UNIT 6 UPLIFT PRESSURE AND EXIT GRADIENT

Structure

6.1 INTRODUCTION

In Unit 4 you learnt about weirs and barrages while in Unit 5 the various components of weirs and barrages were discussed. The design considerations were also covered. In this Unit you will learn how the uplift pressures act on a floor on a permeable foundation as in barrages and how they are assessed by means of charts.

Objectives

At the end of this unit you will know about

- uplift pressure,
- pile lines,
- Khosla's theory for design of weir floors on permeable foundations,
- exit gradient, and
- use of charts developed by Khosla.

6.2 UPLIFT PRESSURE

The water percolating through the foundation of a barrage exercises an upward pressure on the barrage floor, and if the pressure is not counterbalanced by the weight of the concrete or masonry above it or resisted by the steel reinforcement in the floor, the work will fail by rupture of part of its floor.

According to Bligh, the percolating water follows the outline of the base of the foundation of the work. The length of path thus traversed by water is called the length of creep. The total head h_1 is lost in the creep length L at a uniform rate (Figure 6.1).

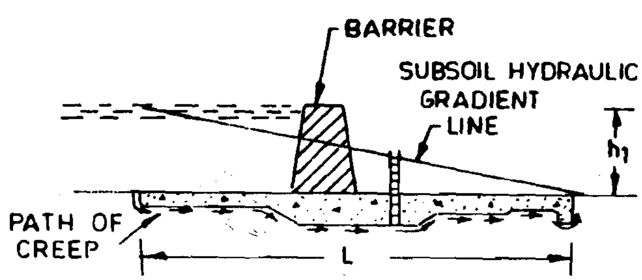


Figure 6.1 : Sub-soil Hydraulic Gradient

The loss of head per unit length of creep, or h_1/L, is called the Hydraulic Gradient. Bligh did not differentiate between horizontal and vertical creep. Consider a horizontal floor with three vertical cutoffs (Figure 6.2). The seepage water will then follow the path indicated by arrows and the creep length,

$$L = b + 2d_1 + 2d_2 + 2d_3 \qquad ...(6.1)$$

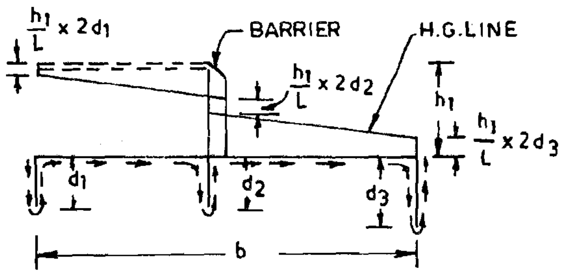


Figure 6.2 : Creep Length

The rate of loss of head or the hydraulic gradient is thus $h_1/[b + 2d_1 + 2d_2 + 2d_3]$ per unit length of creep. There will be losses of head equal to $h_1/L \times 2d_1$, $h_1/L \times 2d_2$, and $h_1/L \times 2d_3$, respectively, in the planes of the three vertical cutoffs and hydraulic gradient line is drawn as shown in the figure. According to Bligh, to ensure the safety of the work against the effects of piping and uplift pressure due to seepage, the following criteria are to be satisfied:

a) **Safety against Piping**

The length of creep should be sufficient to provide a safe hydraulic gradient according to the type of soil, or

$$L = Ch_1 \qquad ...(6.2)$$

where C = Bligh's coefficient for the soil.

Table 6.1 gives the values of C.

Table 6.1 : Recommended Values of Bligh's Coefficient

Type of Soil	Value of C
1) Fine micaceous sand in North Indian rivers	15
2) Coarse grained sand	12
3) Sand mixed with boulder and gravel	5 - 9
4) Loam soil	5 - 9

The hydraulic gradient is then equal to $1/C$ and according to Bligh, if this condition is satisfied (i.e. the hydraulic gradient < $1/C$) there will be no danger of piping. It may be noted that the seepage head, h_1, is to be measured from the water level upstream to the corresponding lowest water level on the downstream. The worst condition giving the maximum value of h_1 should be selected for design. In most cases, this would occur when water is held up to the highest possible level on the upstream side with no discharge to the downstream side, the downstream water level being taken at the downstream bed level.

