Slope Stability

Slope Stability

Lower San Fernando Dam Failure, 1971

Outlines

- Introduction
- Definition of key terms
- Some types of slope failure
- Some causes of slope failure
- Shear Strength of Soils
- Infinite slope
- Two dimensional slope stability analysis

Introduction I

- Slopes in soils and rocks are ubiquitous in nature and in man-made structures.
- Highways, dams, levees, bund-walls and stockpiles are constructed by sloping the lateral faces of the soil
  - Slopes are general less expensive than constructing a walls.
- Natural forces (Wind, water, snow, etc.) change the topography on Earth often creating unstable slopes.
- Failure of such slopes resulted in human loss and destruction.
- Failure may be sudden and catastrophic; others are insidious;
- Failure wither wide spread or localized.

Introduction II

- In this session we will discuss a few methods of analysis from which you should be able to :
  1) Estimate the stability of slopes with simple geometry and geological features
  2) Understand the forces and activities that provoke slope failures
  3) Understand the effects of geology, seepage and pore water pressures on the stability of slopes

Definitions of Key Terms

- Slip or Failure Zone: A thin zone of soil that reaches the critical state or **residual state** and results in movement of the upper soil mass
- Slip plane; failure plane; Slip surface; failure surface: Surface of sliding
- Sliding mass: mass of soil within the slip plane and the ground surface
- Slope angle: Angle of inclination of a slope to the horizontal
- Pore water pressure ratio (r_u): The ratio of pore water force on a slip surface to the total weight of the soil and any external loading.

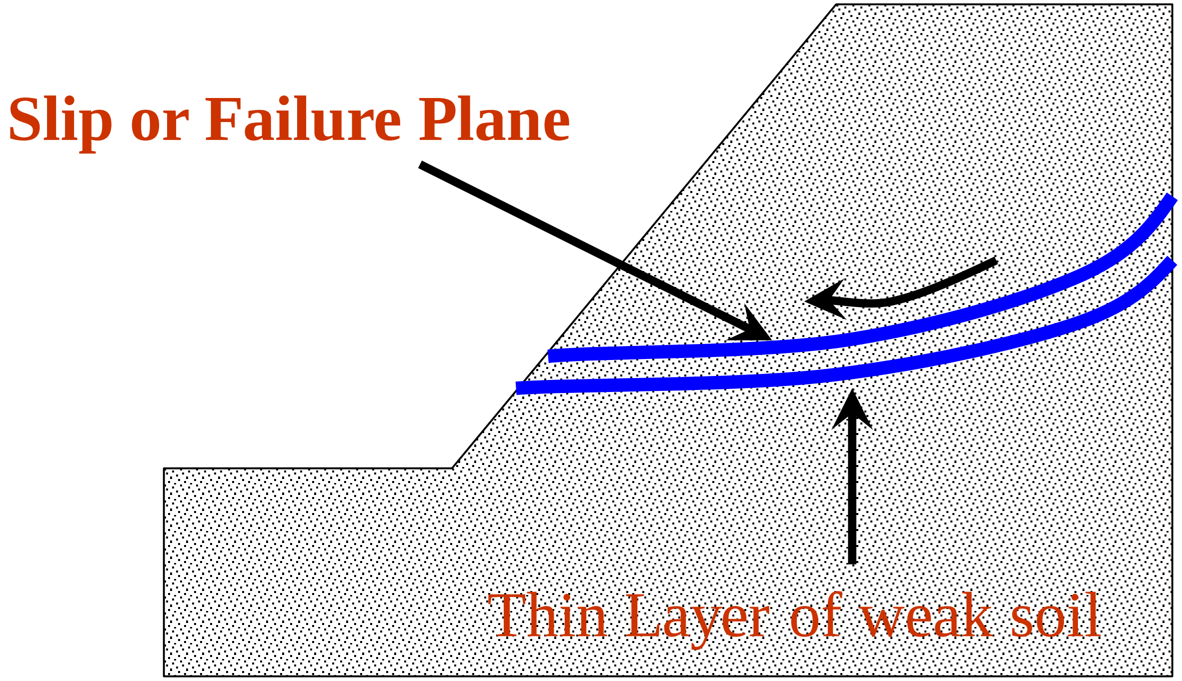
Common Type of Slope Failure

- **Slope failures depends on**
  - The Soil Type,
  - Soil Stratification,
  - Ground Water,
  - Seepage and
  - Geometry.

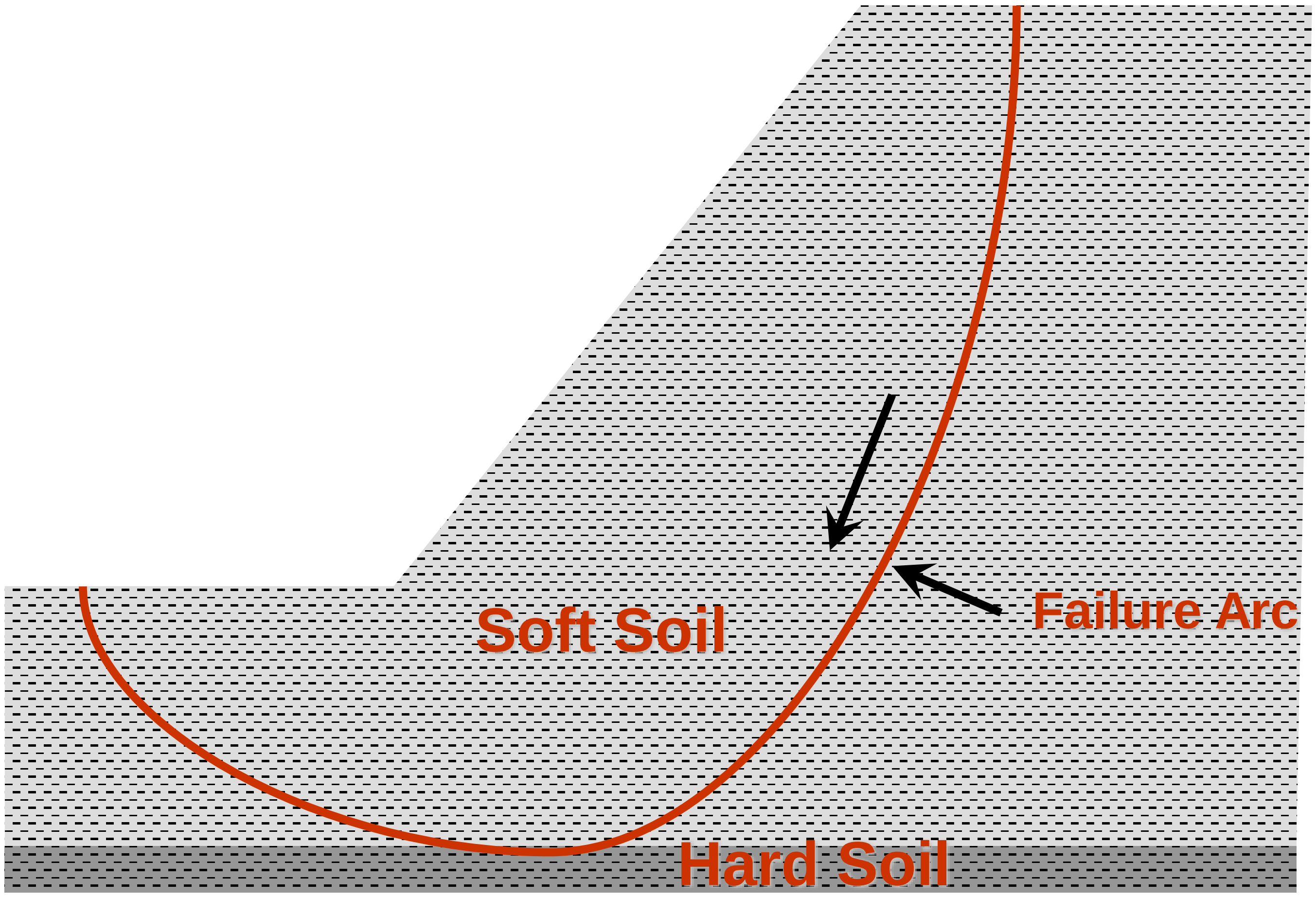
Common Type of Slope failures

- **Common Type**
  - Movement of Soil Mass Along a Thin Layer of Weak Soil
  - Base Slide
  - Toe Slide
  - Slope Slide
  - Flow Slide
  - Block Slide

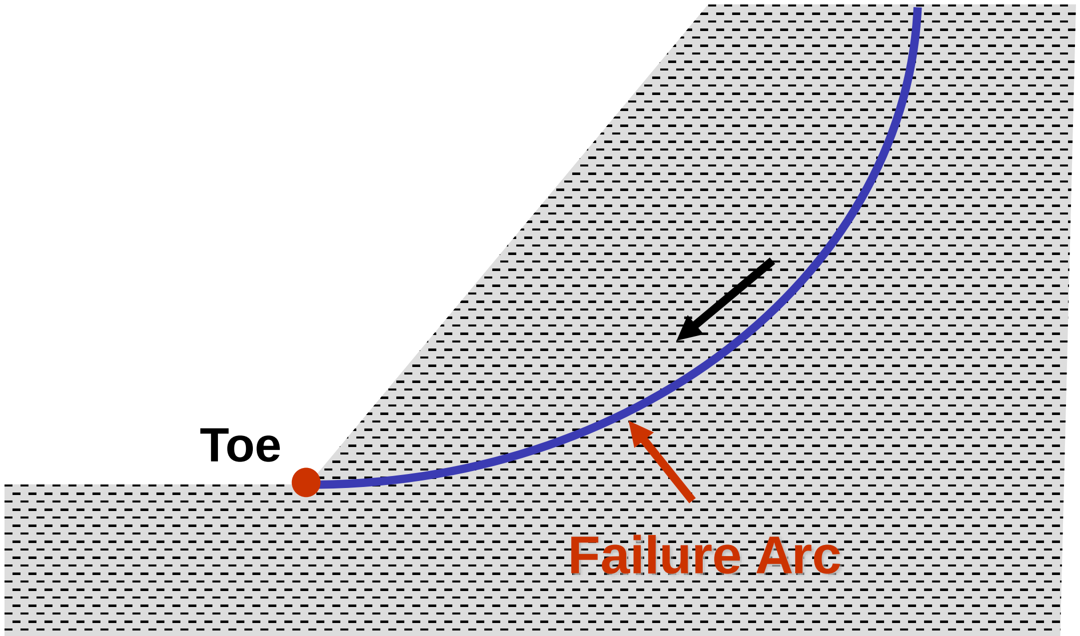
Movement of soil mass along a thin layer of weak soil



