Chapter: 11

Stability of slope

~~Modes of slope fai~~

Slope:-

Slope refers to a soil mass with it's surface inclined to horizontal.

The failure of an earth slope occurs when the forces tending to slide are greater than those tending to stabilize the soil mass along critical surface of failure. (The surface along which the soil mass slides when the failure of earth slope occurs). i.e the ~~soi~~ slope failure occur when there is increase in shear stresses as well as decrease in shear strength of soil.

Causes of instability of slopes, modes of failure and it's remedial measures:-

Causes of instability:-

1) Those causing increase in shear stress

(i) Increase in unit wt. of soil due to wetting.
(ii) Increase in external load.
(iii) Increase in steepness of slope.
(iv) Dynamic or shock load such as earthquake.

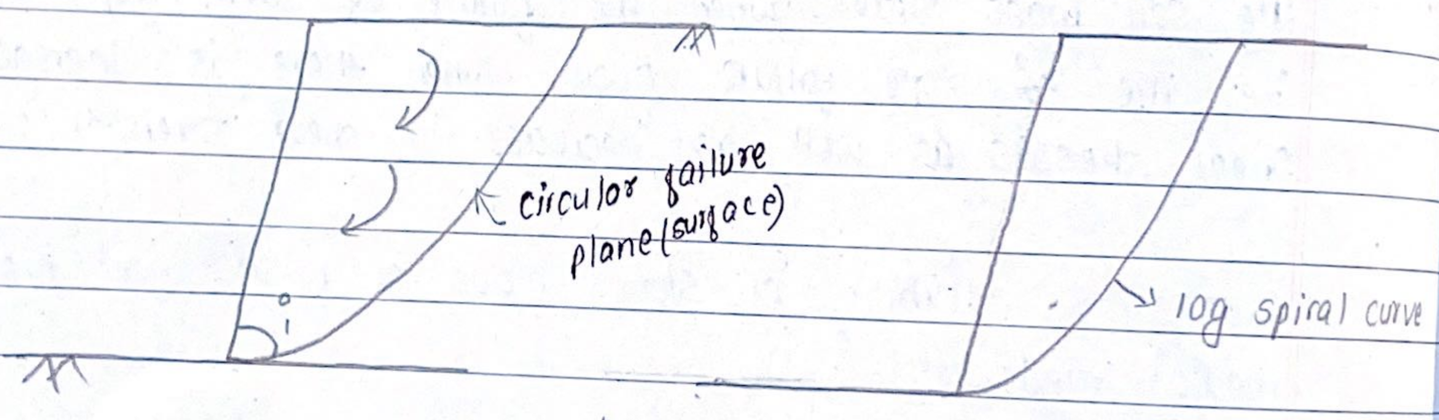
2) Those causing decrease in shear strength.

(i) Increase in pore water pressure.
(ii) Adsorption of water.
(iii) loss of cementing material.
(iv) Weathering
(v) Repeated loading & unloading

Modes of slope failure :-

a) Rotational failure

→ It occurs by reduction of soil mass along the slip surface by downward or outward ~~moment~~ movement of soil mass. The slip surface is generally circular for cohesive soil. (homogeneous soil) but not circular for c-ϕ soil (Non-homogenous soil)

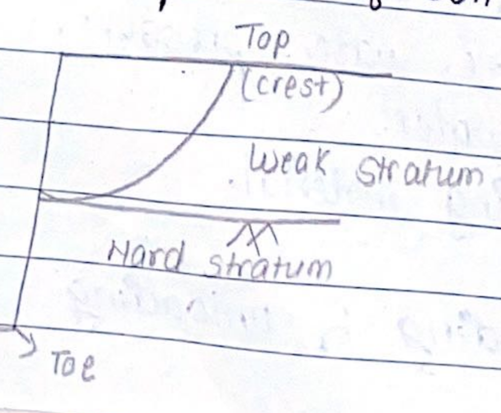


Purely cohesive soil (c-ϕ soil) (Non-circular)

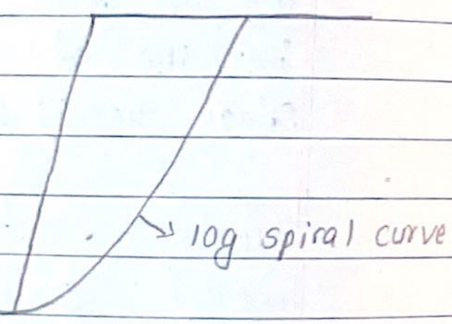
Rotational failure may be classified as :-

→ slope failure/ face failure/surface failure :-

This type of ~~s~~ failure occurs when the slope angle is large and the bottom portion of soil is strong.



soil mass along the slip surface
ment movement of soil mass.
circular for cohesive soil.(homo-
for c-ϕ soil (Non- homogenous



re
ce)

c soil) (Non- circular)

ed as :-

failure :-
rs when the slope angle is
of soil is strong.

