Electrical Analog Studies on the Effect of Choking of Filter and Depth of cut offs on Seepage

by

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Introduction

Flow of water through soil forms an important field of study for a geotechnical engineer. The seepage under or through a hydraulic structure is often critical to its safety and has to be studied carefully.

Unless flow characteristics are determined with reasonable accuracy, a safe design of structure can not be assured. The estimation of flow quantities like uplift pressure, seepage discharge and exit gradient requires solution of some complicated mathematical equations. There are many methods to solve these equations like mathematical analysis, numerical methods, graphical sketching, laboratory model simulations and analogies etc.

The mathematical analysis has limited scope as all the problems are not amenable to mathematical analysis. Also its practical utility is reduced due to very complicated and applied mathematics involved in it. The numerical method can be used to solve a wide range of problems but the calculations involved are very lengthy and tedious. To obtain a reasonably accurate solution by graphical sketching, a great skill is required. Laboratory model simulation techniques are laborious and time consuming. Problem involving non-homogeneous soils and complex boundary conditions are very difficult to deal with these methods.

The analogy between flow of electricity and flow of water, both governed by similar mathematical equations has been used to develop a technique known as electrical analogy to solve flow problems. This laboratory method appears to possess manifold merits. In the present work attempts have been made to study the effect of (*a*) Partial choking of a filter and (*b*) the depth of downstream as well as upstream cut offs on the uplift pressure and exit gradient of a weir by using electrical analogy—conducting paper method.

Theory

Both the flow of water and electric current can be expressed by Laplace equation. The two dimensional form of Laplace equation for an isotropic medium is,

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial z^2} = 0 \tag{1}$$

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where, ϕ represents potential (hydraulic for flow of water and electric for current flow) and x and z are directional variables. Further, Darcy's law governing the flow of water through soils is analogous to Ohm's law for flow of electric current. Thus, measurement of electric potential in an electrical model simulated to represent hydraulic conditions can very well be used to study the hydraulic potential distribution in a soil. Once the equipotential lines are established, the flownet could be sketched by using orthogonal intersection between equipotential and flow lines. The quantities such as rate of flow (q), hydraulic potential or residual head (ϕ), uplift pressure (h_w), seepage pressure (p_s) and exit gradient (i_e) may be obtained from Equations 2, 3, 4, 5 and 6 respectively, as given below:

$$q = kh_1 \frac{Nf}{Nd} \tag{2}$$

in which, k is the coefficient of permeability of the soil, h_1 is the total hydraulic head, N_f are the number of flow lines and N_d are the number of equipotential drops.

$$\phi = h_1 - n \times \Delta h \tag{3}$$

wherein, n are the equipmental drops upto the point at which hydraulic potential is desired and Δh is the potential drop in each flow field.

$$h_w = \phi - z \tag{4}$$

in which, z is the position head of the point above datum measured positive upwards

$$p_s = \phi \gamma_w \tag{5}$$

in which, γ_w is the unit weight of water.

Finally,

$$i_e = \frac{\Delta h}{l} \tag{6}$$

wherein, l is the average length of the flow field at the exit end.

Conducting Paper Method

Electrical analogs of both the category *i.e.* continuous model (Muskat, 1946) as well as lumped parameter model (Landau, 1957; Mcneal, 1953) are in use. Each one is associated with certain merits and drawbacks. Amongst continuous models, the electrolytic solution method (Muskat, 1946) may still be in use for three dimensional flow analysis, but for two dimension problems it is now replaced by conducting paper method (General Electric Co., 1959) due to latter's simplicity in simulating the boundary of any shape and the ease at which results can be obtained.

A dry electrically conducting paper commercially known as 'Teledeltos' paper is used in this method. The boundaries of the problem are drawn on this paper at a suitable scale and accordingly, it is cut. The potential boundaries are then painted with a conducting paint. The selected potentials are applied on the potential boundaries through low voltage source. Wheatstone bridge is set to some desired potential and the probe (potential divider) is moved over conducting paper until a null reading on galvanometer is obtained. The procedure is repeated at different potential settings and several points of equal potentials are obtained through which equipotential lines can be sketched. Potentials at desired points can also be obtained directly by this method. The flowlines can be sketched by further electrical analog of the same geometry but interchanging flow and potential boundaries. Now-a-days a compact instrument known as 'electrical analog plotter' comprising of oscillator and amplifier-cum-null detector circuit is being used.

It is desirable to check the conductivity of the paper in different directions before it is used. Anisotropy of resistance upto 10 per cent is tolerable. However, for higher values the correction for unequal resistivities based upon the principle of scale transformation needs to be applied. Rao and Gupta (1977) narrated a procedure to prepare conducting paper in the laboratory.

Experimental Programme

The instrument. conducting paper etc. used and experimental procedure adopted in the present investigation are briefly described below.

Instrument

The instrument used is the 'Analog plotter' consisting of oscillator circuit and amplifier-cum-null detector circuit. The oscillator circuit gives stable output voltage and frequency (2 volts at 500 cps). Oscillator output is connected to the potentiometer with a calibrated dial. A potential dividing probe is provided for detecting equipotential point. The amplifier-cum-null detector circuit amplifies the voltage at the signal and raises the input impedence of the null detector. The amplified signal is rectified and directed through a micro-ammeter for reading the null point. Figure 1

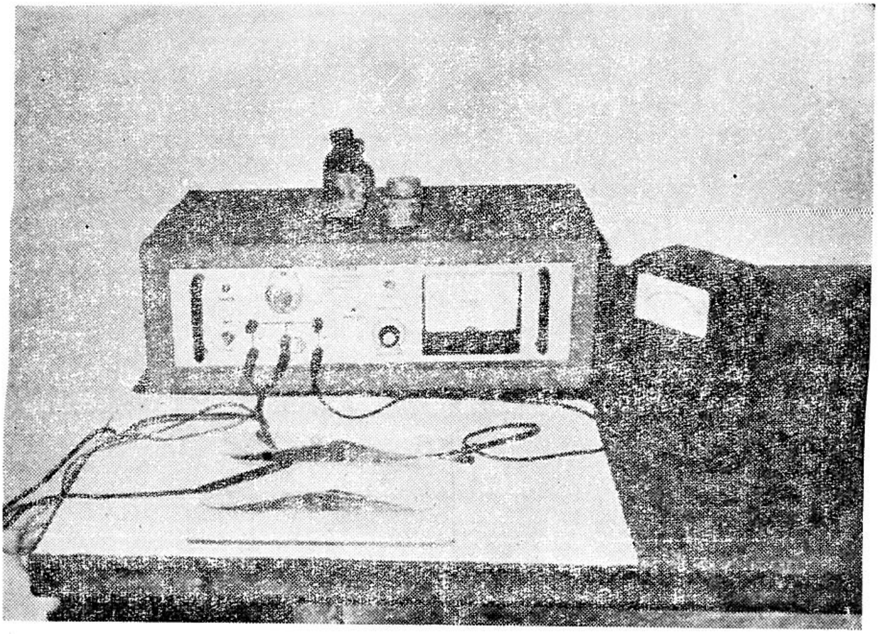


FIGURE 1 View of the 'Electrical Analog Plotter' and Accessories

shows overall view of the instrument used and a schematic arrangement of facilities and connections on it is displayed in Fig. 2.

