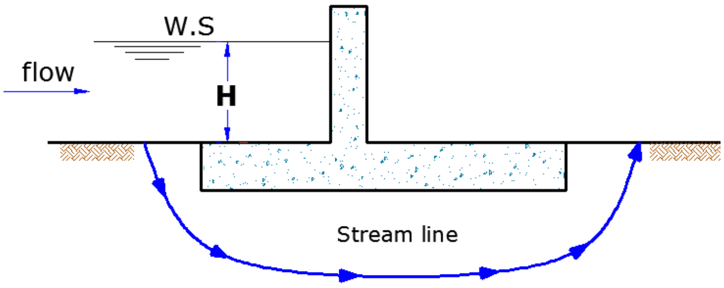
Theories of Seepage and Uplift pressure

Causes of failure of weir or barrage founded on pervious permeable foundations:

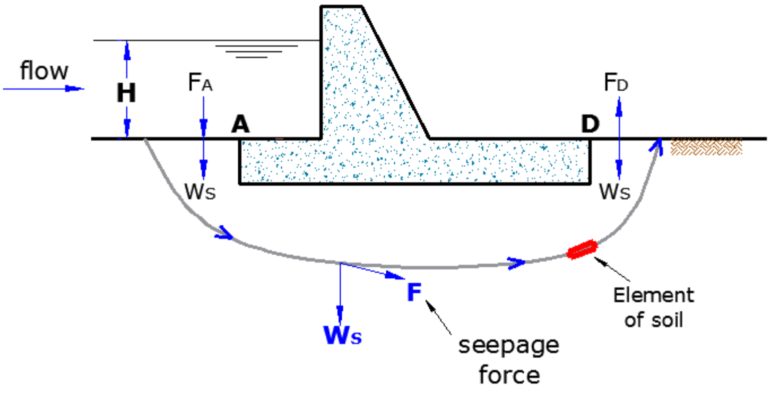
1. Failure due to Subsurface Flow:-

The water seeping below the body of the hydraulic structures endangers the stability of the structure and may cause its failure either by:



(a) Failure by Piping or undermining force

The water from the upstream side continuously percolates through the bottom of the foundation and emerges at the downstream end of the weir or barrage floor. The force of percolating water removes the soil particles by scouring at the point of emergence. As the process of removal of soil particles goes on continuously, a depression is formed which extends backwards towards the upstream through the bottom of the foundation. A hollow pipe like formation thus develops under the foundation due to which the weir or barrage may fail by subsiding. This phenomenon is known as failure by piping or undermining.



Critical condition is when (F=ws) and this will take place at the exit, in this case the value of Exit gradient equal to (one).

In the design, an adequate safety factor is allowed on this critical value, Exit gradient between (0.22 – 0.15) are usually used. This can be controlled by using D/S cutoff, the Exit gradient is considerably reduced a cutoff depth increases.

Also inverted filters are usually provided under D/S protection works to safeguard against piping.

Factor of safety against undermining (f)

$$f = \frac{ws}{F} = \frac{\gamma(1-n)(s-1)}{\gamma.i.e} = \frac{(1-n)(s-1)}{i.e}$$

n: porosity

γ: unit weight of water

s: specific gravity of the soil

Example: what is the exit gradient of an irrigation structure built on the permeable foundation if the natural bed material have n=0.35 and s=2.5, if it is to be (5 × safer) against undermining?

$$\boldsymbol{f = \frac{(1-n)(s-1)}{ie} \longrightarrow \therefore \quad i.e = \frac{(1-n)(s-1)}{f}}$$

$$\therefore \quad \mathbf{i.e = \frac{(1-0.35)(2.5-1)}{5} = 0.195 \quad \rightarrow \therefore O.K}$$

(b) Failure by Direct uplift pressure

The percolating water exerts an upward pressure on the foundation of the weir or barrage. If this uplift pressure is not counterbalanced by the self-weight of the structure, it may fail by rapture.

2. <u>Failure by Surface Flow:-</u>

(a) By hydraulic jump

When the water flows with a very high velocity over the crest of the weir or over the gates of the barrage, then hydraulic jump develops. This hydraulic jump causes a suction pressure or negative pressure on the downstream side which acts in the direction uplift pressure. If the thickness of the impervious floor is sufficient, then the structure fails by rapture.

(b) By scouring

During floods, the gates of the barrage are kept open and the water flows with high velocity. The water may also flow with very high velocity over the crest of the weir. Both the cases can result in scouring effect on the downstream and on the upstream side of the structure. Due to scouring of the soil on both sides of the structure, its stability gets endangered by shearing.

Seepage and uplift pressure can be finding by:

1. Bligh's creep theory
2. Lane's weighted creep theory
3. Flow net analysis
4. Khosla's theory

Bligh's Creep Theory

According to Bligh's Theory, the percolating water follows the outline of the base of the foundation of the hydraulic structures. In other words, water creeps along the bottom contour of the structure. The length of the path thus traversed by water is called the (Length of the creep).

It is assumed in this theory that the loss of head is proportional to the length of the creep.

Consider a horizontal floor of length (B) impounding a depth of water (H).

If (H) is the total head loss between the upstream and the downstream and (L) is the length of creep, then the loss of head per unit of creep length $\left(\frac{H}{L}\right)$ is called the hydraulic gradient.

At any distance (length of creep) = L_1 and the head is H_1

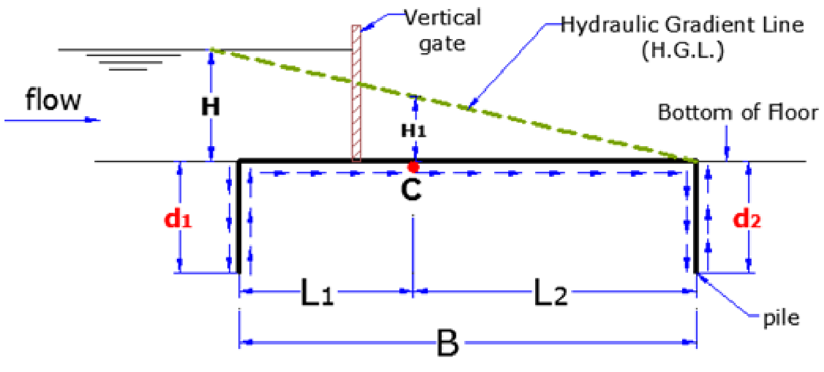


Figure (a)

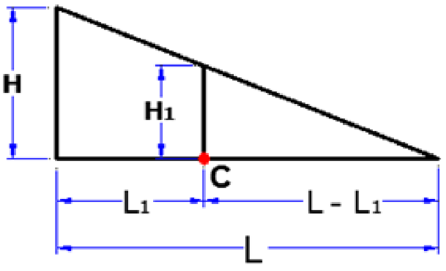


Figure (b)

From figure (a) above

L: Total creep length = (d_1*2 + L_1+L_2 + d_2*2)

L_1: Creep length at the point that would to find the uplift pressure = (d_1*2 + L_1)

From figure (b) above, the uplift head at point (C)

$$\frac{H}{L} = \frac{H_1}{L - L_1} \quad \rightarrow \quad H_1 = \frac{H}{L}(L - L_1) \quad \rightarrow \quad H_C = H\left(1 - \frac{L_1}{L}\right)$$

