UNIT- V

SLOPE STABILITY

Introduction :-

* An Earth slope is an unsupported, inclined surface of soil mass.

Slopes →
- Artificial (or) Man made — Ex:- Cutting & Embankments for highways & railways
- Natural — Ex:- Hill side & Valleys, Coastal and river cliffs.

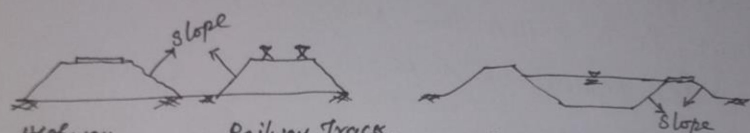


Fig Highway   Fig Railway Track.   Fig Canal

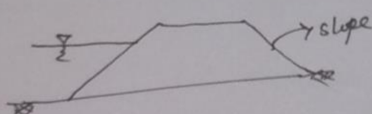


Fig Earth Dam.

* The failure of a mass of soil located beneath a slope is called a "**slide**". It involves a downward and outward movement of the entire mass of soil that participates in the failure.

Forces cause slope failure :-

- ✓ Gravitational force (self weight)
- ✓ Seepage force
- ✓ Earthquake forces
- ✓ Construction equipment Load.
- ✓ Erosion of the surface of slopes due to flowing water
- ✓ Sudden lowering of water adjacent to a slope.

TYPES OF SLOPES :-

* The slopes either natural (or) man made, can be divided into two types.

- Infinite slope
- Finite slope.

→ Infinite slope :-

* If a slope represents the boundary surface 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.

- Ex: Mountain slope.

→ Finite slope :-

* If the slope is of limited extent, it is called a finite slope.

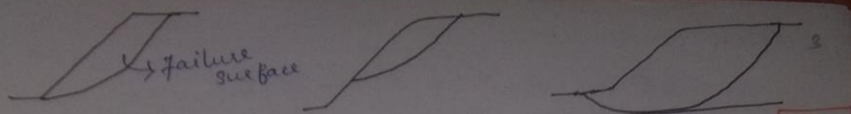
- Ex: Earth dam, Embankments & cuts.

TYPES OF SLOPE FAILURE :-

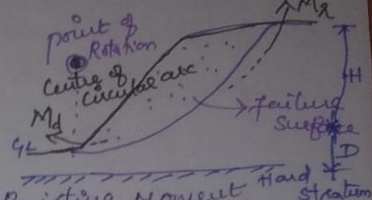
- Rotational failure
- Translational failure
- Compound failure
- Wedge failure

Rotational failure :-

* Failure occurs by rotation along a slip surface by downward and outward movement of the soil mass. * Generally occurs in the case of finite slopes & failure along slip surface (curved)



*Rotational slips ← Toe failure, slope failure, Base failure



*Factor of Safety $F \Rightarrow \frac{M_r}{M_d}$

- M_r - Resisting moment
- M_d - driving moment.

when $M_d > M_r$ - failure occurs.

NOTE:

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

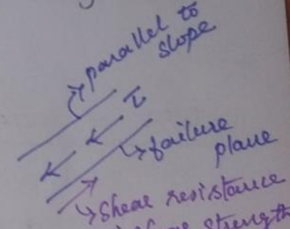
Translational failure:-

*Generally occurs in infinite slopes along a long failure surface parallel to the slope.

*Factor of safety $F = S/\tau$

*If $\tau > S$ - failure occurs.

$F > 1 \Rightarrow$ safe
$F < 1 \Rightarrow$ unsafe
$F = 0 \Rightarrow$ critical



Compound failure :-

*It is a combination of the rotational slips and the translational slip.

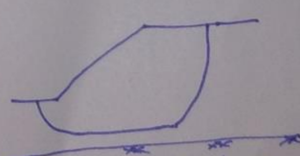


Fig: Compound failure

Wedge failure :-

* A failure along an inclined plane is known as plane failure (or) Wedge failure (or) block failure

*occurs in the case of finite slopes

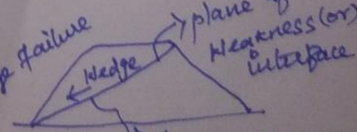


Fig Wedge failure

4

STABILITY OF SLOPES:-

* Stable Existing slopes may be subjected to failure due to
  - Man - induced external forces, removal of Earth below the toe of the slope land.
  - Development of cracks and saturation with water intrusion.
  - Earthquake
  - Erosion, etc...

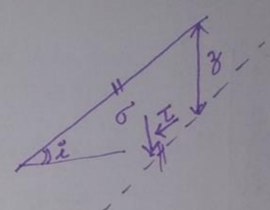
* Careful design for stability is required to avoid failure in Earthen dam, embankment, Excavation and Earth moving works.

