SEEPAGE THEORIES

Highly Important for RPSC AEn Mains (2018)
LEARNING OUTCOME

After taking this lecture, students should be able to:

(1). Understand the seepage phenomenon and its importance in the design of hydraulic structures,

(2). Apply the seepage theories to calculate the uplift pressures at various point under hydraulic structures of complex bed configurations
Seepage is the slow escape of a liquid or gas through porous material or small holes.

Seepage is one of the applications of ground water hydraulic. The aims of studying seepage in civil engineering are:

1- To find the discharge of seepage through and beneath the structure
2- To find up lift pressure under the structure
3- To find solution for foundation and piping failures
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Hydraulic structures may either be founded on an impervious solid rock foundation or on pervious foundation.

Whenever such a structure is founded on pervious foundation, it is subjected to seepage of water beneath the structure, in addition to all other forces.

Schematic Diagram of a dam

US: upstream side  DS: downstream side

Tail water

In case of no tail water

In case of tail water exist

Uplift pressure due to seepage

Schematic Diagram of a dam
SEEPAGE THEORIES

The water seeping below the body of the hydraulic structure, endanger the stability of the structure and may cause its failure, either by

(1). Piping(also called undermining); or by
(2). Direct uplift
SEEPAGE THEORIES

(1). Failure by Piping or undermining

When seepage water retains sufficient residual force at the emerging downstream end of the work, it may lift up the soil particles. This leads to increased porosity of the soil by progressive removal of soil from beneath the foundation. The structure may ultimately subside into the hollow so formed, resulting in the failure of the structure.
SEEPAGE THEORIES

(2). Failure by Direct uplift.

The water seeping below the structure, exerts an uplift pressure on the floor of structure. If this pressure is not counterbalanced by the weight of the concrete of masonry floor, the structure will fail by rupture of a part of the floor.
SEEPAGE THEORIES

Generally there are three seepage theories

1. Bligh’s creep theory
2. Lane weighted creep theory
3. Khosla theory
1. **Bligh’s creep theory**

- According to Bligh’s Theory, the percolating water follows the outline of the base of the foundation of the hydraulic structure. 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, $L$. 

  $$L = LH + LV$$

- Further, it is assumed in this theory, that the loss of head is proportional to the length of the creep.

- If $HL$ 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 (i.e. $HL/L$) is called the **hydraulic gradient**.

- Note, Bligh makes no distinction between horizontal and vertical creep.
Consider a section a shown in Fig above. Let $HL$ be the difference of water levels between upstream and downstream ends. Water will seep along the bottom contour as shown by arrows. It starts percolating at $A$ and emerges at $B$.

*The total length of creep is given by*

$$L = d_1 + d_1 + L_1 + d_2 + d_2 + L_2 + d_3 + d_3$$

$$= (L_1 + L_2) + 2(d_1 + d_2 + d_3) = b + 2(d_1 + d_2 + d_3)$$
Head loss per unit length or hydraulic gradient = \[ \frac{H_L}{b + 2 \times (d_1 + d_2 + d_3)} \] = \frac{H_L}{L}

And the head losses \( \left( \frac{H_L}{L} \times 2d_1 \right) \left( \frac{H_L}{L} \times 2d_2 \right) \left( \frac{H_L}{L} \times 2d_3 \right) \) will occur at locations of three vertical cutoffs.

The hydraulic gradient line (H.G. Line) can then be drawn as shown in figure above.
SEEPAGE THEORIES

(i) Safety against piping or undermining:

According to Bligh, the safety against piping can be ensured by providing sufficient creep length, given by \( L = C \cdot H \cdot L \), where \( C \) is the Bligh’s Coefficient for the soil. Different values of \( C \) for different types of soils are tabulated below:

<table>
<thead>
<tr>
<th>SL No.</th>
<th>Type of Soil</th>
<th>Value of C</th>
<th>Safe Hydraulic gradient should be less than</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fine micaceous sand</td>
<td>15</td>
<td>1/15</td>
</tr>
<tr>
<td>2</td>
<td>Coarse grained sand</td>
<td>12</td>
<td>1/12</td>
</tr>
<tr>
<td>3</td>
<td>Sand mixed with boulder and gravel, and for loam soil</td>
<td>5 to 9</td>
<td>1/5 to 1/9</td>
</tr>
<tr>
<td>4</td>
<td>Light sand and mud</td>
<td>8</td>
<td>1/8</td>
</tr>
</tbody>
</table>

