classmate

Date
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Geotech

Section-A
Unit-I

Stability of Slopes:-

Causes of failure:- Due to
(i) the action of gravitational forces, and
(ii) seepage forces with the soil.
(iii) excavation or undercutting of foot
(iv) gradual disintegration of the structure of the soil

* Cofferdams:→

- Cofferdam is a temporary structure built to enclose an area surrounded by water for excavation of foundations.
- It is generally required for foundations of structures such as bridge piers, docks, locks and dams, which are built in open water.
- Cofferdams are also used for laying foundations in open land where there is a high ground water table.

Types :→

1) Earth Cofferdams 2) Rockfill Cofferdams
3) Single-Sheet pile cofferdams
4) Double-Wall Sheet piling Cofferdams
5) Braced Cofferdams
6) Cellular Cofferdams
(a) Diaphragm type (b) Circular type
(c) Cloverleaf type

1) Earth Cofferdams:→

⊠ C–φ Analysis :→

- In order to test the stability of the slope of Cohesion & friction (c–φ) soil, a trial slip circle is drawn, and the material above it is divided into a convenient no. of strips or slices.
- The forces b/w the slices are neglected and each slice is assumed to act independently as a column of soil of unit thickness and of width b.
- The weight W of each slice is assumed to act at its centre.
- If the weight of each slice is resolved into normal (N) & tangential (T) components, the normal components will pass through the centre of rotation (O), and hence do not cause any driving moment on the slice.
- However, the tangential component T causes a driving moment $M_D = T \times r$, where r is the radius of slip circle.
- If C is unit cohesion & ΔL is curved length of each slice then the resisting force is equal to $(C\Delta L + N\tan\phi)$

Hence factor of safety against sliding is

$$F = \frac{M_R}{M_D} = \frac{C\hat{L} + \tan\phi\,\Sigma N}{\Sigma T}$$

P.T.O.

Friction ~~C-le~~ M Circle Method :->

- This method also assumes the failure surface as the arc of a circle.
- Any vector representing reaction ΔR at an obiquity ϕ to an element of the failure arc AD will be tangential to the small circle. This small circle of radius $r\sin\phi$ is called friction circle or ϕ-circle.
- Forces acting on the sliding wedge ABDA are:

(i) the weight W of the wedge
(ii) total frictional resistance or resultant R, and
(iii) total cohesive resistance $c\hat{L}$ developed along the slip circle.

- If slip arc is divided into elementary arcs of length ΔL, the elementary reaction ΔR will be tangential to the friction circle.
- However, in this method, it is assumed that the resultant reaction is tangential to the friction circle. The error involved in this assumption is of small magnitude.

$\therefore$ Total Cohesive resistance $= C_m\hat{L}$

$$= C_m \Sigma \Delta L$$

C_m = Mobilised unit Cohesion.

$\boxed{\text{Fig. P.No - 620}}$ $\boxed{a = r\frac{\hat{L}}{L}}$

Thus, factor of safety F_c w.r.t Cohesive strength is given by

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

The circle giving minimum Factor of safety is the critical slip circle.

Taylor's Stability Number And Curves:-

- The total cohesive force $c\hat{L}$, which resists the slipping along the slip arc at critical equilibrium, is proportional to the cohesion c and height H of the slope.
- The force causing instability is the weight of the wedge which is equal to unit weight γ and the area of wedge is proportional to the square of height H.
- Hence, the wt. of the wedge is pro. to $\gamma \times H^2$.
- If F_c is the factor of safety w.r.t cohesion we have

$$\frac{c \times H}{F_c \times \gamma H^2} = \frac{c}{F_c \gamma H} = S_n \quad \text{---(1)}$$

$\frac{c}{F_c \gamma H}$ is called Taylor's stability no. $= S_n$ ..

Let ~~c~~ c_m = Mobilised Unit Cohesion

$$\text{or, } c_m = \frac{c}{F_c}$$

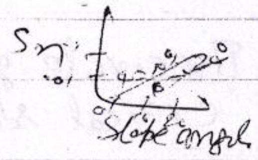
$$\text{Then, } S_n = \frac{c}{F_c \cdot \gamma \cdot H} = \frac{c_m}{\gamma H}$$

If H_c = Critical ht., then FOS w.r.t ht is also equal to FOS w.r.t cohesion,

$$F_c = \frac{H_c}{H}$$

$$\text{Hence, } S_n = \frac{c}{F_c \cdot \gamma H} = \frac{c}{\gamma H_c} = \frac{c_m}{\gamma H}$$

$\boxed{\text{Fig. P No. - 623}}$



Curves:–

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... cohesion
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... no. = S_n

