposition
8. Softhening
9. Crumbling
10. Cyclic loading

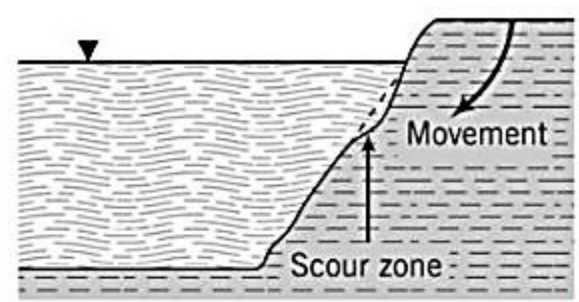
Increase in shear stress

1. Additional loads on top of slope
2. Increase in pore water pressure
3. Increase in weight of soil due to the saturation
4. Construction activities at the toe of the slope
5. Sudden drawdown
6. Earthquake

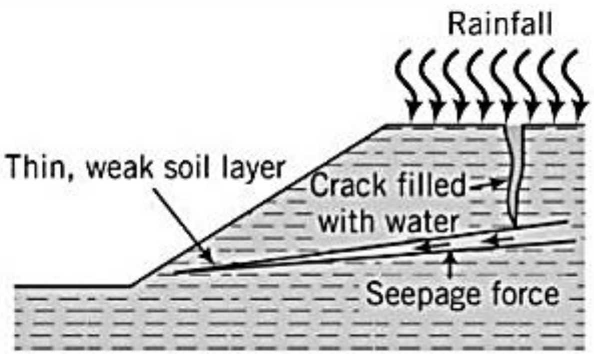
Causes of slope failure



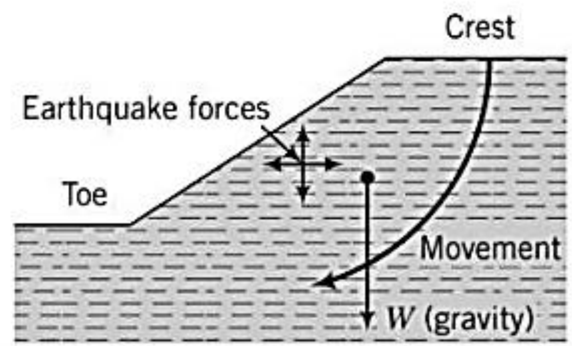
(*a*) Steepening of slope by erosion



(*b*) Scour by rivers and streams

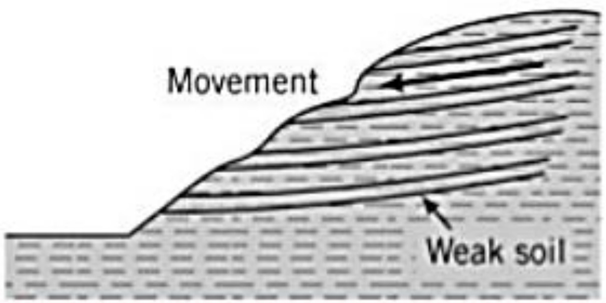


(*c*) Rainfall fills crack and introduces seepage forces in the thin, weak soil layer

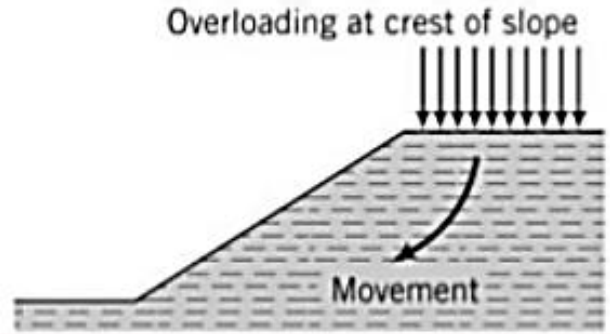


(*d*) Gravity and earthquake forces

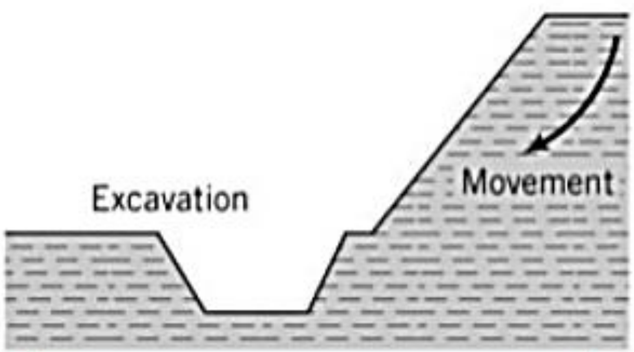
Causes of slope failure



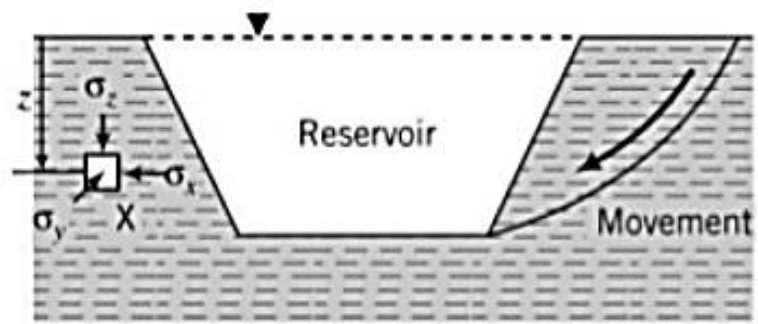
(*e*) Geological feature—soil stratification