Teledeltos Paper

Very high quality commercially available conducting papers were used in the present work. These offered resistances of around 2000 and 1985 ohms/square cms in longitudinal and transverse directions respectively.

Silver Paint

Commercially available silver paint prepared by dissolving silver in methyl iso-butyl-ketone was used to make conducting linings to simulate boundary conditions on the model cut from teledeltos paper.

Procedure

As mentioned earlier, a typical section representating the problem to be studied was drawn on to the teledeltos paper. The paper is cut along the boundary flow lines. A coating of silver paint is applied along the equipotential boundaries. After drying the paint, 100 per cent and 0 per cent potential surfaces are connected to +ve and —ve terminals respectively of the instrument. The probe was connected to null terminal. Zero adjustment was verified by shorting the null terminal. The proble was placed at the point at which the potential was desired. Potential selector was so adjusted to obtain zero reading at null detector. The potential displayed at the potential selector dial corresponds to the potential (per cent) at that point.

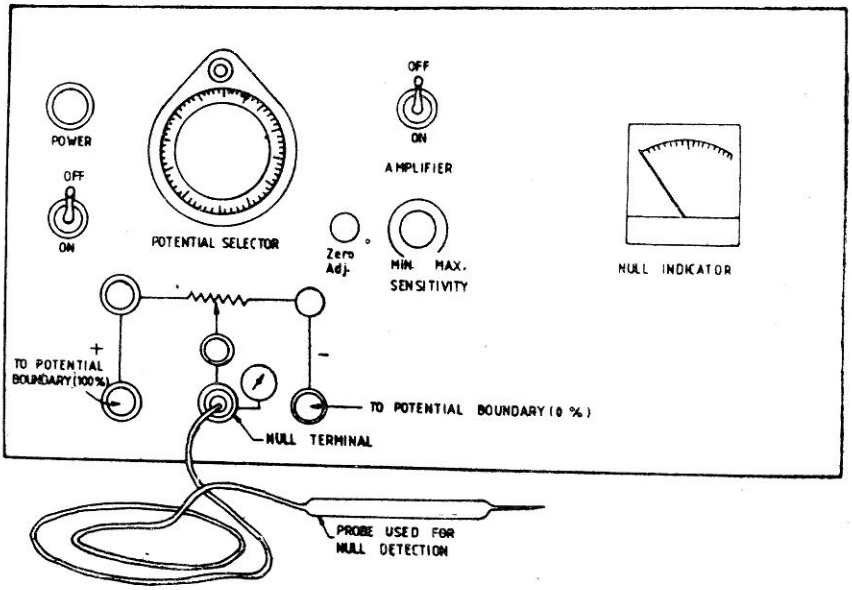


FIGURE 2 Arrangement of Facilities and Connections on the Instrument

Effect of Choking of Filter on Seepage

Problem

To ensure the stability of hydraulic structures against uplift pressure and piping, the following conditions need to be satisfied in the design:

(1) At every section total downward stress due to structural load should be more than the total uplift pressure acting on the foundation.

(2) Exit gradient should be within safe limits.

To satisfy these conditions sufficient floor thickness is provided in the design to counterbalance the anticipated uplift pressure. The exit gradient is kept within safe limits by providing downstream cutoff of adequate depth. Apart from satisfying these theoretical conditions some additional safety measures are adopted due to generally existing complexities in the foundation strata and other unknown factors. In barrages just downstream of concrete floor an inverted filter is provided to ensure safe exit of water without causing piping. As the permeability of filter is very high in comparison of subsoil, the loss of head through it is negligible. For the purpose of structural design of floor filter, it is assumed to be fully effective in releasing the residual head of water at downstream. Due to choking of the filter, it may not remain fully effective for all the period during its life time (Khosla et al, 1954). With this in mind, in this problem the effect of choking of filter on uplift pressure and exit gradient has been studied.

Model

For the present study a typical barrage section shown in Fig. 3 (*a*) was considered. The barrage was designed with the help of Khosla's curves and thickness of the floor at every section was about 5 per cent in excess of what was approximately required to counterbalance the anticipated range of uplift pressures. Upstream water level (assumed) and elevations of various points on the barrage section are given in the figure. Fully effective filter was represented in the model by covering full filter length with the continuous coating of silver paint. To simulate partial choking of filter, the entire filter was divided in 20 equal parts. The required number of these parts corresponding to the desired percentage of choking to be represented in the model in each case was removed by cutting out the paper as shown in Fig. 3 (*b*). Care was taken to select parts to be cutout in such a fashion that they lie in a staggered manner over the entire length of filter.

The uplift pressures at nine key points marked along the barrage section on Fig. 4, and exit gradients along downstream pile were observed for 20 per cent, 40 per cent, 60 percent, 80 per cent and 100 per cent choking of filter.

Results and Discussion

The results of hydraulic potentials (also referred as residual heads) recorded at various points along the barrage floor are presented in Table 1. The observations of residual heads at different depths along downstream cut off are given in Table 2.

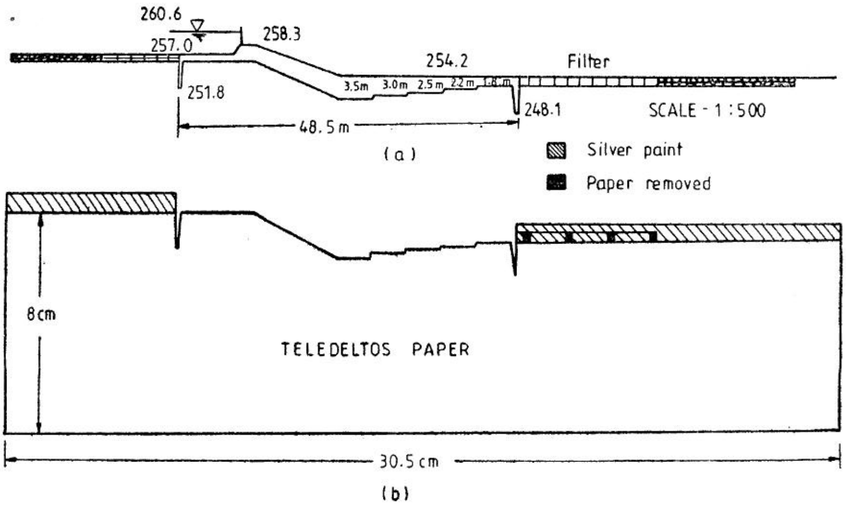


FIGURE 3 **(a) Typical Section of the Barrage and its Filter.**
(b) Model of Barrage on Teledeltos Paper (Filter 20 per cent Choked)

Uplift pressure

Uplift pressure heads have been evaluated at various points by subtracting elevation head from the total residual heads. For direct comparison with uplift pressure, weight of floor has also been expressed in terms of water heads at these points. Table 3 shows the values of uplift pressures at these points. The variation of uplift pressure heads with distance from upstream end of floor has been presented on figure 4 for two extreme conditions viz filter fully effective and filter fully choked. The weight of the floor in terms of water heads is also shown in this figure.