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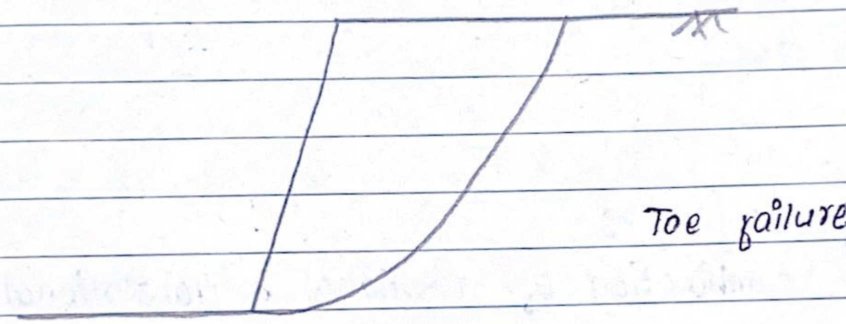
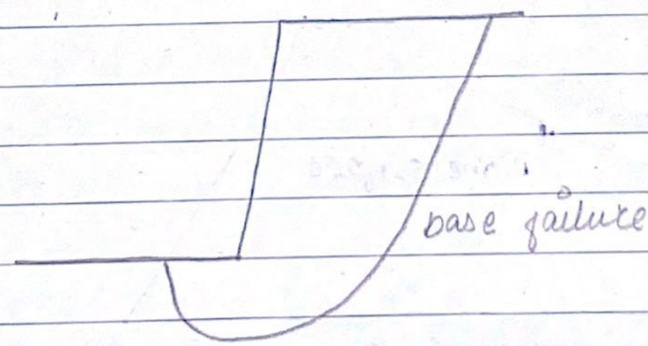
→ Toe failure :-

The failure surface passes through toe. It occurs when the soil is homogenous.



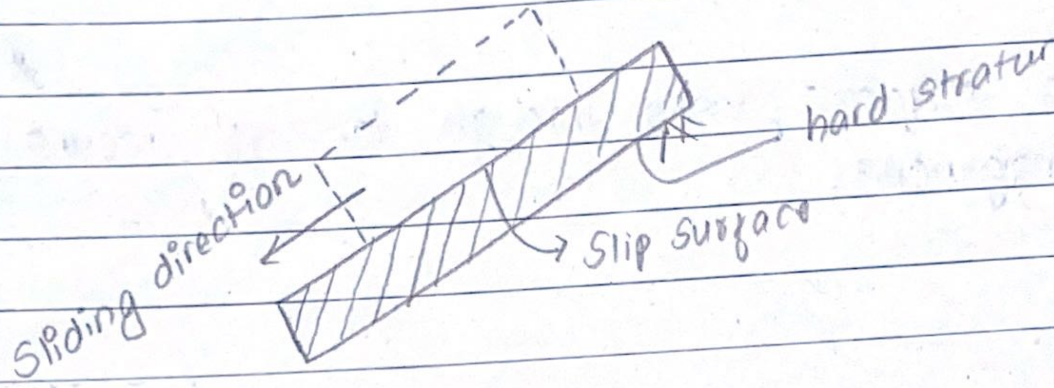
→ Base failure :-

Failure surface passes below toe. It occurs when the soil below the toe is weak & soft.



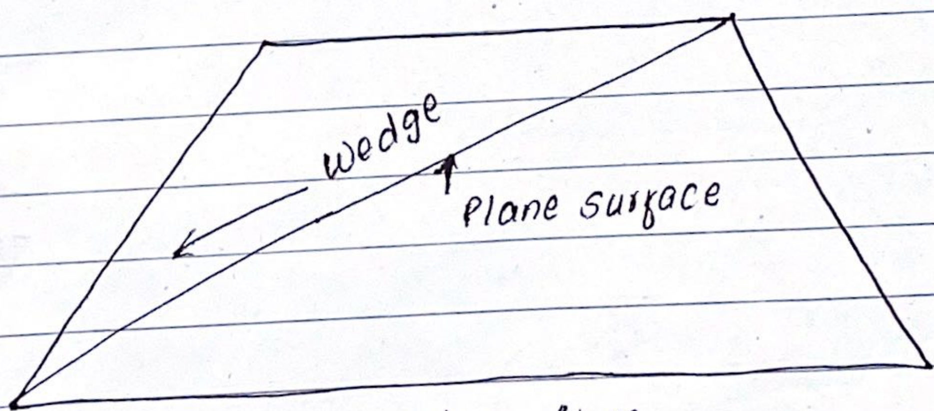
b) Translational failure :-

It occurs due to movement of soil mass along the failure surface parallel to the slope. The slope of failure surface is influenced by pressure of any hard stratum at a shallow depth below the slope surface.



c) compound failure (slip):-
It is the combination of rotational & translational failure (slip).

