Fayoum University

Faculty of Engineering

Department of Civil Engineering

CE 402: Part D

Lecture No. (17)

Slope Stability Analysis

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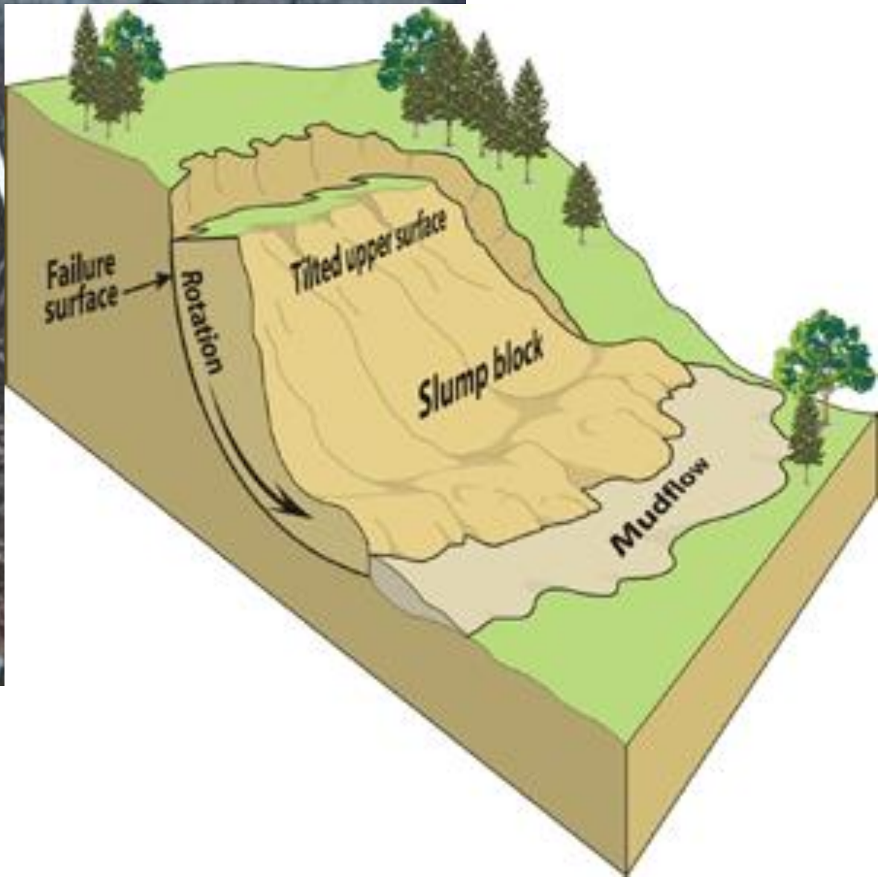
Definition

- It is an earth body which provides a gradual change in ground surface elevation between two different levels .

Slope Stability



Types Of Slopes

Natural slopes

(Mountains, Valley sides,…………………….)

Man-made slopes

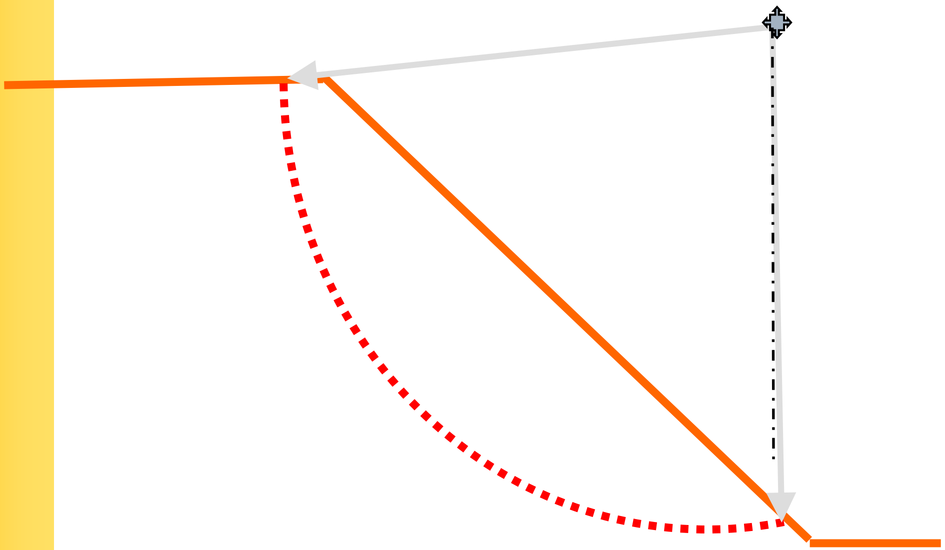
(Canal banks, Earth dams, Road cuts,…..)

Types Of Slopes Failures

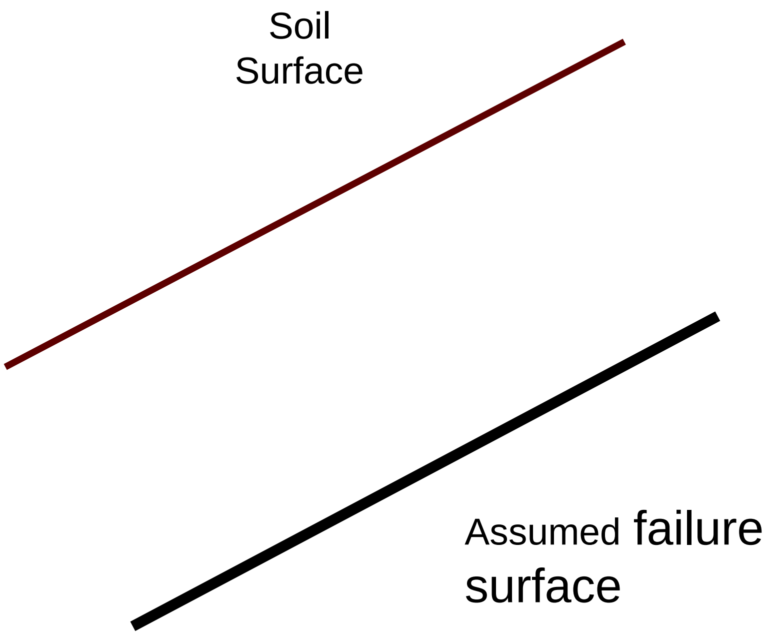
1. Infinite slopes
2. Finite slopes

- Rotational slip.   (Circular, non-circular)
- Transitional slip.
- Compound slip.

Types Of Slopes Failures



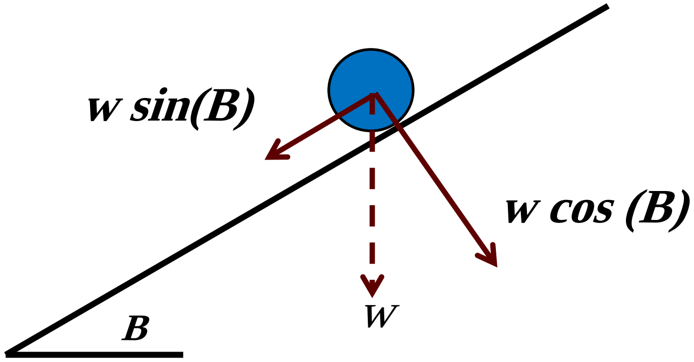
Rotational slip



Infinite slopes

Infinite Slopes In Sand

Factor of safety in sandy slopes is **independent** of the height of the slope.