The uplift pressure at point (C) = uplift head at point C (H_C) * γw

$\gamma w = 1\ t/m^3$, $\gamma w = 10\ kN/m^3$ (unit weight of water)

Thickness of floor at point (C) tc = $\frac{4}{3}\left[\frac{H_1}{\gamma c - \gamma w}\right]$

H_1: uplift pressure, γc: density of concrete

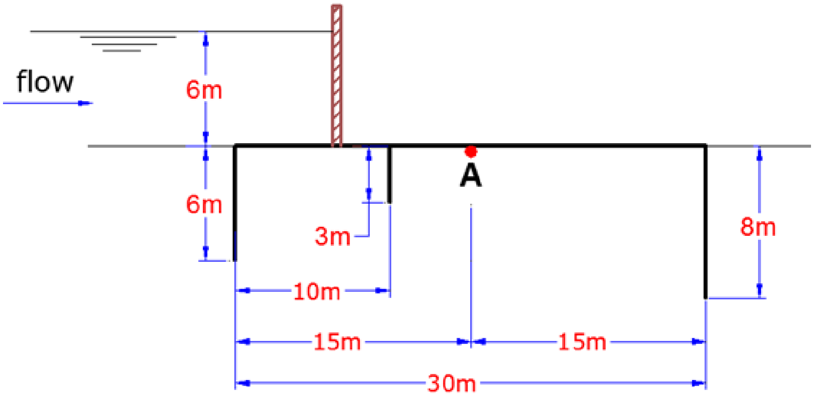
$\frac{H}{L}$ = Hydraulic Gradient

Table shown the values of Bligh's safe hydraulic gradient for different types of soils

Type of Soil	***Value of (C)*** ***Bligh's Coefficient for the soil***	***Safe Hydraulic Gradient should be less than***
Light sand and mud	18	1/18
Fine sand	15	1/15
Coarse sand	12	1/12
Sand mixed with boulders	5 - 9	1/5 - 1/9

- The hydraulic gradient must be kept under a safe limit in order to ensure safety against piping.

Example: Find the hydraulic gradient and the uplift pressure at a point 15 m from the upstream end of the floor shown below; also find the thickness of floor at this point.



Sol.

The total creep length = 6 * 2 + 10 + 3 * 2 + 20 + 8 * 2 = 64 m

Hydraulic Gradient = $\frac{H}{L} = \frac{6}{64} = \frac{1}{10.7}$

So the structure will be safe against piping for sand mixed with boulders but not for then types of soil.

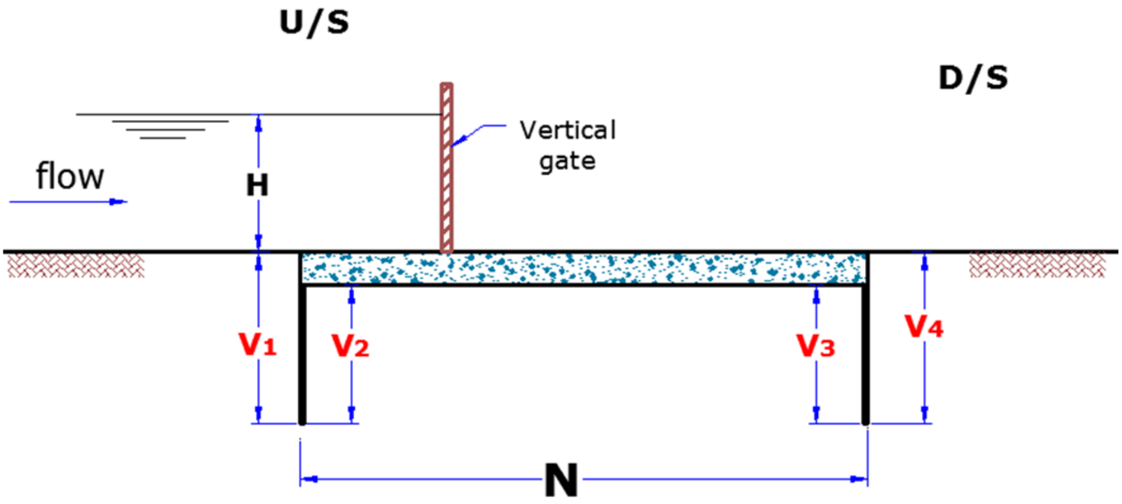
Creep length up to point (A) = 6 * 2 + 15 + 3 * 2 = 33 m

The uplift head at point (A) = $H_A = H\left(1-\frac{L_1}{L}\right) = 6\left(1-\frac{33}{64}\right) = 2.91\ m$

The uplift pressure at point (A) = $H_A * \gamma w = 2.91 * 10 = 29.1\ kN/m^2$

Thickness of floor at point (A) = $\frac{4}{3}\left[\frac{H_1}{\gamma c - \gamma w}\right] = \frac{4}{3}\left[\frac{29.1}{24-10}\right] = 2.77 \approx 3.0\ m$

Lane's Theory



$$Lw = \frac{1}{3}N + V$$

Lw: Lane's creep length

N: is the sum of all the horizontal contacts plus the sloping contacts less than 45°.

V: is the sum of all the vertical contacts $V_1+V_2+V_3+V_4+\ldots$ plus the sloping contacts equal or greater than 45°.

H: difference of water levels u/s and d/s.

❖ To ensure safety against piping under the structure (Lw) must not be less than (C * H)

$$C = \frac{Lw}{H}$$

C: is an empirical coefficient depending on the nature of soil, see the table below.

Table for the Lane's creep coefficient

Type of Soil	Value of (C)
Very find sand and silt	**8.5**
Fine sand and alluvial soils	**7.0**
Medium sand	**6.0**
Coarse sand	**5.0**
Fine gravel	**4.0**
Medium gravel	**3.5**
Coarse gravel	**3.0**
Coarse gravel with boulders	**2.5**
Soft clay	**3.0**
Medium clay	**2.0**
Hard clay	**1.8**
Very hard clay	**1.6**

The uplift pressure by this method can be calculated as follows:

$$Pi = 100\left(\frac{Lw - Li}{Lw}\right)$$

Lw: is the total creep line length calculated by Lane's method

Li: is the sum of creep line length to point (i) at which uplift pressure has to be calculated.

Pi: the percentage pressure at point (i).

