# MODULE 5

## Section I

## Slope Stability Analysis & Design

# Slope Stability Analysis and Design

**Slope stability analysis** is performed to assess the safe design of a human-made or natural slopes (e.g. embankments, road cuts, open-pit mining, excavations, landfills etc.) and the equilibrium conditions.

The main objectives of slope stability analysis are finding endangered areas, investigation of potential failure mechanisms, determination of the slope sensitivity to different triggering mechanisms, designing of optimal slopes with regard to safety, reliability and economics, designing possible remedial measures, e.g. barriers and stabilization.

# FACTORS AFFECTING SLOPE STABILITY

1- Soil Type

2- Geometry of the cross section (Height, slope angle, etc.)

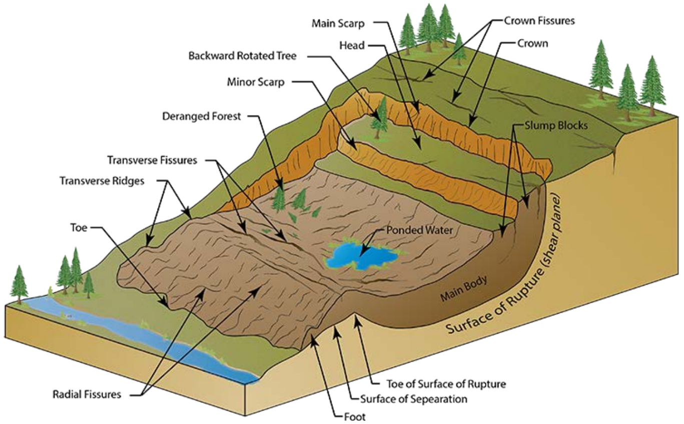
3- Moisture Content

4- Pore water pressure

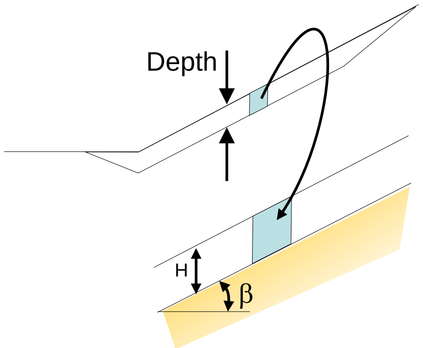
5- Additional loads

6- Shear Strength reduction

7- Vibrations and Earthquake

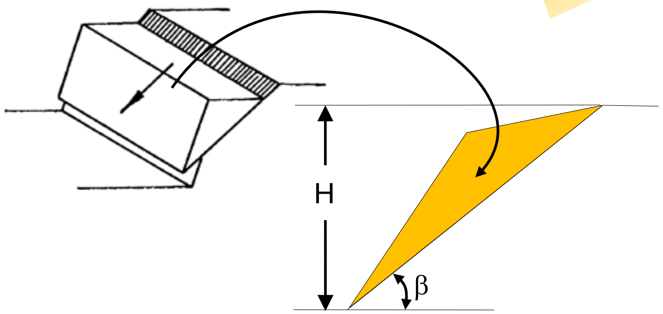


# To Analyze and Design Slopes:



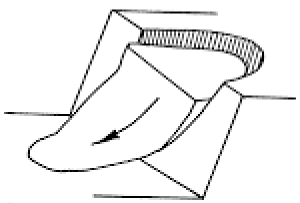

## 1- Planar Failures (Determinate Problems)

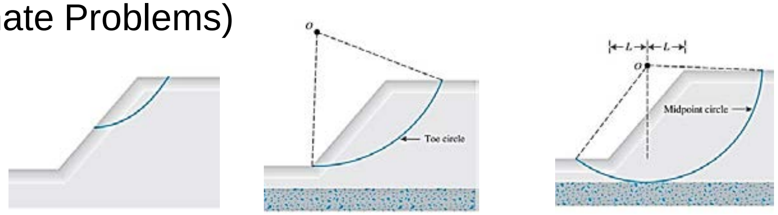
- Infinite Failures Small depth, Long failure surface
- Finite Slope Failures Simple wedge



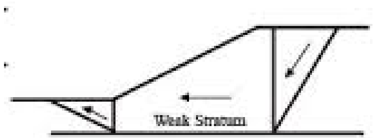

## 2- Circular Failures (Determinate & Indeterminate Problems)

- *Above Toe*
- *Through Toe*
- *Deep seated*






## 3- Wedge Failures Multiple Planer Failure




## 4- Complex Failures Combination of Planar & Circular

# 1. Planar Failures

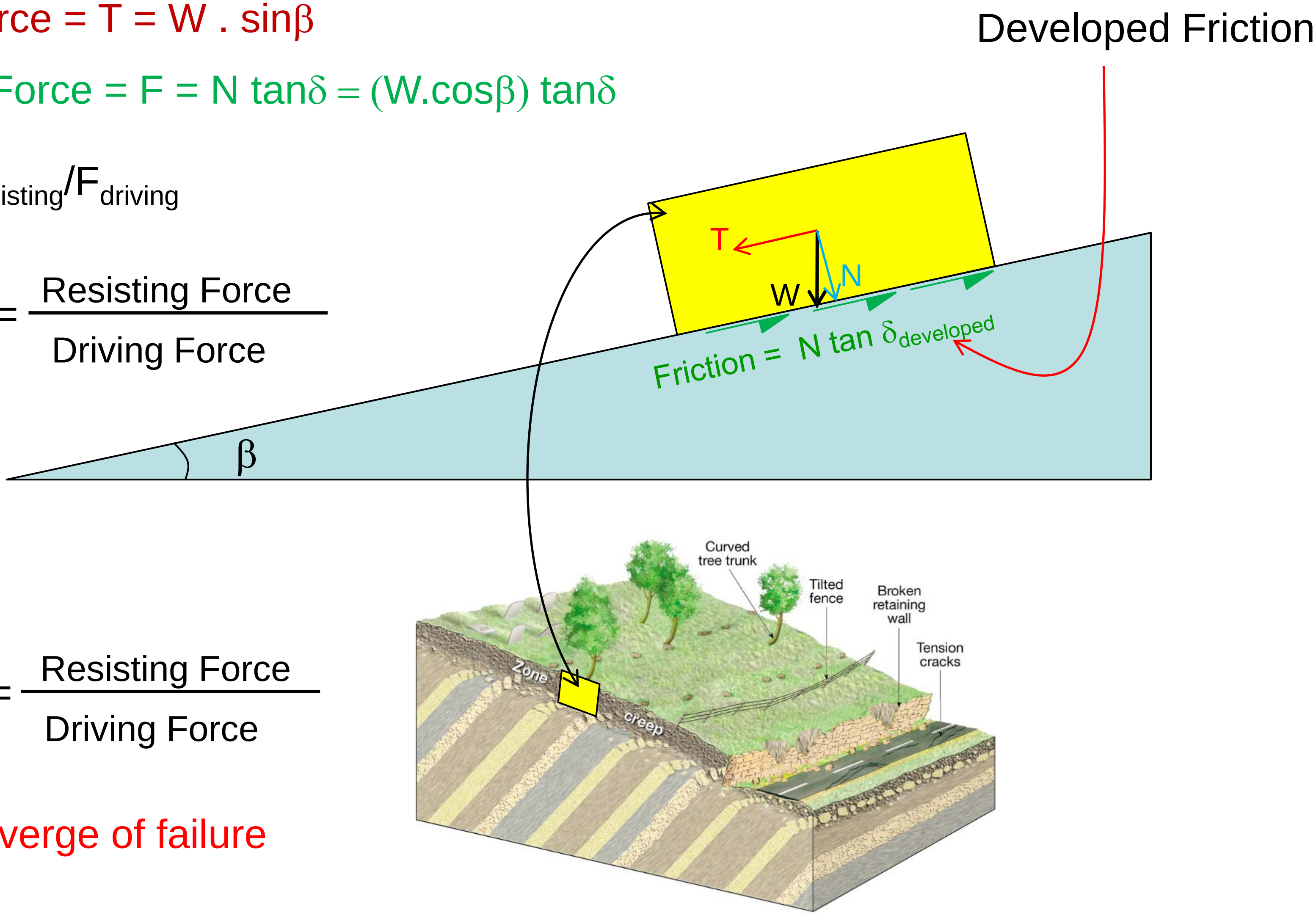
## The Concept of Developed Friction

Driving Force = T = W . sin$\beta$

Resisting Force = F = N tan$\delta$ = (W.cos$\beta$) tan$\delta$

F.S. = $F_{resisting}/F_{driving}$

$$F.S. = 2.5 = \frac{\text{Resisting Force}}{\text{Driving Force}}$$




$$F.S. = 1 = \frac{\text{Resisting Force}}{\text{Driving Force}}$$

On the verge of failure

## FACTOR OF SAFETY

1- For Shear Strength

$$\tau_{developed} = \tau / F.S.$$

$$\tau_{developed} = (c + \sigma \tan\phi) / F.S.$$

2- For Shear Parameters

$$c_d = c / F.S.$$

$$\tan\phi_d = \tan\phi / F.S.$$

Developed cohesion or Mobilized cohesion

Developed angle of friction

3- For Height of the Slope

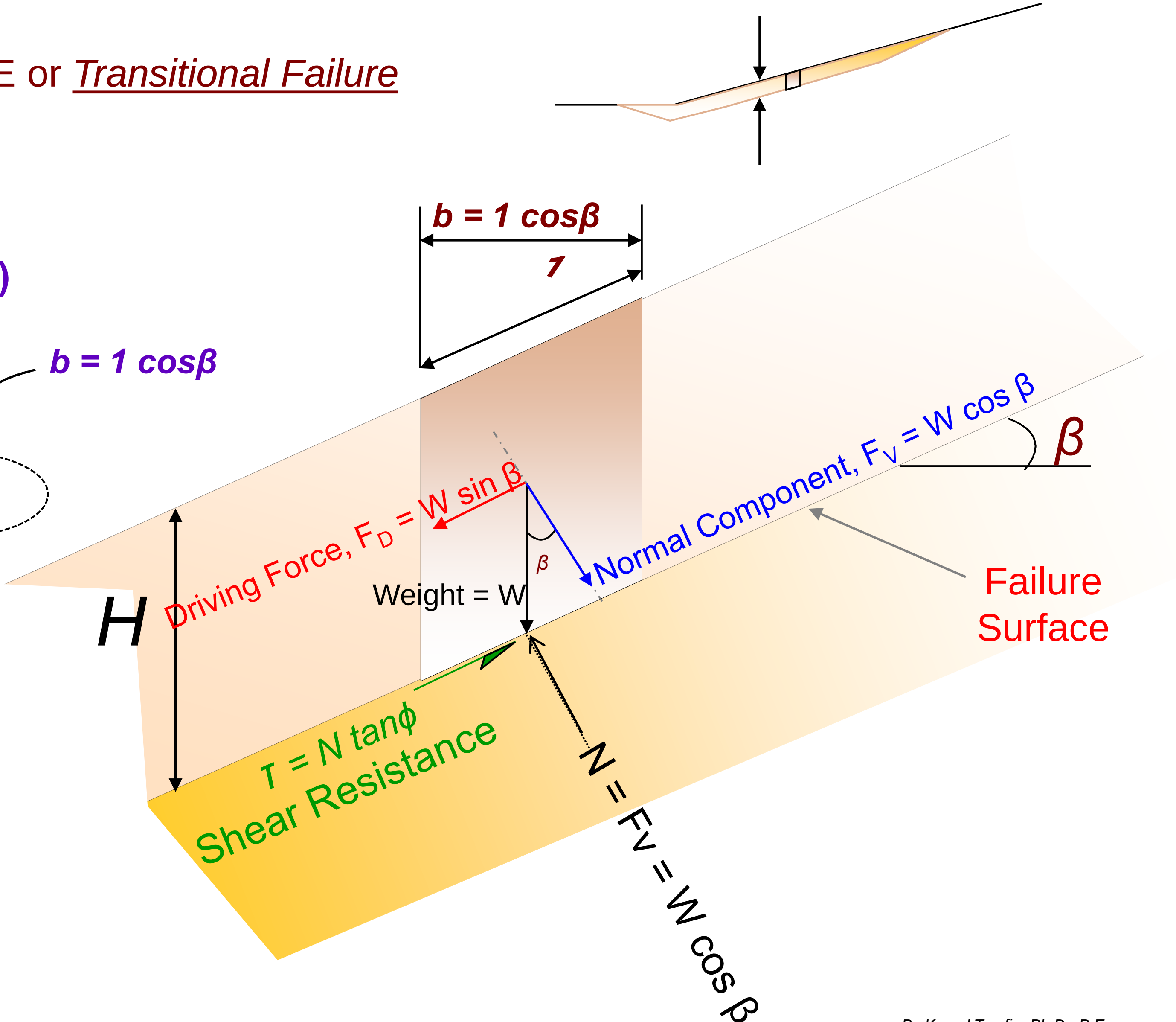
$$H_{design} = H_c / F.S.$$

# INFINITE SLOPE

## I. PLANAR FAILURE or *Transitional Failure*

### A- Dry Soil ($\phi$ soil)

$$W = \gamma\, H \cos\beta$$

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# A- Dry Soil ($\phi$ soil)

$$W = \gamma\, H \cos\beta$$ ← $b = 1 \cos\beta$

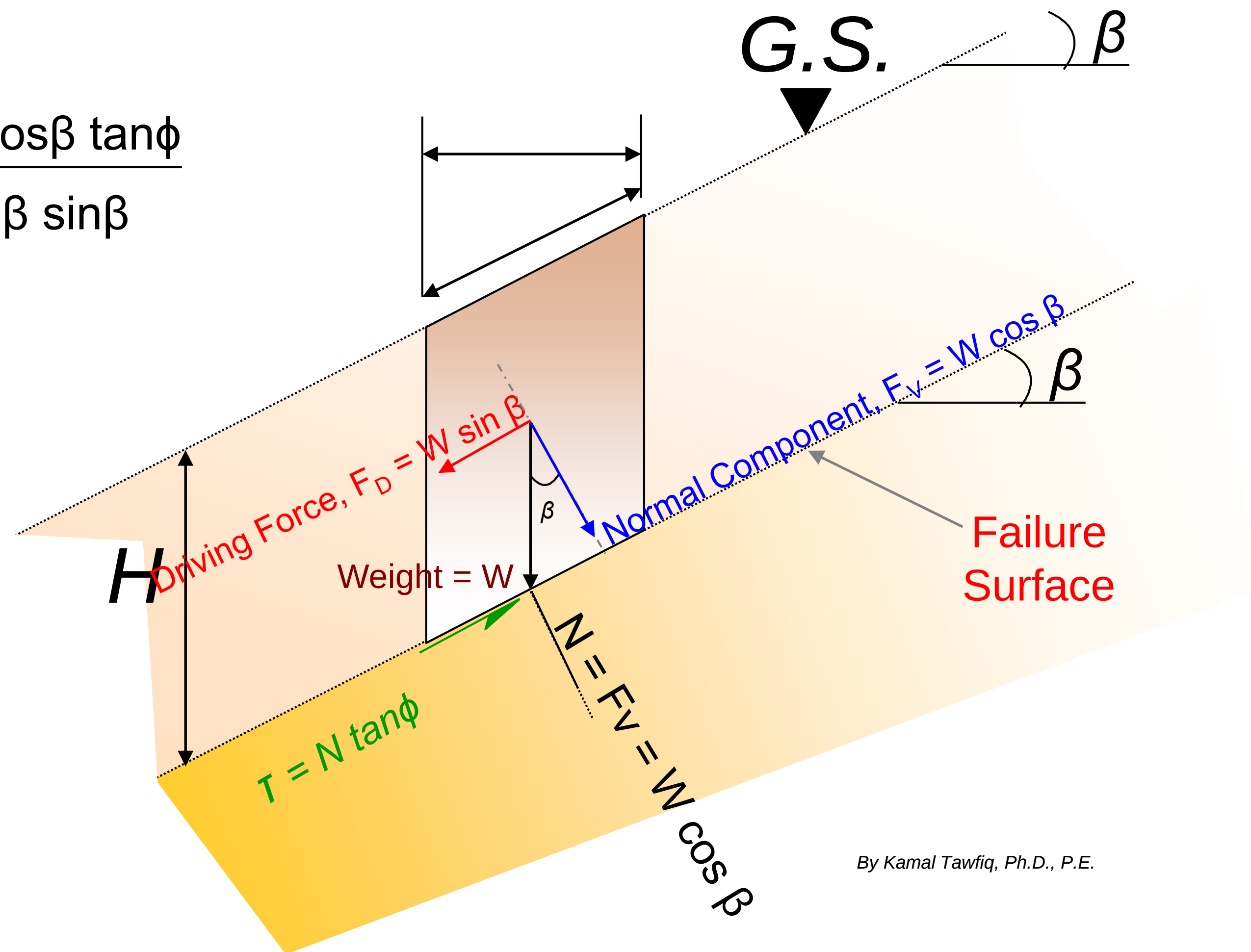
Driving Force = $F_D = \gamma\, H \cos\beta \sin\beta$