Driving forces = *w sin B*

Resisting forces = $N * \mu = w \cos(B) * \tan(\varphi)$

$$F.S = w \cos(B) \tan(\varphi) / w \sin(B) = \tan(\varphi) / \tan(B)$$

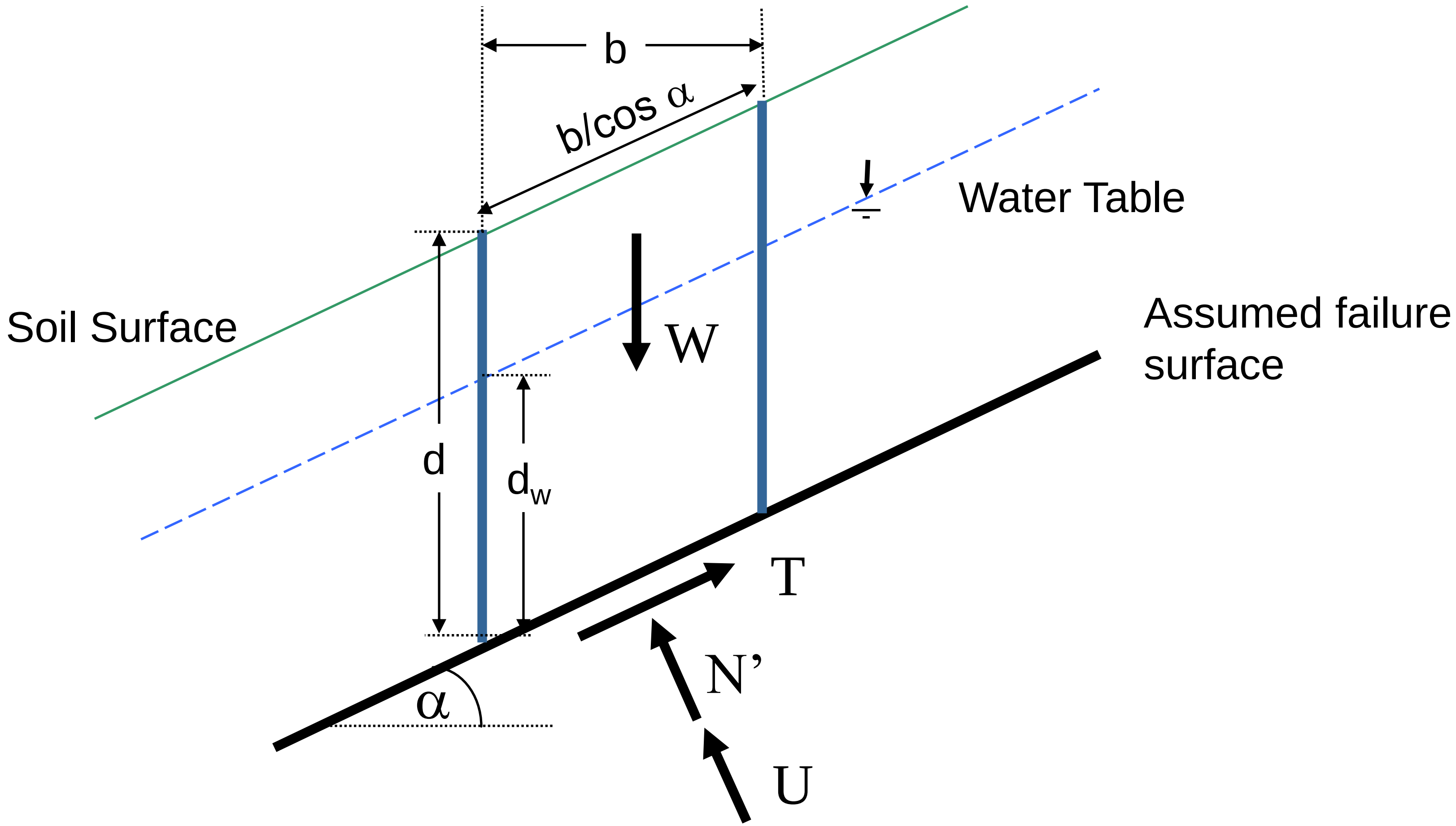
$$\mathbf{F.S = \tan(\varphi) / \tan(B)}$$

Example (1):

Find the factor of safety of a slope of infinite extent having a slope angle = 25°. The slope is made of cohesionless soil with ϕ = 30°.

$$F.S. = \frac{\tan\phi'}{\tan\beta} = \frac{\tan 30}{\tan 25} = 1.238$$

Infinite Slopes

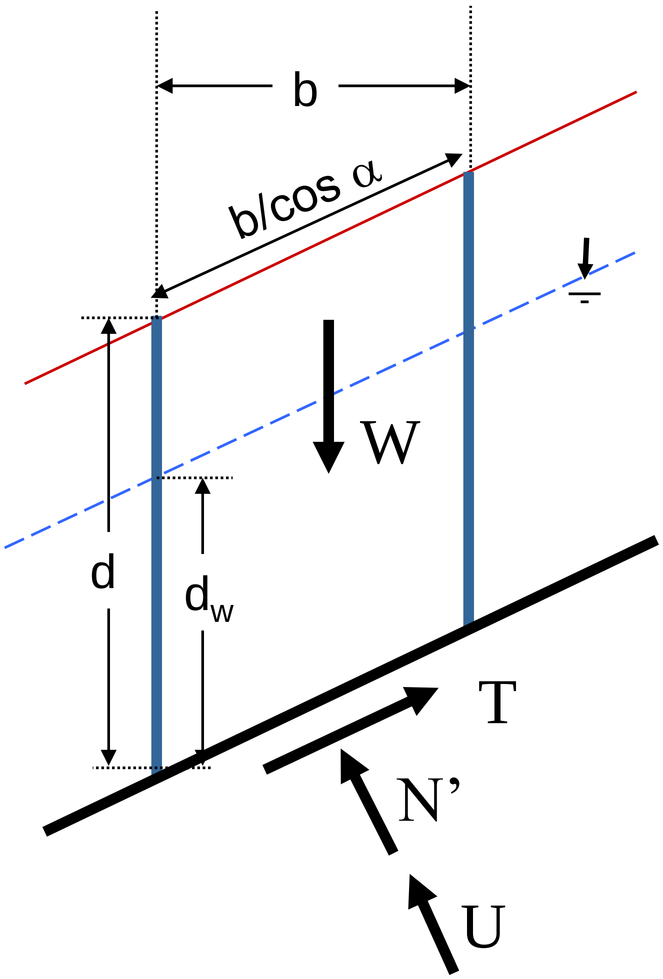


Infinite Slopes

From equilibrium

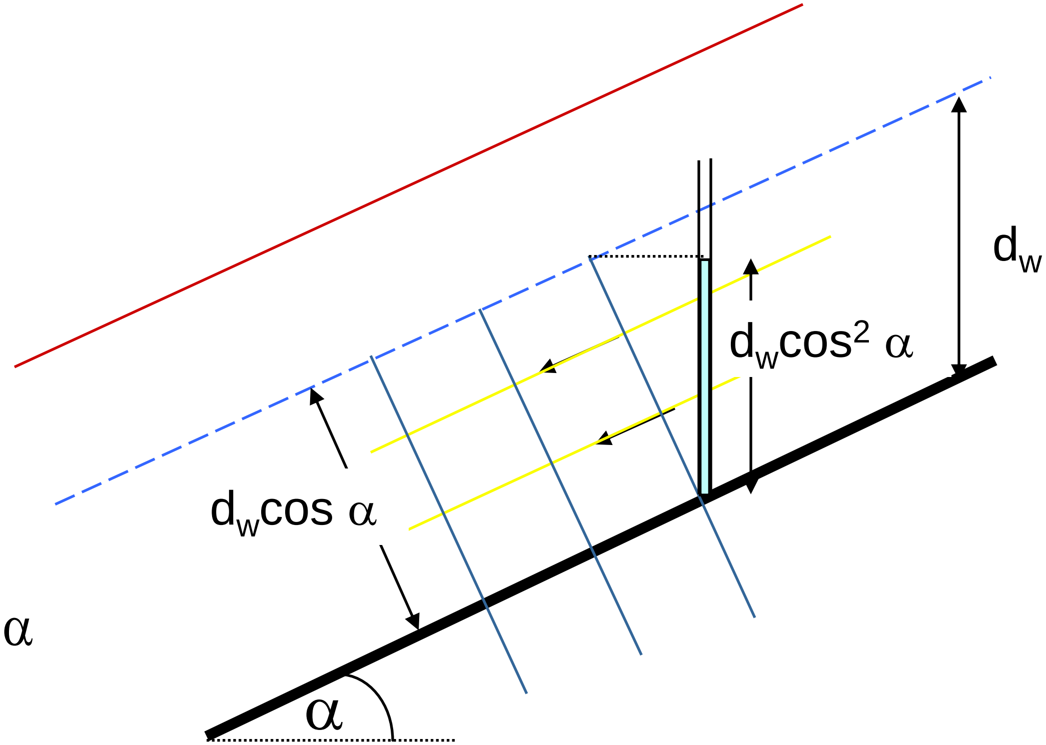
$$N = W \cos \alpha = \gamma b d \cos \alpha$$

