COMBINED CONFINED/UNCONFINED SEEPAGE BENEATH HYDRAULIC STRUCTURES

Part II, Experimental Study

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ABSTRACT

An experimental study was carried out, in this paper, to investigate the problem of combined confined /unconfined seepage beneath hydraulic structures. Seepage flow beneath floors of tail escape structures presents a good example for the problem of combined seepage. The floor is provided with one row sheet pile. Study includes verification and adjustment of the predicted equations, describing the combined seepage, in part I [1]. Analysis of the experimental results are carried out to get the effect of various factors on the combined seepage characteristics; separation of seepage flow from the underside of floor, uplift pressures, and seepage discharge. Experiments were conducted using the Hele-Shaw model with motor's oil as a viscous flow. Results are presented in the form of charts and empirical formulas.

Keywords: *Seepage, Combined Seepage, Hydraulic structures.*

NOTATIONS

b	Distance between the two prespex sheets of the model, mm,
D	Depth of the sheet pile, cm,
g	Gravity acceleration, cm/sec^2,
H	Difference between upstream and downstream water levels, cm,
H_o	Depth of free seepage flow at the sheet pile above the impervious layer, or the initial depth of unconfined seepage, cm,
H_1	Depth of flow at the upstream side, cm,
H_2	Free board of the drain, cm,
δH	Vertical projection of the sloping downstream seepage face, cm,
h_1	Potential at any point along the floor, cm,
K_s	Coefficient of permeability, or the hydraulic conductivity, $K_s = \frac{gb^2}{12\nu}$ cm./sec.,
L	Horizontal length of floor, cm,
ℓ_1	Length of floor before the sheet pile, cm,
$'\ell_1$	The unseparated length of the floor, cm,
ℓ_2	Horizontal distance between sheet pile and the intersection of seepage line with flow surface in the drain, cm,
ℓ'_2	The horizontal distance from point of separation to the intersection of seepage line with the downstream flow surface, cm,
Q	Quantity of seepage per unit width, cm^3/ sec/cm,
S	The horizontal distance of seepage face behind the floor, cm,
t	Thickness of the floor, cm,
x	Fractional distance of the floor length, cm,
z	Height of the downstream water level above the impervious layer, cm,
ν	Kinematic viscosity of the oil,cm^2/sec,
θ	The side slope angle.

1. INTRODUCTION

Seepage flow, underneath hydraulic structures, may either be confined or unconfined. However, combination of both confined and unconfined seepage may also be occurred in the same flow field below hydraulic structures. Seepage flow under tail escape structures presents a good example for the combined confined/unconfined seepage problem. Tail escape structures are characterized by discrepancy between the upstream and downstream levels of both water and seepage surfaces.

Downstream seepage surface is lowered and shaped to match the lowered levels of the receiving drain. This often makes seepage flow separates from the underside of floors of such structures. Here, two probable cases of separation may take place; the first is when the seepage flow separates from both floor and back of the sheet pile. The second, occurs when the seepage flow separates from the floor only, as shown in Figure (1). Occurrence of any of the two former cases mainly depends on the flow depths H_1 & H_2 and the distance S. In both cases, the vertical plane, at the point of separation, "O" divides the flow domain below the floor into two adjacent zones; I and II as shown in Figure (1). The first zone, which is located upstream the separation point, is equipped with confined seepage. In the other, which follows the separation point, the seepage line represents the free surface of unconfined seepage. Hereby, occurrence of confined and unconfined seepage at the same flow domain beneath hydraulic structures, presents a combined confined/unconfined seepage problem.

Review of previous studies for confined and unconfined seepage problems is presented in part I [1]. In part I, a theoretical approach for the combined seepage problem was given. The approach is concerned with the first case of separation. The solution enables to determine the initial depth of the unconfined seepage flow, H_o, and in turn to determine the seepage quantity Q.

In the present work, the theoretical equations derived in part I, are checked using the experimental results. Study also aims at investigating the effect of various factors on the characteristics of combined seepage flow; separation, uplift pressure, and seepage discharge. These factors are; the horizontal distance S, depth of the sheet pile D and the flow depths H_1 & H_2.