(*f*) Overloading at the crest of the slope

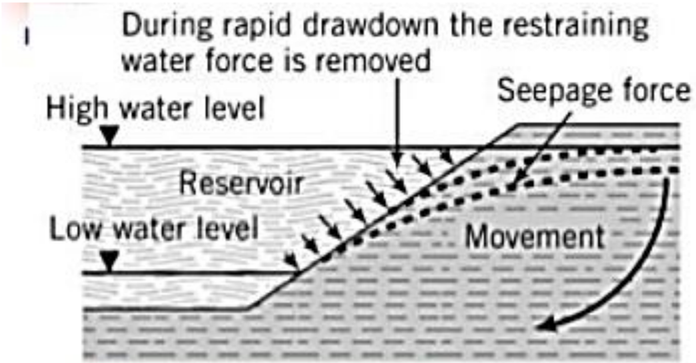


(*g*) Excavation at toe of the slope

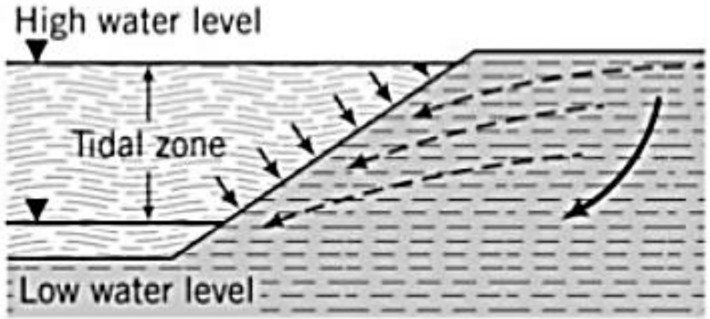


(*h*) Reservoir stresses

Causes of slope failure

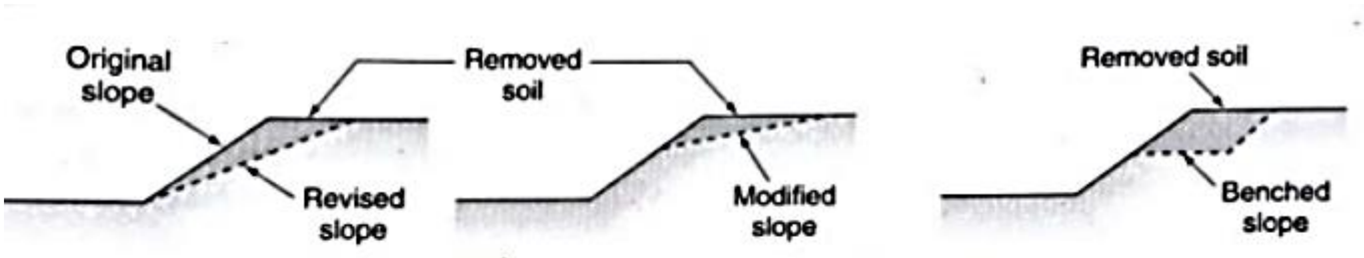


(i) Rapid drawdown

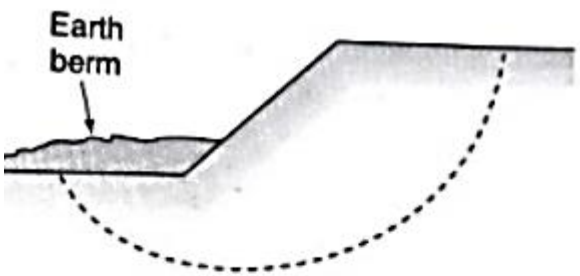


(j) Groundwater seepage

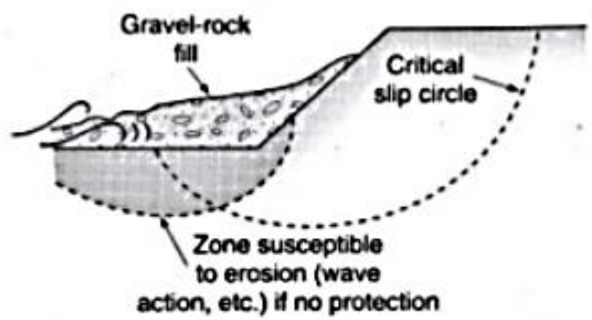
Slope stabilizing measures



(a) Slopes flattened or benched

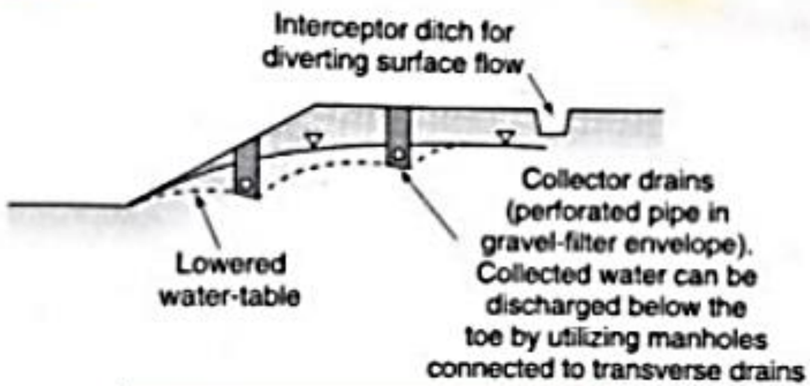


(b) Berm provided at toe (weight increases the resistance to sliding)

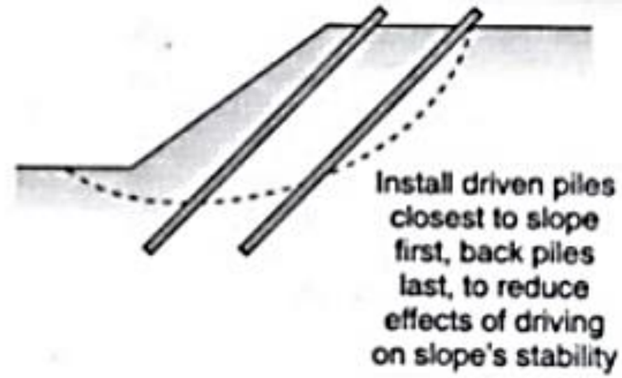


(c) Protection against erosion provided at toe

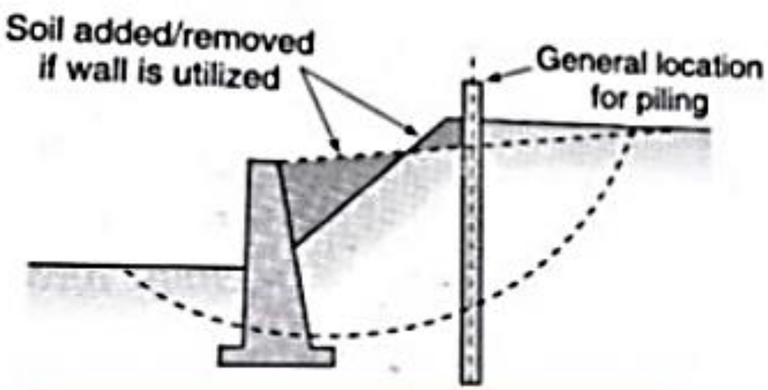
Slope stabilizing measures



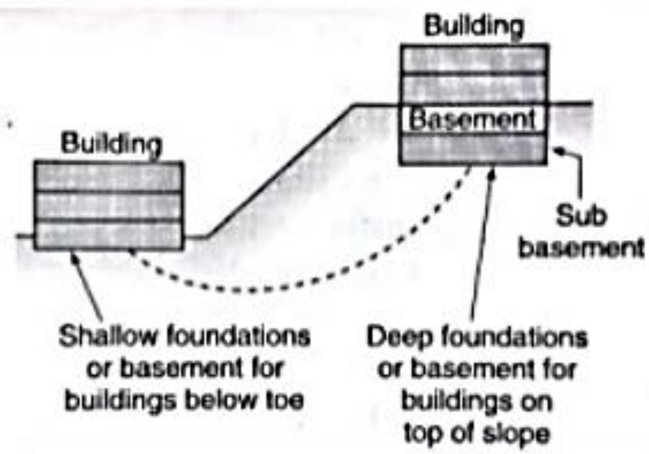
(d) Lowering of groundwater table to reduce pore pressures in the slope



(e) Use of driven or cast-in-place piles

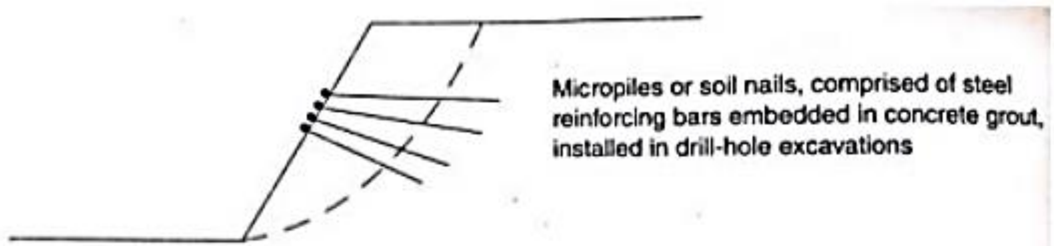


(f) Retaining wall OR sheetpiling OR cylinder piles provided to increase resistance to sliding

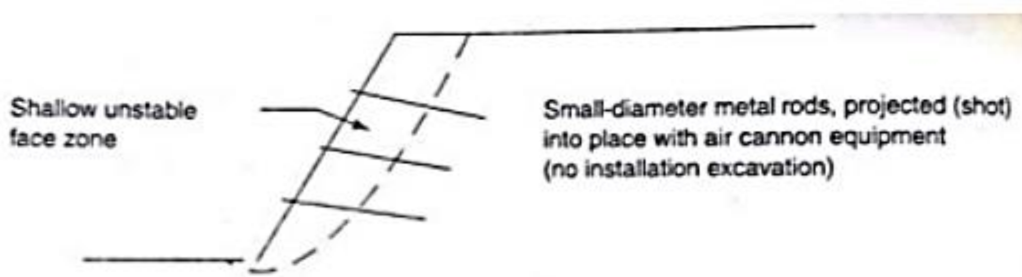


(g) Plan for building design to aid slope stability

Slope stabilizing measures



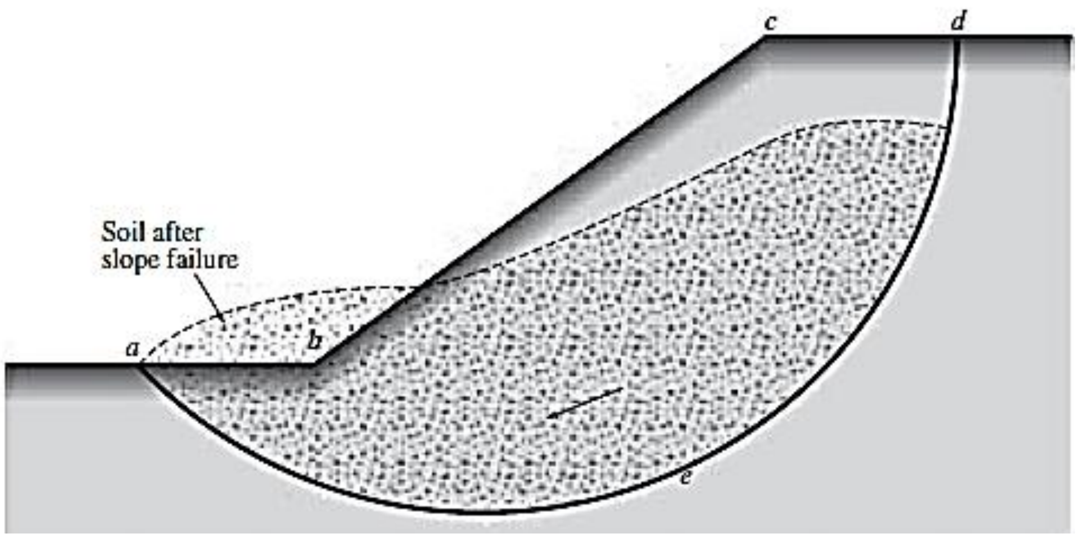
(h) Micropiles or soil nails (reticulated network), attaches unstable face soil zone to deeper stable zone (refer to Chapter 13)



