UNIVERSITAS TRISAKTI
PRODI TEKNIK PERTAMBANGAN

Slope Stability

MTT6201 – MEKANIKA TANAH

12st session
1.5 hours

Lecturer :
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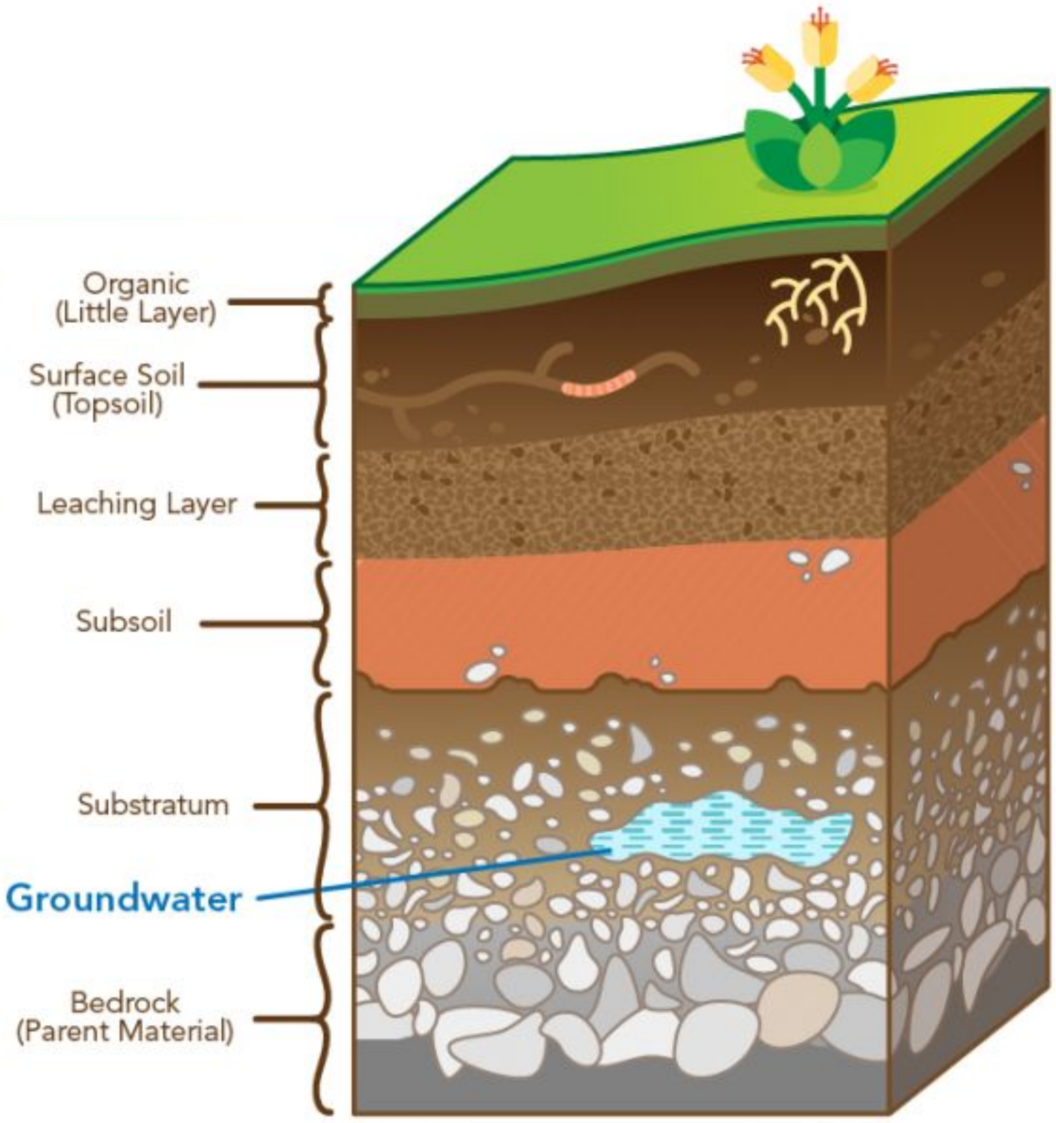


SYLLABUS

1. Introduction
2. Pengertian Tentang Tanah dan Batuan, Partikel Tanah
3. Analisis Ayakan dan Analysis Hydrometer
4. Hubungan Volume, Berat, Porositas, Kadar air, Kerapatan Relative Tanah
5. Konsistensi Tanah, Batas Plastis, Batas Cair
6. Klasifikasi tanah berdasarkan USDA, AASHTO, dan Unified
7. Tegangan Efektif dan penentuan tegangan bidang

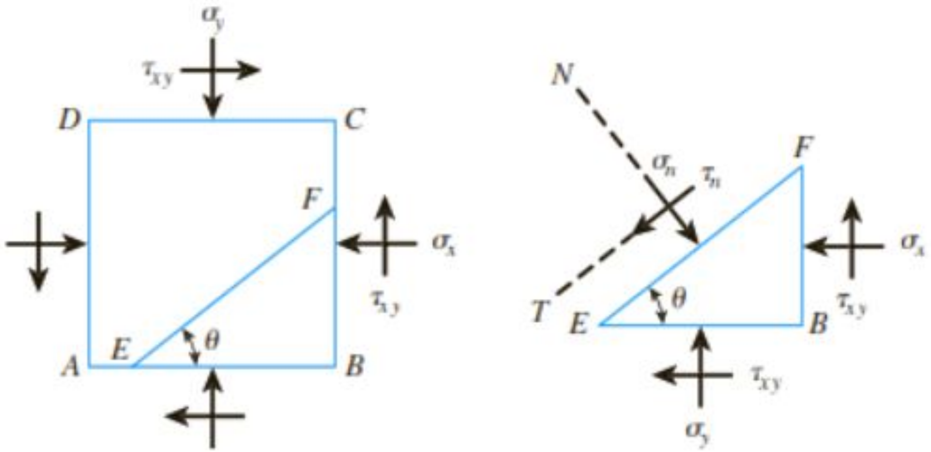
Mid Term

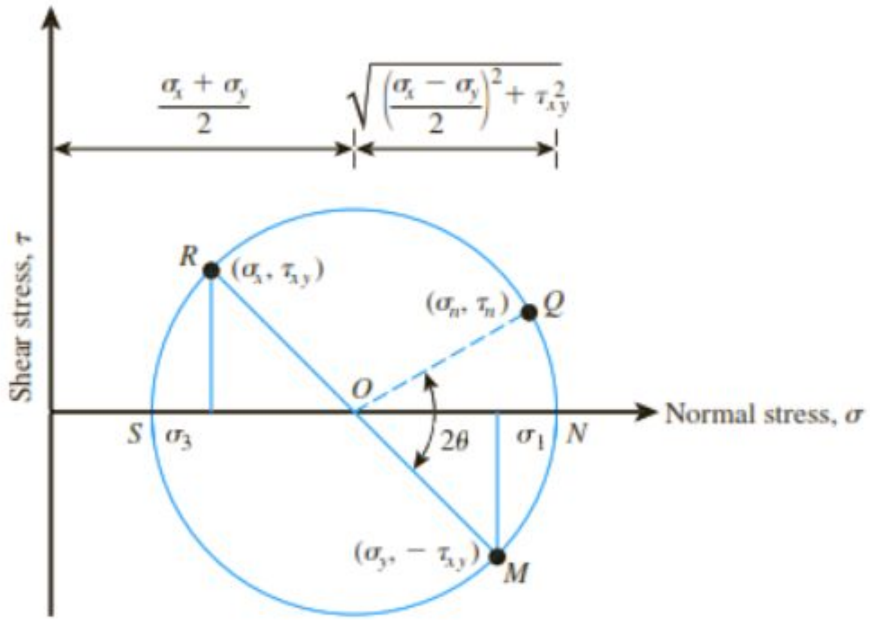
1. Konsep Tegangan, regangan, dan kekuatan tanah
2. Kekuatan geser tanah
3. Kompaksi
4. Permeabilitas dan rembesan
5. Aliran Air dalam tanah
6. **Kestabilan lereng**
7. Daya dukung tanah

Final Term

OBJECTIVE

Stresses in Soil





$$\sigma_n = \frac{\sigma_y + \sigma_x}{2} + \frac{\sigma_y - \sigma_x}{2}\cos 2\theta + \tau_{xy}\sin 2\theta$$

Major principal stress:

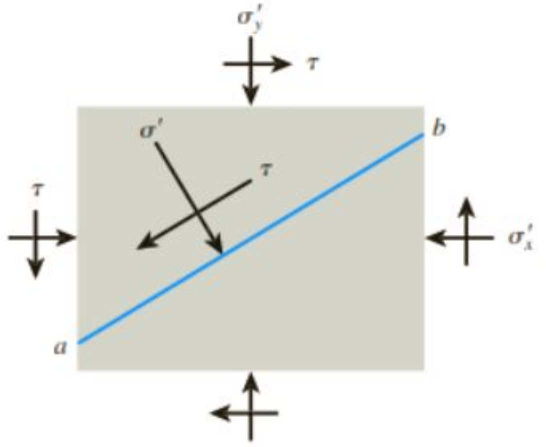
$$\sigma_n = \sigma_1 = \frac{\sigma_y + \sigma_x}{2} + \sqrt{\left[\frac{(\sigma_y - \sigma_x)}{2}\right]^2 + \tau_{xy}^2}$$

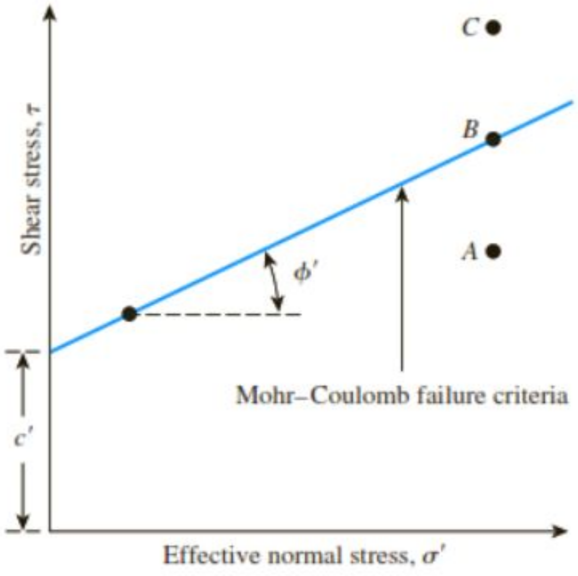
Minor principal stress:

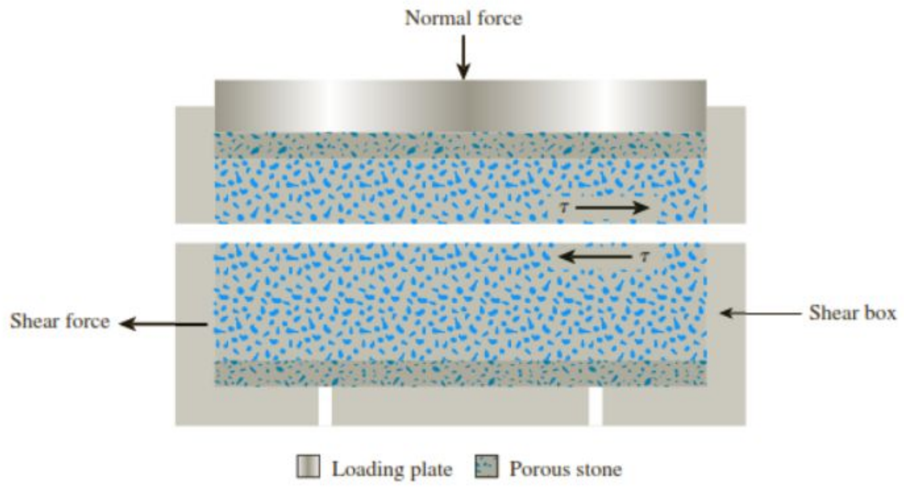
$$\sigma_n = \sigma_3 = \frac{\sigma_y + \sigma_x}{2} - \sqrt{\left[\frac{(\sigma_y - \sigma_x)}{2}\right]^2 + \tau_{xy}^2}$$