Then the uplift pressure at point (i) = Ui

Ui = H * Pi * γw

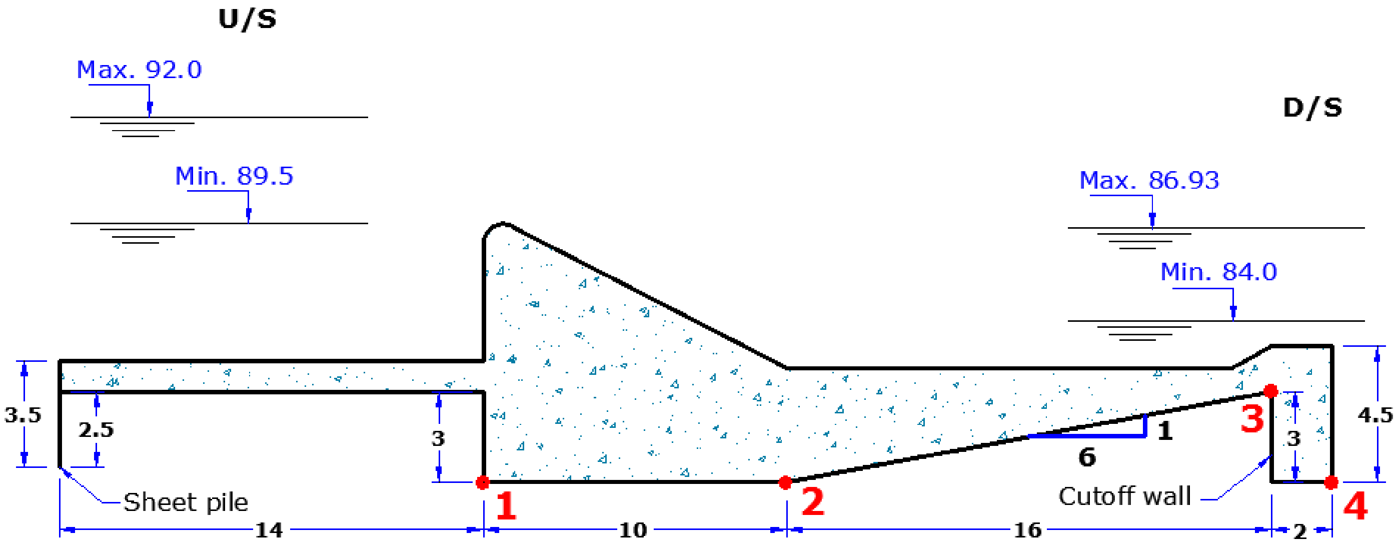
Where (H) is the maximum head of water

Thickness of floor at point (i) = ti

$$ti = \frac{4}{3}\left[\frac{Ui}{\gamma c - \gamma w}\right]$$

Lane's creep coefficient $(C) = \frac{Lw}{H}$

Example: For the diversion weir shown in the following sketch. Find the net uplift pressure under the structure at points (1, 2, 3, and 4) and draw the uplift pressure diagram, then find the thickness of floor at points (2, 3), use (C=4), All dimensions are in meters.



Sol.

$$Lw = \frac{1}{3}\sum N + \sum V$$

$$Lw = 3.5 + 2.5 + 3 + 3 + 4.5 + \left(\frac{14+10+16.3+2}{3}\right) = 30.6 \text{ m}$$

H = Max. difference of water levels u/s and d/s (H=89.5 – 84.0=5.5m)

C * H = 4 * 5.5 = 22

So Lw > C * H → the structure safe against piping.

Important note:

If (C * H > Lw) increase u/s apron length or increase cutoffs Number and depth.

According to Lane's method

$$Pi = 100\left(\frac{Lw-Li}{Lw}\right), \quad Ui = H * Pi * \gamma w, \quad ti = \frac{4}{3}\left[\frac{Ui}{\gamma c-\gamma w}\right]$$

Point	Li (m)	Pi %	Ui kN/m^2	Thickness of floor (m)	
				Required	Adopted
1	3.5+2.5+3+14/3 = 13.67	55.33	30.43		
2	13.67+10/3 = 16.93	44.5	24.475	2.33	2.5
3	16.93+18.25/3 = 23	24.6	13.53	1.42	1.5
4	23+3+2/3 = 26.67	12.6	6.93		

At point (1)

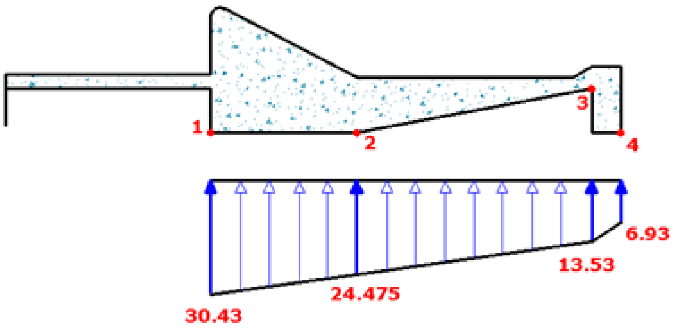
Lw = 30.6 m

L_1 = 3.5+2.5+3+14/3 = 13.67 m

$$P_1 = 100\left(\frac{Lw - Li}{Lw}\right) = 100\left(\frac{30.6 - 13.6}{30.6}\right) = 55.33\ \%$$

$U_1 = H * P_1 * \gamma w = 5.5 * 0.5533 * 10 = 30.43$ kN/m^2

t_1 = not required at point (1)

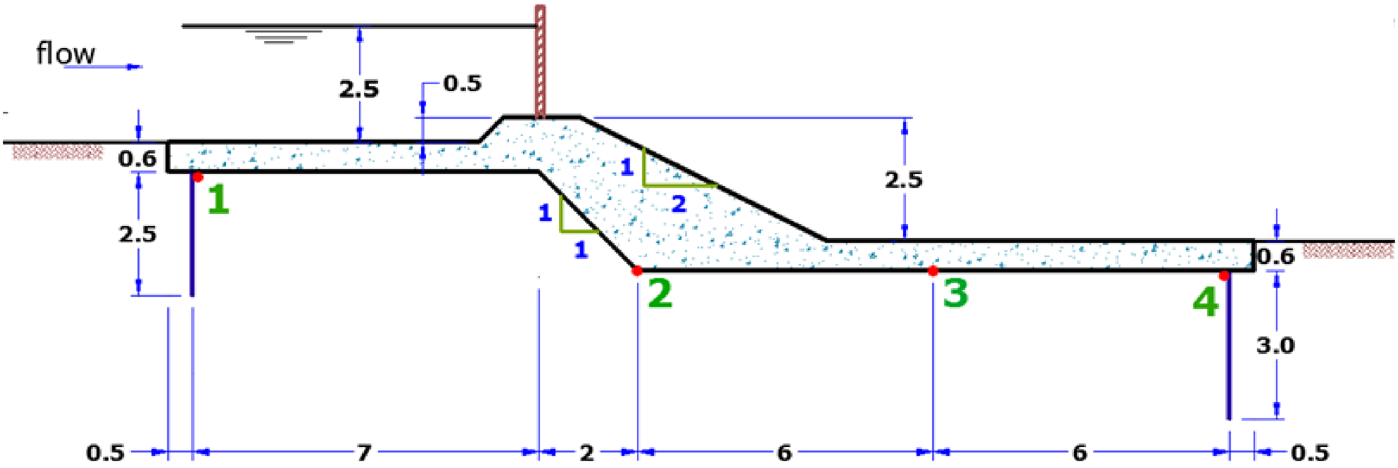


Uplift Pressure Diagram

Example: For the structure shown below and by using Bligh and Lane methods find the following:

1) The uplift pressure at points (1, 2, 3, and 4)
2) The thickness of floor at points (2, 3, and 4)
3) Check the structure against piping

(Use Lane's creep coefficient =5)