Resisting Force = $F_R = \gamma\, H \cos\beta \cos\beta \tan\phi$

$FS = F_R/F_D$

$$FS = \frac{\gamma\, H \cos\beta \cos\beta \tan\phi}{\gamma\, H \cos\beta \sin\beta}$$

$$FS = \frac{\tan\phi}{\tan\beta}$$

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# <u>B- Submerged Soil</u> (ϕ soil)

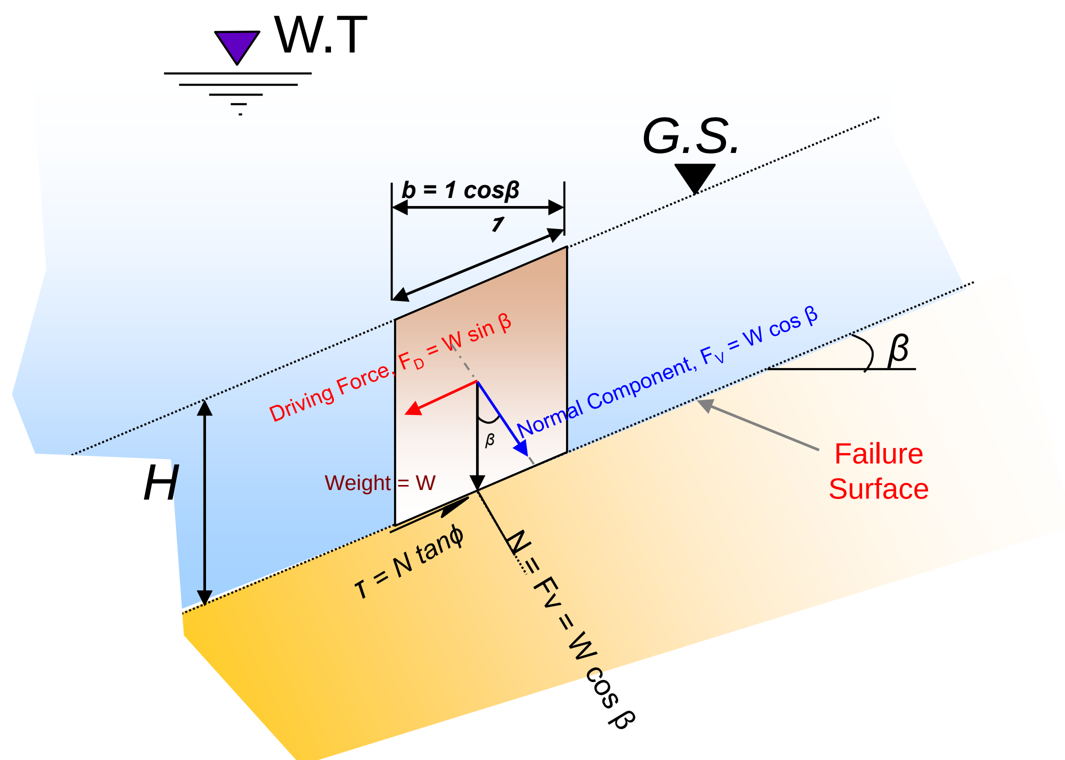
$$W = \gamma\, H \cos\beta$$

Driving Force = $F_D = \gamma\ H\ c\bar{o}s\ \beta\ \sin\beta$
Resisting Force = $F_R = \gamma\ H\ c\bar{o}s\ \beta\ \cos\beta\ \tan\phi$

$FS = F_R / F_D$

$$FS = \frac{\bar{\gamma}\ H \cos\beta \cos\beta \tan\phi}{\bar{\gamma}\ H \cos\beta \sin\beta}$$

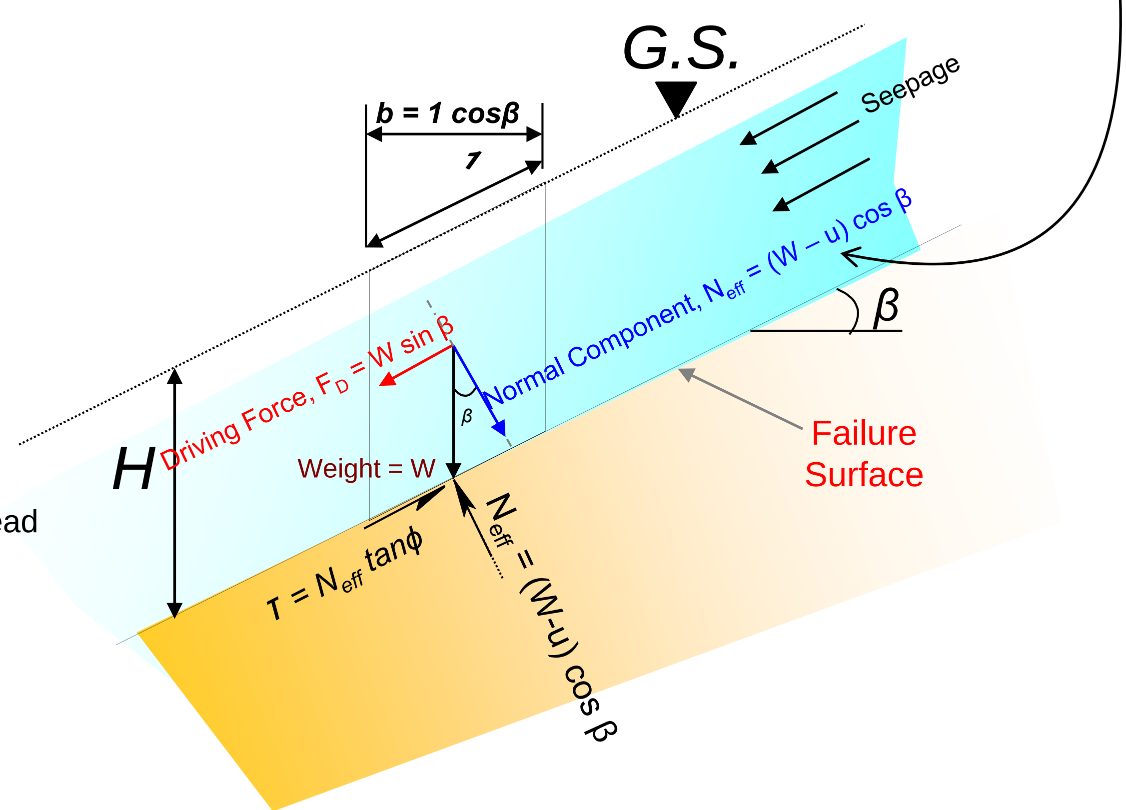
$$FS = \frac{\tan\phi}{\tan\beta}$$



# C- Seepage Parallel to Slope (φ soil)

$$FS = \frac{\tan\phi}{\tan\beta}\left(1 - \frac{\gamma_w Z}{\gamma_{soil} H \cos^2\beta}\right)$$

Pore Water Pressure (u)




Z = Pressure Head

What is Pressure Head?
What is Total Head?
What is Elevation Head?

Total Head = Elevation Head+ Pressure Head

Go to Next Page

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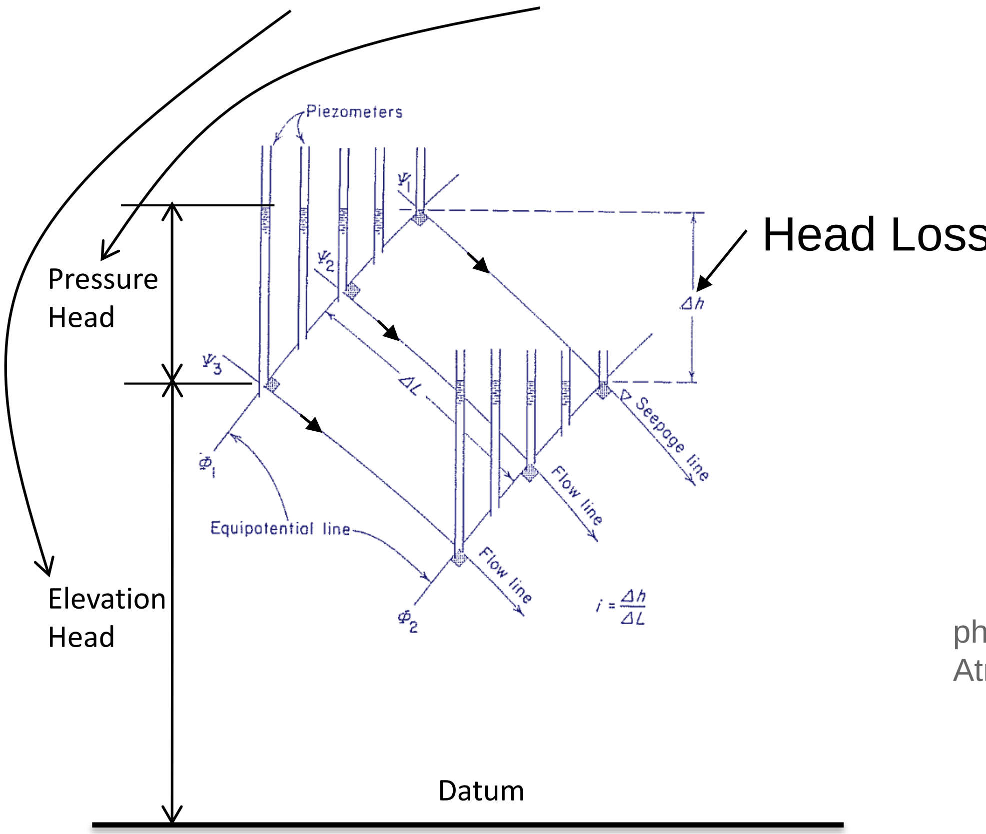
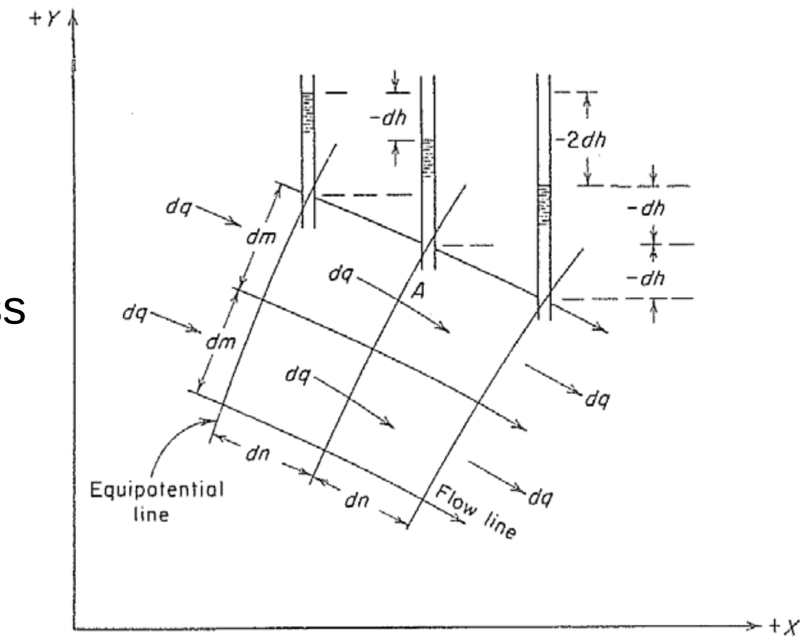
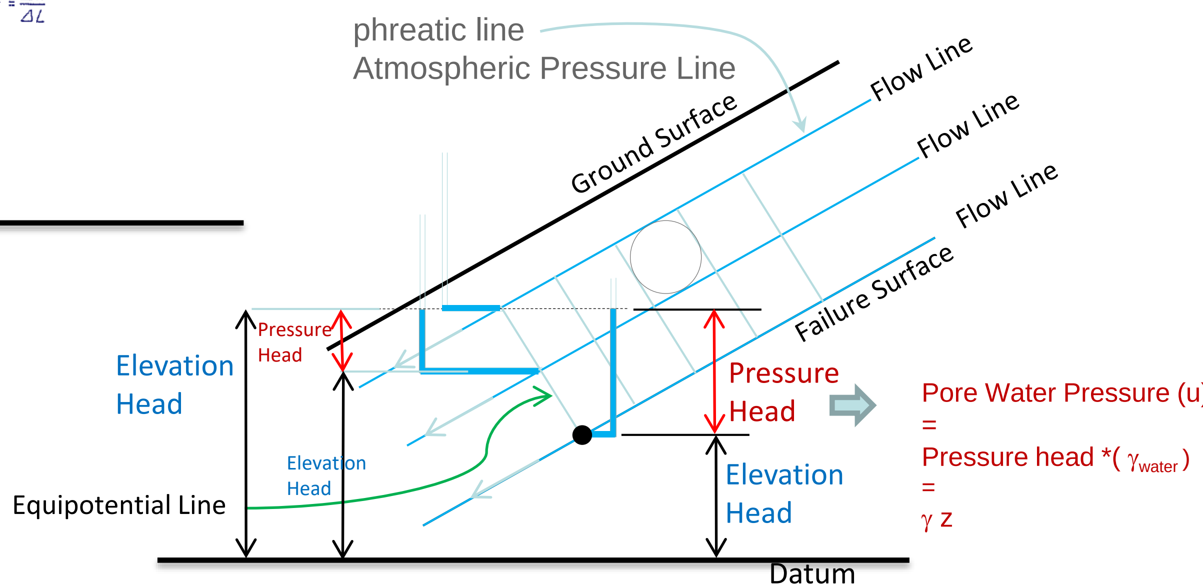
# Total Head, Elevation Head and Pressure Head

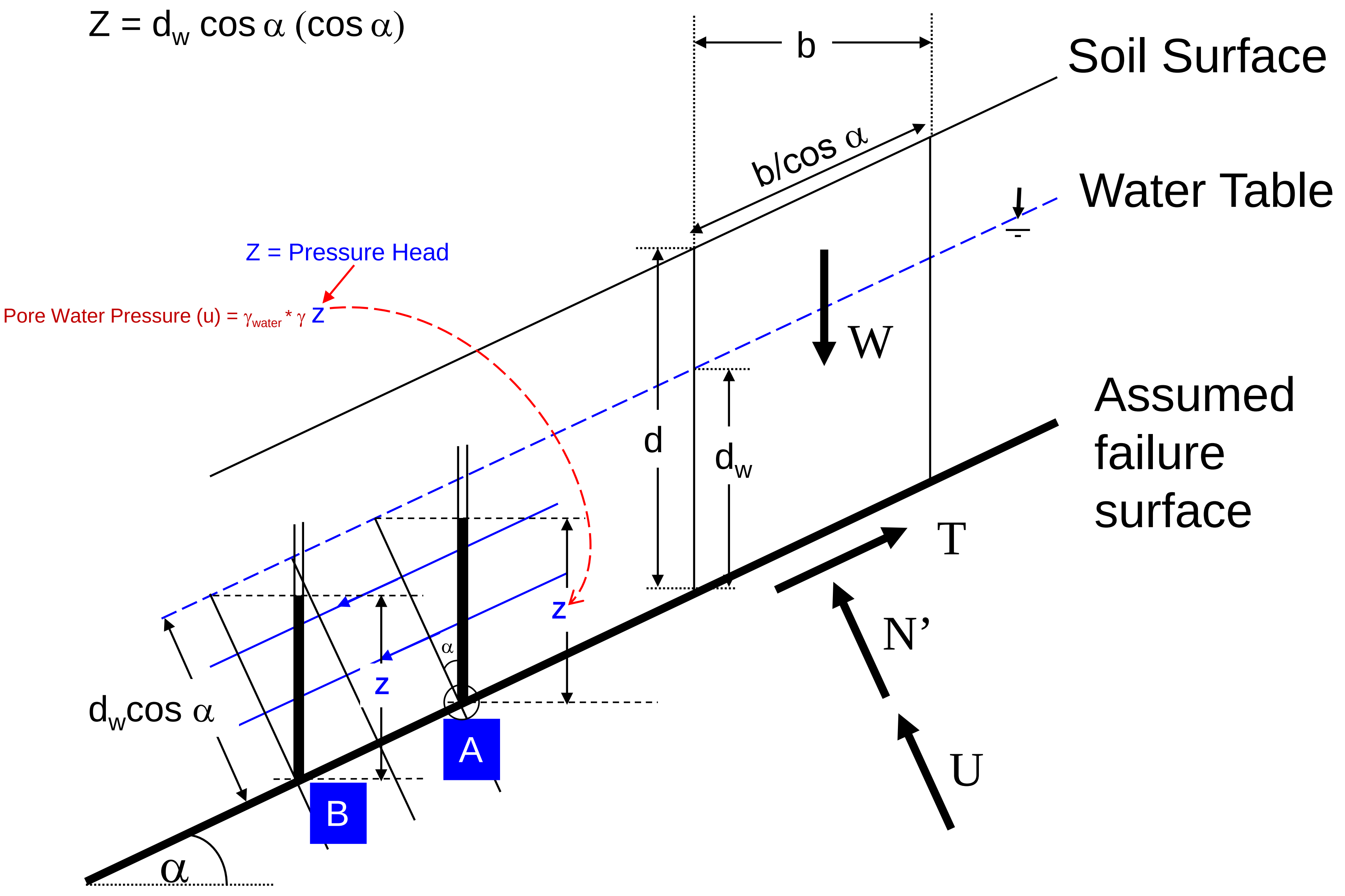
Total Head = Elevation Head+ Pressure Head



For the infinite slope shown below, what is the pore water pressure at point A ?