b) **Safety against Uplift Pressure**

At any point, the hydraulic gradient line measures the extent to which there is residual head to cause uplift pressures. If a piezometric pipe is inserted through the impervious floor upto its bottom, water will rise up in the pipe to the level of the hydraulic gradient line (Figure 6.1). Supposing that the height of the hydraulic gradient line above the bottom of the floor at any point is h', the uplift pressure exercised by the water at that point is wh'. If the floor thickness at the point is t and the specific gravity of the material of the floor, G, the downward force per unit area due to the weight of the floor is twG. For equilibrium, the two forces must balance, or,

$$wh' = twG$$

or,

$$t = \frac{h'}{G} \qquad ...(6.3)$$

The ordinate, h', from the hydraulic gradient line to the bottom of the floor can only be known after the floor thicknesses have been determined. The surface profile of the floor is determined by considerations of surface flow and is known. It is thus more convenient to put Eq. (6.3) in the following workable form

$$h' = tG \qquad ...(6.4)$$

Deduct t from both sides:

$$h' - t = t(G-1) \qquad ...(6.5)$$

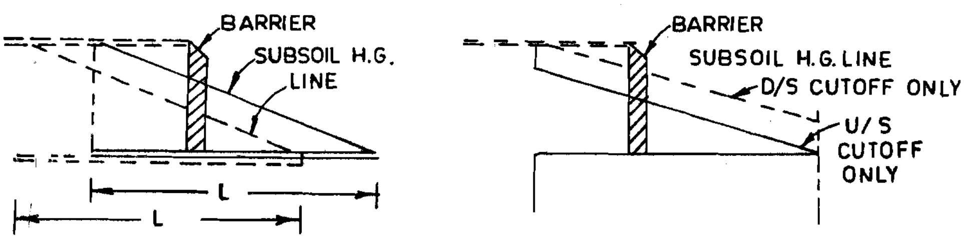
or

$$t = \frac{(h'-t)}{(G-1)} \qquad ...(6.6)$$

$(h' - t)$ is the ordinate measured from the hydraulic gradient line to the top of the floor and is known in all cases. Dividing it by $(G - 1)$ or the submerged specific gravity of the floor material, the thickness of the floor is directly determined.

It may be noted that upstream of the barrier (the crest wall or gates or shutters) which holds up the water and creates the seepage head, h_1, the uplift pressures are more than counterbalanced by the weight of the water standing on the floor. When there is no water standing upstream of the barrier, there will be no seepage head and no uplift pressure. If the water is standing on the upstream side of the barrier and causing uplift pressures, its own downward weight is bound to be more than the uplift pressures. The upstream floor, therefore, is to be kept at the minimum practical thickness to resist wear, impact of flowing water or development of cracks. The floor downstream of the barrier must be designed in accordance with Eq. (6.6).

As the upstream floor can be kept at the minimum thickness feasible, while the downstream floor has to be designed to resist uplift pressure and is therefore, thicker, it would be economical to provide as much of the total required creep length upstream of the barrier as possible. A minimum floor length is, of course, always required downstream, from consideration of surface flow to resist the action of fast flowing water whenever it is passed below the barrier and must be provided. Not only does the provision of maximum possible creep length upstream of the barrier increase the upstream floor length which is itself free from the effects of uplift pressure but it also reduces uplift pressures on that part of the floor which must be provided downstream. This is so because a larger percentage of the total creep having taken place upto the barrier, the residual heads on the downstream floor are reduced. This is shown in Figure 6.3(a) which shows the effect of shifting the floor relative to the barrier, the total length remaining the same, while Figure 6.3(b) shows the effect of u/s and d/s cutoffs. It will be seen that an upstream vertical cutoff reduces pressures all over the floor while a downstream vertical cutoff increases them.



(a) The Effect of Shifting the Floor Relative to the Barrier, the Total Length Remaining the Same
(b) Effect of U/S and D/S Cutoffs

Figure 6.3

SAQ 1

i) How do you define uplift pressure?

ii) How can you provide safety against piping?

iii) How can you provide safety against uplift pressure?

iv) How do you determine the safe floor thickness to counter uplift?