... $\frac{C_m}{\gamma H}$

8) $i = \tan^{-1}\frac{1}{2} = 26.5^\circ$

Given, $\phi = 10^\circ$, $C = 25\ kN/m^2$
$\gamma = 19\ kN/m^2$
$H = 10\ m$

$\therefore S_n = 0.064$

But $\left[S_n = \frac{C}{F_c \times \gamma \times H}\right] \Rightarrow \left[F_c = \frac{C}{S_n \gamma H}\right]$

$= \frac{25}{0.064 \times 19 \times 10} = 2.06$

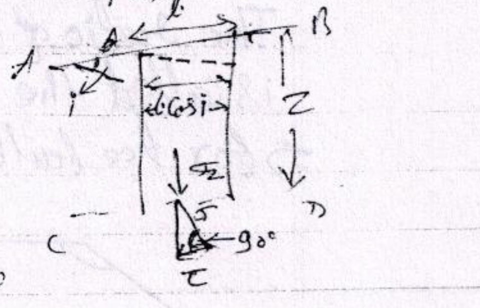
$\left[\text{Now, } H_c = F_c \cdot H = 2.06 \times 10 = 20.6\ m\right]$

• Alternatively

$\left[H_c = \frac{C}{\gamma S_n} = \frac{25}{19 \times 0.064} = 20.6\ m\right]$

Stability Analysis of Infinite Slopes:–

For an infinite slope, the soil pr. and soil stresses on any plane parallel to the slope surface are identical, and therefore, the failure of the slope usually involves a sliding of soil mass along a plane parallel to the slope at some depth.



wt of prism $= W = \gamma \cdot Z \cdot b \cos i$

Ver. stress $\sigma_z = \frac{W}{b} = \gamma \cdot Z \cos i$

If σ & τ are the stress comp. normal and tangential to the surface CD, we have

$\sigma = \sigma_z \cos i = \gamma Z \cos^2 i$, & $\tau = \sigma_z \sin i = \gamma \cdot Z \cos i \sin i$

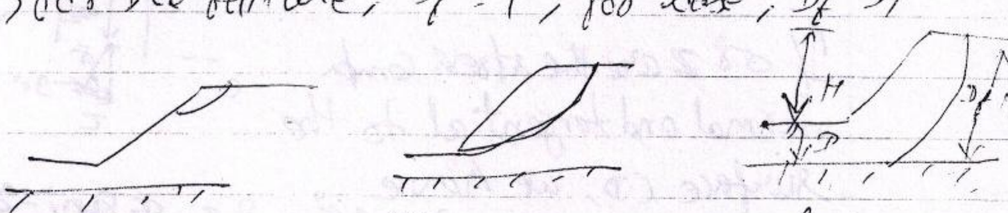
Tangential Comp. τ is called shear stress
where, b = length
z = depth
Hor. length of prism = $b \cos i$
Vol. /unit length of prism = $z \cdot b \cdot \cos i$

Finite-Slope

Failure of finite slope occurs along a surface which is a curve.

- Two basic types of failure are
(i) Slope & (ii) base failure.
- If the failure occurs along a surface of sliding that intersects the slope at or above its toe, the slide is known as slope failure.
- Slope failure is called as a face failure, if the arc passes above the toe, or toe failure if the arc passes through the toe.
- If the soil beneath the toe of the slope is weak the failure occurs along a surface that passes at some distance below the toe of the slope. Such type of failure is called base failure.

The ratio of total depth $(H+D)$ to depth H is called the depth factor D_f
⇒ for toe failure, $D_f = 1$, for base, $D_f > 1$



Face failure Toe base

☒ FOS Ratio of Cohesion unit to mobilised Cohesive unit

write, $F_c = \frac{c}{c_m}$

and Taylor's eqn completely

Stability of Slopes

☒ Causes of failure :- Due to

(i) the action of gravitational forces

(ii) Seepage forces within the soil.

(iii) excavation or undercutting of the foot of slope

(iv) gradual disintegration of the structure of the soil.

- The failure of a mass of soil located beneath a slope is called a slide
- An analysis of stability of slope consists of two parts:

(1) the determination of the most severely stressed internal surface and the magnitude of the shearing stress to which it is subjected.

(2) the determination of the shearing strength along this surface.

Slopes may be of two types:

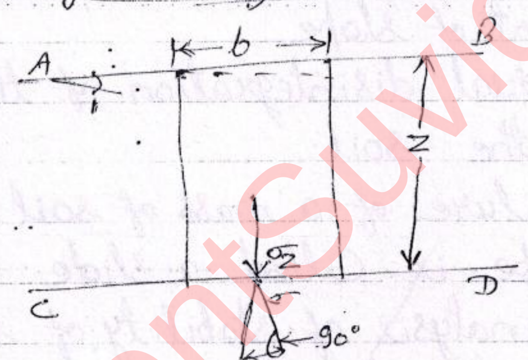
Infinite slope and finite slope.