2. THEORETICAL EQUATIONS

In part I, the problem of combined seepage was theoretically investigated. The first case of separation, in which the flow separates from both the floor and the back of the sheet pile, was dealt with. Theoretical equations, for the initial depth of seepage flow H_o and the seepage discharge Q, were obtained in the forms,

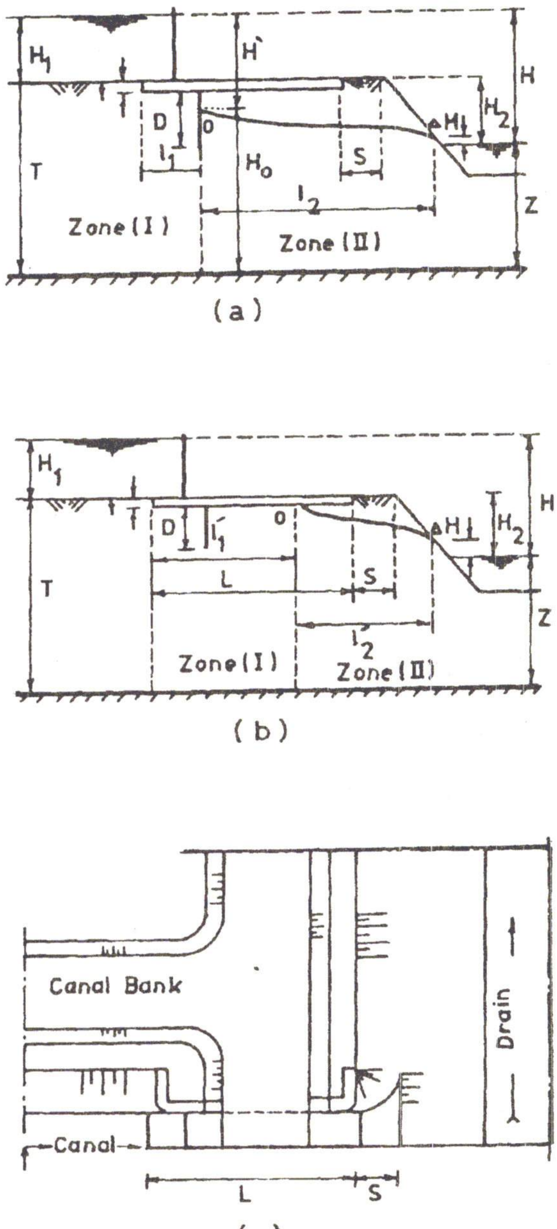

Figure 1. Definition Sketches; a- Separation of seepage flow from both floor and sheet pile, b- Separation from floor only; c- Half plan.

$$Q = K_s \left(\frac{H_o^2 - Z^2}{2\ell_2}\right), \text{ and} \tag{1}$$

$$H_o = \sqrt{(T-H_2)^2 + 2\ell_2(T+H_1)\frac{K'}{K} + \left(\ell_2\frac{K'}{K}\right)^2} - \ell_2 . \frac{K'}{k} \tag{2}$$

where, $$\ell_2 = L - \ell_1 + S + H_2 . \cot. \theta, \tag{3}$$

K, K′ are the constants of the complete elliptical integral of the first kind, and

K_s is the coefficient of permeability.

The values of the constant K′/K can be determined from special tables [2] according to the values of the modules m, where

$$m = \cos\left(\frac{\pi}{2} , \frac{D}{T}\right)\sqrt{\tanh^2\left(\frac{\pi}{2} . \frac{\ell_1}{T}\right) + \tan^2\left(\frac{\pi}{2} . \frac{D}{T}\right)} \quad (4)$$

3. EXPERIMENTAL SET UP

The characteristics of combined seepage beneath floor of a tail escape structure, provided with one row sheet piles, are experimentally investigated using the Hele Shaw model. The model was prepared to satisfy the conditions recommended in Ref. [3] to eliminate the effect of impervious ends of the model.

Figure (2) shows the model arrangements, which consist of two vertical prespex sheets (1) each of 1320 x 800 x 10 mm. The two sheets are kept 1.5 mm apart using klingarite sheet (2). The floor model is also formed from the same klingarite sheet. The floor length L equals 10 cm., and its depression depth t equals 0.5 cm.