6.3 PILE LINE

In the earlier days cutoffs were provided at the ends of the floor of hydraulic structures. These cutoffs were of masonry. In later structures these masonry cutoffs were replaced by steel sheet piles driven into the soil at the desired locations. The behaviour of the steel sheet piles in reducing uplift pressures was the same as the cutoffs. The pile line forms a barrier in the foundation around which the seepage water creeps, down on one side and up on the other.

SAQ 2

Where are pile lines used?

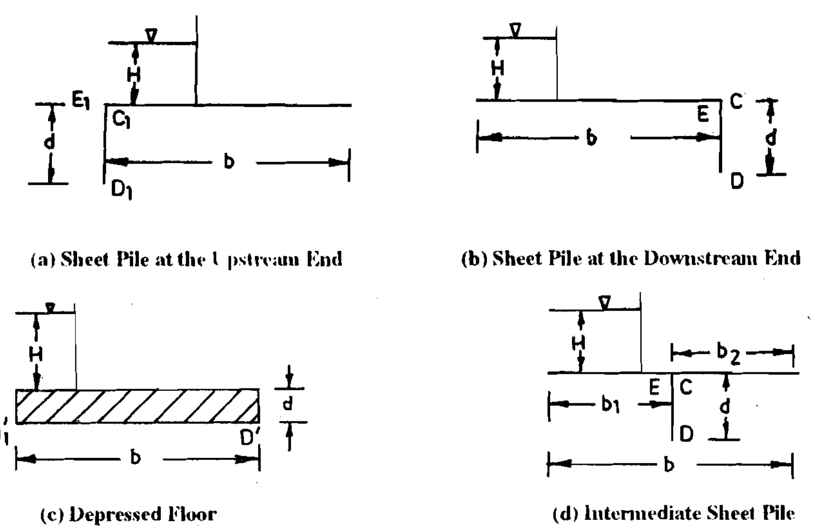
6.4 KHOSLA'S THEORY FOR DESIGN OF WEIR FLOORS ON PERMEABLE FOUNDATIONS

The usual barrage and weir sections do not conform to a simple elementary form and a direct solution of the Laplace equation governing the flow of seepage water is not possible. To apply the analytic solution to any practical composite profile of a weir or a barrage, Khosla and his associates evolved the method of independent variables. In this method, a composite weir or barrage section is split up into a number of simple standard forms where analytical solutions are known. The most useful standard forms among them are:

a) A straight horizontal floor of negligible thickness with a sheet pile at either end [Figure 6.4 (a) and 6.4 (b)],

b) A straight horizontal floor depressed below the bed but with no vertical cutoff [Figure 6.4 (c)], and

c) A straight horizontal floor of negligible thickness with a sheet pile at intermediate position [Figure 6.4 (d)].



(a) Sheet Pile at the Upstream End

(b) Sheet Pile at the Downstream End

(c) Depressed Floor

(d) Intermediate Sheet Pile

Figure 6.4 : Simple Standard Profiles

In general, the usual weir section consists of a combination of all the three forms mentioned above: the entire length of the floor with any one of the pile lines, etc. making up one such form. Each elementary form is then treated as independent of the others. The pressures at the key points are then read off from the curves given in charts. These key points are the junction points of the floor and the pile line of that particular elementary form, the bottom point of that pile line and the bottom corners in the case of a depressed floor.

The percentage pressure observed from the curves for the simple form into which the profile has been broken up, is valid for the profile as a whole if corrected for:

a) mutual interference of pile,

b) the floor thickness, and

c) the slope of the floor.

Corrections for Mutual Interference of Piles

Let

C = correction to be applied as percentage of head,

b' = distance between the two pile lines,

D = depth of the pile line, the influence of which has to be determined on the neighbouring pile of depth, d. D is to be measured below the level at which interference is desired,

d = depth of pile on which the effect of pile of depth, D is sought to be determined, and

b = total floor length.

$$\text{Then, } C = 19\sqrt{\left(\frac{D}{b'}\right)} \cdot \left[\frac{(d+D)}{b}\right] \qquad \text{...(6.7)}$$

This correction is positive for points in the rear of back water and negative for 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 latter is equal to or smaller than the former and is at a distance less than twice the length of the outer pile. In Figure 6.5 which shows a sketch for mutual interference of sheet piles and slope of floor, the dimensions have been marked as they will apply to point C on pile line 1 owing to the influence of the pile line 2. The effect of the interference of a pile is to be determined only for the face of the adjacent pile towards the interfering pile, e.g. pile line 2 will interfere with the downstream face of pile line 1 and upstream face of pile line 3.