Figure 4 indicates that only for 100 percent choking condition, uplift pressure increases to such a value that near the downstream edge the weight of floor is unable to counterbalance it. This clearly emphasises that for the design of floor thickness an allowance of about 5 per cent is sufficient to account for the rise in uplift pressure due to expected choking of filter, unless soil conditions are so adverse to cause the danger of 100 per cent choking.

The variation of uplift pressure at two selected points i.e. at point 2 and 9 with degree of choking has been plotted in Fig. 5. It is interesting to note that at point 2 uplift pressure increases marginally with increase in degree of choking. The maximum increase in uplift pressure corresponding to 100 per cent choking at point 2 is only 4.2 per cent. However, at point 9 this increase is marginal only upto 80 per cent of choking and beyond this the increase is substantial. The maximum increase at this point is 21.8 per cent corresponding to 100 per cent choking.

Exit Gradient

Exit gradients have been computed by observing potentials at various depth along the downstream cutoff. The residual head has been plotted

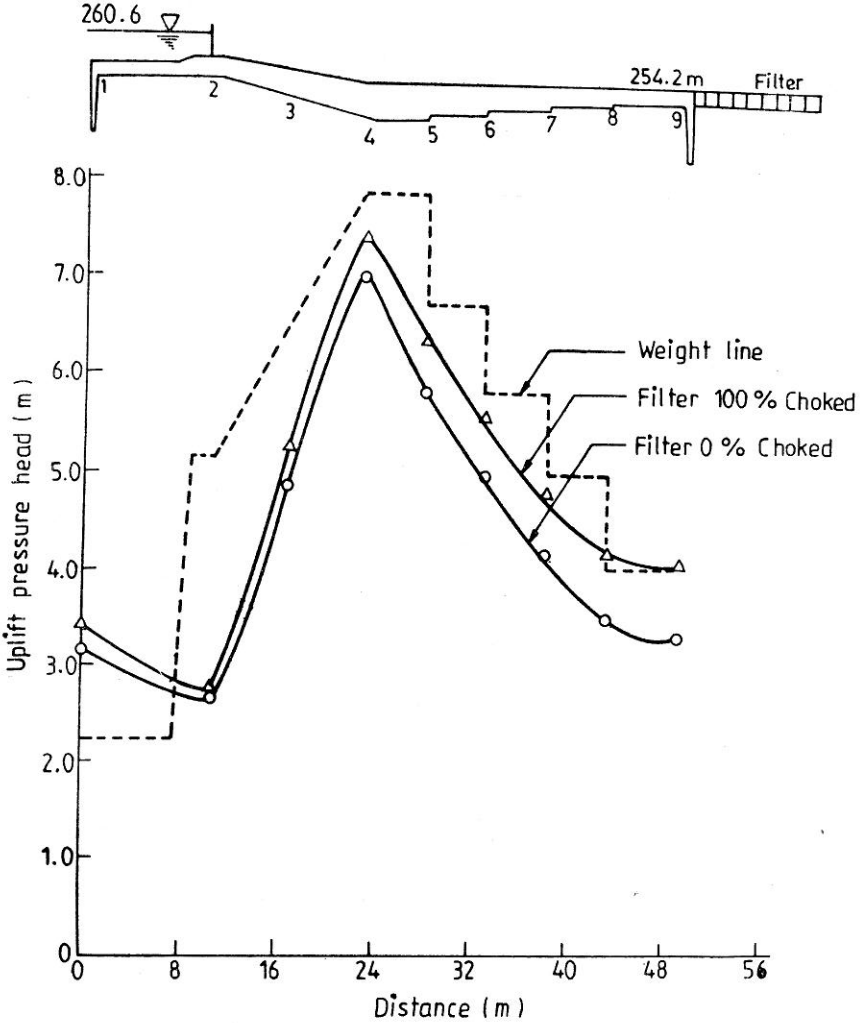


FIGURE 4 Effect of Choking of Filter on uplift pressure along the Floor.

against depth along the downstream cutoff in figure 6. The initial slope of plot gives the maximum exit gradient. The variation of exist gradient with degree of choking has been depicted in Fig. 7. Exit gradient increases with degree of choking of filter. Quantitatively, exit gradient Increases from 0.147 to 0.16 i. e. by 8.8 per cent as choking of filter increases from zero to 80 per cent.

Effect of Depth of cut offs of Weir on Seepage

Problem

In the weir on permeable foundation, provision of sheet piles at appropriate locations and of appropriate depth is very important. While

TABLE 1

Residual Heads Along Floor

Points	Distance from u/s end of floor (m)	Residual head (per cent of max. differential head)					
		Degree of choking (per cent)					
		0	20	40	60	80	100
1	0.0	77.7	77.6	77.8	78.3	78.8	81.0
2	10.7	69.5	69.7	70.0	70.8	71.2	74.3
3	16.7	63.7	64.0	64.3	65.0	65.8	69.5
4	23.0	54.4	54.7	54.8	65.6	56.4	61.2
5	28.0	43.7	43.7	44.1	44.9	45.9	51.9
6	33.0	36.7	36.7	37.1	38.0	39.2	46.0
7	38.0	30.6	30.7	30.9	31.8	33.2	40.6
8	43.0	25.8	26.0	26.2	27.0	28.6	36.8
9	49.0	23.6	23.8	24.0	24.8	26.3	35.1

TABLE 2

Residual Heads Along Downstream Cut Off

Depth along downstream cutoff (*m*)	Residual head (m)				
	Degree of choking (per cent)				
	0	20	40	60	80
0.8	0.154	0.154	0.192	0.230	0.371
1.6	0.275	0.282	0.314	0.352	0.512
2.4	0.390	0.397	0.442	0.480	0.627
3.2	0.530	0.550	0.589	0.634	0.774

TABLE 3

Uplift Pressure Along Floor

Points	Distance from u/s end of floor (*m*)	Uplift pressure (*m*)						Weight of floor in terms of water head (*m*)
		Degree of choking (per cent)						
		0	20	40	60	80	100	
1	0.0	3.17	3.17	3.18	3.21	3.24	3.38	2.24
2	10.7	2.65	2.66	2.68	2.73	2.76	2.76	5.15
3	16.7	4.87	4.90	4.92	4.96	5.01	5.25	6.50
4	23.0	6.98	7.00	7.01	7.06	7.11	7.42	7.84
5	28.0	5.29	5.89	5.82	5.87	5.94	6.32	6.72
6	33.0	4.95	4.95	4.98	5.03	5.11	5.54	5.82
7	38.0	4.16	4.16	4.18	4.24	4.32	4.80	4.93
8	43.0	3.45	3.46	3.48	3.54	3.63	4.15	4.03
9	49.0	3.31	3.32	3.34	3.39	3.48	4.04	4.03

