15. STABILITY OF SLOPES

→ Forces which cause failure of Slopes:

(i) Gravitational Force.

(ii) Seepage force.

(iii) Earthquake Force.

(iv) Construction equipment loads.

→ Types of Slopes:

(i) Infinite slope. Eg: mountain slope.

(ii) Finite slope Eg: embankment of roads, earthen dams, canals etc.

→ Types of Slope Failures:

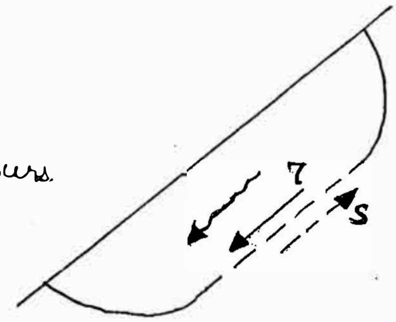
(i) Translational failure.

(ii) Rotational Failure.

(iii) Wedge Failure.

(iv) Compound Failure.

* Translational Failure.



If $\tau > s$; translational failure occurs.

∴ to avoid failure, τ must be kept less than s.

$$FOS = \frac{s}{\tau}$$

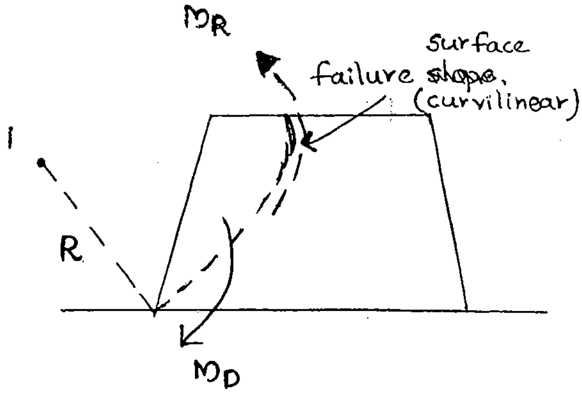
if

FOS > 1 ; it is safe.

FOS < 1 ; unsafe.

FOS = 1 ; critical

* Rotational Failure



M_D = driving moment.

M_R = resisting moment.

If $M_D > M_R$, failure occurs

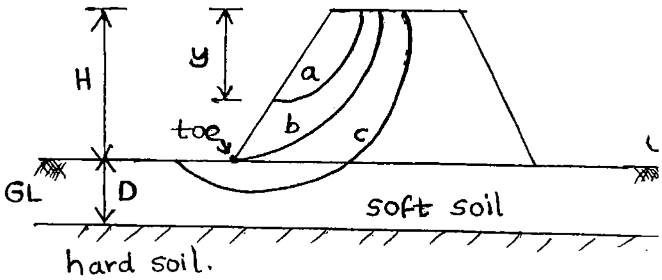
$$\therefore \boxed{FOS = \frac{M_R}{M_D}}$$

– types of rotational failures :-

a) Face failure

b) Toe failure.

c) Base failure.



Depth factor, $D_F = \frac{H+D}{H}$

For base failure, $D_F > 1$ (when there is soft soil)

For toe failure, $D_F = 1$ (when there is no soft soil).

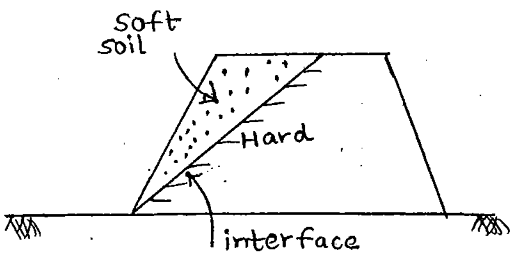
For face failure, $D_F < 1$

Depth factor, $D_F = \frac{y}{H}$

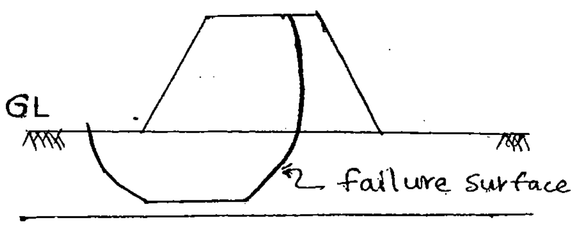
where $y \rightarrow$ vertical depth of point where failure surface passes as shown.

