Subject Name: **Geotechnical Engineering-I**

Subject Code: **CE-6003**

Semester: **6^{th}**

UNIT 4

Stability of Slopes: Infinite and finite slopes. Types of slope failures, Rotational slips. Stability number. Effect of ground water. Selection of shear strength parameters in slope stability analysis. Analytical and graphical methods of stability analysis. Stability of Earth dams.

STABILITY OF SLOPES

A slope is an inclined boundary surface between air and the body of an earthwork such as highways, cut or fill, railway cut or fill, earth dams, levees and river training works. The stability of slope is one the most important one in civil engineering practice. A fairly common engineering failure of slope is slipping of an embankment or cutting. The factor leading to instability can generally be classified as

1. Those causing increased stress and
2. Those causing a reduction in strength.

Factors causing increased stress include:

a) Increased unit weight of soil by wetting
b) Added external loads (moving loads, buildings etc)
c) Steepened slopes either by excavation or by erosion
d) Shock loads

Loss of strength may occur by

a) Vibration and earthquakes
b) Increase in moisture content
) Freezing and thawing action
d) Increase in pore pressure
e) Loss of cementing pressure

Therefore a sensible design of the slope of these structures is very essential since a structural failure may lead to loss of human life and money. The common method of a slope stability analysis of natural slopes and slopes formed by cutting and filling are based on limiting equilibrium.

In this type of analysis the factor of safety with regard to the slope stability is estimated by examining the condition of equilibrium when incipient failure is assumed along a predetermined failure plane and then comparing the strength necessary to maintain equilibrium with the available strength of the soil. Stability analysis of slopes are based on the following assumptions:

1. Problems are two dimensional
2. Coulomb's theory can be used to compute shear strength and shear strength is assumed as uniform along the slip surface.
3. The flow net in case of seepage can be drawn and seepage forces evaluated.

The stability analysis could be split up into two categories:

1. The stability analysis of infinite slopes

2. The stability analysis of finite slopes.

Stability analysis of the infinite slope: The limit equilibrium method is used for the analysis of finite slopes. Slopes extending to infinity do not exists in nature. For all practical purposes any slope of great extent with soil conditions essentially same for all identical depth below the surface are known as infinite slopes.

a) Infinite slopes in dry sand: The figure 1 shows the failure conditions for an infinite slope of cohesionless soil.

The factor of safety of an infinite slope is defined as the ratio of soil strength in the required shear stress for equilibrium. The factor of safety against sliding is given by

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

Where τ_f =shear strength

= mobilized shear strength due to gravity

ϕ = angle of internal friction

i = inclined angle of slope.

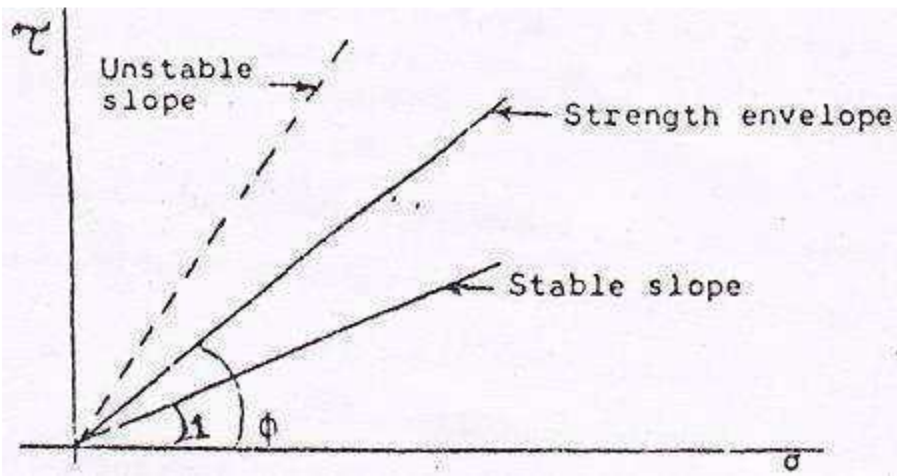

Fig.1- Failure condition for an infinite slope of cohesionless soil

b) Infinite slope in $c-\phi$ soils: In $c-\phi$ soil, the slope is stable as long as the slope angle i is equal to or less than the angle of internal friction ϕ. If the slope angle i, is greater than ϕ, the slope can be stable only upto limited height known as critical height is given by

$$H_c = \frac{C}{\gamma(\tan i - \tan\phi)\cos^2 i}$$

Where C= cohesion

γ = unit weight

ϕ = angle of internal friction

i = slope angle

H_c = critical height

= critical height

If the factor of safety Fc is applied in cohesion, the mobilized cohesion at depth H, given by

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

Then the depth H calculated by using mobilized cohesion Cm will not be critical. the factor of safety against height also represents the factor of safety with respect to cohesion Fc.