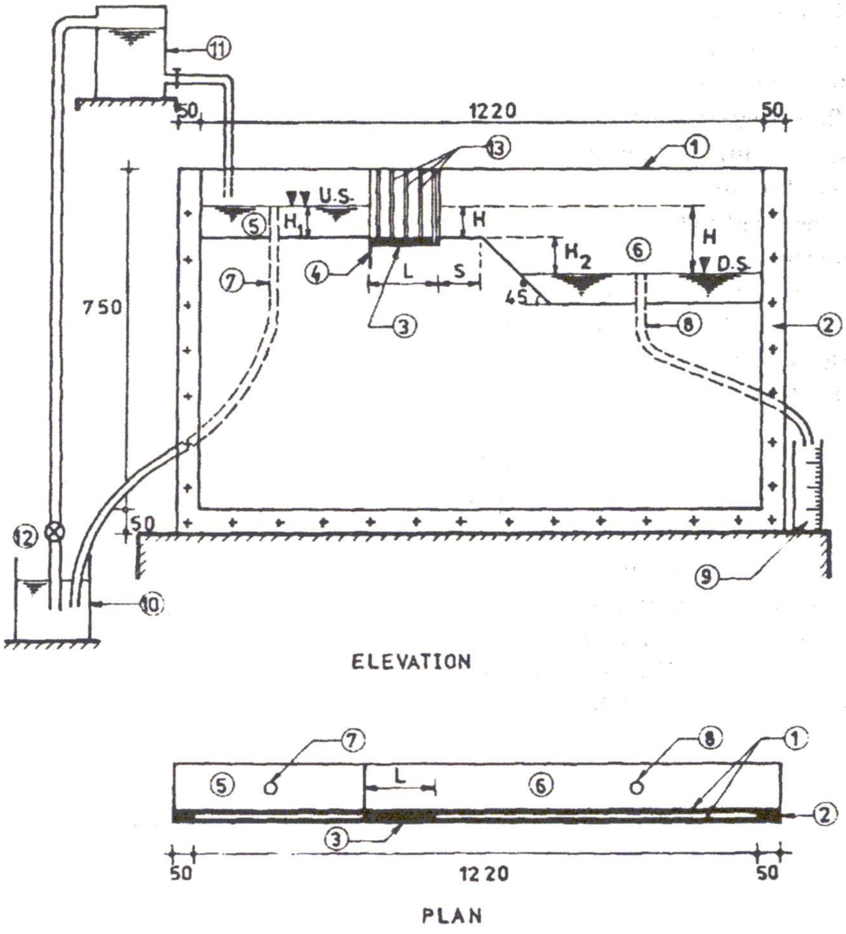

Figure 2. Experimental model (Dim.in mm.);

1- Prespex sheets. 2- Klingarite sheet. 3- Floor model. 4- Sheet pile.
5- U.S. tank. 6- D.S. tank. 7- U.S. Tube. 8- D.S. Tube.
9- Graduated tube 10- Collecting tank. 11- Elevated tank. 12- Pump.
13- Piezometers.

The downstream seepage surface was lowered with slope 1:1 (θ=45°). Both upstream and downstream sides are provided with tanks (5) and (6) having overflow tubes (7) and (8), respectively, to maintain constant levels at the two sides. These tubes could be moved vertically to change the level of the flow surface. The overflowing discharge from tube (8) is measured by graduated glass cylinder (9) to determine the seepage quantity. The overflowing oil from the tubes is collected in tank (10) from which oil is dispatched to an elevated tank (11) by pump (12). The oil flows from tank (11) to feed the upstream side.

The motor's oil, super 7500-20 W 150, was chosen as a viscous flow between the two prespex sheets. Pressure distribution on the floor was measured by piezometers (13). Piezometers were formed by slotting the model to vertical notches each of 2 mm wide. To eliminate the effect of surface tension in the piezometers, the flow surface, in both upstream and downstream sides, was initially kept at the same level. Then the heights of oil in piezometers, due to surface tension, were measured to be abstracted from any further measurements of pressures.

Experiments were performed by varying the horizontal distance S with a relative variation of S/L = 0.0, 0.2, 0.4, 0.6, 0.8, and 1.0. For each value of S/L, the relative depth of sheet pile D/L was taken as D/L = 0.1, 0.2, 0.3, 0.4, and 0.5. A set of experiments, including the variation of flow depths H_1 and H_2, were conducted for each sheet pile depth.

As mentioned in Part I, and referring to Eq. (4), the only possible effect of the sheet pile depth is obtained when the sheet pile is located at the upstream end of the floor, i.e. $\ell_1/T = 0$. When the sheet pile is placed near the center of the floor the uplift pressures are found independent of the pile depths [4]. Locating the sheet pile near the center is a purely academic case and cannot be used in practice. Hereby, in experiments, the sheet pile is positioned at the upstream end of floor.