Note: The hydraulic gradient i.e. \( HL/L \) is then equal to \( 1/C \). Hence, it may be stated that the hydraulic gradient must be kept under a safe limit in order to ensure safety against piping. i.e.,

\[ HL/L \leq 1/C \]
(ii) Safety against uplift pressure:

The ordinates of the H.G line above the bottom of the floor represent the residual uplift water head at each point. Say for example, if at any point, the ordinate of H.G line above the bottom of the floor is 1 m, then 1 m head of water will act as uplift at that point. If $h'$ meters is this ordinate, then water pressure equal to $h'$ meters will act at this point, and has to be counterbalanced by the weight of the floor of thickness say $t$.

\[
\text{Uplift pressure} = \gamma_w \times h' \quad \text{[where } \gamma_w \text{ is the unit weight of water]}
\]

\[
\text{Downward pressure} = (\gamma_w \times G) \times t \quad \text{[Where } G \text{ is the specific gravity of the floor material]}
\]

For equilibrium,

\[
\gamma_w \times h' = \gamma_w \times G \times t
\]

\[
\Rightarrow h' = G \times t
\]

Subtracting $t$ on both sides, we get

\[
(h' - t) = (G \times t - t) = t(G - 1)
\]

\[
\Rightarrow t = \frac{h'}{G - 1} = \frac{h}{G - 1}
\]

Where,

- $h' - t = h = \text{Ordinate of the H.G line above the top of the floor}$
- $G - 1 = \text{Submerged specific gravity of the floor material}$
2. Lane’s Weighted Creep Theory

Bligh, in his theory, had calculated the length of the creep, by simply adding the horizontal creep length and the vertical creep length, thereby making no distinction between the two creeps.

However, Lane, on the basis of his analysis carried out on about 200 dams all over the world, stipulated that the horizontal creep is less effective in reducing uplift (or in causing loss of head) than the vertical creep.

He, therefore, suggested a weightage factor of 1/3 for the horizontal creep, as against 1.0 for the vertical creep.

\[ L = \frac{L_H}{3} + L_V \]
Thus in Fig, the total Lane’s creep length \((L_I)\) is given by
\[
L_I = (d_1 + d_1) + (1/3) L_1 + (d_2 + d_2) + (1/3) L_2 + (d_3 + d_3)
\]
\[
= (1/3) (L_1 + L_2) + 2(d_1 + d_2 + d_3)
\]
\[
= (1/3) b + 2(d_1 + d_2 + d_3)
\]
(i) Safety against piping or undermining:

To ensure safety against piping, according to this theory, the creep length $L_i$ must no be less than $C_1HL$, where $HL$ is the head causing flow, and $C_1$ is Lane’s creep coefficient given in table.

<table>
<thead>
<tr>
<th>SL No.</th>
<th>Type of Soil</th>
<th>Value of Lane’s Coefficient $C_1$</th>
<th>Safe Lane’s Hydraulic gradient should be less than</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very fine sand or silt</td>
<td>8.5</td>
<td>1/8.5</td>
</tr>
<tr>
<td>2</td>
<td>Fine sand</td>
<td>7.0</td>
<td>1/7</td>
</tr>
<tr>
<td>3</td>
<td>Coarse sand</td>
<td>5.0</td>
<td>1/5</td>
</tr>
<tr>
<td>4</td>
<td>Gravel and sand</td>
<td>3.5 to 3.0</td>
<td>1/3.5 to 1/3</td>
</tr>
<tr>
<td>5</td>
<td>Boulders, gravels and sand</td>
<td>2.5 to 3.0</td>
<td>1/2.5 to 1/3</td>
</tr>
<tr>
<td>6</td>
<td>Clayey soils</td>
<td>3.0 to 1.6</td>
<td>1/3 to 1/1.6</td>
</tr>
</tbody>
</table>

Note: The hydraulic gradient i.e. $HL/L_i$ is then equal to $1/C_1$. Hence, it may be stated that the hydraulic gradient must be kept under a safe limit in order to ensure safety against piping.

(ii) Safety against uplift pressure:

Same formulas as in Bligh’s theory.
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Using Bligh’ creep theory and Lane weighted creep theory, uplift pressure at any point under the structure can be calculated using the following formula

\[ UA = H(1 - LA/L) \]

Where
- \( UA \) = residual uplift pressure at any point A (excess HL)
- \( H \) = total uplift pressure at upstream (~HL)
- \( LA \) = creep length up to point A
- \( L \) = total creep length of the structure
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Example: Find the hydraulic gradient and the head at point D of the following structure for Static condition.