Source : Braja M Das, 2015;

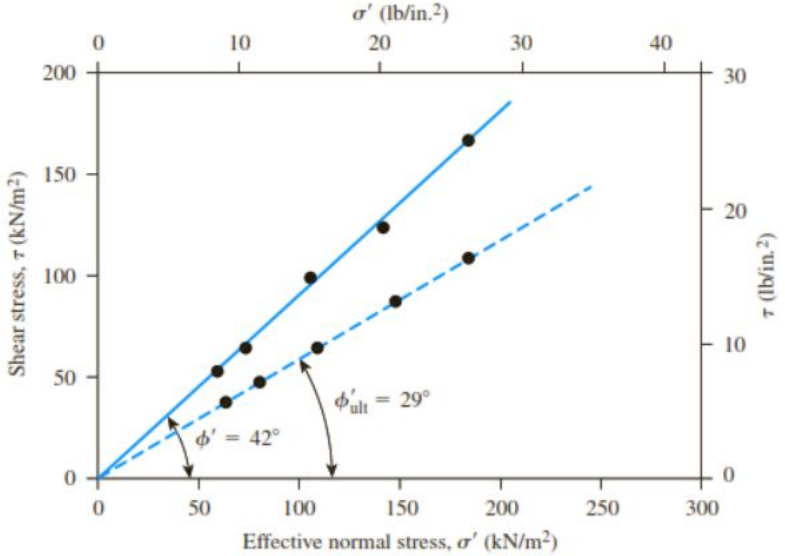
Shear Strength in Soil







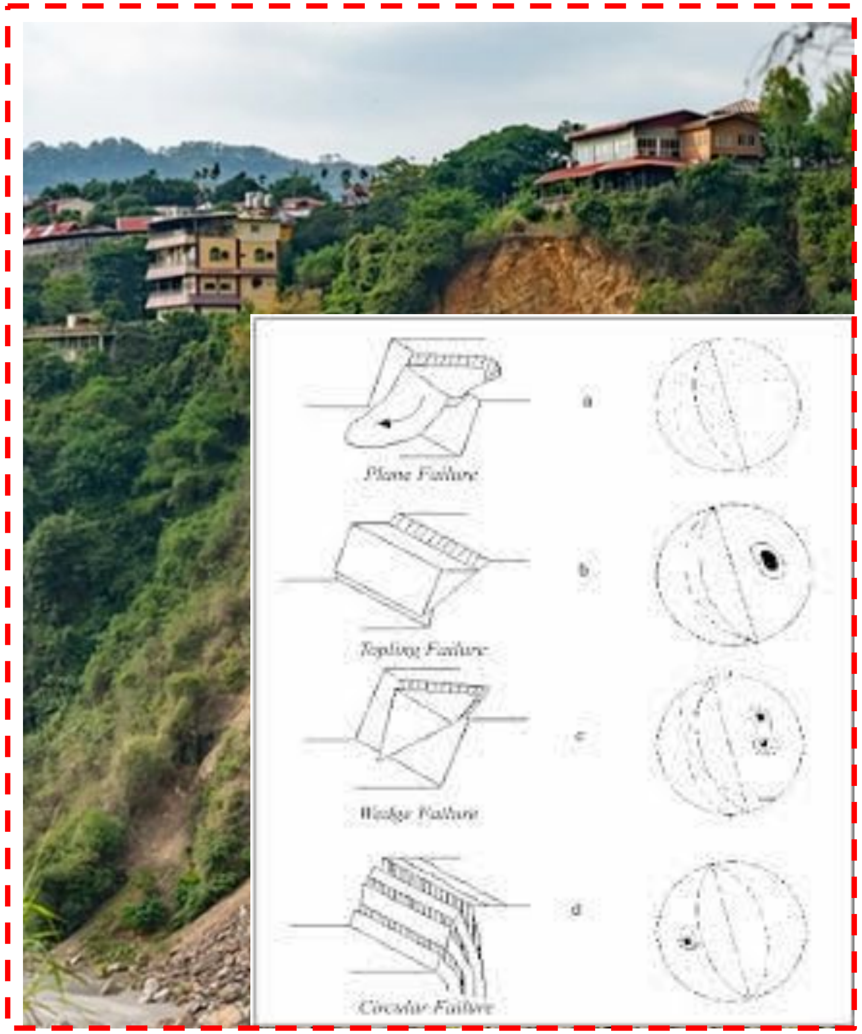
$$\tau_f = c + \sigma \tan \phi$$

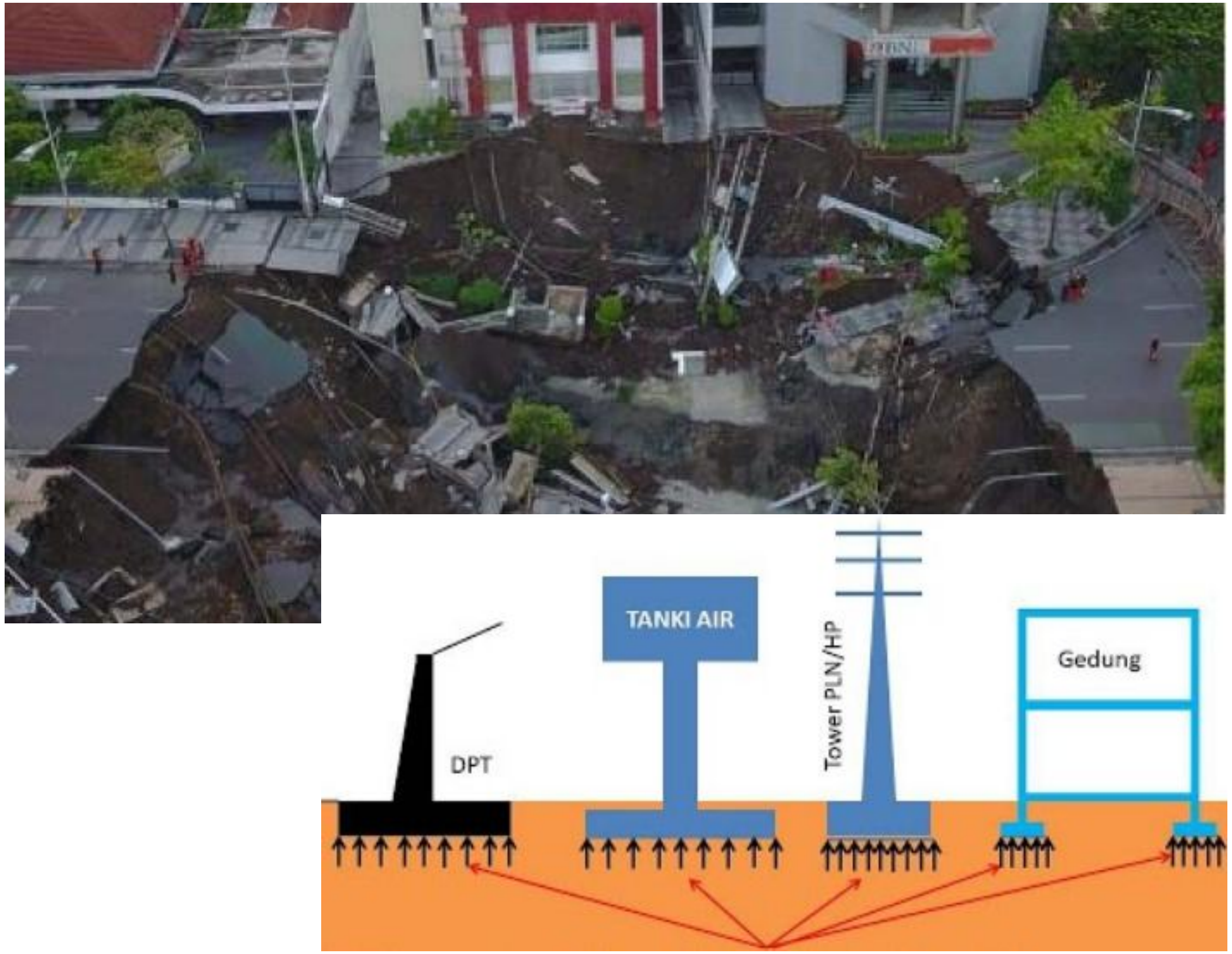


Source : Braja M Das, 2015;

Failure in Surface

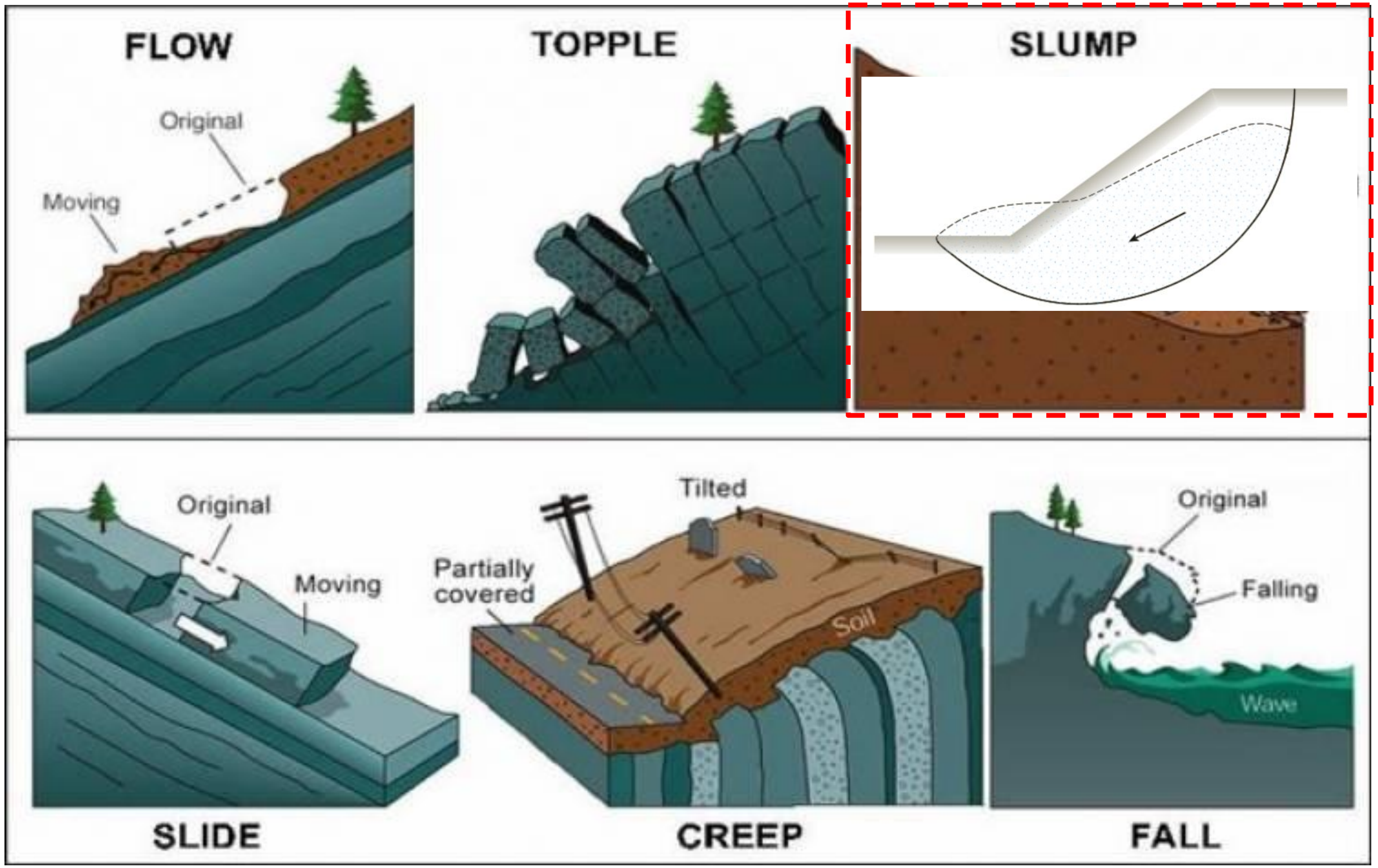
Shear Strength in Soil





Source : Braja M Das, 2015;