* Wedge Failure

The soft soil above the interface b/w soft soil and hard soil will fail as a wedge.



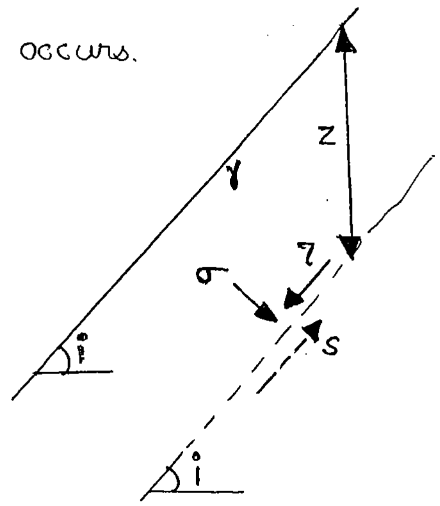
* Compound Failure.



→ Infinite Slope:

- generally, translational failure occurs.

$$FOS = \frac{S}{\tau}$$



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

$$\sigma = \gamma z \cos^2 i$$

$$\tau = \gamma z \cos i . \sin i.$$

* Infinite Slope in c-ϕ soil:-

a) Dry or Partially Saturated Soil.

$$FOS = \frac{c + \sigma \tan\phi}{\tau} = \frac{c + \gamma z \cos^2 i \tan\phi}{\gamma z \cos i . \sin i};$$ (at a depth

b) Fully submerged soil. (mountain in ocean).

$$FOS = \frac{c' + \gamma' z \cos^2 i . \tan\phi'}{\gamma z \cos i . \sin i}$$

c) If there is seepage parallel to slope. (rain water seeping).

$$FOS = \frac{c' + \gamma' z \cos^2 i . \tan\phi'}{\gamma_{sat} . z . \cos i . \sin i}$$

* Infinite slope in Cohesionless soils $(c = 0)$

imp

a) Dry or Partially Saturated Soil.

$$FOS = \frac{\tan\phi}{\tan i}$$ (If $i > \phi$; it fails)

b) For fully submerged slope.

$$FOS = \frac{\tan\phi'}{\tan i}$$

c) Seepage parallel to slope,

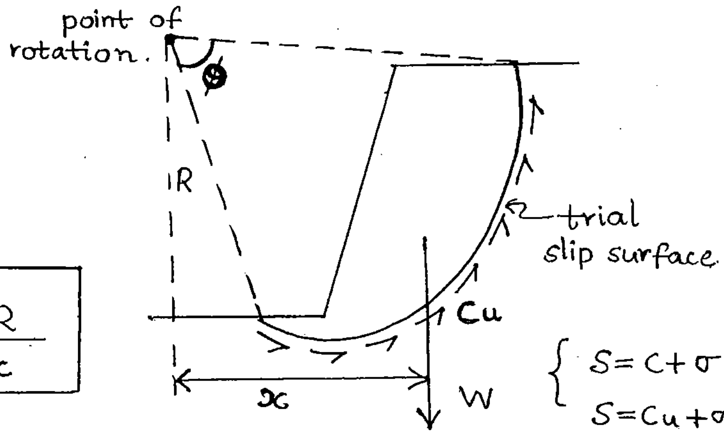
$$FOS = \left(\frac{\gamma'}{\gamma_{sat}}\right) \frac{\tan\phi'}{\tan i}$$

→ Finite Slope

- generally, rotational failure occurs.
- methods of analysis:
  1. $\phi_u = 0$ Analysis.
  2. Method of slices.
  3. Bishop's method.
  4. Friction circle method.
  5. Stability number method.

* $\phi_u = 0$ Analysis:

- suitable only for undrained saturated clays.
- graphical method based on trial & error



$\therefore M_D = W.x$

$M_R = C_u . \hat{L} \times 1 \times R$

$$FOS = \frac{M_R}{M_D} = \frac{C_u \hat{L} R}{W.x}$$

$\{ S = c + \sigma \tan\phi$
$S = C_u + \sigma \tan$
$\Rightarrow S = C_u \}$

$\hat{L}$ → arc length.

$$\hat{L} = R\theta . \frac{\pi}{180}$$

W → weight of trial failure wedge.

