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When a dam is built on porous strata such as generally exist at the beds of rivers, there is an underground flow through the porous strata under the masonry. Accompanying this flow, there will be a pressure acting upwards from below on the masonry floor. There have been many attempts to investigate by direct measurements from laboratory models of weirs, the way in which this pressure varies with different forms of design. The usual method for model work is to build a tank of convenient size with a number of holes fitted with manometers. The tank is then filled with sand representing the subsoil strata and the model of the weir is placed on the sand. A head of water is maintained on the upstream side of the model and the pressure distribution is indicated by the manometers. A very large number of measurements and readings are required to obtain satisfactory results. The method is very laborious.

An accurate and quick method for studying this pressure distribution was, therefore, highly desirable. N. N. Pavlovsky (Reference to Pavlovsky's work is found in the Proceedings of the International Congress of Dams) suggested as early as 1921, that an electrical potential method could be employed for the purpose of studying the subsoil pressures under dams. Some attempts were made in this direction by Hebert and co-workers (Technical Memorandum 1934, No. 384, United States Department of the Interior Bureau of Reclamation) in America, but no definite conclusions were reached. The reason for the non-agreement in the case of the experiments of the electric and hydraulic models is apparently due to inaccuracies in Coleman's (Transaction of the American Society of Civil Engineers, 1916, vol. 80, page 421) model and in the technique of Hebert's electrical method. Hebert also compared the electrical results with those obtained by Khosla with actual Panjnad weir and found that they did not agree. At that time, the complete conditions giving the pressure distribution at Panjnad were not known and some of these were not simulated in Hebert's model.

In the present paper, the following investigations are reported: (a) Comparison of the uplift pressure in simple structures obtained by hydraulic and electrical methods; (Memoirs of the Punjab Irrigation Research Institute, Lahore, Vol. V, No. 4, 1935) (Proceedings of the Indian Academy of Sciences 1935, Vol. 2, page 22.) (b) Distribution of pressure under flush and depressed floors with one sheet pile; (Proceedings of the Indian Academy of Sciences 1935, Vol. 2, page 646.) (c) Distribution of pressure under floors with one sheet pile, but having the upstream and downstream aprons at different levels, such as occurs in falls. (Proceedings of the Indian Academy of Sciences 1936, (In Print)).

(a). Comparison of the Uplift Pressure in Simple Structures, Obtained by Hydraulic and Electrical methods. Fig. 1 shows the arrangement for the electrical method of estimating the uplift pressure. The floor of the hydraulic model is represented by BC an ebonite plate 1 ft long. The upstream and downstream levels are represented by AB and CD, two conductors each one foot and a half long. The subsoil is represented by the electrolyte in the tank. The dimensions of the tank were 4 ft x 3 ft and 3" deep. The outer boundary of the tank was made elliptical as in ARD to correspond to one of the stream lines of flow. This precaution was found necessary to obtain accurate results. The telephone system to obtain the null point was very sensitive, the required A.C being obtained from the amplifier and oscillator system as shown in Fig. 1. The arrangement gave a very sharp null point. The equi-potential lines corresponding to decrements of 5% of the potential between the ends of BC, can thus be obtained and marked directly on the base of the tank and traced.

The next attempt was to obtain similar equi-pressure lines in an actual hydraulic experiment. A tank of the same dimensions as used in the electrical method was employed for this purpose. Maintaining different upstream and downstream levels, the pressures were obtained by the usual method, a sufficiently lengthy series being taken so that the probable errors of experimental observations could be determined by statistical analysis. (Memoirs of the Punjab Irrigation Research Institute, Vol. II, No. 13 and 14 1935). When the pressure distribution obtained by this method and the potential distribution obtained by the electrical method were compared, the results were found to agree within 3 per cent. Two cases were first compared, a simple floor 12" long, and a simple floor 12" long with a sheet pile $5\frac{2}{5}$ " giving values of α as ∞ and 5, where α stands for the ratio of the length of the horizontal masonry to that of the sheet pile. For such a case a theory has also been worked out by Weaver (Journal of Mathematics & Physics, 1932, Vol. XI, page 114.) for obtaining the pressure distribution. The results of the electrical method agreed within 0.2 per cent of the theoretical values. The results obtained by the different methods are compared in Fig. 2, where the distributions, only across the bases of the weir, are shown. Two other cases, one of a depressed floor and the other of a depressed floor with a sheet pile were also compared, and the results by the hydraulic and electrical methods were found to agree. Models of electrical, hydraulic and prototype compared for Khanki and Marala with complete agreement.