4. EXPERIMENTAL VERIFICATIONS

4.1. *The initial depth of unconfined flow* H_o

The measured values of T, L, S, ℓ_1, D, H_1 and H_2 were substituted in Eqs. (2) and (4) to calculate the initial depth of unconfined seepage flow H_o. The calculated values of H_o are compared with the measured ones. A complete agreement is obtained as shown in Table (1). The values of S/L, D/L, and H_2/L, listed in Table (1), are the only ones for which separation of seepage flow from the sheet pile is taken place. It is seen, from Table (1), that H_o increases as S increases while it decreases when D and H_2 increases. This fact is theoretically confirmed in part I.

4.2 *The seepage discharge*

The values of H_o, calculated form Eq. (2), were used in Eq. (1) to determine the values of seepage discharge Q. The calculated values of Q are compared to the measured ones as shown in Table (1). However, comparison indicates obvious discrepancies specially for small values of H_2. The resulting deviations in the discharge values may be referred to Depuits assumptions [5]. On the other hand, neglecting the effect of the height of seepage face δH, above the downstream flow level, may lead to some discrepancies.

To reduce deviations, as possible, the height of seepage face, δH, is introduced in the discharge equation. That is the value of Z in Eq. (1) is replaced by Z_1, where $Z_1 = Z + \delta H$ or $Z_1 = T + \delta H - H_2$.

The height of seepage face, δH, was measured for various values of S, D, and H_2. As shown in Figures (3) and (4), the value of δH decreases as S and D increase, while it increases when H_2 increases. Using the experimental measurements, the height of seepage face is evaluated as a function of L, S, D, and H_2. An empirical equation, including the prior parameters, is developed in the form;

$$\frac{\delta H}{H_2} = \sqrt{\frac{H_2}{L}}\left[0.5 - 0.1\sqrt{\frac{S}{L}} - \left(\frac{D}{L}\right)^3\right] \tag{5}$$

To adjust Eq. (1), fitting curves for measured and calculated values, of seepage discharge, Q, were performed using computer facilities. Accordingly, a modified discharge equation is obtained in the forms;

$$Q = 0.43\left[K_s\frac{(H_o^2 - Z_1^2)}{2\ell_2}\right]^{4/3}, \qquad (6)$$

for D/L = 0.2, with correlation coefficient, R = 0.99, and

$$Q = 1.08\left[K_s\left(\frac{H_o^2 - Z_1^2}{2\ell_2}\right)\right] - 1.9, \qquad (7)$$

for D/L up to 0.5, with correlation coefficient, R=0.95.
where,

$$Z_1 = T + \delta H - H_2.$$

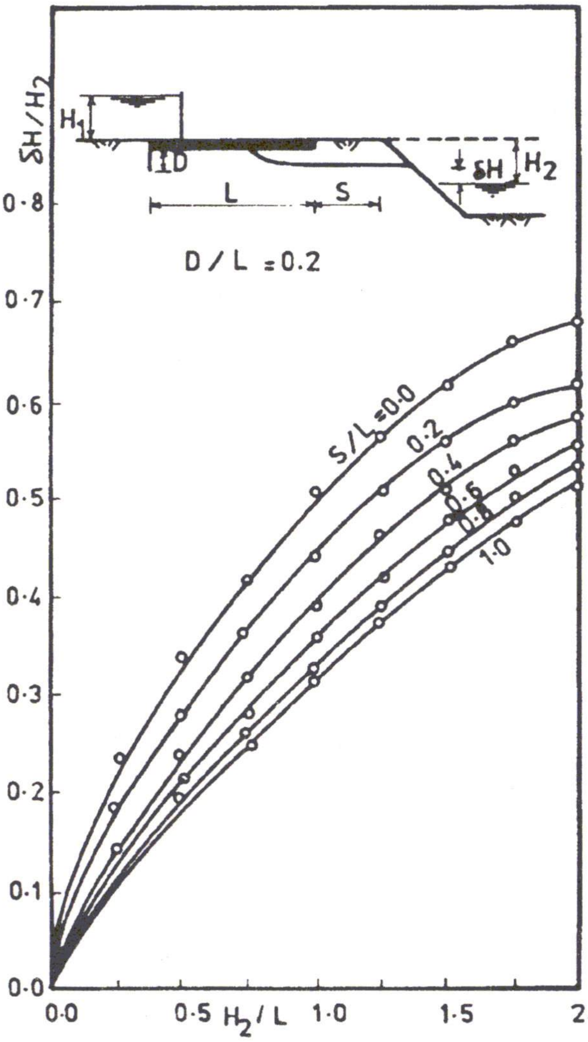

Figure 3. The effect of both distance S, and head H_2 on the height of seepage face δH for D/L = 0.2.