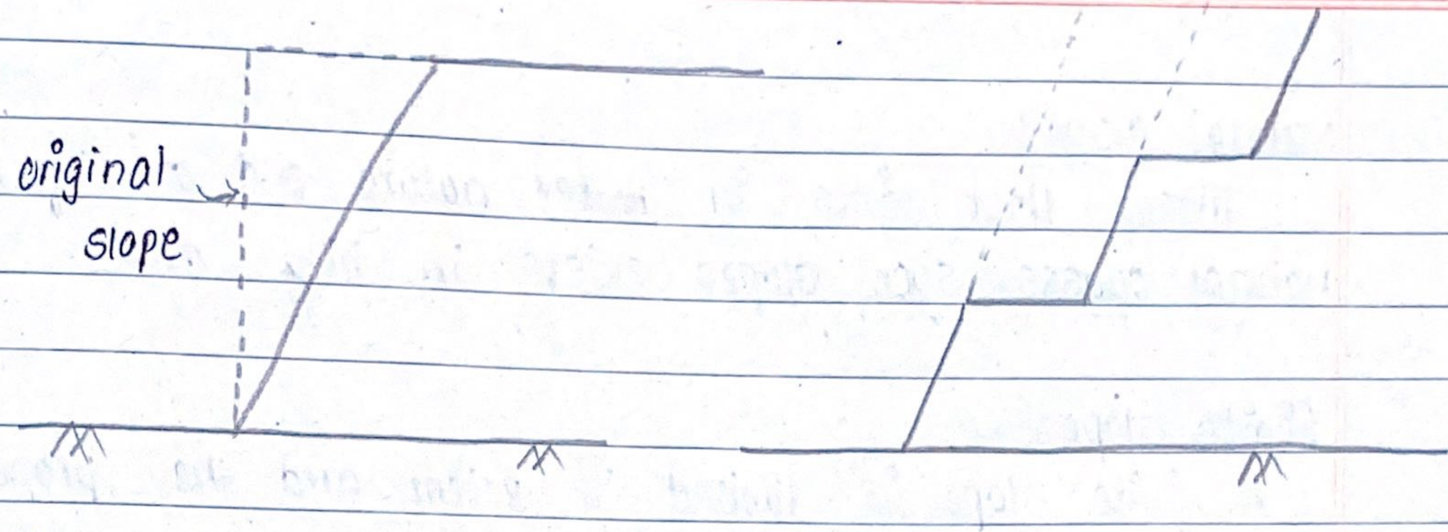
d) wedge failure:-
A failure along an inclined plane. It occurs when distinct block & wedge of soil mass gets separated.



wedge failure

Remedial ~~fail~~ measures for slope failure:-

1) Slope Reduction:-
Flattening the slope reduces the wt. of potential sliding mass and consequently the driving force resulting in increase of factor of safety.



a) Direct slope reduction b) flattening by cutting the berms

Densification or Hardening of soil :-
Densification of ground increases the shearing resistance of soil. Thus, it increases the stability of slope. Soil densification can be achieved by treating the soil with lime or cement.

Vegetation :-
Planting trees on the surface of ~~soil~~ slope is beneficial to protect the slope against shallow slides. The plants enhance the stability of slope by its diff engineering function.

Construction of earth retaining structure :-
Retaining structures such as retaining walls, at the toe of slope increases the resistance of sliding mass.

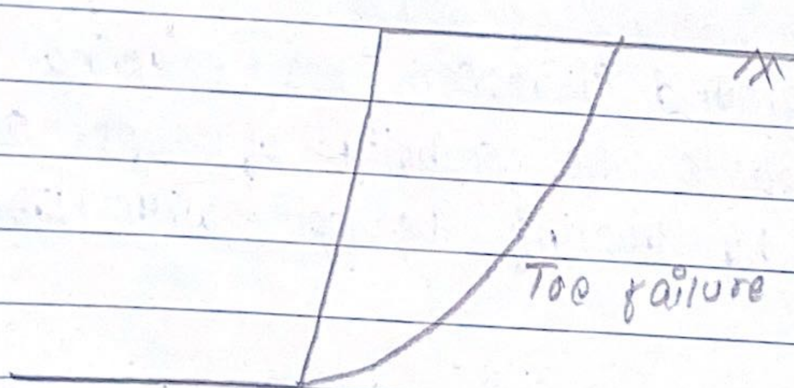
Finite and Infinite slope :-
Man-made slope :-
The sides of cuttings, the slopes of embankments constructed for roads, canal etc and the slopes of earth damps for storing water.

Natural slope :-

Those that exists in ~~water~~ nature and are formed by natural causes. Such slopes exists in hilly areas.