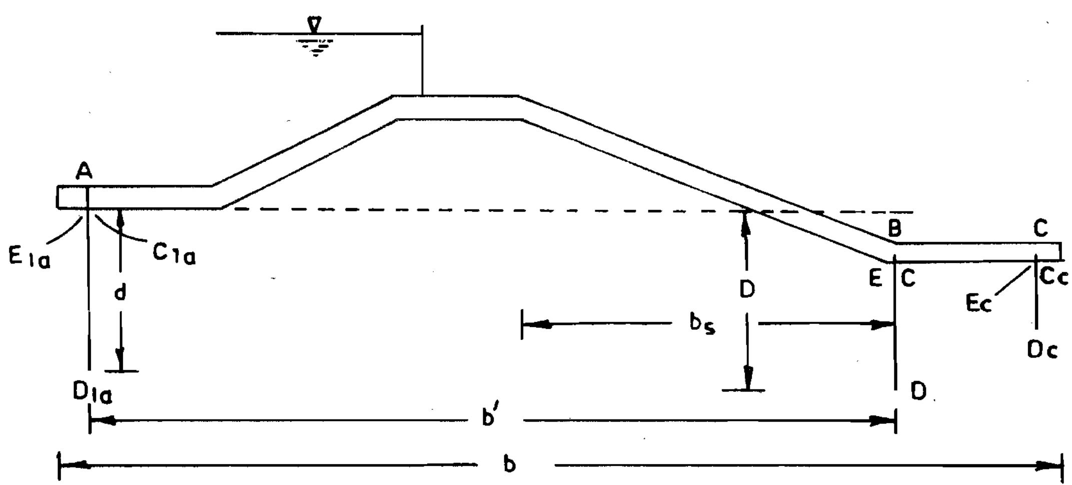


Figure 6.5 : Sketch for Mutual Interference of Sheet Piles and Slope of Floor

Correction for Floor Thickness

In the standard forms with vertical cutoffs the thickness of the floor is assumed to be negligible. Thus, as observed from the curves, the pressure at the junction point E and C pertain to the level at the top of the floor whereas the actual junctions is with the bottom of the floor. The pressures at the actual points E and C are interpolated by assuming straight line variation from the hypothetical point E to D and also from D to C (Figure 6.5).

Correction for the Slope of Floor

A suitable percentage correction is to be applied for a sloping floor, the correction being plus for the down and minus for the up slopes following the direction of flow. The values of the corrections are given in Table 6.2.

Table 6.2 : Corrections for Floor Slope

Slope (V :H)	Correction as % of Pressure
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	1.0

The correction is applicable to the key points of the pile line fixed at the beginning or the ends of the slope. Thus in Figure 6.5 the slope correction is applicable only to point E and pile line 2. The percentage correction given in the above table is to be further multiplied by the proportion of the horizontal length of slope to the distance between the two pile lines in between which the sloping floor is located. In Figure 6.5, the correction to be applied at E, pile line 2 will be obtained by multiplying the appropriate figure from the above table by (b_s/b').

6.5 EXIT GRADIENT

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

$$G_E = \left(\frac{H}{d}\right) \cdot \frac{1}{(\pi \sqrt{\lambda})} \qquad ...(6.8)$$

where,

$$\lambda = \frac{1 + \sqrt{(1 + \alpha^2)}}{2} \qquad ...(6.9)$$

and

$$\alpha = b / d \qquad ...(6.10)$$

From the curve in Figure 6.6, for any value of α or b/d, the corresponding value of $\frac{1}{\pi \sqrt{\lambda}}$ can be read off. Knowing the values of H and d, the value of G_E is easily calculated. It is obvious from Eq. (6.8) that if $d = 0$, G_E is infinite. It is, therefore, essential that a vertical cutoff should be provided at the downstream end of the floor. To safeguard against piping, the exit gradient must not be allowed to exceed a certain safe limit for different soils as given in Table 6.3. The uplift pressures must be kept as low as possible consistent with the safety at the exit, so as to keep the floor thickness to the minimum.