The water percolates at A and exits at B.
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Example: 1. Using Blight’s Creep theory

Total creep length, $L_c = 2 + 5 \times 2 + 10 + 2 \times 3 + 20 + 2 \times 7 + 2 = 64m$

Hydraulic gradient, $i = \frac{H}{L} = \frac{\Delta H}{L_c} = \frac{6}{64} = \frac{1}{10.66}$

According to the Bligh’s table, the structure is safe on gravel and sand but not on coarse and fine sand.

Remember $\frac{H}{L} \leq \frac{1}{C}$ !!!

Creep length up to point D ($L_{cD}$) $= 2 + 5 \times 2 + 15 + 2 \times 3 = 33m$

The residual uplift pressure head at D = $U_D = \Delta H(1-L_{cD}/L_c)$

$= 6(1-33/64) = 2.9m$
Example: 1. Using Blight’ Creep theory

The thickness of floor at any point should be sufficient to resist the residual uplift pressure. If h_D is the unbalanced head at point D, then

\[ h_D = U_D - (\text{elevation of point D} - \text{elevation of DS floor}) = 2.9 - (0) = 2.9 \text{ m} \] (Note: Point D is at the same level of DS floor level).

The thickness of floor, T_D, at point D should be \( h_D/(G-1) \) where G is the specific gravity of the concrete floor, let \( G_s = 2.24 \), then

\[ T_D = h_D/(G-1) = 2.9/(2.24-1) = 2.34\text{m} \]
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Example: 2. Using Lane Weighted Creep theory

Weighted creep length, Lwc = 2 + 2*5 + 2*3 + 2*7 + 2 + (10+20)/3 = 44m

Up to point D, LwcD = 2 + 2*5 + 3*2 +15/3 = 23m

Hydraulic gradient, \( i = \frac{HL}{L} = \frac{\Delta H}{Lwc} = \frac{6}{44} = \frac{1}{7.3} \)

According to Lane’s table the structure is safe on fine sand but not on very fine

Similarly

The residual uplift pressure head at D = UD = \( \Delta H(1-LwcD/Lwc) \)

\[ = 6(1-23/44) = 2.86m \]

\( T_D = h_D/(G-1) = 2.86/(2.24-1) = 2.3m \)
3. **Khosla’s Theory**

The seepage water does not creep along the outlines of hydraulic structure as started by Bligh, but on the other hand, this water moves along a set of stream-lines. This steady seepage in a vertical plane for a homogeneous soil can be expressed by *Laplacian equation*:

\[
\frac{d^2 \phi}{dx^2} + \frac{d^2 \phi}{dz^2} = 0
\]

Where, \(\phi\) = Flow potential = \(Kh\); \(K\) = the co-efficient of permeability of soil as defined by Darcy’s law, and \(h\) is the residual head at any point within the soil.

The above equation represents two sets of curves intersecting each other orthogonally. The resultant flow diagram showing both of the curves is called a *Flow Net*. 
Stream Lines: The streamlines represent the paths along which the water flows through the sub-soil. Every particle entering the soil at a given point upstream of the work, will trace out its own path and will represent a streamline. The first streamline follows the bottom contour of the works and is the same as Bligh’s path of creep. The remaining streamlines follow smooth curves transiting slowly from the outline of the foundation to a semi-ellipse, as shown below.
An equipotential line represents the joining of points of equal residual head, hence if piezometers were installed on an equipotential line, the water will rise in all of them up to the same level.

Every water particle on line AB is having a residual head \( h = h_1 \), and on CD is having a residual head \( h = 0 \), and hence, AB and CD are equipotential lines.
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Exit Gradient

The seepage water exerts a force at each point in the direction of flow and tangential to the streamlines as shown in figure above. This force (F) has an upward component from the point where the streamlines turns upward.

This force has the maximum disturbing tendency at the exit end, because the direction of this force at the exit point is vertically upward, and hence full force acts as its upward component. For the soil grain to remain stable, the submerged weight of soil grain should be more than this upward disturbing force. The disturbing force at any point is proportional to the gradient of pressure of water at that point (i.e. \( dp/dl \)). This gradient of pressure of water at the exit end is called the exit gradient. In order that the soil particles at exit remain stable, the upward pressure at exit should be safe. In other words, the exit gradient should be safe.
SEEPAGE THEORIES

Critical Exit Gradient

This exit gradient is said to be critical, when the upward disturbing force on the grain is just equal to the submerged weight of the grain at the exit. When a factor of safety equal to 4 to 5 is used, the exit gradient can then be taken as safe. In other words, an exit gradient equal to $1/4$ to $1/5$ of the critical exit gradient is ensured, so as to keep the structure safe against piping.