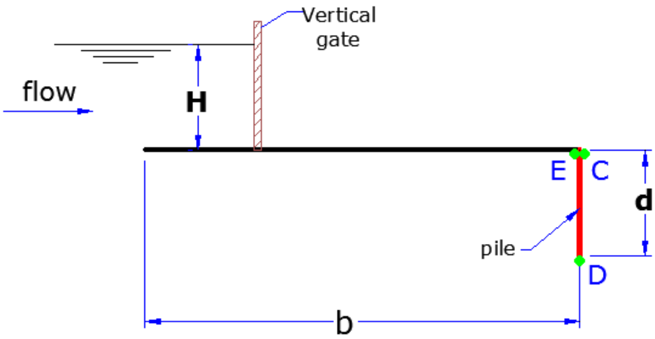


Khosla's Method

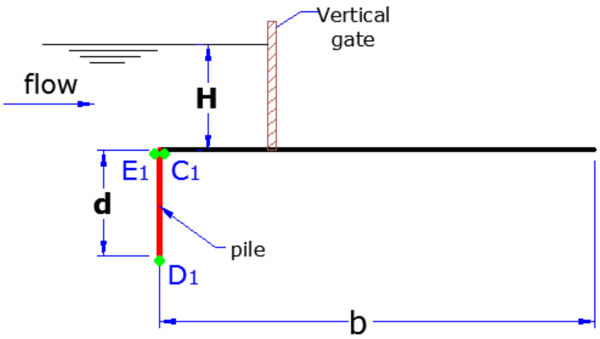
It is used to find the uplift pressure at the key points in hydraulic structures like weirs or barrage.

In this method a complete section of the hydraulic structure is split up in to a number of simple standard forms of known analytical solution as shown below.

A. Horizontal straight floor of negligible thickness with a sheet pile at the **u/s** and a sheet pile at the **d/s** end.

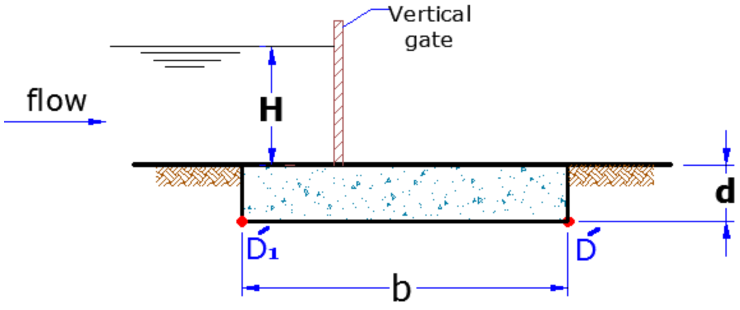


Pile at D/S end



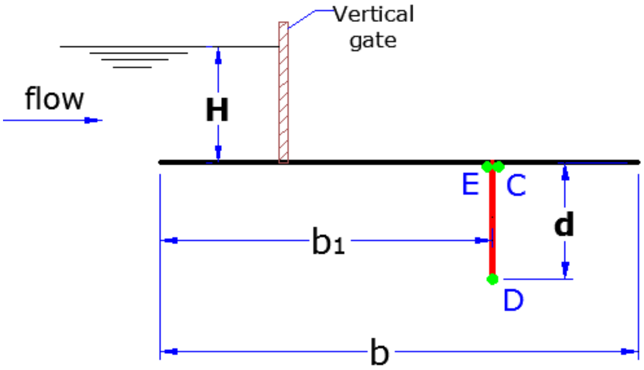
Pile at U/S end

B. Horizontal straight floor depressed below the bed and having no vertical cut off at all.



Depressed pile or Floor

C. Horizontal straight floor of negligible thickness with a cut off sheet pile at some intermediate point.



Intermediate Pile

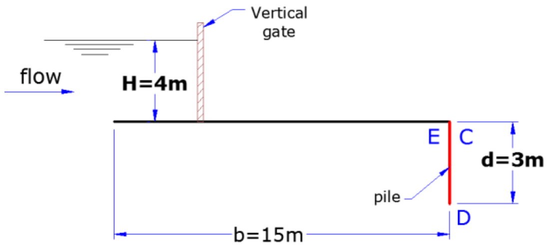
Example: length of horizontal floor is 15m and 3m deep vertical sheet pile, head of water is 4m, find the uplift pressure at the key points.

Sol.

From figure (15)

$$\propto = \frac{b}{d} = \frac{15}{3} = 5 \quad \rightarrow \quad \therefore \frac{1}{\propto} = \frac{1}{5} = 0.2 \quad or \quad \frac{1}{\propto} = \frac{d}{b} = \frac{3}{15} = 0.2$$

a) If pile is provided at D/S end.



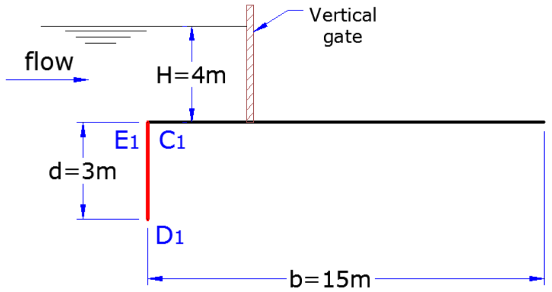
$\emptyset\, D = 27\%\ of\ H \rightarrow pressure\ at\ D$

$P_D = \frac{27}{100} \times H = 0.27 \times 4 = 1.08\ m,$ Pressure head of water

$\emptyset\, E = 40\%\ of\ H \rightarrow pressure\ at\ E, P_E = 0.4 \times 4 = 1.6\ m$

b) If pile is provided at U/S end.

In this case pressure at key points C₁, D₁ can be found out by first finding ØD and ØE for the case when pile is at D/S end and then by following relation below:



$\emptyset C_1 = 100 - \emptyset\, E$

$\emptyset D_1 = 100 - \emptyset\, D$

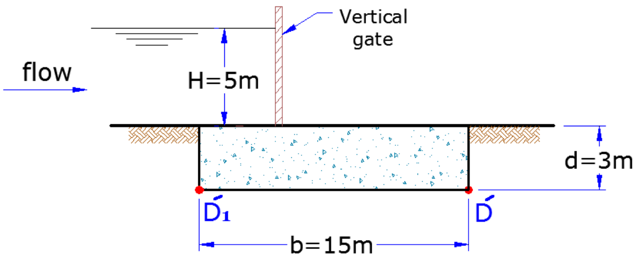
For our case $\emptyset E = 40\%\ and\ \emptyset D = 27\%$

$\therefore \emptyset C_1 = 100 - 40 = 60\%\ of\ H \implies$

$\therefore P_{C1} = 0.6 \times 4 = 2.4\ m$

$\therefore \emptyset D_1 = 100 - 27 = 73\%\ of\ H \implies \therefore P_{D1} = 0.73 \times 4 = 2.92\ m$

Example: Thickness of the floor is 3m and length of the floor is 15m. Find the uplift pressure at bottom points of D/S and U/S ends of the floor. Water fill is 5m above the floor.