Fc is given by

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

A dimensionless parameter called a stability number is often useful for the analysis of slopes of $c - \phi$ soils and can be defined by the following equation

$$S_n = \frac{C_m}{\gamma H} = \frac{C}{F_c \gamma H} = \cos^2 i(\tan i - \tan \phi)$$

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Where Sn= stability number (a dimensionless quantity)

The reciprocal of stability number is known as stability factor.

Fig.2 shows the failure condition of an infinite slope of cohesive soil.

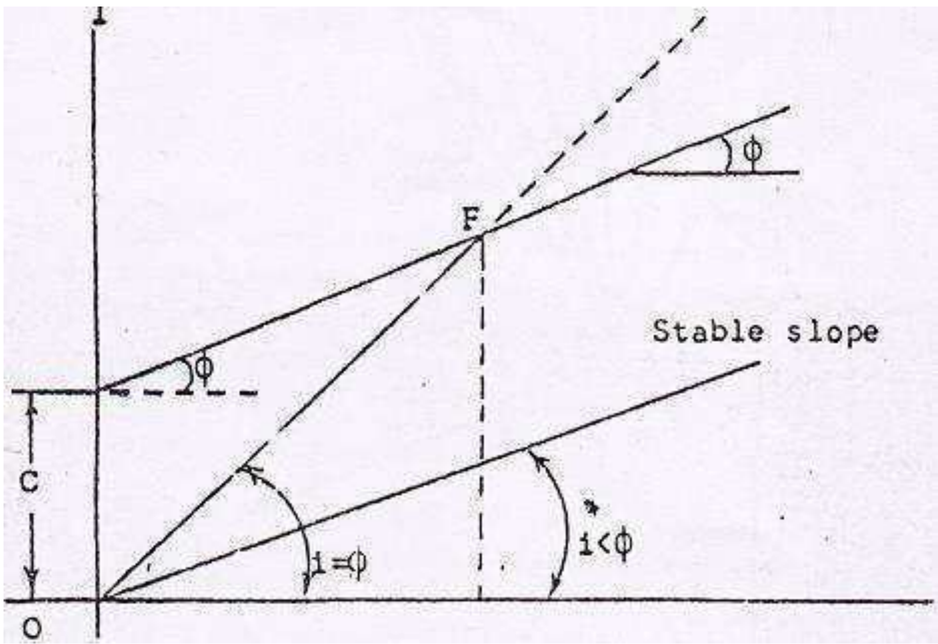
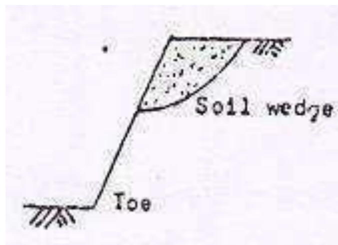


Fig. 2 – Failure condition of an infinite slope of cohesive soil

Stability analysis of finite slopes: Failure of finite slopes occurs along a curved surface. In stability analysis of finite slopes, the real surface of rupture is replaced by an arc of a circle. As to the mode of failure, the slope may fail basically in the following two ways:

a) The failure surface passing through the toe of the slope or above the toe of slope is known as slope failure.

b) The rupture is deep seated and passes through the embankment supporting soil below the toe of the slope is known as base failure.



a) Slope failure above toe (or face failure)

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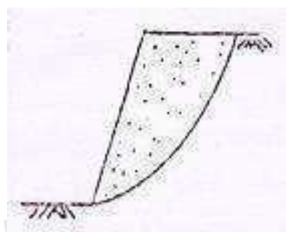
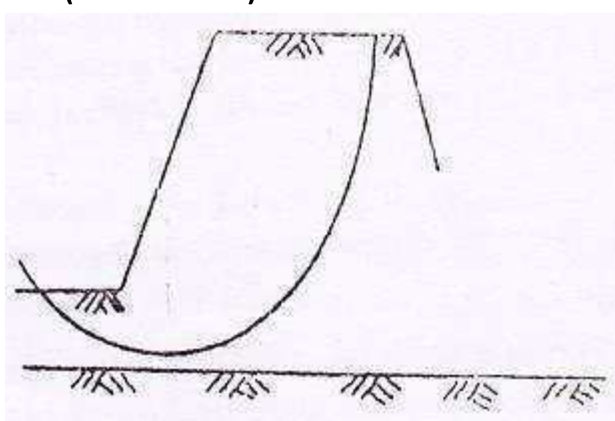