$W = a \times 1 \times \gamma$; a → area of trial failure wedge.

↳ use γ' for submerged slope. (canal running full)

use γ_{sat} for sudden drawdown conditi

$FOS \propto \frac{1}{W}$; but $W \propto \gamma$

$\Rightarrow FOS \propto \frac{1}{\gamma}$

$\therefore$ for a canal slope, the critical condition is sudden drawdown condition.

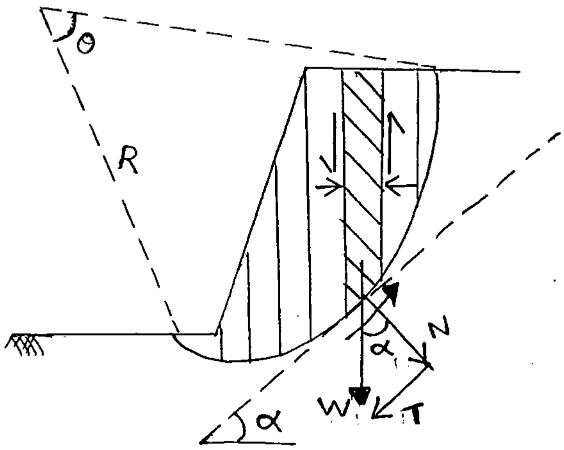
- Canal will have more FOS when running full compard to sudden drawdown condition.

  During sudden drawdown, γ increases to γ_{sat} and $\therefore$ FOS decreases.

- Among the various trials, the trial slip surface which gives min. factor of safety is called '<u>Critical Slip Surface</u>' and that min. FOS is taken as the FOS of the slope.

* Method of Slices :

- used for all soils.
- trial and error.
- forces acting on the sides of slices <u>are neglected</u>.



$$F = \frac{c\hat{L} + \Sigma N \tan\phi}{\Sigma T}$$

$N = W\cos\alpha$

$T = W\sin\alpha$

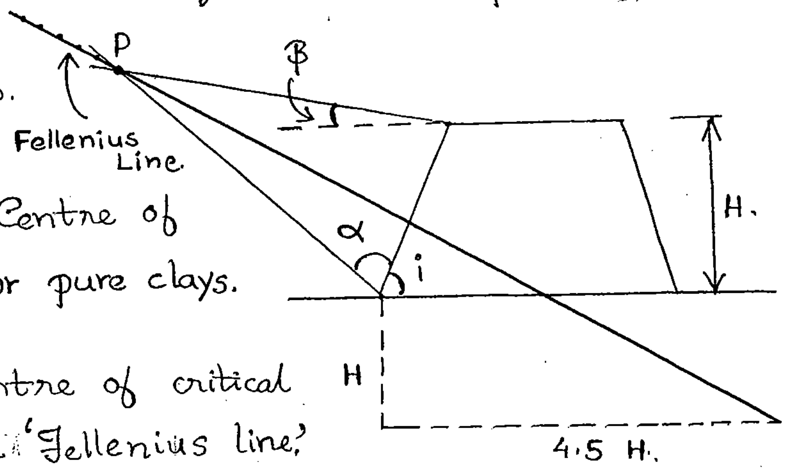
- When there is seepage,

$$F = \frac{c'\hat{L} + \Sigma (N-U) \tan\phi'}{\Sigma T}$$

$\Sigma U \rightarrow$ sum of neutral forces.

- Fellenius method to identify Critical Slip Circle:-

$\alpha, \beta \rightarrow$ direction angles. (depend on i)



Point 'P' represents Centre of Critical Slip circle for pure clays.

For c-ϕ soils, the centre of critical slip circle lies on the 'Fellenius line.'

* Bishop's Method.
  - forces acting on the sides of slices are also <u>considered</u>
  - trial and error

* Friction Circle Method.
  - trial and error

c = cohesion

c_m = mobilised cohesion.

ϕ = angle of internal friction.

ϕ_m = mobilised angle of internal friction.

S = shear strength.

S_m = mobilised shear strength.