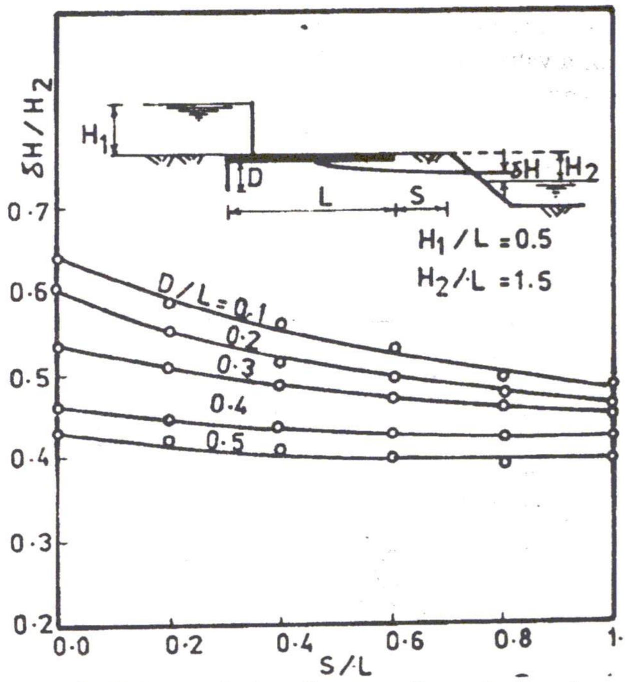

Figure 4. Effect of the distance S, and the sheet pile depth D on the height of seepage face δH for H_1=0.5 L, and H_2 = 1.5 L.

5. EXPERIMENTAL RESULTS AND DISCUSSION

5.1. *Separation of seepage flow from the floor*

The second case of separation, in which the seepage flow separates from the lower-side of floor only as shown in Figure (1-b), is experimentally investigated. Experiments showed that seepage flow departs the lower-side of the floor, creating free seepage zone. Experimental results showed that, length of separation is mainly affected by variation of the horizontal distance S, depth of sheet pile D, and depths of flow H_1, H_2. In the experimental procedure, the values of the unseparated length of floor ℓ'_1 were measured for all values of $0 \leq S/L \leq 1.0$ and $0.1 \leq D/L \leq 0.5$. However, a value of S/L = 0.4 is chosen to investigate the effect of D, H_1, and H_2 on the separation. Also a value of D/L = 0.2 is taken to show the effect of S_1, H_1, and H_2. The analysis is performed according to the following three approaches.

In the first approach, the depth H_2 was kept constant and equals 0.5 L, while the relative upstream depth H_1/L was varied from zero to 1.0. For a value of $D/L = 0.2$, the length ℓ'_1 increases as S and H_1 increase. However, the effect of H_1 decreases as S increases, as shown in Figure (5). For a constant value of $S/L = 0.4$, the length ℓ'_1 increases when H_1 increases, while it decreases as D increases, Figure (6).