Types



Cruden and Varnes (1996) classied the slope failures into the following ve major categories. They are

1. **Fall.** This is the detachment of soil and/or rock fragments that fall down a slope
2. **Topple.** This is a forward rotation of soil and/or rock mass about an axis below the center of gravity of mass being displaced
3. **Slide.** This is the downward movement of a soil mass occurring on a surface of rupture
4. **Spread.** This is a form of slide by translation. It occurs by “sudden movement of water-bearing seams of sands or silts overlain by clays or loaded by silts”.
5. **Flow.** This is a downward movement of soil mass similar to a viscous fluid

Source : Braja M Das, 2015;

Slope failure

Concept of Safety – “Factor of Safety (FoS)”

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

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

$$\tau_d = c'_d + \sigma' \tan \phi'_d$$

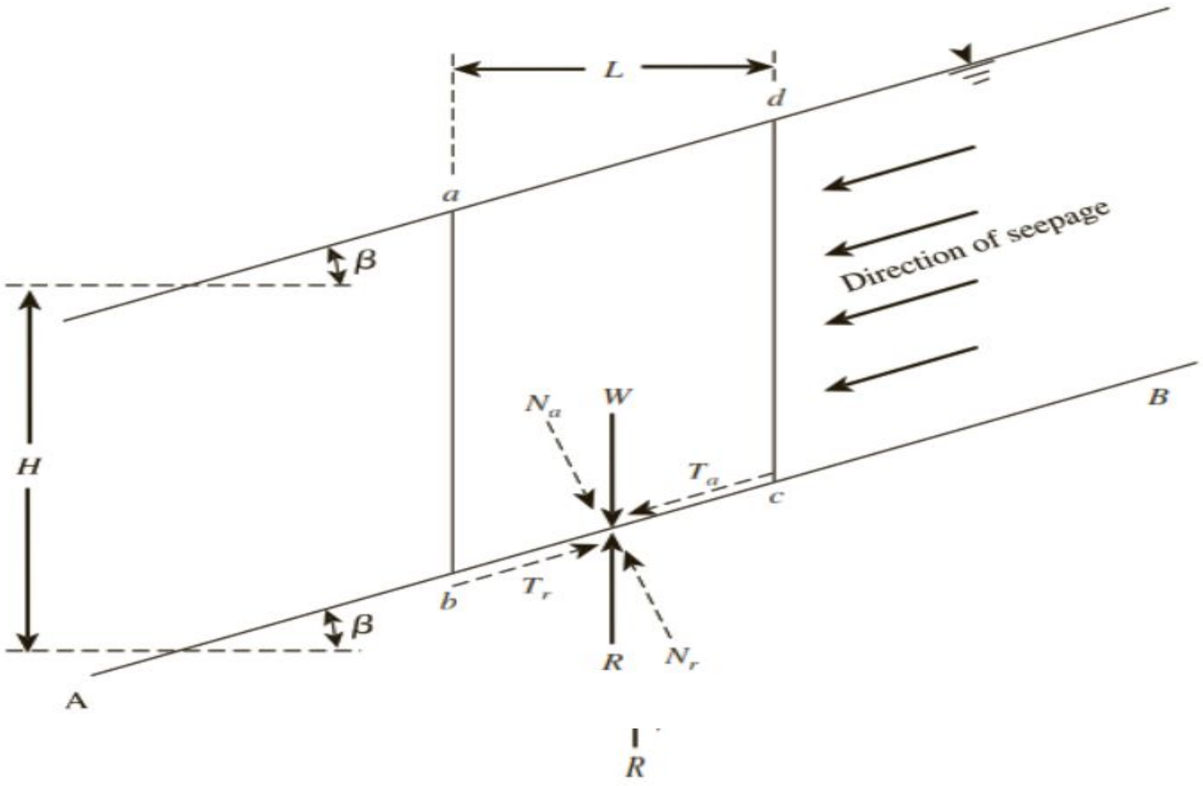
$$F_s = \frac{c' + \sigma' \tan \phi'}{c'_d + \sigma' \tan \phi'_d}$$

F_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

c' = cohesion
ϕ' = angle of friction
σ' = normal stress on the potential failure surface

When F_s is equal to 1, the slope is in a state of impending failure. Generally, a value of 1.5 for the factor of safety with respect to strength is acceptable for the design of a stable slope.

Simple case – Infinite Slope



With Seepage

$$W = (\text{Volume of soil element}) \times (\text{Unit weight of soil}) = \gamma LH$$

$$\sigma' = \frac{N_a}{\text{Area of base}} = \frac{\gamma LH \cos\beta}{\left(\frac{L}{\cos\beta}\right)} = \gamma H \cos^2\beta$$

$$\tau = \frac{T_a}{\text{Area of base}} = \frac{\gamma LH \sin\beta}{\left(\frac{L}{\cos\beta}\right)} = \gamma H \cos\beta \sin\beta$$

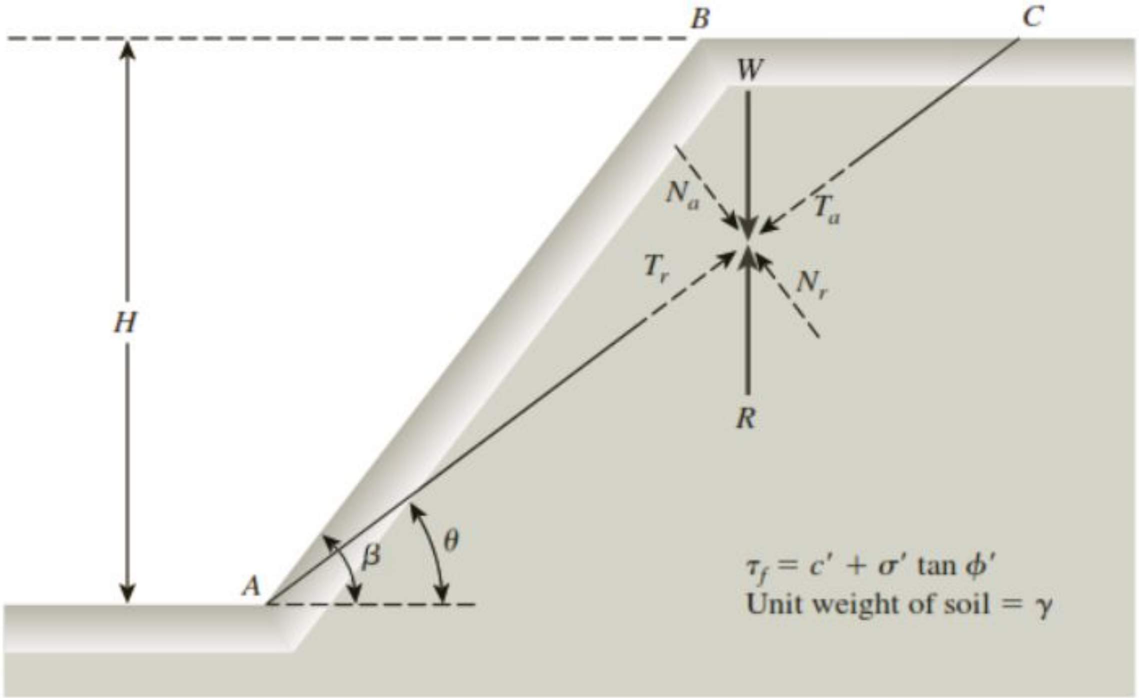
Without Seepage

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

With Seepage

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

Plane - Culmann



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

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

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

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

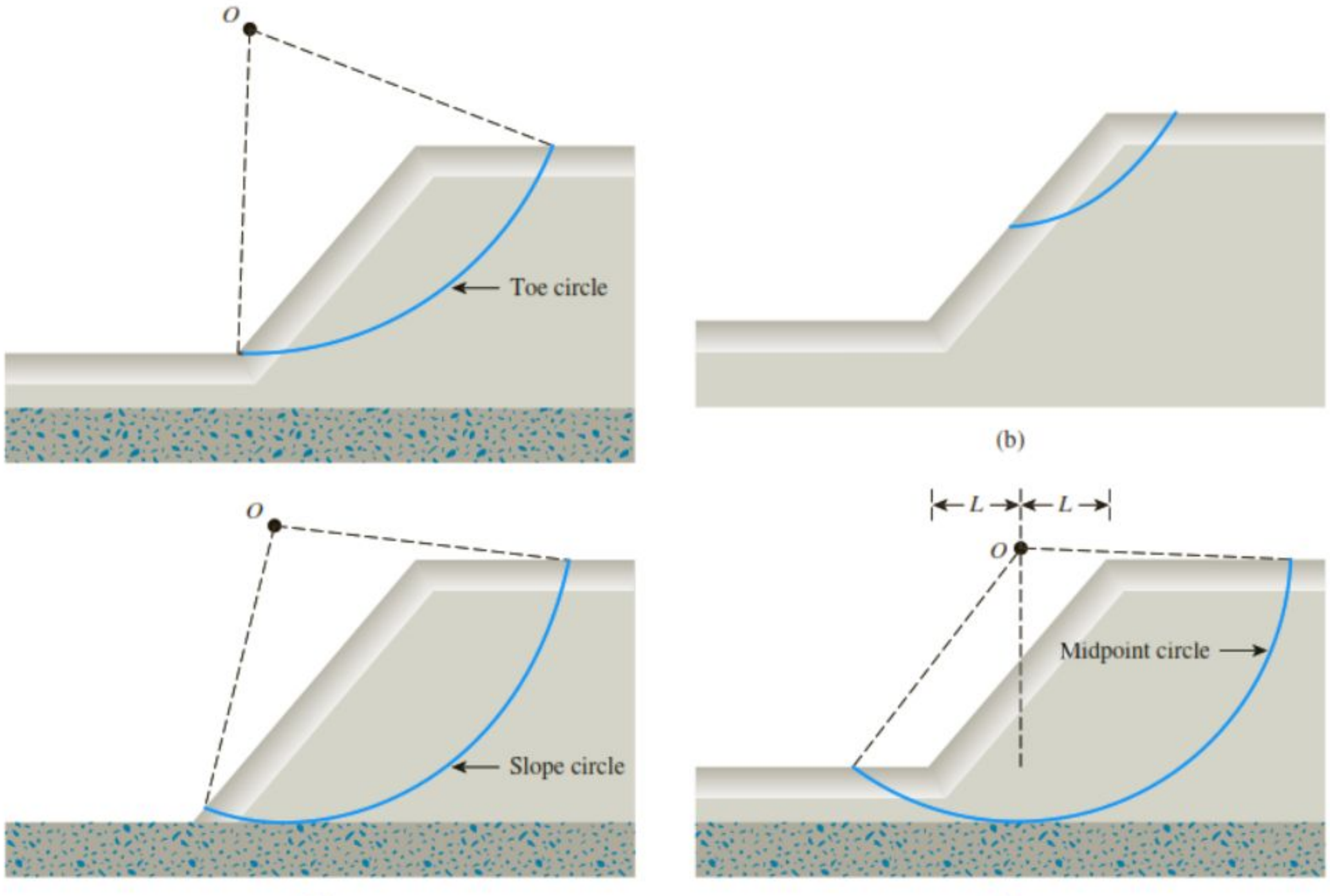
Culmann's analysis is based on the assumption that the failure of a slope occurs along a plane when the average shearing stress tending to cause the slip is more than the shear strength of the soil. Also, the most critical plane is the one that has a minimum ratio of the average shearing stress that tends to cause failure to the shear strength of soil.

$$c'_d = \frac{\gamma H}{4}\left[\frac{1-\cos(\beta-\phi'_d)}{\sin\beta\ \cos\phi'_d}\right]$$