(i) Launched soils nails reinforce unstable face zone and attach to deeper stable zone (method limited to stabilizing shallow face zones); see Chapter 17

Slope Stability

If the ground surface is not horizontal, a component of gravity will cause the soil to move downward. If the component of gravity is large enough, slope failure can ocur.The driving force overcomes the resistance from the shear strength of the soil along the rupture surface.



The task of the engineer charged with analyzing slope stability is to determine the factor of safety. Generally, the factor of safety is defined as;

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

where

FS_s = factor of safety with respect to strength

τ_f = average shear strength of the soil

τ_d = average shear stress developed along the potential failure surface

The shear strength of a soil consists of two components, cohesion and friction, and may be expressed as

$$\tau_f = c' + \sigma' \tan \phi'$$

where

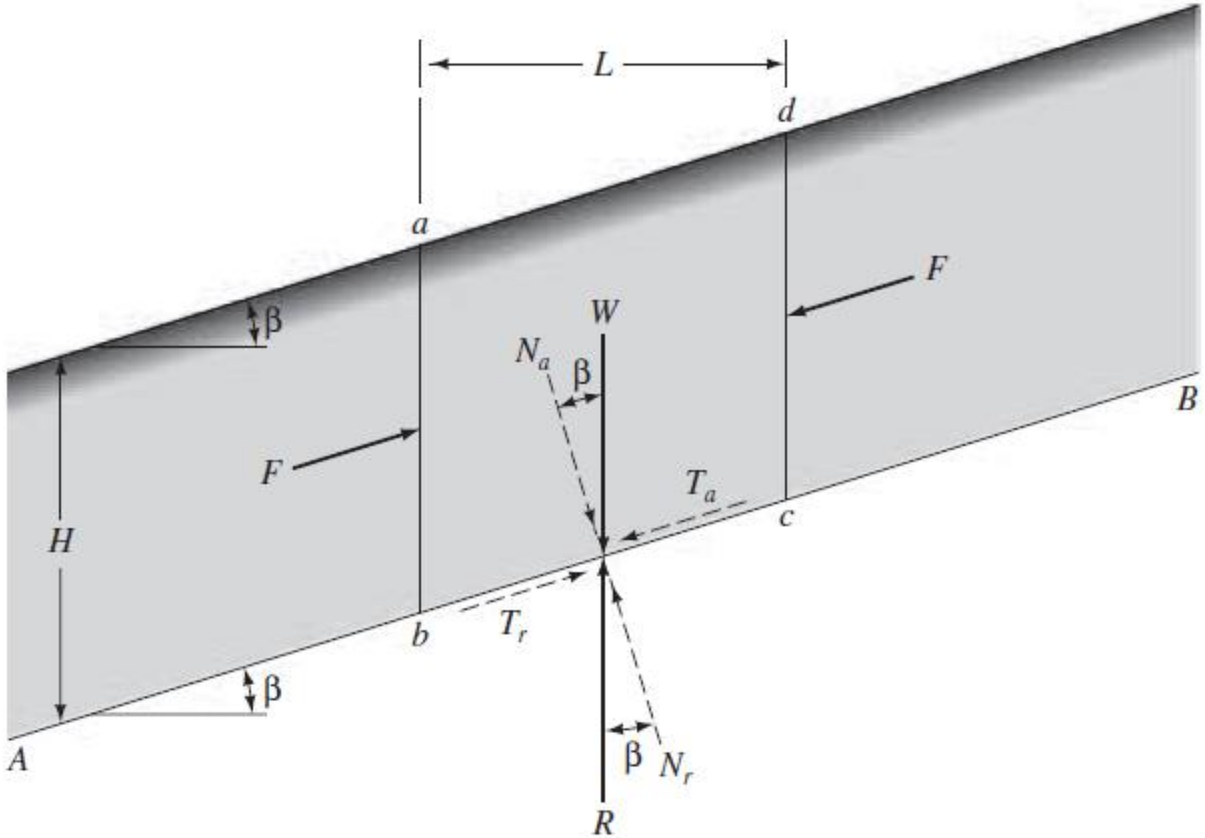
c' = cohesion

ϕ' = drained angle of friction

σ' = effective normal stress on the potential failure surface

- Stability of Infinite Slopes;

An infinite slope is one in which *L* is much greater than the slope height.



$$\tau_f = c' + \sigma' \tan \phi'$$

$$W = (\text{volume of the soil element}) \times (\text{unit weight of soil}) = \gamma L H$$

The weight, W, can be resolved into two components:

1. Force perpendicular to the plane $AB = N_a = W \cos \beta = \gamma L H \cos \beta$.
2. Force parallel to the plane $AB = T_a = W \sin \beta = \gamma L H \sin \beta$. Note that this is the force that tends to cause the slip along the plane.

The effective normal stress σ and the shear stress τ at the base of the slope element can be given as;

$$\sigma' = \frac{N_a}{\text{area of the base}} = \frac{\gamma L H \cos \beta}{\left(\dfrac{L}{\cos \beta}\right)} = \gamma H \cos^2 \beta \qquad \tau = \frac{T_a}{\text{area of the base}} = \frac{\gamma L H \sin \beta}{\left(\dfrac{L}{\cos \beta}\right)} = \gamma H \cos \beta \sin \beta$$

The reaction to the weight W is an equal and opposite force R. The normal and tangential components of R with respect to the plane AB are N_r and T_r:

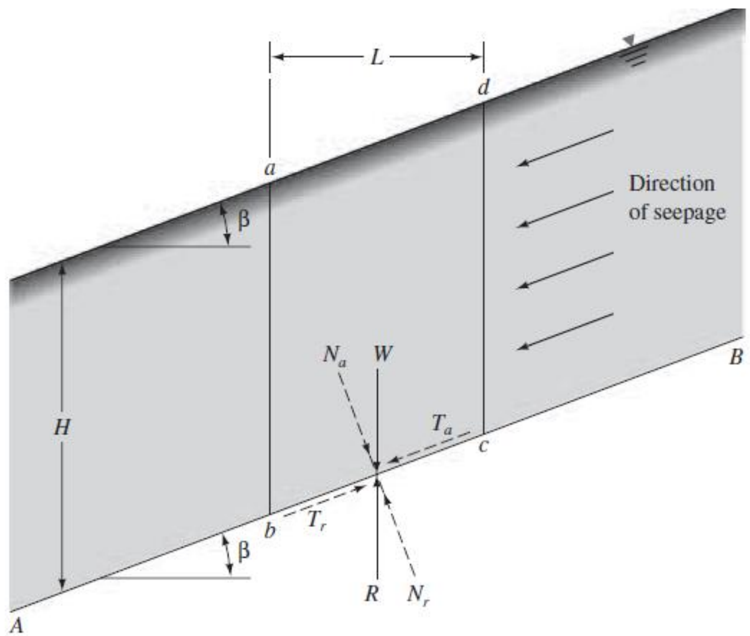
$$N_r = R \cos \beta = W \cos \beta$$

$$T_r = R \sin \beta = W \sin \beta$$

For equilibrium;

$$FS_s = \frac{c'}{\gamma H \cos^2 \beta \tan \beta} + \frac{\tan \phi'}{\tan \beta}$$

If there is seepage through the soil and the ground water level coincides with the ground surface as shown in Figure, the factor of safety with respect to strength can be obtained as