If a slope represents the boundary surfaces of a semi-infinite soil mass, and the soil properties for all identical depths below the surface are constant, it is called an infinite slope.

If the slope is of limited extent, it is called a finite slope. Slopes extending to infinity do not exist in nature.

Eg:- inclined faces of earth dam, embankments and cuts etc.

⊠ Stability Analysis of Infinite Slopes



Let CD represents failure plane at depth z below the surface.

Consider a prism of soil of inclined length b along the slope, and depth z upto the critical surface. The horizontal length of prism is $b\cos i$, and its volume per unit length of prism is $z \cdot b \cdot \cos i$.

$\therefore$ Weight of prism $= W = \gamma \cdot z \cdot b\cos i$

$\therefore$ Vertical stress σ_z on the surface CD is

$$\sigma_z = \frac{W}{b} = \gamma \cdot z \cdot \cos i \qquad \text{—— (1)}$$

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If τ & σ are the stress component tangential ~~to the~~ and normal to the surface CD, we have

$$\sigma = \sigma_z \cos i = \gamma z \cos^2 i \quad \text{— (2)}$$

$$\& \quad \tau = \sigma_z \sin i = \gamma z \cos i \sin i \quad \text{— (3)}$$

The factor of safety of the slope against sliding due to shear is given by

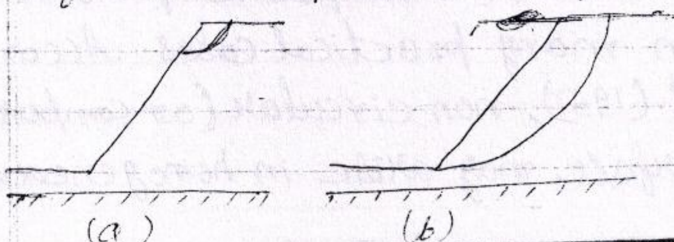
$$F = \frac{\tau_f}{\tau}$$

τ_f = Shear Strength, and
τ = Shear Stress

☒ Stability Analysis of finite slopes :→

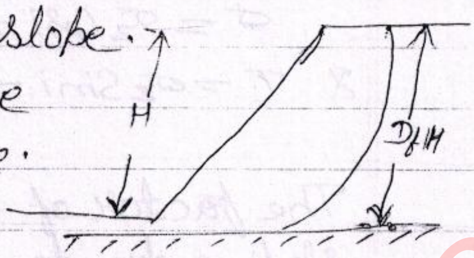
Failure of finite slopes occurs along a surface which is curve.
Two basic types of failure of a finite slope may occur : (i) Slope failure, and
(ii) Basic failure

• If the failure occurs along a surface of sliding that intersects the slope at or above its toe, the slide is known as slope failure. Slope failure is called as a face failure if the arc passes above the toe, or toe failure if the arc passes through the toe.



(a) Face failure
(b) Toe failure

- On the other hand, if the soil beneath the toe of the slope is weak the failure occurs along a surface that passes at some distance below the toe of the slope. Such a type of failure is called base failure.
- The ratio of the total depth $(H+D)$ to depth H is called the depth factor D_f.



(c) Base failure

- For toe failure, $D_f = 1$, for base failure, $D_f > 1$

Types of slip surfaces or failure Surfaces:

The rupture of a finite slop may take place along one of the following failure surfaces.

1) Planar Failure Surface
2) Circular Failure Surface
3) Non-Circular Failure Surface

- Planar failure surface may commonly occur in a soil deposit or embankment with a specific plane of weakness.
- Circular rupture surface was first proposed by Petterson (1916).
- Non circular (or composite) failure surface occur in many practical cases. According to Bennett (1951), non circular (or composite) slip surface may arise in homogeneous dams

having one or more of the following:
(i) finite of infinite depth
(ii) Rigid boundary planes of maximum or zero shear
(iii) Presence of relatively stronger or weaker layer.

According to Morgenstern and Price (1965) in non-homogeneous earth dams may occur are:
(i) Presence of a soft layer in foundation
(ii) Use of different type of soil or rock in the dam section with varying strength and pore pressure condition.
(iii) Use of drainage blankets to facilitate dissipation of pore pressures.