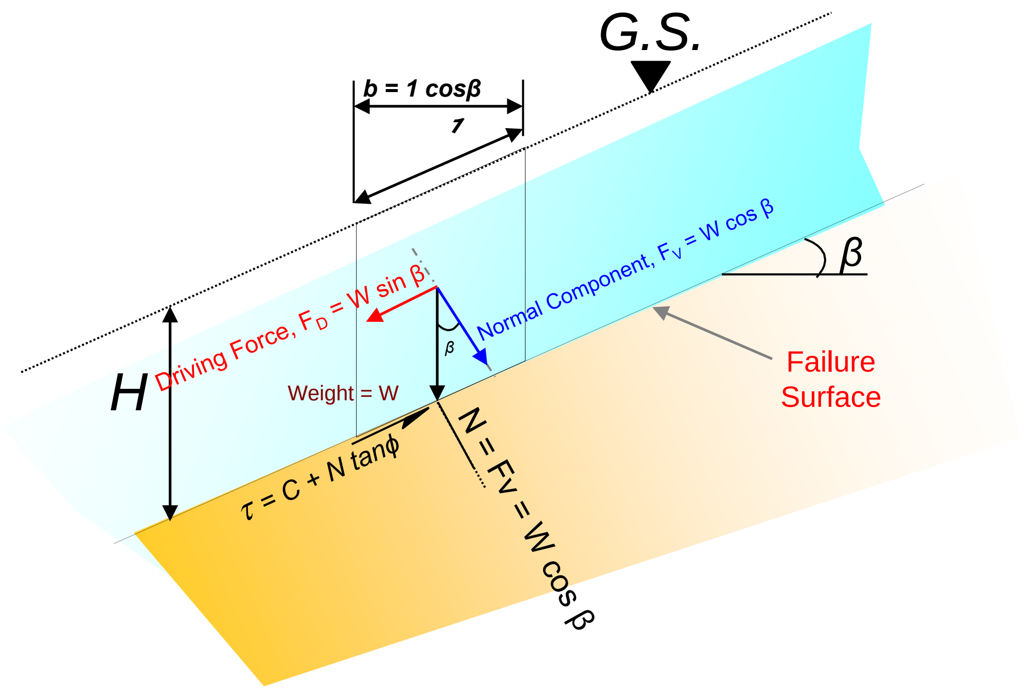


# D- Infinite Slope in c - ϕ soil *(with seepage)*

$$FS = \frac{c}{\gamma_{soil}\, H \cos\beta \sin\beta} + \left(1 - \frac{u}{\gamma_{soil}\, H \cos^2\beta}\right) \frac{\tan\phi}{\tan\beta}$$

*If no seepage*:
u = 0

*If Submerged Slope*:
u = 0 $\gamma = \gamma'$

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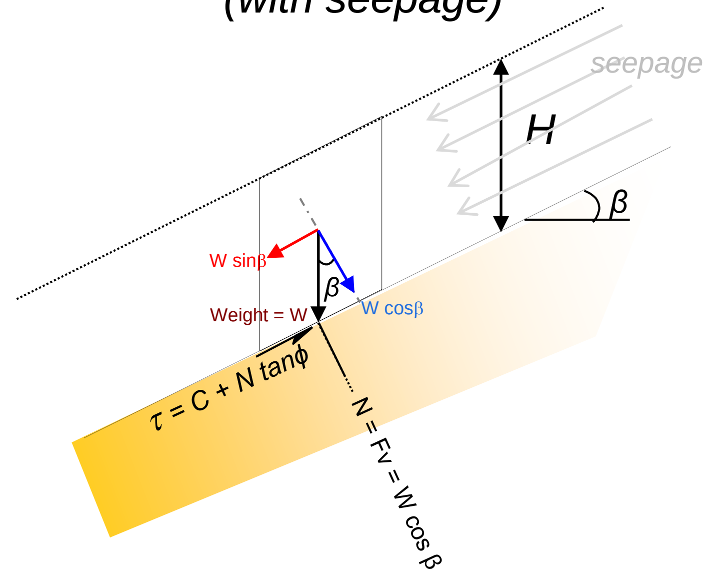
## Critical Height $H_c$ at FS = 1

*(with seepage)*




$$FS = \frac{c}{\gamma_{soil}\, H \cos\beta \sin\beta} + \left(1 - \frac{u}{\gamma_{soil}\, H \cos^2\beta}\right) \frac{\tan\phi}{\tan\beta} = 1$$

$$H_c = \frac{c - u \tan\phi}{\gamma_{soil} \cos^2\beta\, (\tan\beta - \tan\phi)}$$

## Stability Number Ns

$$Ns = \frac{c}{\gamma Hc} \qquad r_u = \frac{u}{\gamma H} = \text{pore water pressure ratio}$$

General Equation:

$$H_c = \frac{c}{\gamma_{soil}\, [\sin\beta \cos\beta - \tan\phi\, (\cos^2\beta - r_u)]}$$

Or

$$H = \frac{c_{dev}}{\gamma_{soil}\, [\sin\beta \cos\beta - \tan\phi_{dev}\, (\cos^2\beta - r_u)]}$$

$$c_{dev} = \frac{c}{FS_c}$$

$$\tan\phi_{dev} = \frac{\tan\phi}{FS_\phi}$$

$$\phi_{dev} = \tan^{-1}\left(\frac{\tan\phi}{FS_\phi}\right)$$

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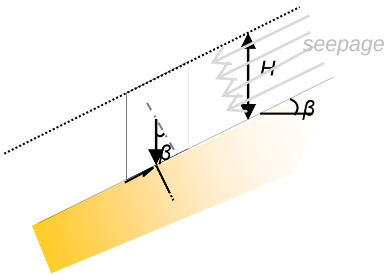
## General Equation:

$$H_c = \frac{c}{\gamma_{soil}\,[\sin\beta \cos\beta - \tan\phi\,(\cos^2\beta - r_u)]}$$



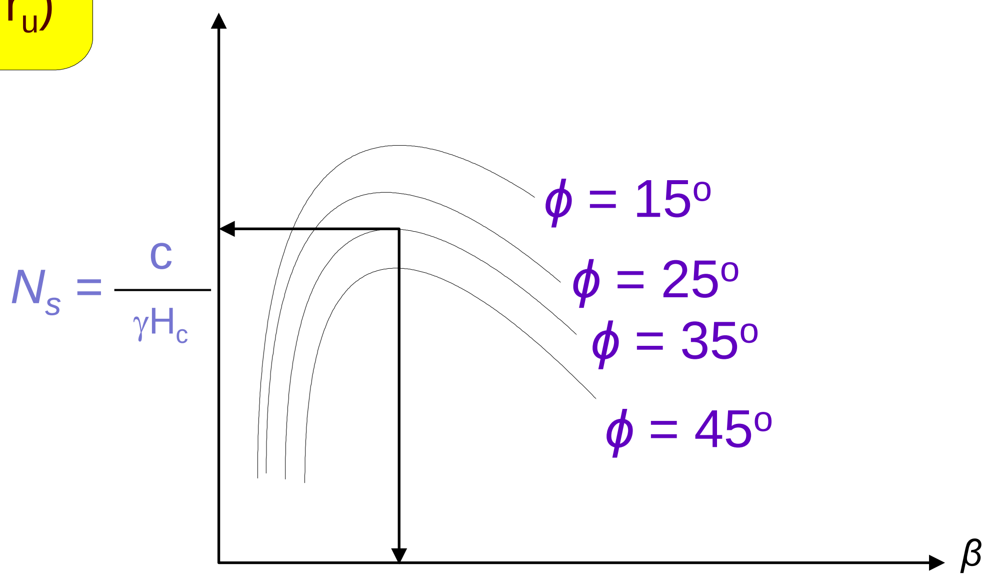

$$N_s = \frac{c}{\gamma H_c} = \sin\beta \cos\beta - \tan\phi\,(\cos^2\beta - r_u)$$

$$N_s = \frac{c_d}{\gamma H} = \sin\beta \cos\beta - \tan\phi_d\,(\cos^2\beta - r_u)$$

$$Ns = \frac{c_d}{\gamma H} = \sin\beta \cos\beta - \tan\phi_d\,(\cos^2\beta - r_u)$$

$$c_d = \frac{c}{FS_c}$$

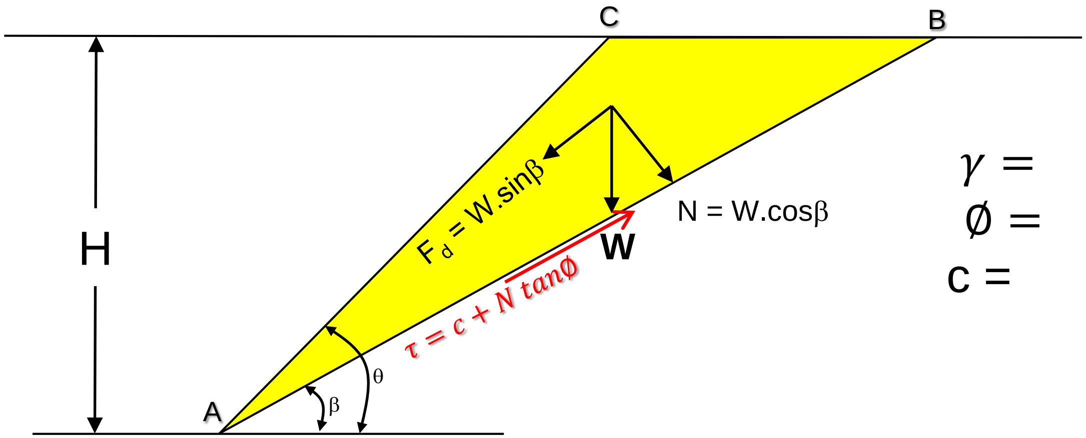
$$\tan\phi_d = \frac{\tan\phi}{FS_\phi}$$



# Planar Slope Failure

Finite Slope

$$H_{cr} = \frac{4c}{\gamma}\left[\frac{\sin\beta\ \cos\emptyset}{1-\cos(\beta - \emptyset)}\right]$$




$\gamma =$

$\emptyset =$

$c =$

$$H_{design} = \frac{4cd}{\gamma}\left[\frac{\sin\beta\ \cos\emptyset_d}{1-\cos(\beta - \emptyset_d)}\right]$$

$$c_d = \frac{\gamma H}{4}\left[\frac{1-\cos(\beta-\emptyset_d)}{\sin\beta\ \cos\emptyset_d}\right]$$

Example:

Given:

β= 30°

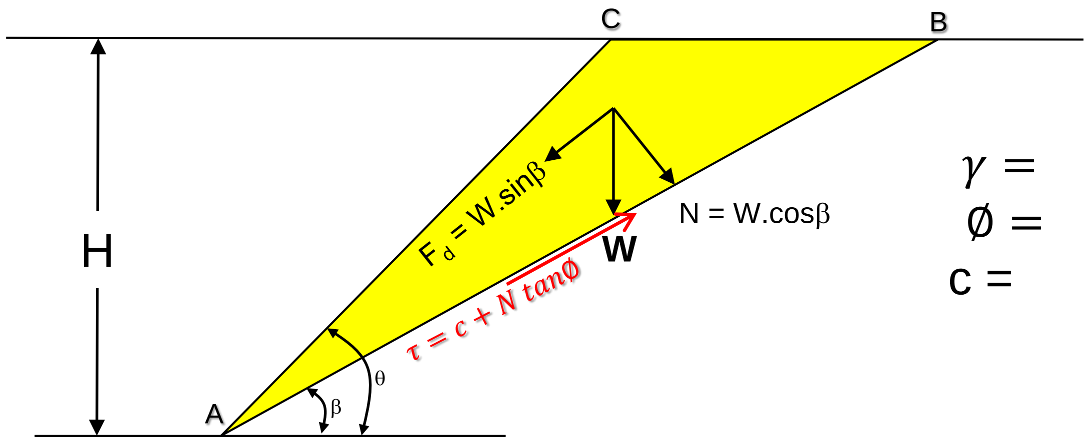
ϕ= 32°

c = 180 psf

F.S = 1.5

Find:

Safe Height




$\gamma =$

$\emptyset =$

c =

$$c_d = \frac{\gamma H}{4}\left[\frac{1 - cos(\beta - \emptyset_d)}{Sin\beta\ cos\emptyset_d}\right]$$

$$H_{cr} = \frac{4c}{\gamma}\left[\frac{sin\beta\ \cos\emptyset}{1 - cos(\beta - \emptyset)}\right]$$

# MODULE 5

## Section II

## Slope Stability Analysis & Design

# Circular Failure Surface (Cohesive Soil)

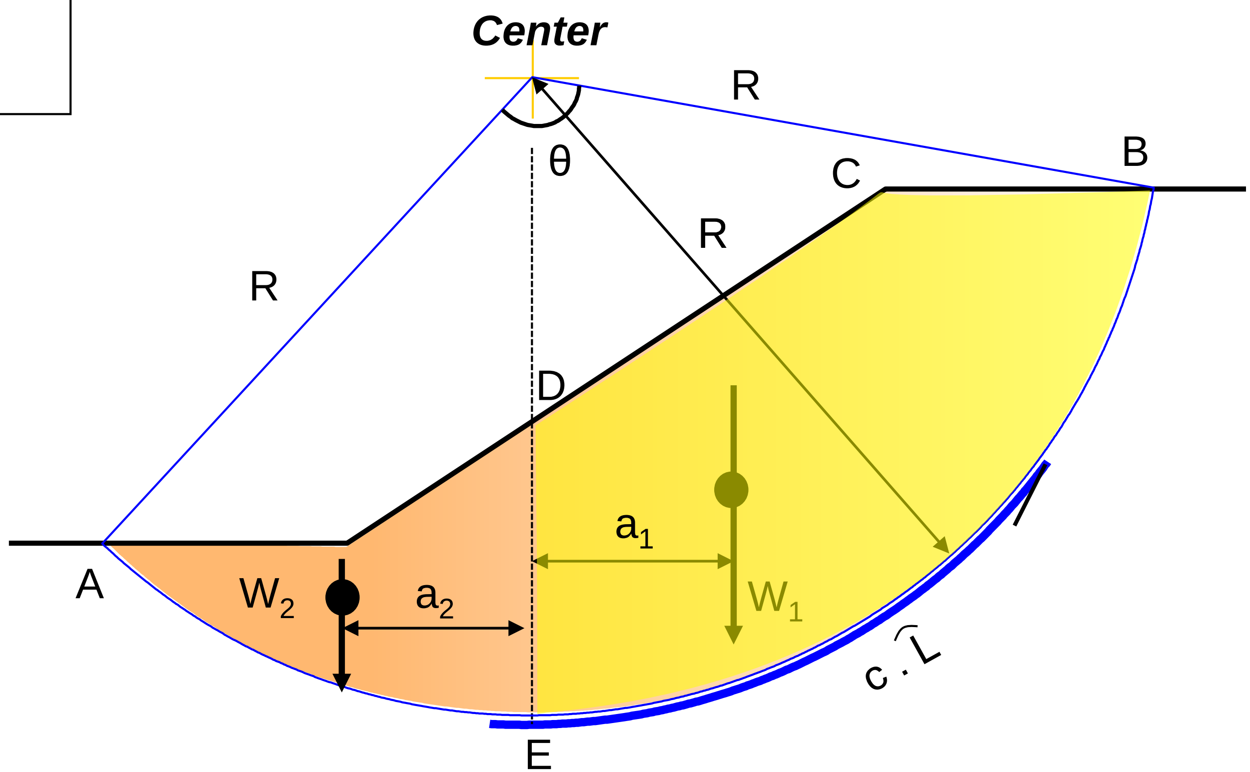
Determinate Problem

Number of Unknowns = Number of Equilibrium Equations

$$F.S. = \frac{M_{resisting}}{M_{driving}}$$

$M_{driving} = W_1 \, . \, a_1$

$W_1 = \text{Area (BCDE)} \, . \, \gamma_{soil}$




$$M_{resisting} = c \, . \, \widehat{L} + W_2 \, . \, a_2 = c \, . \, (R.\theta) \, R + W_2 \, . \, a_2$$