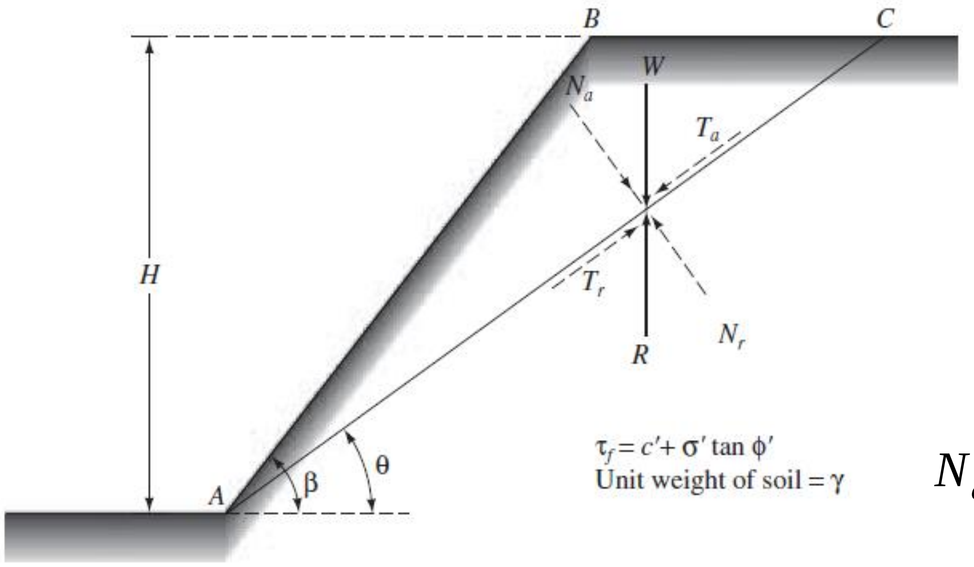
$$FS_s = \frac{c'}{\gamma_{sat} H \cos^2 \beta \tan \beta} + \frac{\gamma'}{\gamma_{sat}} \frac{\tan \phi'}{\tan \beta}$$

- Stability of Finite Slopes;

- When the value of *Hcr* approaches the height of the slope, the slope is generally considered finite.
- When analyzing the stability of a finite slope in a homogeneous soil, for simplicity, we need to make an assumption about the general shape of the surface of potential failure.

Analysis of Finite Slope with Plane Failure Surface (Culmann's Method)

This analysis is based on the assumption that the failure of a slope occurs along a plane



The weight of the wedge *ABC* *W*:

$$W = \frac{1}{2}(H)(\overline{B}\overline{C})(1)(\gamma)$$

$$= \frac{1}{2}\gamma H^2 \left[\frac{\sin(\beta-\theta)}{\sin\beta - \sin\theta}\right]$$

$$N_a = W\cos\theta = \frac{1}{2}\gamma H^2 \left[\frac{\sin(\beta-\theta)}{\sin\beta\sin\theta}\right]\cos\theta$$

$$T_a = W\sin\theta = \frac{1}{2}\gamma H^2 \left[\frac{\sin(\beta-\theta)}{\sin\beta\sin\theta}\right]\sin\theta$$

$$\sigma = \frac{1}{2}\gamma H \left[\frac{\sin(\beta-\theta)}{\sin\beta\sin\theta}\right]\sin\theta\cos\theta$$

$$\tau = \frac{1}{2}\gamma H \left[\frac{\sin(\beta-\theta)}{\sin\beta\sin\theta}\right]\sin^2\theta$$

$$\tau_d = c_d + \sigma\tan\phi_d = c_d + \frac{1}{2}\gamma H \left[\frac{\sin(\beta-\theta)}{\sin\beta\sin\theta}\right]\cos\theta\sin^2\theta\tan\phi_d$$

$$c_d = \frac{1}{2}\gamma H\left[\frac{\sin(\beta-\theta)(\sin\theta-\cos\theta\tan\phi_d)}{\sin\beta}\right]$$

$$\frac{\partial c_d}{\partial\theta} = 0$$

$$\frac{\partial c_d}{\partial\theta}\left[\sin(\beta-\theta)(\sin\theta-\cos\theta\tan\phi_d\right] = 0$$

$$\theta_{cr} = \frac{\beta+\phi_d}{2}$$

$$c_d = \frac{\gamma H}{4}\left[\frac{1-(\cos\beta-\phi_d)}{\sin\beta\cos\phi_d}\right]$$

Maximum slope height c_d=c ve $\phi_d=\phi$

$$H_{cr} = \frac{4c}{\gamma}\left[\frac{\sin\beta\cos\phi_d}{1-(\cos\beta-\phi_d)}\right]$$

- ***Analysis of Finite Slope with Circularly Cylindrical Failure Surface—General***

Various procedures of stability analysis may, in general, be divided into two major classes:

1. *Mass procedure*. In this case, the mass of the soil above the surface of sliding is taken as a unit. This procedure is useful when the soil that forms the slope is assumed to be homogeneous, although this is hardly the case in most natural slopes.

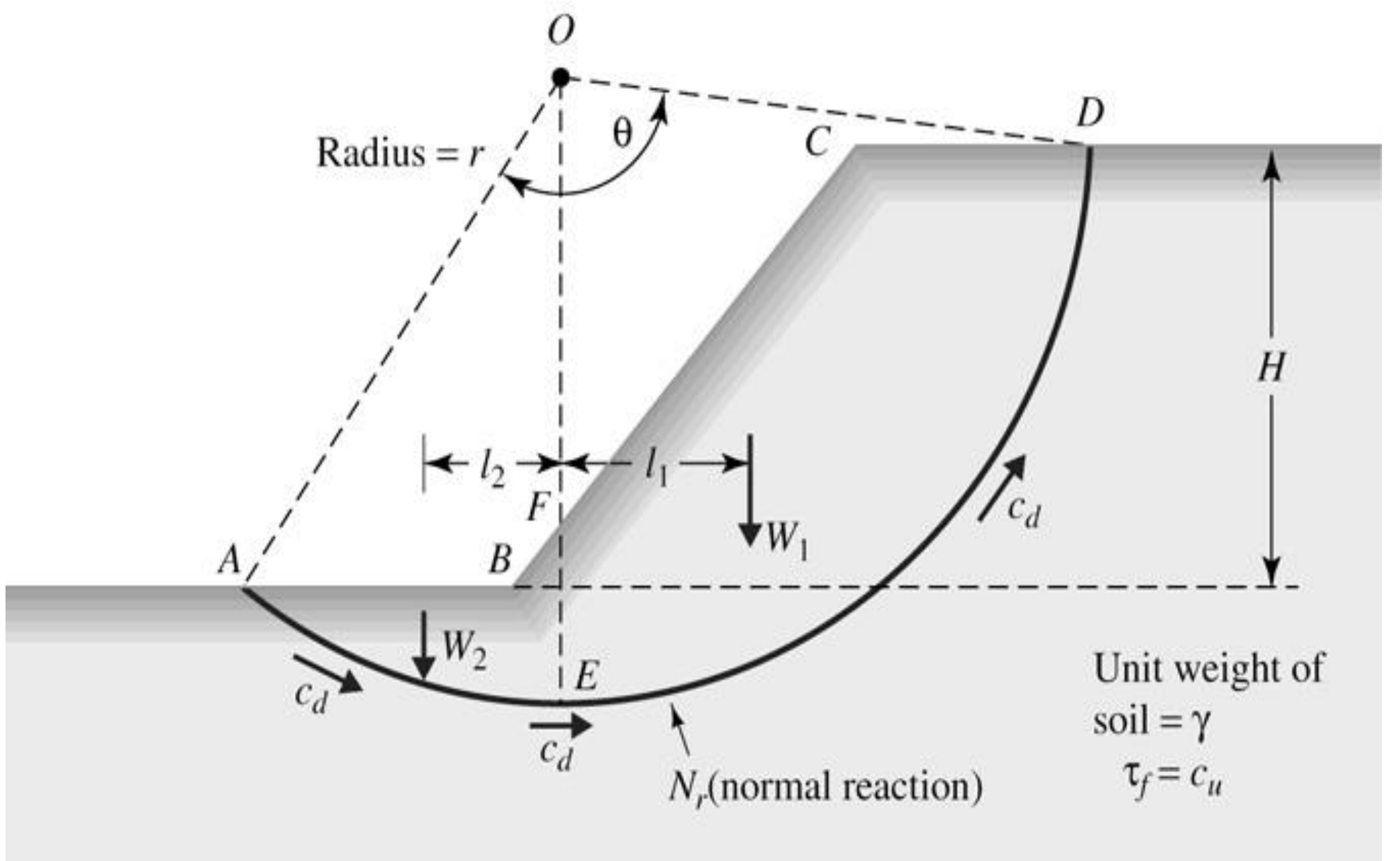
2. *Method of slices*. In this procedure, the soil above the surface of sliding is divided into a number of vertical parallel slices. The stability of each of the slices is calculated separately. This is a versatile technique in which the nonhomogeneity of the soils and pore water pressure can be taken into consideration. It also accounts for the variation of the normal stress along the potential failure surface.