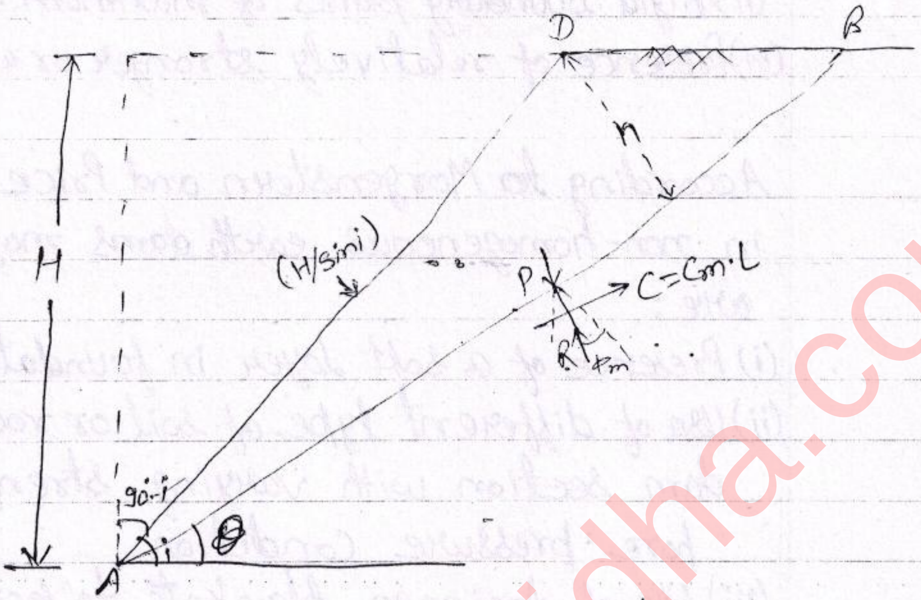
Method of Analysis :→

The stability of a finite slope can be investigated by following common methods:
1) Culmann's method of planer failure surface
2) The Swedish circle method (Slip circle method) IMP
3) The friction circle method
4) Bishop's method

1) Planer failure Surface : Culmann's Method

Let AB be any probable slip plane. The wedge ADB is in equilibrium under the action of three forces:
(i) Weight of the wedge, $W = \frac{1}{2} AB \cdot h\gamma = \frac{1}{2} L \cdot h \cdot \gamma$ —(1)
(ii) The cohesive force C along the surface AB, resisting motion $= C_m \cdot L$

(ii) The reaction R, inclined at angle ϕ_m to the normal.



Culmann's Slip Plane

(iii) The reaction R, inclined at angle ϕ_m to the normal.

Now,

$$AD = \frac{h}{\sin(i-\phi)} = \frac{H}{\sin i}$$

Hence, $h = \dfrac{H \sin(i-\theta)}{\sin i}$

Substituting in (i), we get

$$W = \frac{1}{2} L \gamma H \frac{\sin(i-\theta)}{\sin i}$$

If c and ϕ are the appropriate shear strength parameters, the shear strength (τ_f) along the slip plane is

$$\tau_f = c \cdot L + W \cos\theta \cdot \tan\phi$$

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shear strength

The weight component parallel to the plane AC causing sliding is $\tau = W\sin\theta$

$\therefore$ Factor of Safety, $F = \frac{\tau_f}{\tau} = \frac{cL + W\cos\theta\tan\phi}{W\sin\theta}$

Substituting the value of W in the above expression, we get

$$\boxed{F = \frac{c + \frac{1}{2}\gamma H[\sin(i-\theta)/\sin i]\cos\theta\tan\phi}{\frac{1}{2}\gamma H[\sin(i-\theta)/\sin i]\sin\theta}}$$

This method is suitable for very steep slopes.

2) <u>The Swedish Slip Circle Method:→</u>

This method assumes that the surface of sliding is an arc of a circle. We shall consider two cases:

(i) analysis of purely cohesive soil ($\phi_u = 0$ analysis)

(ii) analysis of a soil possessing both cohesion and friction ($c-\phi$ analysis)

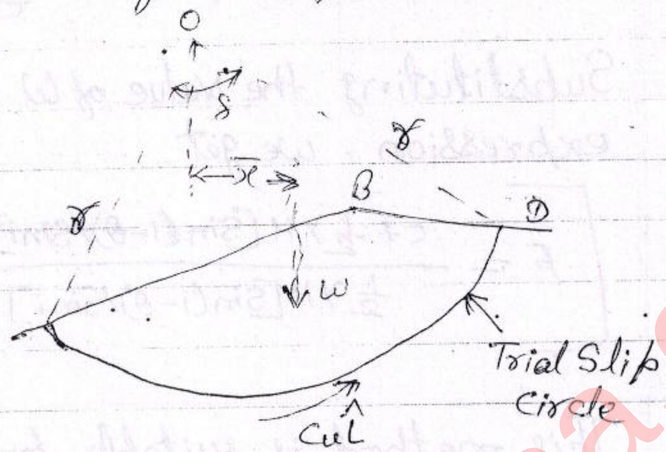
(i) <u>$\phi_u = 0$ analysis:→</u>

This method consists in assuming a number of trial slip circles, and finding the factor of safety of each.