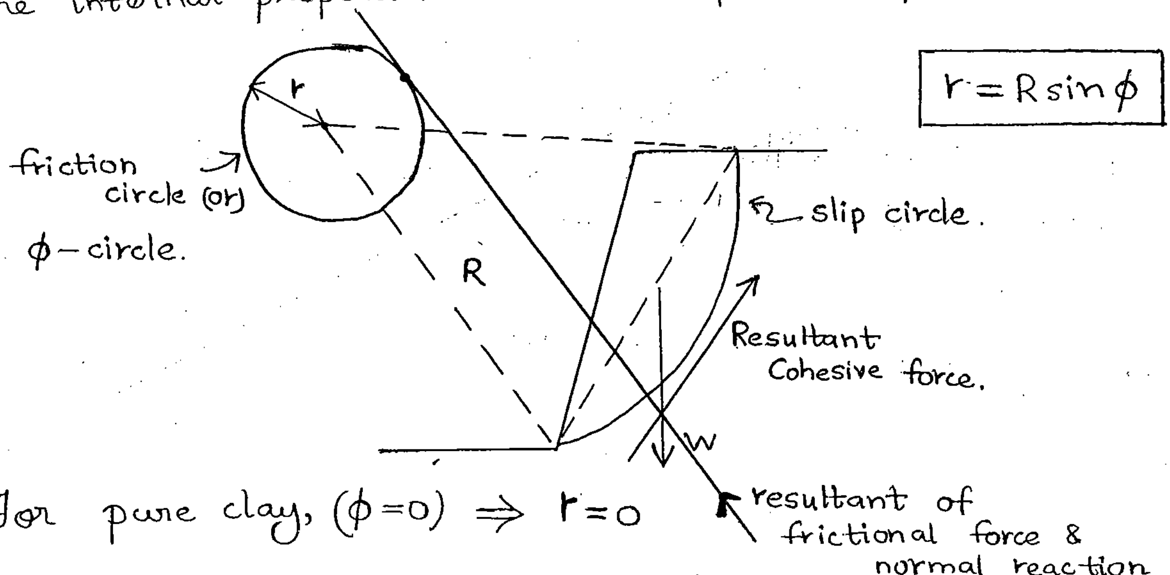
⊙ 'Mobilised' means actually developed to keep system (wedge) in eqbm.

FOS wrt cohesion, $F_c = \frac{c}{c_m}$

FOS wrt friction, $F_\phi = \frac{\tan\phi}{\tan\phi_m}$

FOS wrt shear strength, $F = \frac{S}{S_m} = \frac{c + \sigma\tan\phi}{c_m + \sigma\tan\phi_m}$

σ remains the same as its related to weight, whereas c & ϕ are internal properties which develops as required.



$$r = R\sin\phi$$

⊙ For pure clay, $(\phi = 0) \Rightarrow r = 0$

⊙ Resultant of frictional force and normal reaction will be tangential to the friction circle.

* Taylor's Stability Number Method.

- developed based on Friction Circle method.
- Stability number, $S_n = \frac{C}{F_c \cdot \gamma H}$

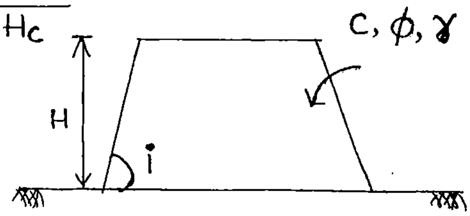
where $F_c = \frac{C}{C_m} = \frac{H_c}{H}$; $H_c \rightarrow$ critical height.

$H_c \rightarrow$ max. permitted height which can provided for given soil against failure.

$H \rightarrow$ safe or actual height.

$$\Rightarrow \quad S_n = \frac{C_m}{\gamma H} = \frac{C}{\gamma H_c}$$

$$\therefore \quad F_c = \frac{C}{S_n \gamma H}$$



⊙ S_n depends on i & ϕ_m (or) i & depth factor

Knowing F_ϕ & ϕ value, ϕ_m can be calculated by:-

$$F_\phi = \frac{\tan\phi}{\tan\phi_m}.$$

Max. value of $S_n = 0.261$ (for $i = 90°$ & $\phi_m = 0$)

⊙ Except for cohesionless soil, this method is suitable for all soils. (for cohesionless, $c = 0 \Rightarrow F_c = 0$; meaningless)

⊙ For submerged slope, use γ'

For sudden draw down condition, use γ_{sat} & $\phi_m = \phi_w$

ϕ_w = weighted friction angle = $\frac{\gamma'}{\gamma_{sat}} \cdot \phi$

25th Sept,
THURSDAY
n-89

01. $F = \dfrac{c + \gamma z \cos^2 i \tan\phi}{\gamma z \cos i . \sin i}$ → for c-φ soil.

i can be greater than φ.