Mass procedure : ***Slopes in Homogeneous Clay Soil (Undrained Condition)*** (ϕ=0, c>0)

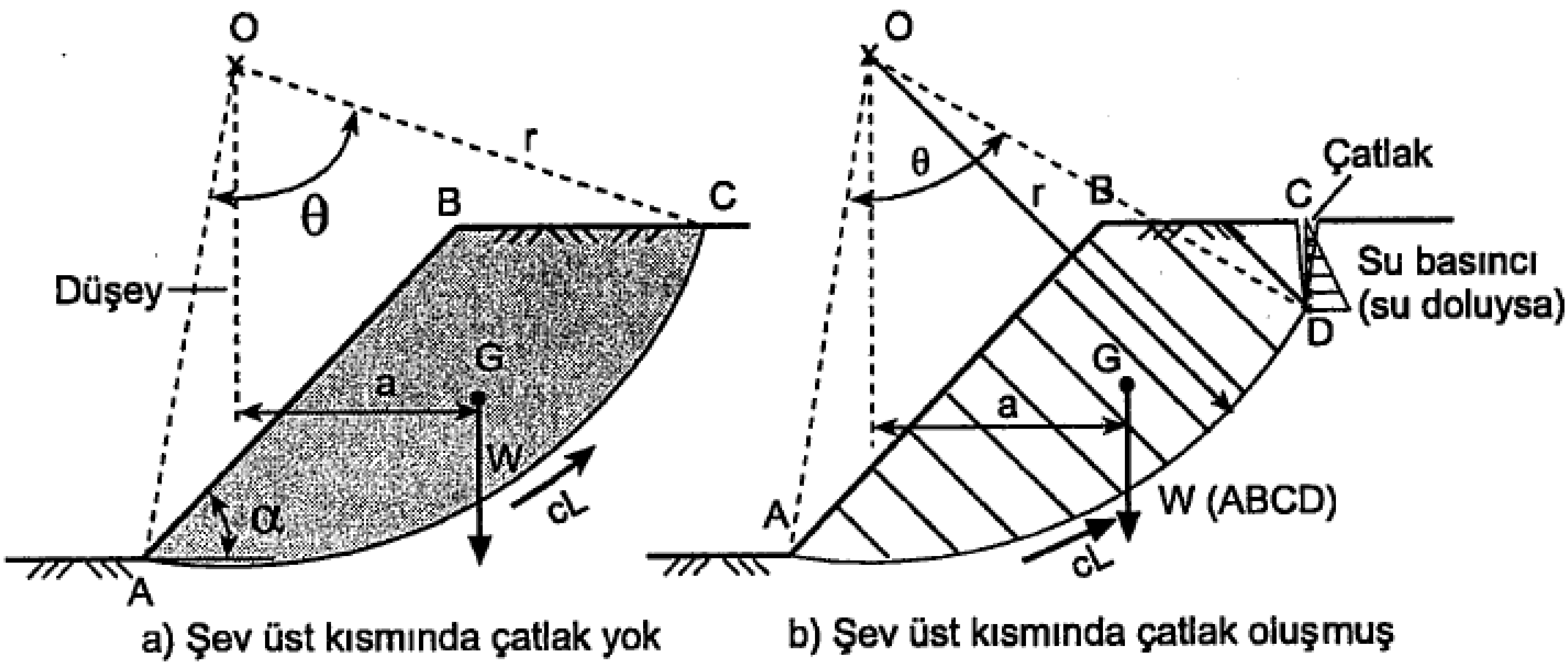
$$\Sigma M_D = W l_1$$

$$\Sigma M_R = c_d R L = c_d R^2$$

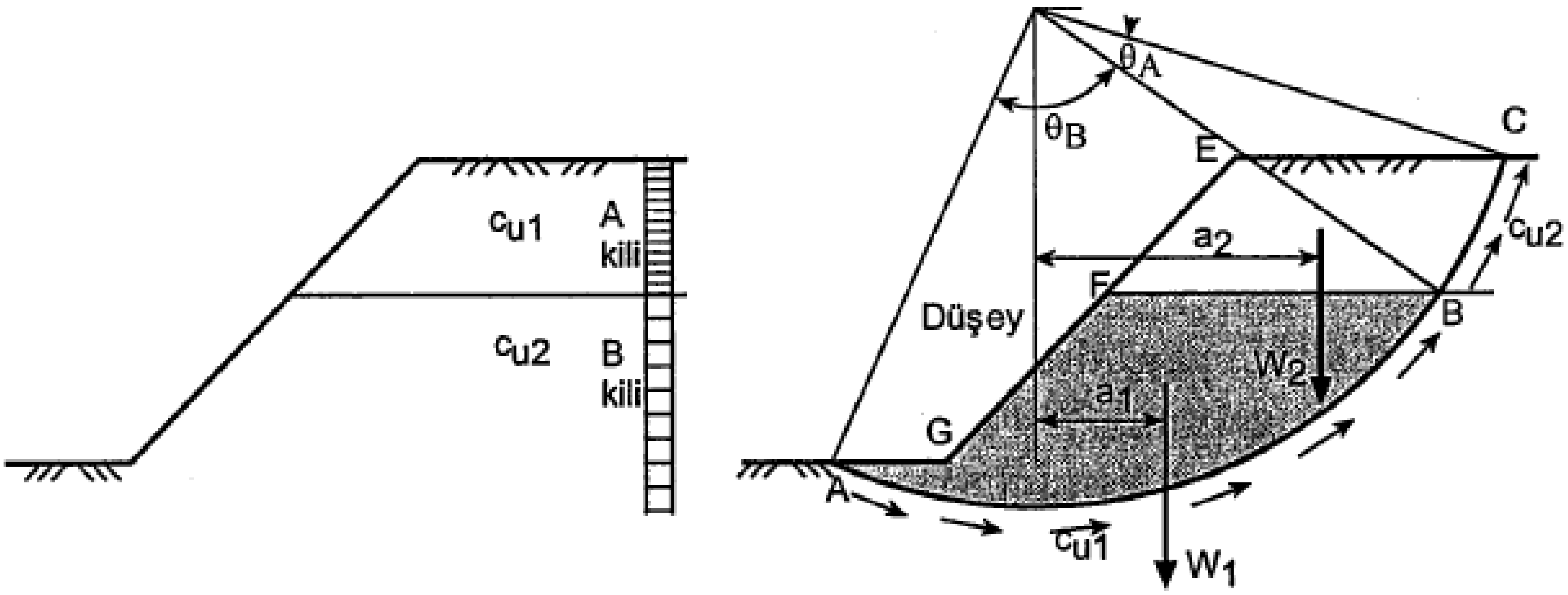
$$FS = \frac{c_d R^2}{W l_1}$$



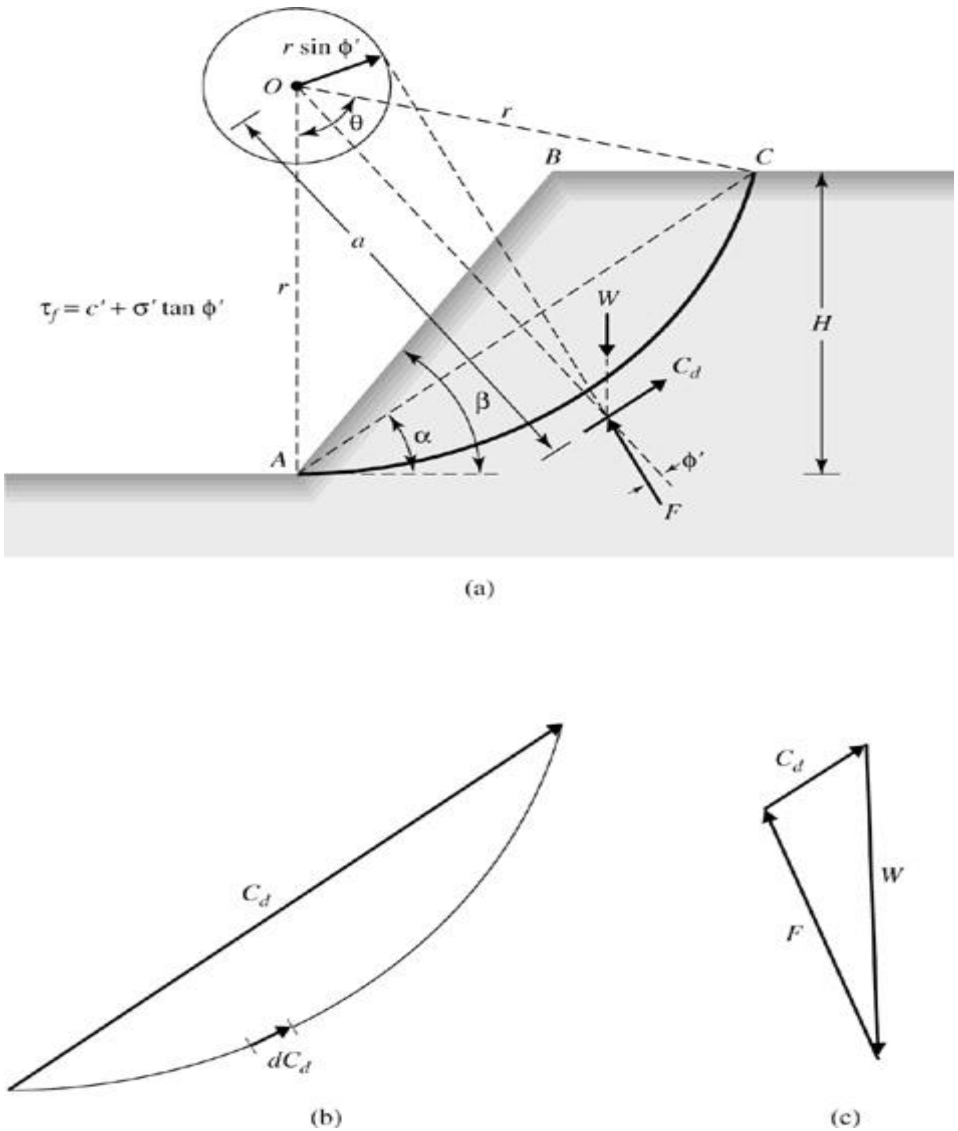
Layered cohesive soil (ϕ=0)



Layered cohesive soil (ϕ=0)



Mass procedure :Slopes in Homogeneous Soil (ϕ>0, c>0)



Rsinϕ Dairesi Yöntemi

Weight of the soil wedge
W=(area of ABC)*(γ)

1. C_d- the resultant of the cohesive force :

$$C_d = c_d(\overline{A}\,\overline{C})$$

$$C_d(a) = c_d(\widehat{AC})r$$

2. F- the resultant of the normal and frictional forces along the surface of sliding

$$c_d = \gamma H[f(\alpha,\beta,\theta,\phi)]$$

$$\frac{c'}{\gamma H_{cr}} = f(\alpha, \beta, \theta, \phi') = m$$

where;
m stability number

Mass procedure : Taylor's Chart(1937)

Undrained condition is valid for saturated clay ; Φu=0

Using total stres, factor of safety;

$$FS = \frac{\sum r\{c' b \sec\alpha + (N - ub\sec\alpha) tg\phi'\}}{\sum dW.x + \sum k.dW.e + A_L.a_L - A_R.a_R + L.d - \sum N.f}$$