STABILITY ANALYSIS OF SLOPES

* Slope stability is an Extremely important Consideration in the design and construction of Earth structures such as Earth dams, Embankment, canals etc.

* The stability analysis of both infinite slopes and finite slopes must be carried separately,

Infinite slopes:-



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

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

Factor of Safety $F = \frac{s}{\tau} \Rightarrow \frac{c + \sigma \tan\phi}{\tau}$

* $$F = \frac{c + \gamma z \cos^2 i \tan\phi}{\gamma z \cos i \sin i}$$

where i – Angle of infinite slope
ϕ – Effective angle of internal friction of the soil.

If $c = 0$

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

for stable slopes $i < \phi$

for seepage parallel to the slope

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

Infinite slopes in c-φ soils

If there is no water

* $F = \dfrac{c + \gamma z \cos^2 i \tan\varphi}{\gamma z \cos i \sin i}$

If slope is submerged

* $F = \dfrac{c' + \gamma' z \cos^2 i \tan\varphi'}{\gamma' z \cos i \sin i}$

If there is seepage parallel to slope

* $F = \dfrac{c' + \gamma' z \cos^2 i \tan\varphi'}{\gamma_{sat} z \cos i \sin i}$

$\Rightarrow \dfrac{\gamma'}{\gamma_{sat}} \dfrac{\tan\varphi'}{\tan i}$

Infinite slopes in Cohesionless Soils [c = 0]

If there is no water

* $F = \dfrac{\tan\varphi}{\tan i}$

If slope is submerged

* $F = \dfrac{\tan\varphi'}{\tan i}$

If there is seepage parallel to slope

* $F = \left[\dfrac{\gamma'}{\gamma_{sat}}\right] \dfrac{\tan\varphi'}{\tan i}$

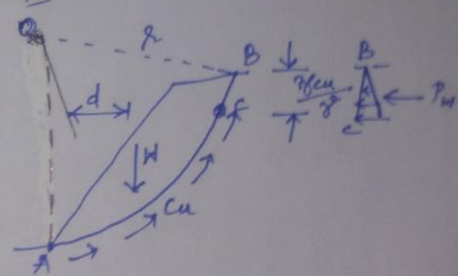
Finite slopes:-

- $\phi_u = 0$ Analysis
- method of slices (or) Swedish circle method
- Bishop's method
- Friction circle method
- Stability number method (Taylor's)

(1) $\phi_u = 0$ Analysis:-

- ⇒ Suitable for saturated undrained clays [$\phi_u = 0$] [i.e. pure clays] & $c = c_u$
- ⇒ Trial & Error method
- ⇒ Graphical method

* On this Analysis the failure surface is assumed to be a circular arc AB. Let failure surface with centre 'O' and radius 'r' i.e [OB = OA = r].



* The total weight 'W' above the failure surface causes instability. For equilibrium, the shear strength to be mobilised along the failure surface can be expressed as

$$\tau_m = \frac{s}{F} = \boxed{\frac{c_u}{F}}$$

where F ⇒ factor of safety

Taking moments about O

$$W \times d = \left(\frac{c_u}{F}\right) L_a r$$

where L_a is length of arc AB & d is the lever arm of W about 'O'.

* $$F = \frac{C_u L_a r}{W \times d}$$

If a tension crack develops and water enters the crack, the hydrostatic pressure force P_w acts on the portion BC of the arc at a height of $h/3$ from C, where h is the depth of tension crack, equal to $2C_u/\gamma$. The arc length in that case is equal to AC.

(2) Swedish circle method :- (Method of slices) / (Fellenius Method)

*⇒ The actual shape of a slip surface in the case of finite slopes is curvilinear.

*⇒ It is suitable for all types of soils.

*⇒ Trial & Error method

*⇒ graphical method

In this method two types of analysis are carried.

- Analysis of purely cohesive soil (or) $\phi_u = 0$ analysis
- Analysis of cohesive - frictional soil (or) $c-\phi$ analysis

Analysis of Purely cohesive soil (or) $\phi_u = 0$ analysis :-

* The stability analysis of an embankment immediately after its construction, based on total stresses is called as $\phi = 0$ analysis (or) purely cohesive soil analysis.

* This method assumes that the soil has had no time to drain and the shear strength parameters used to relate to the undrained strength with respect to total stresses.

Let W - self weight of sliding soil mass

- C - cohesion of soil mass
- R - Radius of arc
- θ - Angle made by arc at 'O'
- $\hat{L}$ - Arc length
- $\hat{L} = R\theta$

The overturning moment is caused by self weight of the soil mass.

$$M_o = W\bar{x}$$

The resisting moment is developed by cohesive force on the arc of soil mass.