Table 6.3 : Safe Exit Gradients for Different Types of Soils

Type of Material	Safe Exit Gradient
Shingle	1/4 – 1/5
Coarse sand	1/5 – 1/6
Find sand	1/6 – 1/7

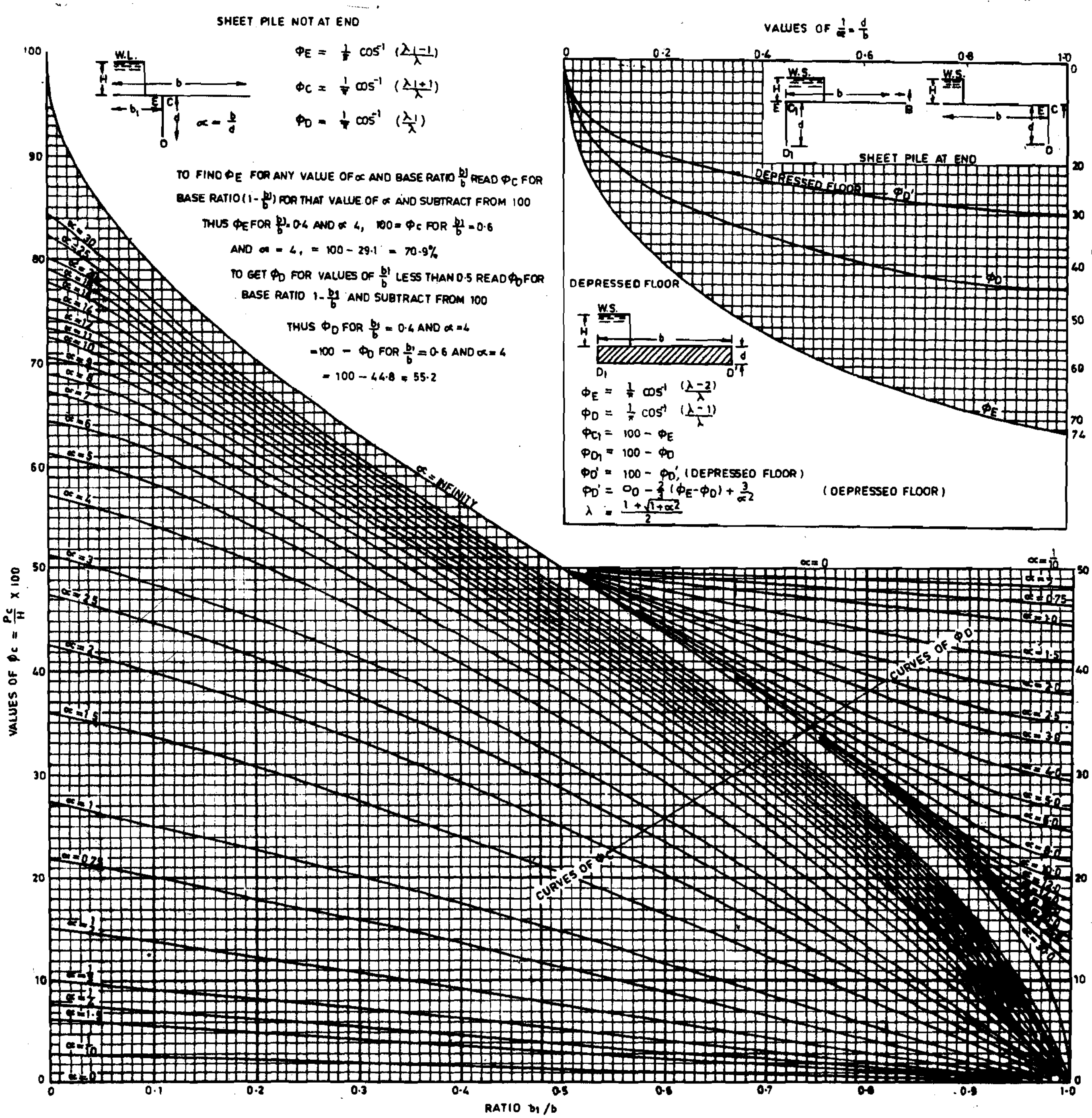


Figure 6.6 : Khosla's Pressure Curves

SAQ 3

What aspects of floor on permeable foundations can be assessed by Khosla's curves?