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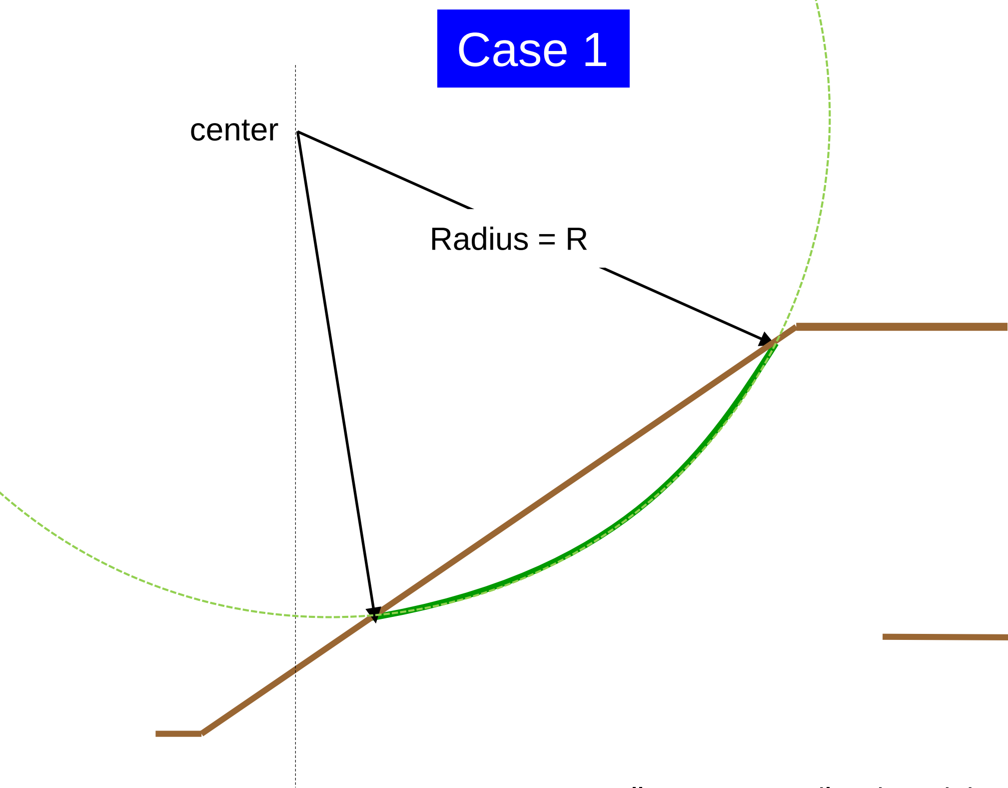
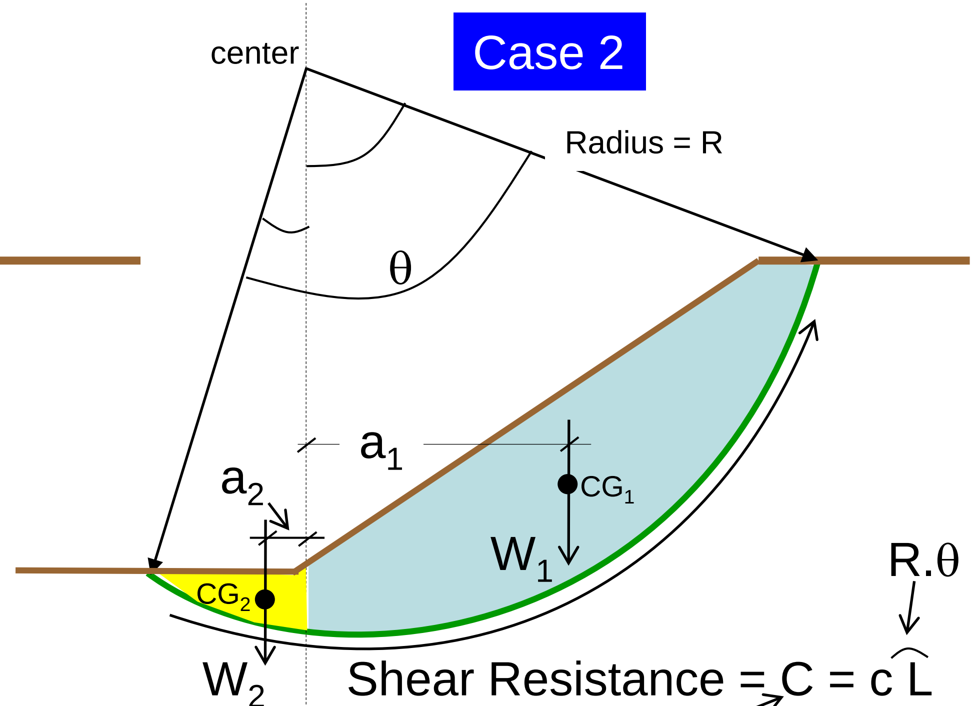
# Circular Method in Clayey Soil ($\phi = 0$)

$$\text{Factor of Safety} = \frac{\text{Resisting Moment } (M_R)}{\text{Driving Moment } (M_D)}$$




Shear Resistance = $C = c\,\widehat{L}$

Yellow Area x Soil Unit Weigh

Resisting Moment $(M_R) = W_2 \times a_2 + C \times R$

Driving Moment $(M_D) = W_1 \times a_1$

Green Area x Soil Unit Weigh

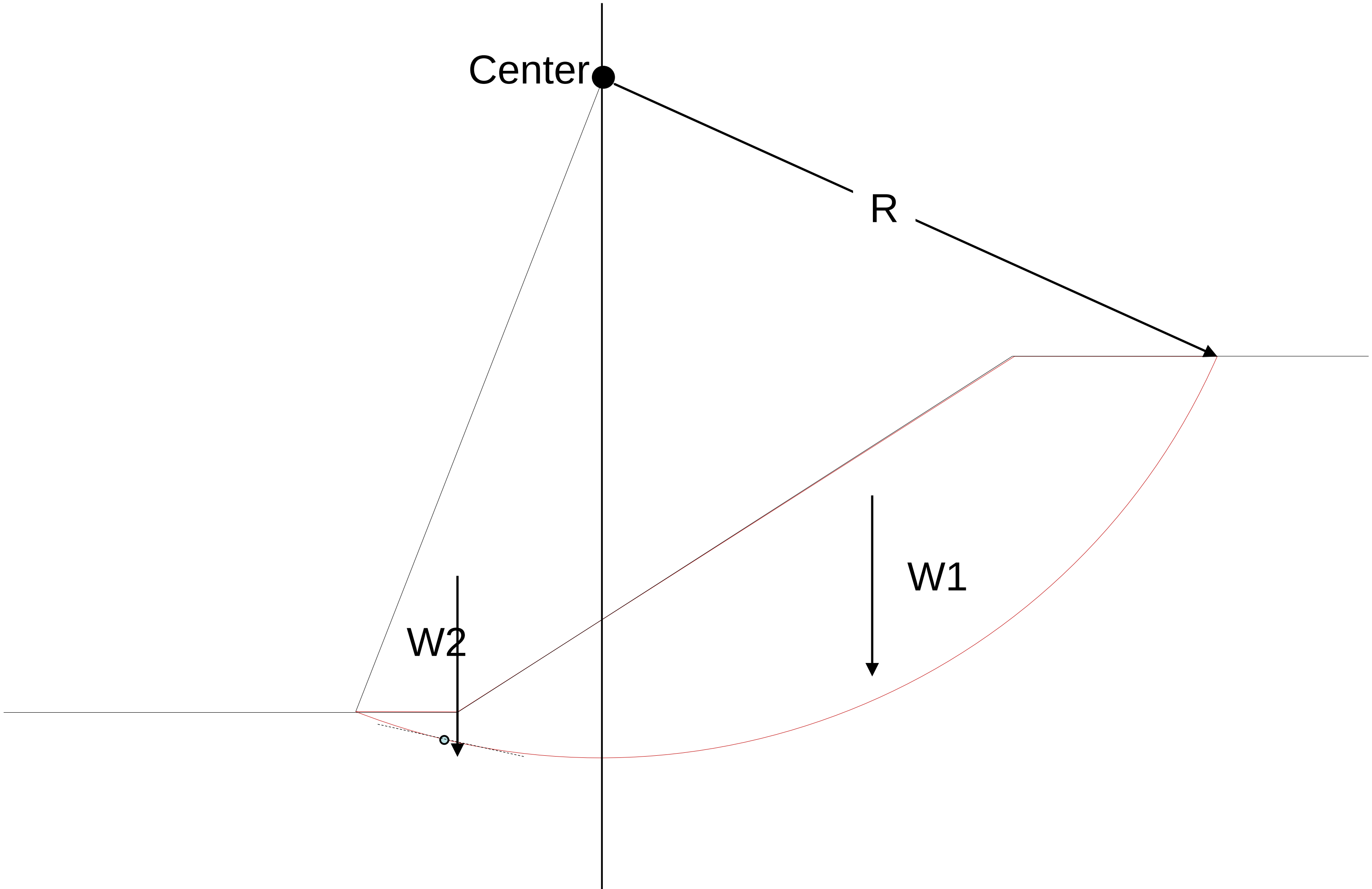
How to find $W_1$, $W_2$, $CG_1$ and $CG_2$ ?

Refer to your Eng. Mechanics course

# Circuler Failure Surface in C - ϕ Soil

Indeterminate Problem
Number of Unknowns ≠ Number of Equilibrium Equations

*W varies from point to point. Therefore, N & F will vary from point to point*

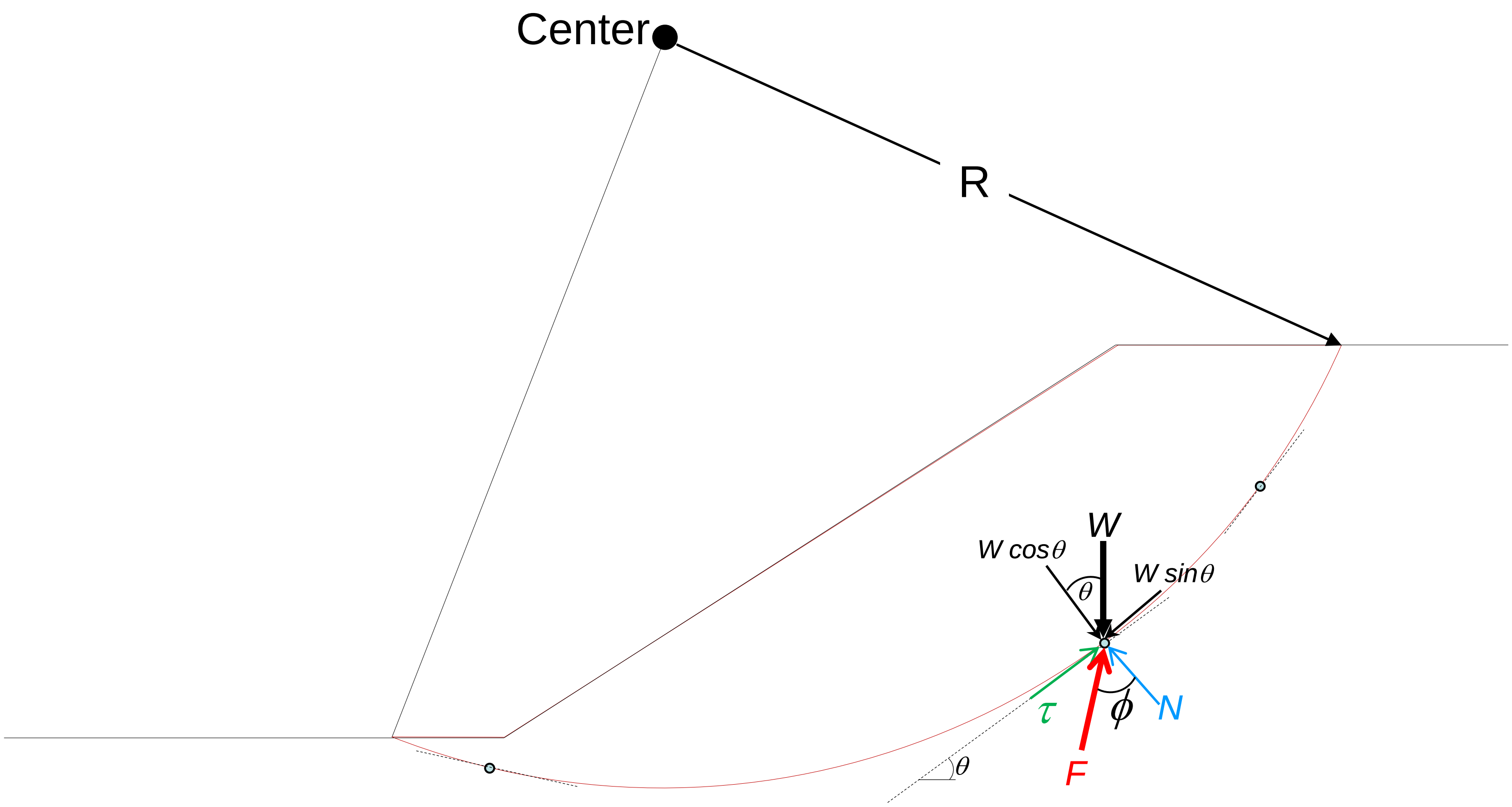


# Circuler Failure Surface in C - ϕ Soil

Indeterminate Problem

Number of Unknowns ≠ Number of Equilibrium Equations

*W varies from point to point. Therefore, N & F will vary from point to point*



# Stability Number

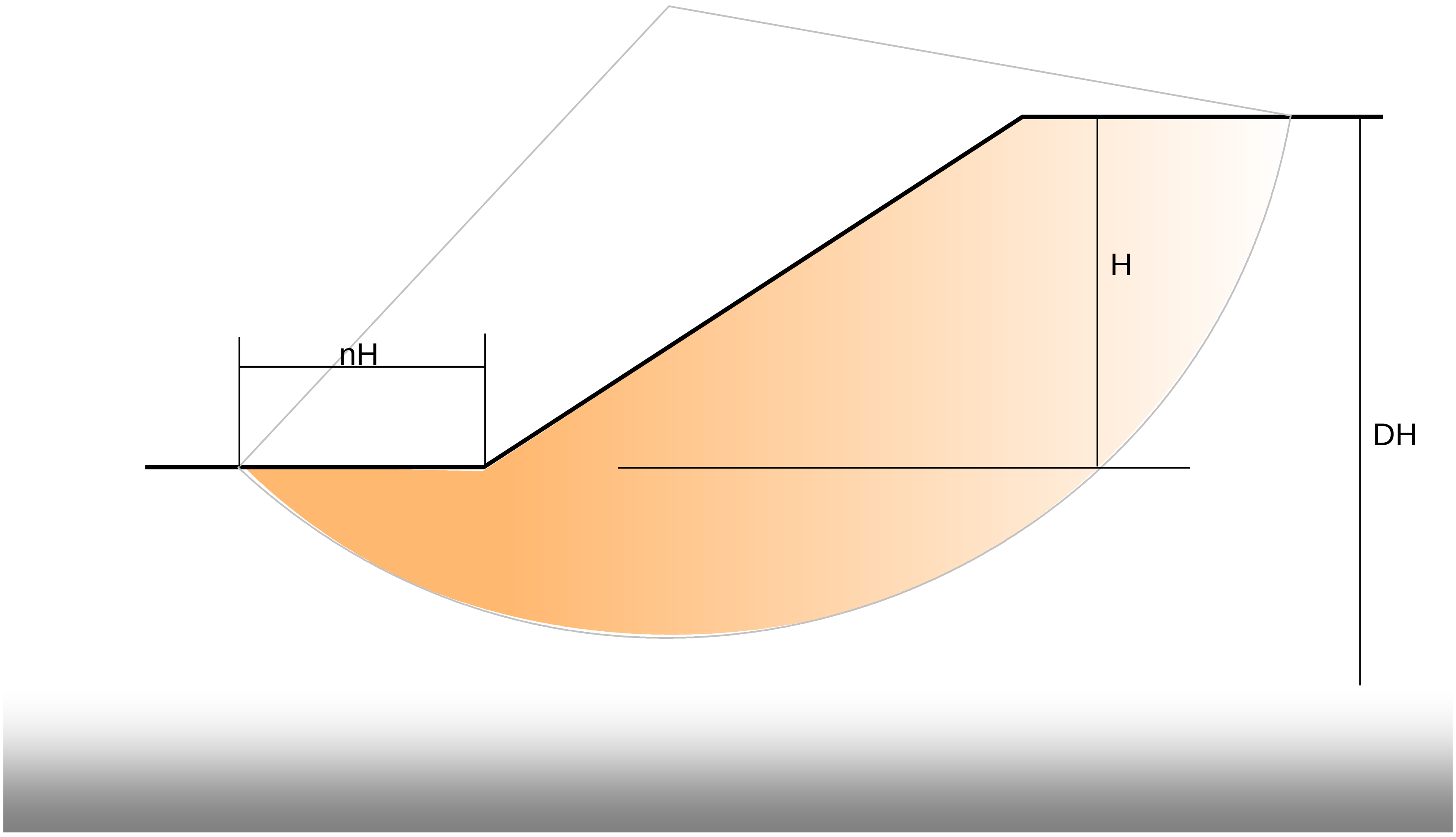
- A variety of charted solutions exist for the simple geometry considered above.

- For the undrained (total stress) analysis of slopes charts produced by Taylor are often used.