$c' \rightarrow cu$ $\quad u \rightarrow 0 \quad \phi' \rightarrow \phi u = 0$

For circular failure surface;
(r=R), (x=Rsinα)

$$FS = \frac{\sum c_u b.\sec\alpha}{\sum dW.\sin\alpha}$$

Mass procedure : **Taylor's Charts (1937)**

$$FS = \frac{\sum c_u b.\sec\alpha}{\sum dW.\sin\alpha}$$

Where;

dW = weight of slide = b.h.γ

β:slope angle

H: height of slope

$$FS = \frac{c_u}{\gamma.H} \frac{\sum b.\sec\alpha}{\sum \frac{h}{H} b.\sin\alpha} = \frac{c_u}{\gamma.H}\frac{1}{S} \quad \text{veya} \quad \frac{c_u}{\gamma.H}.N_s$$

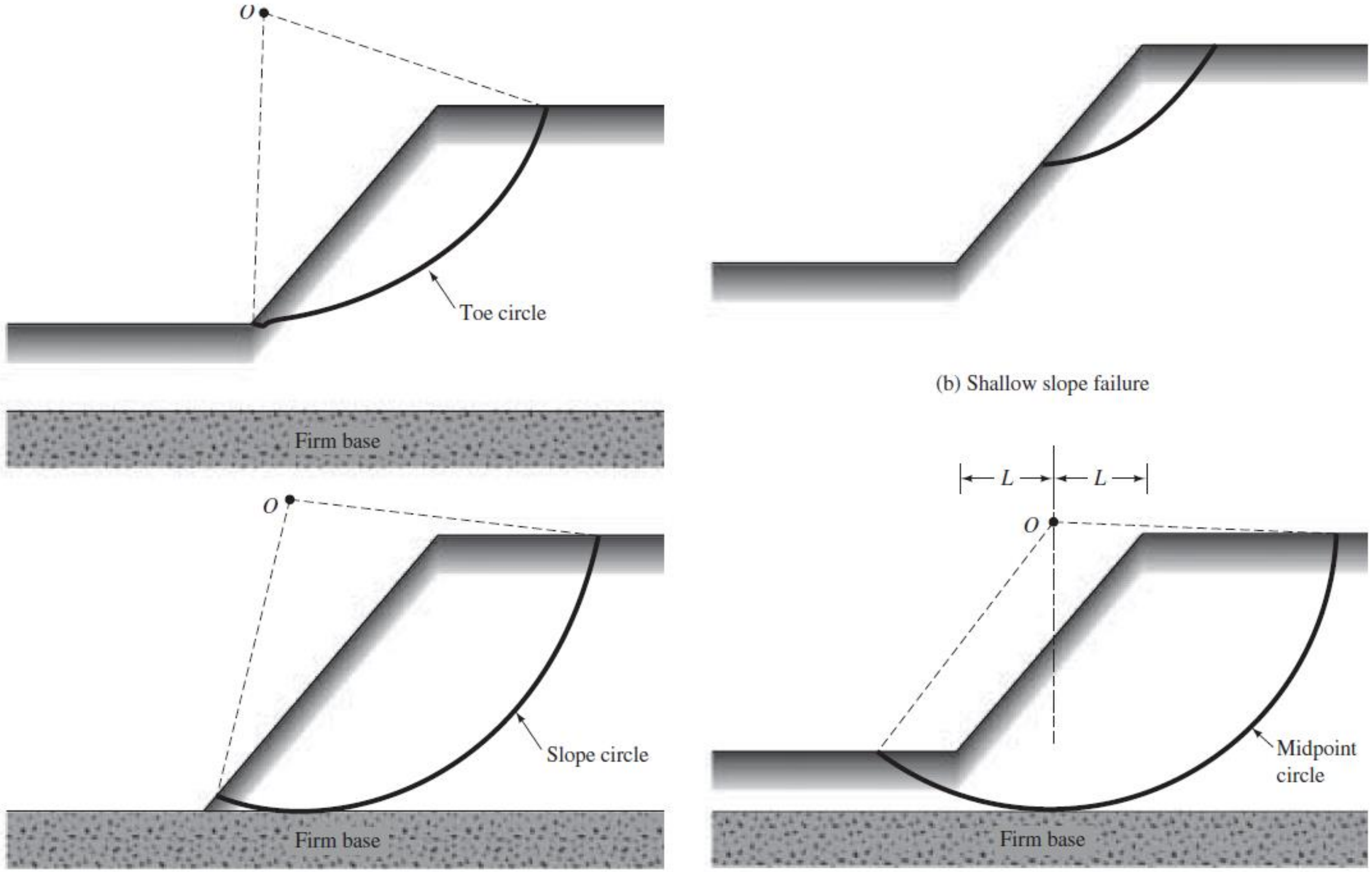
where;

Ns: stability number

Mass procedure : **Taylor's Charts (1937)**

- Taylor's chart can be used for undrained condition.
- The failure surface is circular and shear strength is determined using Mohr-Coulomb failure criteria.
- Tension cracks are ignored.
- For slope angle greater than 53, the critical circle is always a toe circle.
- For < 53, the critical circle may be a toe, slope, or midpoint circle, depending on the location of the firm base under the slope.