The maximum height of the slope for which critical equilibrium occurs

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

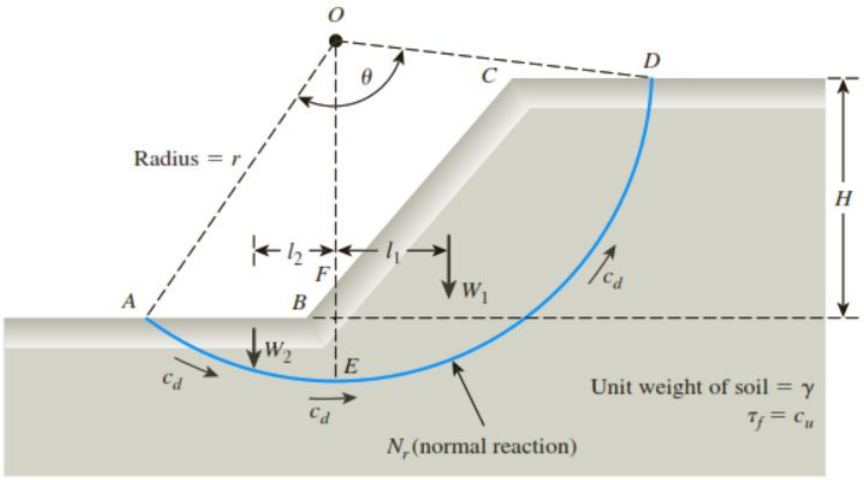
Circular – Failure Modes



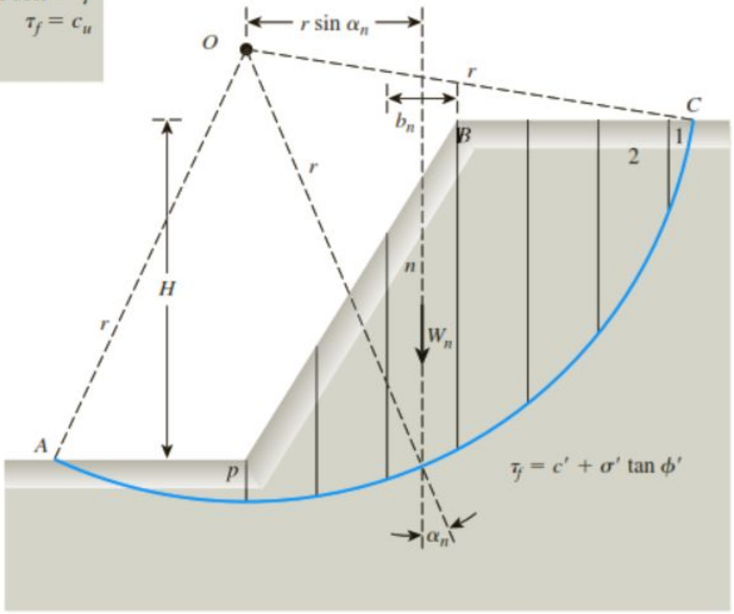
In general, nite slope failure occurs in one of the following modes :

1. When the failure occurs in such a way that the surface of sliding intersects th slope at or above its toe, it is called a **slope failure**
   - The failure circle is referred to as a **toe circle** if it passes through the toe of the slope,
   - And as a **slope circle** if it passes above the toe of the slope. Under certain circumstances, a shallow slope failure can occur,
2. When the failure occurs in such a way that the surface of sliding passes at some distance below the toe of the slope, it is called **a base failure** The failure circle in the case of base failure is called a **midpoint circle.**

Circular – Types of Analysis



Mass Procedure



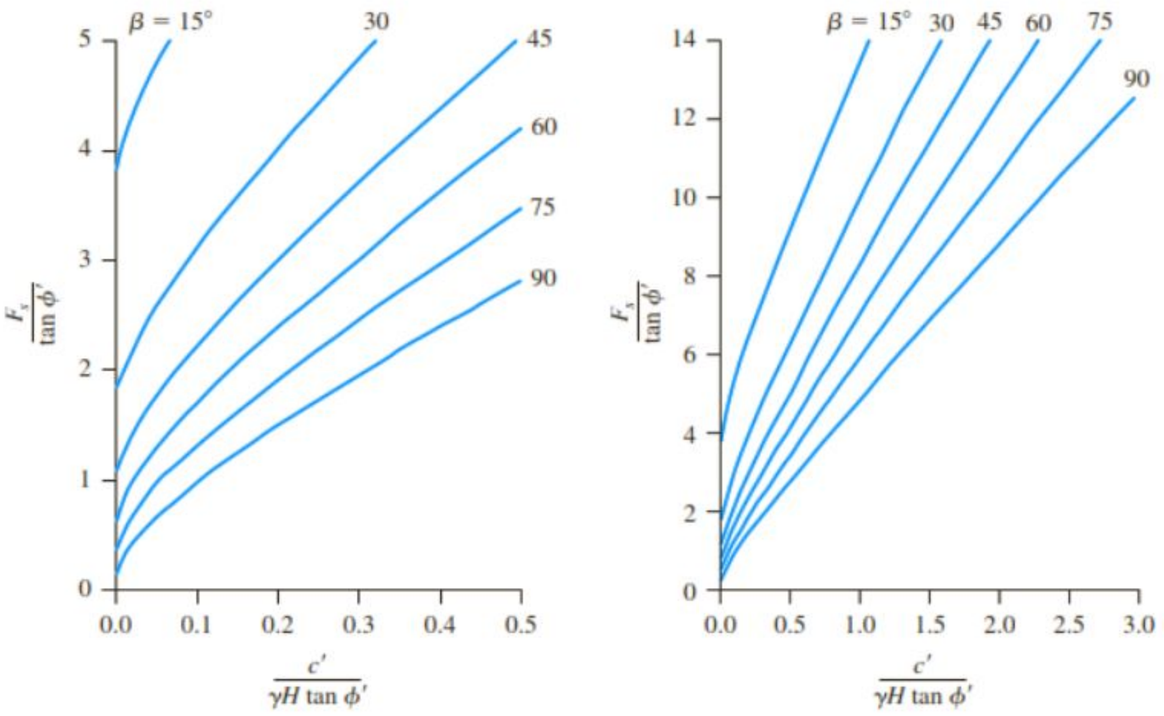
Method of Slices

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 not 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 slice 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.

Slope failure – Finite Slope - Circular

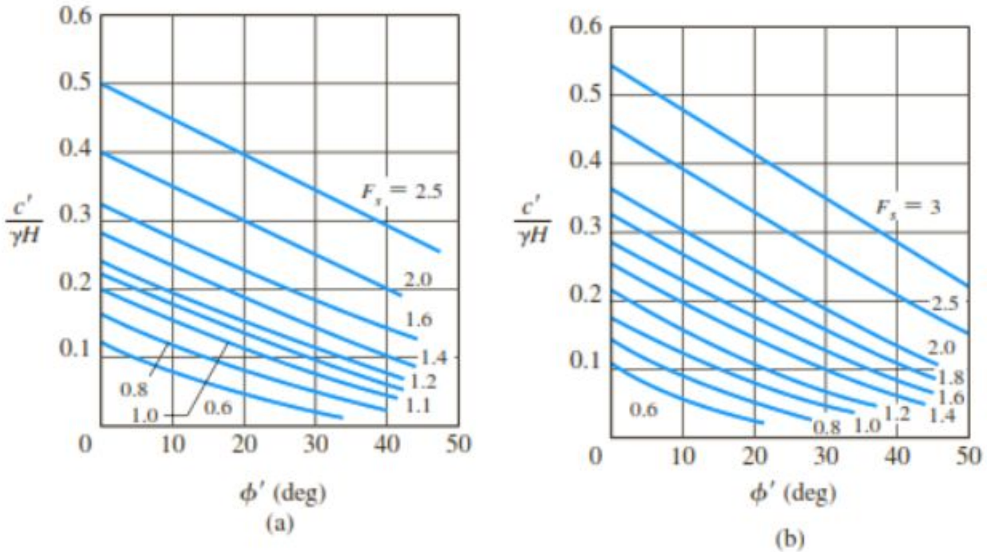
Analysis – Mass Procedure



Michalowski's analysis for stability of simple slopes

Types of analysis :

- Mass Procedure—Slopes in Homogeneous Clay Soil with φ=0
- Slopes in Clay Soil with φ= 0; and c_u Increasing with Depth
- Mass Procedure—Slopes in Homogeneous c' - φ' Soil (Analysis of Michalowski (2002))



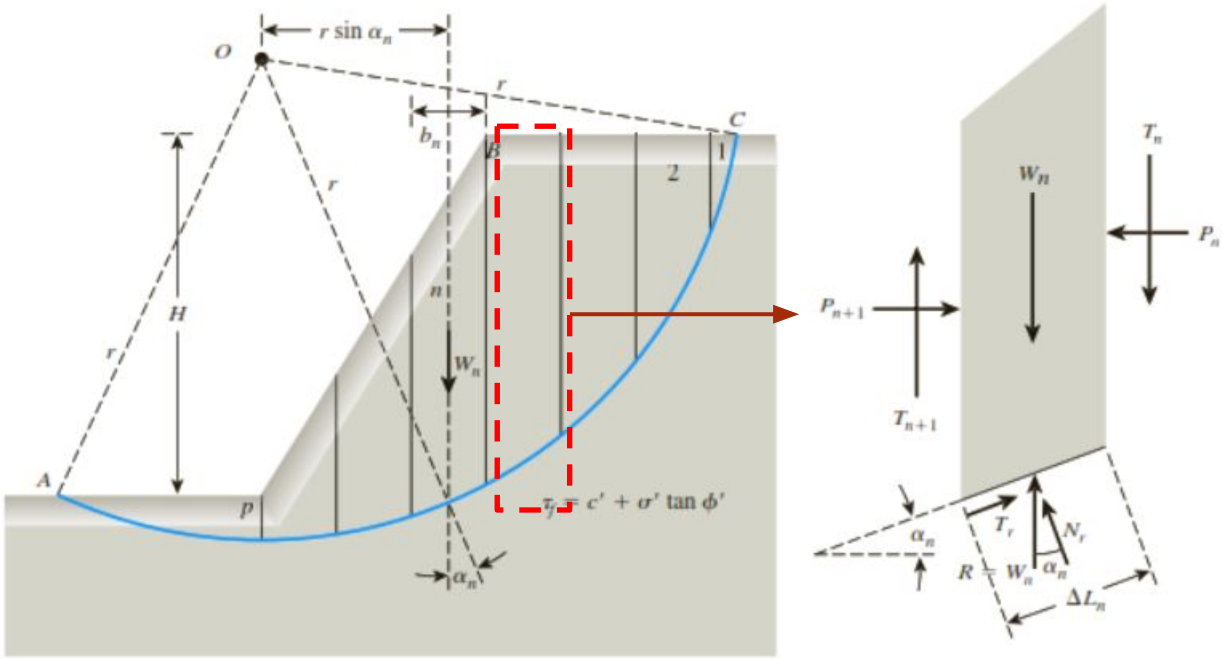
Contours of equal factors of safety:

(a) slope 1 vertical to 0.5 horizontal;