Figure 6.7 shows the pressure distribution under floors with different slopes.

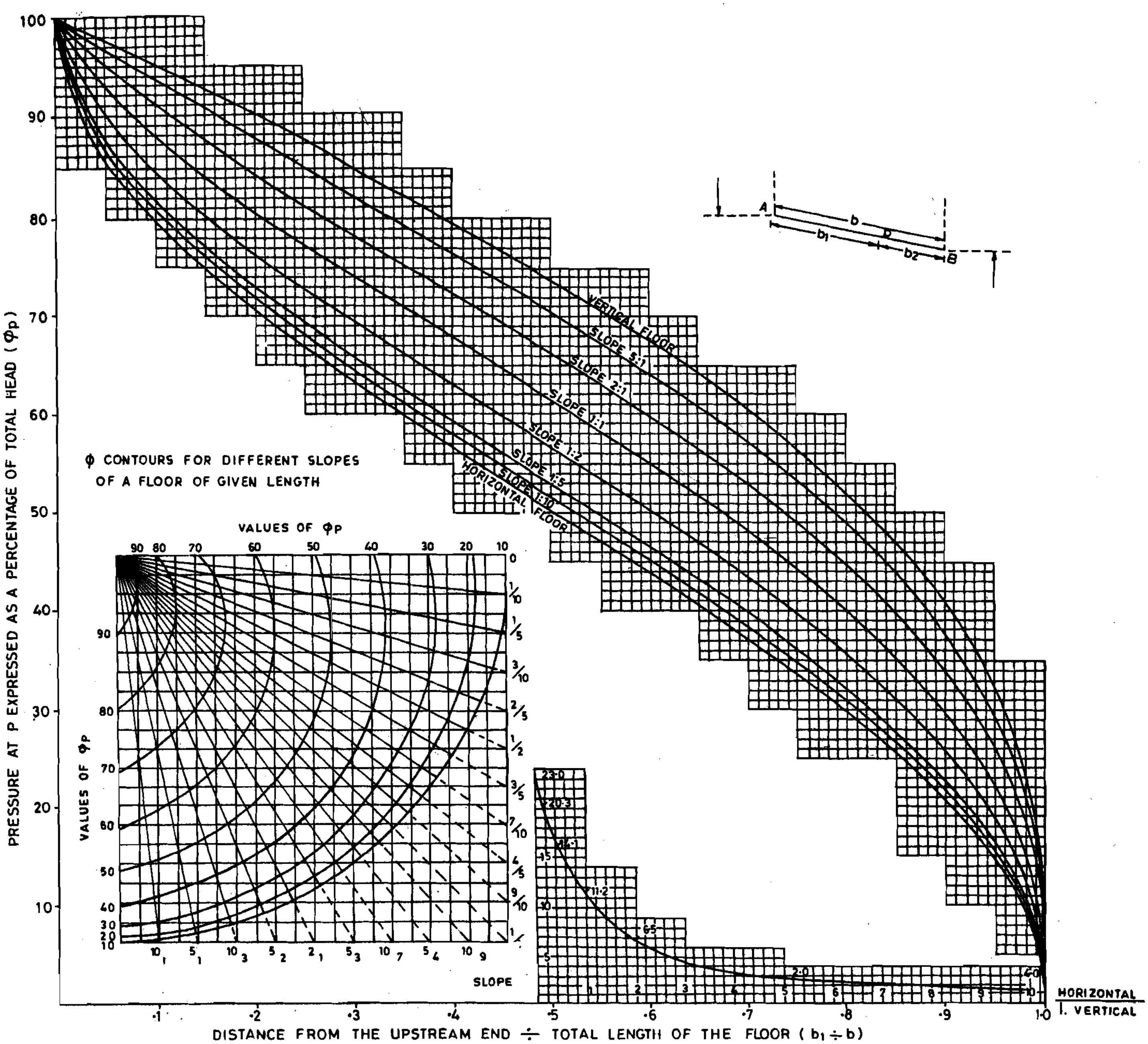


Figure 6.7 : Pressure Distribution under Floors with Different Slopes

SAQ 4

What do you understand by exit gradient and safe exit gradient?