Mass procedure : ***Taylor's Chart(1937)***



(a) Slope failure

(b) Shallow slope failure

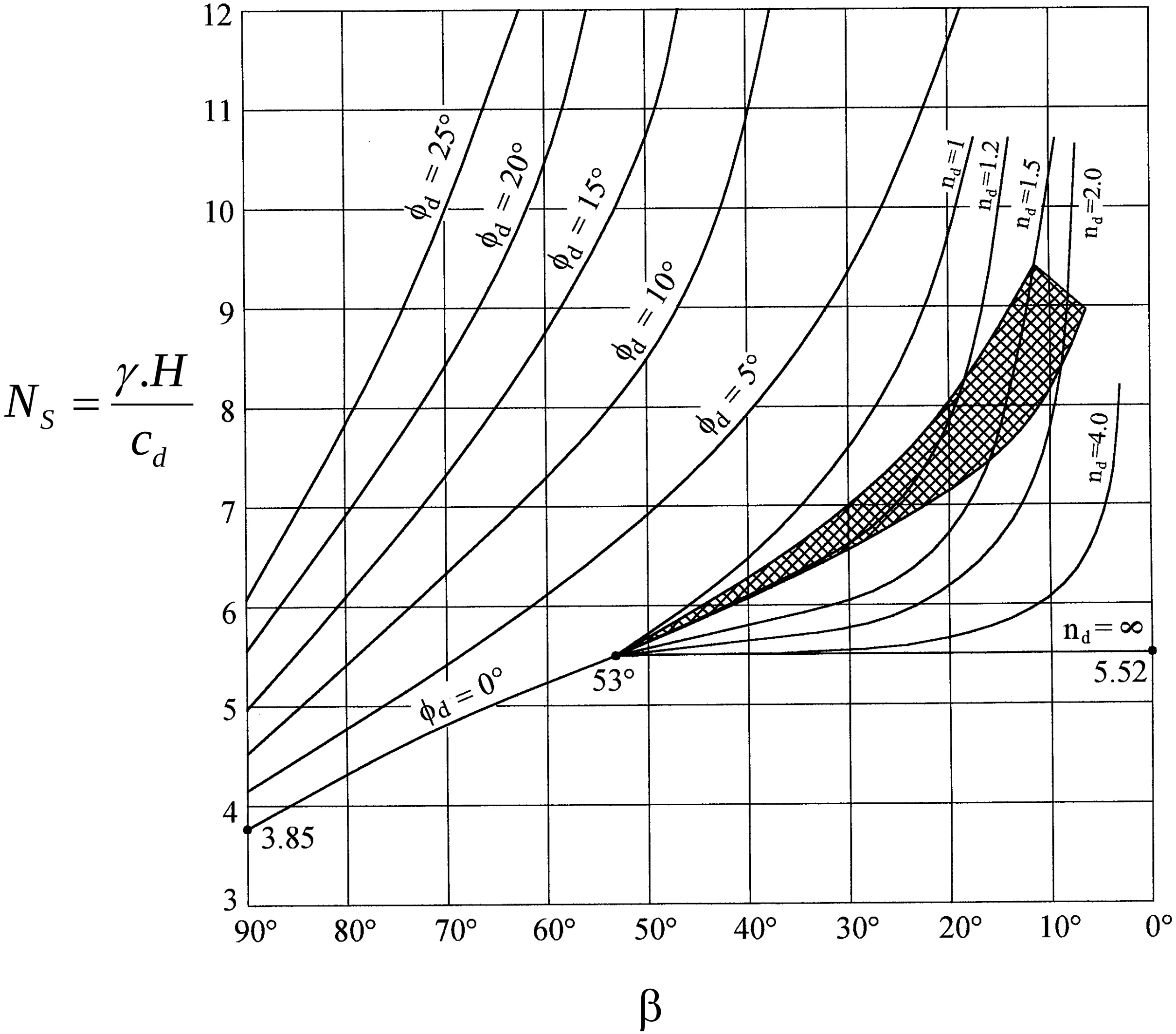
(c) Base failure

Mass procedure : **Taylor's Chart(1937)**

$$c_d = \frac{c}{FS}$$

$$\phi_d = tg^{-1}\left(\frac{tg\phi}{FS}\right)$$

$$N_S = \frac{\gamma . H}{c_d}$$



Mass procedure : ***Taylor's Chart(1937)***

Taylor's charts also developed for $\phi > 0°$ homogenous soil.

$$c_d = \frac{c}{FS} \qquad \phi_d = tg^{-1}\left(\frac{tg\phi}{FS}\right)$$

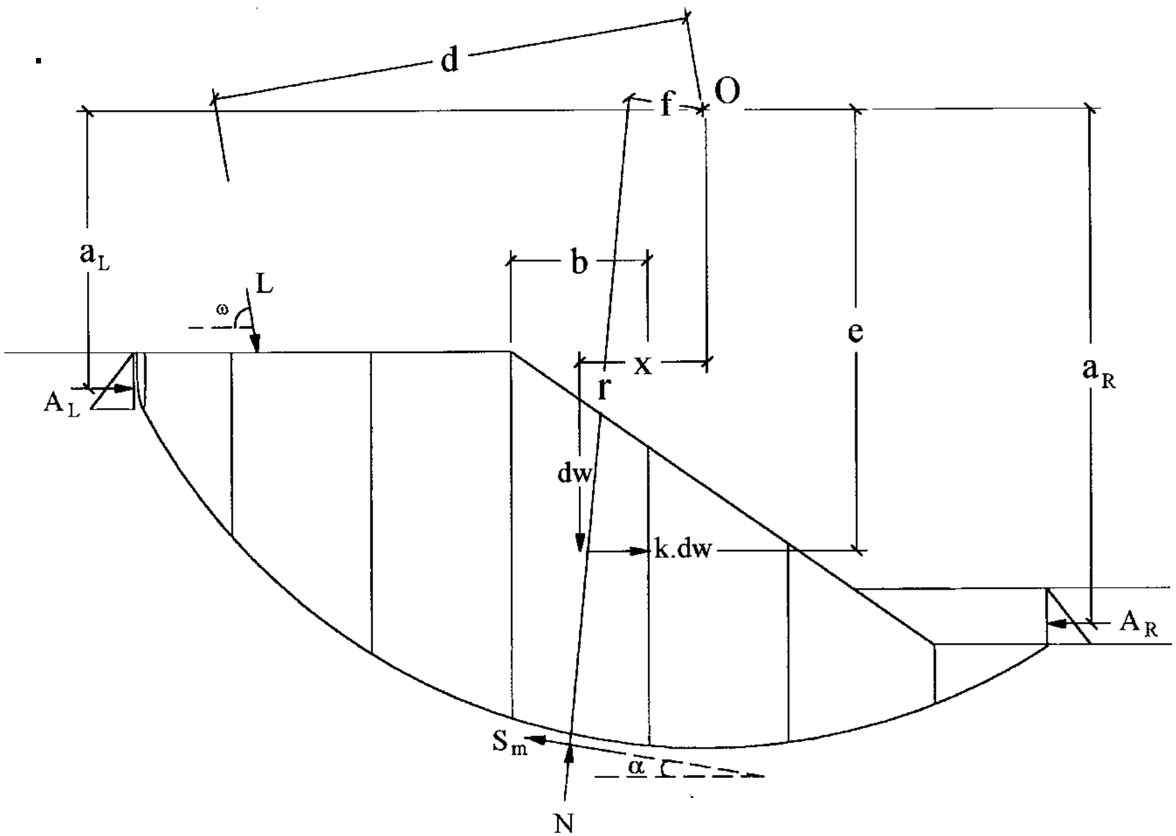
$$N_s = \frac{\gamma . H}{\frac{c}{FS}}$$

Method of slices

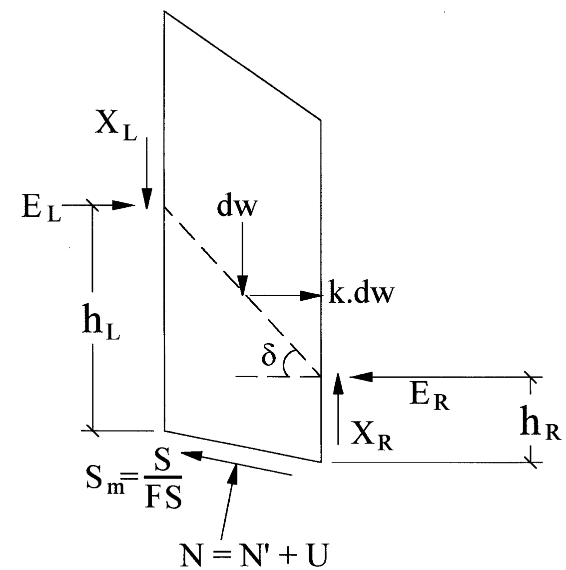
- Ordinary Method of Slices
- Bishop Simplified Method
- Janbu Simplified Method
- Bishop’s Rigorous Method
- Janbu’s Generalized Method
- Spencer’s Method
- Morgenstren-Price Method
- General Limit Equilibrium Method

Method of slices

Stability analysis using the method of slices can be explained by referring to Figure in which *AC* is an arc of a circle representing the trial failure surface. The soil above the trial failure surface is divided into several vertical slices. The width of each slice need not be the same.