03. $S_n = \dfrac{c}{F_c \gamma H}$ ⇒ $F_c \propto \dfrac{1}{\gamma}$

04. $F = \dfrac{\gamma'}{\gamma_{sat}} \dfrac{\tan\phi'}{\tan i}$

$1.5 = \dfrac{19-9.81}{9.81} \dfrac{\tan 36}{\tan i}$

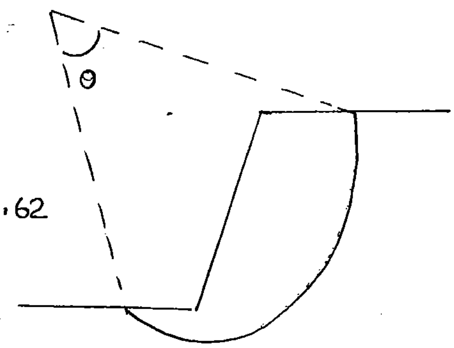
$i = 13.18^0$

If no seepage,

$F = \dfrac{\tan\phi}{\tan i}$ ⇒ $F = 3.10^0$

05. Ignoring the crack,

a) $\theta = 109 + 12 = 121^0$



$\hat{L} = R\theta \dfrac{\pi}{180} = 14.5 \times 121 \times \dfrac{\pi}{180} = 30.62$

$w = a \times 1 \times \gamma$

$= 110 \times 1 \times 18 = 1980$

$\bar{x} = 3.75$ m.

$Fos = \dfrac{c\hat{L}R}{wx} = \dfrac{27 \times 30.62 \times 14.5}{1980 \times 3.75} = 1.61$

b). $\theta = 109^0$,

$L = R\theta \times \dfrac{\pi}{180} = 27.585$

$w = a \times 1 \times \gamma$ $\qquad \bar{x} = 3.75$ m.

$= (110 - 1.5) \times 18$

$= 1953$

$F = \dfrac{C_u \hat{L} R}{w\bar{x}}$

$= \dfrac{27 \times 27.585 \times 14.5}{1953 \times 3.75} = 1.47$

6. $H = 25\,m$, $C = 35$, $\phi = 15^\circ$

a) $\gamma = 20$.

$$F_\phi = \frac{\tan\phi}{\tan\phi_m}$$

$$1.5 = \frac{\tan 15}{\tan\phi_m} \Rightarrow \phi_m \approx 10^\circ$$

For $\phi_m = 10^\circ$, $S_n = 0.06$.

$$S_n = \frac{c}{F_c\,\gamma H}$$

$$0.06 = \frac{35}{F_c \times 20 \times 25} \Rightarrow F_c = 1.167$$

b) If $F_c = 1.5$, $F_\phi = ?$

$$S_n = \frac{c}{F_c\,\gamma H} = 0.05$$

$\phi_m = 12.5^\circ$ (From table given).

$$F_\phi = \frac{\tan\phi}{\tan\phi_m} = \frac{\tan 15^\circ}{\tan 12.5^\circ} = 1.208$$

7. Canal running full, (submerged condition)

a) $$S_n = \frac{c}{F_c\,\gamma' H}$$

Since F_ϕ is not given, take $\phi_m = \phi$.

$\therefore\ \phi_m = 15^\circ \rightarrow S_n = 0.083$.