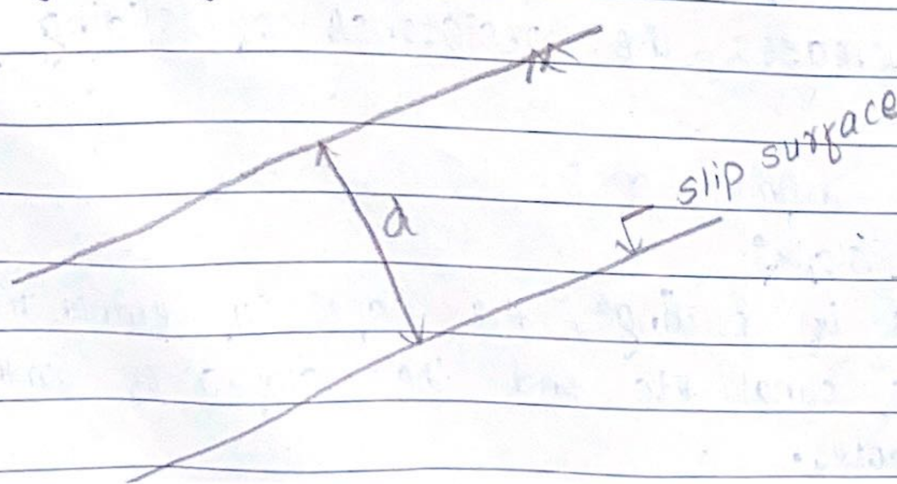
Finite slope :-

A finite slope is limited in extent and the properties of soil will not be same at identical depth and the slip surface will be ~~occured~~ at a curve as shown.

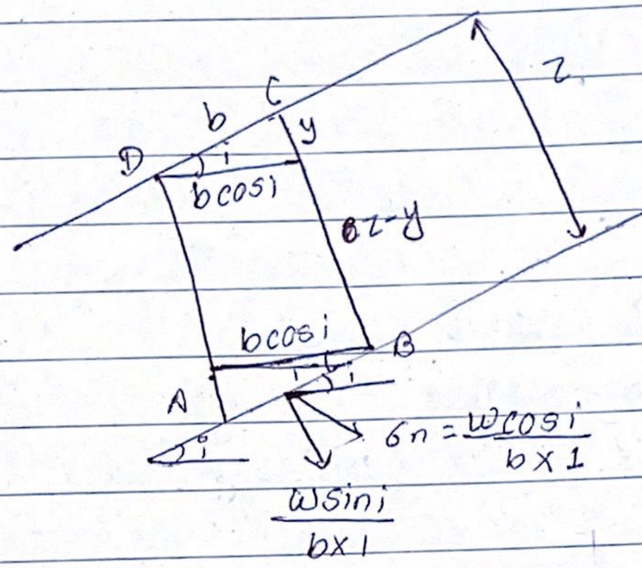


Infinite slope :-

An infinite slope is very large in extent (theoritically infinite) and the properties of soil will be same at identical depth so that slip surface will be a plane parallel to surface of slope. For eg:- long face of mountain.



Stability analysis of infinite slope :-



let us consider a small element ABCD in an infinite slope. The element is considered to be a prism of soil which forms a part of sliding mass. let the slip plane in a slope having slope angle i is at a depth z below the surface of slope. let the inclined width of element is b & has an unit thickness perpendicular to the plane of paper.

Here;

$W = \gamma \times V$

Volume = Area of ABCD

$= b\cos i (z-y) + \frac{1}{2} \times b\cos i \times y \times 2$

$= b\cos i \times z - by\cos i + by\cos i$

$= bz\cos i$

$\sigma_n = \frac{W\cos i}{b \times 1} = \frac{\gamma \times bz\cos i \times \cos i}{b}$

~~$\sigma_n = \gamma \times z$~~

$$\boxed{\sigma_n = \gamma z \cos^2 i}$$

$$\tau = \frac{W \sin i}{b} = \frac{\gamma b z \cos i \times \sin i}{b}$$

$$\boxed{\tau = \gamma z \cos i \sin i}$$

$$FOS = \frac{\text{shear strength}}{\text{shear stress}}$$

FOS > 1 → slope is stable

FOS < 1 → slope is unstable

FOS = 1 → slope is critical (critically stable)

$$\boxed{FOS = \frac{C + \sigma_n \tan\phi}{\gamma z \cos i \sin i}}$$

1) for cohesionless soil,

$$FOS = \frac{C + \sigma_n \tan\phi}{\gamma z \cos i \sin i}$$

$$= \frac{\gamma z \cos^2 i \tan\phi}{\gamma z \cos i \sin i}$$

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

2) for cohesive soil,

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

3) for submerged soil,

$$FOS = \frac{C + \gamma_{sub} \times z \times \cos^2 i \times \tan\phi}{\gamma_{sub} \times z \times \cos i \times \sin i}$$

where;

$$\gamma_{sub} = \gamma_{sat} - \gamma_w$$

4) For steady seepage along the slope
(For seepage parallel to the slope)

$$FOS = \frac{C + \gamma_{sub} \times z \times \cos^2 i \times \tan\phi}{\gamma_{sat} \times z \times \cos i \times \sin i}$$