Sol.

$$\frac{1}{\propto} = \frac{d}{b} = \frac{3}{15} = 0.2$$

From figure (15)

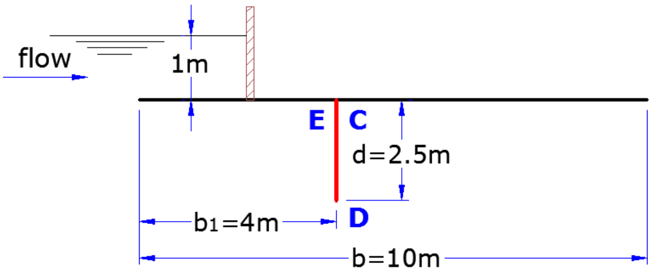
$\emptyset \acute{D} = 18\%\ of\ H \rightarrow \therefore pressure\ at\ \emptyset \acute{D} = 0.18 \times 5 = 0.4\ m$

$\emptyset \acute{D}_1 = 100 - \emptyset \acute{D} = 100 - 18 = 82\%\ of\ H \rightarrow P\acute{D}_1 = 0.82 \times 5 = 4.1\ m$

Example: find the pressure at points **C, D, E** if the floor have intermediate pile, b=10m, b_1=4m, head of water 1m and d=2.5m.

Sol.

$$\propto = \frac{b}{d} = \frac{10}{2.5} = 4 \Rightarrow \text{Ratio} = \frac{b_1}{b} = \frac{4}{10} = 0.4$$



From figure (15)

$$\therefore \emptyset C = 41\%\ of\ H$$

$To\ find\ \emptyset E\ for\ any\ value\ of(\alpha)\ and\ base\ ratio\ \frac{b_1}{b}\ read\ \emptyset C\ for\ base\ ratio\ \left(1-\frac{b_1}{b}\right)\ for\ that\ \ value\ of(\alpha), and\ subtracte\ from\ 100$

$$\therefore 1-0.4 = 0.6\ and\ \propto = 4 \ \rightarrow\ \emptyset C = 29\%$$

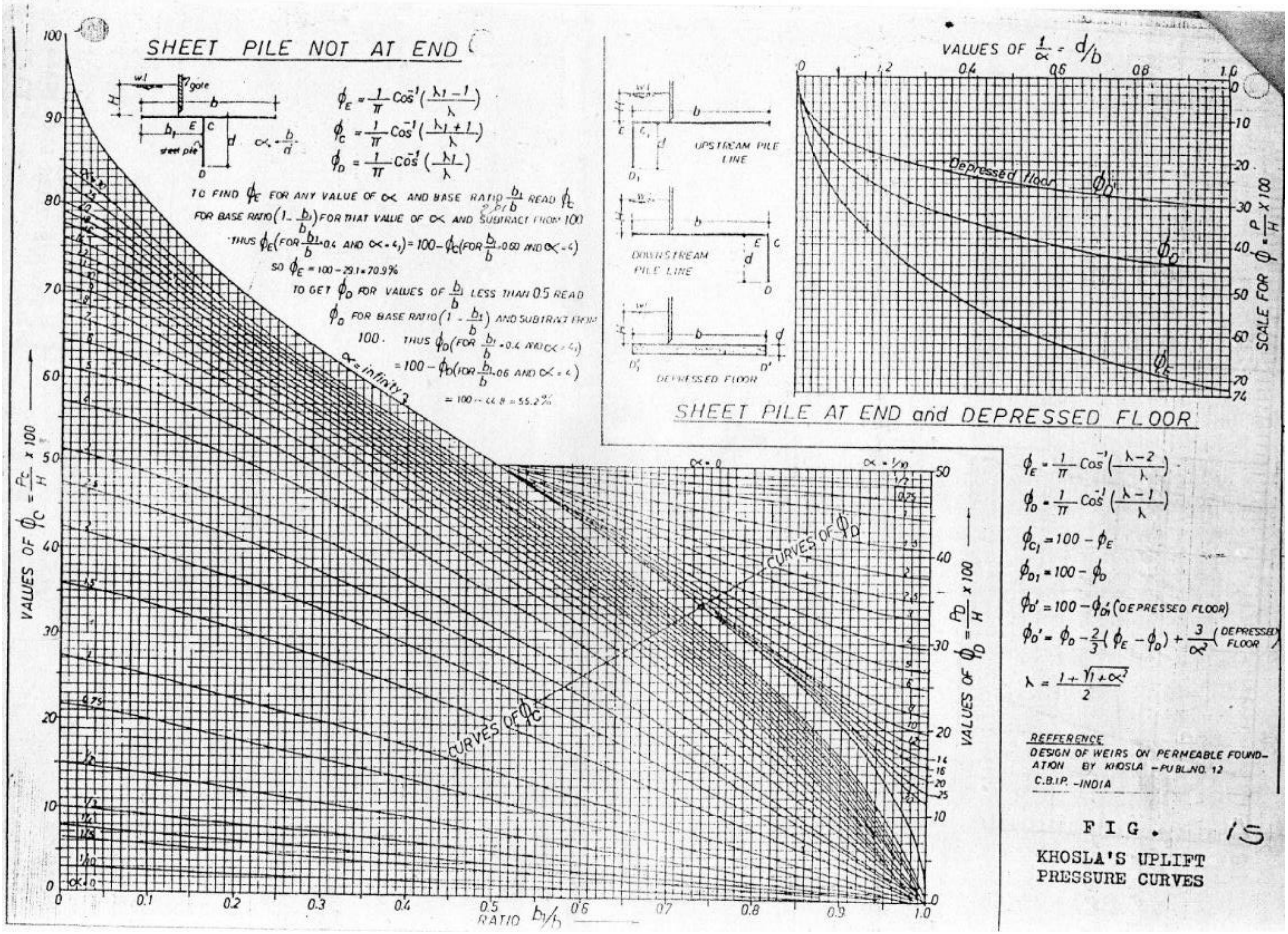
$$\emptyset E = 100-29 = 71\%\ of\ H \ \rightarrow \therefore P_E = 0.71 \times 1 = 0.71\ m$$

$To\ get\ \emptyset D\ for\ values\ of\ \frac{b_1}{b}\ less\ than\ 0.5\ read\ \emptyset D\ for\ base\ ratio \left(1-\frac{b_1}{b}\right)\ and\ subtracte\ from\ 100$

$$\therefore \emptyset D\ for\ \propto = 4\ and\ (1-0.4 = 0.6) \rightarrow\ \emptyset D = 45\%$$

$$\emptyset D = 100-45 = 55\%\ of\ H$$

$$\therefore P_D = 0.55 \times 1 = 0.55\ m\ \ pressure\ head\ of\ water$$



SHEET PILE NOT AT END

$$\phi_E = \frac{1}{\pi} \cos^{-1}\left(\frac{\lambda_1 - 1}{\lambda}\right)$$

$$\phi_C = \frac{1}{\pi} \cos^{-1}\left(\frac{\lambda_1 + 1}{\lambda}\right)$$

$$\phi_D = \frac{1}{\pi} \cos^{-1}\left(\frac{\lambda_1}{\lambda}\right)$$

TO FIND ϕ_E FOR ANY VALUE OF α AND BASE RATIO $\frac{b_1}{b}$ READ ϕ_C FOR BASE RATIO $\left(1 - \frac{b_1}{b}\right)$ FOR THAT VALUE OF α AND SUBTRACT FROM 100