The submerged weight ($W_s$) of a unit volume of soil is given as:

$$
\gamma_w (1 - n) (S_s - 1)
$$

Where, $\gamma_w = \text{unit weight of water.}$  
$S_s = \text{Specific gravity of soil particles}$  
$n = \text{Porosity of the soil material}$

For critical conditions to occur at the exit point

$$
F = W_s
$$

Where $F$ is the upward disturbing force on the grain  
Force $F = \text{pressure gradient at that point} = \frac{dp}{dl} = \gamma_w \times \frac{dh}{dl}$

$$
\therefore \gamma_w \frac{dh}{dl} = \gamma_w (1 - n) (S_s - 1)
$$

$$
\frac{dh}{dl} = (1 - n) (S_s - 1)
$$
SEEPAGE THEORIES

Khosla’s Method of independent variables for determination of pressures and exit gradient for seepage below a weir or a barrage

In order to know as to how the seepage below the foundation of a hydraulic structure is taking place, it is necessary to plot the flow net. In other words, we must solve the Laplacian equations.

This can be accomplished either by mathematical solution of the Laplacian equations, or by Electrical analogy method, or by graphical sketching by adjusting the streamlines and equipotential lines with respect to the boundary conditions. These are complicated methods and are time consuming.

Therefore, for designing hydraulic structures such as weirs or barrage or pervious foundations, Khosla has evolved a simple, quick and an accurate approach, called Method of Independent Variables.
SEEPAGE THEORIES

In this method, a complex profile like that of a weir is broken into a number of simple profiles; each of which can be solved mathematically. Mathematical solutions of flownets for these simple standard profiles have been presented in the form of equations given in Figures (slide 29&30) and curves given in Plate (slide 31&32), which can be used for determining the percentage pressures at the various key points.

The simple profiles, which are most useful for analysis, are:

(i) A straight horizontal floor of negligible thickness with a sheet pile line on the u/s end and d/s end.

(ii) A straight horizontal floor depressed below the bed but without any vertical cut-offs.

(iii) A straight horizontal floor of negligible thickness with a sheet pile line at some intermediate point.
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\[ \phi_{C_1} = 100 - \phi_{E} \]
\[ \phi_{D_1} = 100 - \phi_{D} \]

\[ \phi_{E} = \frac{1}{\pi} \cos^{-1} \left( \frac{\lambda - 2}{\lambda} \right) \]
\[ \phi_{D} = \frac{1}{\pi} \cos^{-1} \left( \frac{\lambda - 1}{\lambda} \right) \]

where \[ \lambda = \frac{1 + \sqrt{1 + \alpha^2}}{2} \]
\[ \alpha = \frac{b}{d} \text{ (respective)} \]
\[ \phi_{D'} = \phi_D - \frac{2}{3} (\phi_E - \phi_D) + \frac{3}{\alpha^2} \]
\[ \phi'_{D_1} = 100 - \phi_{D'} \]

(c)

\[ \phi_E = \frac{1}{\pi} \cos^{-1} \left( \frac{\lambda_1 - 1}{\lambda} \right) \]
\[ \phi_D = \frac{1}{\pi} \cos^{-1} \left( \frac{\lambda_1}{\lambda} \right) \]
\[ \phi_C = \frac{1}{\pi} \cos^{-1} \left( \frac{\lambda_1 + 1}{\lambda} \right) \]

where
\[ \lambda = \frac{\sqrt{1 + \alpha_1^2} + \sqrt{1 + \alpha_2^2}}{2} \]
\[ \lambda_1 = \frac{\sqrt{1 + \alpha_1^2} - \sqrt{1 + \alpha_2^2}}{2} \]
\[ \alpha_1 = b_1/d \]
\[ \alpha_2 = b_2/d \]

(d)
Khasid's Pressure Curves

Sheet pile not at end

\[ \alpha = \frac{b_1}{d} \]

\[ \phi_E = \frac{1}{\pi} \cos^{-1} \left( \frac{b_1}{d} \right) \]

\[ \phi_C = \frac{1}{\pi} \cos^{-1} \left( \frac{b_1}{d} \right) \]

\[ \phi_D = \frac{1}{\pi} \cos^{-1} \left( \frac{b_1}{d} \right) \]

To find \( \phi \) for any value of \( \alpha \) and base ratio \( b/b_0 \), read \( \phi \) for base ratio \( (1-b/b_0) \) for that value of \( \alpha \) and subtract from 100.