The circle corresponding to the minimum factor of safety is the <u>critical slip circle</u>.

Let AD be a trial slip circle, with r as the radius and O as the centre of rotation.

Let W be the weight of the soil of the wedge ABDA of unit ~~as the centre of rotation.~~ thickness, acting through its centroid.



If C_u is the unit cohesion and $\hat{L}$ = Length of the slip arc $AD = \frac{2\pi r\delta}{360°}$,

the shear resistance developed along the slip surface will be equal to $C_u\hat{L}$.

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Factor of safety F is then given by

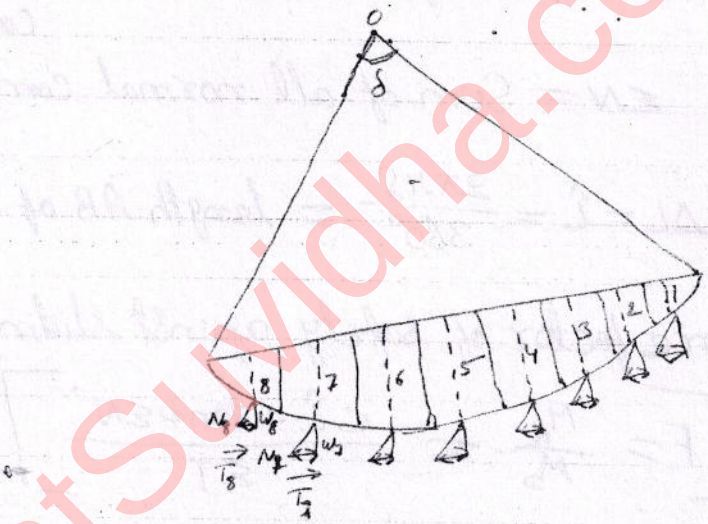
$$F = \frac{M_R}{M_D} = \frac{C_u \hat{L} r}{W\bar{x}}$$

Effect of tension Crack:

If a tension crack of depth $z_0 \left(= \frac{2c}{\gamma}\right)$ develops, water will enter in the crack, exerting a hydrostatic pressure force P_w action on the portion DE at a height $z_0/3$ from E. Hence the arc portion DE will be ineffective in resisting the slide.

(ii) C-φ Analysis :→

- In order to test the stability of the slope of a c-φ ~~analysis~~ soil, trial slip circle is drawn, and the material above the assumed slip surfaces is divided into a convenient number of vertical strips or slices.
- The forces between the slices are neglected, and each slice is assumed to act independently



as a column of soil of unit thickness and of width b.

- The weight W of each slice is assumed to act as its centre.
- If this weight of each slice is resolved into normal (N) and tangential (T) components, the normal components will pass through the centre of rotation (O), and hence do not cause any driving moment on the slice.
- However, the tangential component T causes a driving moment $M_D = T \times r$, where r is the radius of the slip circle.

- If c is the unit cohesion and ΔL is the curved length of each slice then the resisting force, from Coulomb's equation is equal to $(c\Delta L + N\tan\phi)$.

For entire slip surface AB, we have

Driving moment $M_D = r\Sigma T$

Resisting moment $M_R = r[c\Sigma\Delta L + \tan\phi\,\Sigma N]$

where, ΣT = algebric sum of all tangential components

ΣN = Sum of all normal components

$$\Sigma\Delta L = \hat{L} = \frac{2\pi r\delta}{360^\circ} = \text{length AB of slip circle}$$

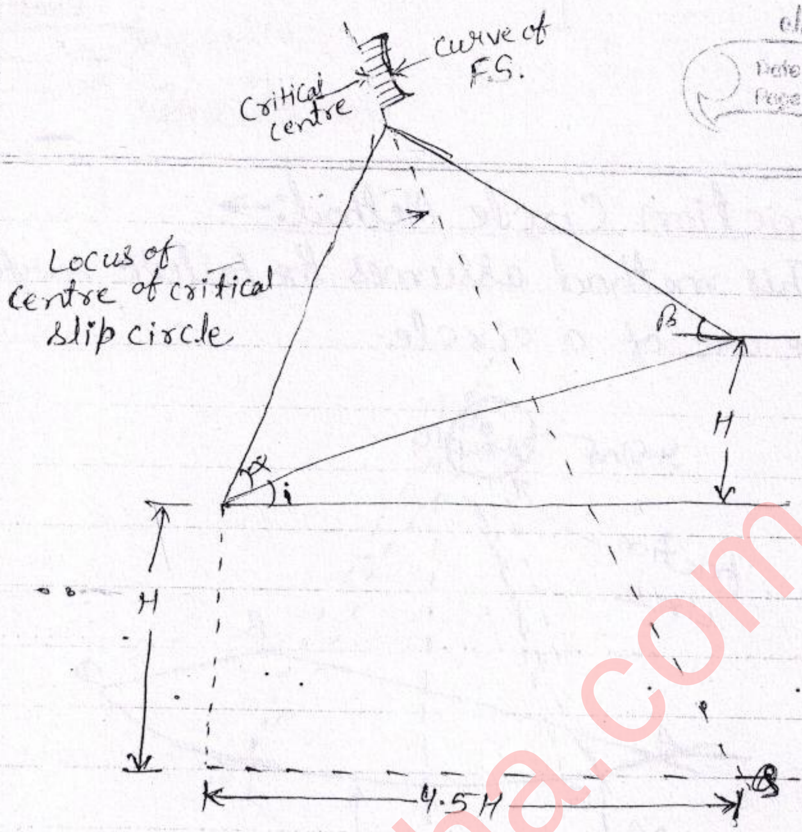
Hence factor of safety against sliding is