THUS $\phi_E\left(\text{FOR } \frac{b_1}{b} = 0.4 \text{ AND } \alpha = 4\right) = 100 - \phi_C\left(\text{FOR } \frac{b_1}{b} = 0.60 \text{ AND } \alpha = 4\right)$

SO $\phi_E = 100 - 29.1 = 70.9\%$

TO GET ϕ_D FOR VALUES OF $\frac{b_1}{b}$ LESS THAN 0.5 READ ϕ_D FOR BASE RATIO $\left(1 - \frac{b_1}{b}\right)$ AND SUBTRACT FROM 100. THUS $\phi_D\left(\text{FOR } \frac{b_1}{b} = 0.4 \text{ AND } \alpha = 4\right)$

$= 100 - \phi_D\left(\text{FOR } \frac{b_1}{b} = 0.6 \text{ AND } \alpha = 4\right)$

$= 100 - 44.8 = 55.2\%$

SHEET PILE AT END and DEPRESSED FLOOR

$$\phi_E = \frac{1}{\pi} \cos^{-1}\left(\frac{\lambda - 2}{\lambda}\right)$$

$$\phi_D = \frac{1}{\pi} \cos^{-1}\left(\frac{\lambda - 1}{\lambda}\right)$$

$$\phi_{C_1} = 100 - \phi_E$$

$$\phi_{D_1} = 100 - \phi_D$$

$$\phi_{D'} = 100 - \phi_{D_1'} \text{ (DEPRESSED FLOOR)}$$

$$\phi_{D'} = \phi_D - \frac{2}{3}(\phi_E - \phi_D) + \frac{3}{\alpha^2} \text{ (DEPRESSED FLOOR)}$$

$$\lambda = \frac{1 + \sqrt{1 + \alpha^2}}{2}$$

REFFERENCE

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FIG. 15

KHOSLA'S UPLIFT PRESSURE CURVES

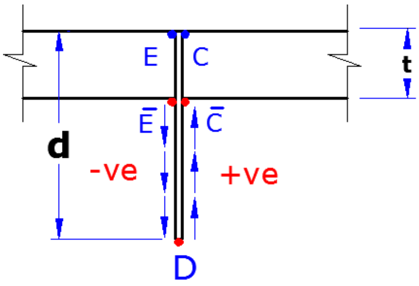
Corrections for the Khosla's method

1. Correction due to floor thickness (C_t)
2. Correction due to pile interference (C_p)
3. Correction due to slope (C_s)

1- Thickness Correction

$$C_t\ for\ point\ C = \frac{t}{d}[\emptyset D - \emptyset C]$$

$$C_t\ for\ point\ E = \frac{t}{d}[\emptyset E - \emptyset D]$$



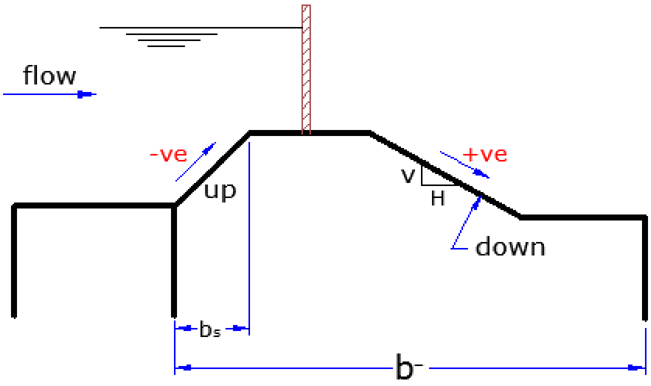
أي ان النقاط الحقيقية لكل من C, E
هي في واقع الحال C^{-}, E^{-}

Note: The pressure $P_E^- < P_E$ so the correction is (–) for E and the direction of flow is down, and the $P_C^- > P_C$ so the correction is (+) for C and the direction of flow is up.

2- Correction due to slope

$$C_S = \mp \frac{b_s}{b^-} \times C$$

$$= \mp C.F \times \frac{Horizontal\ length\ of\ slope}{Distanse\ between\ two\ piles}$$



b_s= horizontal length of slope

b^-= distance between two piles

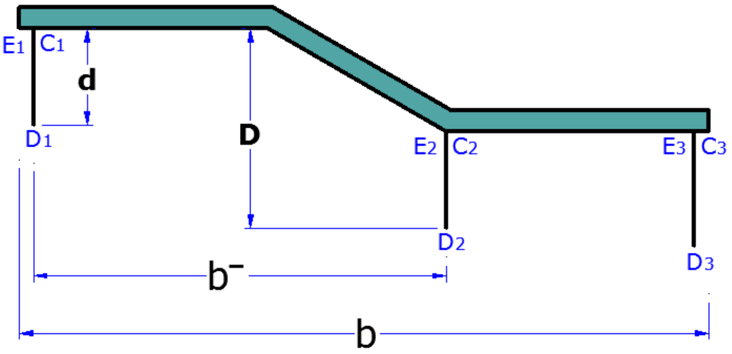
C = correction factor for slope

Values of correction for standard slopes shown in the table below:

Slope	Correction Factor (C.F)
1:1	11.2
1:2	6.5
1:3	4.5
1:4	3.3
1:5	2.8
1:6	2.5
1:7	2.3
1:8	1

ملاحظة: يؤخذ التصحيح نتيجة الميلان فقط عندما تكون بدايته او نهايته مرتبطة ب (pile) فيؤخذ تأثيره على ذلك ال (pile) .

3- Correction due to pile interference



$$C_p = \mp 19\sqrt{\frac{D}{\bar{b}}} \times \left[\frac{d+D}{b}\right]$$

Where:

Cp = correction in percentage (%)

b‾ = the distance between two piles

b = total floor length

d = depth of pile on which the effect is to be taken

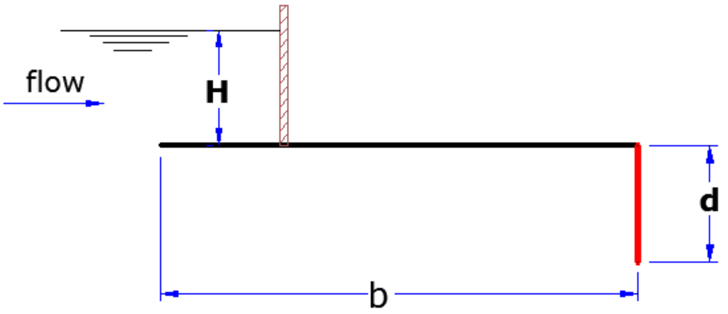
D = depth of pile line, the influence of which has to determine on the neighboring pile of depth (d).

Note: This correction is (+ve) for points rear of back water and (–ve) for points forward in the direction of flow.