M_R = Cohesive force × Perpendicular distance

$$\Rightarrow c\hat{L} \times 1 \times R$$

$$M_R = cR^2\theta$$

For equilibrium $M_o = M_R$

$$W\bar{x} = cR^2\theta$$

Factor of Safety $\Rightarrow \dfrac{\text{Resisting moment } (M_R)}{\text{Overturning moment } (M_o)}$

$$\Rightarrow \boxed{\frac{cR^2\theta}{W\bar{x}} > 1}$$

Here the overturning moment $M_o = W\bar{x}$ is dependent on the cohesion mobilised which will be less than the maximum cohesion of soil.

Analysis of Cohesive - Frictional Soil (or) c-φ Analysis (or) Swedish Method of Slices

11

Let
- W - weight of slice where failure plane makes an angle 'θ'
- c - Cohesion of soil
- $\hat{l}$ - arc length of each slice.

The cohesive force (F_c) is developed by each slice

* $F_c = c\hat{l} \times 1$

The sliding force (or) disturbing force causing the movement of each slice is

* $F_{d1} = W \sin\theta$

The movement of slice causing the development of frictional force on the failure plane of each slice which is given by

* frictional force $F_f = \mu W \cos\theta$

* Resisting (or) Stability force on one slice $F_R = \begin{Bmatrix} \text{frictional} \\ \text{force}(F_f) \end{Bmatrix} + \begin{Bmatrix} \text{Cohesive} \\ \text{force}(F_c) \end{Bmatrix}$

$\Rightarrow F_{R_1} = \mu W \cos\theta + c\hat{l}$

* Total resisting force $F_R = \Sigma F_{R1} = \Sigma[\mu W \cos\theta + c\hat{l}]$

$\Rightarrow \Sigma[\tan\varphi . W\cos\theta] + c\hat{l}$

$\hat{l} = R\theta$

* Total disturbing force $F_d = \Sigma F_{d1}$

$F_d = \Sigma[W \sin\theta]$

$$FOS = \frac{\text{Total resisting force } (F_R)}{\text{Total disturbing force } (F_d)} > 1$$

$$\Rightarrow \frac{\Sigma [\tan\varphi \cdot W\cos\theta] + cL}{\Sigma [W\sin\theta]} > 1$$

If pore water pressure is to be considered then, the pore water opposes the downward load.

$$*\ FOS\ F = \frac{\Sigma [\tan\varphi\,(W\cos\theta - u)] + cL}{\Sigma [W\sin\theta]} > 1$$

In the above equations 'Wcosθ' is the Normal force (N) and 'W sinθ' is tangential force (T). Hence the above equations can be written as

$$*\ FOS = \frac{\Sigma [N\tan\varphi] + CR\theta}{\Sigma T}$$

without pore water pressure

$$*\ FOS = \frac{\Sigma [(N-u)\tan\varphi] + CR\theta}{\Sigma T}$$

with pore water pressure

(3) Bishop's Method of Stability Analysis of slope (or) Bishop's Simplified Method of Slices

12

Consider a single slice for analysis and the forces on the slices are,

- W – the weight of slice
- N – Normal force on failure surface 'cd'
- U – pore water pressure on the failure surface 'cd'
- F_R – shear resistance acting on 'cd'.
- E_1 & E_2 – Normal forces on the vertical sides 'ad & bc'
- T_1 & T_2 – shear forces on the vertical sides 'ad & bc'
- θ – Inclination of failure surface with horizontal

The Normal force $N = W \cos\theta$

Tangential force $T = W \sin\theta$

The unit stresses on the failure surface 'cd' having length 'l' is

Normal stress $\sigma = \frac{N}{l} \Rightarrow \frac{W\cos\theta}{l}$

The shear strength of each slice is given by

$$\tau = c'_m + (\sigma - u)\tan\varphi'_m$$

$$\Rightarrow c'_m + \left(\frac{W\cos\theta}{l} - u\right)\tan\varphi'_m$$

- c'_m – Eff. cohesion
- φ'_m – Eff angle of friction

The shearing resistance on the base of the slice is

$$\tau l = c'_m l + (W\cos\theta - ul)\tan\phi'_m$$

* Total resisting force $F_R = \Sigma\left[c'_m l + (W\cos\theta - ul)\tan\phi_m\right]$

* Total disturbing force $F_d = \Sigma\left[W\sin\theta\right]$

* Factor of safety $FOS = \frac{F_R}{F_d}$

$$FOS = \frac{\Sigma\left[c_m l + (W\cos\theta - ul)\tan\phi_m\right]}{\Sigma\left[W\sin\theta\right]}$$

For Equilibrium $\Sigma F_v = 0$

$$\Rightarrow (N - ul)\cos\theta - (W - ul\cos\theta) - T_1 + T_2 + F_R\sin\theta = 0 \rightarrow (I)$$