Thus \( \phi \) for \( b/b_0 < 0.6 \) and \( \alpha \leq 1 \), \( 100 - \phi \) for \( b/b_0 > 0.6 \) and \( \alpha < 1 \).

To get \( \phi \) for values of \( b/b_0 < 0.5 \), read \( \phi \) for base ratio \( (1-b/b_0) \) and subtract from 100.

Thus \( \phi \) for \( b/b_0 < 0.4 \) and \( \alpha < 1 \), \( 100 - \phi \) for \( b/b_0 > 0.4 \) and \( \alpha < 1 \).

\[ \phi = \frac{1}{\pi} \cos^{-1} \left( \frac{b_1}{d} \right) \]

\[ \phi_C = \frac{1}{\pi} \cos^{-1} \left( \frac{b_1}{d} \right) \]

\[ \phi_E = \frac{1}{\pi} \cos^{-1} \left( \frac{b_1}{d} \right) \]

\[ \phi = 100 - \phi_E \]

\[ \phi_D = 100 - \phi_C \]

\[ \phi_D = 100 - \phi \] (Depressed floor)

\[ \phi_D = \phi - 2/3 \] (Depressed floor)

\[ \beta = \frac{b_1}{d} \]
Plate 11.2

\[ \alpha = \frac{b}{d} \]

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

\[ G_E = \frac{H}{d} \frac{1}{\pi \sqrt{\lambda}} \]
SEEPAGE THEORIES

The key points are the junctions of the floor and the pole lines on either side, and the bottom point of the pile line, and the bottom corners in the case of a depressed floor.

The percentage pressures at these key points for the simple forms into which the complex profile has been broken is valid for the complex profile itself, if corrected for

(a) Correction for the mutual interference of piles
(b) Correction for the thickness of floor
(c) Correction for the slope of the floor
SEEPAGE THEORIES

(a) Correction for the Mutual interference of Piles

The correction, \( C \), to be applied as percentage of head due to this effect, is given by

\[
C = 19 \sqrt\frac{D}{b'} \left( \frac{d + D}{b} \right)
\]

Where,

\( b' = \text{The distance between two pile lines.} \)

\( D = \text{The depth of the pile line, the influence of which has to be determined on the neighboring pile of depth, } d. \text{ D is to be measured below the level at which interference is desired.} \)

\( d = \text{The depth of the pile on which the effect is considered} \)

\( b = \text{Total floor length} \)
(a) Correction for the Mutual interference of Piles

The correction is positive for the points in the rear of back water, and subtractive for the points forward in the direction of flow. This equation does not apply to the effect of an outer pile on an intermediate pile, if the intermediate pile is equal to or smaller than the outer pile and is at a distance less than twice the length of the outer pile.
(a) Correction for the Mutual interference of Piles

Suppose in the above figure, we are considering the influence of the pile no (2) on pile no (1) for correcting the pressure at C1. Since the point C1 is in the rear, this correction shall be positive.

While the correction to be applied to E2 due to pile no (1) shall be negative, since the point E2 is in the forward direction of flow. Similarly, the correction at C2 due to pile no (3) is positive and the correction at E3 due to pile no (2) is negative.
SEEPAGE THEORIES

(b) Correction for the thickness of floor

In the standard form profiles, the floor is assumed to have negligible thickness. Hence, the percentage pressures calculated by Khosla’s equations or graphs shall pertain to the top levels of the floor. While the actual junction points E and C are at the bottom of the floor. Hence, the pressures at the actual points are calculated by assuming a straight line pressure variation.

Since the corrected pressure at E1 should be less than the calculated pressure at E1’, the correction to be applied for the joint E1 shall be negative. Similarly, the pressure calculated C1’ is less than the corrected pressure at C1, and hence, the correction to be applied at point C1 is positive.
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(b) Correction for the thickness of floor

\[ \varphi_{E1} = 1 \text{ don't need any correction} \]

\[ (C_t)_{C1} = \frac{t_1 \times (\varphi_{D1} - \varphi_{C1})}{d_1} \quad (+ve) \]

\[ (C_t)_{E2} = \frac{t_2 \times (\varphi_{E2} - \varphi_{D2})}{d_2} \quad (-ve) \]

\[ (C_t)_{C2} = \frac{t_2 \times (\varphi_{D2} - \varphi_{C2})}{d_2} \quad (+ve) \]

\[ (C_t)_{E3} = \frac{t_3 \times (\varphi_{E3} - \varphi_{D3})}{d_3} \quad (-ve) \]

\[ \varphi_{C3} = 0 \text{ don't need any correction} \]

\[ \text{Ct represent correction} \]
SEEPAGE THEORIES

(c) Correction for the slope of the floor

A correction is applied for a slopping floor, and is taken as positive for the downward slopes, and negative for the upward slopes following the direction of flow. Values of correction of standard slopes such as 1 : 1, 2 : 1, 3 : 1, etc. are tabulated below.