Q) A long natural slope in an oven consolidated clay ($C = 10\ kN/m^2$, $\phi = 25^\circ$, $\gamma_{sat} = 20\ kN/m^3$) is inclined at 10° to the horizontal. The water table is at surface & seepage is parallel to the slope. If a plane of slip had developed at a depth 5m below the surface, determine the factor of safety. Take $\gamma_w = 10\ kN/m^3$)

Soln

$$\gamma_{sub} = \gamma_{sat} - \gamma_w = 20 - 10$$

$$= 10\ kN/m^3$$

$$FOS = \frac{C + \gamma_{sub} \times z \times \cos^2 i \times \tan\phi}{\gamma_{sat} \times z \times \cos i \times \sin i}$$

$$= \frac{10 + 10 \times 5 \times \cos^2 10 \times \tan 25}{20 \times 5 \times \cos 10 \times \sin 10}$$

$$= 1.907$$

Slope is stable. Since $FOS = 1.907 > 1$.

Critical height of slope

When the slope is critically ~~slope~~ stable;

i.e FOS = 1

$$\frac{\text{Shear strength}}{\text{Shear stress}} = 1$$

or. shear stress = shear strength

or; $\gamma z \cos i \sin i = c + \gamma z \cos^2 i \tan\phi$

or; $\gamma z \cos i \sin i - \gamma z \cos^2 i \tan\phi = c$

or; $$z = \frac{c}{\gamma \cos i(\sin i - \cos i \tan\phi)} = Z_c$$

Z_c = critical ht. of slope

→ The critical ht. of slope is max. ht of slope that can be built without failure. Expression for ht when the slope is just stable is called critical ht. of slope.

Taylor's stability number

There are two body forces which govern the stability of slope.

i) Gravity force (due to unit wt) which is a cause of instability.

ii) cohesive force which contribute to stability in a soil mass.

According to Taylor, the max^m ht of a slope that can be built without failure is directly proportional to cohesion & inversely proportional to unit wt.

Mathematically;

$$Z_c \propto C$$

$$Z_c \propto 1/\gamma$$

$$Z_c \propto \frac{c}{\gamma}$$

$$Z_c = S_n \times \frac{c}{\gamma}$$

$$\boxed{S_n = \frac{\gamma \times Z_c}{c}}$$ $S_n \rightarrow$ stability number

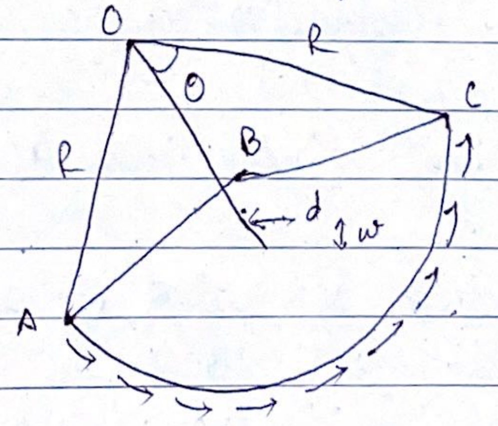
Importance of stability number

→ It helps to determine FOS for a slope of ht. z at an angle i in a soil for which γ, c & ϕ are known.

→ It helps to determine the max. ht upto which a slope can be allowed to a certain slope length.

Stability analysis of finite slope

i) $\phi = 0$ analysis (total stress analysis)
(used for cohesive soil)



Overturning moment about O (M_o) = $w \times d$
(Driving moment)

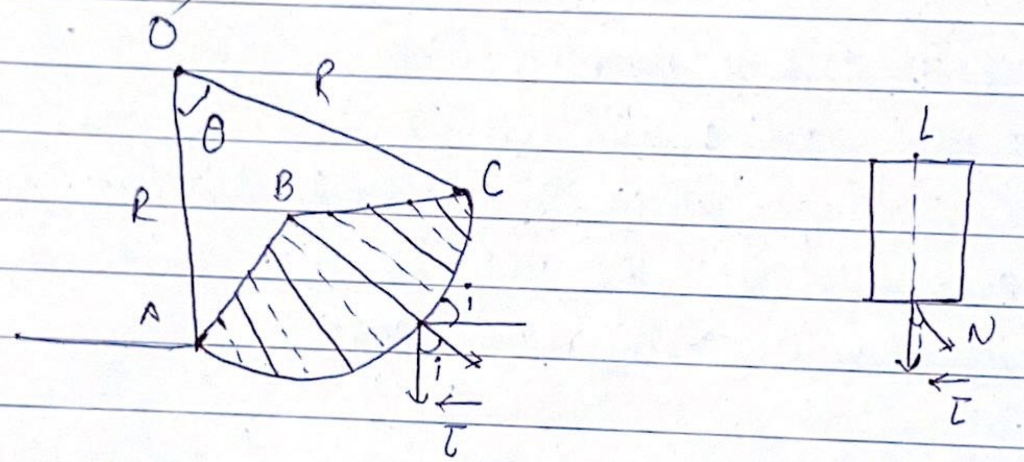
Resisting moment about O (M_r) = $c \times l_a \times R$
$= c \times R\theta \times R$