Factor of safety $F = \frac{F_t}{F_R}$

$$F = \frac{c_m l + (N - ul)\tan\phi_m}{F_R}$$

$$F_R = \frac{c_m l}{F} + \left(\frac{N - ul}{F}\right)\tan\phi_m \rightarrow (II)$$

Sub in (I)

$$(N - ul)\cos\theta - (W - ul\cos\theta) - T_1 + T_2 + \left[\frac{c_m l}{F} + \left(\frac{N - ul}{F}\right)\tan\phi_m\right]\sin\theta = 0$$

$$N - u = \frac{W - U\cos\theta + \Delta T - \frac{c_m l}{F}\sin\theta}{\cos\theta + \frac{\tan\phi_m \cdot \sin\theta}{F}} \rightarrow (III)$$

$\because U = ul$

$\Delta T = T_1 - T_2$

For equilibrium of the mass above the failure surface is obtained by taking moment about 'O'. 15

$$\Sigma M_O = (W \sin\theta) R - F_R \times R = 0$$

$$F_R = W \sin\theta \longrightarrow \text{IV}$$

from II & III

$$F_R = \frac{C_m l}{F} + \frac{(N-U)}{F} \tan\varphi_m$$

$$F_R = \frac{1}{F}\left[C_m l + \tan\varphi_m \left[W - U\cos\theta\right] + \Delta T\right] \frac{1}{m_\theta}$$

Sub IV

$$\text{FOS } F = \frac{\Sigma\left(C_m l + (W - u\cos\theta + \Delta T)\tan\varphi_m\right] \frac{1}{m_\theta}}{\Sigma W \sin\theta}$$

where $m_\theta = \cos\theta + \frac{\tan\varphi_m \cdot \sin\theta}{F}$

* The factor of safety value must be computed by trial and error method. If $\Sigma(T_1 - T_2)\tan\varphi_m = 0$ is assumed, then an error of 1% will occur.

(4) Friction Circle Method :-

* In the friction circle method, a trial circle representing the failure plane is drawn with 'O' as centre and radius R. A concentric circle is drawn at centre 'O' having radius 'R sinφ'. Any line tangent to inner circle must intersect the trial circle at an angle 'φ' with radius 'R'. This line tangent to inner circle shows the direction of resultant force acting on the sliding wedge. This inner circle is called as the 'Friction circle' (or) φ- circle.

* The friction circle method of slope analysis is very much useful for both graphical and mathematical solutions.

The forces acting on the sliding wedge are

W - weight of wedge of soil

P - resultant inter granular force

Cm - Mobile cohesive force along slip surface.

Similarly, the total mobilised cohesive force (C_m) can be obtained by the equation

$$C_m = C_{me}\, l_c$$

where
l_c - chord length
C_{me} - Mobile unit cohesion
C_m - Total mobile cohesion.

$$(FOS)_{cohesion} = F_c = \frac{c}{c_{m_1}}$$

$$(FOS)_{friction} = F_\varphi = \frac{\tan\varphi}{\tan\varphi_m}$$

$$(FOS)_{shear\ strength} = F_s \Rightarrow \frac{c' + \bar{\sigma}\tan\varphi'}{c_m + \bar{\sigma}\tan\varphi_m}$$

Several trial circles must be investigated in order to locate the critical circle, which is the one having the minimum value of factor of safety with respect to total shear strength.

(5) Taylor's Stability Number Method [N (or) S_n]

* Taylor (1937) suggested the idea of analysing the stability of a large number of slopes through a wide range of slope angles and angle of internal friction, and then representing the results by an abstract number known as "stability Number".

* Hence this method is known as "Taylor's stability Number method."

WKT

* Taylor's stability Number N (or) $S_n = \frac{C_m}{F_c H \gamma}$

* $(FOS)_{cohesion} \Rightarrow F_c = \frac{C_m}{N H \gamma}$

* $(FOS)_{shear\ strength} \Rightarrow F_s = \frac{\tan\varphi}{\tan\varphi_m}$.

19

Slope protection Measures (or) Improving The Stability of Slope

* Provide flatter slope - this will reduce the weight of soil wedge tending to slide.
* Provide proper drainage to reduce the seepage forces and to lower the subsurface water.
* Protect the toe of the slope to increase the resisting moment. This will protect the base failure of the slopes.
* Densification of cohesive soil by vibrofloation.
* Achieving better consolidation by surcharging electro-osmosis (or) other methods.
* Providing growting of cement (or) other chemicals in the specific zones of slopes.
* Installing sheet piles and retaining walls which provides lateral support.
* Stabilisation of soil by modifying (or) improving the soil property of the existing soil with the help of admixtures.