<table>
<thead>
<tr>
<th>Slope (H : V)</th>
<th>Correction Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 : 1</td>
<td>11.2</td>
</tr>
<tr>
<td>2 : 1</td>
<td>6.5</td>
</tr>
<tr>
<td>3 : 1</td>
<td>4.5</td>
</tr>
<tr>
<td>4 : 1</td>
<td>3.3</td>
</tr>
<tr>
<td>5 : 1</td>
<td>2.8</td>
</tr>
<tr>
<td>6 : 1</td>
<td>2.5</td>
</tr>
<tr>
<td>7 : 1</td>
<td>2.3</td>
</tr>
<tr>
<td>8 : 1</td>
<td>2.0</td>
</tr>
</tbody>
</table>

**The correction factor given above is to be multiplied by the horizontal length of the slope and divided by the distance between the two pile lines between which the sloping floor is located. This correction is applicable only to the key points of the pile line fixed at the start or the end of the slope.**
SEEPAGE THEORIES

Exit gradient (GE)

It has been determined that for a standard form consisting of a floor length \((b)\) with a vertical cutoff of depth \((d)\), the exit gradient at its downstream end is given by

\[
G_E = \frac{H}{d} \times \frac{1}{\pi \sqrt{\lambda}}
\]

Where, \(\lambda = \frac{1 + \sqrt{1 + \frac{\alpha^2}{2}}} {2}\)

\[\alpha = \frac{b}{d}\]

\[H = \text{Maximum Seepage Head}\]

<table>
<thead>
<tr>
<th>Type of Soil</th>
<th>Safe exit gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shingle</td>
<td>1/4 to 1/5 (0.25 to 0.20)</td>
</tr>
<tr>
<td>Coarse Sand</td>
<td>1/5 to 1/6 (0.20 to 0.17)</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>1/6 to 1/7 (0.17 to 0.14)</td>
</tr>
</tbody>
</table>
SEEPAGE THEORIES

Example: Determine the percentage pressures at various key points in figure below. Also determine the exit gradient and plot the hydraulic gradient line for pond level on upstream and no flow on downstream.
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(1) For upstream Pile Line No. 1

Total length of the floor, \( b = 57.0 \) m

Depth of u/s pile line, \( d = 154 - 148 = 6 \) m

\( \alpha = \frac{b}{d} = \frac{57}{6} = 9.5 \)

\( \frac{1}{\alpha} = \frac{1}{9.5} = 0.105 \)

From curve 11.1a

\( \phi_{C1} = 100 - 29 = 71 \% \)

\( \phi_{D1} = 100 - 20 = 80 \% \)

\( \phi_{E1} = 100\% \)

Correction required at \( \phi_{C1} \) !!!
SEEPAGE THEORIES

Corrections for $\varphi C_1$

(i). Correction at $C_1$ for Mutual Interference of Piles ($\varphi C_1$) is affected by intermediate pile No.2

$$\text{Correction} = 19 \times \sqrt{\frac{D}{b'}} \left( \frac{d + D}{b} \right)$$

$$= 19 \times \sqrt{\frac{5}{15.8}} \times \left( \frac{5 + 5}{57} \right)$$

$$= 1.88\%$$

Where, $D =$ Depth of pile No.2 = $153 - 148 = 5$ m

$d =$ Depth of pile No. 1 = $153 - 148 = 5$ m

$b'$ = Distance between two piles = $15.8$ m

$b =$ Total floor length = $57$ m

Since the point $C_1$ is in the rear in the direction of flow, the correction is (+) ve.