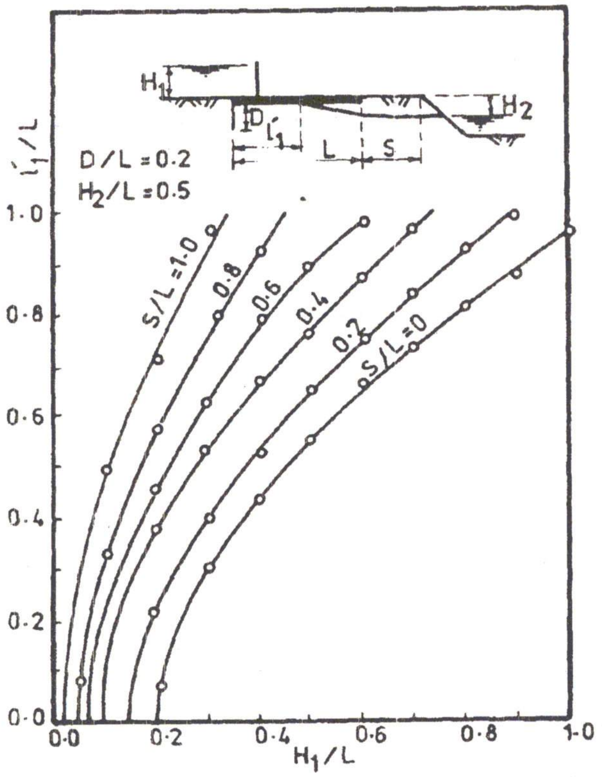

Figure 5. Variation of the unseparated length of floor with variation of H_1 for $D/L = 0.2$ and $H_2/L=0.5$.

In the second approach, the upstream depth H_1 was maintained constant value equals 0.5L, while the downstream flow level was gradually lowered to increase H_2 with equal increments each of 0.25L. Considering a value of $D/L = 0.2$, the length ℓ'_1 decreases as H_2 increases, while it increases as S increases as depicted in Figure (7). In Figure (8), for a constant value of $S/L = 0.4$, the length ℓ'_1 decreases when the depth of sheet pile D increases. The effect of H_2 on ℓ'_1 becomes greater for deeper sheet piles. Thus, for values of $D/L > 0.3$, and $H_2/L \leq 2.0$, the length ℓ'_1 equals zero. This meant that, the flow not only separates from the floor but also separates from the back of the sheet pile.

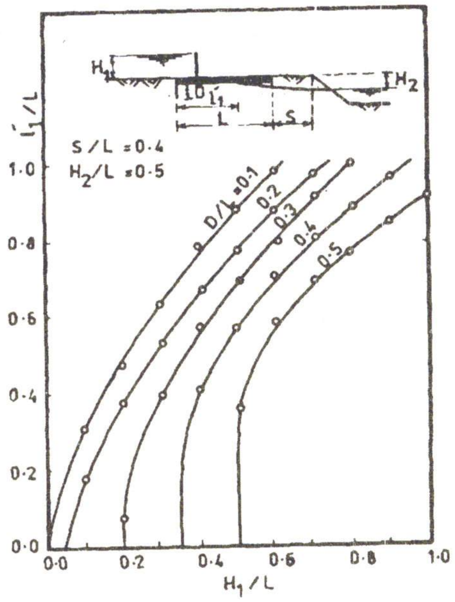

Figure 6. Variation of the unseparated length of floor with variation of H_1 for $D/L = 0.2$ and $H_2/L=0.5$.

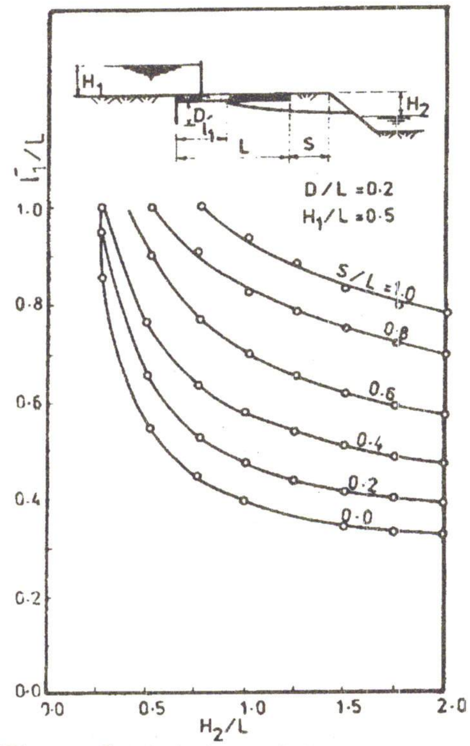

Figure 7. Variation of the unseparated length of floor with variation of H_2 for $D/L = 0.2$ and $H_1/L=0.5$.