(b) slope 1 vertical to 0.75 horizontal

Slope failure – Finite Slope - Circular

Analysis – Slice Methods

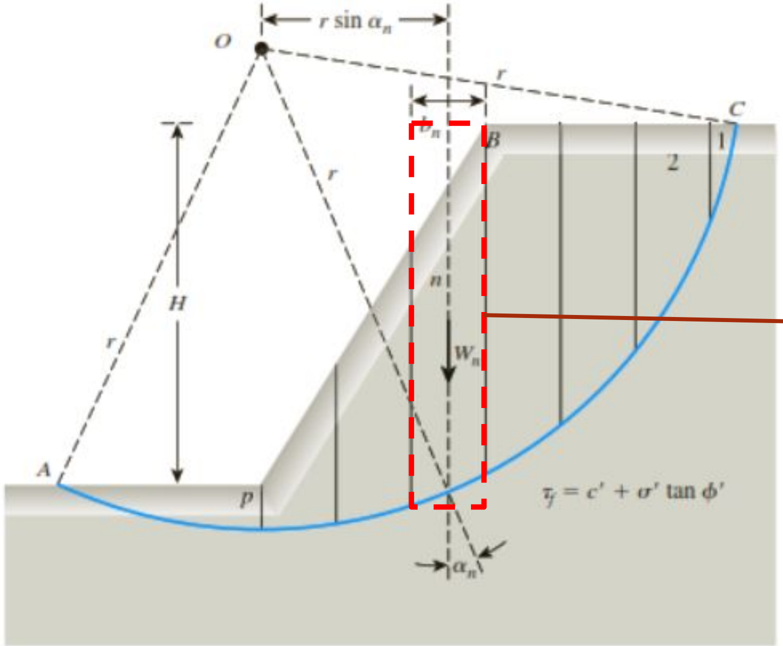


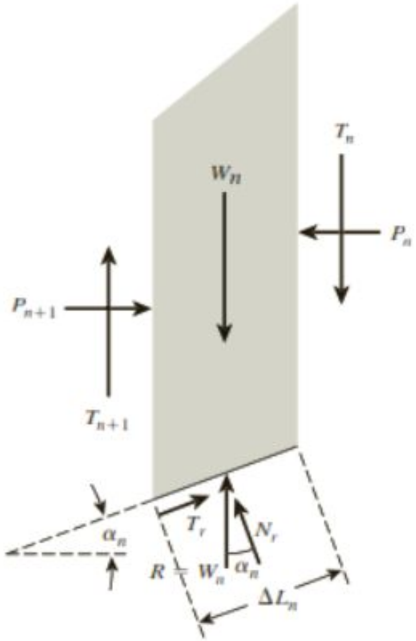
Types of analysis :

- Ordinary Methods of Slices
- Bishop's Simplified Method of Slices
- Bishop and Morgenstern solution
- Spencer's solution
- Michalowski's solution

Slope failure – Finite Slope - Circular

Slice Methods – Ordinary Methods of Slices



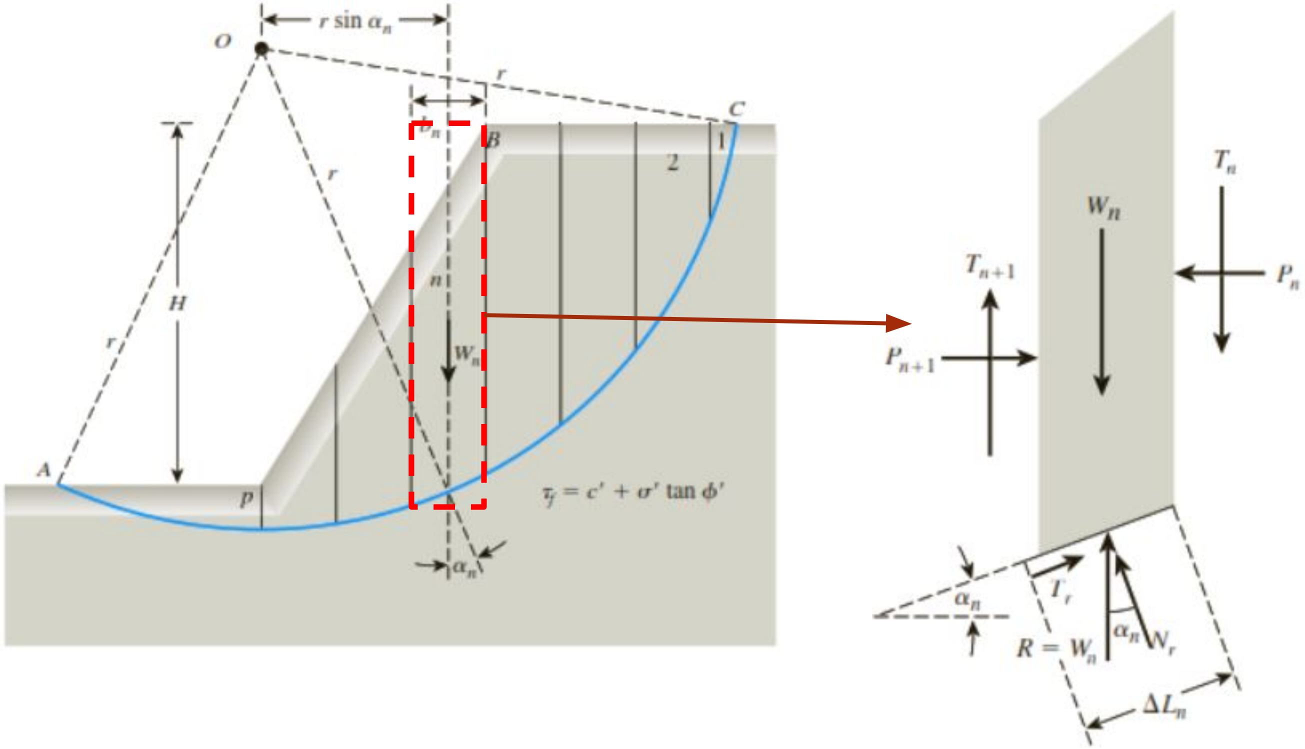


$$T_r = \tau_d(\Delta L_n) = \frac{\tau_f(\Delta L_n)}{F_s} = \frac{1}{F_s}[c' + \sigma' \tan \phi']\Delta L_n$$

$$\frac{N_r}{\Delta L_n} = \frac{W_n \cos \alpha_n}{\Delta L_n}$$

$$F_s = \frac{\sum_{n=1}^{n=p} (c'\Delta L_n + W_n \cos \alpha_n \tan \phi')}{\sum_{n=1}^{n=p} W_n \sin \alpha_n}$$

Slice Methods – Bishop's Simplified Method of Slices



In 1955, Bishop proposed a more rened solution to the ordinary method of slices.

In this method, **the effect of forces on the sides of each slice** are accounted for to some degree

$$m_{\alpha(n)} = \cos \alpha_n + \frac{\tan \phi' \sin \alpha_n}{F_s}$$

$$F_s = \frac{\sum_{n=1}^{n=p} (c' b_n + W_n \tan \phi') \frac{1}{m_{\alpha(n)}}}{\sum_{n=1}^{n=p} W_n \sin \alpha_n}$$

Slice Methods – Bishop and Morgenstern solution

In this method, **the effect of forces on the sides of each slice** are accounted for to some degree

$$r_{u(n)} = \frac{u_n}{\gamma z_n} = \frac{h_n \gamma_w}{\gamma z_n}$$

$$F_s = \left[\frac{1}{\sum_{n=1}^{n=p} \frac{b_n}{H}\frac{z_n}{H}\sin\alpha_n}\right] \times \sum_{n=1}^{n=p}\left\{\frac{\left[\frac{c'}{\gamma H}\frac{b_n}{H} + \frac{b_n}{H}\frac{z_n}{H}(1-r_u)\tan\phi'\right]}{m_{\alpha(n)}}\right\}$$

$$F_s = m' - n'r_u$$

Step 1. Obtain ϕ', β, and $c'/\gamma H$.
Step 2. Obtain r_u (weighted average value).
Step 3. From Table 15.5, obtain the values of m' and n' for $D = 1, 1.25$, and 1.5 (for the required parameters ϕ', β, r_u, and $c'/\gamma H$).
Step 4. Determine F_s, using the values of m' and n' for each value of D.
Step 5. The required value of F_s is the smallest one obtained in Step 4.

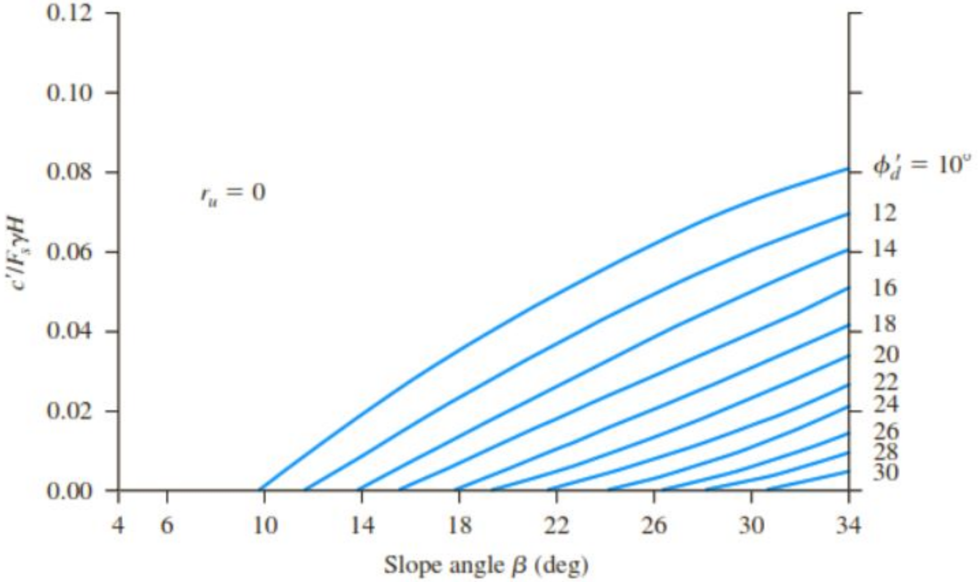
a. Stability coefficients m' and n' for $c'/\gamma H = 0$

	Stability coefficients for earth slopes							
	Slope 2:1		Slope 3:1		Slope 4:1		Slope 5:1	
ϕ'	m'	n'	m'	n'	m'	n'	m'	n'
10.0	0.353	0.441	0.529	0.588	0.705	0.749	0.882	0.917
12.5	0.443	0.554	0.665	0.739	0.887	0.943	1.109	1.153
15.0	0.536	0.670	0.804	0.893	1.072	1.139	1.340	1.393
17.5	0.631	0.789	0.946	1.051	1.261	1.340	1.577	1.639
20.0	0.728	0.910	1.092	1.213	1.456	1.547	1.820	1.892
22.5	0.828	1.035	1.243	1.381	1.657	1.761	2.071	2.153
25.0	0.933	1.166	1.399	1.554	1.865	1.982	2.332	2.424
27.5	1.041	1.301	1.562	1.736	2.082	2.213	2.603	2.706
30.0	1.155	1.444	1.732	1.924	2.309	2.454	2.887	3.001
32.5	1.274	1.593	1.911	2.123	2.548	2.708	3.185	3.311
35.0	1.400	1.750	2.101	2.334	2.801	2.977	3.501	3.639
37.5	1.535	1.919	2.302	2.558	3.069	3.261	3.837	3.989
40.0	1.678	2.098	2.517	2.797	3.356	3.566	4.196	4.362

Slice Methods – Spencer's solution

Bishop's simplied method of slices described satisfies the equations of equilibrium with **respect to the moment but not with respect to the forces**

Spencer (1967) has provided a method to determine the factor of safety (F_s) by taking into account the interslice forces



Step 1. Determine c', γ, H, β, ϕ', and r_u for the given slope.
Step 2. Assume a value of F_s.
Step 3. Calculate $c'/[F_{s(\text{assumed})}\ \gamma H]$.
↑
Step 2