$$T = W \sin \alpha = \gamma b d \sin \alpha$$



Infinite Slope

$$u = \gamma_w \ d_w \ \cos^2 \alpha$$



$$U = u\left(\frac{b}{\cos\alpha}\right) = \gamma_w \, b \, d_w \cos\alpha$$

Infinite Slopes

On the failure plane $\tau = c' + \sigma' \tan \phi'$

Defining the factor of Safety, F, by

$$F = \frac{\tau_f}{\tau} = \frac{\text{shear stress required for failure}}{\text{actual shear stress}}$$

$$F = \frac{c' + (\gamma d - \gamma_w d_w) \cos^2 \alpha \tan \phi'}{\gamma d \sin \alpha \cos \alpha}$$

Infinite Slopes

If c' = 0

$$F = \left(1 - \frac{\gamma_w d_w}{\gamma d}\right) \frac{\tan\phi'_{cs}}{\tan\alpha}$$

$$F = \frac{\tan\phi'_{cs}}{\tan\alpha}$$

$$\alpha = \phi'_{cs}$$

Infinite Slopes

If c' = 0

$$F = \left(1 - \frac{\gamma_w d_w}{\gamma d}\right) \frac{\tan \phi'_{cs}}{\tan \alpha}$$

If the water is at the soil surface, $d = d_w$ and when $F = 1$

$$\tan\alpha = \left(1 - \frac{\gamma_w}{\gamma}\right) \tan\varphi'_{cs}$$

For typical values it is found that α is about 0.5 ϕ'

Water reduces the stable angle of the slope by 50%

Example (2):

Analyze the slope of infinite extent if it is made of clay having *c' - 30 kN/m²*, $\phi' = 20°$, *e = 0.65 and* $G_s = 2.7$ *and under the following conditions:*

(i) when the soil is dry,

(ii) when water seeps parallel to the surface of the slope,

(iii) when the slope is submerged.

Example (2):

$$\gamma_d = \frac{G_s}{1+e}\gamma_w = \frac{2.70}{1+0.65}*9.81 = 16.05 kN/m^2$$

$$\gamma_{sat} = \frac{G_s + e}{1+e}\gamma_w = \frac{2.70+0.65}{1+0.65}*9.81 = 19.90 kN/m^2$$

(i) when the soil is dry,

$$F_s = \frac{c' + (\gamma d - \gamma_w d_w)\cos^2\alpha \tan\phi'}{\gamma d \sin\alpha \cos\alpha}$$

$$1.00 = \frac{30 + (16.05*d)\cos^2 25 \tan 20}{16.05*d \sin 25 \cos 25}$$

$$d = 22.23 m$$

Example (2):

ii) when water seeps parallel **to the surface of the slope,**

$$F_s = \frac{c' + (\gamma d - \gamma_w d_w)\cos^2\alpha \tan\phi'}{\gamma d \sin\alpha \cos\alpha}$$

$$1.00 = \frac{30 + (19.90 - 9.81) * d \cos^2 25 \tan 20}{19.90 * d \sin 25 \cos 25}$$

$$d = 6.52m$$

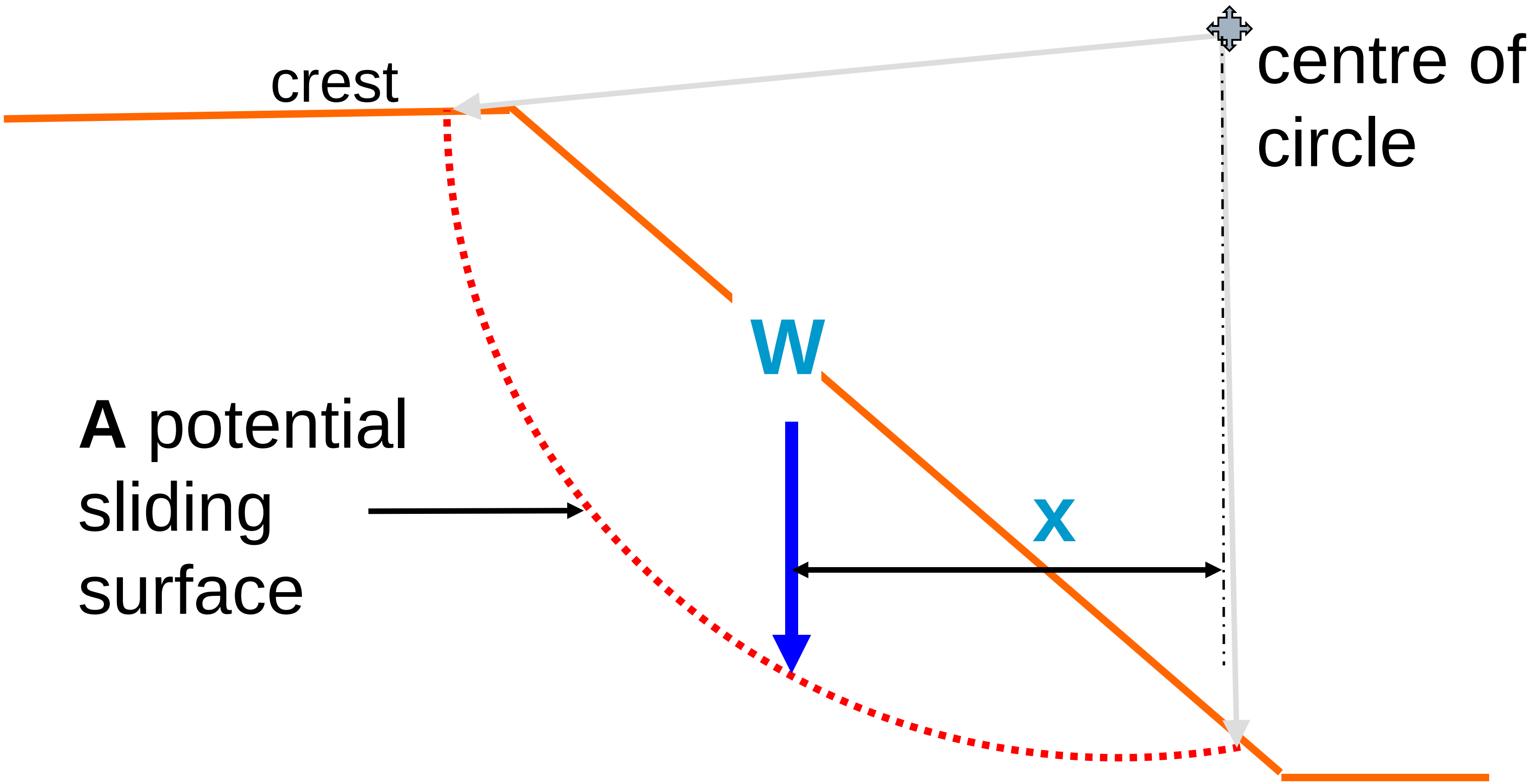
iii) when the slope is submerged.