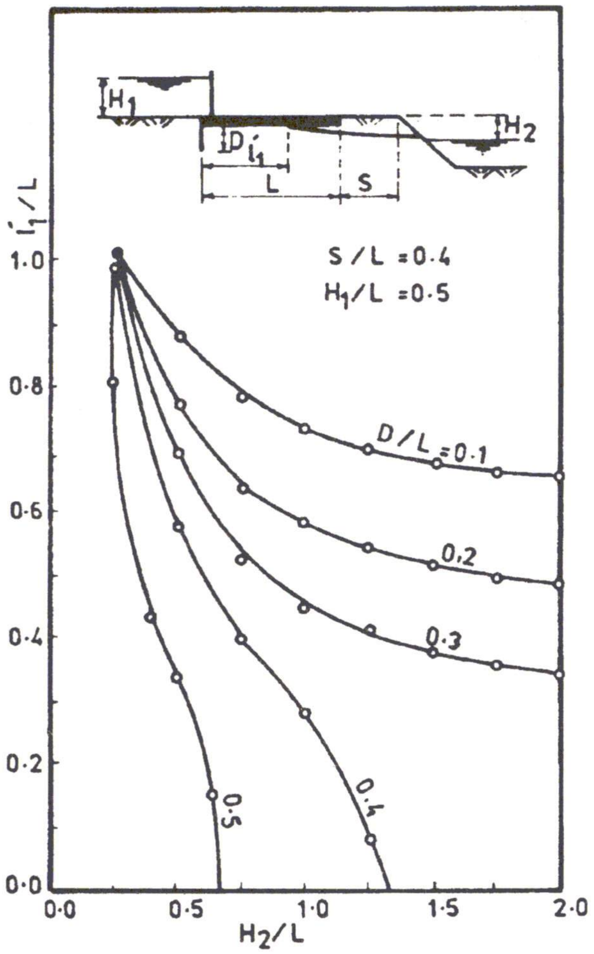

Figure 8. Variation of the unseparated length of floor with variation of H_2 for $S/L = 0.4$ and $H_1/L=0.5$.

In the third approach both H_1 and H_2 were equally increased with relative values vary from zero to 1.0 L. As shown in Figures (9) and (10), the unseparated length ℓ'_1 decreases as H_2 increases reaching a minimum value of $H_1/L = H_2/L \simeq 0.4$, after which ℓ'_1 increases as H_1 increases. As presented in Figure (9), the effect of H_1 and H_2 on ℓ'_1 becomes smaller for large values of S. when $S/L \geq 0.8$, separation thoroughly disappears. On the other hand, the effect of variation of depths H_1 and H_2 on the length ℓ'_1 decreases as the depth of sheet pile decreases, as demonstrated in Figure (10).

Analyzing the measured values of the unseparated length of floor ℓ'_1, an empirical equation is obtained, to evaluate ℓ'_1, in the form,

$$\frac{\ell'_1}{L} = 0.6\sqrt{\frac{H_1}{H_2-\delta H}} + 0.6\frac{S}{L} - \frac{D}{L} \tag{8}$$

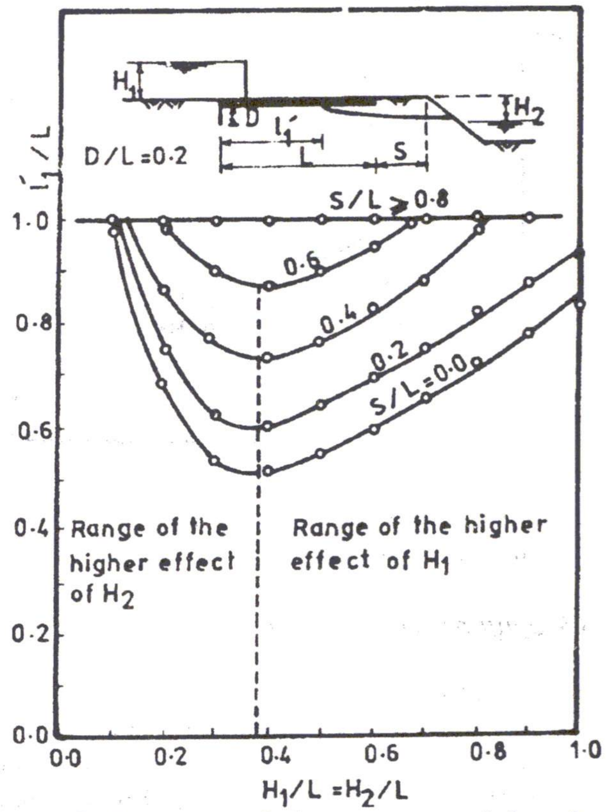

Figure 9. Variation of the unseparated length of floor with variation of H_1 and H_2 for $D/L = 0.2$.