where, θ is in radian

$$FOS = \frac{M_r}{M_o}$$

$$\boxed{FOS = \frac{c \times R^2 \theta}{w \times d}}$$

ii) $c-\phi$ analysis (swedish. circle method)
(Slice method)



Assumptions:-

→ Slip surface is cylindrical i.e arc of circle is section
→ The sliding soil mass is assumed to contain infinite number of vertical slices.
→ The force of intersection bet^n adjacent slices are neglected.

Let AC be a slip circle of radius R, centre O & central angle $\angle AOC = \theta$. Let soil mass ABCA be divided into no. of vertical slices 1, 2, 3 ... n. The wt. of slices be $W_1, W_2, W_3 \ldots W_n$ acting through the CG of respective slices are resolved into normal component $N_1, N_2, N_3 \ldots N$ & tangential component $T_1, T_2, T_3 \ldots$ let us take moment about centre of rotation 'O'.

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Driving moment (overturning moment)

$M_o = \Sigma T \times R$

For resisting moment;

let C be the cohesion per unit length,

Total cohesive force $= C \times L$

Normal component $= \Sigma N \tan\phi$

Resisting moment $(M_r) = (C \times L + \Sigma N \tan\phi) \times R$

$$FOS = \frac{M_r}{M_o} = \frac{[CL + \Sigma N \tan\phi] R}{\Sigma T \times R}$$

If neutral force is given

$$FOS = \frac{CL + \Sigma (N - U) \tan\phi}{\Sigma T}$$

L = total length of arc

C = cohesion

ΣN = algebric sum of normal component of wt. of slice $= W \cos i$

ΣT = " " " tangential " of " "
" $= W \sin i$

2009 fall.

A slope inclined at 16° to the horizontal to be made i[n] cohesionless deposit having the following properties. $G = 2.7$, $e = 0.72$ & $\phi = 35^\circ$. Determine the FOS of slope against shear failure if water percolates in a direction parallel to the surface.

Solⁿ

$G = 2.7$

$e = 0.72$

$\phi = 35^\circ$

$i = 16^\circ$

$\gamma_w = 9.81\ kN/m^3 \ /\ 10\ kN/m^3$

$$FOS = \frac{C + \gamma_{sub} \times Z \times \cos^2 i \times \tan\phi}{\gamma_{sat} \times Z \times \cos i \times \sin i}$$

$$\gamma_{sat} = \left(\frac{G+e}{1+e}\right)\gamma_w$$

$$= \left(\frac{2.7 + 0.72}{1 + 0.72}\right) \times 10$$

$$= 19.88\ kN/m^3$$

γ_{sub} (submerged) $= \gamma_{sat} - \gamma_w$

$= 19.88 - 10$

$= 9.88\ kN/m^3$

$C = 0$

$$FOS = \frac{\gamma_{sub} \times Z \times \cos^2 i \times \tan\phi}{\gamma_{sat} \times Z \times \cos i \times \sin i}$$

$$= \frac{9.88 \times \cos(16^\circ) \times \tan 35^\circ}{19.88 \times \sin(16^\circ)}$$

$= 1.213 > 1$

∴ The slope is stable.

2013 S — A temporary cutting of 8m deep is to be made in a clay having an unit wt of 18 KN/m³ and an average cohesion of 20 KN/m². A hard stratum exist at a depth of 12m below the ground surface. Use taylor's stability chart to estimate if a 30° slope is safe.

If factor of safety of 1.25 is considered necessary. find the safe slope angle. for $D_F = 1.5$, $i = 30^\circ$, $S_n = 0.163$

Solution;

ht. of slope = 8 m

$C = 20\ KN/m^2$

$\gamma = 18\ KN/m^3$

ht. up to the ground surface = 12 m

$$D_F = \frac{\text{ht. up to g.s}}{\text{ht. of slope}} = \frac{12}{8} = 1.5\ m$$

$$FOS = \frac{C}{S_n \times \gamma \times H}$$

$$= \frac{20}{0.163 \times 18 \times 8}$$

$= 0.852 < 1$

∴ The slope is unstable.