Therefore, Correction due to pile interference on $C_1 = 1.88\%$ (+ ve)
SEEPAGE THEORIES

(ii). Correction at C1 due to thickness of floor:

\[(C_t)_{C1} = \frac{t_1 \cdot (\phi_{D1} - \phi_{C1})}{d_1} \quad (+\text{ve})\]

\[= (80\%-71\%)/(154-148) \times (154-153) = 1.5\%\]

(iii). Correction due to slope at C1

=0 (no slope starting or end at C1)

Hence corrected \((\phi_{C1}) = \text{computed } \phi_{C1} + \text{corrections}\)

= 71\% + 1.88\% + 1.5\%

= 74.38\%
SEEPAGE THEORIES

(2) For intermediate Pile Line No. 2

d = 154 – 148 = 6 m
b = 57 m
α = b/d = 57/6 = 9.5
we have b1 in this case
b1 = 0.6 + 15.8 = 16.4
b = 57 m
b1/b = 16.4/57 = 0.298 (for φC2)
b2/b=1 – b1/b = 1 – 0.298 = 0.702
Using curves of plate 11.1 (b),

φE2 = 100 – 30 = 70 %
φC2 = 56 %
φD2 = 100 – 37 = 63 %
\[ \varphi_{E2} = 100 - 30 = 70\% \]
\[ \varphi_{C2} = 56\% \]
\[ \varphi_{D2} = 100 - 37 = 63\% \]
Corrections for $\phi E2$

(i). Correction at $E2$ for sheet pile lines. Pile No. (1) will affect the pressure at $E2$ and since $E2$ is in the forward direction of flow, this correction shall be – ve. The amount of this correction is given as:

Correction = $19 \sqrt{\frac{D}{b'}} \left( \frac{d+D}{b} \right)$

$= 19 \times \sqrt{\frac{5}{15.7}} \times \frac{5+5}{57}$

$= 1.88\% \text{ }(-\text{ve})$
SEEPAGE THEORIES

(ii). Correction at E2 due to thickness of floor:

\[
(C_t)_{E2} = \frac{t_2 \cdot (\varphi_{E2} - \varphi_{D2})}{d_2} \quad (-ve)
\]

\[
= (70\%-63\%)/(154-148) \cdot (154-153) = 1.17\%
\]

(iii). Correction due to slope at E2

= 0 (no slope starting or end at E2)

Hence corrected (\varphi_{E2}) = computed \varphi_{E2} + corrections

= 70\%-1.88\%-1.17\%

= 66.95\%
SEEPAGE THEORIES

Corrections for \( \phi C2 \)

(i). Correction at C2 due to pile interference. Pressure at C2 is affected by pile No.(3) and since the point C2 is in the back water in the direction of flow, this correction is (+) ve. The amount of this correction is given as:

\[
\text{Correction} = 19 \sqrt{\frac{D}{b'}} \left( \frac{d + D}{b} \right)
\]

\[
= 19 \times \frac{11}{40} \times \left( \frac{11+5}{57} \right)
\]

\[
= 2.89\% \text{ (+ ve)}
\]

Where, \( D \) = Depth of pile No.3, the effect of which is considered below the level at which interference is desired = 153 – 141.7 = 11.3 m

\( d \) = Depth of pile No. 2, the effect on which is considered = 153 – 148= 5 m

\( b' \) = Distance between two piles (2 & 3) = 40 m

\( b \) = Total floor length = 57 m
SEEPAGE THEORIES

(ii). Correction at C2 due to floor thickness.

\[(C_t)_{C2} = \frac{t_2 \times (\phi_{D2} - \phi_{C2})}{d_2} \]  (+ve)

\[= (63\%-56\%)/(154-148)*(154-153) = 1.17\% \]

(iii). Correction due to slope at C2

Since the point C2 is situated at the start of a slope of 3:1, i.e. an up slope in the direction of flow; the correction is negative

Correction factor for 3:1 slope from table = 4.5

Horizontal length of the slope = 3 m

Distance between two pile lines between which the sloping floor is located = 40 m

Actual correction = 4.5 \times (3/40) = 0.34 \% (- ve)

Hence corrected \((\phi_{E2}) = \text{computed }\phi_{E2} + \text{corrections}\)

\[= 56\%+2.88\%+1.17\%-0.34\%=59.72\% \]
SEEPAGE THEORIES

(3) Downstream Pile Line No. 3

\[ d = 152 - 141.7 = 10.3 \, \text{m} \]

\[ b = 57 \, \text{m} \]

\[ 1/\alpha = 10.3/57 = 0.181 \]

From curves of Plate 11.1 (a), we get

\[ \phi_{C3} = 0 \% \]

\[ \phi_{D3} = 26 \% \]

\[ \phi_{E3} = 38 \% \]