Exit gradient (G.E)

The pressure gradient at the exit point is called exit gradient (GE).

$$G.E = \frac{H}{d} \times \frac{1}{\pi\sqrt{\lambda}}$$



Where:

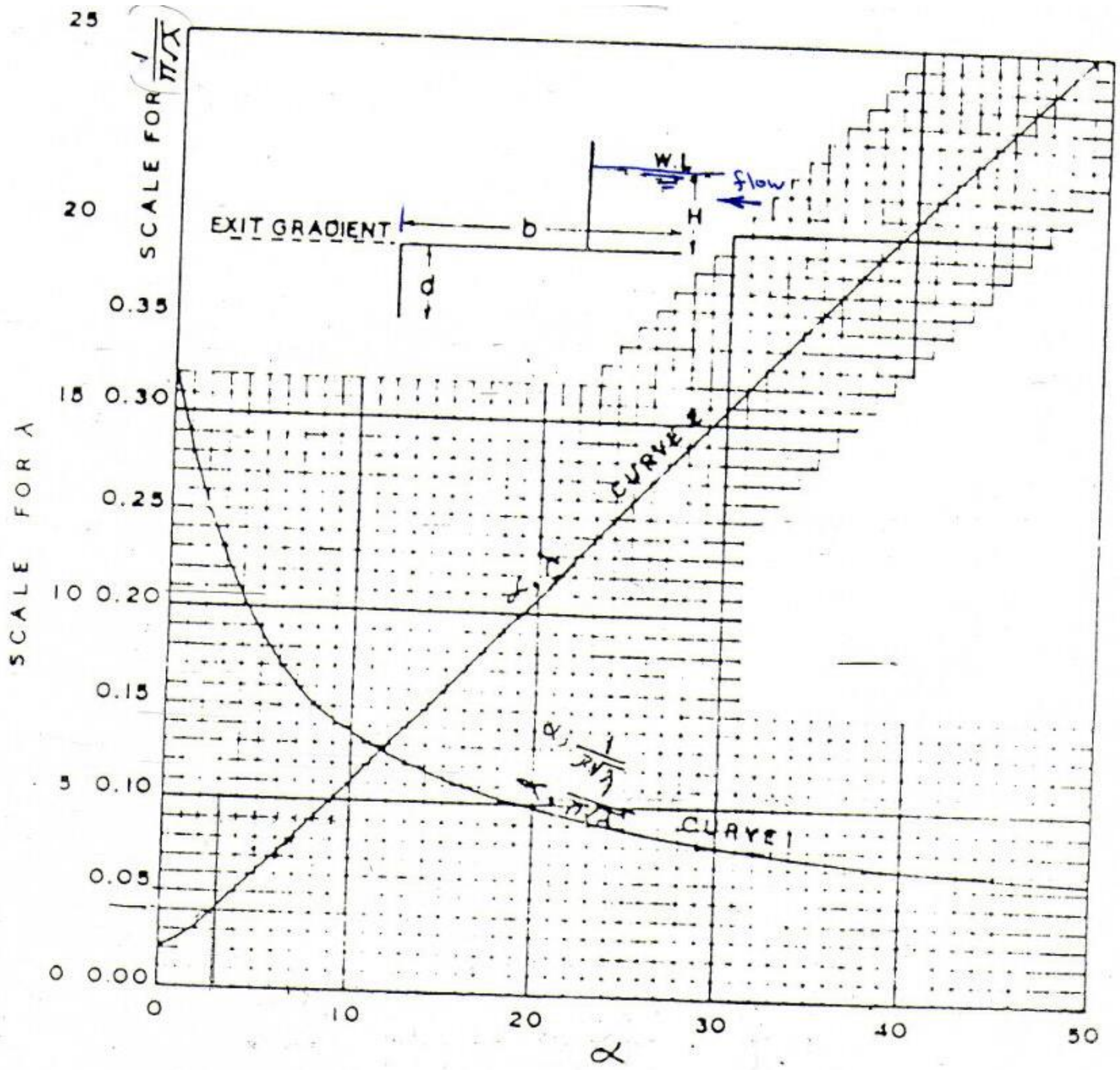
d = D/S cutoff (depth of d/s pile)

H = maximum static head

$$\lambda = \frac{1+\sqrt{1+\alpha^2}}{2} \quad , \quad \alpha = \frac{b}{d}$$

Type of soil	Safe exit gradient type
Shingle	1/4 to 1/5
Coarse sand	1/5 to 1/6
Fine sand	1/6 to 1/7

The value of (G.E) can be compute from fig. (13).



$$\alpha = \frac{b}{d}$$

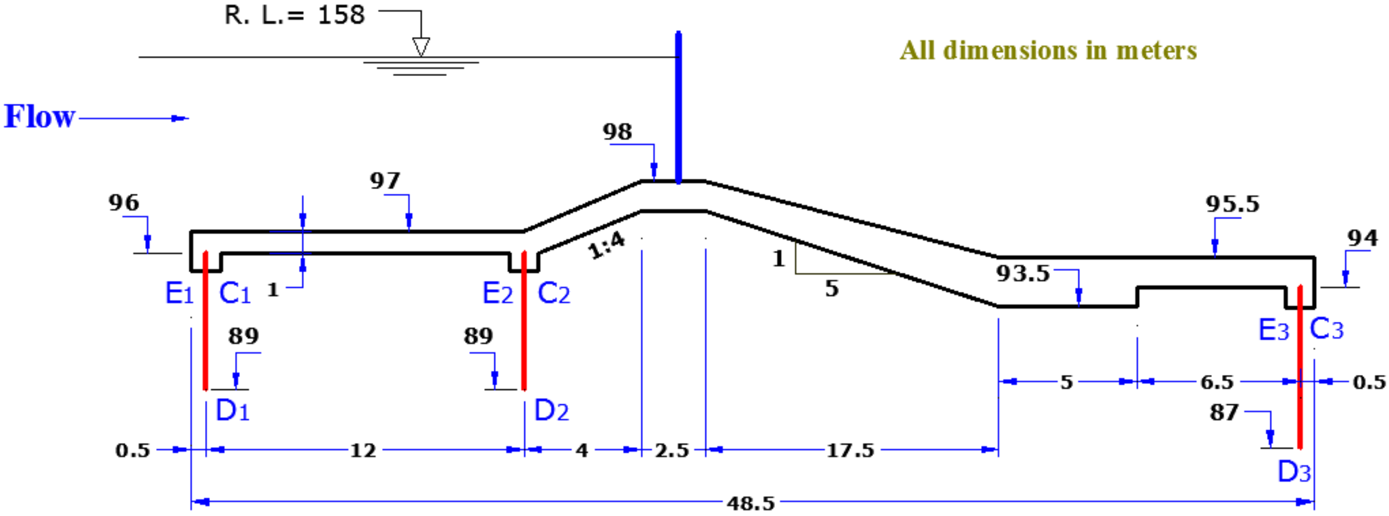
$$\lambda = \frac{1+\sqrt{1+\alpha^2}}{2}$$

$$G_E = \frac{H}{d}\,\frac{1}{\pi\sqrt{\lambda}}$$

FIG. 13

KHOSLA'S EXIT GRADIENT CURVES

Example: Shows the sketch of the barrage below. The various dimensions and reduced levels are shown in the figure; determine the uplift pressure at the key points and the exit gradient to check the structure against piping, permissible exit gradient is (1/8).



Sol.