$$\left[F = \frac{M_R}{M_D} = \frac{c\hat{L} + \tan\phi\,\Sigma N}{\Sigma T}\right]$$

The circle giving the minimum factor of safety is the critical slip circle.

Method of locating centre of critical slip circle, or, "Fellinious Method" :→

- In order to reduce the number of trials, to find the centre of critical slip circle, Fellinius has given a method of locating the locus on which the probable centre may lie.
- For a homogeneous $c-\phi$ soil, the centre of slip circle lie on a line PQ, in which the point

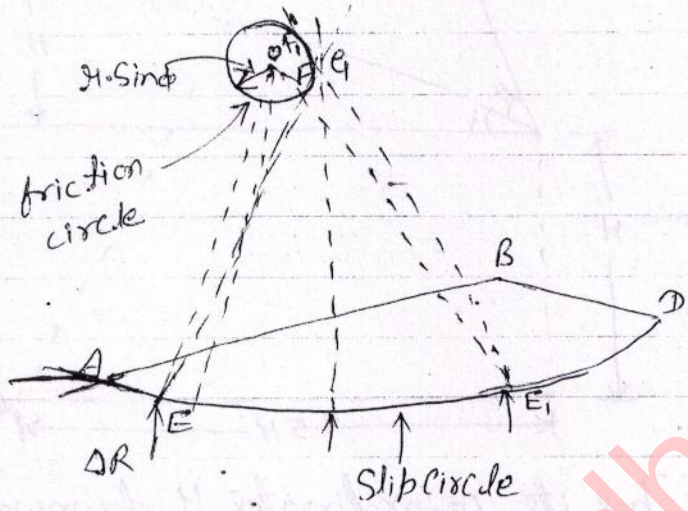


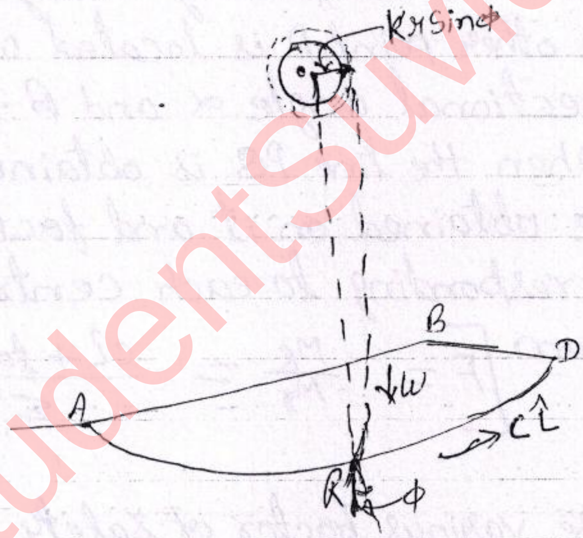
• Q has its co-ordinates H downwards from toe and 4.5H horizontally away.
• The other point P is located with the help of directional angle α and β.
• When the line PQ is obtained, trial centres are obtained on it and factor of safety corresponding to each centre is calculated from
$$\left[F = \frac{M_R}{M_D} = \frac{c\hat{L} + \tan\phi \, \Sigma N}{\Sigma T}\right]$$

These various factor of safety so obtained are plotted as ordinates on the corresponding centres and a smooth curve is obtained.
• The centre corresponding to the lowest factor of safety is the critical circle centre.
• For a $\phi = 0$ soil, P represents the centre of the critical circle.

Friction Circle Method:→

- This method assumes the failure surface as the arc of a circle.