Correction required at \( \phi_{E3} \) !!!
SEEPAGE THEORIES

Corrections for $\varphi_{E3}$

(i). Correction due to piles. The point E3 is affected by pile No. 2, and since E3 is in the forward direction of flow from pile No. 3, this correction is negative and its amount is given by

\[
\text{Correction} = 19 \sqrt{\frac{D}{b'}} \left( \frac{d + D}{b} \right) \\
= 19 \times \sqrt{\frac{2.7}{40}} \times \left( \frac{9 + 2.7}{57} \right) \\
= 1.02 \% \text{ (-ve)}
\]

Where, $D =$ Depth of pile No. 2, the effect of which is considered $= 150.7 - 148 = 2.7$ m  \\
$d =$ Depth of pile No. 3, the effect on which is considered $= 150 - 141.7 = 9$ m  \\
$b' =$ Distance between two piles $= 40$ m  \\
$b =$ Total floor length $= 57$ m
SEEPAGE THEORIES

(ii). *Correction due to floor thickness*

\[
(C_t)_{E3} = \frac{t_3 \times (\phi_{E3} - \phi_{D3})}{d_3} \quad \text{(-ve)}
\]

\[
= \frac{(38\%-26\%)/(152-141.7) \times (1.3)}{0.74\%}=1.51\%
\]

(iii). *Correction due to slope at E3*

= 0 (no slope starting or end at E3)

Hence corrected \((\phi_{E3})\) = computed \(\phi_{E3}\) + corrections

\[
= 38\%-1.02\% - 0.76\% 1.51\%
\]

\[
= 36.22\% 35.47\%
\]
SEEPAGE THEORIES

The corrected pressure coefficients at various key points are tabulated below in Table below

<table>
<thead>
<tr>
<th>Upstream Pile No. 1</th>
<th>Intermediate Pile No.2</th>
<th>Downstream Pile No. 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varphi_{E_1} = 100%$</td>
<td>$\varphi_{E_2} = 66.95%$</td>
<td>$\varphi_{E_3} = 35.47%$</td>
</tr>
<tr>
<td>$\varphi_{D_1} = 80%$</td>
<td>$\varphi_{D_2} = 63%$</td>
<td>$\varphi_{D_3} = 26%$</td>
</tr>
<tr>
<td>$\varphi_{C_1} = 74.38%$</td>
<td>$\varphi_{C_2} = 59.72%$</td>
<td>$\varphi_{C_3} = 0%$</td>
</tr>
</tbody>
</table>

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SEEPAGE THEORIES

Exit Gradient

Let the water be headed up to pond level, \( \text{i.e. on RL 158 m on the upstream side with no flow downstream} \)

The maximum seepage head, \( H = 158 - 152 = 6 \text{ m} \)

The depth of d/s cur-off, \( d = 152 - 141.7 = 10.3 \text{ m} \)

Total floor length, \( b = 57 \text{ m} \)

\( \alpha = \frac{b}{d} = \frac{57}{10.3} = 5.53 \)

\[
G_E = \frac{H}{d} \times \frac{1}{\pi \sqrt{\lambda}} \quad \text{Where,} \quad \lambda = \frac{1 + \sqrt{1 + \alpha^2}}{2}
\]

\[
\alpha = \frac{b}{d} \\
H = \text{Maximum Seepage Head}
\]

Hence,

\[
G_E = \frac{H}{d} \times \frac{1}{\pi \sqrt{\lambda}} = \frac{6}{10.3} \times 0.18 = 0.105
\]

Hence, the exit gradient shall be equal to 0.105, \( \text{i.e. 1 in 9.53, which is very much safe.} \)
SEEPAGE THEORIES

Exit Gradient

For a value of $\alpha = 5.53$, $\frac{1}{\pi \sqrt{\lambda}}$ from curves of Plate 11.2 is equal to 0.18.

Hence, $G_E = \frac{H}{d} \times \frac{1}{\pi \sqrt{\lambda}} = \frac{6}{10.3} \times 0.18 = 0.105$

Hence, the exit gradient shall be equal to 0.105, i.e. 1 in 9.53, which is very much safe.
PRACTICE PROBLEM: 1

Use Khosla’s curves to calculate the percentage uplift pressure at points C1, E2, C2, D3 and E3 for a barrage foundation profile shown in figure below applying necessary corrections. Also determine the exit gradient. [Assume: floor thickness = 1 m]
PRACTICE PROBLEM: 2

For the Barrage shown in the figure below,
Using all three theories:

(a). Draw H.G.L. (hydraulic gradient line) for static head condition
(b). Check the safety against piping failure; assume the bed soil of the river is coarse sand.
(c). Find the uplift pressure head at point A & B
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