$$F_s = \frac{c' + (\gamma d - \gamma_w d_w)\cos^2\alpha \tan\phi'}{\gamma d \sin\alpha \cos\alpha}$$

$$1.00 = \frac{30 + (19.90 - 9.81) * d \cos^2 25 \tan 20}{(19.90 - 9.81) * d \sin 25 \cos 25}$$

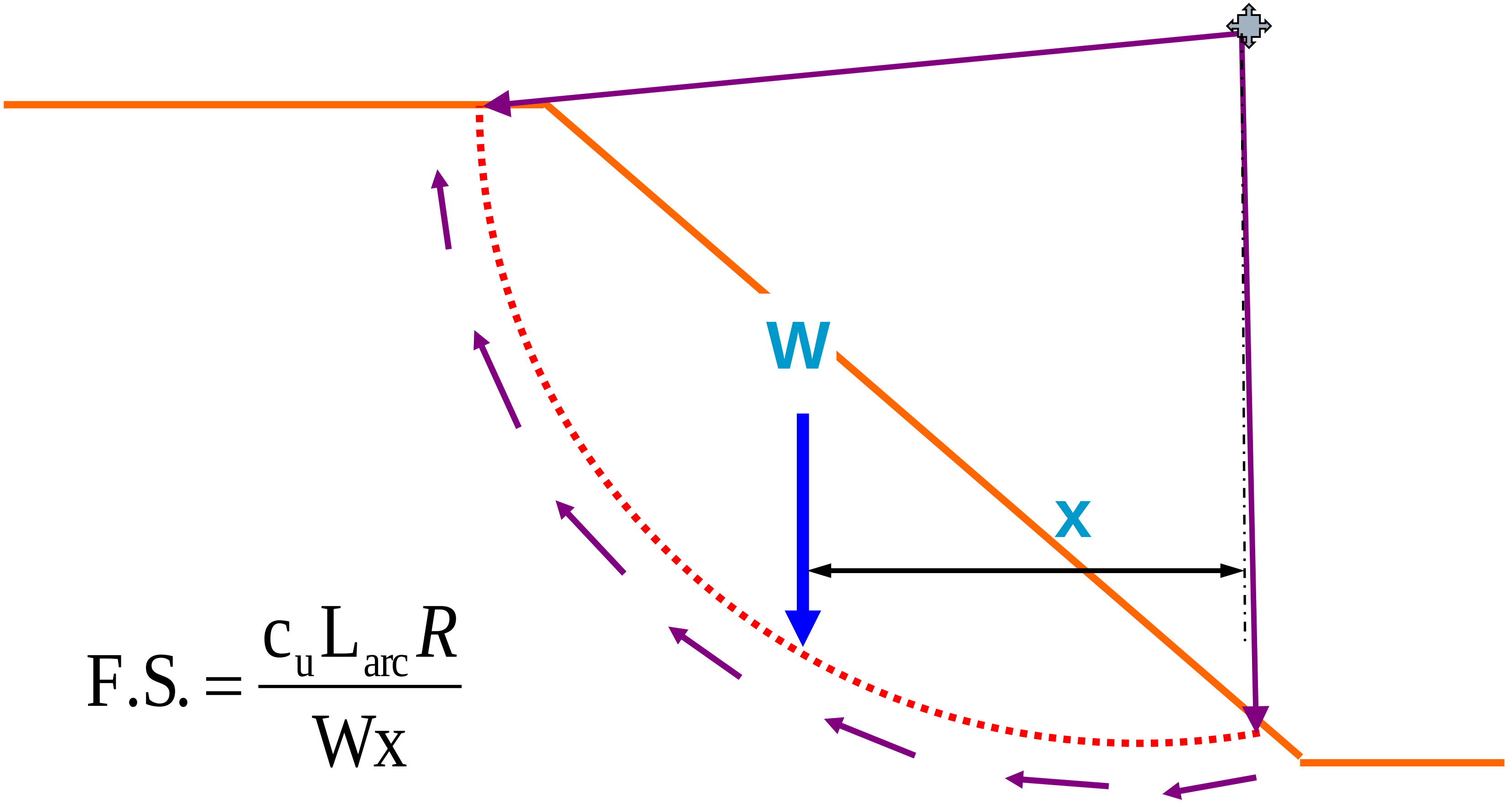
$$d = 35.37m$$

Circular Slips