- Any vector representing reaction ΔR at an obliquity φ to an element of the failure arc AD will be tangential to the small circle. This small circle of radius r sinφ is, therefore, called friction cricle or φ-circle.
- The forces acting on the sliding wedge ABDA are: (i) the weight W of the wedge

(ii) th

(iii) t

(ii) the total frictional resistance or resultant R
(iii) total cohesive resistance $c\hat{L}$ developed along the slip circle.

However in the friction circle method, it is assumed that the resultant reaction is tangential to the friction circle. The error involved in this assumption is of small magnitude.

Let c_m = mobilised unit cohesion

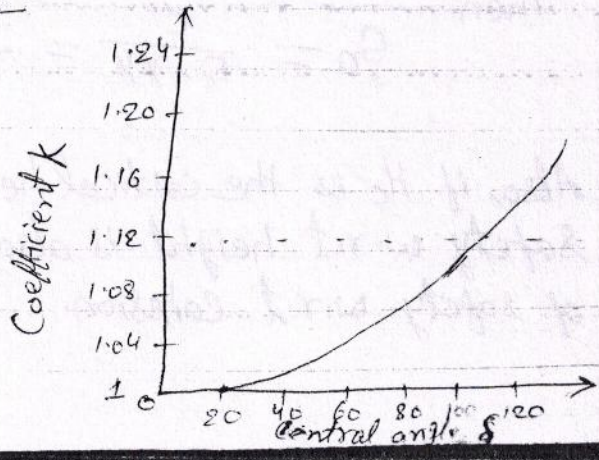
$\therefore$ Mobilised cohesion on elementary arc of length $\Delta L = c_m \cdot \Delta L$

$\therefore$ Total cohesive resistance $= c_m \hat{L} = c_m \Sigma \Delta L$

The factor of safety F_c w.r.t cohesive strength, based on the assumption that frictional strength has been fully mobilised, is given by

$$F_c = \frac{c}{c_m}$$

A number of slip circles are taken and factor of safety for each is found. The circle giving minimum factor of safety is the <u>critical slip circle</u>.



Taylor's Stability Number and Stability curves :→

- The total cohesive force $c\hat{L}$, which resists the slipping along the slip arc at critical equilibrium, is proportional to the cohesive c and the height H of the slope.
- The force causing instability is the weight of the wedge which is equal to unit weight γ and the area of the wedge which is proportional to the square of the height H.
- Hence the weight of the wedge is proportional to $\gamma \times H^2$. If F_c is the factor of safety w.r.t Cohesion, we have

$$\frac{c \times H}{F_c \times \gamma H^2} = \frac{c}{F_c \gamma H} = S_n \quad \text{—(1)}$$

The dimensionless quantity $\frac{c}{F_c \gamma H}$ is called

Taylor's Stability number S_n.

Let c_m = mobilised unit cohesion

or, $c_m = \frac{c}{F_c}$

Then

$$S_n = \frac{c}{F_c \cdot \gamma \cdot H} = \frac{c_m}{\gamma H}$$

Also, if H_c is the critical height, the factor of safety w.r.t height is also equal to the factor of safety w.r.t cohesion.

i.e., $F_c = \frac{H_c}{H}$

Hence, $\left[S_n = \frac{c}{F_c \gamma H} = \frac{c}{\gamma H_c} = \frac{C_m}{\gamma H} \right]$

When a soil possesses both cohesion and friction, the factor of safety F is to be provided w.r.t cohesion as well as friction. The average shear stress S which would be developed for a given factor of safety F would be

$$\left[S = \frac{c}{F} + \sigma \frac{\tan\phi}{F} \right]$$

Stability of Slopes of earth dam:→

It is tested under the following conditions:

1) Stability of downstream slope during steady seepage.
2) Stability of upstream slope during sudden drawdown.
3) Stability of upstream & downstream slopes during and immediately after construction.

1) Stability of downstream slope during steady seepage:→

Critical condition of d/s slope occurs when the reservoir is full and percolation is at its maximum.