TABLE 4

Potential Along Weir for Different Depths of u/s Pile

Points	Distance from upstream edge (*m*)	Hydraulic potentials (per cent of total head)					
		Upstream pile depths (*m*)					
		0	2.0	4.0	8.0	12.0	16.0
1	0	100.0	74.5	65.7	58.1	51.4	46.5
2	8	71.8	65.2	60.6	55.4	48.7	45.5
3	16	61.5	56.5	53.7	50.1	45.8	42.7
4	24	53.6	50.0	47.7	44.8	41.8	39.2
5	30	49.2	45.7	43.6	41.2	38.8	36.4
6	36	46.0	42.9	41.9	38.9	36.4	34.3
7	38	45.2	42.0	40.2	38.2	35.7	33.8
8	48	39.3	36.6	35.0	33.2	31.4	29.6
9	58	31.7	29.6	28.4	27.0	25.2	24.2
10	66	26.0	24.3	23.3	22.1	20.5	19.8
11	74	19.9	18.4	17.8	16.9	15.0	14.5
12	80	17.2	16.1	15.3	14.7	13.5	13.3

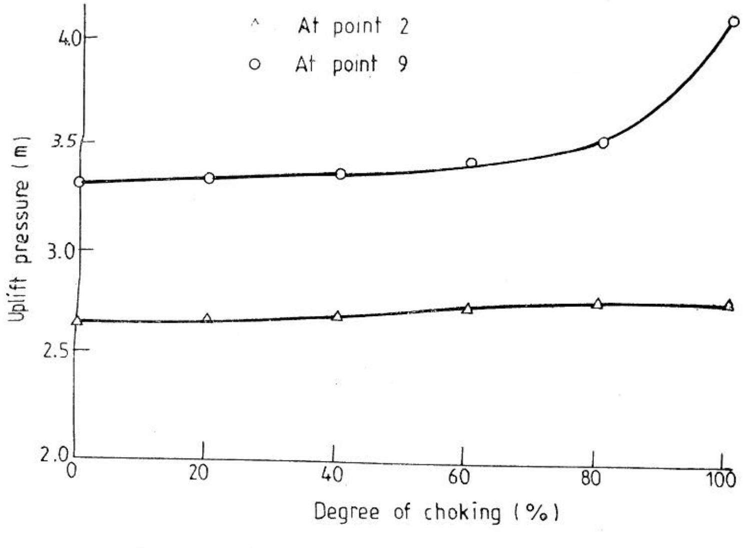
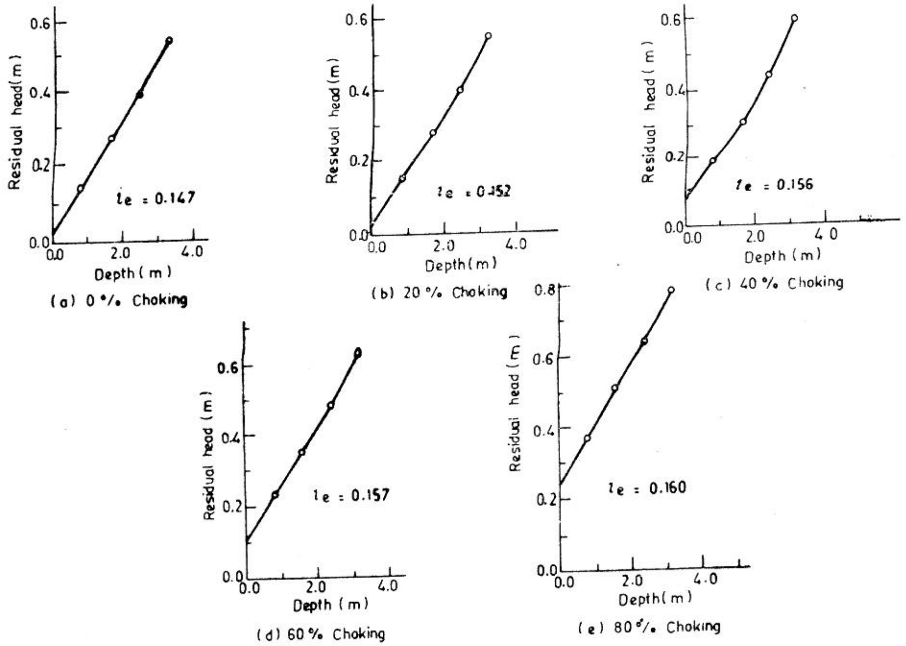


FIGURE 5 Variation of Uplift Pressure with Degree of Choking of Filter.



(a) 0 % Choking

(b) 20 % Choking

(c) 40 % Choking

(d) 60 % Choking

(e) 80 % Choking

FIGURE 6 Residual Heads along Downstream cut off for Different Degree of Filter Choking

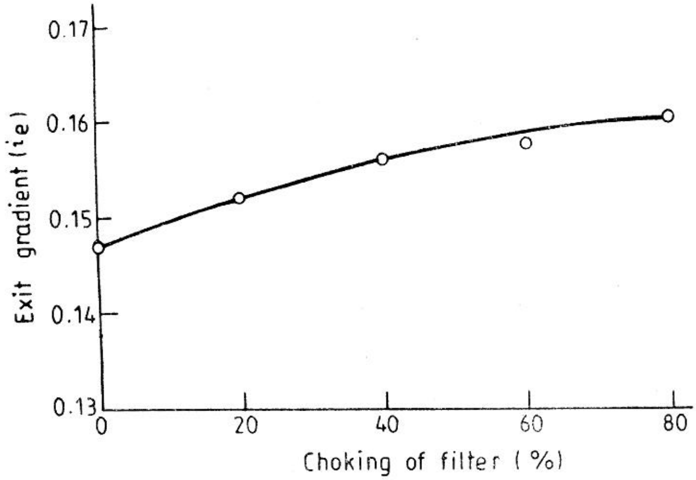


FIGURE 7 Variation of Exit Gradient with Degree of Choking of Filter

designing the weir, location and depth of pile line is decided in such a manner that structure is safe against surface flow as well as subsurface flow. Normally, one pile line is provided at downstream end to keep the exit gradient within safe limit and hold the structure safely on the soil under adverse conditions like scouring. The second one is provided at the upstream end, depth of which is decided on scour consideration. Apart from holding the structure under the condition of maximum possible scouring upstream pile line has the effect of reducing the uplift pressure throughout along the floor of weir. It may also have some effect on exit gradient. In this problem, effect of depth of pile line on exit gradient and uplift pressure has been studied. The results have also been compared with theoretical results obtained by Khosla (1954) using method of independent variables.