CIRCULAR SLIPS Stability
<u>Case 1</u>: $\phi' = 0$

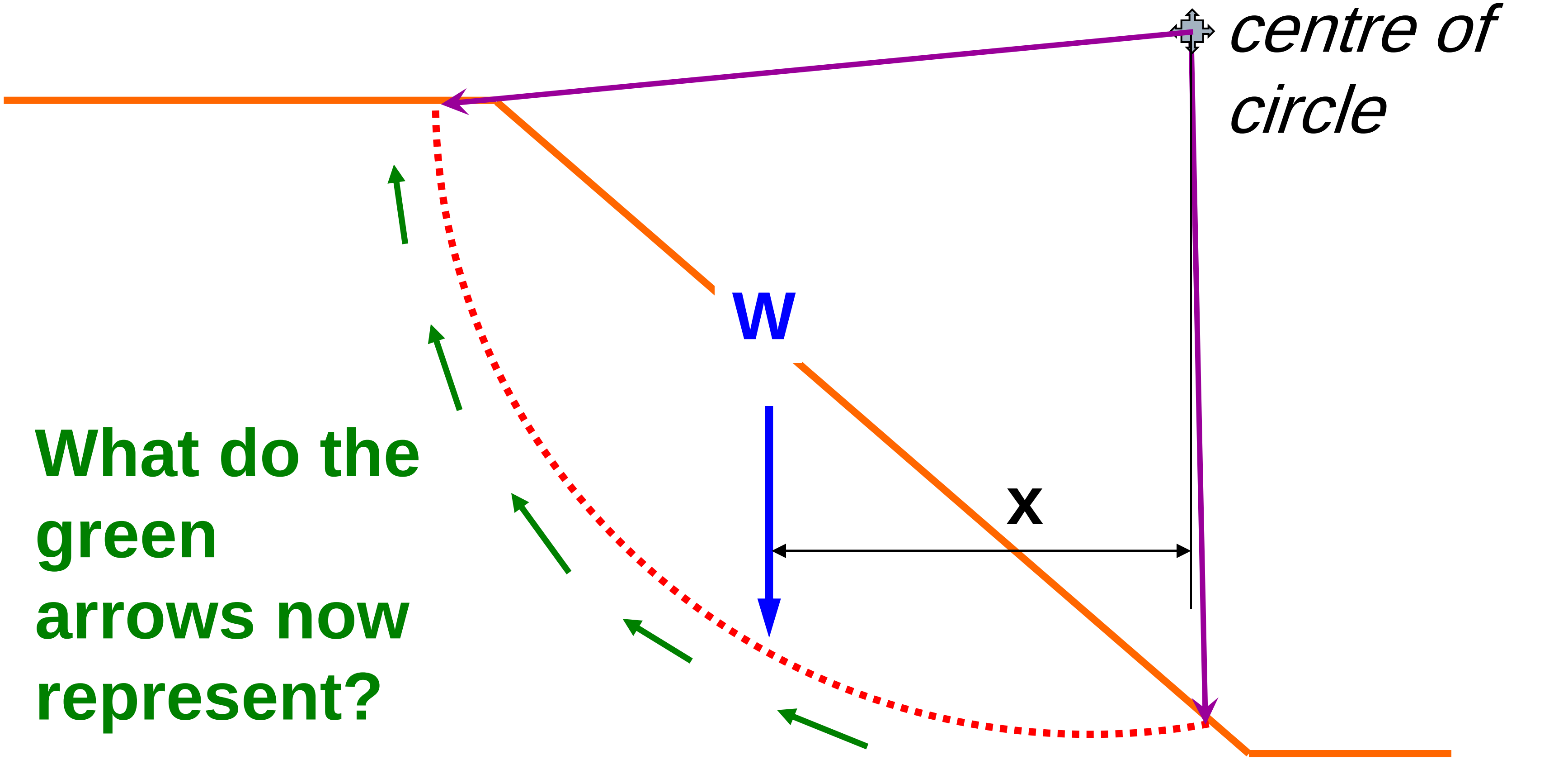
Stability? *Limit equilibrium*



$$F.S. = \frac{c_u L_{arc} R}{Wx}$$

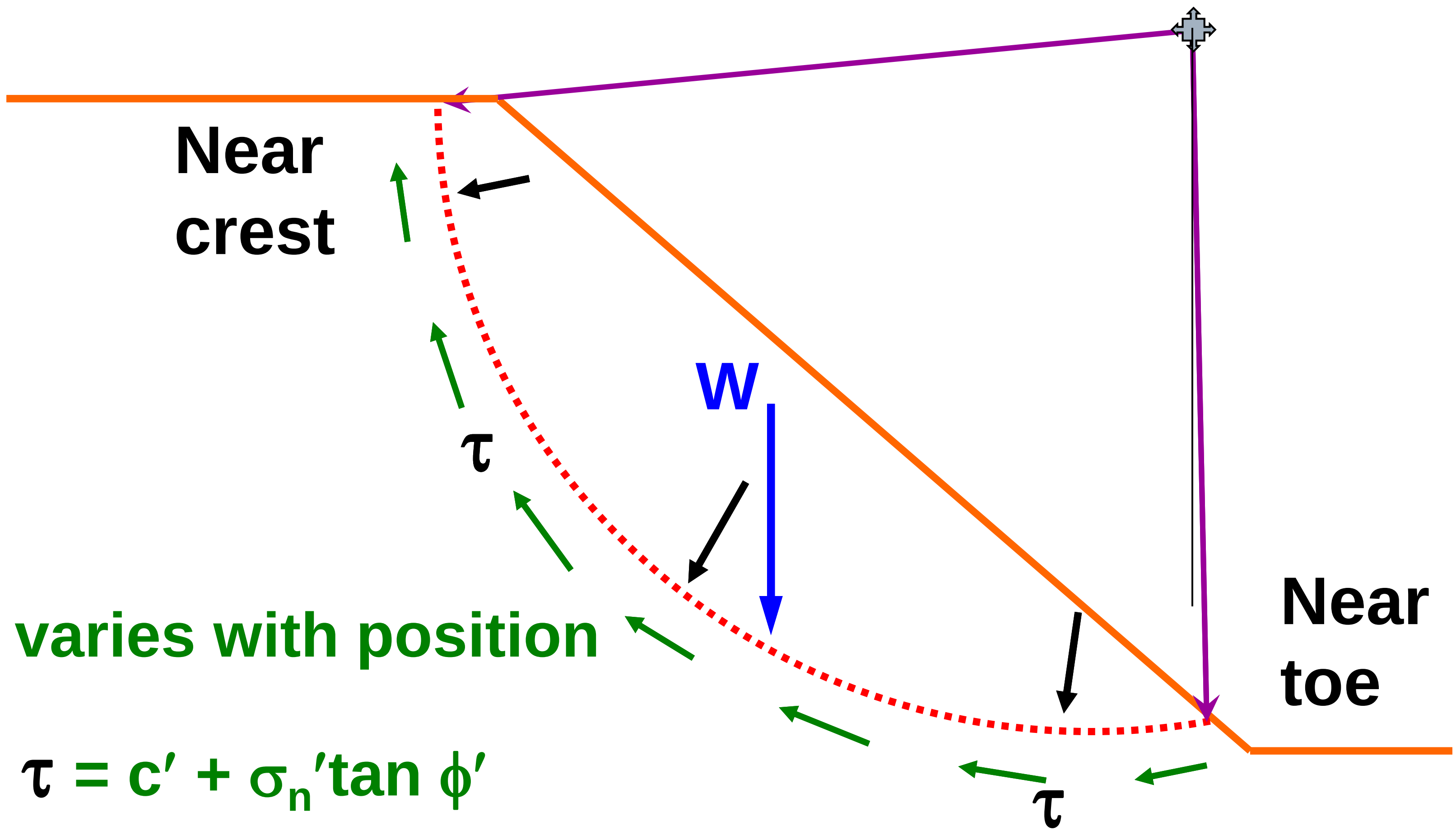
CIRCULAR SLIPS Stability

Case 2: $\phi' \neq 0$



What do the green arrows now represent?