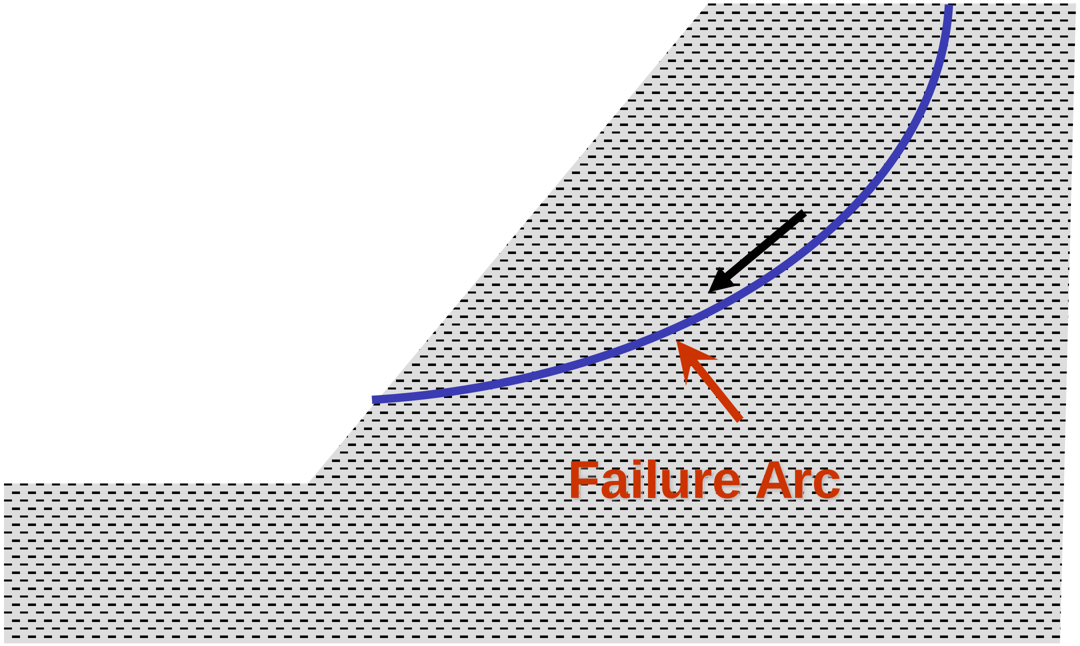
Base Slide



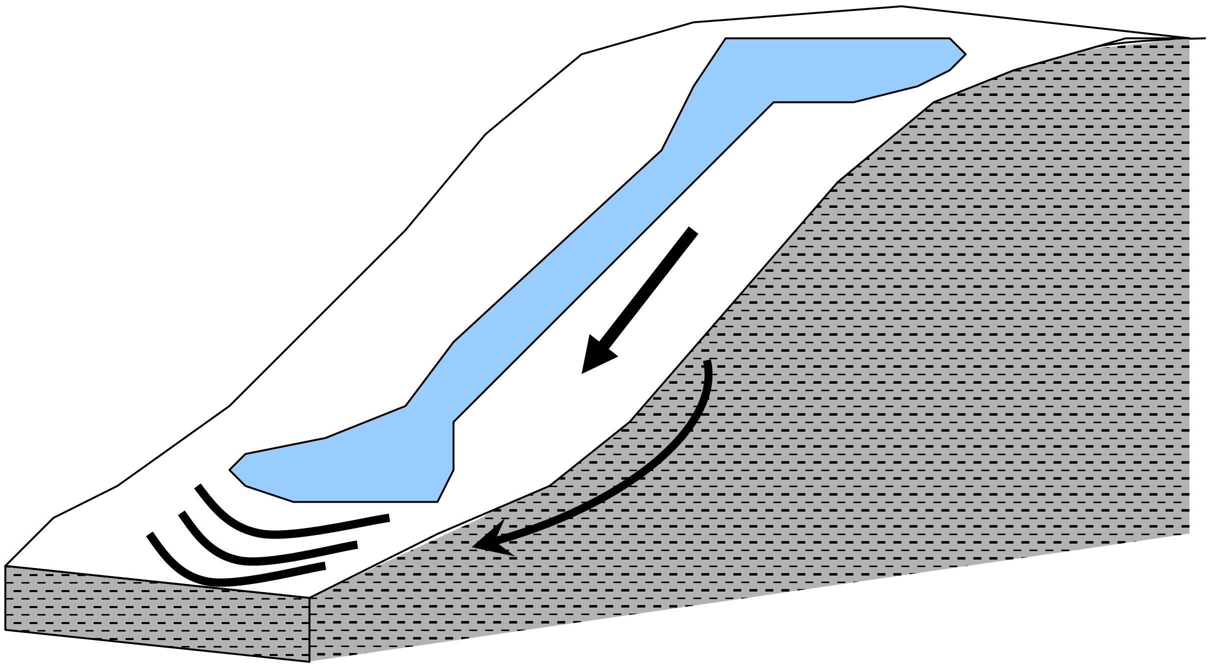
Toe Slide



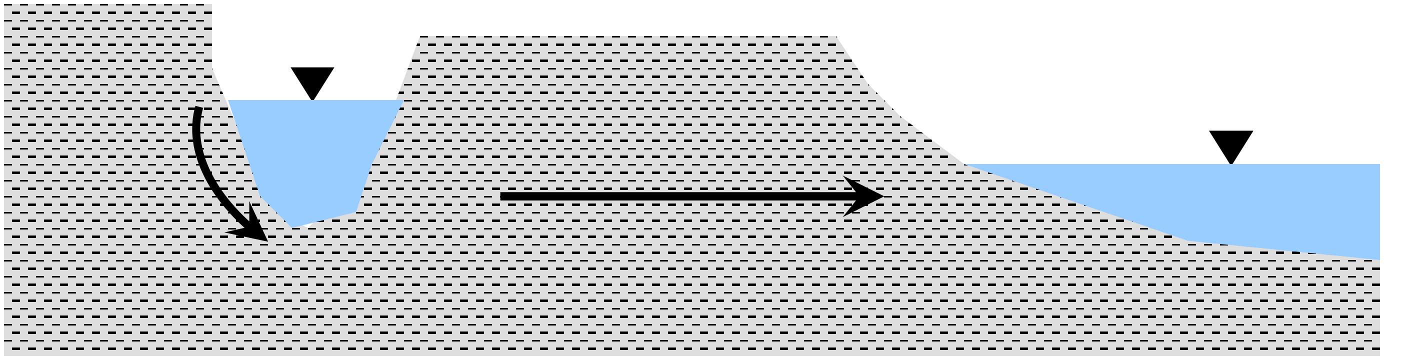
Slope Slide



Flow Slide



Block Slide

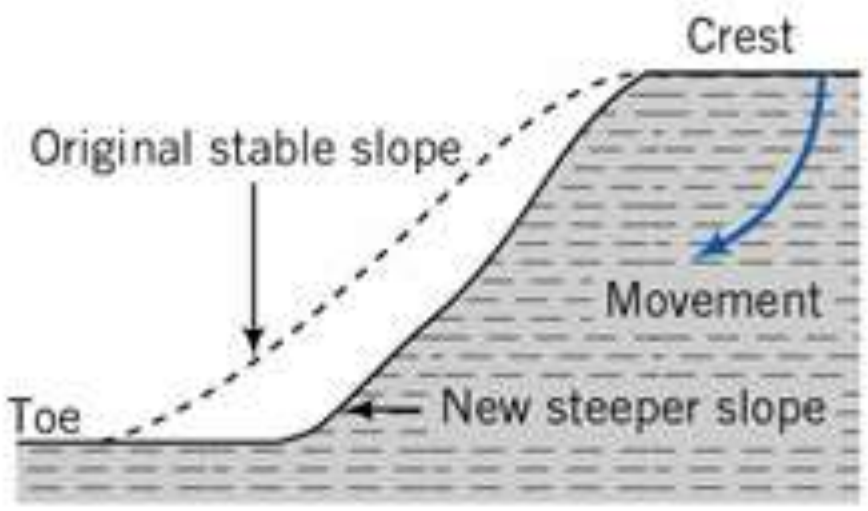


Some causes of slope failure

- Erosion
- Rainfall
- Earthquake
- Geological factures
- External loading
- Construction activity
- Excavated slope
- Fill Slope
- Rapid draw Down

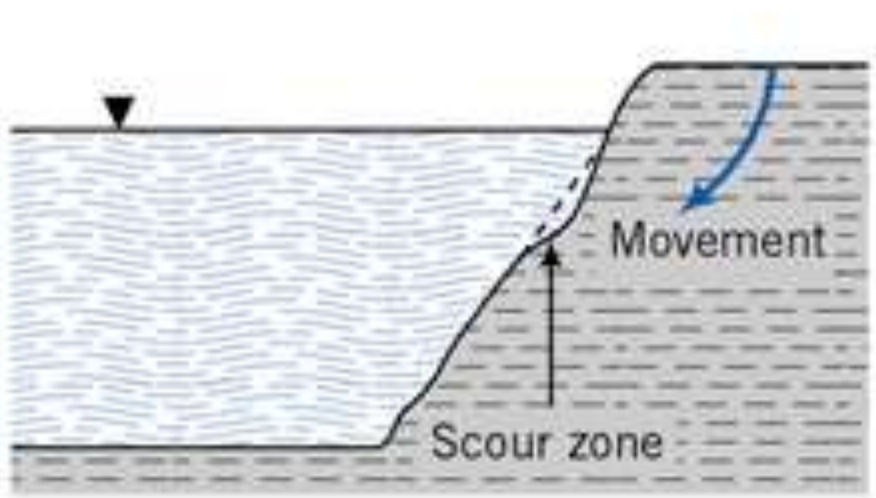
Steepening by Erosion

- Water and wind continuously erode natural and man made slopes.
- Erosion changes the geometry of the slope, ultimately resulting in slope failures or, more aptly a landslide.