6.6 USE OF CHARTS

The use of charts developed by Khosla to determine the uplift pressures is illustrated by an example.

Example 6.1

Figure 6.8 shows a barrage floor with sheet piles at the upstream, downstream and intermediate position of the floor. The charts have been used to determine the pressure at various points under the floor, as given below.

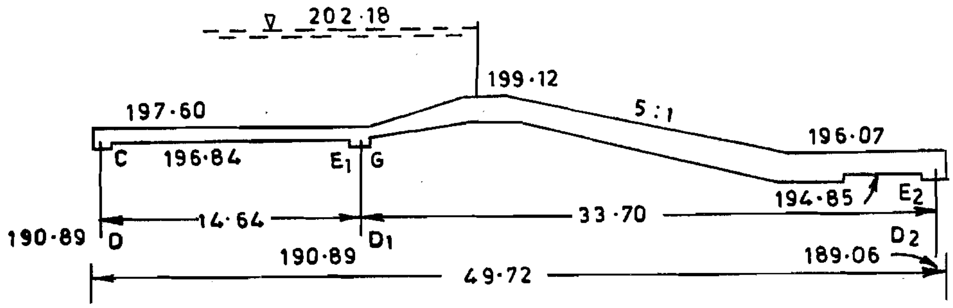


Figure 6.8 : Design (Example 6.1)

Solution

For Upstream Pile Line :

$$d = 197.60 - 190.89 = 6.71 \text{ m}$$

$$b = 49.72 \text{ m}$$

$$1/\alpha = d/b = 6.71/49.72 = 0.135$$

From curves $\phi_D = 77.7\,\%$, $\phi_C = 68\,\%$

ϕ_C correction for thickness of floor

$$= [197.60 - 196.84]\,(77.7 - 68)/6.71 = 1.1\,\%\,(+)$$

ϕ_C correction for interference of second pile line

$$= 19\,[\sqrt{(5.95/14.64)}] \times (5.95 + 5.95)/49.72 = 2.9\,\%\,(+)$$

Here

$$D = 196.84 - 190.89 = 5.95 \text{ m}$$

$$d = 196.84 - 189.06 = 7.78 \text{ m}$$

Hence, corrected value of $\phi_C = 68 + 1.1 + 2.9 = 72\,\%$.

For Intermediate Pile Line :

$$d = 197.60 - 190.89 = 6.71 \text{ m}$$

$$\alpha = b/d = 49.72/6.71 = 7.4$$

$$b_1 = 14.64 \text{ m}$$

$$b = 49.72 \text{ m}$$

$$b_1/b = 14.64/49.72 = 0.307$$

From curves, $\phi_{E1} = 71.4\,\%$, $\phi_{D1} = 61.4\,\%$, $\phi_{C1} = 53.2\,\%$

$$\phi_{E1}\text{, correction for depth} = \frac{(197.60 - 196.84) \times (71.4 - 61.4)}{6.71} = 1.1\,\%\,(-)$$

ϕ_{E1}, correction for interference of first pile line = 2.9 % (–), the value remaining the same as both pile lines are equal in depth and placed at the same level.

Corrected $\phi_{E1} = 71.4 - 1.1 - 2.9 = 67.4\,\%$

ϕ_{C1}, correction for depth $= \frac{(197.6 - 196.84) \times (61.4 - 53.2)}{6.71} = 0.9\ \%\ (+)$

ϕ_{C1}, correction for interference of third pile line

$$d = 196.84 - 190.89 = 5.95 \text{ m}$$

$$D = 196.84 - 189.06 = 7.78 \text{ m}$$

Hence, correction $= \frac{19\ [\sqrt{(7.78/33.70)}] \times (7.78 + 5.95)}{49.72} = 2.5\ \%\ (+)$.