L = external load,
AL= pore water pressure,
AR =pore water pressure



Forces acting on slice

Method of slices

Equations	Condition
n	Moment equilibrium for each slice
$2n$	Force equilibrium in two directions (for each slice)
n	Mohr–Coulomb relationship between shear strength and normal effective stress
$4n$	**Total number of equations**

Unknowns	Variable
1	Factor of safety
n	Normal force at base of each slice, N'
n	Location of normal force, N'
n	Shear force at base of each slice, S_m
$n-1$	Interslice force, Z
$n-1$	Inclination of interslice force, θ
$n-1$	Location of interslice force (line of thrust)
$6n-2$	**Total number of unknowns**

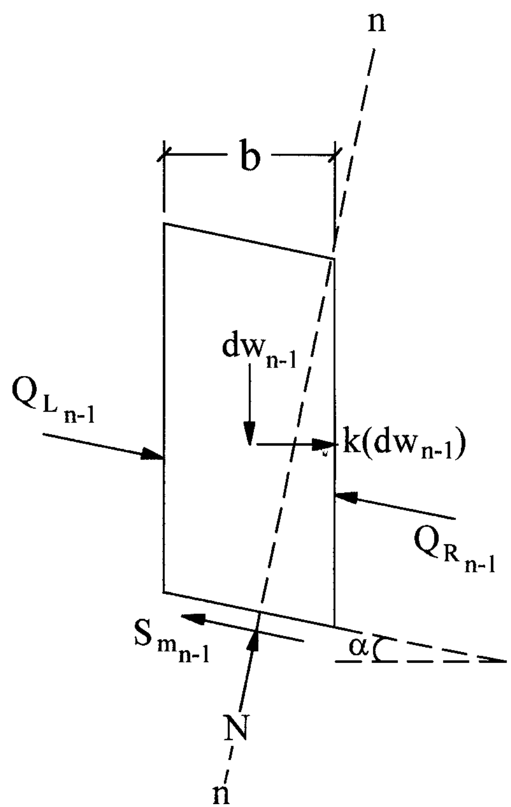
There are 6n-2 unknowns

4 equations can be written for the limit equilibrium of the system

Providing the number of unknowns can be reduced by making some simplifying assumptions

Ordinary Method of Slices

- The method assumes that the resultant of the interslice forces for all slices is parallel to the base of the slice.
- This assumption fails to satisfy interslice equilibrium, where adjasent slices have different base inclination



STEPS FOR METHOD OF SLICES

1. Assume trial failure surface. The soil above the trial failure is divided into several vertical slices. Calculate the weight of each slice.
2. Calculate vertical and horizontal components of slice weight.
3. Multiply the normal forces (dWCosα) at base of each slice by tgϕ and find sum of these forces.
4. Multiply the base of slice length by cohesion (c) and find sum of these forces.
5. Find the sum of the horizontal forces.
6. Factor of safety, F=(3+4)/(5).

$$F = \frac{\sum_1^n [(W_i \cos(\alpha_i) - u_i l_i) \tan \phi_i + c_i l_i]}{\sum_1^n W_i \sin(\alpha_i)}$$

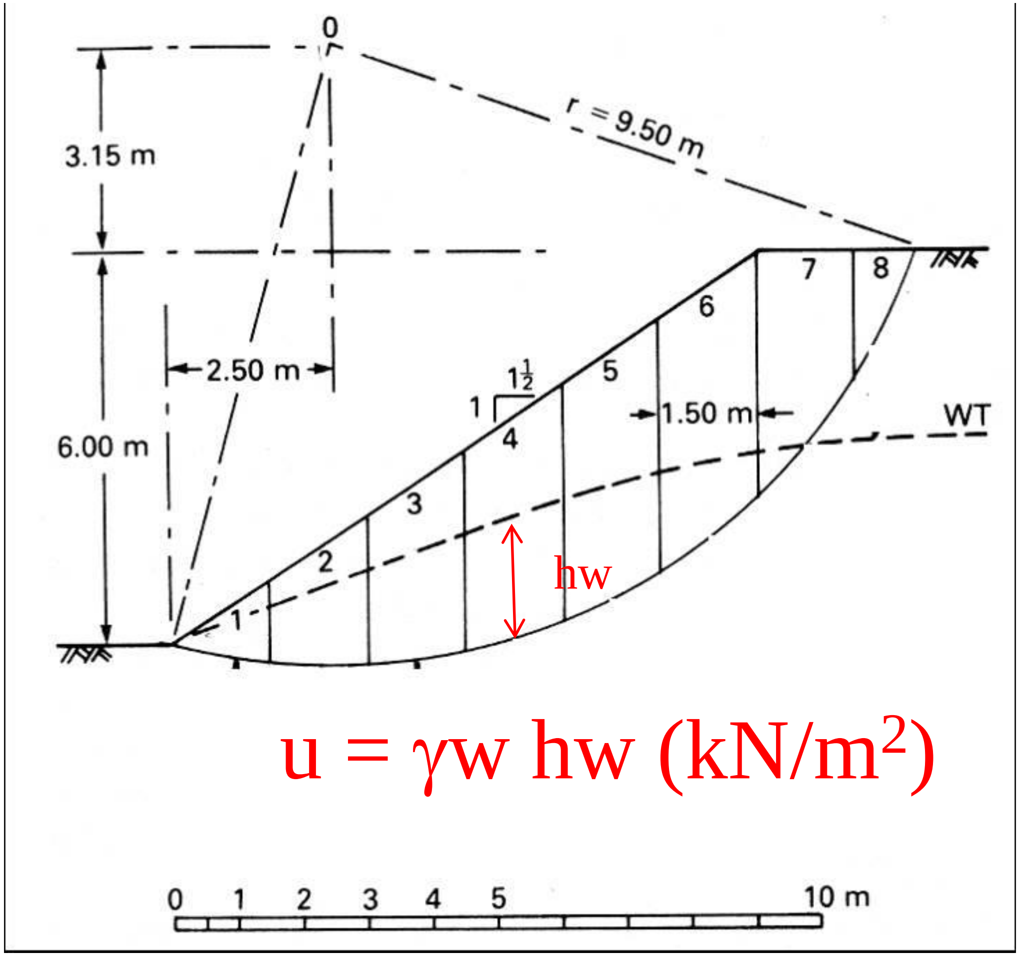
METHOD OF SLICES-Drained Conditions

- c': effective cohesion
- ϕ': effective internal firiction angle
- u :pore water pressure at base of slice

$$FS = \frac{\sum r\{c'b\sec\alpha + (N - ub\sec\alpha)tg\phi'\}}{\sum dW.x + A_L.a_L - A_R.a_R + L.d - \sum N.f}$$

$$F = \frac{\sum\left[c'\,b\,Sec\alpha + \left(dw\,Cos\alpha - ub\,Sec\alpha\right)tg\,\phi'\right]}{\sum dw\,Sin\alpha}$$

Pore water pressure effect



$$u = \gamma w \ hw \ (kN/m^2)$$

Soil Type	Method
$c=0$	Infinite slope
$c>0$ $\phi>0$	Cullman
$c>>0$ $\phi=0$	Circular surface ($r\sin\phi$)
$c>0$ $\phi>0$	Method of slices