b) Slope failure through toe (or toe failure)



c) Base failure

The base failure generally occurs particularly when the soil beneath the embankment is softer and more plastic than the slope forming soil itself. There are several methods available for the stability analysis but the following methods are simple and widely practiced.

1. Slip circle method (Swedish circle method)

2. Friction circle method

Swedish circle method or method of slices: The method assumes the surface of sliding is an arc of a circle. This was established by studying the failure or embankments in Sweden. (fig.4)

Analysis of the purely cohesive soils (ϕ_u = 0 analysis)

Consider a likely circular slip surface AD (fig.4) with centre at O.

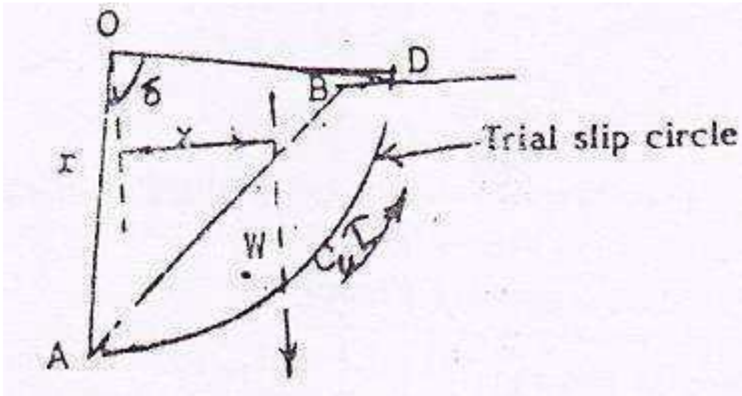


Fig: 4- Slip circle: Cohesive soil

The disturbing moment of the cylinder of the soil about O= Wx

Where 'x' is the distance of the line of action of W from the vertical line passing through the center of rotation.

If Cu is the unit cohesion, L= length of the slip arc,

$$AD = \frac{2\pi\gamma\delta}{360}$$

The shear resistance developed along the slip surface will be equal to Cu.L.

The resisting moment preventing the soil from moving is all due to friction along arc length AD which has a lever arm equal to radius r about O.

Resisting moment = cohesion x arc length AD x r = CuL.r

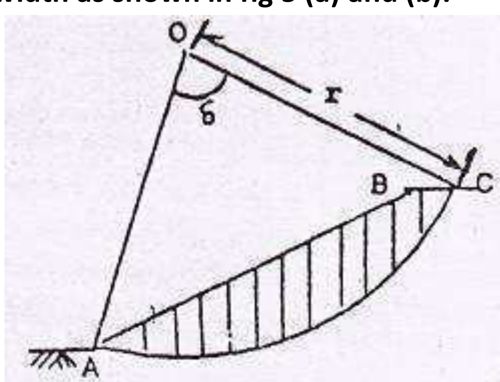
Factor of safety against sliding = (Resisting moment / Disturbing moment)

$$= \frac{C_u L r}{W x}$$

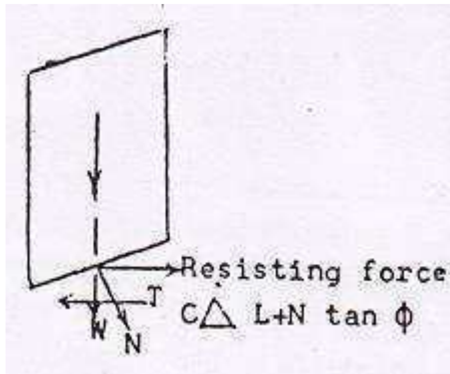
A series of slip circles are checked, and the lowest factor of safety is the likely failure plane.

$c - \phi$ Soil ($c - \phi$ Analysis)

In order to study stability of the slope of a $c - \phi$ soil, a possible slip circle is chosen and divided into strips of equal width as shown in fig 5 (a) and (b).



a) Slip circle: Friction soil



b) One strip

Fig.5

Consider one strip as shown in figure 5(b). The forces between the slices are neglected. Vertical weight W can be considered in two components (1) at right angles to arc of circle (normal component) and (2) tangential to arc of circle (tangential component).