ϕ_{C1}, correction for slope from Table 6.1, slope correction for a slope of 1 in 4 (of floor bottom) = 3.3 % (–) as the slope is upward in the direction of flow.

Length of slope = 2.44 m and the distance between the two pile lines is 33.70 m, hence the actual correction to be applied

$$= 3.3 \times (2.44\ /33.70) = 0.24\ \%\ (-).$$

Hence, corrected value of $\phi_{C1} = 53.2 + 0.9 + 2.5 - 0.24 = 56.4\ \%$.

Downstream Pile Line

$$d = 196.07 - 189.06 = 7.01 \text{ m},$$

$$1/\alpha = d/b = 49.72\ /7.01 = 0.143.$$

$$\phi_{D2} = 23\ \%,\ \phi_{E2} = 33\ \%$$

ϕ_{E2} correction for interference of intermediate pile line

$$D = 194.85 - 190.89 = 3.96 \text{ m}$$

$$d = 194.85 - 189.06 = 5.79 \text{ m}$$

Correction $= 19\ [\sqrt{(3.96/33.70)}] \times (3.96 + 5.79)/49.72 = 1.3\ \%\ (-)$.

Hence, corrected value of $\phi_{E2} = 33 - 1.7 - 1.3 = 30\ \%$.

Exit Gradient

Let the water be headed up to a level of 202.18 m on the upstream side with no flow downstream.

The seepage head, h_1 = 202.18 – 196.07 = 6.11 m

The depth of cutoff, d = 196.07 – 189.06 = 7.01 m

$$\alpha = b/d = 49.72\ /7.01 = 7.1$$

From Figure 9.4 (c), $\frac{1}{\pi\sqrt{\lambda}} = 0.158$ for $\alpha = 7.1$.

Hence, $G_E = \left(\frac{h_1}{d}\right) . \frac{1}{(\pi\sqrt{\lambda})} = 6.11 \times \frac{0.158}{7.01} = 0.137$.

The exit gradient with no scour, will therefore, be 0.137 or 1 in 7.3.

6.7 SUMMARY

In this unit, you have understood the development of uplift pressure under the floor of a barrage. The role of steel sheet piles in reducing the uplift pressures is very important. The barrage floor comprising a finite thickness and pile lines under the upstream and downstream ends of the concrete floor make it a composite profile and Khosla's theory for design of weir floor on permeable foundation simplifies the structure into a number of simple standard forms where analytical solutions are known. The charts developed by him are used to determine the pressures and the exit gradient.

6.8 KEY WORDS

Bligh's Theory	:	A theory given by Bligh to work out the hydraulic gradient for the safety of the structure
Exit Gradient	:	It is a ratio of head loss over a certain length of flow.
Khosla's Theory for Design of Weir Floors on Permeable Foundations	:	Theory given by Khosla to design a weir or barrage floor by the method of independent variables. A composite floor is considered to be formed of a number of simple standard forms for which analytical solutions are known.
Pile Lines	:	They are barriers formed in the foundation of a weir or barrage around which the seepage water creeps.
Safety against Piping	:	This can be ensured by providing sufficient length of creep so as to have a safe hydraulic gradient.
Safety against Uplift Pressure	:	The downward weight of the concrete floor under submerged condition should be able to resist the uplift pressure due to the residual head due to the hydraulic gradient.
Uplift Pressure	:	It is caused by the residual head due to the hydraulic gradient.
Use of Charts Developed by Khosla	:	Khosla has developed charts for analysing composite floors by breaking them into simple forms for which analytical solutions are available.

6.9 ANSWERS TO SAQs

Answers all SAQs with respect to the preceding text.

FURTHER READINGS

1) Asawa G.L., (1993), *Irrigation Engineering*, Wiley Eastern Ltd, New Delhi, 568p.

2) Singh, Bharat (1988), *Fundamentals of Irrigation Engineering*, Nem Chand & Bros, Roorkee, 8th ed., 608 p.

3) Varshney R. S., Gupta S. C., Gupta R., (1972), *Theory and Design of Irrigation Structures*, Nem Chand & Bros., Roorkee, 858p.

4) Varshney R.S., (1986), *Hydropower Structures*, Nem Chand & Bros., Roorkee, 3rd ed., 906p.