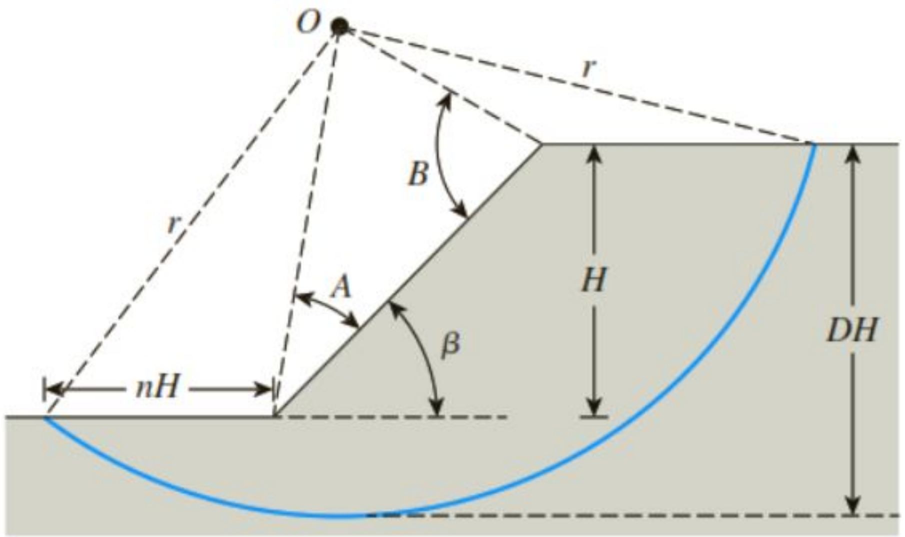
Step 4. With the value of $c'/F_s\gamma H$ calculated in step 3 and the slope angle β, enter the proper chart in Figure 15.35 to obtain ϕ'_d. Note that Figures 15.35 a, b, and c, are, respectively, for r_u of 0, 0.25, and 0.5, respectively.
Step 5. Calculate $F_s = \tan\phi' / \tan\phi'_d$.
↑
Step 4

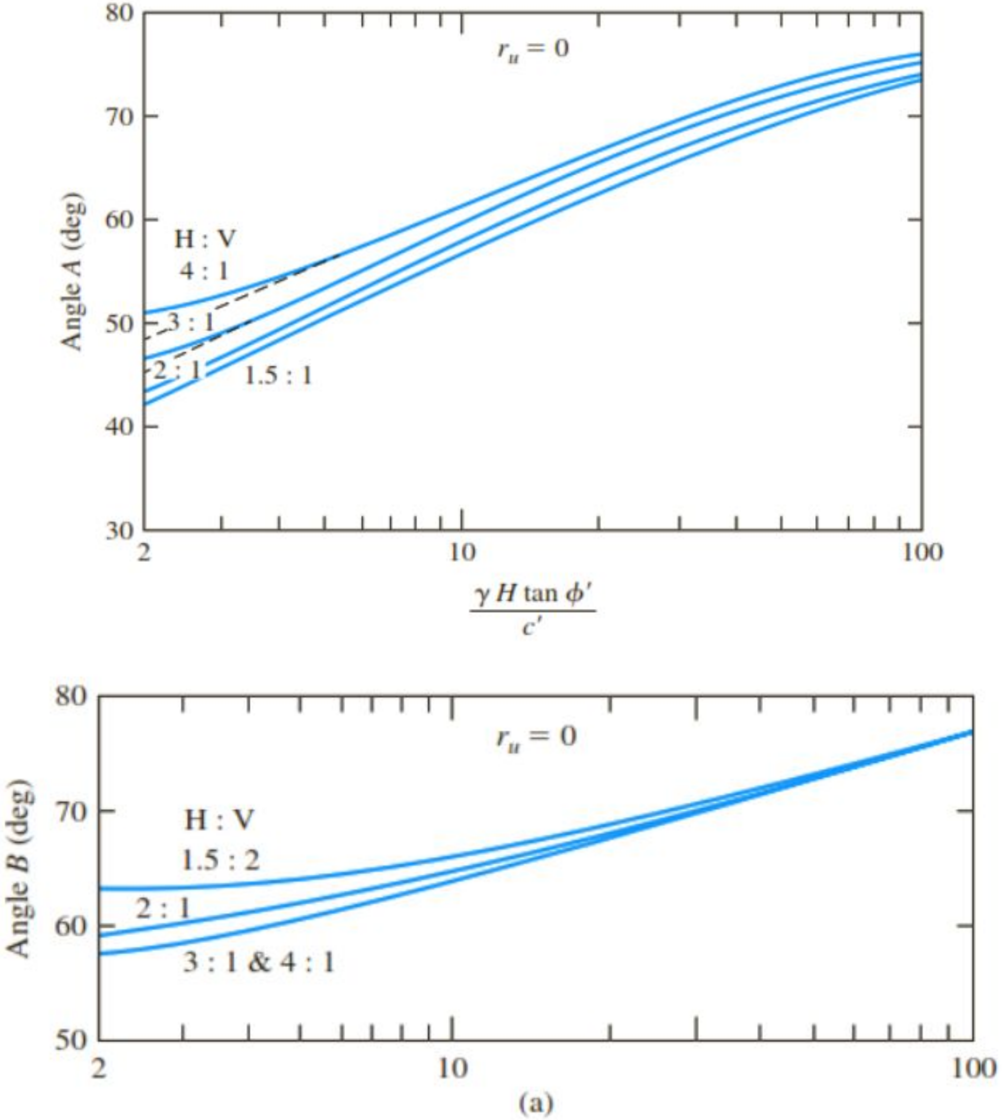
Step 6. If the values of F_s as assumed in step 2 are not the same as those calculated in step 5, repeat steps 2, 3, 4, and 5 until they are the same.

Slice Methods – Spencer's solution (Location Failure Circle)

Bishop's simplied method of slices described satisfies the equations of equilibrium with **respect to the moment but not with respect to the forces**

Spencer (1967) has provided a method to determine the factor of safety (F_s) by taking into account the interslice forces



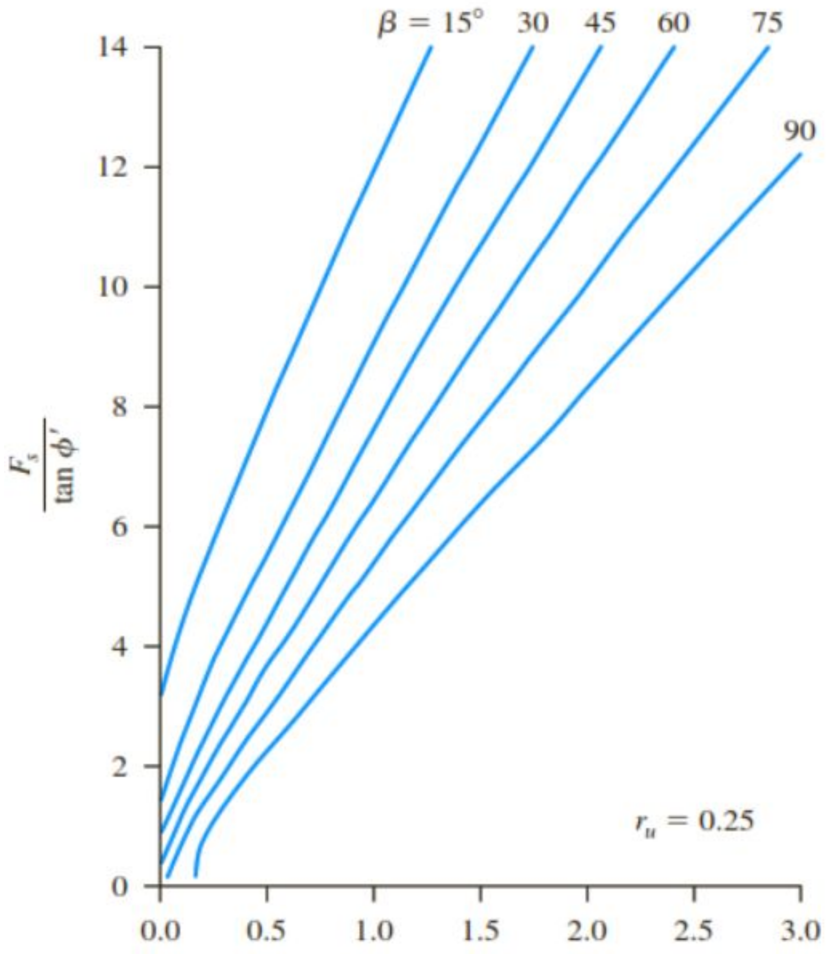


Slice Methods – Michalowski's solution

Michalowski (2002) used the **kinematic approach** to analyze slopes with steady-state seepage

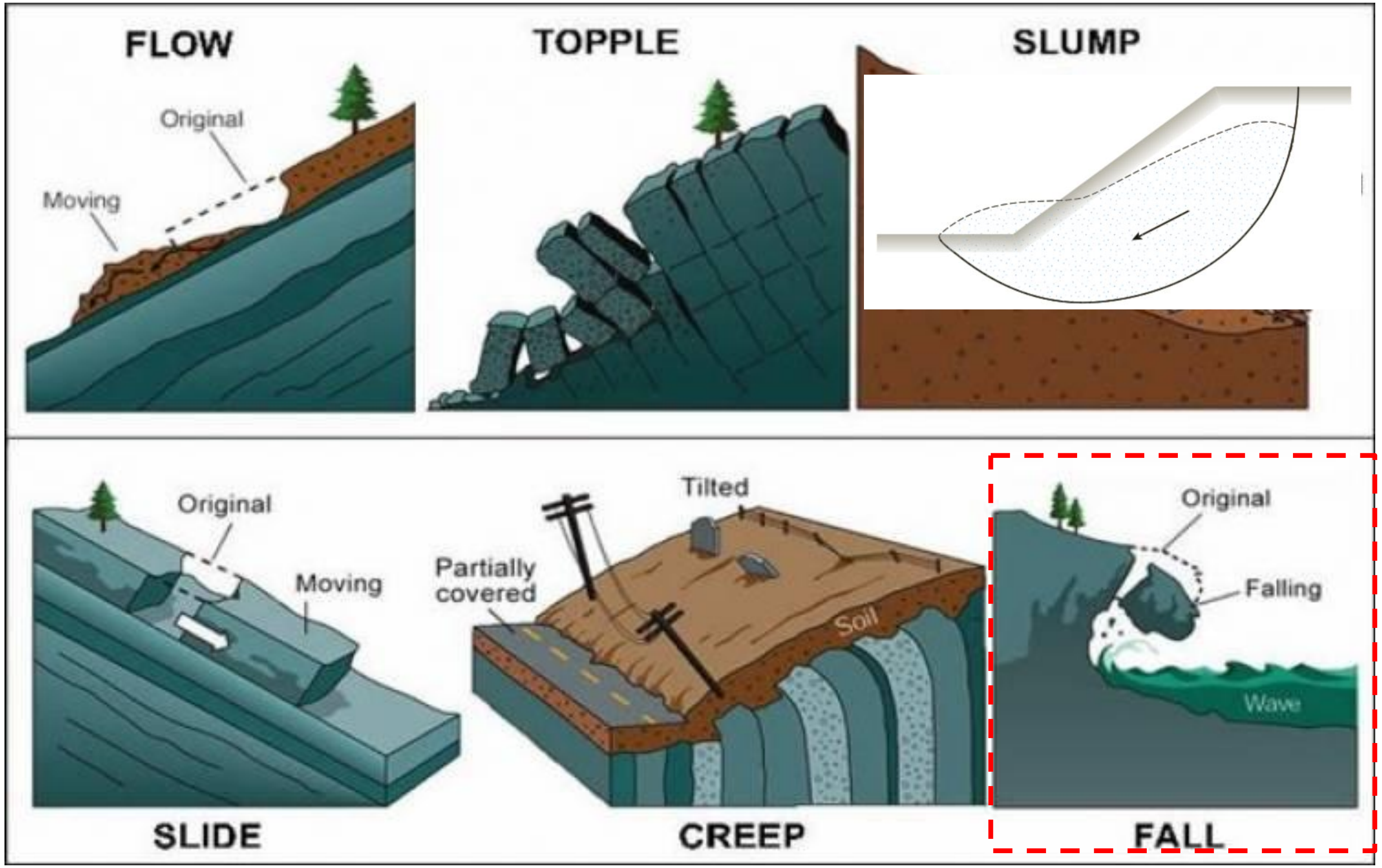
Table 15.6 Michalowski's stability numbers for steady seepage with $r_u = 0.25$