$C_v = \frac{T_v \cdot d^2}{t_{90\%}}$

when;

FOS = 1.25

$$FOS = \frac{C}{S_n \times \gamma \times H}$$

$$S_n = \frac{C}{FOS \times \gamma \times H}$$

$$= \frac{20}{1.25 \times 18 \times 8}$$

$$= 0.11$$

from stability chart;

$S_n = 0.11$, $D_f = 1.5$, $i = 11^\circ$ - chart बाट निकालेको i.

An embankment 10m ~~high~~ high is inclined at an angle of 35° to the horizontal. A stability analysis by the method of slice gave following forces per unit length.

Σ shearing force = 440 KN, Σ normal force = 880 KN, Σ neutral force = 200 KN

The length of failure Arch is 26 m. laboratory tests on soil indicated the effective values of C & ϕ as 20 KN/m^2 & 18° respectively. Determine the factor of safety of slope with respect to i) shearing strength ii) cohesion.

solution;

① FOS w.r.t shearing strength

$$FOS = \frac{CL + \Sigma(N-U)\tan\phi}{\Sigma T}$$

N → normal force

U → neutral force

T → shearing ,,

L → length of arc

$$= \frac{20 \times 26 + \Sigma(880 - 200) \times \tan(18^\circ)}{440}$$

$= 1.683 > 1$

∴ The slope is stable.

(2) FOS w.r.t cohesion

$$FOS = \frac{Cl}{\Sigma T}$$

$$= \frac{20 \times 26}{440}$$

$= 1.18 > 1$

∴ The slope is stable.

An infinite slope is made of clay with following properties.
$\gamma_t = 18\ kN/m^3$, $\phi = 28^\circ$, $\gamma' = 9\ kN/m^3$; $C = 25\ kN/m^2$
$\gamma_t \to \gamma_{sat}$, $\gamma' \to \gamma_{sub}$

If the slope has inclination of 35° & height ~~=~~ 12m determine stability of slope when:-

i) Slope is submerged.
ii) Seepage is parallel to slope.

(1) When the slope is submerged

$$FOS = \frac{C + \gamma_{sub} \times z \times \cos^2 i \times \tan\phi}{\gamma_{sub} \times z \times \cos i \times \sin i}$$

$$= \frac{25 + 9 \times 12 \times \cos^2(35^\circ) \times \tan 28^\circ}{9 \times 12 \times \cos(35^\circ) \times \sin 35^\circ}$$

$= 1.25 > 1$

∴ Slope is stable.

(2) when the seepage is parallel;

$$FOS = \frac{c + \gamma_{sub} \times z \times \cos^2 i \times \tan\phi}{\gamma_{sat} \times z \times \cos i \times \sin i}$$

$= 0.626 < 1$

Slope is (Unstable)

A canal is to be excavated at a depth of 6m below ground level through a soil having following characteristics. $C = 15\ KN/m^2$, $\phi = 20^\circ$, $e = 0.9$, $G = 2.67$. The slope of bank is 1 in 1. Determine the factor of safety w.r.t cohesion when canal runs full. For $i = 45^\circ$, $\phi = 20^\circ$, $S_n = 0.062$.

Solution;

$$FOS = \frac{C}{S_n \times \gamma_{sub} \times H}$$

$\gamma_{sub} = \gamma_{sat} - \gamma_w$

$\gamma_{sat} = \left(\frac{G+e}{1+e}\right)\gamma_w = 18.78$

$\gamma_{sub} = 18.78 - 10$

$= 8.78\ KN/m^3$

For rapid draw down;

$\phi_w = \left(\frac{\gamma_{sub}}{\gamma_{sat}}\right) \times \phi \rightarrow$ original