Water Scouring

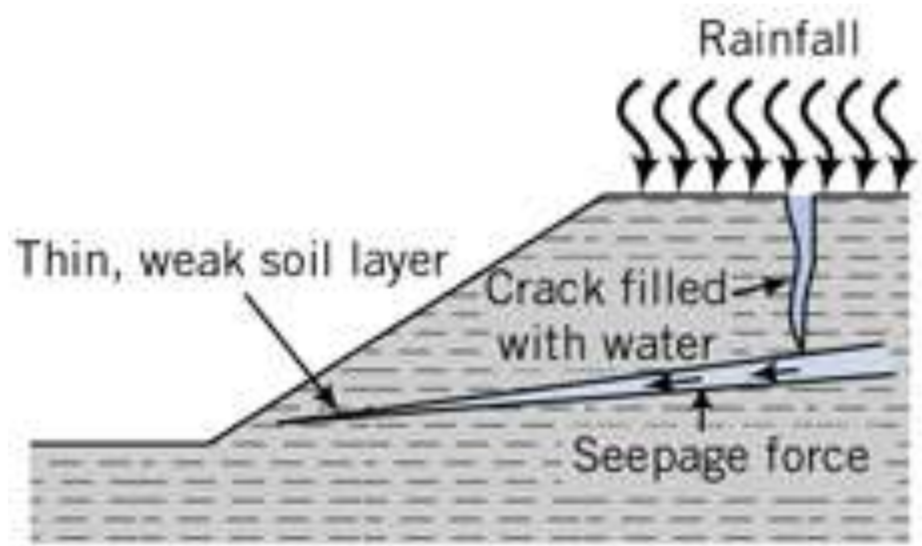
- Rivers and stream continuously scour their banks undermining their natural or man made slopes



Scouring by water movement

Rainfall

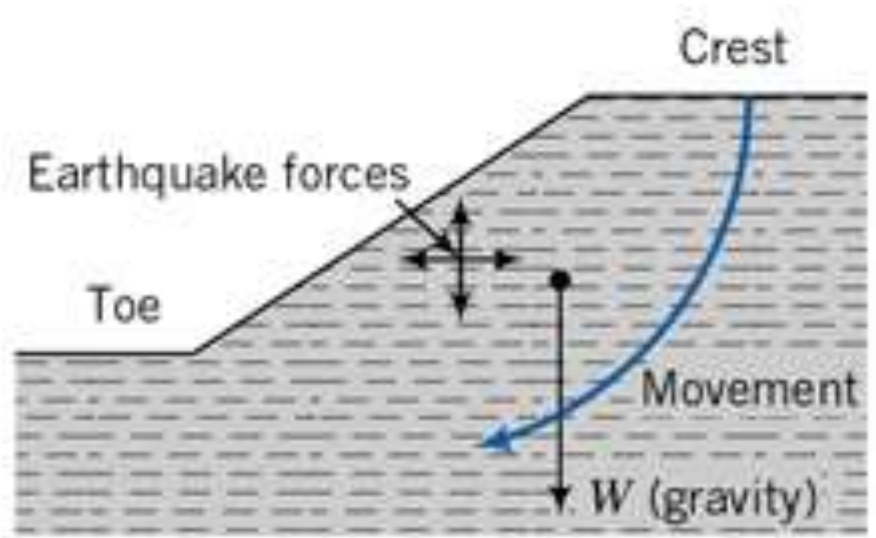
Long period of rainfall saturate, soften and erode soils. Water enter into exiting crack and may weaken underlying soil layers leading to failure e.g. mudslides



Rainfall fills crack and introduces seepage forces in the thin, weak soil layer

Earthquake

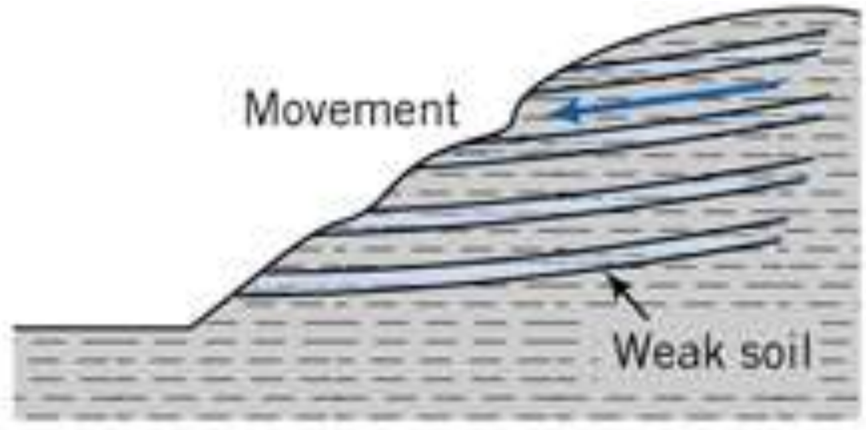
- Earthquake introduced dynamic forces. Especially dynamic shear forces that reduce the shear strength and stiffness of the soil. Pore water pressures rise and lead to liquefaction



Gravity and Earthquake forces

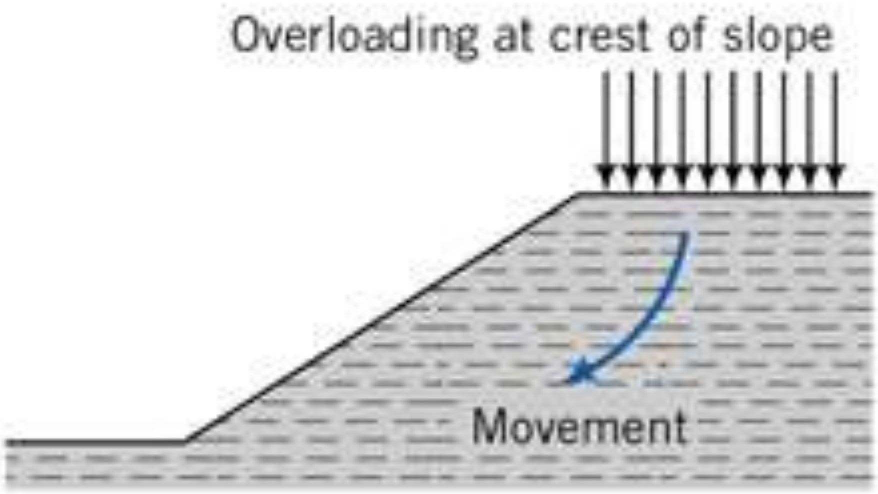
Geological factures

- Sloping stratified soils are prone to translational slide a long weak layer



External loading

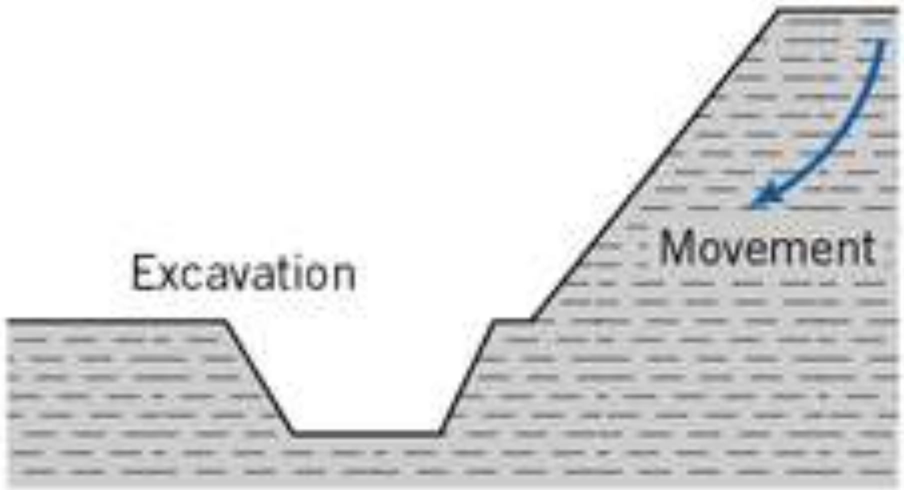
- Loads placed on the crest of a slope add to the gravitational load and may cause slope failures.



- Load places at the toe called a berm, will increase the stability of the slope. Berms are often used to the remediate problem slopes.

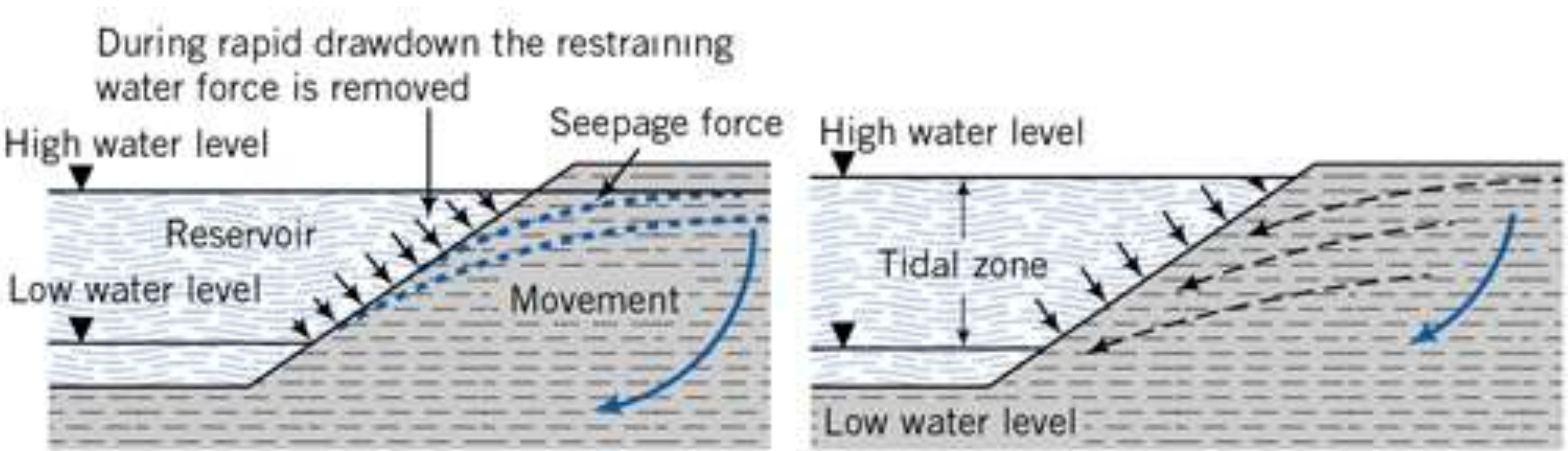
Construction Activity

- Excavated slopes: If the slope failures were to occur, they would take place after construction is completed.
- Fill slopes: failure occur during construction or immediately after construction.



Rapid Draw Down

- Later force provided by water removed and excess p.w.p does not have enough time to dissipated



Infinite slope I

Analysis of a Plane Translational Slip

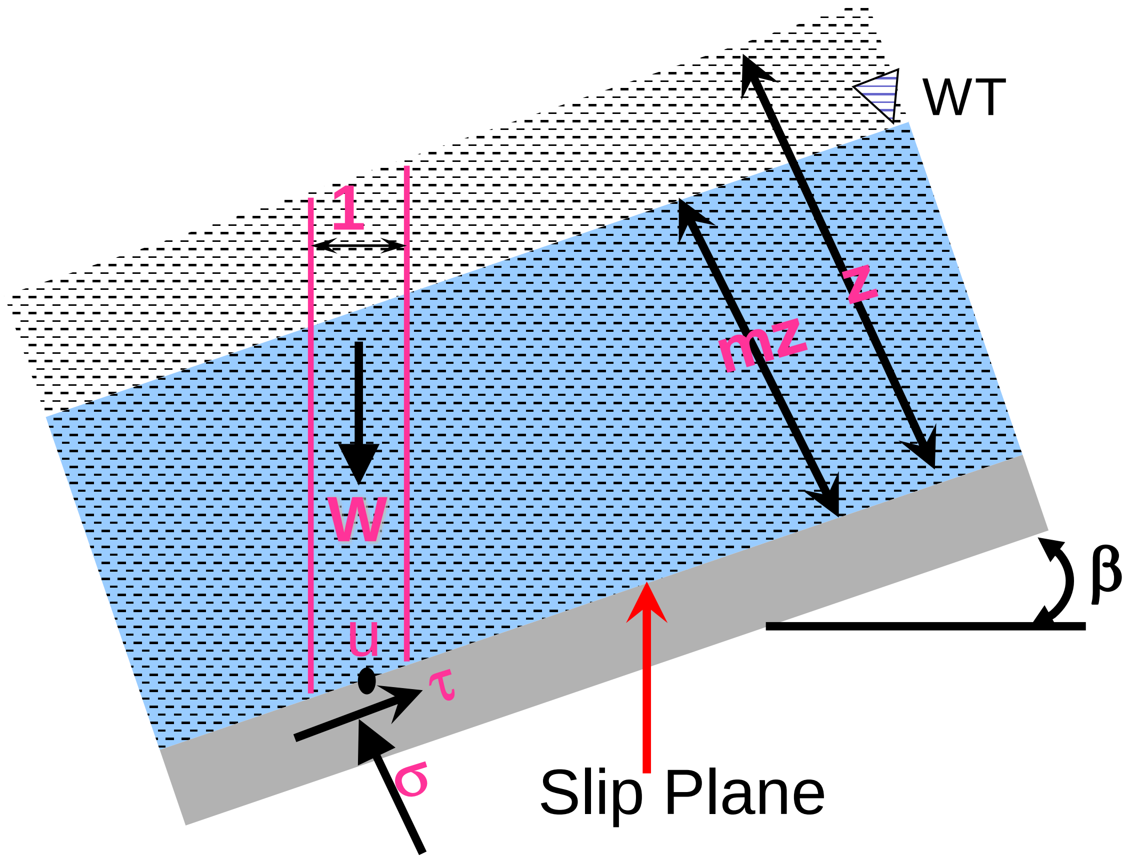
Infinite slope I

- Definition:
  - Infinite Slope: a slope that have dimension extended over great distance.
- Assumption:
  - The potential Failure surface is parallel to the surface of the Slope
  - Failure surface depth << the length of slope
  - End effects are ignored