Force on Slip Plane:
c', ϕ' soil



$\therefore \tau$ varies with position

$$\tau = c' + \sigma_n' \tan \phi'$$

Overall Stability Method

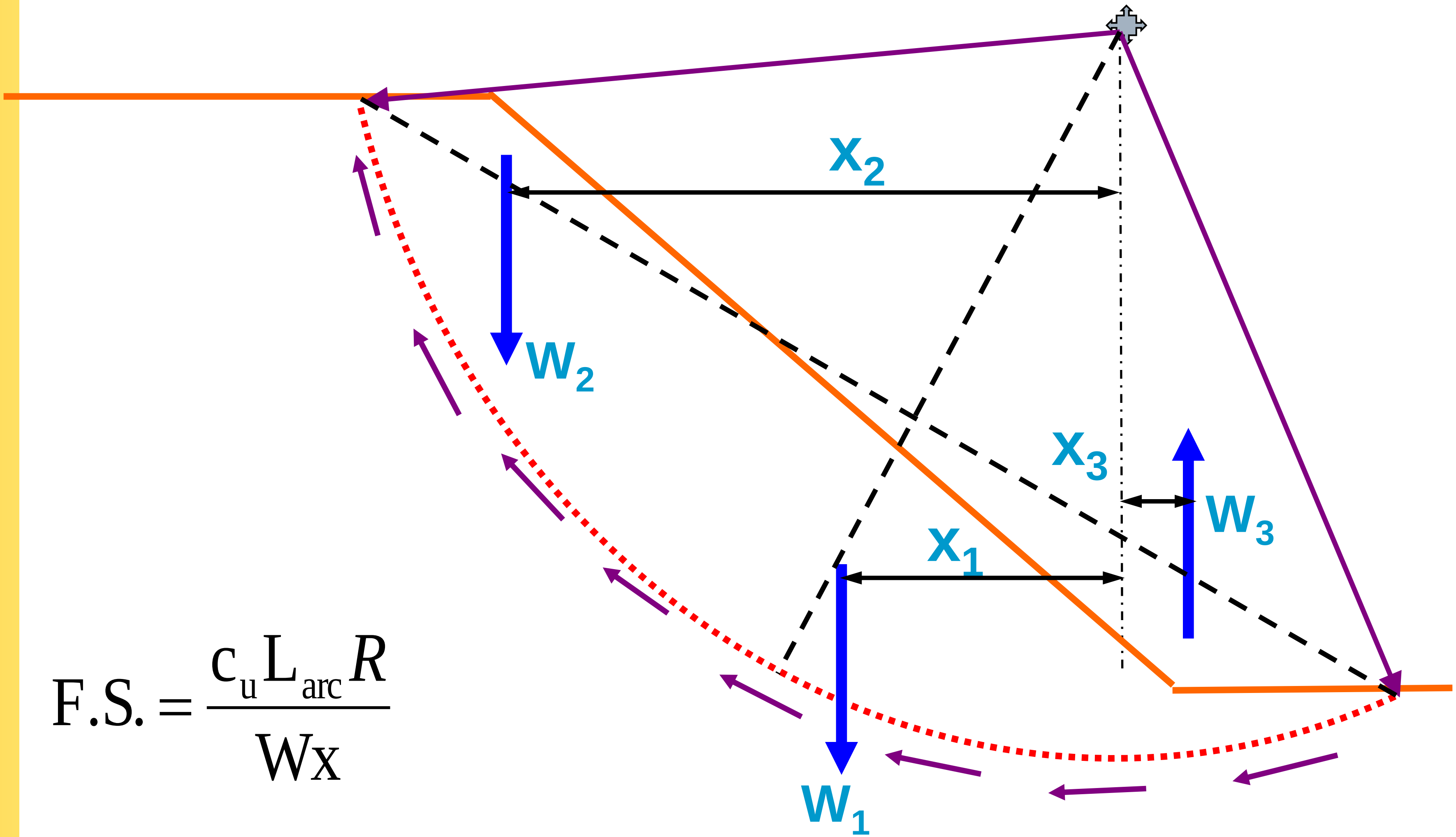
For Cohesive Soil Only

$C_u = \surd$

$\phi = 0.0$

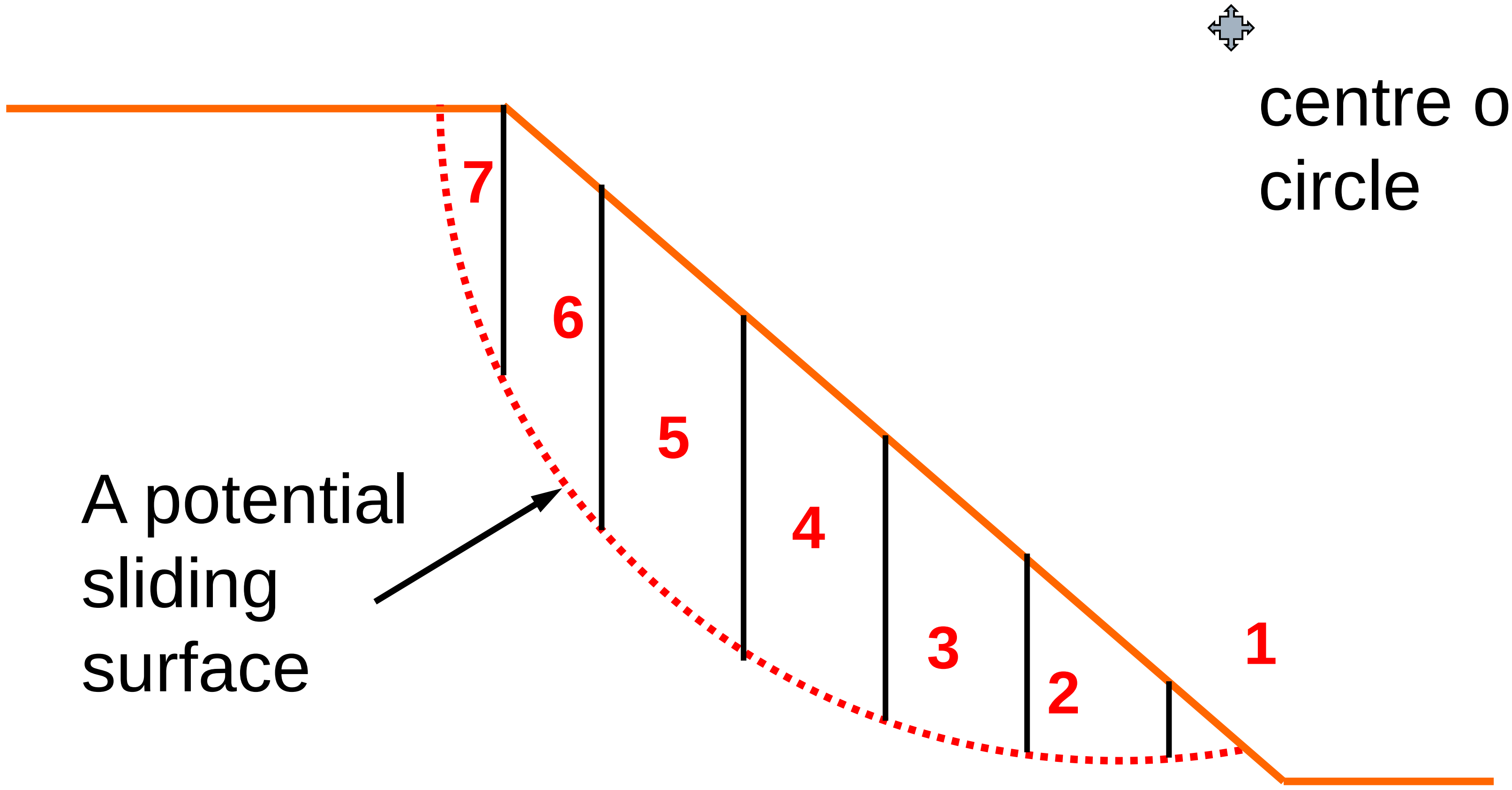
$$F.S. = \frac{c_u L_{arc} R}{Wx}$$

Overall Stability Method



$$F.S. = \frac{c_u L_{arc} R}{Wx}$$

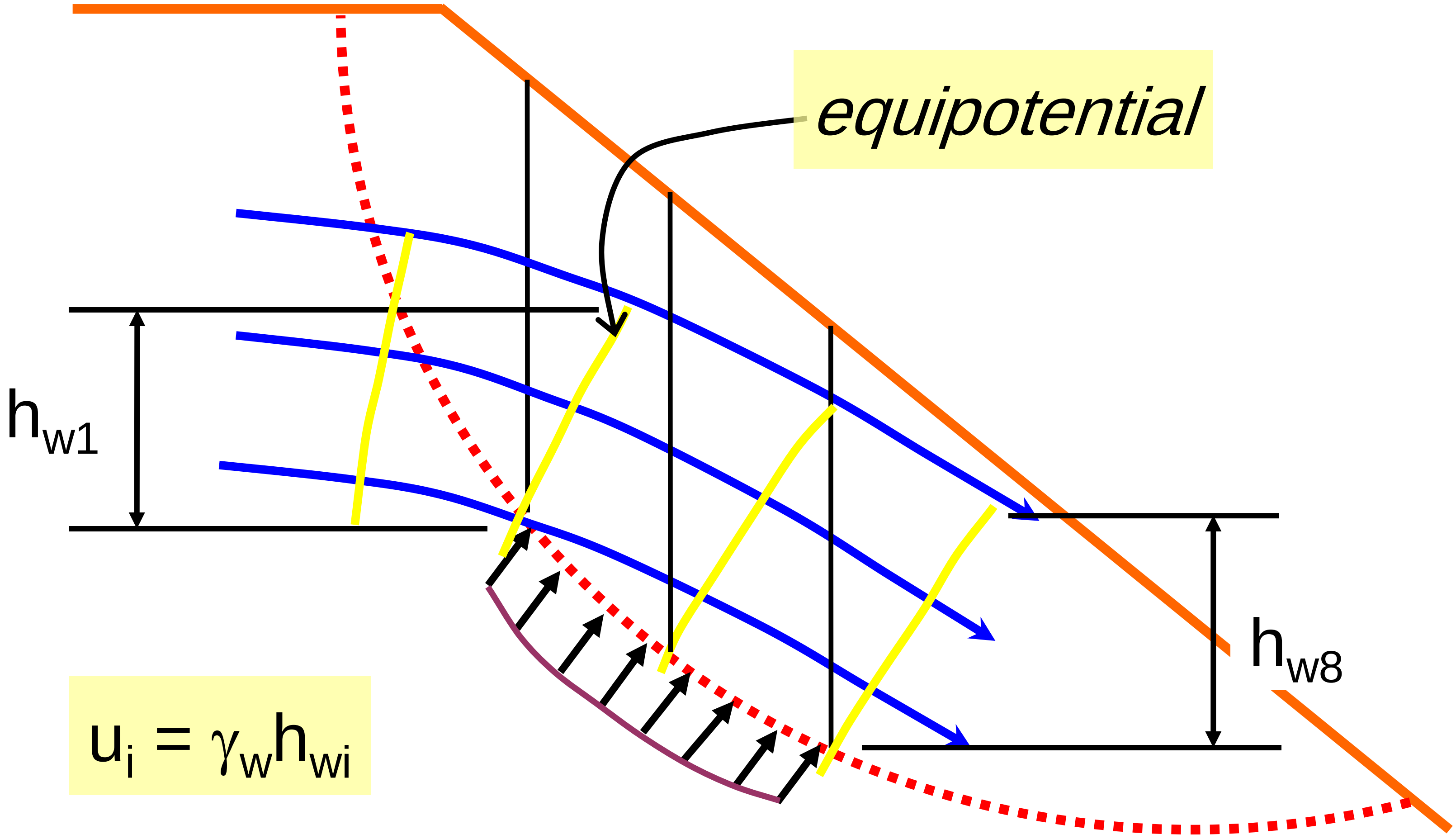
CIRCULAR SLIPS
"Method of Slices"