Consider pile line (1), U/S end pile

d = 97 – 89 = 8 m

b = 48.5 m

$$\frac{1}{\alpha} = \frac{d}{b} = \frac{8}{48.5} = 0.165$$

$ØC_1$ = 100 – ØE, $ØD_1$ = 100 – ØD

From Khosla's figure

$ØC_1$ = 100 – ØE = 100 – 36 = 64%

$ØD_1$ = 100 – ØD = 100 – 25 = 75%

$ØE_1$ = 100%

Correction for $ØC_1$:

1- Correction for floor thickness

t = 97 – 96 = 1 m

$$Ct_{\emptyset C1} = \frac{t}{d}[\emptyset_{D1} - \emptyset_{C1}] = \frac{1}{8}[75 - 64] = 1.37 \ \ (+ve) \uparrow$$

2- Mutual interference correction for pile (1) due to pile (2)

$$C_p = \mp 19\sqrt{\frac{D}{\acute{b}}} \times \left[\frac{d+D}{b}\right]$$

d = 96 – 89 = 7 m

$\acute{b}$ = 12 m

b = 48.5 m

D = 96 – 89 = 7 m

$$C_{p_{\emptyset C1}} = +19\sqrt{\frac{7}{12}} \times \left[\frac{7+7}{48.5}\right] = 4.19\% \ \ (positive)$$

Hence corrected pressure at point ($ØC_1$)

$ØC_1$ = 64 + 1.37 + 4.19 = 69.56 %

$ØD_1$ = 75%

Consider intermediate pile

d = 97 – 89 = 8 m

b = 48.5 m

b1 = 12.5 m

$$\alpha = \frac{b}{d} = \frac{48.5}{8} = 6.1 \ \ , \qquad \frac{b_1}{b} = \frac{12.5}{48.5} = 0.26 \quad \rightarrow base\ ratio$$

From Khosla's figure

$ØC_2$ = 54%

To find $ØE_2$ use base ratio (1 – b_1/b)

1 – 0.26 = 0.74 , α = 6.1 $\longrightarrow$ ØC = 24%

So $ØE_2$ = 100 – 24 = 76% of H

To find $ØD_2$ use base ratio (1 – b_1/b)

1 – 0.26 = 0.74 , α = 6.1 $\longrightarrow$ ØD = 36%

So $ØD_2$ = 100 – 36 = 64% of H

<u>Correction on (ØC₂):</u>

1- Correction for floor thickness

t = 97 – 96 = 1 m

$$Ct_{\emptyset C2} = \frac{t}{d}[\emptyset_{D2} - \emptyset_{C2}] = \frac{1}{8}[64 - 54] = 1.25 \ (+ve) \uparrow$$

2- Correction for interference of pile (3) (D/S end pile)

d = 96 – 89 = 7 m

D = 96 – 87 = 9 m , $\acute{b} = 35.5\, m$

$$C_{p_{\emptyset C2}} = +19\sqrt{\frac{9}{35.5}} \times \left[\frac{7+9}{48.5}\right] = 3.16\% \ (positive)$$

3- Correction due to slope

bs = 4.0 m, $\acute{b} = 35.5\, m$

$$C_{s\,\emptyset C2} = \mp \frac{bs}{\acute{b}} \times C$$

From the table and for the slope equal to (1:4) the value of C = 3.3

$$C_{s\,\emptyset C2} = -\left[\frac{4}{35.5} \times 3.3\right] = -0.37\% \quad (-ve)$$

<u>Correction on (ØE₂):</u>

$$Ct_{\emptyset E2} = \frac{t}{d}[\emptyset_{E2} - \emptyset_{D2}] = -\frac{1}{8}[76 - 64] = -1.5 \ (-ve) \downarrow$$

$$C_{p_{\emptyset E2}} = -19\sqrt{\frac{7}{12}} \times \left[\frac{7+7}{48.5}\right] = -4.2\% \ (negitive)$$

Hence corrected pressures are

$\emptyset E_2$ = 76 – (1.5 + 4.2) = 70.5% of H

$\emptyset C_2$ = 54 + 1.25 + 3.16 – 0.37 = 58% of H

Pile (3) at the D/S end

d = 95.5 – 87 = 8.5 m

$$\frac{1}{\alpha} = \frac{d}{b} = \frac{8.5}{48.5} = 0.175$$

From khosla's figure

$\emptyset E_3$ = 37%

$\emptyset D_3$ = 25%

$\emptyset C_3$ = 0.0%

Correction on ($\emptyset E_3$):

t = 1.5 m , d = 8.5 m

$$Ct_{\emptyset E3} = \frac{t}{d}[\emptyset_{E3} - \emptyset_{D3}] = -\frac{1.5}{8.5}[37 - 25] = -2.12 \ \ (-ve) \ \downarrow$$

$$C_{p_{\emptyset E3}} = \mp 19\sqrt{\frac{D}{\acute{b}} \times}\left[\frac{d + D}{b}\right] = -19\sqrt{\frac{5}{35.5} \times}\left[\frac{7 + 5}{48.5}\right] = -1.76\% \ \ (negitive)$$

Hence corrected pressure is

$\emptyset E_3$ = 37 – (2.12+1.76) = 33.12% of H

Max. Head = 100.5 – 95.5 = 5.0 m

Point	% pressure , Ø	Pressure head in meters
C_1	69.56	3.48=(69.56/100)*5
D_1	75	3.75
C_2	58	2.9
D_2	64	3.2
E_2	70.5	3.525
E_3	33.12	1.66
D_3	25	1.25

Exit Gradient (GE)

H = 5.0 m

Depth of cutoff at D/S end = 95.5 – 87 = 8.5 m

$$\alpha = \frac{b}{d} = \frac{48.5}{8.5} = 5.7$$

From exit gradient curve (Figure 13) and for α = 5.7

$$\frac{1}{\pi\sqrt{\lambda}} = 0.175$$

$$\therefore\ GE\ = \frac{H}{d} \times \frac{1}{\pi\sqrt{\lambda}} = \frac{5}{8.5} \times 0.175 = \frac{1}{9.7} < \frac{1}{8}\ \ \rightarrow\ Hence\ \frac{1}{9.7}\ exit\ gradient\ is\ safe.$$

Hence the structure will be safe against piping

To find the Exit Gradient by using the equations:

$$\alpha = \frac{b}{d} = \frac{48.5}{8.5} = 5.7$$

$$\lambda = \frac{1 + \sqrt{1 + (\alpha)^2}}{2} = \frac{1 + \sqrt{1 + (5.7)^2}}{2} = 3.39$$

$$\therefore GE\ = \frac{H}{d} \times \frac{1}{\pi\sqrt{\lambda}} = \frac{5}{8.5} \times \frac{1}{3.14\sqrt{3.39}} = \frac{1}{9.8} < \frac{1}{8} \rightarrow\ Hence\ \frac{1}{9.8}\ exit\ gradient\ is\ safe.$$

Hence the structure will be safe against piping.

Depth of Cutoff

The sheet piles at the ends must go below the deepest anticipated scour level.

a) D/S cutoff

The depth d of the cutoff can be obtained from the following equation;

D/S *cutoff* = *(1.25 to 1.5) R* .

The normal depth of scour (R) is given by Lacey's equation as:

$$R = 1.35\left(\frac{q^2}{f}\right)^{\frac{1}{3}}$$

R = scour depth, m

f = silt factor = $1.76\sqrt{D_{mm}}$

D_{mm} = Diameter of particle of soil in mm.

$q = \frac{Q}{B}$ (discharge per unit widthm^3/s/m)

b) U/S cutoff

U/S cutoff = (1 to 1.25) R