Infinite Slope II

- Assumption Continued:
  - The failure mass moves as an essentially rigid body, the deformation of which do not influence the problem
  - The shearing resistance of the soil mass at various point along the slide of the failure surface is independent of orientation
  - The Factor of safety is defined in term of the average shear strength along this surface.

Infinite Slope III



Infinite Slope IV

Stress in the soil mass and Available Shear Strength

$$\sigma = [(1-m)\gamma + m\gamma_{sat}]z\cos^2\beta$$

$$\tau = [(1-m)\gamma + m\gamma_{sat}]z\sin\beta\cos\beta$$

$$u = mz\gamma_w\cos^2\beta$$

$$\tau_f = c' + (\sigma - u)\tan\phi'$$

Infinite Slope V

Effective stresses (Three Scenarios)

1) 0<m<1

$$\boxed{F.S = \frac{\tau_f}{\tau_m} = \frac{c' + (\sigma - u)\tan\phi'}{[(1-m)\gamma + m\gamma_{sat}]z\sin\beta\cos\beta}}$$

2) m=0 & c'=0.

$$\boxed{F.S = \frac{\tan\phi'}{\tan\beta}}$$

3) m=1 & c'=0.

$$\boxed{F.S = \frac{\gamma'}{\gamma_{sat}}\frac{\tan\phi'}{\tan\beta}}$$

Total stresses: c' $\rightarrow c_u$ and ϕ' $\rightarrow \phi_u$ and u=0

Infinite Slope VI

- Summary:
  1) The maximum stable slope in a coarse grained soil, in the absence of seepage is equal to the friction angle
  2) The maximum stable slopes in coarse grained soil, in the presence of seepage parallel to the slope, is approximately one half the friction angle
  3) The critical slip angle in fine grained soil is 45^o for an infinite slope mechanisms

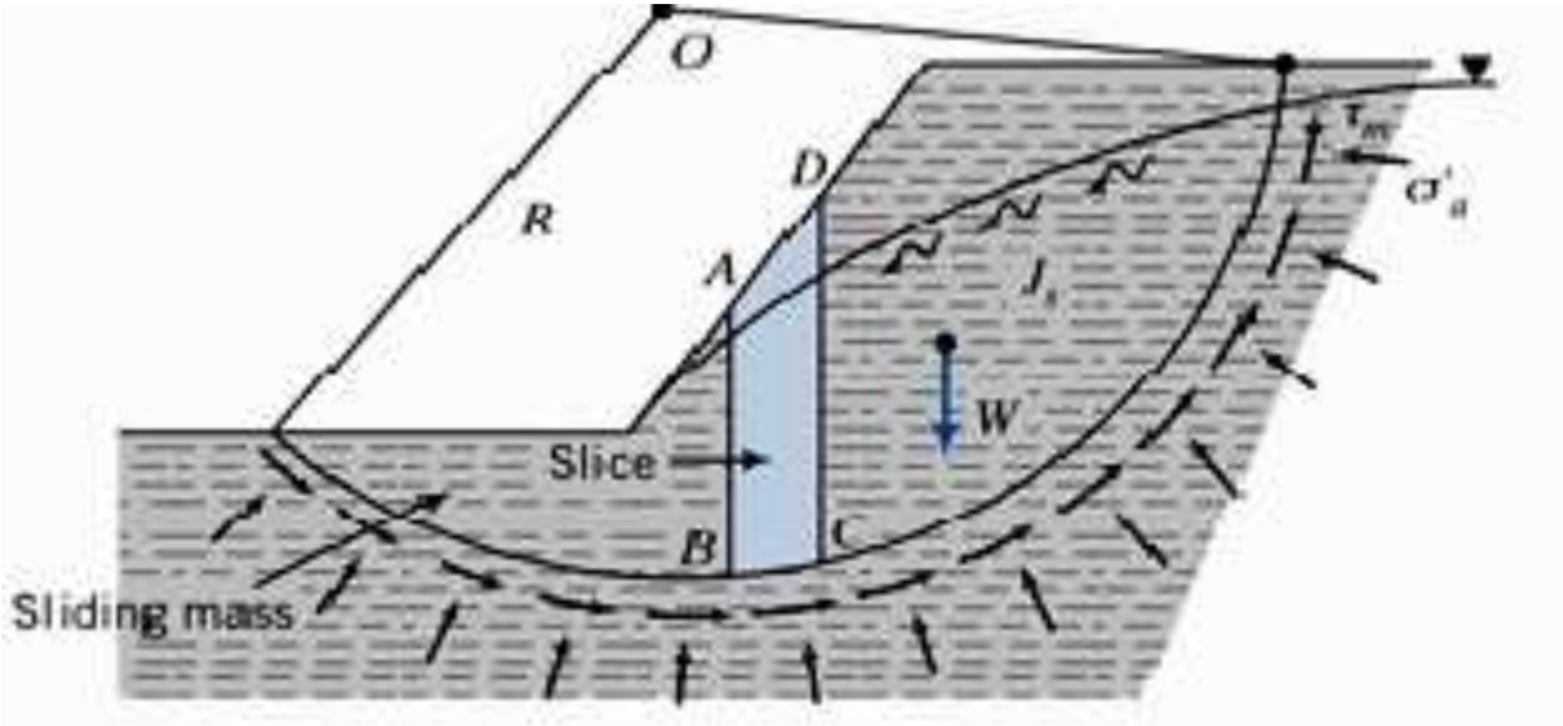
Finite Slopes

Analysis of a Finite Slip Surface

Two Dimensional Slope Stability Analysis

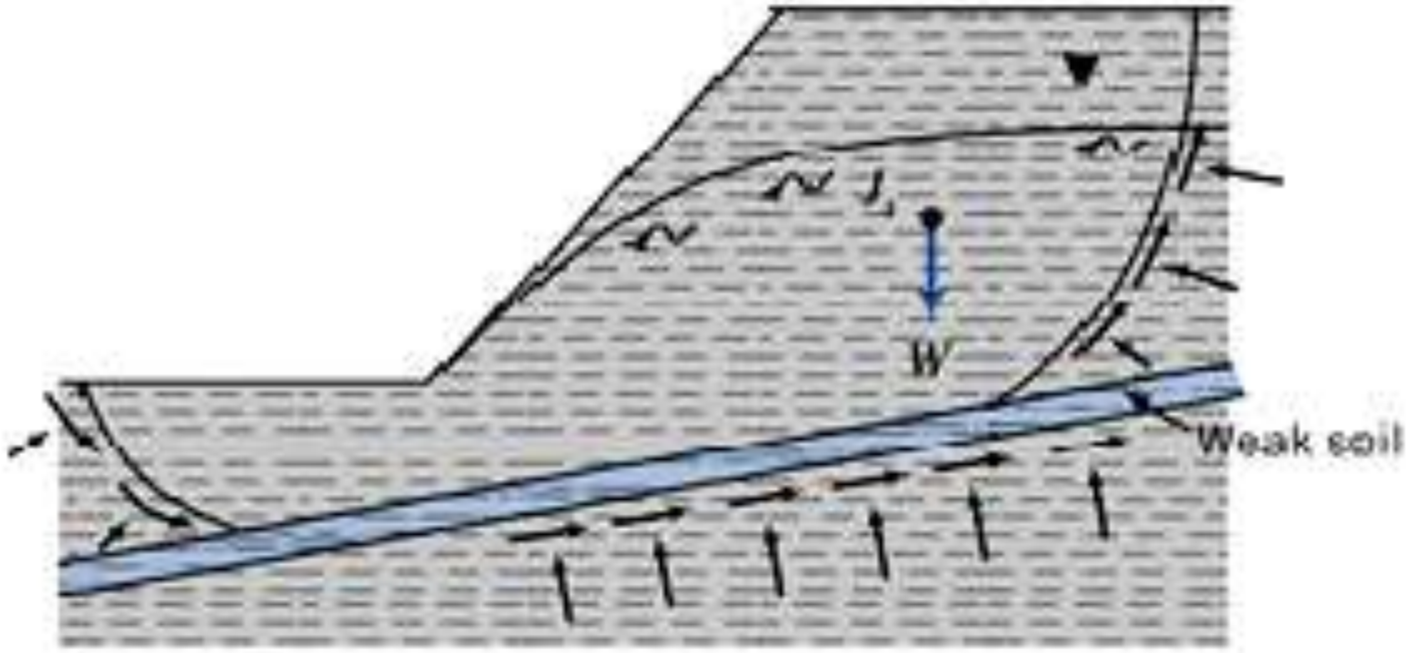
- Slope stability can be analyzed on different method
  - Limit equilibrium (most used)
    - Assume on arc of circle (Fellenius, Bishop)
    - Non circular slope failure (Janbu)
  - Limit analysis
  - Finite difference
  - Finite element (more flexible)