$$S_n = \frac{c}{F_c\,\gamma' H}$$

$$0.083 = \frac{1.4}{F_c \times 0.945 \times 5}$$

$\Rightarrow F_c = 3.56$

b) For suddenly draw down,

$$S_n = \frac{C}{F_c \, \gamma_{sat} \cdot H}$$

$$\phi_m = \phi_w$$

$$\phi_w = \frac{\gamma'}{\gamma_{sat}} \phi \approx 7.5^0 \Rightarrow S_n = 0.122$$

$$\Rightarrow \quad 0.122 = \frac{1.4}{F_c \times 1.945 \times 5}$$

$$\therefore F_c = \underline{\underline{1.18}}$$

8. $F_c = \frac{C}{C_m} = \frac{30}{22} = \underline{\underline{1.36}}$

$$F_\phi = \frac{\tan\phi}{\tan\phi_m} = \frac{\tan 15}{\tan 12} = \underline{\underline{1.26}}$$

$$F = \frac{S}{S_m} = \frac{c' + \sigma' \tan\phi'}{C_m + \sigma' \tan\phi_m} = \frac{62.17}{47.5} = \underline{\underline{1.308}}$$

* To find F_ϕ when $F_c = 1$:

$$S_m = C_m + \sigma \tan\phi_m$$

$$47.5 = \frac{c}{F_c} + 120 \frac{\tan\phi'}{F_\phi}$$

$$= \frac{30}{1} + \frac{120 \tan 15}{F_\phi}$$

$$\Rightarrow \quad F_\phi = \underline{\underline{1.829}}$$

Similarly, to find F_c when $F_\phi = 1$.

$$47.5 = \frac{c}{F_c} + \frac{120 \tan\phi'}{1.}$$

$$F_c = \underline{\underline{1.95}}$$

Q A granular soil possesses $\gamma_{sat} = 20$ kN/m³. If $\phi' = 35°$, and the designed FOS is 1.5, what is safe angle of slope for this soil when seepage occurs parallel to slope surface

$$F = \frac{\gamma'}{\gamma_{sat}} \frac{\tan\phi'}{\tan i}$$

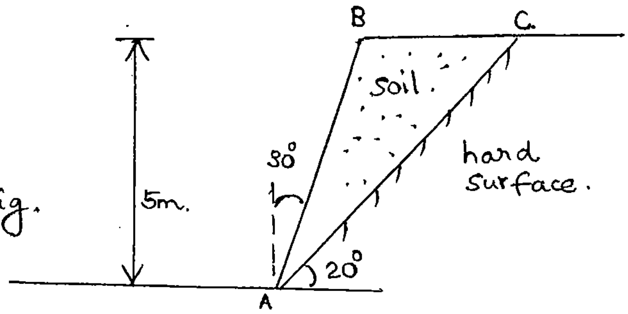
$$1.5 = \frac{10}{20} \frac{\tan 35}{\tan i}$$

$$\Rightarrow i = 13.14°$$

Q $c = 15$ kN/m²

$\phi = 20°$

$\gamma = 18$ kN/m³.



A slope is shown in the fig. If the properties of soil are as above, find the FOS against possible wedge failure at the interface.

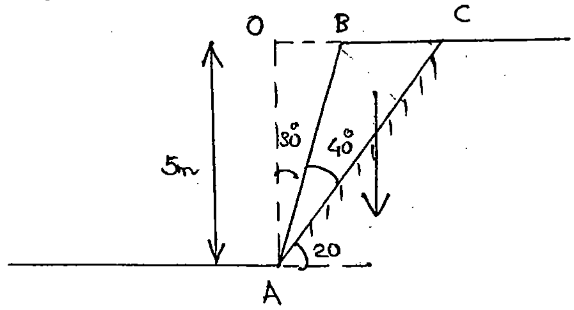
$$F = \frac{CL + N\tan\phi}{T}$$

L = length of AC

N = normal component of weight, w ; $N = W\cos 20$

w → weight of wedge, ABC. $T = W\sin 20$

T = Tangential component of weight, w.



$\tan 70° = \frac{OC}{5}$.

OC = 13.73 m.

$\tan 30° = \frac{OB}{5}$

OB = 2.88 m.

BC = OC − OB = 13.73 − 2.88 = 10.85 m.

$AC = \sqrt{5^2 + 13.73^2} = 14.61\ m$

$W = \left(\frac{1}{2} \times 10.85 \times 5\right) \gamma = 488.25\ kN$

area of wedge.

$N = 488.25 \cos 20 = 458.805$

$T = 488.25 \sin 20 = 166.99$

$$F = \frac{CL + N\tan\phi}{T} = \frac{15 \times 14.61 + 458.805 \tan 20}{167}$$

$$= \underline{\underline{2.31}}.$$