Reasons for Slices

- Frictional shear resistance varies with both σ_N and ϕ'
- Varying cohesion with depth
- Non-uniform pwp's from seepage analysis

PWP influence - "u" from flow net

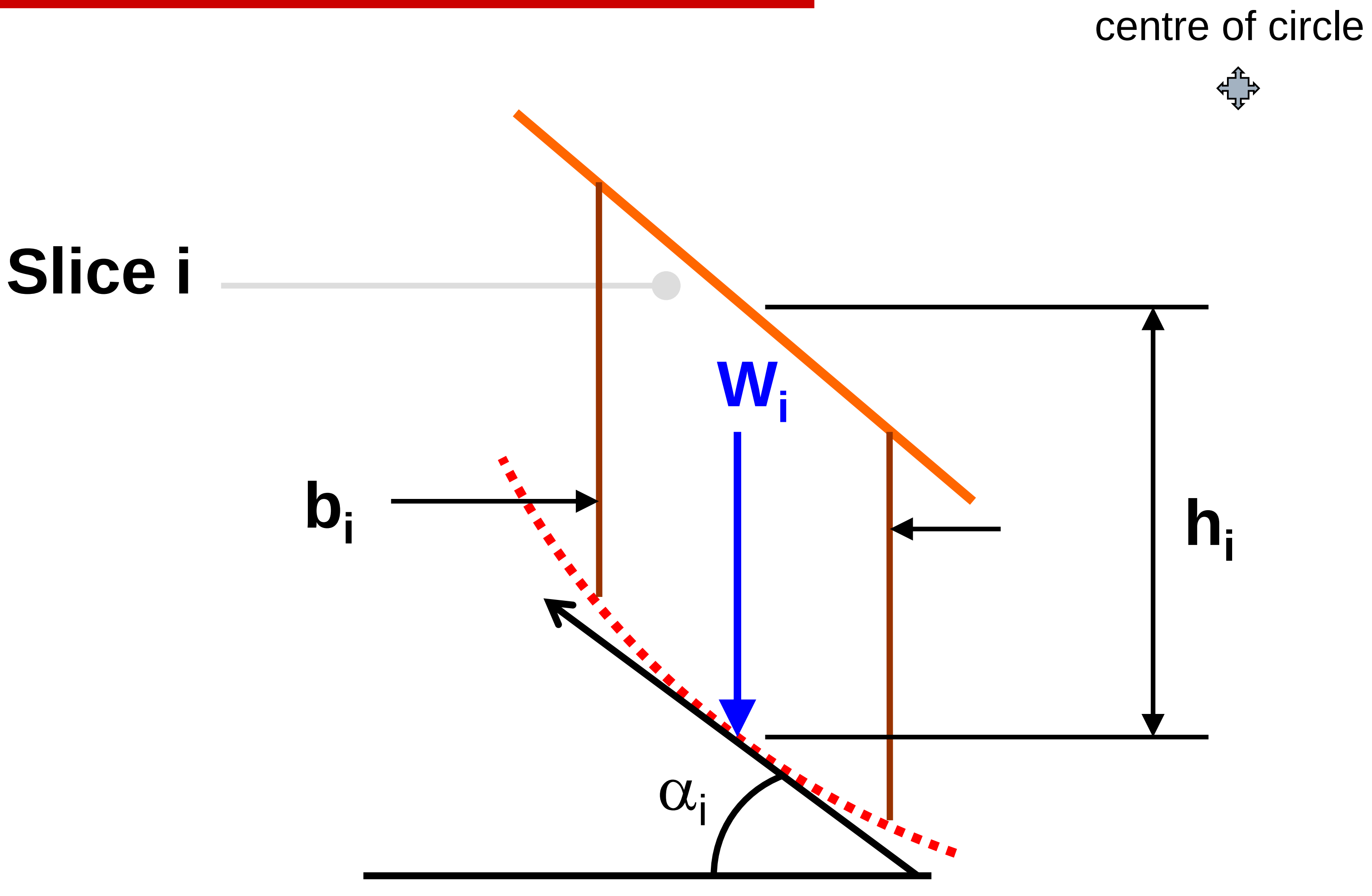


$u_i = \gamma_w h_{wi}$

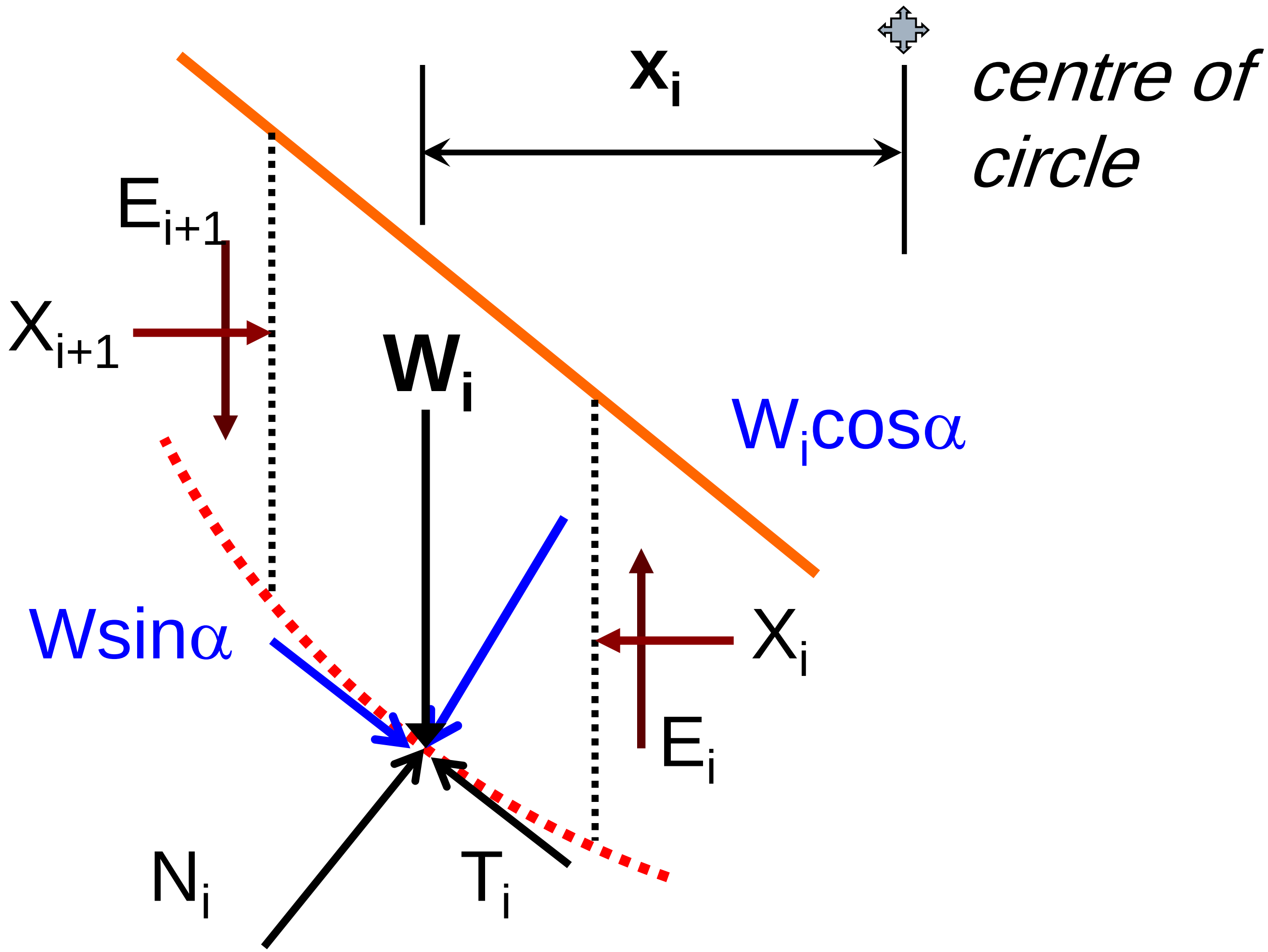
General Method of Slices

- F.o.S by summation over **all slices** for trial failure surface
- 100's of trial surfaces evaluated
  - thank you for the pc!
  - XSLOPE and GALENA
- Lowest F.o.S $\Rightarrow$ *the "critical failure surface"*

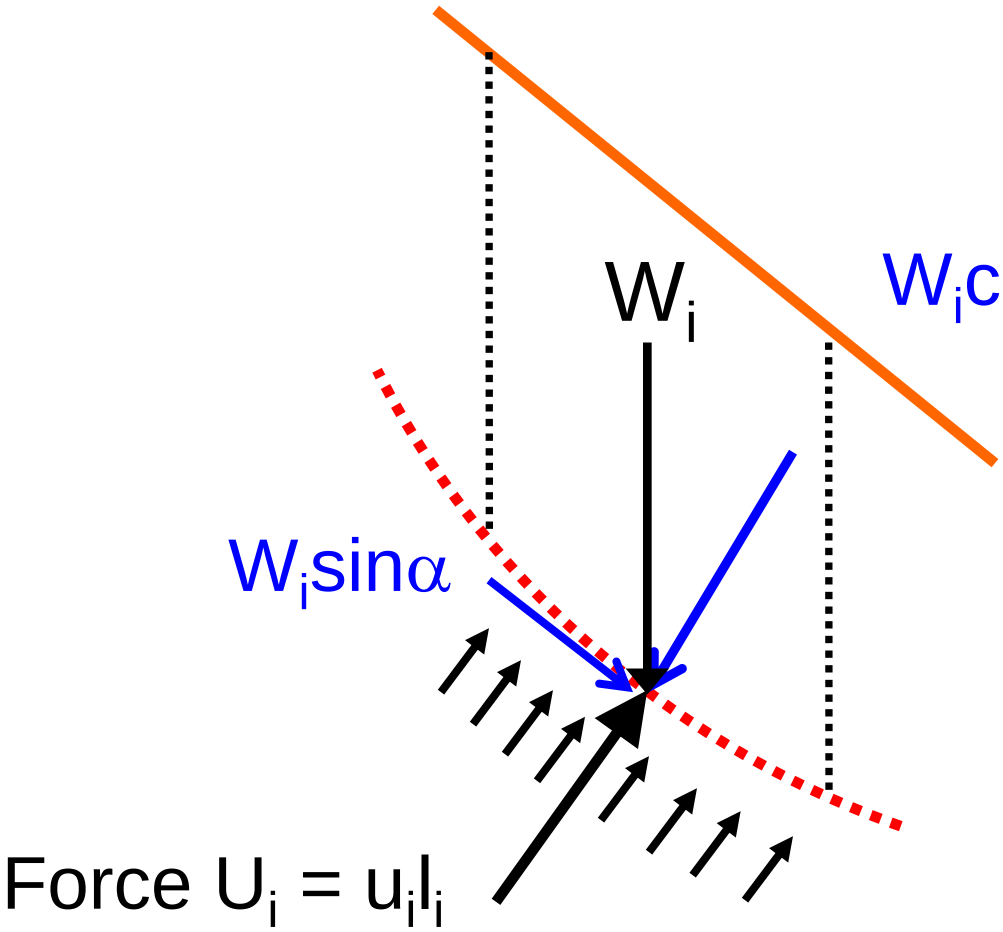
Stability of a Vertical Slice



Stability of a Slice (*no pwp*)



PWP influence



Different Methods of slices

<u>Slices</u> - overall too many unknowns!

- need simplifying assumptions to get a solution!

<u>Side Forces</u>:

- Assumptions for these forces

  = differences in methods

e.g. Fellenius v. Bishop's simplified method

Fellenius Method

Resultant of side forces = zero

i.e. $X_i = X_{i+1}$ and $E_i = E_{i+1}$

<u>For homogeneous soil</u>:

restoring shear force = $c'L_{arc} + \tan\phi'\Sigma N'$

where, $N_i' = W_i \cos\alpha_i - u_i l_i$

and l_i = arc length of slice, i

Factor of Safety - Fellenius

$$F = \frac{\text{restoring shear force}}{\text{sliding force on slip plane}}$$

$$F = \frac{c' L_{arc} + \tan\varphi' \Sigma\left(W\cos\alpha - ul\right)}{\Sigma W \sin\alpha}$$

Warning: method regarded as simplistic and non-conservative

Procedure of Analysis

- Fill the following table with these values

Slice No.	b	h	α	γ	c	φ	W= γhb	L=b/cos α	cL	wcos α tan φ	wsin α
1											