Rotational Failure



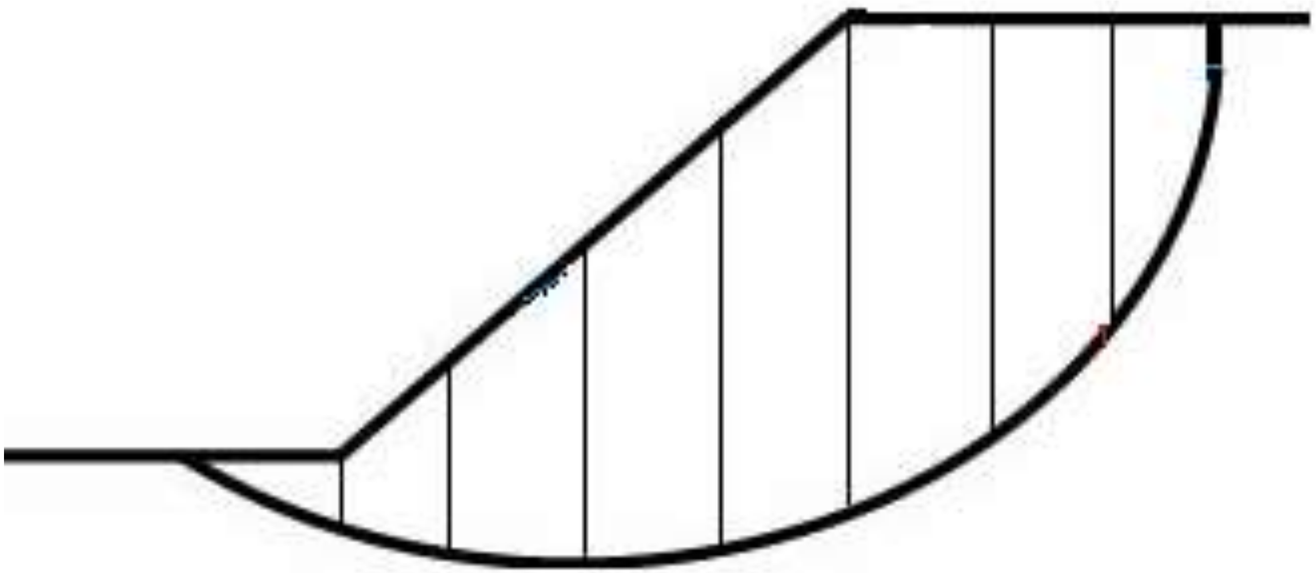
Circular Failure Surface

Rotational Failure

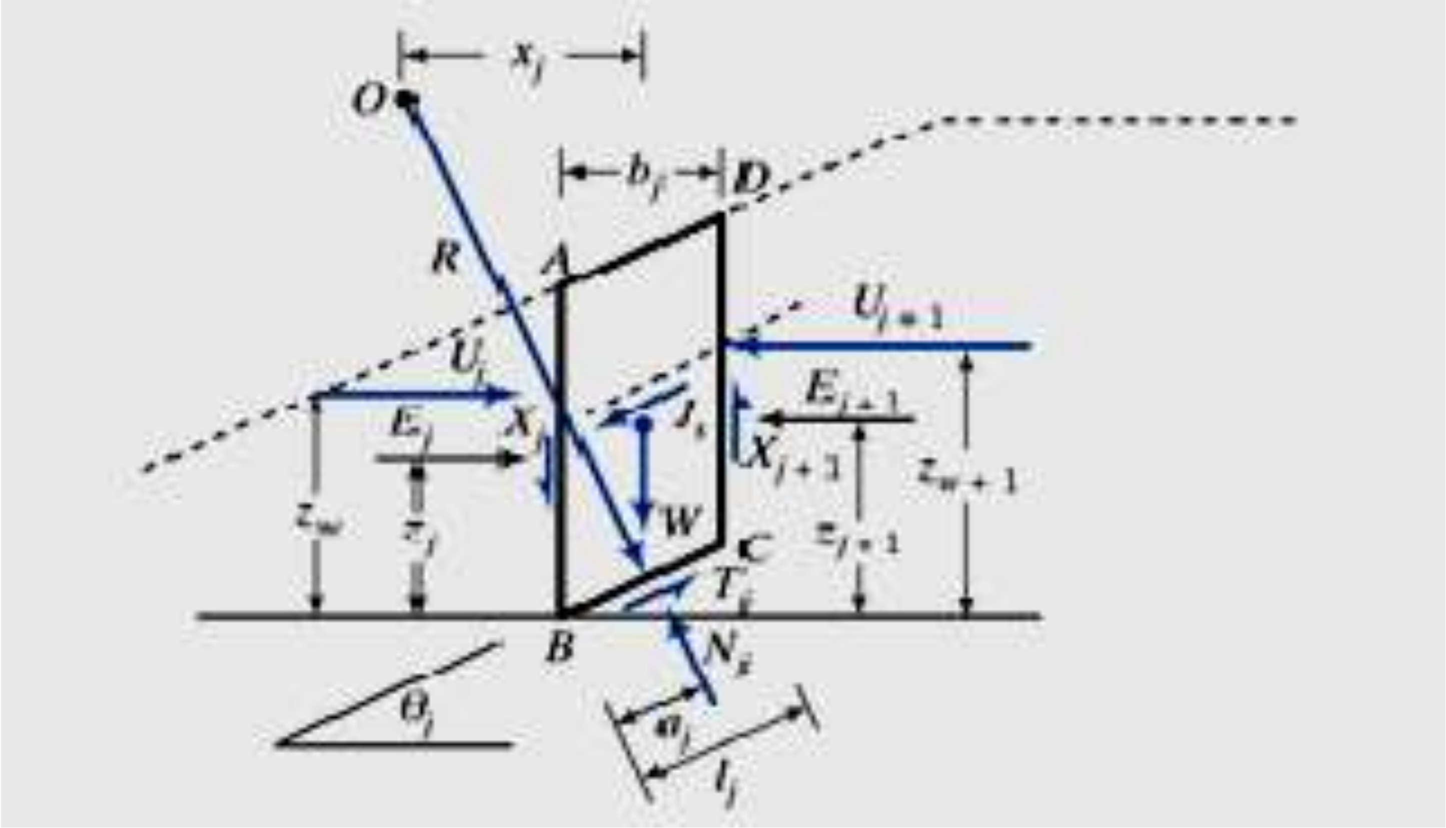


Noncircular Failure Surface

Method of Slices



Forces on Single slice



Forces On Single Slice

- W_j =total weight of a slice including any external load
- E_j = the interslices lateral effective force
- $(Js)_j$ = seepage force on the slice
- N_j = normal force along the slip surface
- X_j = interslices shear forces
- U_j = forces form pore water pressure
- Z_j =Location of the interslices lateral effective force
- Z_w=Location of the pore water force
- a_j = location of normal effective force along the slip surface
- b_j= width of slice
- l_j= length of slip surface along the slice
- θ_j = inclination of slip surface within the slice with respect to horizontal

Equilibrium Assumption and Unknown

- Factors in Equilibrium Formulation of Slope Stability for n slices

Unknown	Number
Ei	n-1
Xi	n-1
Bi	n-1
Ni	n
Ti	n
θi	n
Total Unknown	6n-3

❖**The available Equation is 3n**

Bishop Simplified Method I

- Bishop assumed
  - a circular slip surface
  - E_j and E_{j+1} are collinear
  - U_j and U_{j+1} are collinear
  - N_j acts on center of the arc length
  - Ignore X_j and X_{j+1}

Bishop Simplified Method II
Factor of Safety

- Factor of safety for an ESA

$$F.S = \frac{\sum c'_j l_j + \sum (W_j (1 - r_u)(\tan \phi')_j m_j)}{\sum W_j \sin \theta_j}$$

$$m_j = \frac{1}{\cos \theta_j + \dfrac{\tan(\phi')_j \sin \theta_j}{FS}}$$

- Factor of safety when groundwater is below the slip surface, ru = 0

$$F.S = \frac{\sum c'_j l_j + \sum (W_j (\tan \phi')_j m_j)}{\sum W_j \sin \theta_j}$$

Bishop Simplified Method III
Factor of Safety

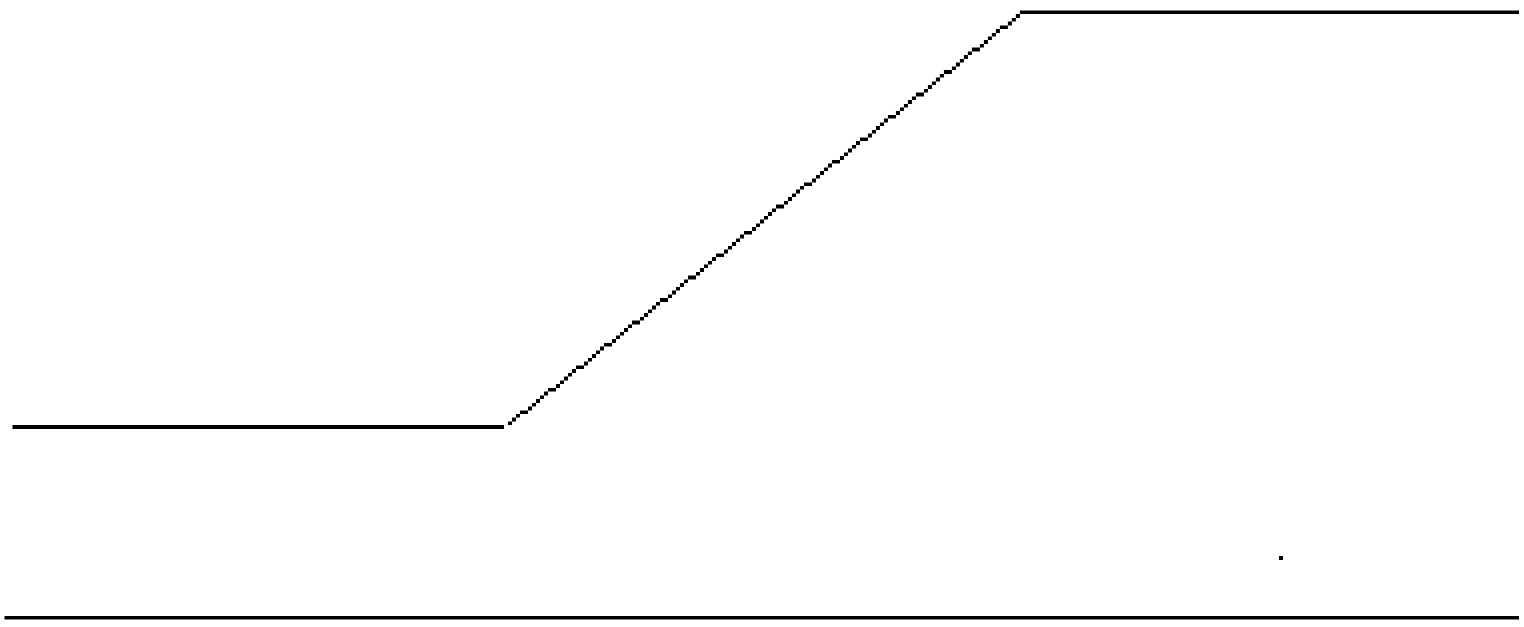
- Factor of safety equation based on TSA

$$\boxed{FS = \frac{\sum (s_u)_j \dfrac{b_j}{\cos\theta_j}}{\sum W_j \sin\theta_j}}$$