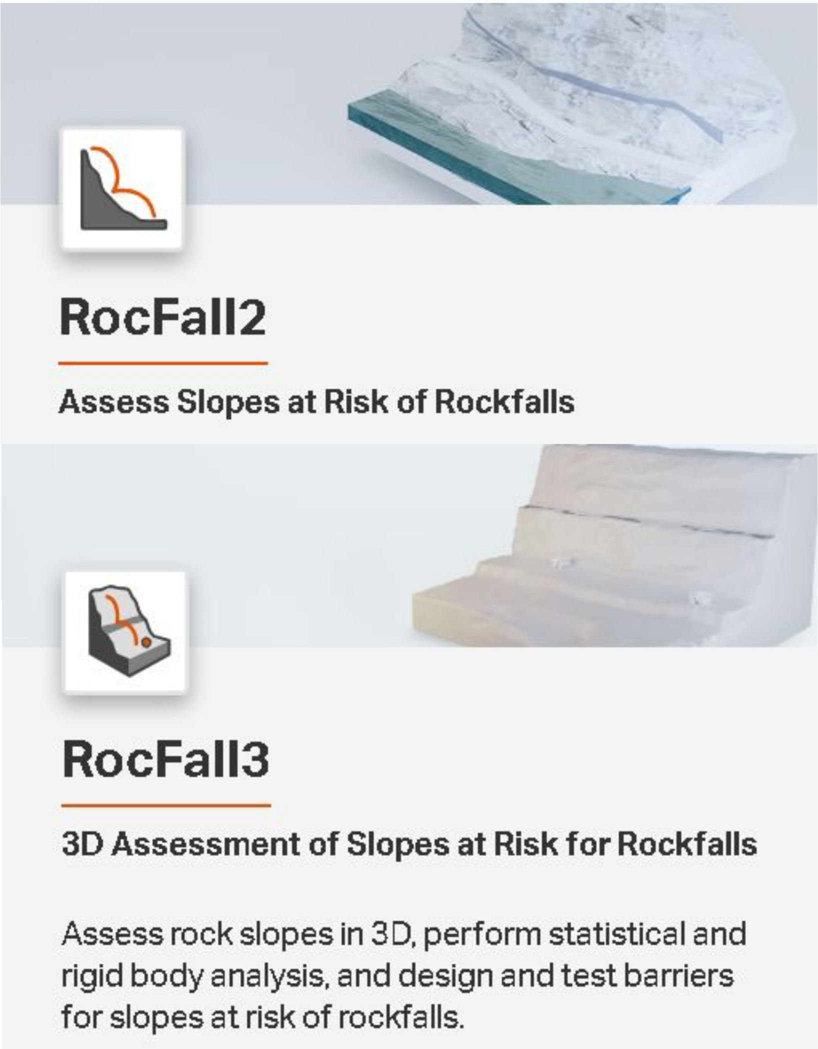
$\frac{c'}{\gamma H \tan\phi'}$	$\frac{F_s}{\tan\phi'}$ $\beta = 15°$	$\beta = 30°$	$\beta = 45°$	$\beta = 60°$	$\beta = 75°$	$\beta = 90°$
0	3.09	1.21	0.82	0.21		
0.05	3.83	1.96	1.27	0.75	0.29	
0.1	4.38	2.43	1.66	1.14	0.68	
0.2	5.10	3.30	2.37	1.81	1.31	0.70
0.3	6.05	4.09	3.05	2.43	1.86	1.29
0.4	6.84	4.79	3.71	3.00	2.39	1.75
0.5	7.74	5.42	4.35	3.58	2.88	2.21
1.0	11.70	8.81	7.41	6.23	5.21	4.22
1.5		12.17	10.44	8.91	7.55	6.15
2.0			13.42	11.59	9.81	8.10
2.5				14.24	12.16	10.08
3.0						11.95



Slope failure

Tools

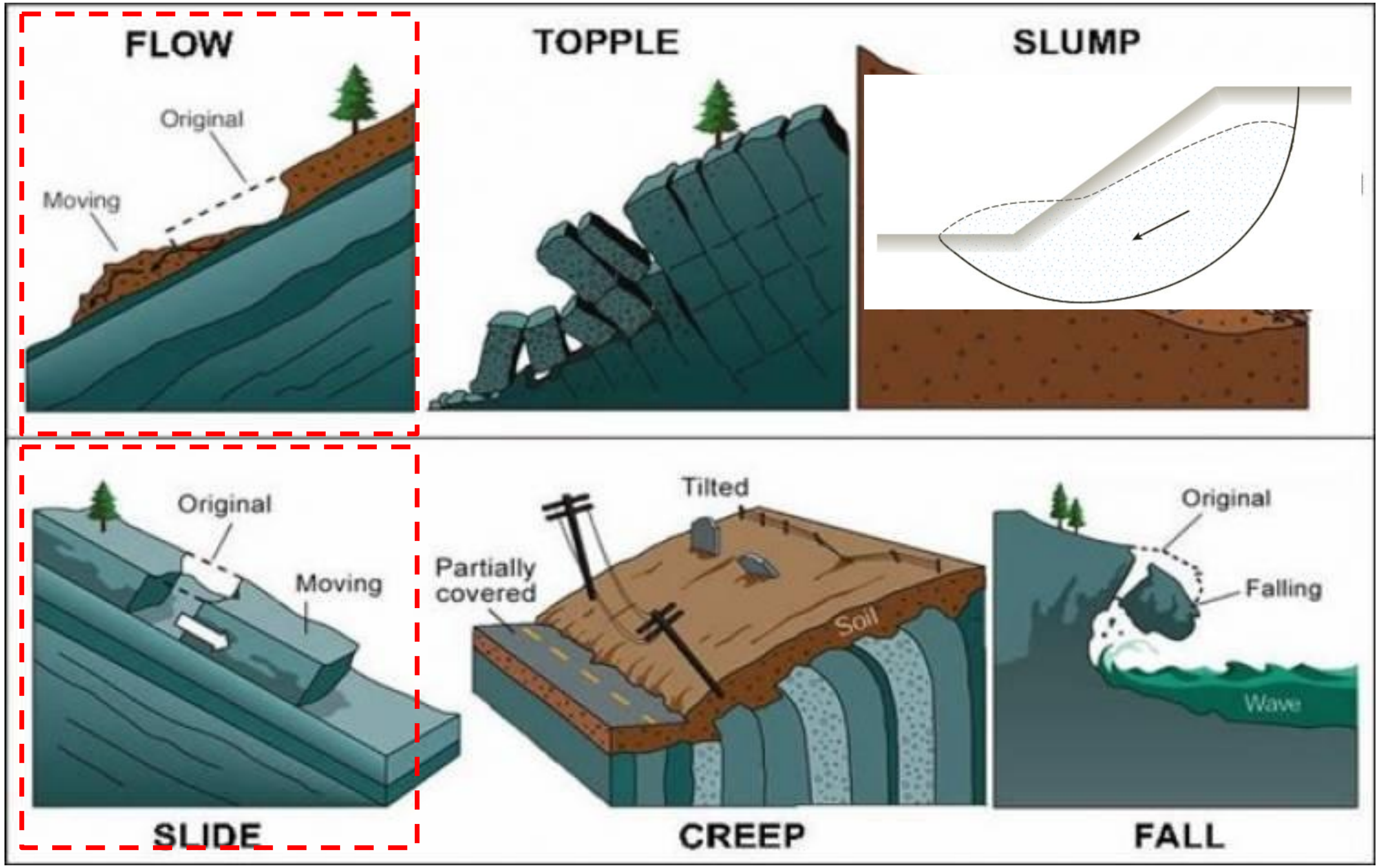




Source : Braja M Das, 2015;

Slope failure

Tools



RocPlane

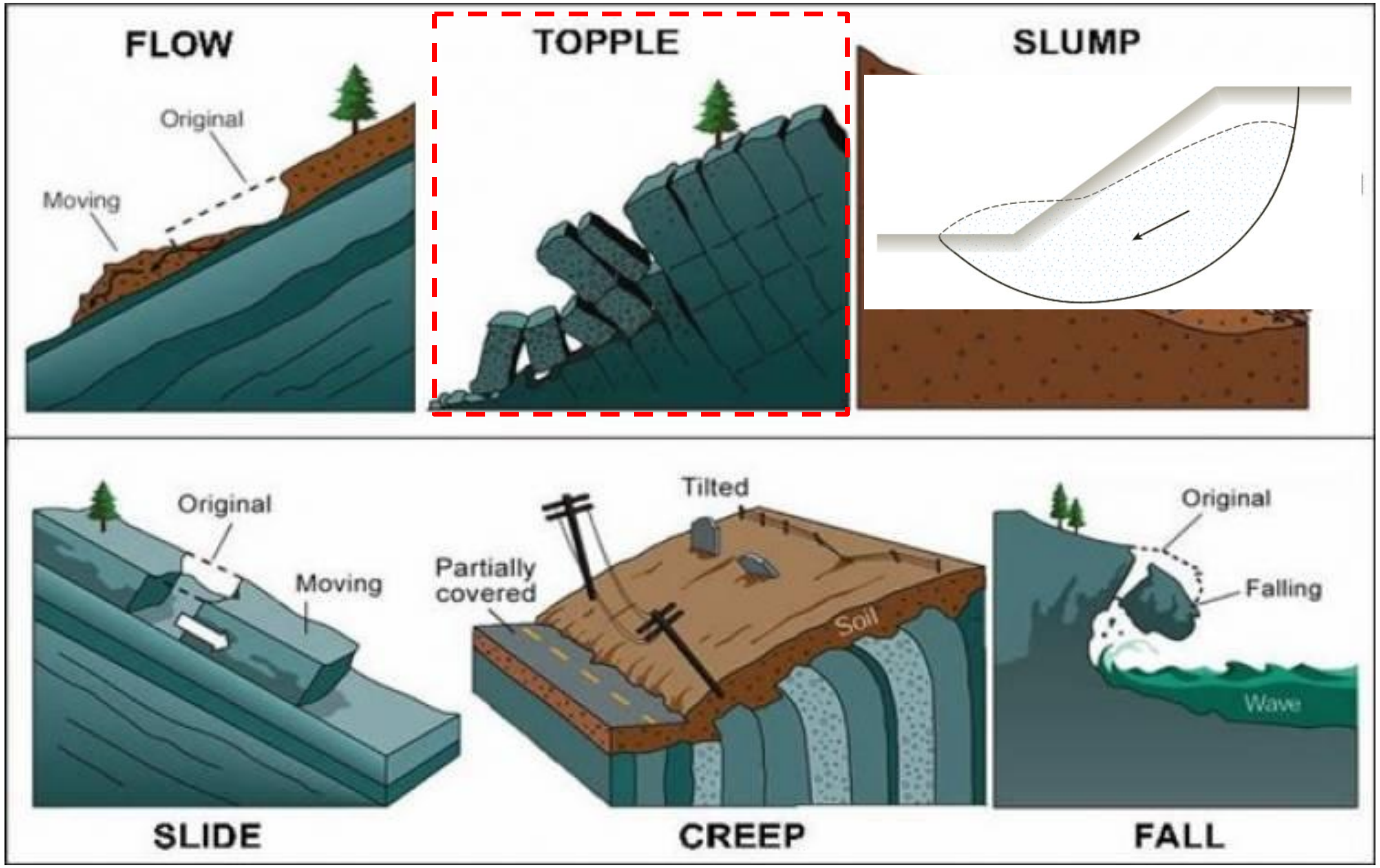
Planar Wedge Analysis for Slopes

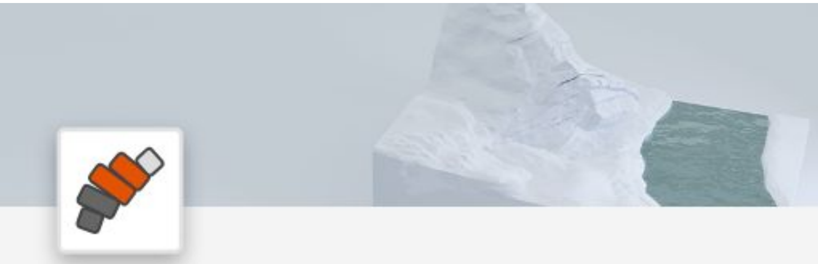
Useful for bench stability in open pit mines, model and analyze the stability of planar wedge rock slopes and visualize them in 2D and 3D.