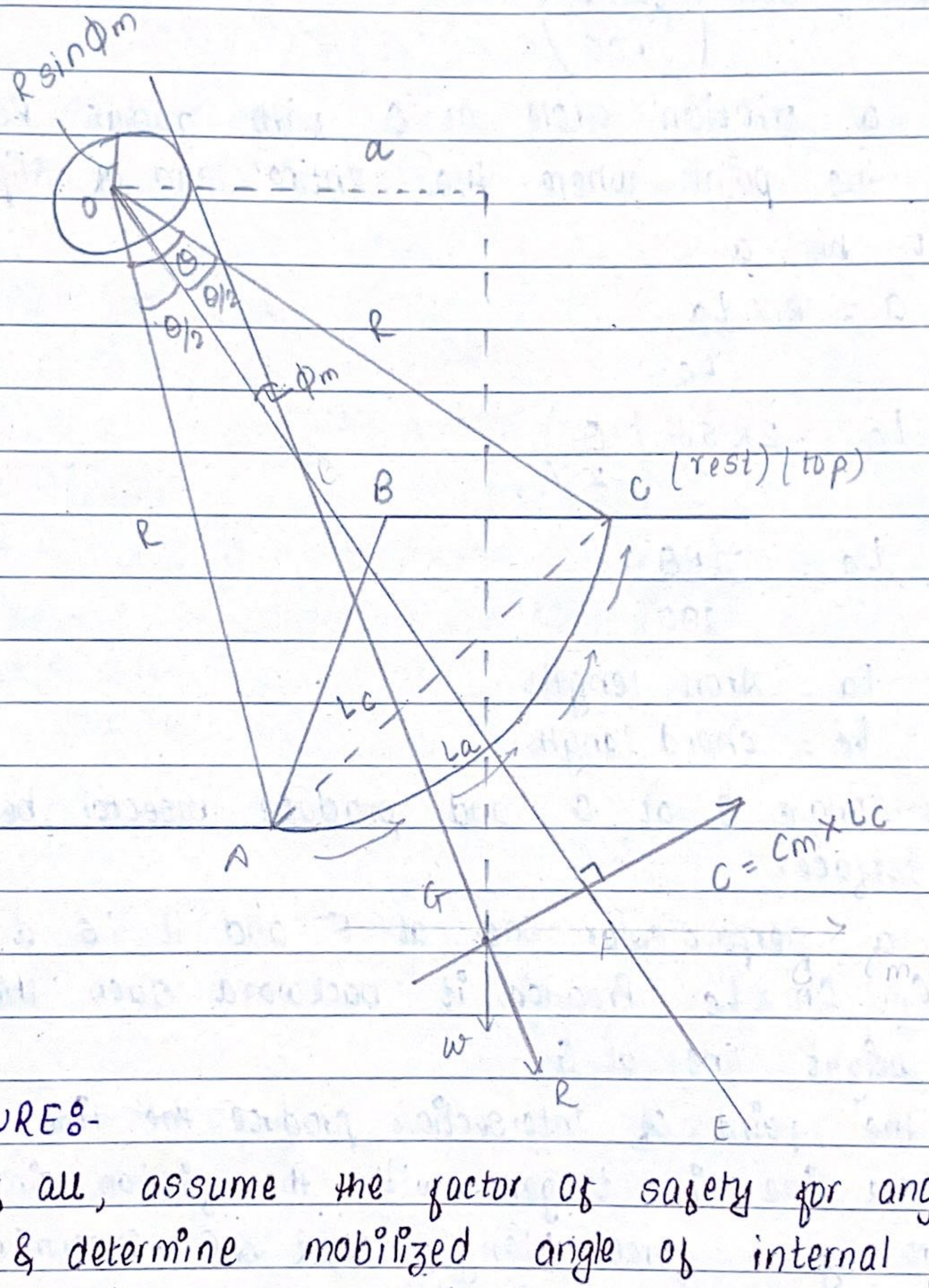
$\phi_w = ?$ ला S_n Tabulated

$$FOS = \frac{15}{0.062 \times 8.78 \times 6}$$

$= 4.592 > 1$

∴ slope is ~~sat~~ stable.

Friction circle method:-



PROCEDURE:-

1) First of all, assume the factor of safety for angle of internal friction & determine mobilized angle of internal friction.

FOS for ϕ,

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

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

$$\phi_m = \tan^{-1}\left(\frac{\tan \phi}{FOS}\right)$$

2) Draw a friction circle at O with radius $R \sin \phi_m$.
3) Locate the point where the entire load of slip surface acts. Let it be a.

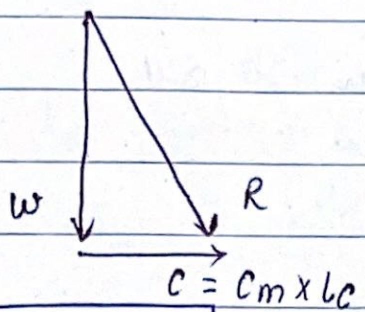
$$a = R \times \frac{l_a}{l_c}$$

$$l_c = 2R \sin\left(\frac{\theta}{2}\right)$$

$$l_a = \frac{\pi R \theta}{180^\circ}$$

where; l_a = Arch length
l_c = chord length

4) Bisect angle θ at O and produce bisector beyond the slip surface.
5) Draw a perpendicular line at F and it is a cohesion line ~~ct~~ $C = C_m \times l_c$. Produce it backward such that it meets the weight line at G.
6) From the point of intersection produce the line onwards such that the line is tangent with the friction circle.
7) By drawing a force triangle W, R & C. Determine the value of C.



$$C_m = \frac{C}{L_c}$$

8) Determine the FOS

$$\therefore FOS = \frac{C}{C_m}$$

C → Cohesion

C_m → mobilized cohesion.

9) If $FOS = FOS_\phi$;
the analysis is correct & the slope is stable else repeat from beginning.