2											
3											
4											
5											
6											
7											
									ΣcL	Σ w cos α tan φ	Σ w sin α

$$F.S = \Sigma\, C * L + \Sigma\, [W * \cos(\alpha) * \tan(\varphi)] / \ \Sigma\, W * \sin(\alpha)$$

Procedure of Analysis

- **Draw the slope and the assumed slip surface with suitable scale.**
- **Divide the slope into slices with the following considerations:**
  1. **No. of slices = 5 : 7**
  2. **The slices have equal width (as possible)**
  3. **Every slice base located in one soil layer.**
- **Determine these values for each slice:**
  1. **Width (b)**
  2. **Average height (h)**
  3. **Angle of inclination of the base of slice (α)**
  4. **Average unit weight of the slice (γ)**
  5. **Shear parameters at the base (c, φ)**

Simplified Bishop Method
- a superior method

- Resultant of side forces acts <u>horizontally</u>
- Apply FoS (F) to restoring shear force
  - $T = [l(c' + \sigma_N' \tan\phi')]/F$
- Sum all vertical forces
  - $W = \Sigma[N'\cos\alpha + [(c'l + N'\tan\phi')\sin\alpha]/F]$
- Solve for N′
- Substitute in $$FoS = \frac{\sum(c'l + N'\tan\phi')}{\sum W\sin\alpha}$$

The Bishop Equation

$$F = \frac{\sum \left[\frac{(c' b_i + (W_i - u_i b_i) \tan\varphi')}{M_i} \right]}{\Sigma W_i \sin\alpha_i}$$

Where

$$M_i = \cos\alpha_i \left(1 + \frac{\tan\alpha_i \tan\varphi'}{F} \right)$$

Simplified Bishop Method

- Requires iteration
  - Assume initial F, then solve for F
  - When trial F and determined F are equal, it's a solution
- Spreadsheet for simple slopes
- XSLOPE and GALENA otherwise
  - 1000 trial surfaces in 1 minute