Source : Braja M Das, 2015;

Slope failure

Tools





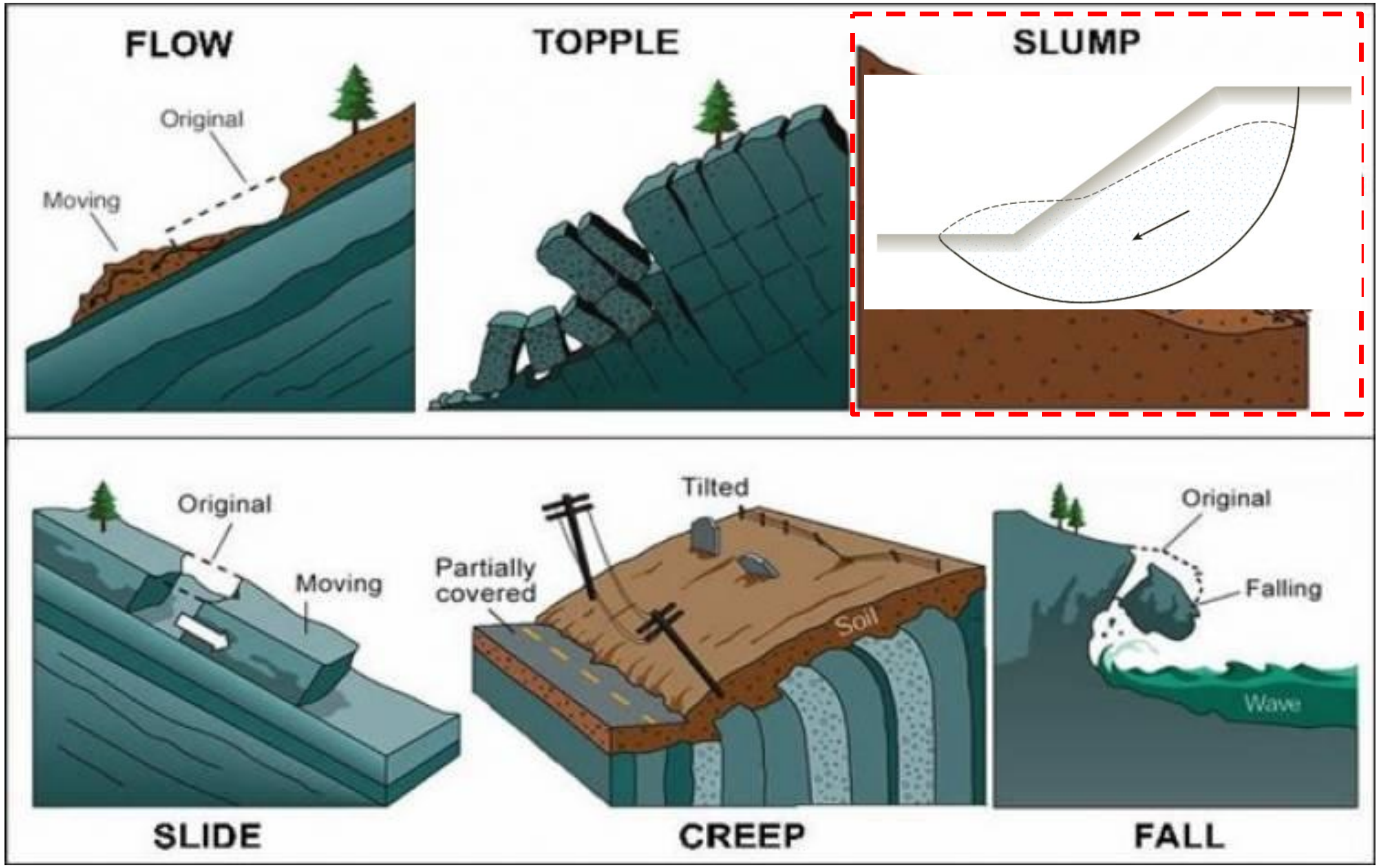
RocTopple

Toppling Stability Analysis for Slopes

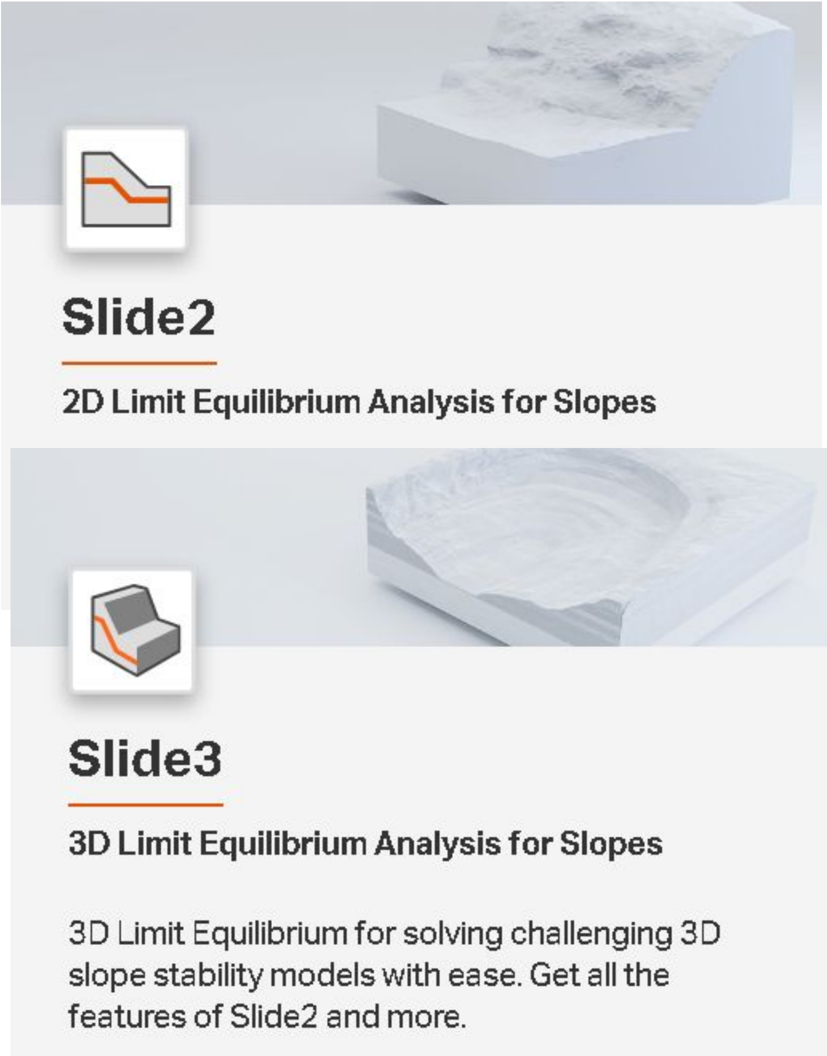
Perform deterministic or probabilistic analysis and support design of toppling blocks with interactive 2D and 3D visualization.

Source : Braja M Das, 2015;

Tools

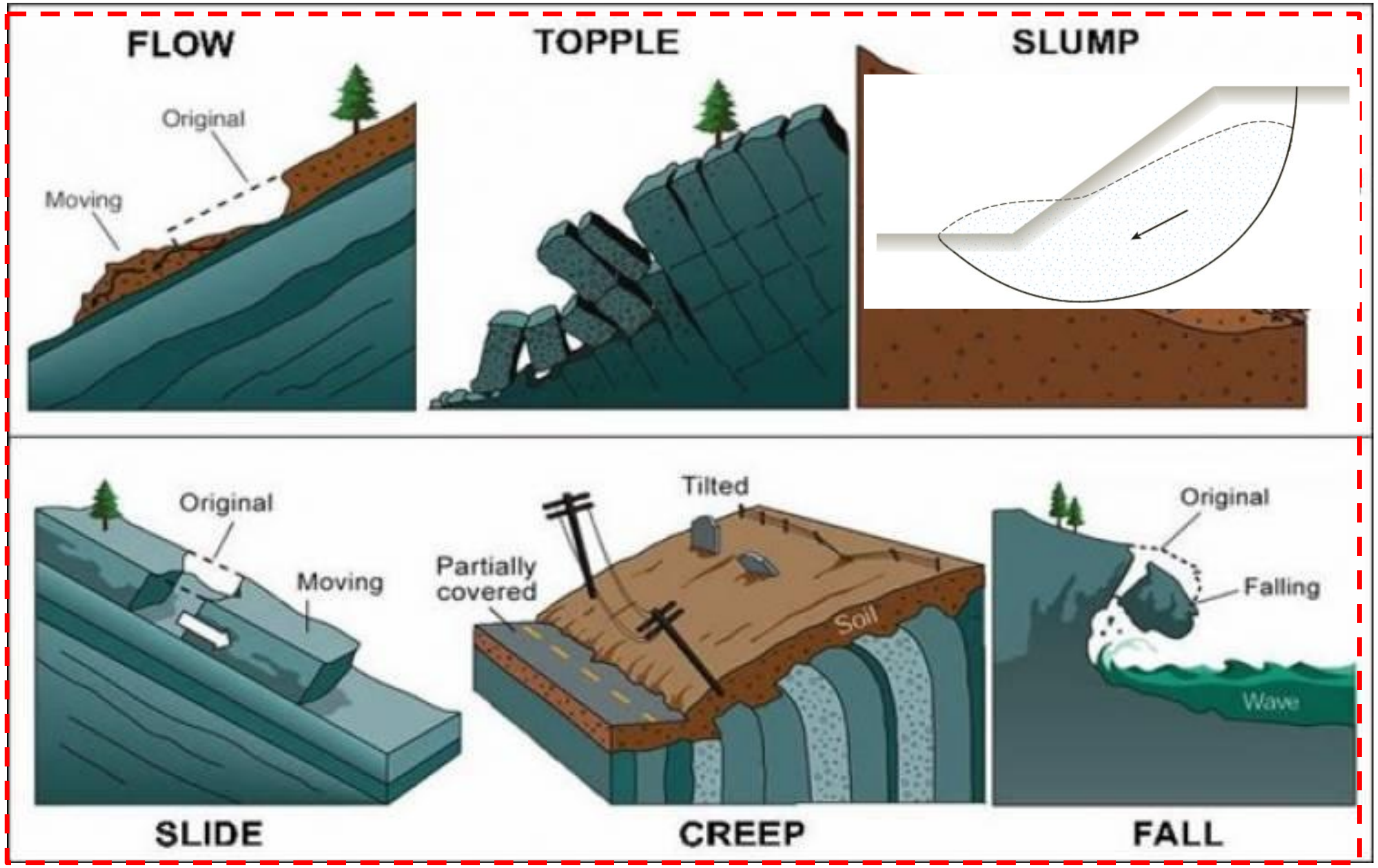


Source : Braja M Das, 2015;



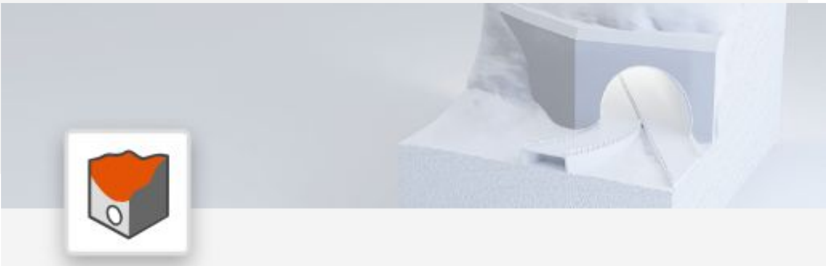
Slope failure

Tools



RS2

2D Finite Element Analysis



RS3

3D Finite Element Analysis

3D Finite Element Analysis using fully-automated shear strength reduction method for advanced analysis of complex 3D models.

Source : Braja M Das, 2015;