- If m=1 the method become Fellenius method of slices

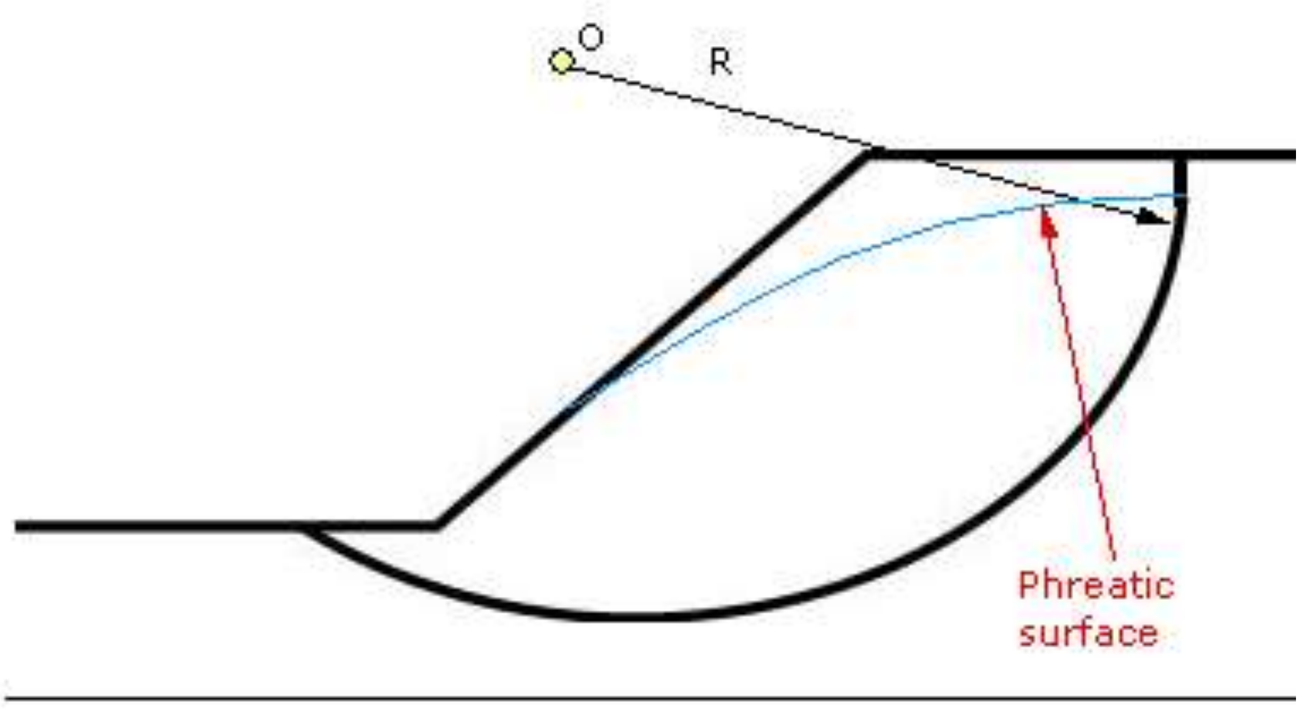
Procedure of analysis Method of slices

- Draw the slope to scale including soil layer



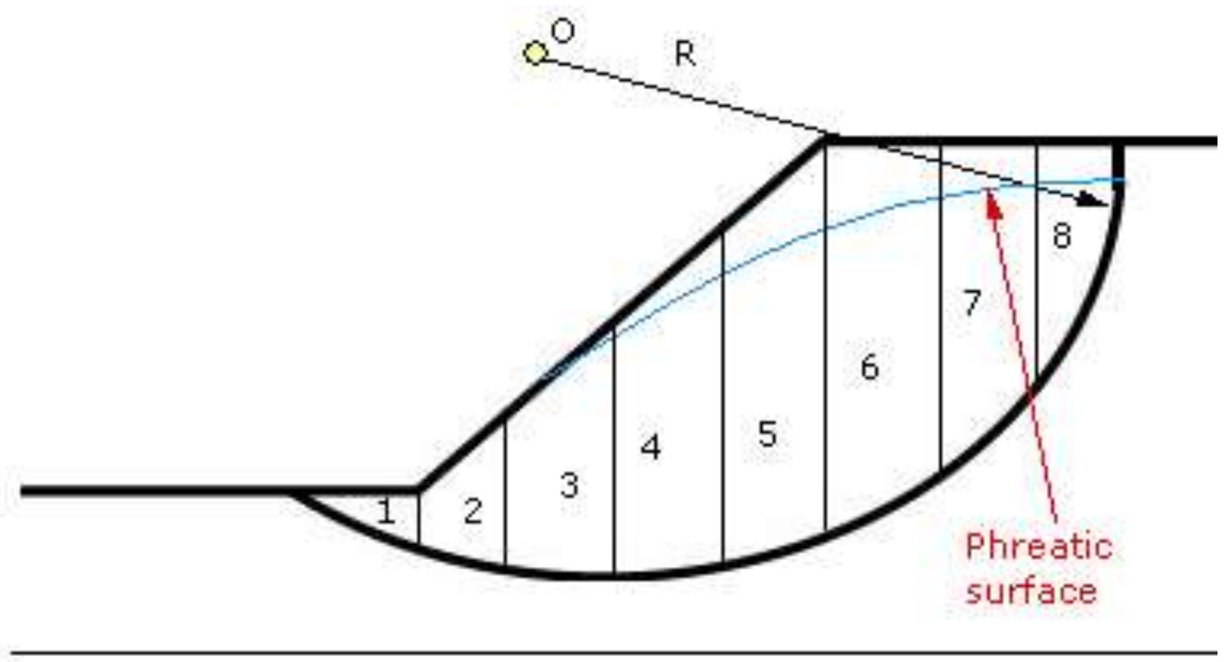
Procedure of Analysis Method of slices

Step 2: Arbitrarily draw a possible slip circle (actually on arc) of a radius R and locate the phreatic surface



Procedure of analysis Method of slices

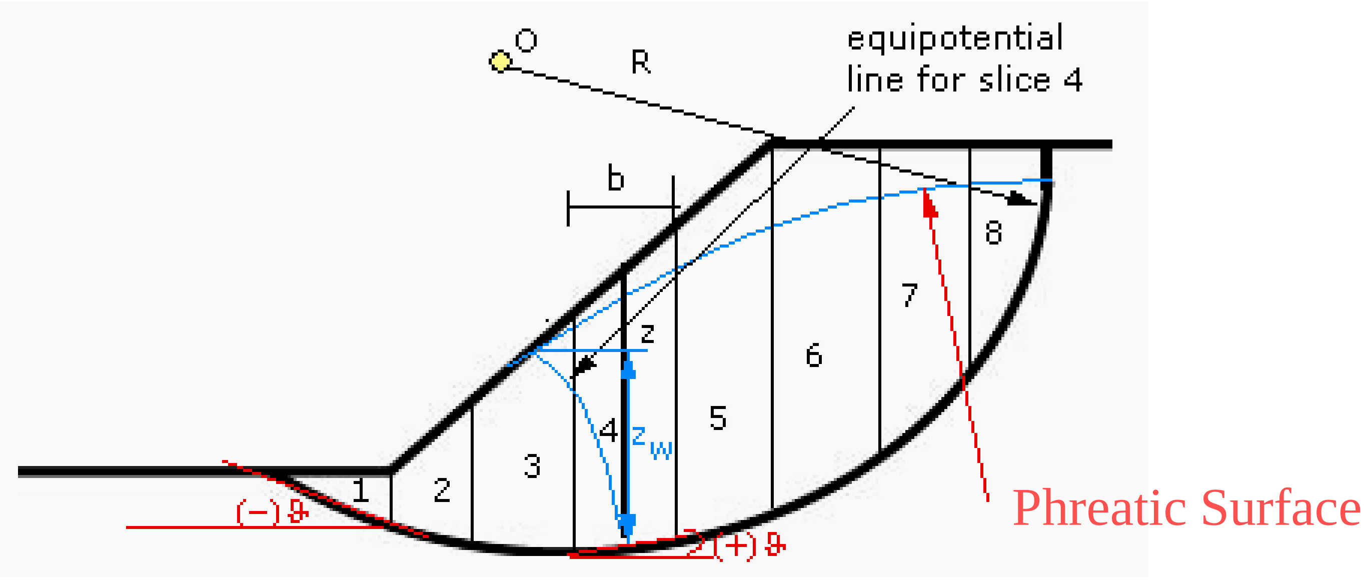
- Step three: divide the circle into slices; try to make them of equal width and 10 slices will be enough for hand calculation



Procedure of analysis Method of slices

- Step four: make table as shown and record b, z, z_w, and θ for each slice

Slice	b	z	W	Zw	ru	θ	mj	l=bcosθ	Cl	Wsinθ	W(1-ru)tanϕ'mj



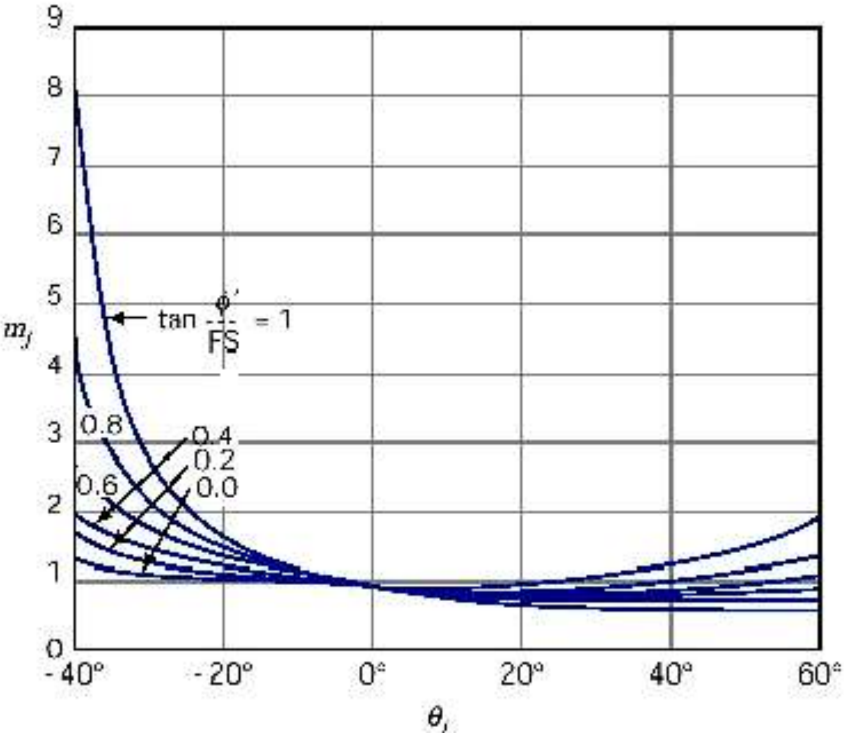
Procedure of analysis Method of slices

- Step five: calculate $W = \gamma b z$, $r_u = z_w \gamma_w / \gamma z$,

assume FS and calculate mj

$$m_j = \frac{1}{\cos\theta_j + \dfrac{\tan(\phi')_j \sin\theta_j}{FS}}$$

complete rest of column

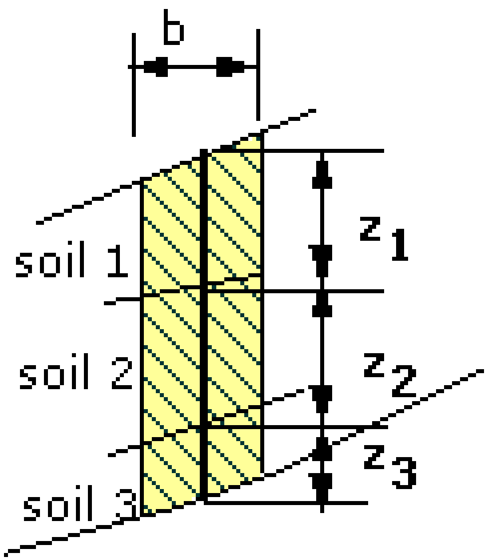


Procedure of analysis Method of slices

- Step Six: Divide the sum of column 10 by the sum of column 9 to get FS.
- If FS is not equal to the assumed value , reiterate until FS calculated and FS are approximately equal