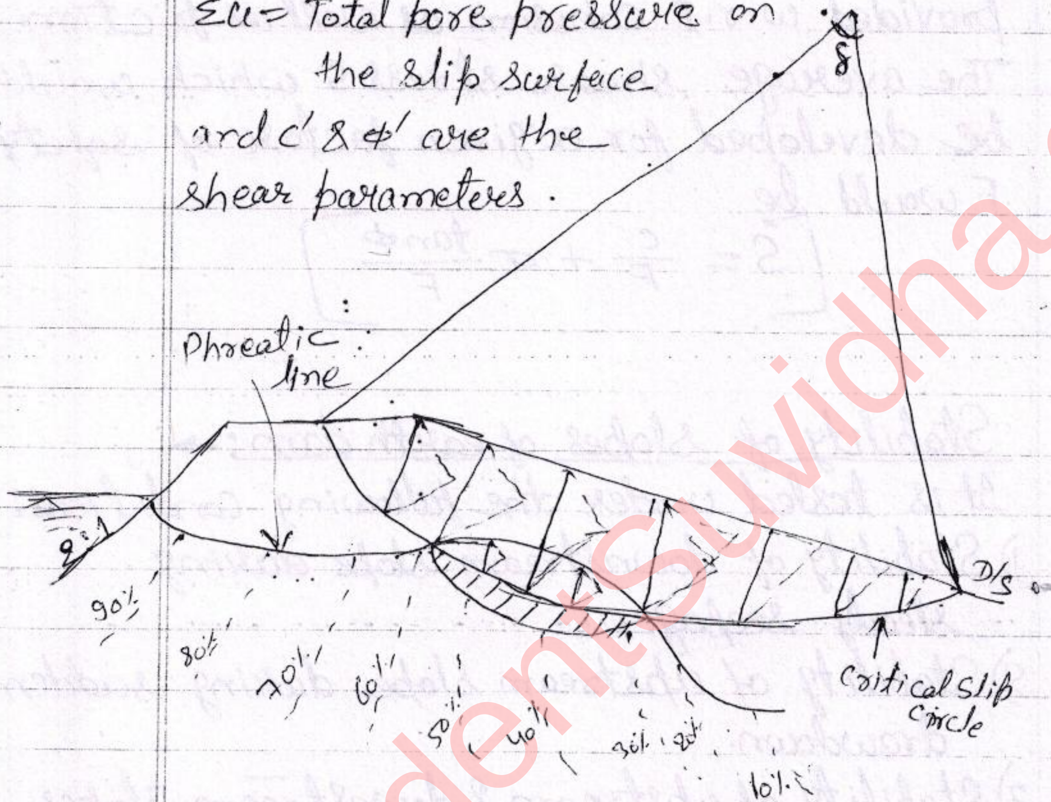
In other words, the pore water pressure (U) acting on the soil mass below the saturation line reduces the effective stress responsible for mobilising shearing resistance. The factor of safety in this case is

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

where,

Σu = Total pore pressure on the slip surface

and c' & ϕ' are the shear parameters.



The pore water pressure at any point is represented by the piezometric head h_w at that point. Thus, the variations of pore water pressure along a likely slip surface is obtained by measuring at each of its intersections with an equipotential line, the vertical height from that intersection to the level at which the equipotential line cuts the phratic line.

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In the absence of a flow net, the factor of safety of the d/s slope can be approximately calculated by

$$F = \frac{c'\hat{l} + \tan\phi' \Sigma N'}{\Sigma T}$$

where the normal component N' are to be calculated on the basis of ~~buyo~~ buoyant unit weight γ' and the dam while T components are to be calculated on the basis of saturated unit weight.

2) <u>Stability of u/s slope during sudden drawdown</u> :→
For the u/s slope, steady seepage does not represent the critical state, because the seepage pressure then acts inwards from this slope and tends to increase the stability ~~of~~ on the u/s side.

- For the u/s slope, the critical condition is when the reservoir is suddenly emptied without allowing any appreciable change in the water level within the saturated mass of soil. This state is known as sudden drawdown.
- With complete drawdown, hydrostatic force acting along the u/s slope at the time of full reservoir is emptied.
- The effect of drawdowns on slope stability varies appreciably with opportunity of drainage at the base.
- If the base ~~slope~~ is quite impervious, flow lines tend to the horizontal and in outward direction towards the slope, which is

quite unfavourable.

- On the other hand if the base material is pervious, flow pattern tends to be downwards and this is more favourable w.r.t stability.
- The magnitude and distribution of pore water pressure on a likely slip surface is estimated from pressure net which is developed from the flow net.
- The factor of safety is calculated by

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

In the absence of the flow net

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

in which N' ~~are~~ is computed w.r.t the submerged density γ' of impervious u/s slope while T components are computed w.r.t saturated density.

3) Stability of u/s and d/s slopes during or immediately after construction:→

- When a dam is built of relatively impervious compressible soil, excess pore pressure develops in the air and water entrapped in the pore space. This is because the soil mass undergoes a change in volume due to compaction of the dam during construction and also due to its down weight.

- ~~If~~ As the pore pressure greatly affects the shear strength of soil, it is essential to known its magnitude for stability analysis.

The estimation of the construction pore pressure is made with the help of Hiff's equation:

$$u = \frac{P_a \Delta}{V_a + h_c V_w - \Delta}$$

where,

u = induced pore pressure

P_a = air pressure in the voids of soil mass

Δ = embankment compression in percent of original total embankment volume.

V_a = Volume of free air voids

V_w = Volume of pore water

h_c = Henry's Constant of solubility of air in water by volume (=0.02 at 68°F)