Model

A weir profile as shown in Fig. 8 is considered for the present study. Total length of floor is 80m and impervious stratum is at a depth of 40m from upstream edge of floor. In actual condition river bed upstream and downstream of floor extends to infinite distance. The size of model, however, has to be limited in such a manner that results do not differ much from that for actual consideration. In the present problem, both upstream and downstream bed have been extended to 20m *i.e.* one forth of the length of weir beyond the edge of floor, thus giving length to depth ratio of model approximately 3: 1. The upstream and downstream cutoffs are simulated by cutting out the paper along the cutoffs.

To study the effect of upstream pile on the uplift pressure and exit gradient, depth of downstream pile line is fixed at 4m and depth of

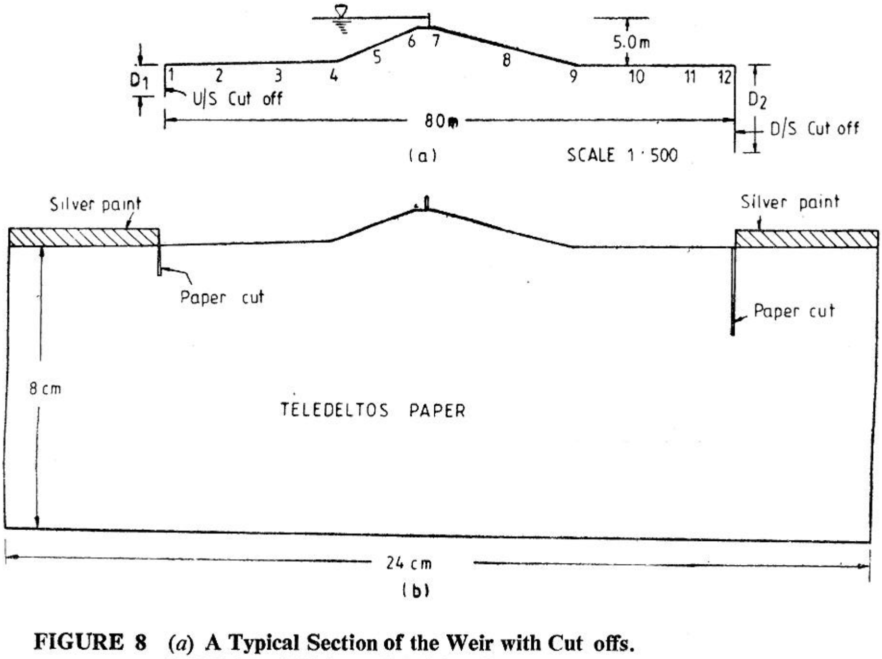


FIGURE 8 **(*a*) A Typical Section of the Weir with Cut offs.**
(*b*) Model of Weir on Teledeltos Paper

upstream piling is varied from zero to 16m. In second set of observations, depth of upstream cutoff is kept 4m and that of downstream cutoff is varied from zero to 16m. The potentials were observed at 12 key points shown in figure 8 along the profile of weir for each test condition. The exit gradient has been determined by observing potentials along the downstream cutoff at various depths.

Results and Discussion

The record of observations of hydraulic potentials along weir for various depths of upstream pile by keeping the depth of d/s pile constant at 4m is given in Table 4. Similarly, Table 5 shows the recorded values of hydraulic potentials along weir for different depths of downstream pile by keeping u/s *pile depeh at 4m constant. The results of residual heads along* downstream cut off are presented in Table 6 and 7 for different depths of u/s and d/s piles respectively.

TABLE 5

Potentials Along Weir for Different Depths of Downstream Pile

Points	Distance from upstream edge (*m*)	Hydraulic potentials (per cent of total head)					
		Depth of downstream pile (*m*)					
		0	2.0	4.0	8.0	12.0	16.0
1	0	69.0	69.8	70.3	71.8	72.9	74.7
2	8	63.9	64.8	65.6	67.3	68.8	70.7
3	16	57.2	58.3	59.3	61.2	63.0	65.2
4	24	51.3	51.3	52.4	54.7	56.8	59.4
5	30	44.6	45.8	47.0	49.7	52.1	55.0
6	36	40.9	42.2	43.4	46.5	49.0	52.0
7	38	40.2	41.6	42.3	45.9	48.4	51.5
8	48	34.0	35.4	36.9	40.3	43.1	46.6
9	58	27.2	28.9	30.5	34.4	37.8	41.7
10	66	20.6	22.6	24.6	29.4	33.5	38.0
11	74	13.1	16.0	18.8	25.2	30.3	35.3
12	80	5.5	11.8	16.3	23.8	29.4	34.7

Uplift pressure

The uplift pressures have been calculated from Tables 4 and 5 by using Equation 4. Figure 9 illustrates hydrualic potential variation along weir for different depths of upstream cut offs. It can be seen that hydraulic potential goes on reducing from u/s edge towards d/s edge of floor. The effect of increase in depth of u/s pile line is to reduce the hydraulic

TABLE 6

Residual Heads Along 4 m Deep Downstream Cutoff

Depth along down-stream cutoff (*m*)	Residual head (*m*)					
	Upstream pile depths (*m*)					
	0	2.0	4.0	8.0	12.0	16.0
1	0.135	0.135	0.135	0.120	0.115	0.115
2	0.27	0.255	0.245	0.235	0.220	0.215
3	0.365	0.345	0.320	0.315	0.290	0.280
4	0.590	0.505	0.475	0.450	0.390	0.415

TABLLE 7

Residual Heads Along Downstream Cutoff with Upstream Pile 4 m Deep

Depth along Down stream cutoff (*m*)	Residual head (*m*)					
	Depth of downstream pile (*m*)					
	0	2.0	4.0	8.0	12.0	16.0
1	0.135	0.18	0.13	0.07	0.08	0.07
2	0.28	0.31	0.22	0.13	0.13	0.11
3	0.32	0.40	0.29	0.16	0.17	0.15
4	0.37	0.45	0.45	0.215	0.23	0.20
5	—	0.49	0.54	0.37	0.30	0.26

potential below the floor. This reduction in hydraulic potential is very much significant near u/s edge whereas at d/s edge it is minimum. For example, with increase in u/s pile depth from 2m to 16 m, reduction in hydraulic potential at point 1 is 28 per cent of total head whereas at point 12 it is only 2.8 per cent of total head.