Procedure of analysis Method of slices

- Multiple soil layer within the slice
  - Find mean height of each soil layer
  - $W=b(\gamma_1 z_1+\gamma_2 z_2+\gamma_3 z_3)$
  - The ϕ' will be for soil layer # three (in this case)



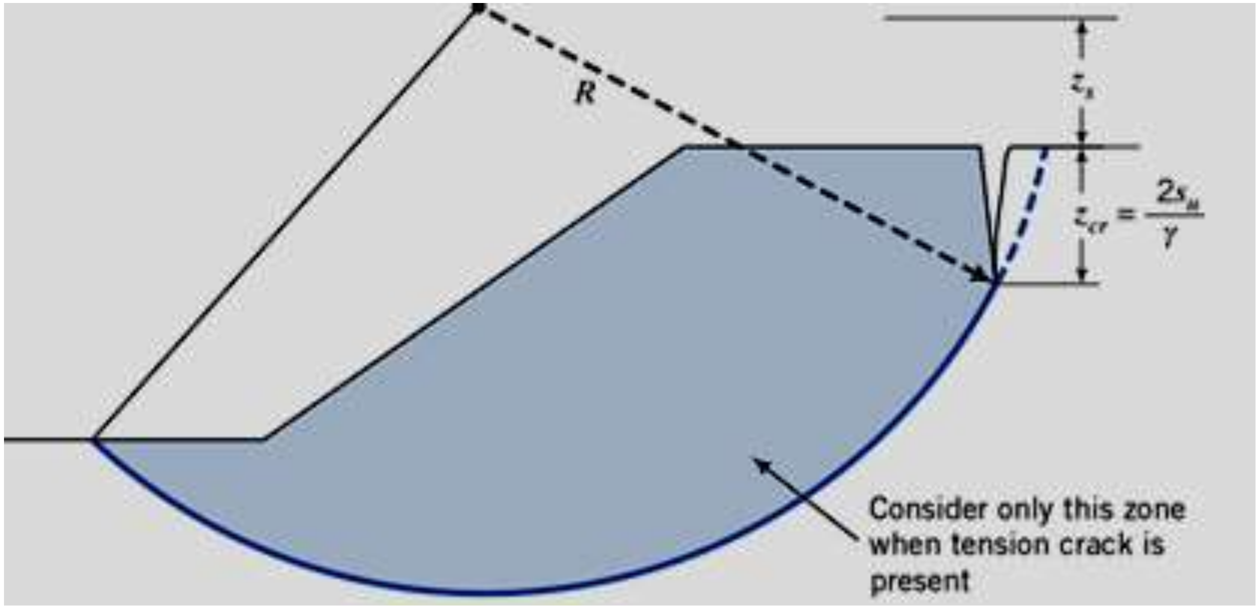
Friction Angle

- For Effective Stress Analysis
  - Use ϕ'_{cs} for most soil
  - Use ϕ'_{res} for fissured over consolidated clay
- For Total Stress Analysis use conservative value of S_u

Tension Crack

- Tension crack developed in fined grain soil.

1. Modify failure surface: failure surface stop at the base of tension crack



2. May Filled with water: reducing FS since the disturbing moment increase

Simplified Janbu's Method I

- Janbu assumed a noncircular slip surface
- Assumed equilibrium of horizontal forces
- Simplified form of Janbu's equation for an ESA

$$F.S = f_o \frac{\sum c'_j l_j + \sum (W_j (1 - r_u)(\tan\phi')_j m_j \cos\theta_j)}{\sum W_j \sin\theta_j}$$

f_o= correction factor for the depth of slope (BTW 1.0 and 1.06)

Simplified Janbu's Method II

- Factor of safety when groundwater is below the slip surface, $r_u = 0$

$$\boxed{F.S = f_o \frac{\sum(c'_j l_j) + \sum(W_j \tan\phi'_j m_j \cos\theta_j)}{\sum(W_j \sin\theta_j)}}$$

- Simplified form of Janbu's equation for a TSA

$$\boxed{F.S = f_o \frac{\sum(Su_j b_j)}{\sum(W_j \tan\theta_j)}}$$

f_o= correction factor for the depth of slope (BTW 1.0 and 1.12)

Summary For Bishop and Janbu

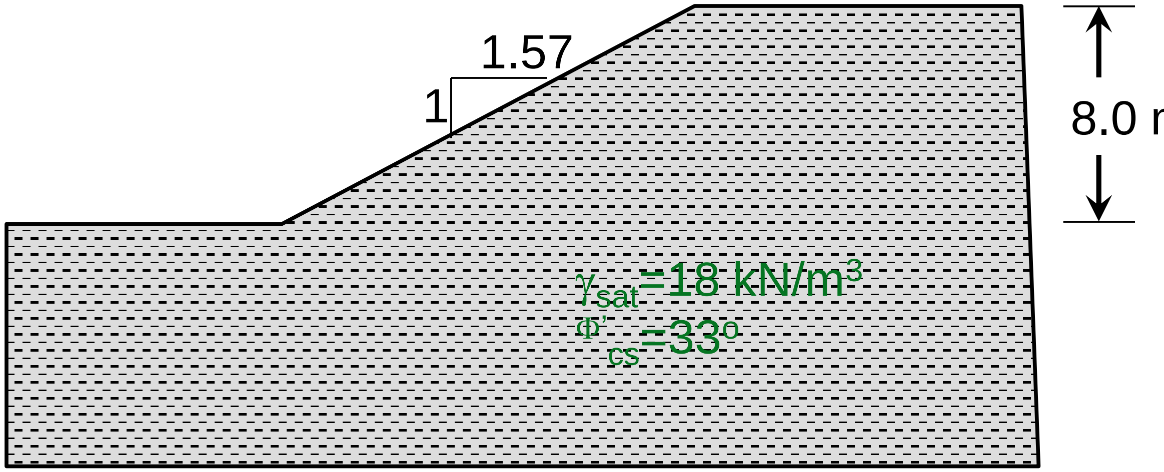
- Bishop (1955) assumes a circular slip plane and consider only moment equilibrium. He neglect seepage force and assumed that lateral normal forces are collinear. In Bishop's simplified, the resultant interface shear is assumed to be zero
- Janbu (1973) assumed a noncircular failure and consider equilibrium of horizontal forces. He made similar assumptions to bishop except that a correct force is applied to replace interface shear
- For slopes in fine grained soils, you should conduct both an ESA and TSA for a long term loading and short term loading condition respectively. For slopes in course grained soil, only ESA is necessary for short term and long term loading provided the loading is static

Microsoft Excel Sheet Solution

Examples of Bishop’s and Janbu’s method by utilizing excel worksheets

Examples # 1

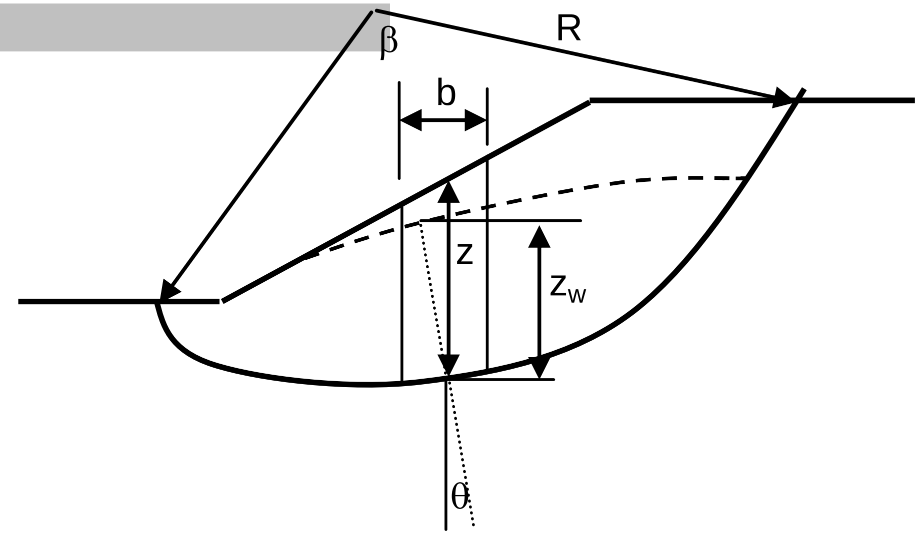
Slope satiability by Bishop's Method using excel sheets



- Using Bishop's method determine FS

1. If there is no tension crack

Examples # 1 Solution



Bishop's simplified method

Homogenous soil

s_u	30	kPa
ϕ'	33	deg.
γ_w	9.8	kN/m^3
γ_{sat}	18	kN/m^3
z_{cr}	3.33	m
z_s	4	m
FS	1.06	assumed

No tension crack

									ESA	TSA
Slice	b	z	W=γbz	z_w	r_u	θ	m_j	W$\sin\theta$	W $(1 - r_u)\tan\phi'\ m_j$	s_u b/$\cos\theta$
	m	m	kN	m		deg				
1	4.9	1	88.2	1	0.54	-23	1.47	-34.5	38.3	159.7
2	2.5	3.6	162.0	3.6	0.54	-10	1.14	-28.1	54.6	76.2
3	2	4.6	165.6	4.6	0.54	0	1.00	0.0	49.0	60.0
4	2	5.6	201.6	5	0.49	9	0.92	31.5	62.1	60.7
5	2	6.5	234.0	5.5	0.46	17	0.88	68.4	72.2	62.7
6	2	6.9	248.4	5.3	0.42	29	0.85	120.4	80.1	68.6
7	2	6.8	244.8	4.5	0.36	39.5	0.86	155.7	87.6	77.8
8	2.5	5.3	238.5	2.9	0.30	49.5	0.90	181.4	97.5	115.5
9	1.6	1.6	46.1	0.1	0.03	65	1.02	41.8	29.6	113.6
							Sum	536.6	570.9	794.8
								FS	**1.06**	**1.48**