The electrical method is thus capable of giving results quite in agreement with those of hydraulic models and the prototype. This is a very important conclusion as it will form the basis of the laws of flow of water under weirs. The empirical theories such as the line of creep theory, and the weighted creep theory are not correct.

(b). Flush and Depressed Floors with a Sheet Pile. A series of experiments were carried out with a flush floor of 12" in the model with lengths of sheet piles, 0, 1, 2, 3, 4, 5, and 6" giving ∞ , 12, 6, 4, 3, 12/5 and 2 for the values of α . The variation of pressure along the base of the weir is shown in Fig. 3. As mentioned before, a theory has been worked by Weaver for this case, and agreement between theory and experiment is clear from Fig. 3.

The variation of pressure at the points A and B of such a structure for different values of α are

shown in Fig. 4. Weaver's expression for the pressures at A and B are

$$\cos\left(\frac{\pi P_A}{100}\right) = \frac{1-\lambda}{\lambda}$$

$$\cos\left(\frac{\pi P_B}{100}\right) = \frac{2}{\lambda} - 1$$

where $\lambda = \frac{1 + \sqrt{1 + \alpha^2}}{2}$ and $\alpha = \frac{L}{d}$

whence P_A and P_B are obtained as percentage pressures. The position of the points A and B are marked in the inset in Fig. 4.

The second series of experiments were conducted with a depressed floor with different lengths of sheet pile. The floor of the model was 12" and it was depressed by 2" giving ratios of depression to length as 1/6. With this floor 6 sheet piles of different lengths as 1", 2", 3", 4", 5" and 6" were investigated, thus giving values of 12, 6, 4, 3, 12/5, and 2 for α_2 . α_2 is the ratio of the length of the floor to that of the pile. See inset in Fig. 5. The variations of pressure at A, B and on B - C are plotted in Fig. 5. So far as known to the authors, no theoretical solution seems to have been obtained for this case.

(c). Uplift Pressure Under Floors with One Sheet Pile, but having Upstream and Downstream Aprons at Different Levels. An illustrative structure is represented in Fig. 6. In this case L_1 , L_2 , d_1 , and d_2 are variables and the problem becomes complicated. For any particular case, the best solution is to obtain the pressures experimentally, but when d_1 is small compared with L_1 and L_2 , an approximate solution is possible as is shown by experiment and theory.

The following experiments were carried out. In the first series, the lengths of downstream apron were varied, the fall d_1 , the length d_2 of the sheet pile, and the length L_1 of the upstream apron in the model being maintained at 1", 4", and 4" respectively. In the second series L_1 , L_2 , and d_1 were kept constant being 7", 7" and 1" respectively, the lengths d_2 alone being varied. The pressure distribution along the floor in the first and second series are shown in Fig. 7 and 8 respectively. It was also found from the experiments that when L_2 was decreased in length from 8" to 0, the change of pressure on the L_1 side was so small as 6 per cent. This can be seen from Fig. 9. This fact is of significance because, one may approximately extend the analysis of a single sheet pile case "not at the heel" worked out by Weaver, (Journal of Mathematics & Physics, 1932, Vol. XI, page 114.) to the one in question taking the floor-length L_2 and length of sheet pile d_2 for the downstream side and L_1 and $d_1 + d_2$ for the upstream. This gives results accurate enough for engineering purposes. It may be emphasized, that this is not a rigorous extension and should not be taken as such for all cases. It is only an approximation useful for practical purposes. The expression to find the pressure under a flush floor, when the sheet pile is not at the heel, is according to Weaver (Journal of Mathematics & Physics, 1932, Vol. XI, page 114.)

$$P_{x,y} = \frac{P_0}{\pi} c(x,y) = \frac{P_0}{\pi} \cos^{-1} \left[\frac{d(\kappa - \lambda) \pm \sqrt{\kappa^2 + d^2}}{d\lambda} \right]$$

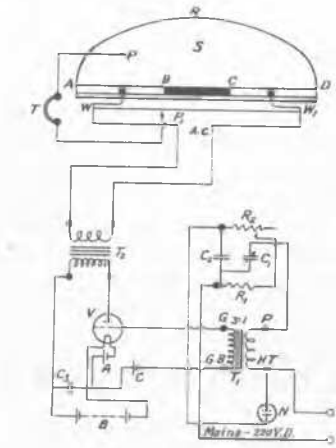
the plus sign holding for $X \geq 0$, the minus sign for $X \leq 0$ and the origin $X=0$ corresponding to the position of the pile. In this expression

$$\kappa = \sqrt{1 + \alpha_1^2}$$

$$\lambda = \frac{1}{2} \sqrt{1 + \alpha_1} + \frac{1}{2} \sqrt{1 + (\alpha - \alpha_1)^2}$$

$$\alpha_1 = \frac{L_2}{d} \quad \text{and} \quad \alpha = \frac{L}{d}$$

d = depth of sheet pile; d_1 and $d_1 + d_2$ in the cases considered here.
 L = the length of floor; $L_1 + L_2$ in the cases considered here.