Figure 10 illustrates the effect of depth of u/s sheet pile on the uplift pressure at point 9 on the floor. It is seen that effectiveness of pile in decreasing the uplift pressure below floor reduces continuously with increase in depth of pile. For example, the reduction in uplift pressure is 3.3 per cent when the pile depth increased from 0 to 4 m, whereas it is only 1 per cent when pile depth increased from 12m to 16m. Similar results are observed at other points also. Hence, it is not desirable to take sheet pile beyond a certain optimum depth which will depend on the length of floor and depth of pervious stratum. Beyond this depth, benefit to be gained

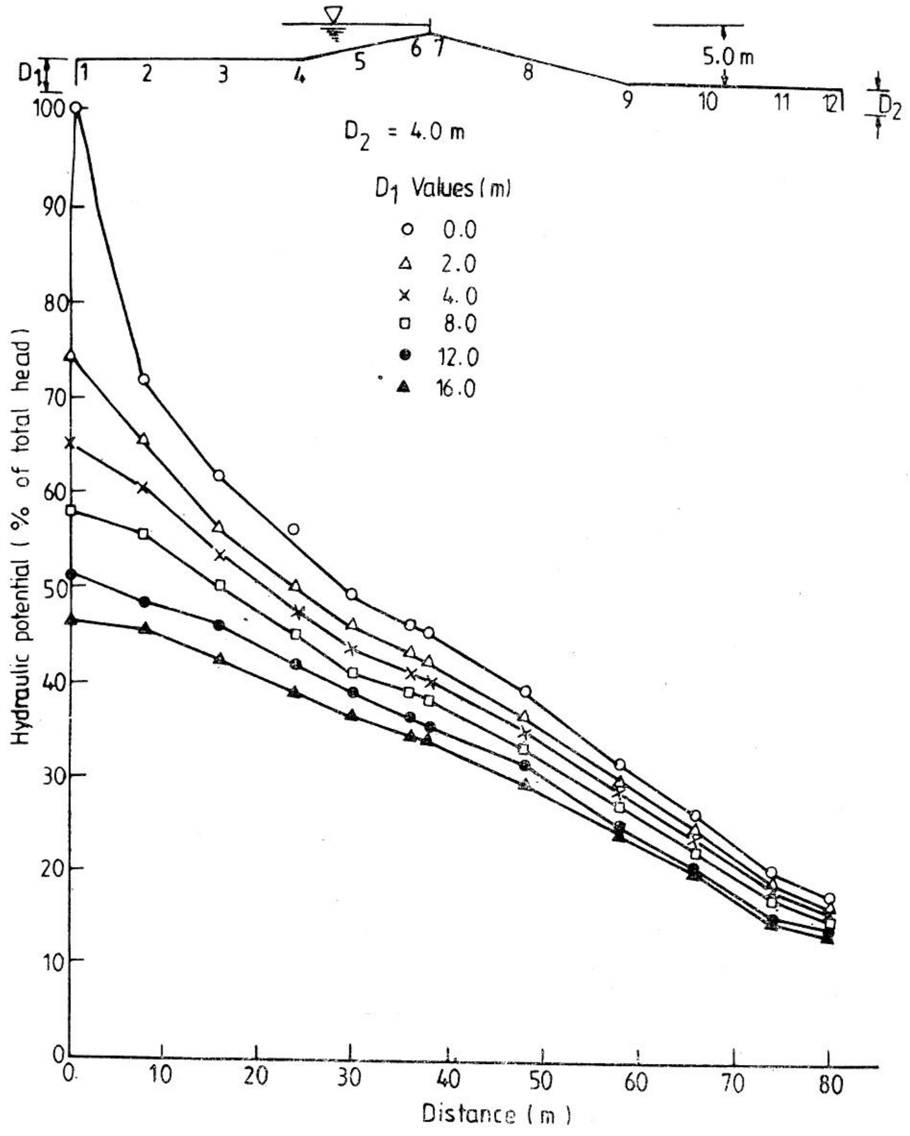


FIGURE 9 Hydraulic Potentials along the Weir for Different Depths of u/s cut off

due to reduction in thickness of floor will be outdone by the cost of deep excavation for sheet pile and increased risk of occurrence of faulty joints.

The variation of hydraulic potentials along the weir for different depths of downstream sheet pile has been shown on Fig. 11. The effect of downstream pile on hydraulic potentials is just opposite to that of upstream pile. Hydraulic potentials increase every where on the floor with increase in depth of downstream pile. However, this increase is significant only near the downstream edge.

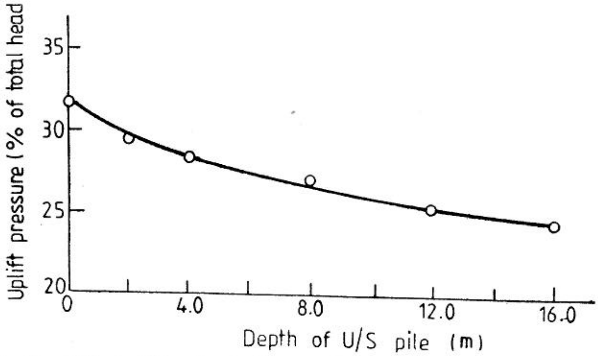
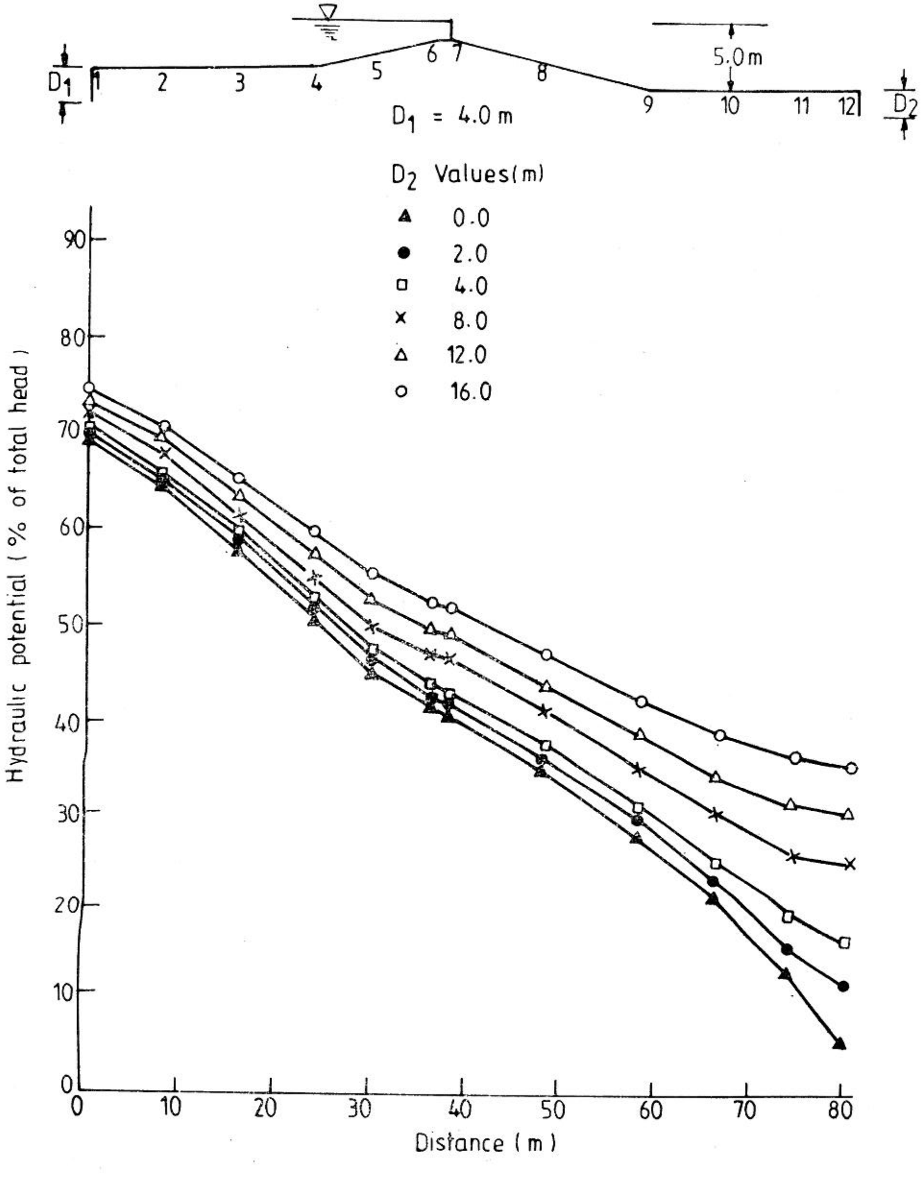