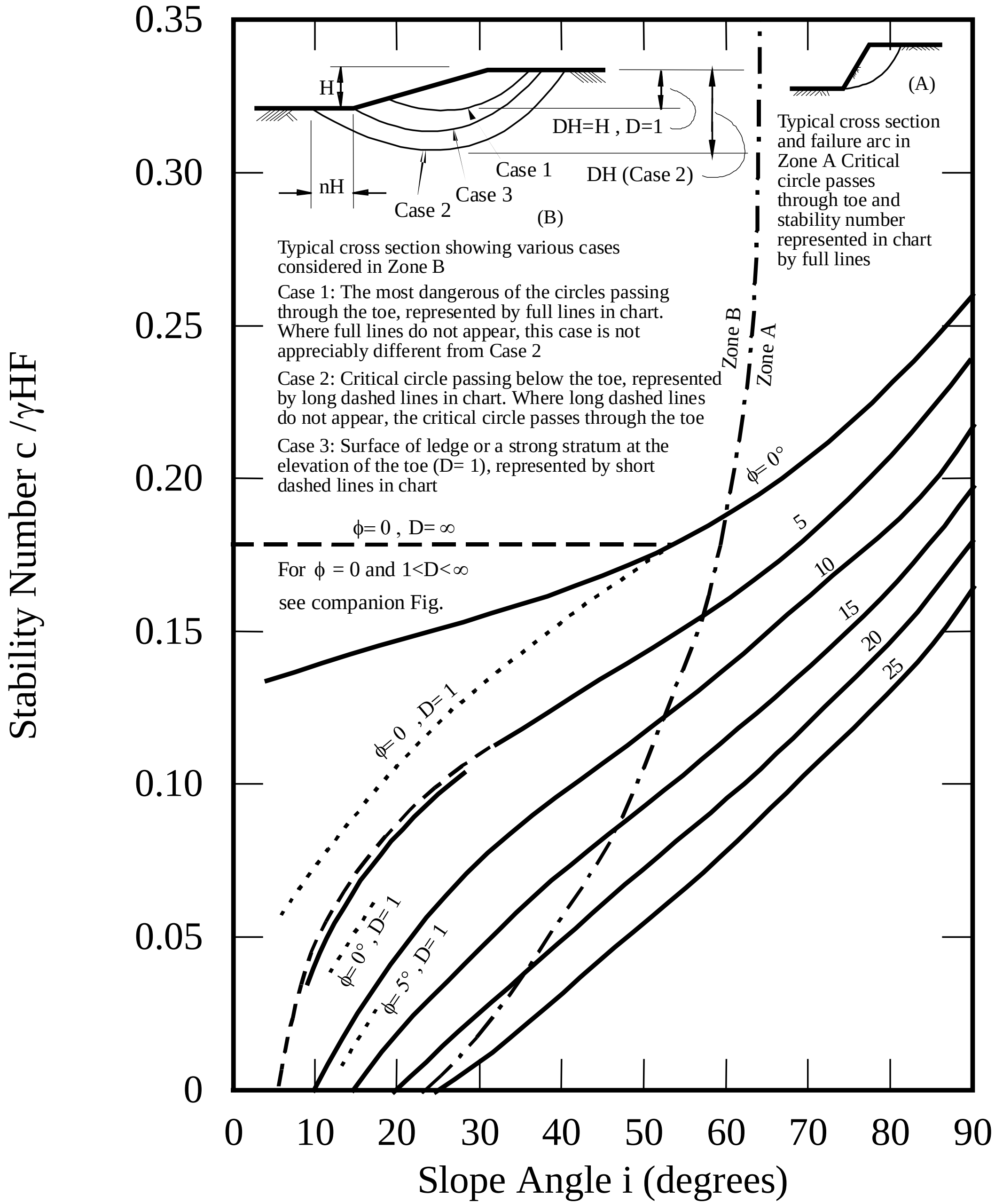
- The charts are based on the analysis of circular failure surfaces, and assume that soil strength is given by a Mohr-Coulomb analysis

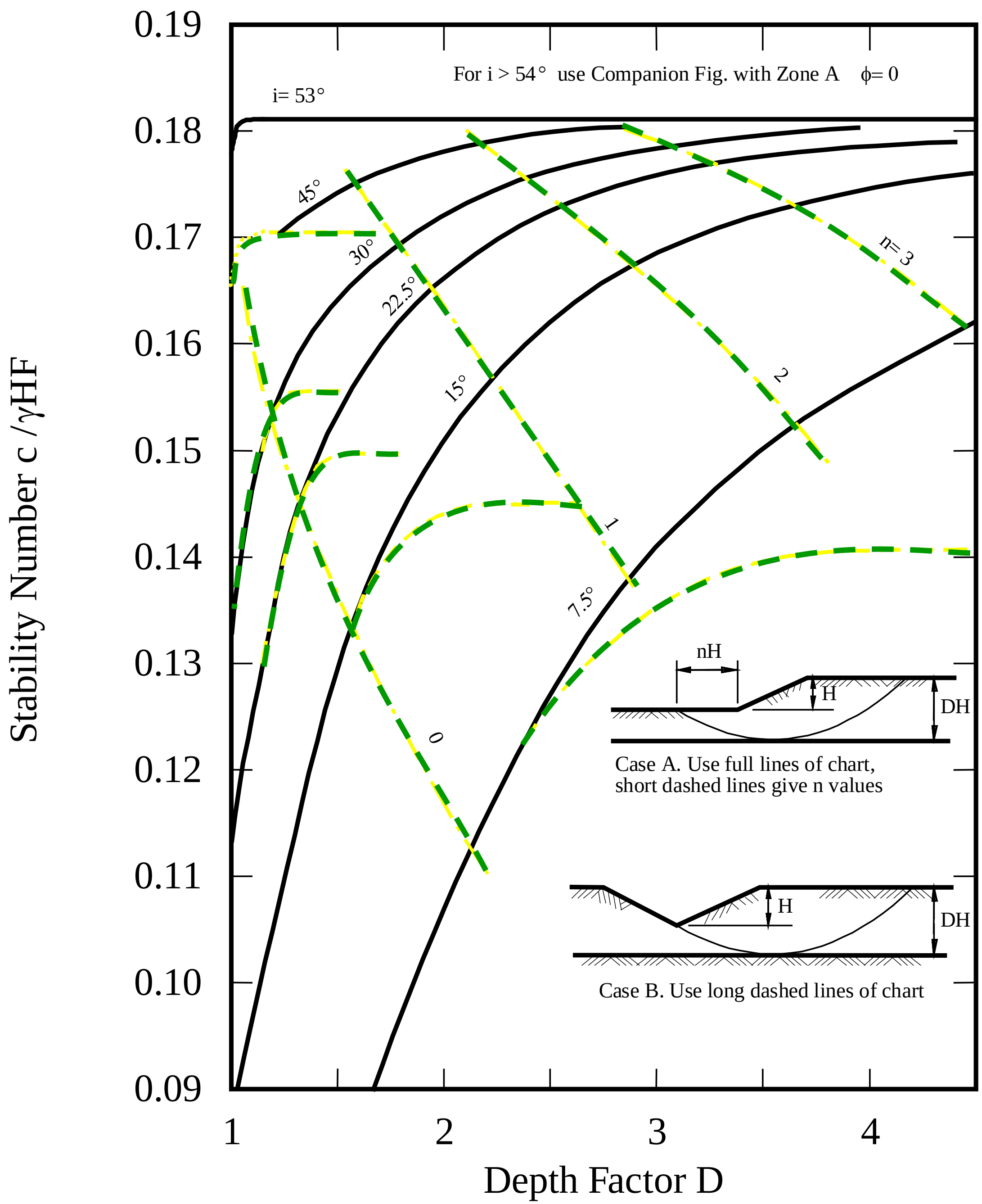
- Tension cracks are not considered

# Taylor's Method



# Taylor's Chart



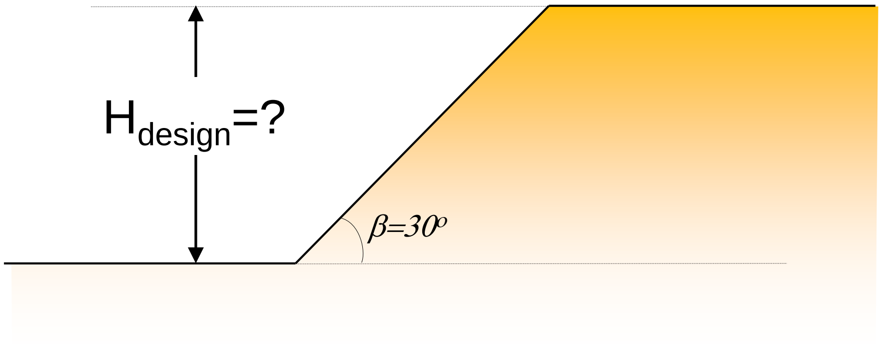


Stability Number c /γHF
Depth Factor D
0.19
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.10
0.09
1
2
3
4
For i > 54° use Companion Fig. with Zone A ϕ= 0
i= 53°
45°
30°
22.5°
15°
7.5°
0
1
2
n= 3
nH
H
DH
Case A. Use full lines of chart,
short dashed lines give n values
Case B. Use long dashed lines of chart

# Example 1:

**Given**:

$c_u$ = 20 kN/m$^2$
$\phi_u$ = 10$^o$
$\gamma_{bulk}$ = 15 kN/m$^3$
F.S. = 1.5




**Find**:

Safe Height (H)

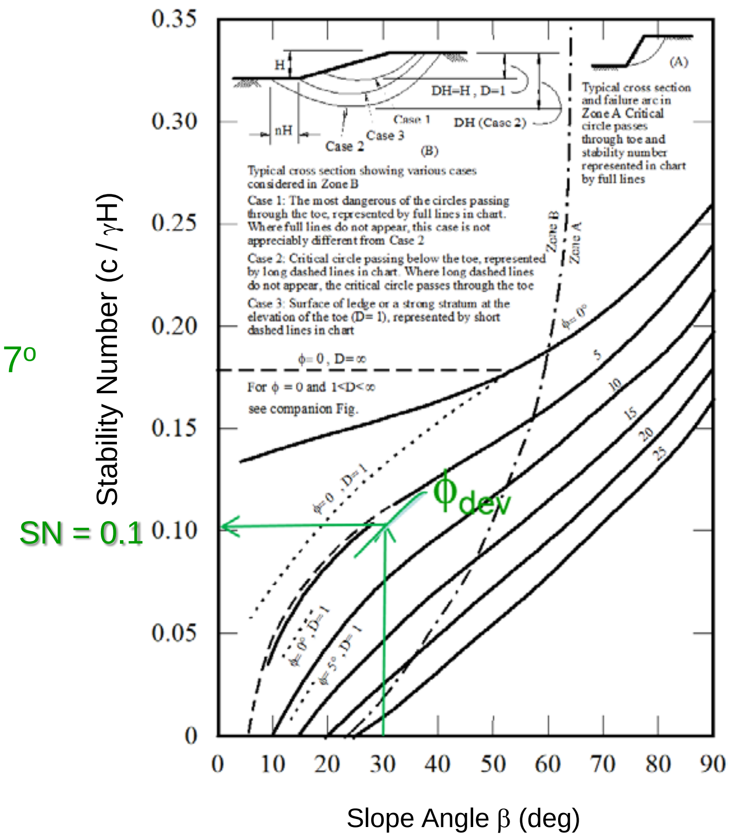
## Solution:

*or β=30$^o$*

Use the chart with *i* = 30$^o$, and $\phi_{dev} = \tan^{-1}\left(\frac{\tan 10^o}{1.5}\right) = 6.7^o$

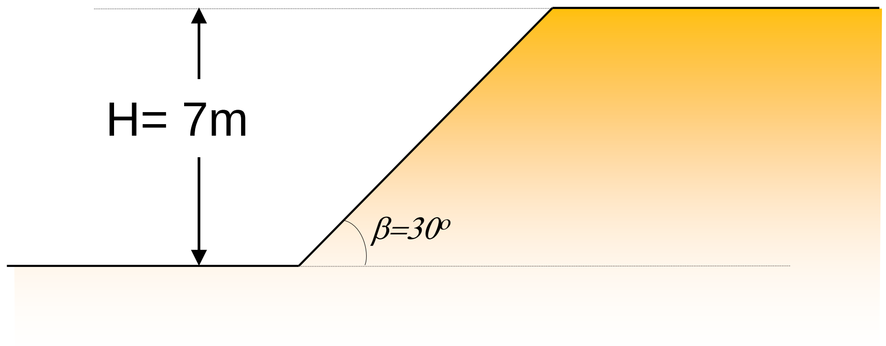
$$SN = 0.1 = \frac{20/1.5}{15 \times H_{design}}$$

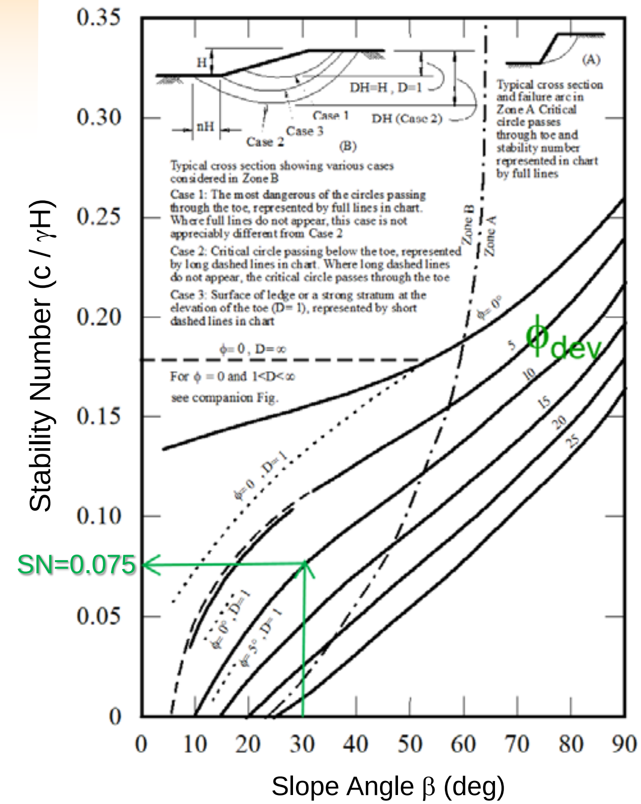
$$H_{design} = \frac{20/1.5}{15 \times 0.1} = 8.88 \text{ m}$$



# Example 2:

**Given**:
$c_u = 20$ kN/m$^2$
$\phi_u = 10^o$
$\gamma_{bulk} = 15$ kN/m$^3$
H = 7 m
$\beta = 30^o$
**Find**:
F.S.




## Solution:

### Trial # 1

1- Assume $FS_\phi = 1$

2- Use the chart with $\beta = 30^o$, and $\phi_{dev} = \tan^{-1}\left(\frac{\tan 10^o}{1.0}\right) = 10^o$

3- Go to the chart and find SN for $\phi_{dev} = 10^o$

$$SN = 0.075 = \frac{c_{dev}}{15 \times 7}$$

4- $c_{dev} = 15 \times 7 \times 0.075 = 7.87$ kN/m$^2$

5- $FS_c = c / c_{dev} = 20 / 7.87 = 2.5$

Therefore the Assumed $FS_\phi \neq$ the calculated $FS_c$

This means the assumed factor of safety was not the right one. So we need to assume another FSϕ and solve the problem again for $FS_c$.

## Trial # 2

1- Assume $FS_\phi = 1.5$

2- Use the chart with $i = 30^o$, and $\phi_{dev} = \tan^{-1}\left(\frac{\tan 10^o}{1.5}\right) = 6.7^o$

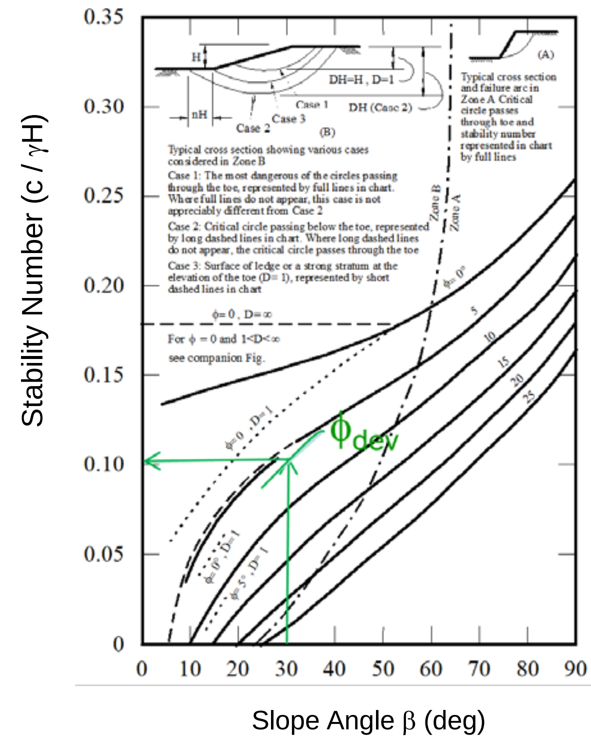
3- Go to the chart and find SN for $\phi_{dev} = 6.7^o$

$$SN = 0.1 = \frac{c_{dev}}{15 \times 7}$$

4- $c_{dev} = 15 \times 7 \times 0.10 = 10.5\ kN/m^2$

5- $FS_c = c / c_{dev} = 20/10.5 = 1.9$

Therefore the Assumed $FS\phi \neq$ the calculated $FS_c$




This means the assumed factor of safety was not the right one. So we need to assume another FSϕ and solve the problem again for $FS_c$.