- | | | | |
|------------------|------------------|-------------------|--------------------|
| AMPLIFIER | | OSCILLATOR | |
| C ₁ | Fixed Condenser | N | Neon Bulb |
| V | Triode Valve | R | High Resistance |
| T | Transformer | R ₁ | Rheostat |
| A | Filament Battery | C ₂ | Variable Condenser |
| B | Plate Battery | C ₃ | Fixed Condenser |
| C | Grid Battery | T | Transformer |

FIG. 1

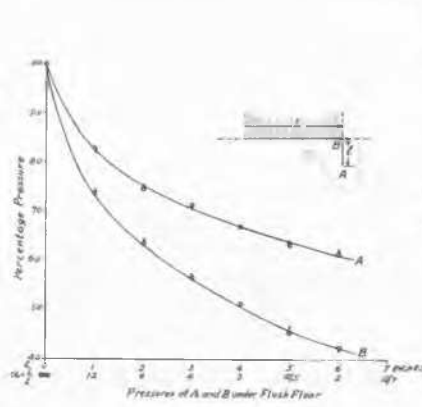


FIG. 4

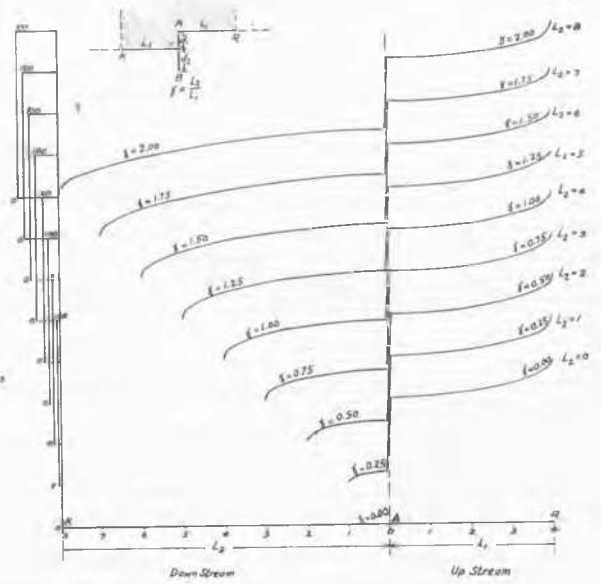
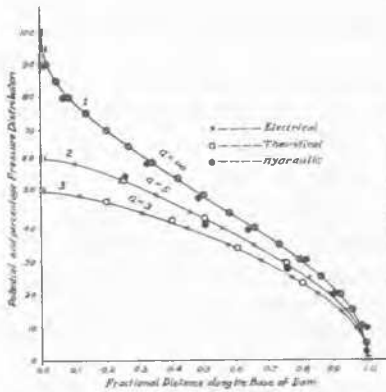


FIG. 7



Distribution of uplift pressure across Base of Dam in percent of head water pressure for various Ratios and of width of Base of Dam to depth of Sheet-Piling at the Heel.