FIGURE 10 Effect of Depth of u/s cut off on the Uplift Pressure at point 9



FIGURF 11 Variation of Hydraulic Potentials along Weir for Different d/s Cut off Depths.

Finally, figure 12 has been drawn to compare experimental values of pressure drop at upstream pile with those given by Khosla's theoretical curves. It is seen that both curves are nearly parallel but theoretical curve indicates lesser pressure drop for a particular depth of upstream pile. One reason for this difference is that Khosla's solution is given for weir on permeable layer of infinite thickness whereas experimental study has been conducted for weir on layer of finite depth.

Exit Gradient

The variation of residual heads along downstream cut off for different depths of u/s and d/s piles are shown in Fig. 13 and Fig. 14 respectively. Figure 15 shows the effect of depth of upstream pile on the exit gradient. The effect of depth of upstream pile on exit gradient is to decrease it but by a marginal amount. Beyond 4m depth of u/s pile the exit gradient becomes almost constant. This result is similar to Khosla's solution in which exit gradient is assumed to vary only with depth of downstream pile and no effect of upstream pile depth is taken into account.

Variation of exit gradient with depth of downstream pile when depth of upstream pile is fixed at 4m is shown in Fig. 16. For comparison, exit gradient values based on Khosla's solution are also given. Exit gradient decreases as depth of d/s pile increases. It is observed that effectiveness of downstream pile in lowering exit gradient reduces for larger depths of pile.

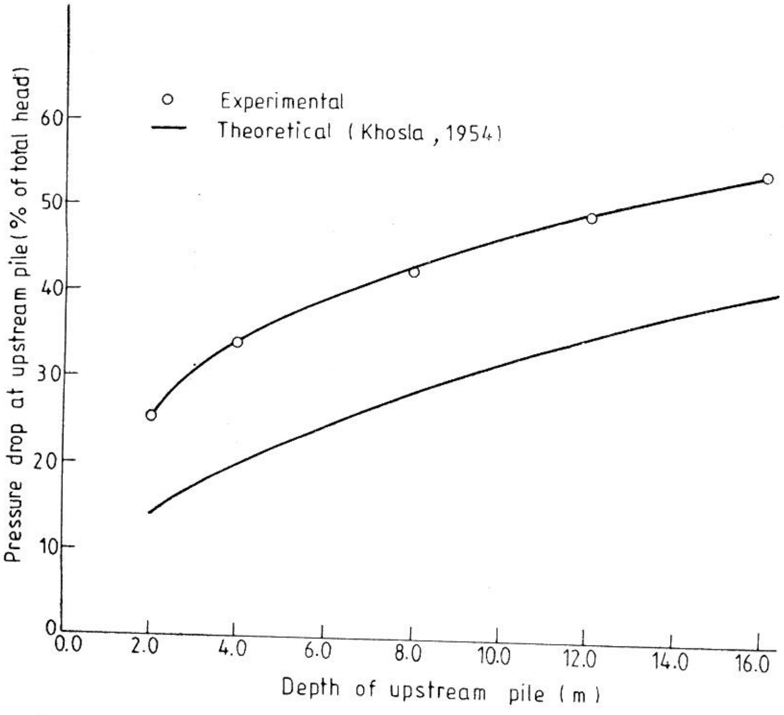
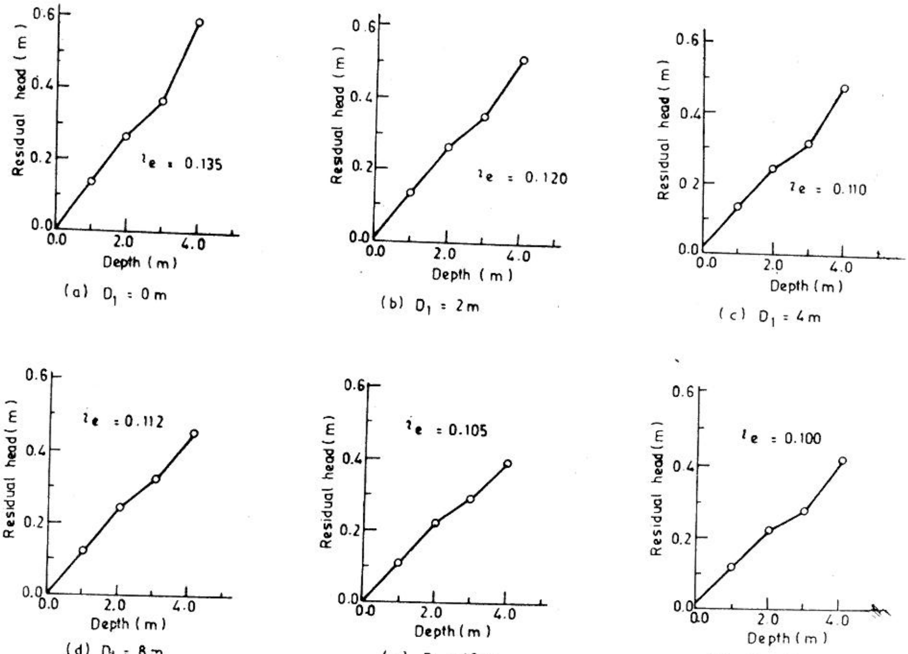


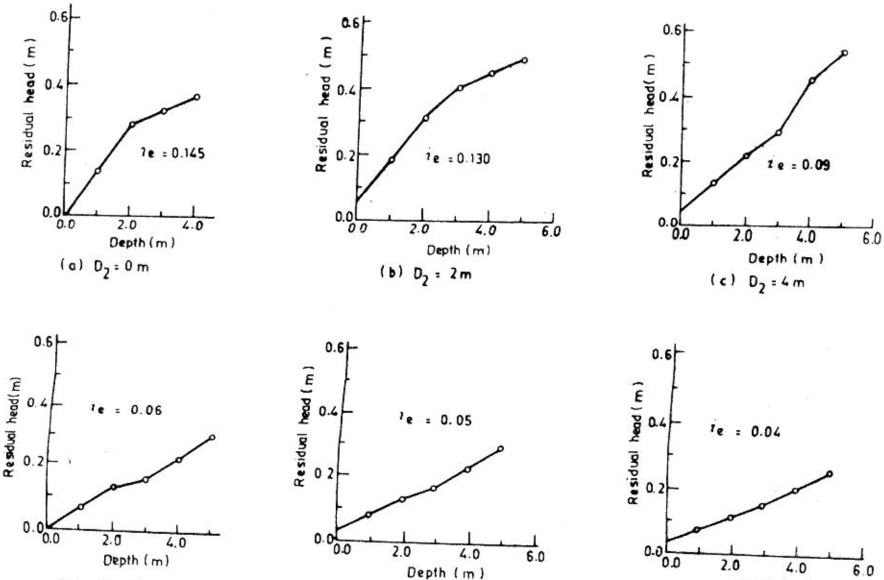
FIGURE 12 Uplift Pressure Drop at u/s Pile with its Depth.