# Trial # 3

1- Assume $FS_{\phi} = 1.8$

2- Use the chart with $i = 30^{o}$, and $\phi_{dev} = \tan^{-1}\left(\frac{\tan 10^{o}}{1.8}\right) = 5.5^{o}$

3- Go to the chart and find SN for $\phi_{dev} = 5.5^{o}$

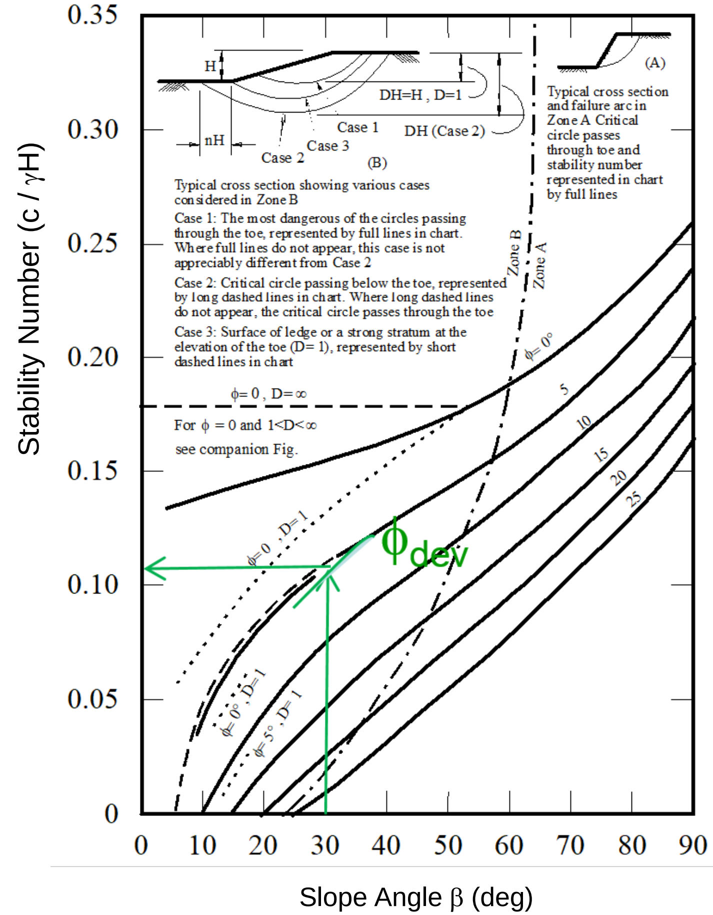
$$SN = 0.11 = \frac{c_{dev}}{15 \times 7}$$

4- $c_{dev} = 15 \times 7 \times 0.11 = 11.55 \text{ kN/m}^2$

5- $FSc = c / c_{dev} = 20/11.55 = 1.73$

Therefore the Assumed $FS\phi \neq$ the calculated $FS_c$

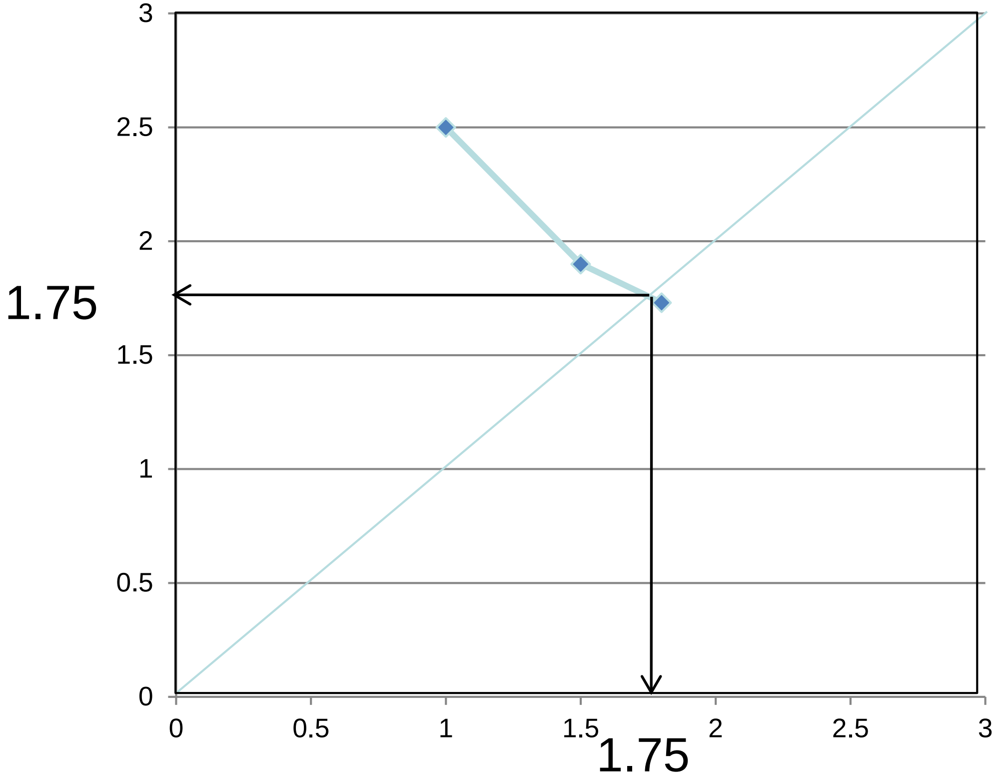
This means the assumed factor of safety was not the right one. So we need to assume another $FS\phi$ and solve the problem again for $FS_c$.



Since we complied three different trials, we are ready to find the right factor of safety by using the 45$^{o}$ line method

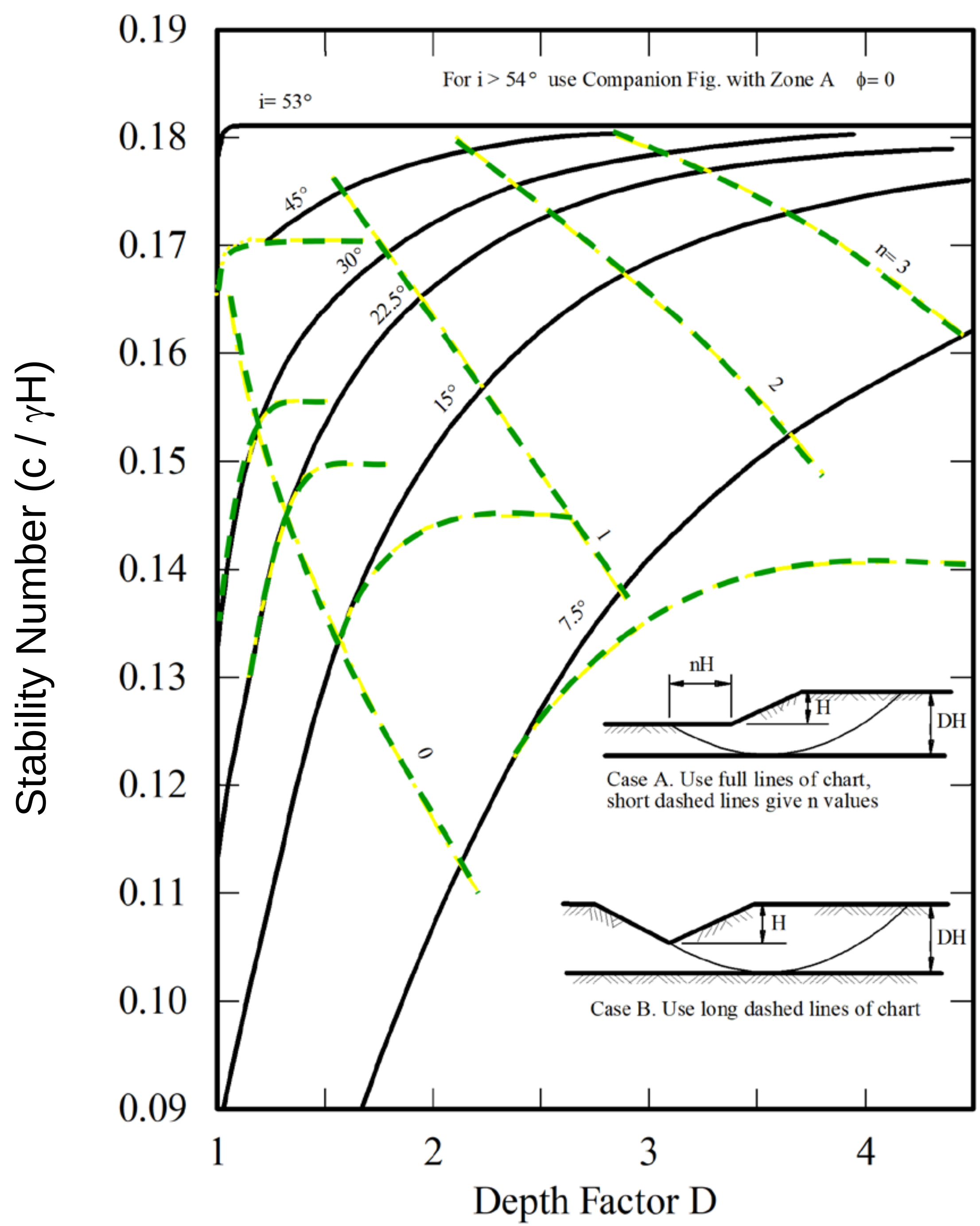
| Assumed FSϕ | Calculated $FS_c$ |
|---|---|
| 1.0 | 2.5 |
| 1.5 | 1.9 |
| 1.8 | 1.73 |

So the correct FS is 1.75



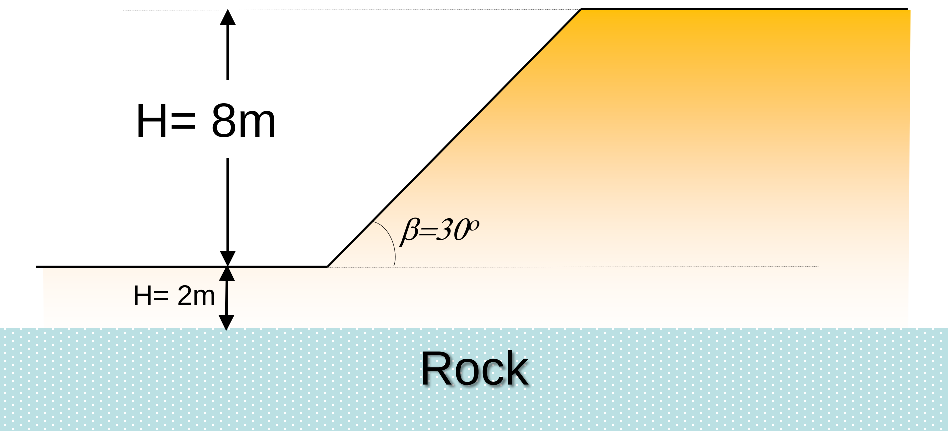
# Taylor's Chart - example

- Zones are marked on the chart indicating whether the failure mode will be shallow or deep-seated.
- If a deep-seated failure is indicated the soil layer must be sufficiently deep to enable this mechanism to occur.
- There is a second chart due to Taylor which can be used when the depth of soil below the base of the slope is limited
- This chart is only valid for $\phi = 0$



Stability Number (c / γH)
0.19
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.10
0.09
For i > 54° use Companion Fig. with Zone A ϕ= 0
i= 53°
45°
30°
22.5°
15°
7.5°
0
1
2
n= 3
nH
H
DH
Case A. Use full lines of chart, short dashed lines give n values
Case B. Use long dashed lines of chart
1
2
3
4
Depth Factor D