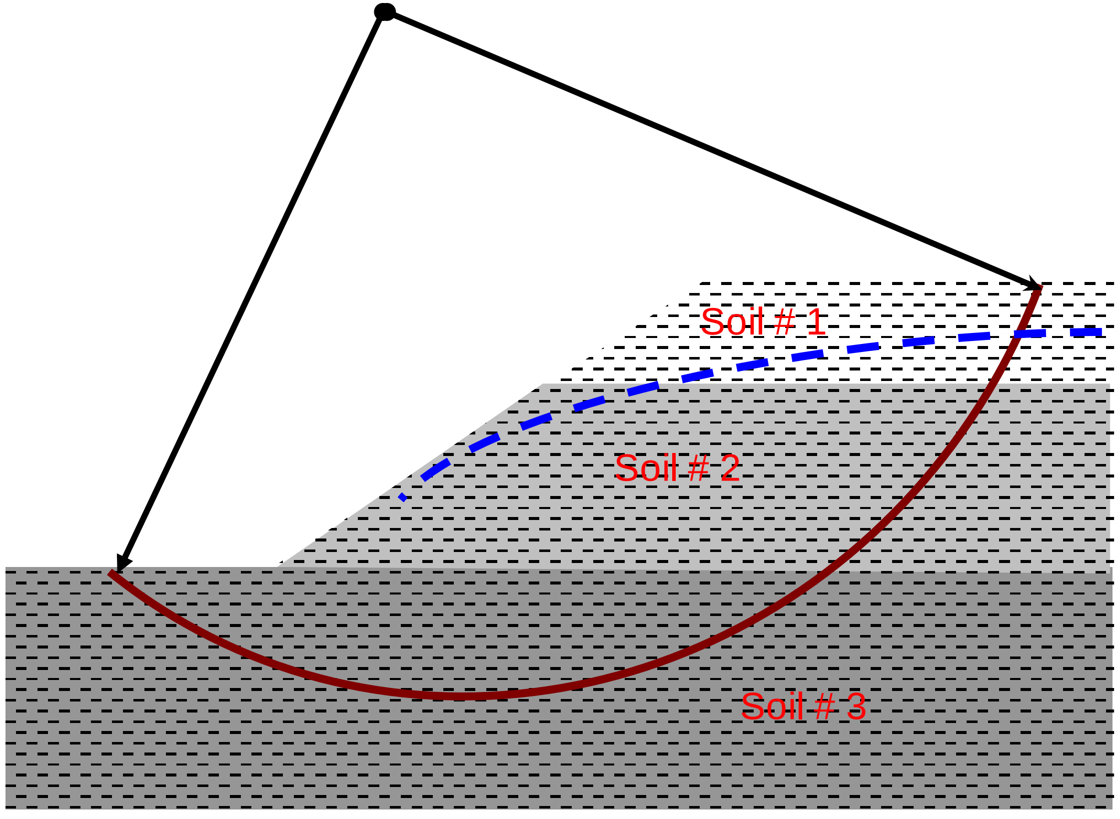
Examples # 1 Solution

No tension crack

									ESA	TSA
Slice	b	z	$W=\gamma bz$	z_w	r_u	θ	m_j	$W\sin\theta$	$W(1 - r_u)\tan\phi' m_j$	$s_u b/\cos\theta$
	m	m	kN	m		deg				
1	4.9	1	88.2	1	0.54	-23	1.47	-34.5	38.3	159.7
2	2.5	3.6	162.0	3.6	0.54	-10	1.14	-28.1	54.6	76.2
3	2	4.6	165.6	4.6	0.54	0	1.00	0.0	49.0	60.0
4	2	5.6	201.6	5	0.49	9	0.92	31.5	62.1	60.7
5	2	6.5	234.0	5.5	0.46	17	0.88	68.4	72.2	62.7
6	2	6.9	248.4	5.3	0.42	29	0.85	120.4	80.1	68.6
7	2	6.8	244.8	4.5	0.36	39.5	0.86	155.7	87.6	77.8
8	2.5	5.3	238.5	2.9	0.30	49.5	0.90	181.4	97.5	115.5
9	1.6	1.6	46.1	0.1	0.03	65	1.02	41.8	29.6	113.6
							Sum	536.6	570.9	794.8
								FS	**1.06**	**1.48**

Examples # 2

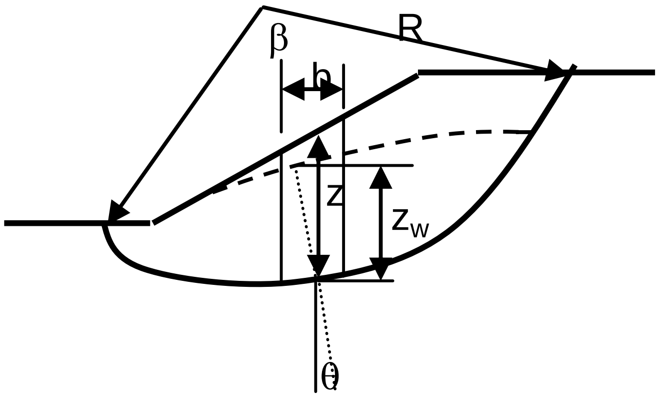
Slope satiability by Bishop’s Method using excel sheet



Examples # 2 Solution

Three soil layers

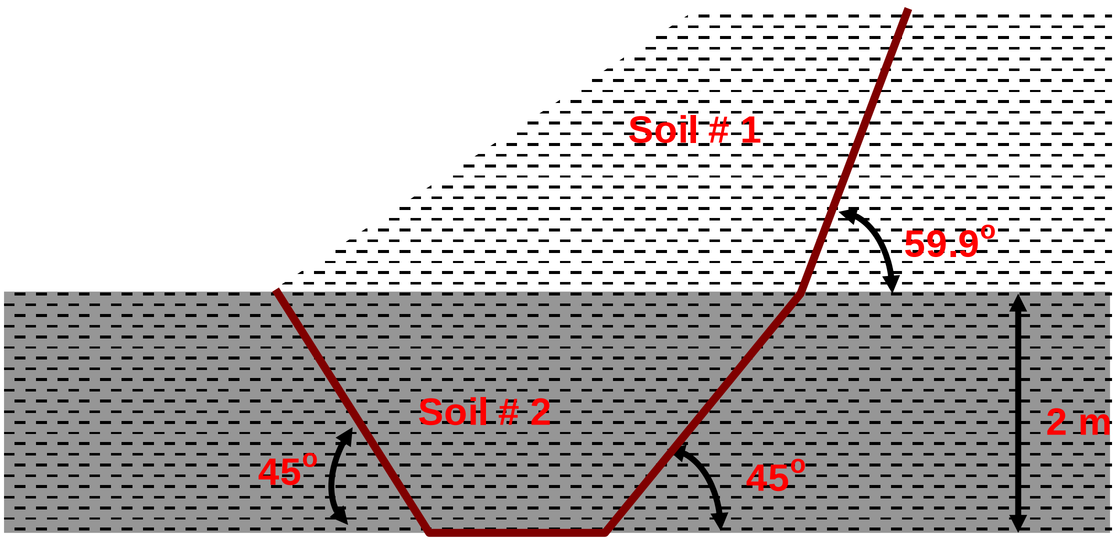
	Soil 1	Soil 2	Soil 3	
s_u	30	42	58	kPa
ϕ'	33	29	25	deg.
γ_w	9.8			kN/m^3
γ_{sat}	18	17.5	17	kN/m^3
FS	1.01	assumed		



											ESA	TSA
Slice	b	z_1	z_2	z_3	$W=\gamma bz$	z_w	r_u	θ	m_j	$W\sin\theta$	$W(1 - r_u)\tan\phi'\ m_j$	$s_u\ b/\cos\theta$
	m	m	m	m	kN	m		deg				
1	4.9	1	0	0	88.2	1	0.54	-23	1.49	-34.5	39.0	159.7
2	2.5	2.3	1.3	0	160.4	3.6	0.55	-10	1.15	-27.8	53.7	76.2
3	2	2.4	2.2	0	163.4	4.6	0.55	0	1.00	0.0	47.6	60.0
4	2	2	3.6	0	198.0	5	0.49	9	0.92	31.0	59.7	60.7
5	2	0.9	4.1	1.5	226.9	5.5	0.48	17	0.87	66.3	67.6	62.7
6	2	0.8	4.1	2	240.3	5.3	0.43	29	0.84	116.5	74.7	68.6
7	2	0	3.7	3.1	234.9	4.5	0.38	39.5	0.89	149.4	72.6	108.9
8	2.5	0	1.5	3.8	227.1	2.9	0.31	49.5	0.94	172.7	81.1	161.7
9	1.6	0	0	1.6	43.5	0.1	0.04	65	1.19	39.4	23.3	219.6
									Sum	513.1	519.1	978.1
										FS	**1.01**	**1.91**

Examples # 3

Slope satiability by Janbu's Method using excel sheets

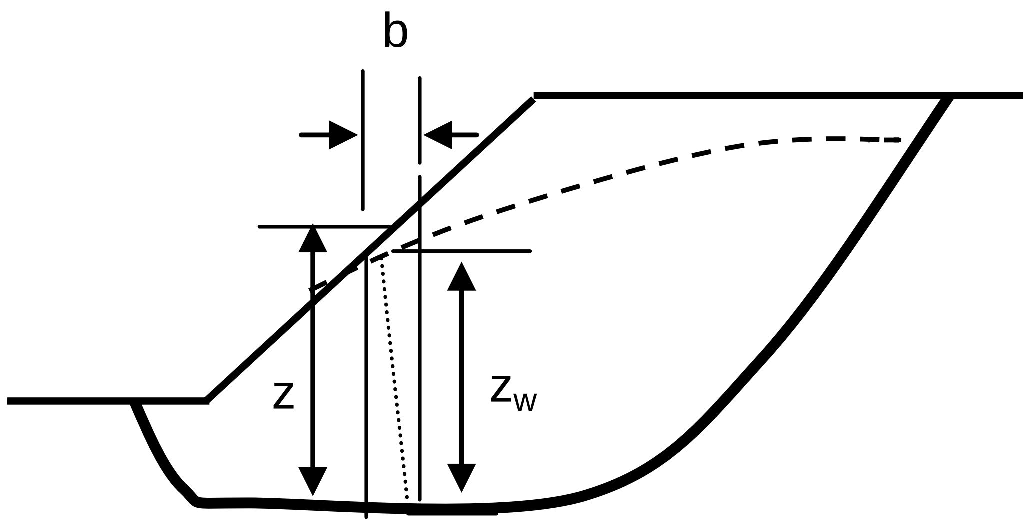


A coarse grained fill was placed on saturated clay. Determine FS if the noncircular slip shown was a failure surface

Examples # 3 Solution

Janbu's method

	Soil 1	Soil 2	
ϕ'	29	33.5	deg.
γ_w	9.8		kN/m^3
γ_{sat}	18	17	kN/m^3
d	4.5		m
l	11.5		
d/l	0.39	f_o	1.06
FS	1.04	ssumed	



Slice	b	z_1	z_2	$W=\gamma bz$	θ	m_j	$W\tan\theta$	$W\tan\phi' \cos\theta\, m_j$
	m	m	m	kN	deg			
1	2	1	0.7	59.8	-45	3.03	-59.8	71.0
2	3.5	2	2.5	274.8	0	1.00	0.0	152.3
3	2	1	4.3	182.2	45	0.92	182.2	65.9
4	2.9	0	2.5	123.3	59.9	0.95	212.6	38.9
						Sum	335.0	328.0
							FS	**1.04**