FIG. 2

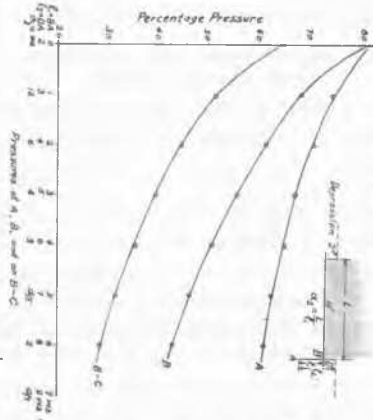


FIG. 5

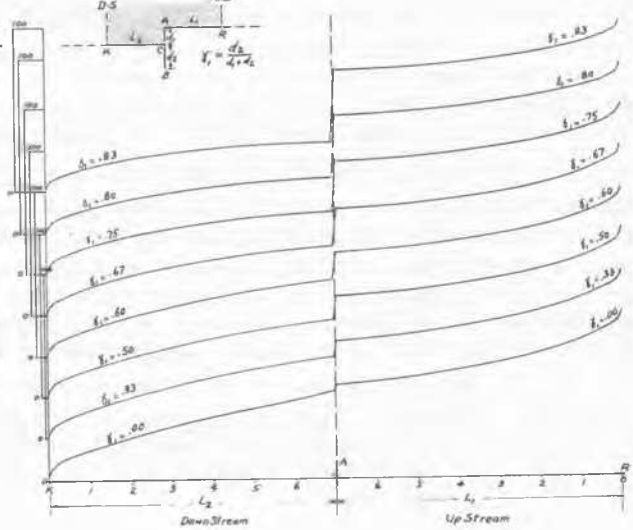


FIG. 8

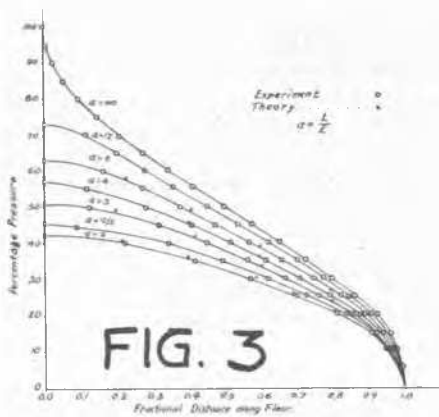


FIG. 3

Pressure Distribution along Flush Floor.

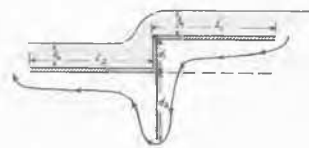


FIG. 6

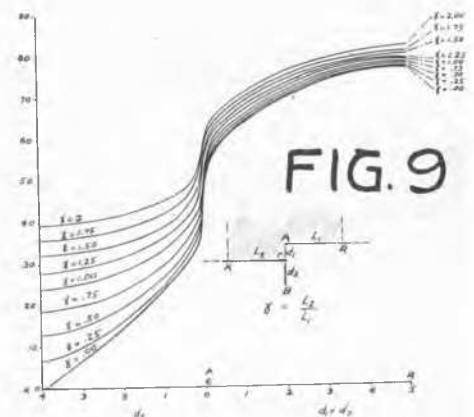


FIG. 9

The results of comparison between theory and experiment are shown in the Table.

T A B L E

<u>Upstream Side.</u>				<u>Downstream Side.</u>			
P_A denotes pressure at A.				P_C denotes pressure at C			
	P_A	P_A		P_C	P_C		
	Theo- reti- cal.	Experi- ment- al.		Theo- reti- cal.	Ex- peri- mental.		
0.800	0.80	77.2	77.0	1.00	1.00	0.0	0.0
1.000	0.80	77.3	77.1	1.25	1.00	7.3	6.8 L_2
1.200	0.80	77.6	77.4	1.50	1.00	13.8	12.9 varying.
1.400	0.80	78.0	78.2	1.75	1.00	19.8	18.7
1.600	0.80	78.5	78.6	2.00	1.00	25.0	24.2 L_1, d_1 & d_2
1.800	0.80	79.1	79.3	2.25	1.00	29.5	27.9 constant
2.000	0.80	79.7	79.9	2.50	1.00	33.3	31.9
2.200	0.80	80.2	80.7	2.75	1.00	36.6	37.1
2.400	0.80	80.7	81.7	3.00	1.00	39.5	39.4
9.33	4.67	56.7	58.4	28.00	14.00	47.7	48.2
7.00	3.50	58.8	60.2	14.00	7.00	45.5	45.6 d_2
5.60	2.80	60.9	62.1	9.33	4.67	43.3	43.3 varying
4.67	2.33	62.9	63.2	7.00	3.50	41.1	40.4 L_1, L_2 & d_1
3.50	1.75	66.5	66.9	4.67	2.33	37.1	36.2 constant
2.80	1.40	69.7	69.7	3.50	1.75	33.5	32.3
2.33	1.17	72.6	72.6	2.80	1.40	30.2	29.2

These cases illustrate the application of the electrical method for obtaining the uplift pressures for purposes of designing weirs. There are, however, other considerations which enter into the design of such works, but the uplift pressure under the idealised conditions of the subsoil forms the basis of the laws for the design of such works. Simple considerations would show that experimental conditions in the models are the worst likely to be experienced on the prototype and, hence, if they can be shown to be satisfactory for the model, they must also be safe for the weir. It has been the main object of this paper to obtain working rules for simple structures and to show that the potential theory holds for the flow of water in subsoil under dams. The mathematical analysis involved in accurately obtaining the pressures under the actual structures is so complicated, that an experimental solution alone will be possible, and the electrical analogy method is capable of giving such a solution quickly and accurately.