# Example 3:




**Given**:

$c_u$ = 20 kN/m$^2$
$\phi_u$ = 0
$\gamma_{bulk}$ = 15 kN/m$^3$
F.S. = 1.5

**Find**:

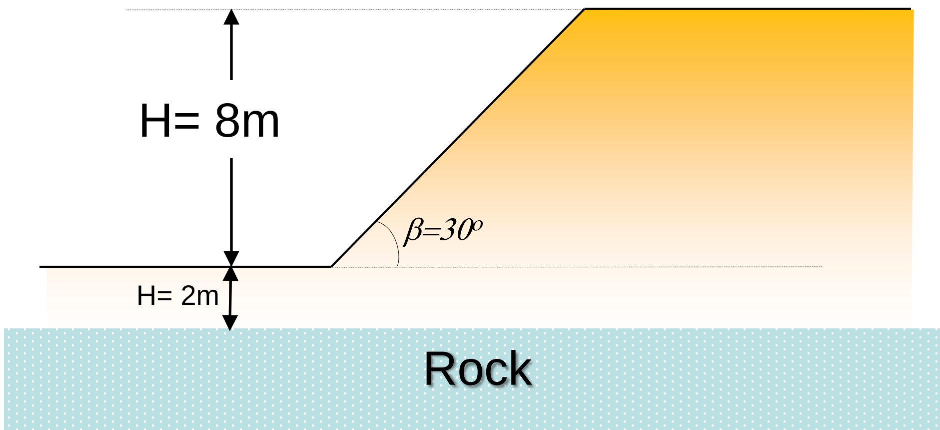
Calculate the depth factor D

Solution

DH = 8+2 = 10 m

D= 1.25

# Example 3:




**Given**:

$c_u$ = 20 kN/m$^2$
$\phi_u$ = 0
$\gamma_{bulk}$ = 15 kN/m$^3$
DH = 10 m

**Find**:

Factor of Safety

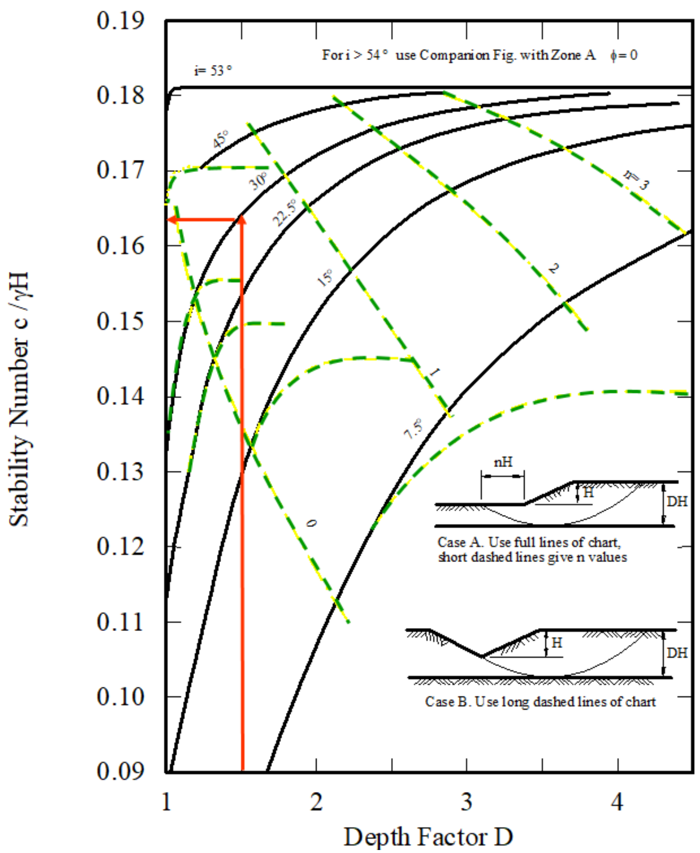
**Solution**

D = 10/8 = 1.25

$$SN = \frac{c_{dev}}{\gamma H} = \frac{c_{dev}}{15\ x\ 8} = 0.165$$

$$c_{dev} = 0.165\ x\ 15\ x\ 8 = 19.8\ kN/m^2$$

$FS_c$ = 1.01



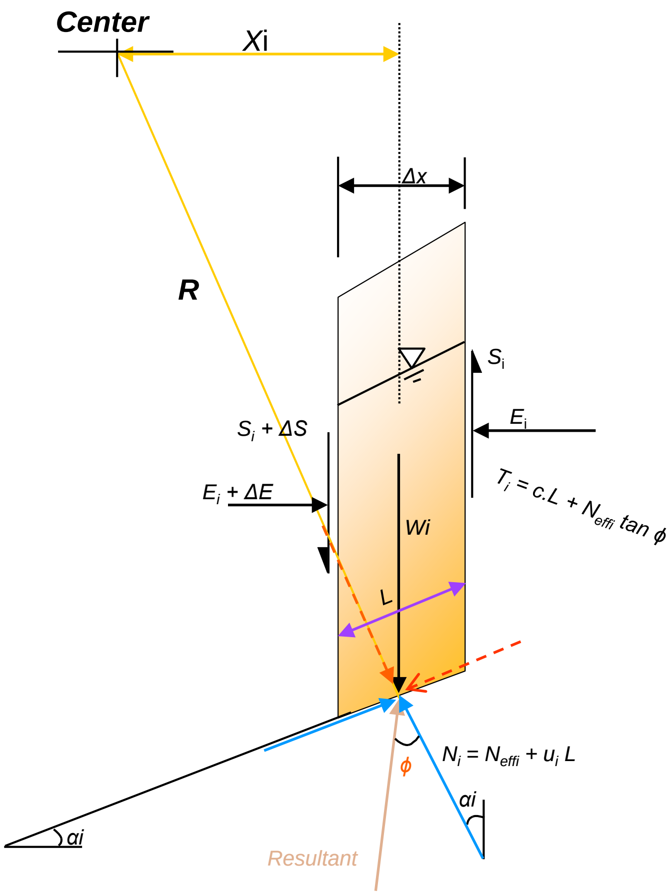
# MODULE 5

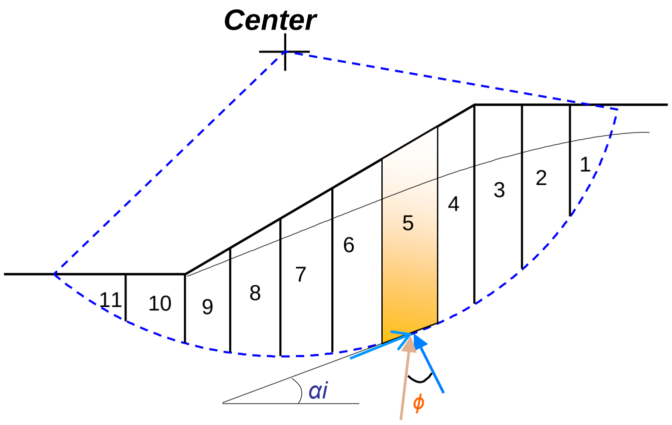
## Section III

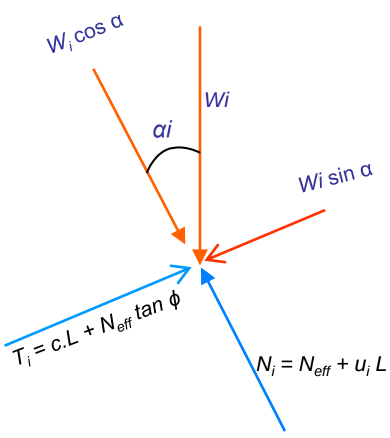
## Slope Stability Analysis & Design

# STATICALLY INDETERMINATE PROBLEMS

## METHOD OF SLICES




By Kamal Tawfiq, Ph.D., P.E

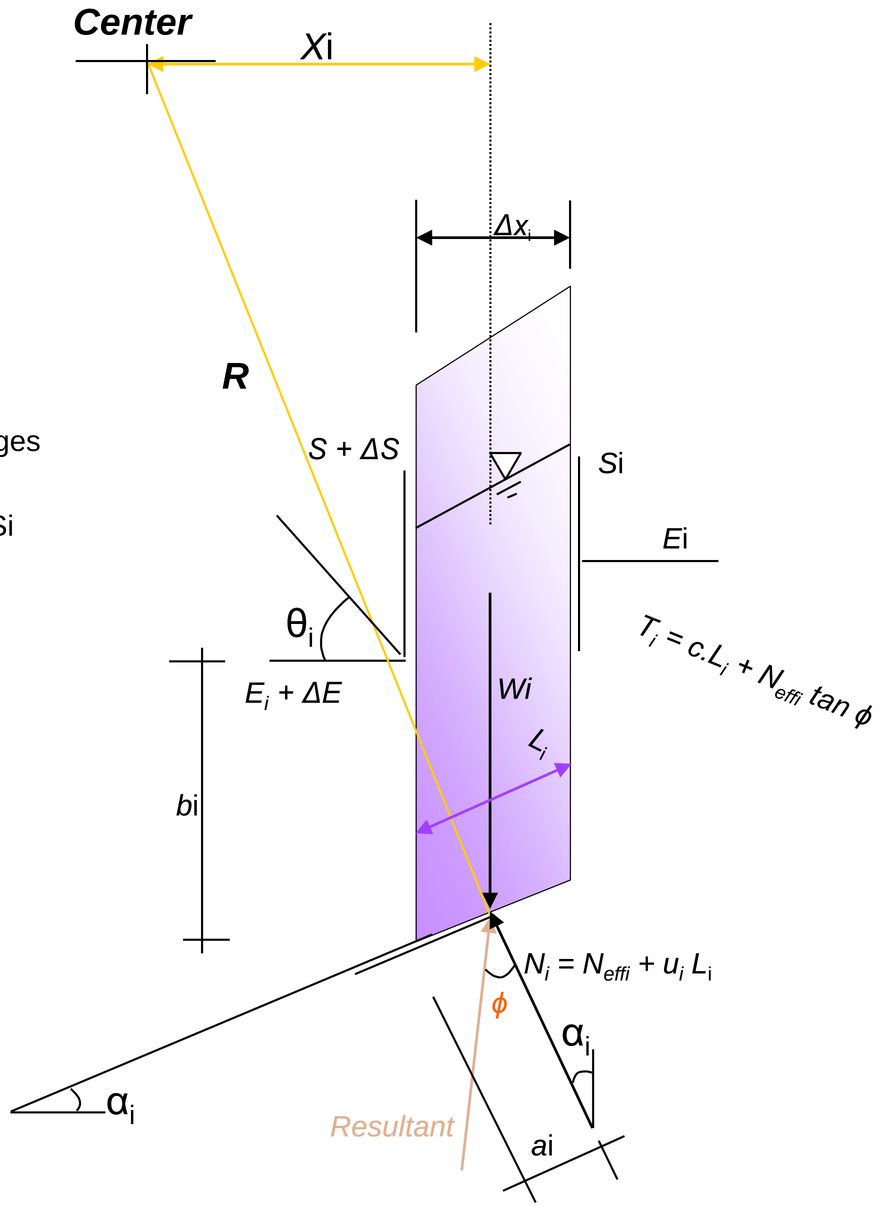
# Unknowns Associated with Force Equilibrium

n = Resultant normal forces $N_i$ on the base of each slice or wedge

1 = Safety factor, which permits the shear forces $T_i$ on the base of each slice to be expressed in terms of Ni

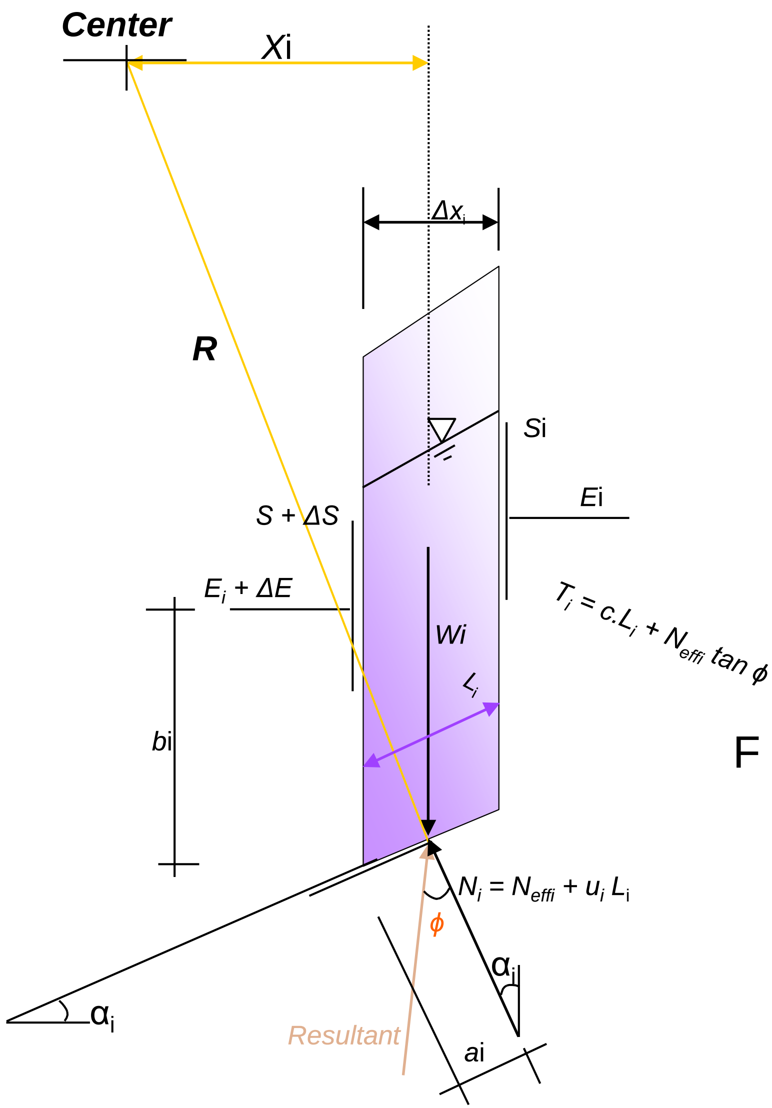
n-1 = Resultant normal forces $E_i$ on each interface between slices or wedges

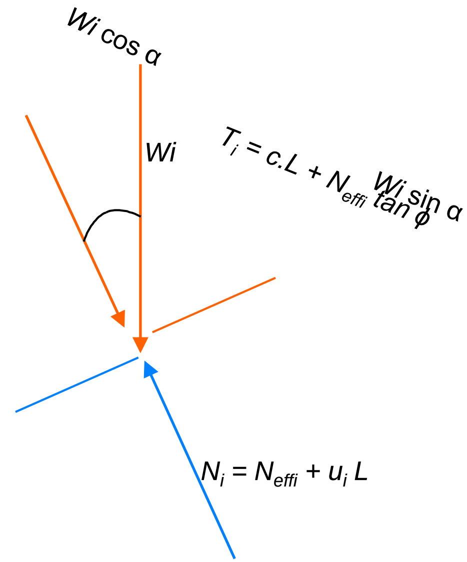
n-1 = Angles $\alpha_i$ which express the relationships between the shear force Si and the normal force $E_i$ on each interface




By Kamal Tawfiq, Ph.D., P.E

# FELLENIUS METHOD (ORDINARY METHOD, SWEDISH METHOD)




$$F = \frac{M_R}{M_D} = \frac{\sum CL_i + (w_i \cos\theta_i - u_i L_i)\tan\phi}{\sum w_i \sin\theta_i}$$

*By Kamal Tawfiq, Ph.D., P.E*

### Ordinary Method of Slices

In this method,[5] it is assumed that the forces actin upon the sides of any slice have *zero resultant in the direction normal to the failure arc for that slice.* This situation is depicted in Fig. 24.12. With this assumption

$$\bar{N}_i + U_i = W_i \cos\theta_i$$

or

$$\bar{N}_i = W_i \cos\theta_i - U_i = W_i \cos\theta_i - u_i \Delta l_i \quad (24.9$$

Combining Eqs. 24.8 and 24.9.

$$F = \frac{\bar{c}L + \tan\bar{\phi} \sum_{i=1}^{i=n} (W_i \cos\theta_i - u_i \Delta l_i)}{\sum_{i=1}^{i=n} W_i \sin\theta_i} \quad (24.10$$

The use of Eq. 24.10 to compute $F$ is illustrated i Example 24.4.

Here the assumption regarding side forces involve $n - 1$ assumptions, while there are only $n - 2$ unknowns Hence the system of slices is overdetermined and i general it is not possible to satisfy statics. Thus th safety factor computed by this method will be in error Numerous examples have shown that the safety facto obtained in this way usually falls *below the lower boun* of solutions that satisfy statics. In some problems, $F$ from this method may be only 10 to 15% below th range of equally correct answers, but in other problem the error may be as much as 60% (e.g., see Whitman and Bailey, 1967).

Despite the errors, this method is widely used in practice because of its early origins, because of its simplicity, and because it errs on the safe side. Hand calculations are feasible, and the method has been programmed for computers. It seems unfortunate that a method which may involve such large errors should be so widely used, and it is to be expected that more accurate

[5] Also known as Swedish Circle Method or Fellenius Method Consideration of slices within the trial wedge was first proposed b Fellenius (1936).

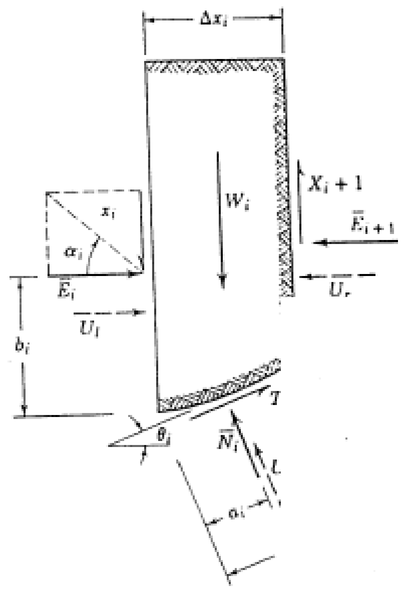
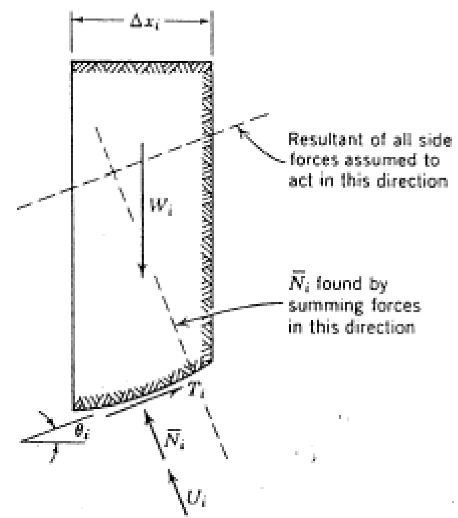



Fig. 24.11 Complete system of for




ig. 24.12 Forces considered in ordinary method of slices.

### Simplified Bishop Method of Slices

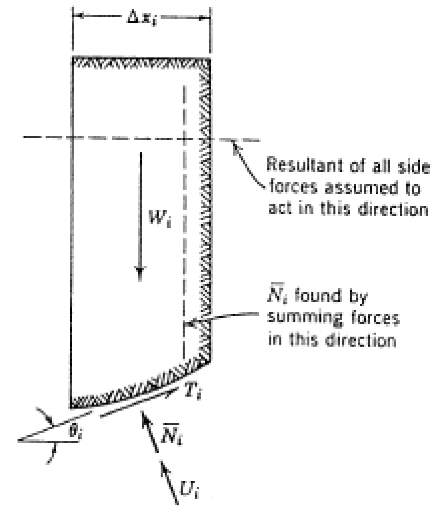
In this newer method[6] it is assumed that the forces acting on the sides of any slice have *zero resultant in the vertical direction.* The forces $\bar{N}_i$ are found by considering the equilibrium of the forces shown in Fig. 24.13. A value of safety factor must be used to express the shear forces $T_i$, and it is assumed that this safety factor equals the $F$ defined by Eq. 24.8. Then:

$$\bar{N}_i = \frac{W_i - u_i\,\Delta x_i - (1/F)\bar{c}\,\Delta x_i \tan\theta_i}{\cos\theta_i[1 + (\tan\theta_i \tan\bar{\phi})/F]} \qquad (24.11)$$

Combining Eqs. 24.8 and 24.11 gives

$$F = \frac{\sum_{i=1}^{i=n} [\bar{c}\,\Delta x_i + (W_i - u_i\,\Delta x_i)\tan\bar{\phi}][1/M_i(\theta)]}{\sum_{i=1}^{i=n} W_i \sin\theta_i} \qquad (24.12)$$

[6] The method was first described by Bishop (1955); the simplified version of the method was developed further by Janbu et al. (1956).




13 Forces considered in simplified Bishop method of

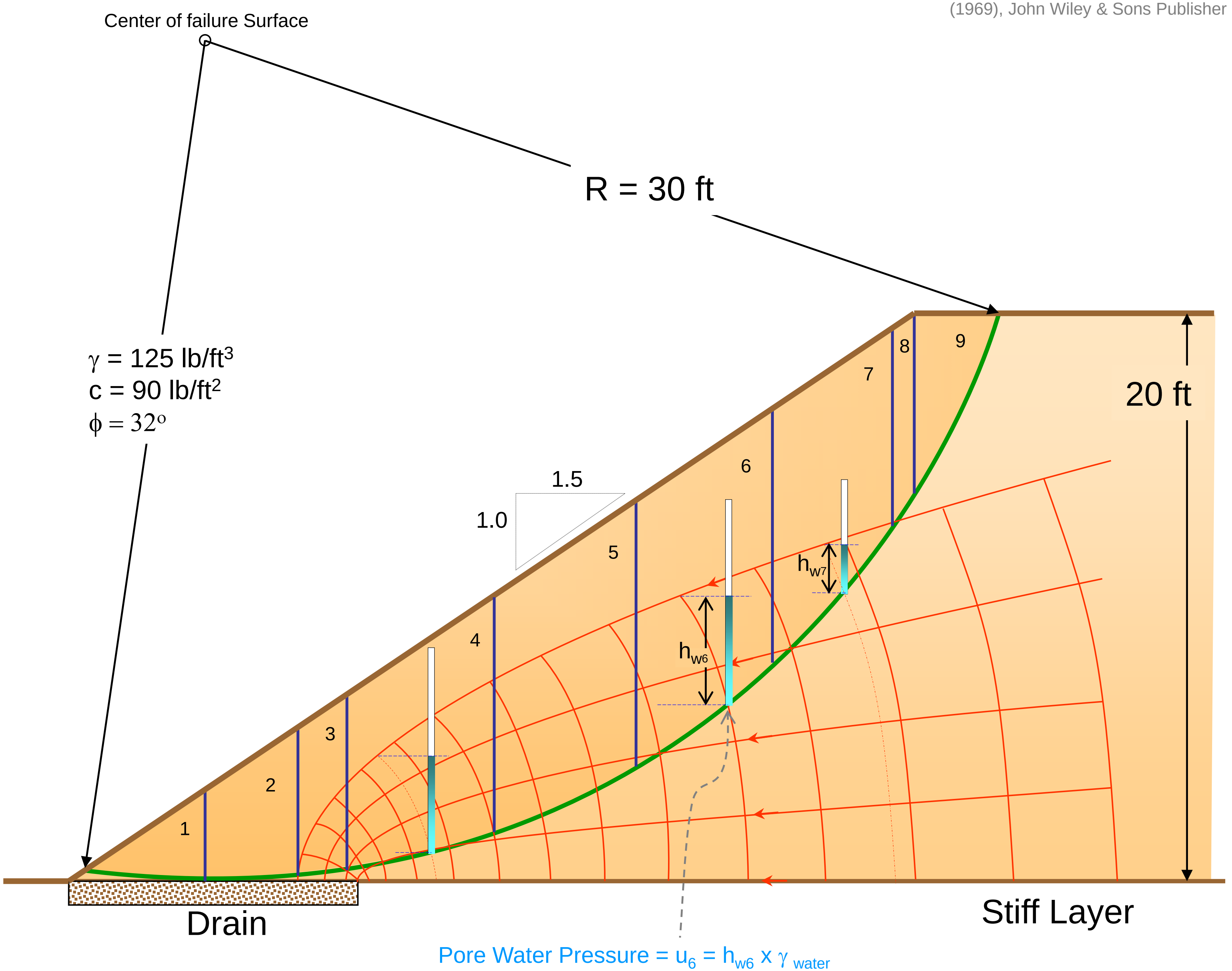
where

$$M_i(\theta) = \cos\theta_i\left(1 + \frac{\tan\theta_i \tan\bar{\phi}}{F}\right) \qquad (24.13)$$

Equation 24.12 is more cumbersome than Eq. 24.10 from the ordinary method, and requires a trial and error solution since $F$ appears on both sides of the equation. However, convergence of trials is very rapid. Example 24.5 illustrates the tabular procedure which may be used. The chart in Fig. 24.14 can be used to evaluate the function $M_i$.