Disturbing moment about centre O = T x r

Total driving moment = $r \sum T$

Where $\sum T$= algebraic sum of all tangential components

The resisting force on one strip is made up of cohesion and friction and is given by:

Resisting force= $C \Delta L + N \tan \phi$

Resisting moment on one strip= $C \Delta L + N \tan \phi$

Total resisting moment = $[C \sum \Delta L + \tan \phi \sum N]r$

$[CI + \tan \phi \sum N]r$

Where $\sum N$= sum of all normal components, L= arc length

Factor of safety

$$= \frac{CI + \tan \phi \sum N}{\sum T}$$

Friction circle method (Fig 3.6 (a) and (b)): The friction circle method of stability analysis of slope is applicable to $c - \phi$ soils. The friction circle method also assumes the failure surface as the arc of a circle.

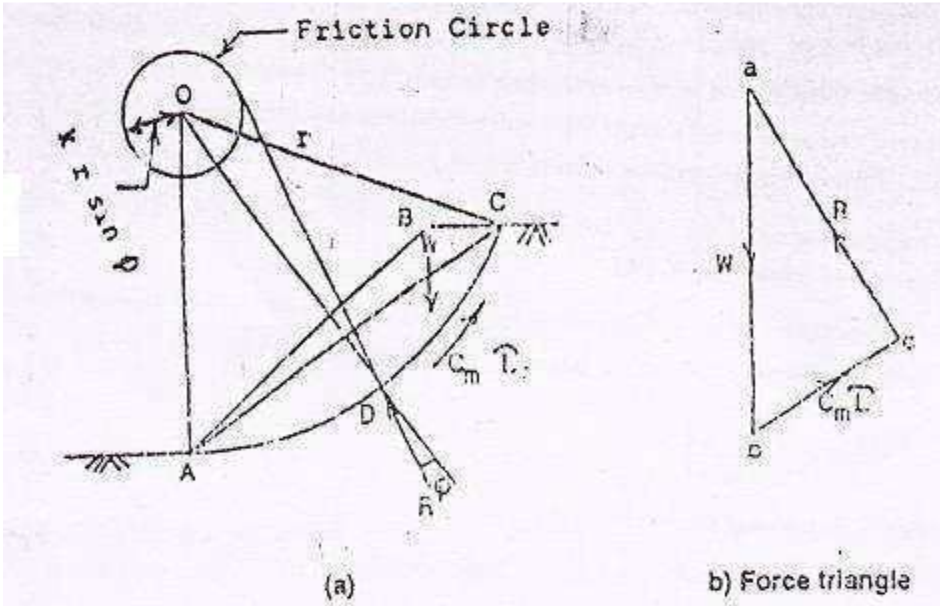


Fig: 6- Friction circle method

Fig.6 shows a failure arc of radius r with O as the centre. In the friction circle method of analysis of $c-\phi$ soil, the resultant reaction vector R at an obliquity of ϕ to an element of he failure arc will be tangential to the small circle of radius kr.sinϕ. The small circle of radius kr.sin is therefore called the friction circle.

In the ϕ circle system with a known ϕ, the following quantities are known.

i. The magnitude and direction of weight of sliding wedge (W)

ii. Direction of resultant reaction (R)

iii. The direction of total cohesion CI (parallel to the chord, I = AC)

To determine the magnitude of R and cohesion Cm, force triangle is constructed in which magnitude of W is known. The factor of safety with respect to cohesion based on the assumption that frictional strength has been fully mobilized, is given by

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

A number of slip circles are analysed and the lowest factor of safety is the likely failure plane.

Stability of the slopes of earth dam: Earth dams must be safe against slope and foundation failure for all operating conditions. There are three generally recognised critical stages based on pore pressure fir which the stability of the embankment should be ascertained. These three situations are (i) end of construction, (ii) steady-state seepage and (iii) rapid drawdown. Usually construction pore pressure reaches their maximum values when the embankment reaches maximum height. After the reservoir has been filled for a long time, pore pressure are determined by steady state seepage conditions and my be estimated by the construction

of flow net. Rapid lowering of the reservoir produces the third critical situation, particularly for low permeable soils.

The upstream slope stability can be critical for the construction of rapid drawdown condition.

The downstream slope should be checked for the construction and steady state seepage condition.