(a) D_1 = 0 m (b) D_1 = 2 m (c) D_1 = 4 m

(d) D_1 = 8 m (e) D_1 = 12 m (f) D_1 = 16 m

FIGURE 13 Residual heads along d/s Cut off for Different Depths of u/s Pile



(a) D_2 = 0 m (b) D_2 = 2 m (c) D_2 = 4 m

(d) D_2 = 8 m (e) D_2 = 12 m (f) D_2 = 16 m

FIGURE 14 Residual Heads along d/s Cut off for Different d/s Pile Depths

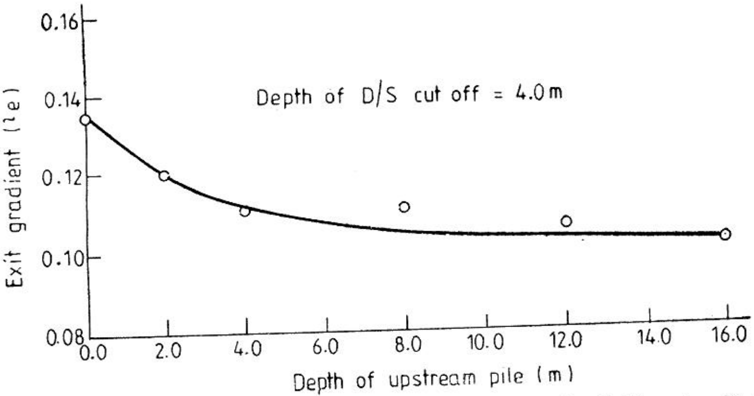


FIGURE 15 Effect of u/s Pile Depths on Exit Gradient (Depth of d/s cut off Constant = 4m)

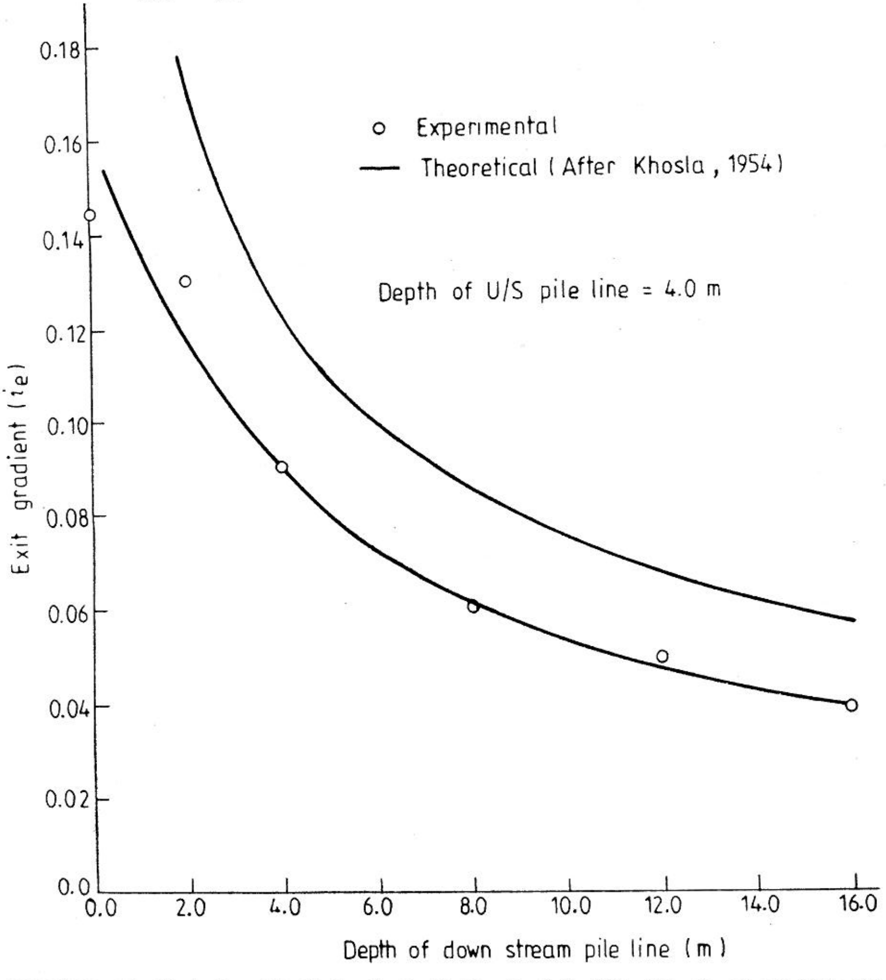


FIGURE 16 Variation of Exit Gradient with Depth of d/s Pile (Depth of u/s Cut off Constant = 4m)

Hence in some cases where exit gradient is very high, increasing the length of floor will be advantageous than providing a very deep downstream pile.

Conclusions

The study of two cases of confined seepage flow conducted by 'Electrical analogy—conducting paper technique' leads to the following conclusions:

1. Electrical analogy—conducting paper technique is viable method to solve 2-dimensional seepage problem even for complex boundary conditions. The method is very simple and rapid.
2. The filter downstream of a weir should be designed very carefully so as to minimise the possibility of choking. While designing the weir, some allowance in its floor thickness should be made to account for the possible choking of filter during its life time.
3. Study of flow under a weir section with upstream and downstream cut offs indicates that effectiveness of cut offs in reducing the uplift pressure and exit gradient, decreases at the large depths of cut offs. Therefore cutoffs should not be taken below an optimum depth which can be determined by carrying out detailed cost analysis.

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Notations

D/S, d/s = downstream
D_1 = depth of upstream cut off
D_2 = depth of downstream cut off
h = hydraulic head
h_w = uplift pressure
h_1 = total hydraulic head
i_e = exit gradient
k = coefficient of permeability
l = average length of flow field
N_d = total number of equipotential drops
N_f = total number of flow lines
n = number of equipotential drops upto certain point.
p_s = seepage pressure
q = discharge
U/S, u/s = upstream
x = directional variable
z = directional variable; position head
γ_w = unit weight of water
ϕ = electric potential; hydraulic potential