The simplified Bishop method also makes $n - 1$ assumptions regarding unknown forces and hence overdetermines the problem so that in general the values of $\bar{N}_i$ and $F$ are not exact. However, numerous examples have shown that this method gives values of $F$ which fall within the range of equally correct solutions as determined by exact methods. There are cases where the Bishop method gives misleading results; e.g., with deep failure circles when $F$ is less than unity (see Whitman and Bailey, 1967). Nonetheless, the Bishop method is recommended for general practice. Hand calculations are possible, and computer programs are available.

This example is from Lambe and Whitman (1969), John Wiley & Sons Publisher




Kamal Tawfiq, Ph.D., P.E.

# 1- Using Ordinary Method of Slices (Swedish Method)

| Slice | Width $\Delta x$ (ft) | Ave Height (ft) | Weight (Kips) | $\theta_i$ | $W_i \sin\theta_i$ | $W_i \cos\theta_i$ | $u_i$ | $\Delta l_i$ | $U_i = u_i \Delta l_i$ | $N_i = W_i \cos\theta_i - U_i$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 4.5 | 1.6 | 0.9 | -1.7 | 0 | 0.9 | 0 | 4.4 | 0 | 0.9 |
| 2 | 3.2 | 4.2 | 1.7 | 2.9 | 0.1 | 1.7 | 0 | 3.2 | 0 | 1.7 |
| 3 | 1.8 | 5.8 | 1.3 | 8.05 | 0.2 | 1.3 | 0.03 | 1.9 | 0.05 | 1.25 |
| 4 | 5.0 | 7.4 | 4.6 | 14.5 | 1.2 | 4.5 | 0.21 | 5.3 | 1.1 | 3.4 |
| 5 | 5.0 | 9.0 | 5.6 | 24.8 | 2.3 | 5.1 | 0.29 | 5.6 | 1.6 | 3.5 |
| 6 | 5.0 | 9.3 | 5.8 | 35.4 | 3.4 | 4.7 | 0.25 | 6.2 | 1.55 | 3.15 |
| 7 | 4.4 | 8.4 | 4.6 | 47.7 | 3.4 | 3.1 | 0.11 | 6.7 | 0.7 | 2.4 |
| 8 | 0.6 | 6.7 | 0.5 | 55.1 | 0.4 | 0.3 | 0 | 1.2 | 0 | 0.3 |
| 9 | 3.2 | 3.8 | 1.5 | 60.4 | 1.3 | 0.7 | 0 | 7.3 | 0 | 0.7 |
| | | | | | 12.3 | | | 41.8 | | 17.3 |

$$\text{F.S.} = \frac{cL + \tan\phi \sum_{i=1}^{i=n} (W_i \cos\theta_i - u_i \Delta l_i)}{\sum_{i=1}^{i=n} W_i \sin\theta_i} = \frac{0.09(41.8) + 17.3 \tan 32^o}{12.3} = \frac{3.76 + 10.82}{12.3} = \frac{14.58}{12.3} = 1.19$$

*Kamal Tawfiq, Ph.D., P.E.*

## 2- Using Simplified Bishop Method

$$\mathbf{M}_i(\theta) = \cos\theta_i \left(1 + \frac{\tan\theta_i \tan\varphi}{F.S.}\right)$$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | | (9) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | $M_i$ | | (7)/(8) | |
| Slice | Width $\Delta x$ (ft) | C $\Delta x_i$ (kips) | $u_i$ $\Delta x_i$ (Kips) | $W_i$-$u_i$ $\Delta x_i$ (Kips) | (5).(tan $\phi$) (Kips) | (3)+(6) (Kips) | *Assume* F=1.25 | *Assume* F=1.35 | F=1.25 | F=1.35 |
| 1 | 4.5 | 0.4 | 0 | 0.9 | 0.55 | 0.95 | 0.97 | 0.97 | 1.0 | 1.0 |
| 2 | 3.2 | 0.29 | 0 | 1.7 | 1.05 | 1.35 | 1.02 | 1.02 | 1.3 | 1.3 |
| 3 | 1.8 | 0.16 | 0.05 | 1.25 | 0.8 | 0.95 | 1.06 | 1.05 | 0.9 | 0.9 |
| 4 | 5.0 | 0.45 | 1.05 | 3.55 | 2.25 | 2.7 | 1.09 | 1.08 | 2.5 | 2.5 |
| 5 | 5.0 | 0.45 | 1.45 | 4.15 | 2.55 | 3.00 | 1.12 | 1.10 | 2.7 | 2.75 |
| 6 | 5.0 | 0.45 | 1.25 | 4.55 | 2.7 | 3.15 | 1.1 | 1.08 | 2.85 | 2.9 |
| 7 | 4.4 | 0.4 | 0.5 | 4.1 | 2.65 | 3.05 | 1.05 | 1.02 | 2.9 | 2.95 |
| 8 | 0.6 | 0.05 | 0 | 0.5 | 0.3 | 0.35 | 0.98 | 0.95 | 0.35 | 0.4 |
| 9 | 3.2 | 0.29 | 0 | 1.5 | 0.95 | 1.25 | 0.93 | 0.92 | 1.3 | 1.35 |
| | | | | | | | | | 15.8 | 16.09 |

$$\text{F.S.} = \frac{\sum_{i=1}^{i=n}\left[c\,\Delta x_i + (W_i - u_i\,\Delta x_i)\tan\phi\right]\left[1/M_i\right]}{\sum_{i=1}^{i=n} W_i \sin\theta_i} =$$

From the previous solution

$$F.S. = 1.25 \qquad F.S. = \frac{15.8}{12.3} = 1.29$$

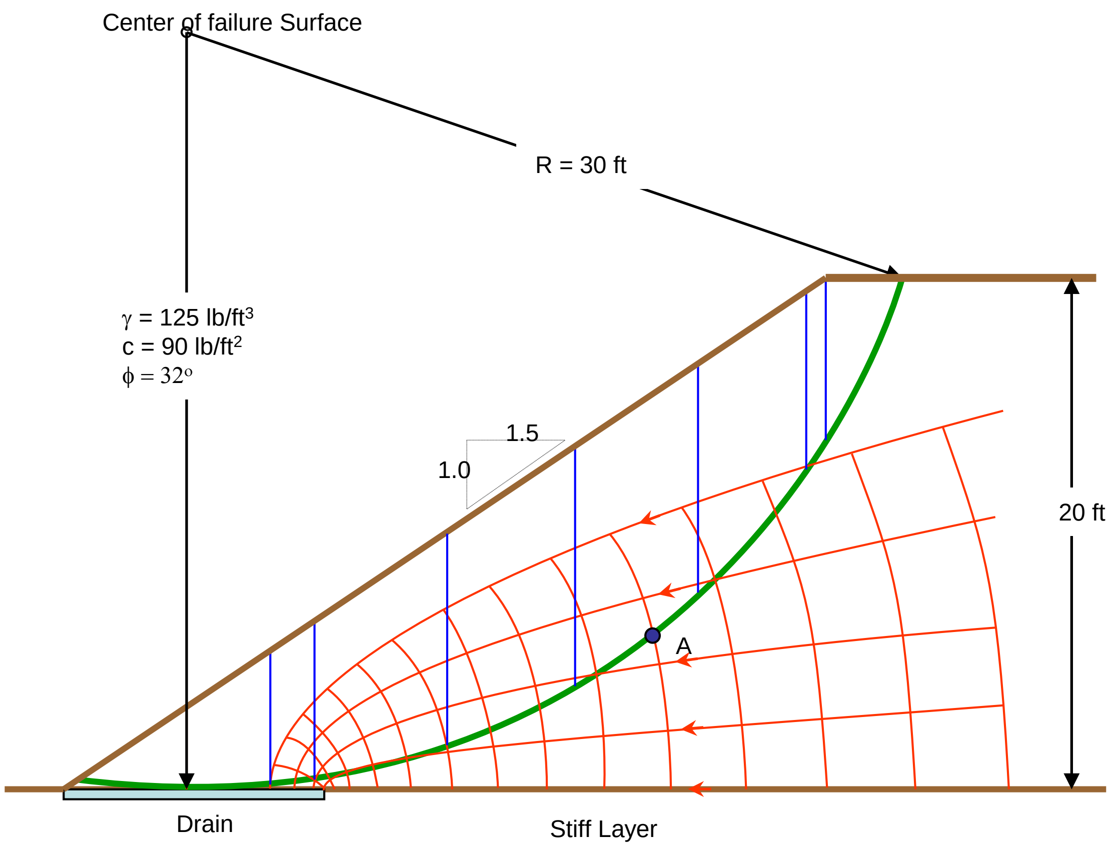
$$F.S. = 1.35 \qquad F.S. = \frac{16.05}{12.3} = 1.31$$

*With assumed* $F.S. = 1.3$ *would give* $F.S. = 1.3$

Name:___________ ID:_________

# CEG 4801 Geotechnical Design
## Spring 2018

What is the pore water pressure at point A?



## 24.7 FINAL COMMENTS ON METHODS OF ANALYSIS

Sections 24.4 to 24.6 have presented in detail methods for computing the safety factor for a given cross section and given failure arc. There are additional considerations involved in applying these methods to practical problems.

It is necessary to make a trial and error search for the failure surface having the smallest factor of safety. When using circular failure surfaces, it is convenient to establish a grid for the centers of circles, to write at each grid point the smallest safety factor for circles centered on the grid point, and then to draw contours of equal safety factor. Figure 24.16 shows an example of contours of equal safety factor. I[illegible]
only circles passing tangent t[illegible]
stratum were considered, but in[illegible]
also be necessary to consider sh[illegible]

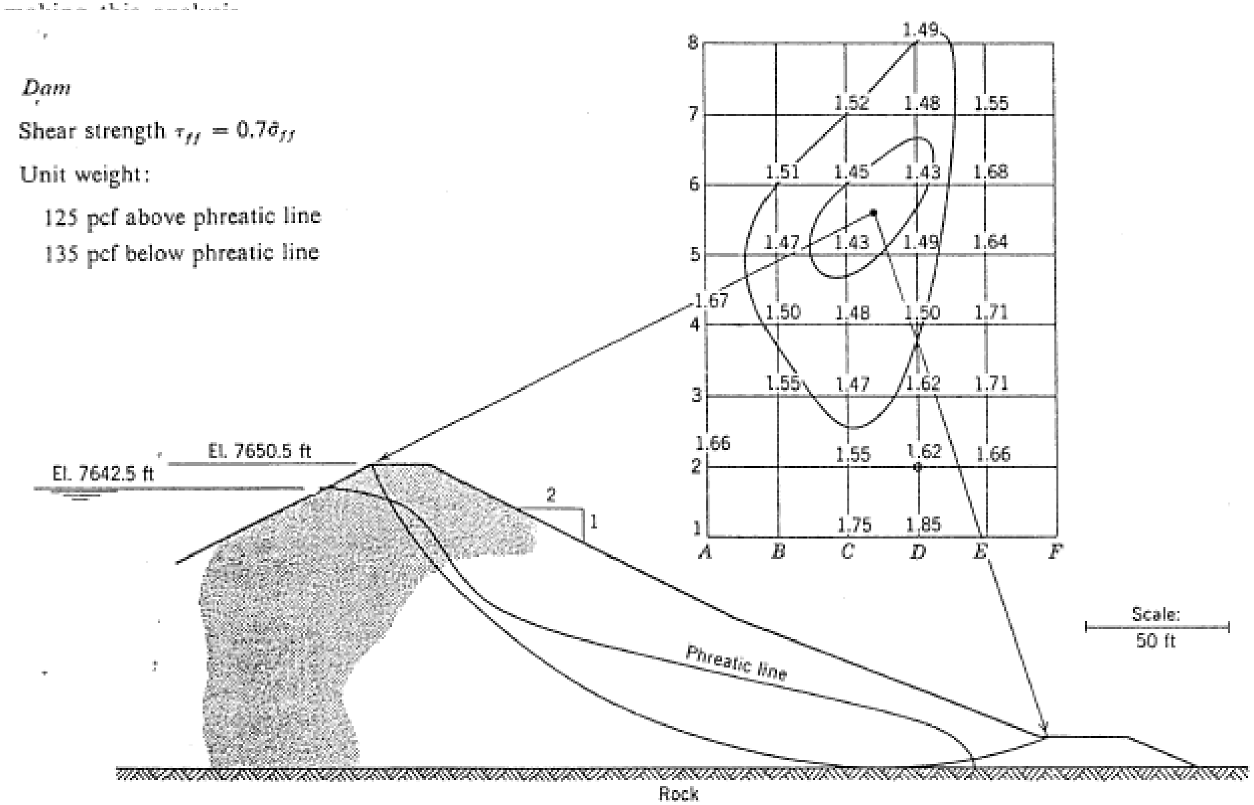
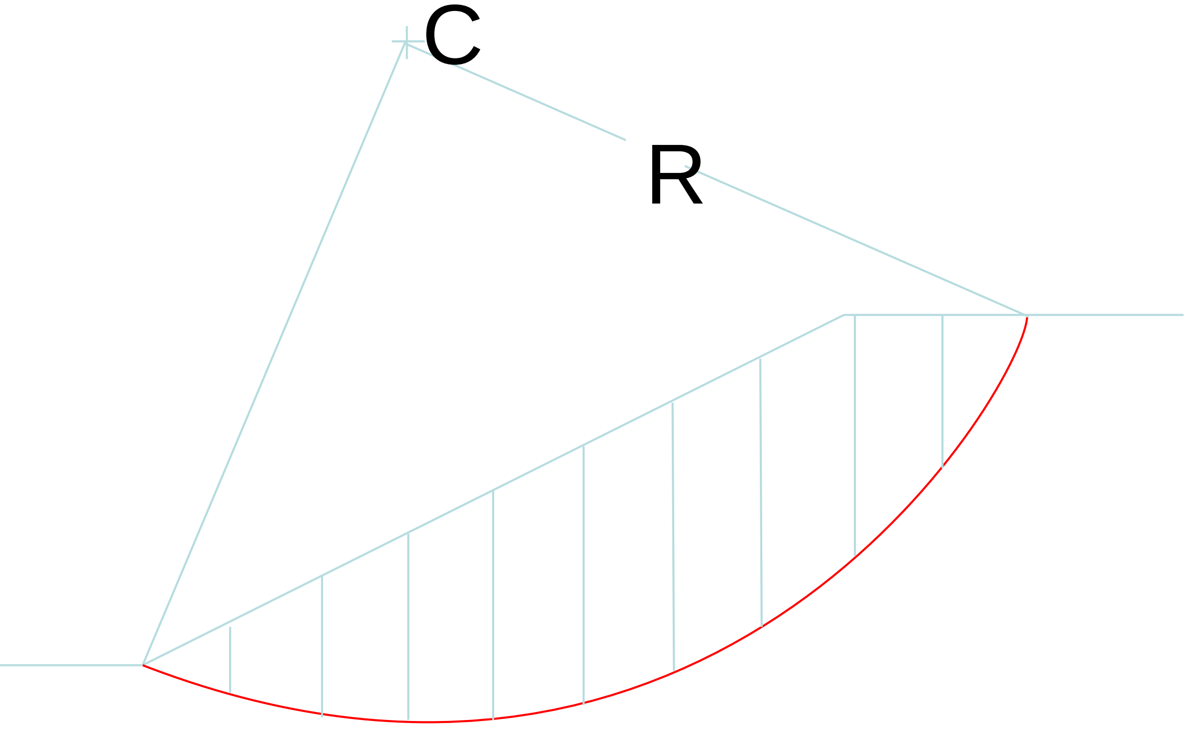



Fig. 24.16 Contours of safety factor.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