5.2 *Separation of seepage flow from the sheet pile*

Experimental measurements showed that, separation of the seepage flow from the sheet pile takes place whenever $D/L > 0.2$ regardless the value of S. As listed in Table (1), separation from the sheet pile increases as both H_2 and D increase, while it decreases as S increases.

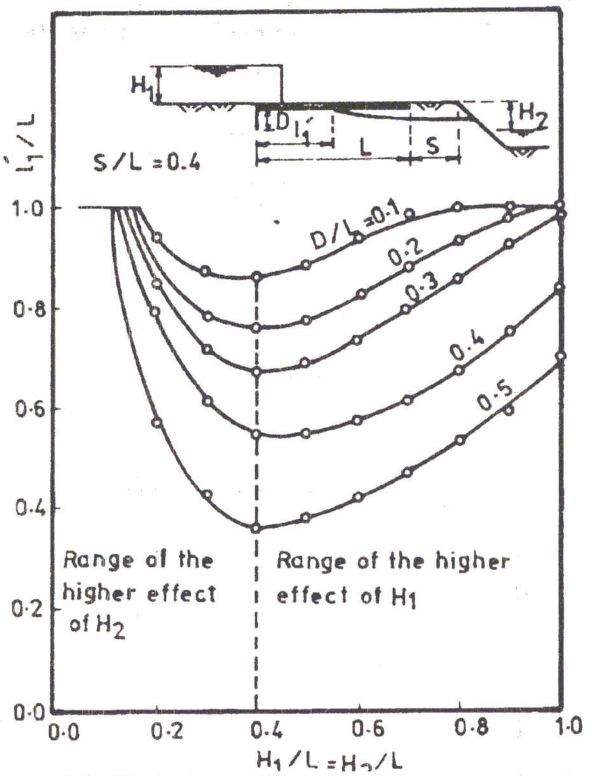

Figure 10. Variation of the unseparated length of floor with variation of both H_1 and H_2 for S/L = 0.4.

5.3 *Uplift pressure along the floor*

Analysis of measured values of the potential head along the floor showed that, the uplift pressure along the floor is affected by the distance S, sheet pile depth D, and the depth H_2. For a constant value of H_1 = 0.5L, the uplift pressure decreases as H_2 increases. On the other hand, the maximum pressure values are obtained when H_2 = 0. These maximum values of pressure increase as S increases as shown in Figure (11). The curve defined by S/L=∞, is plotted according to Pavlosky [6]. At X/L= 0, an increase in the pressure value of 0.2 H and 0.07 H are obtained when S/L increased from zero to 1.0 and from 1.0 to ∞, respectively. As depicted in Figure (11), the minimum pressure values h_1 are obtained when S = 0.0.

The variation of sheet pile depth has a considerable effect on pressure distribution along the floor. For a constant values of S/L = 0.4, the pressure values decrease as D increases, as illustrated in Figure (12).

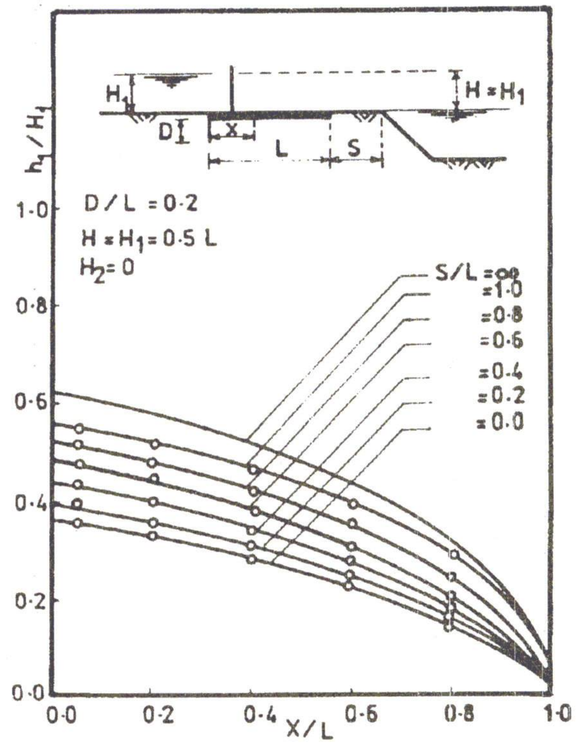

Figure 11. Effect of variation of relative distance S/L on the maximum uplift pressure for D/L=0.2.

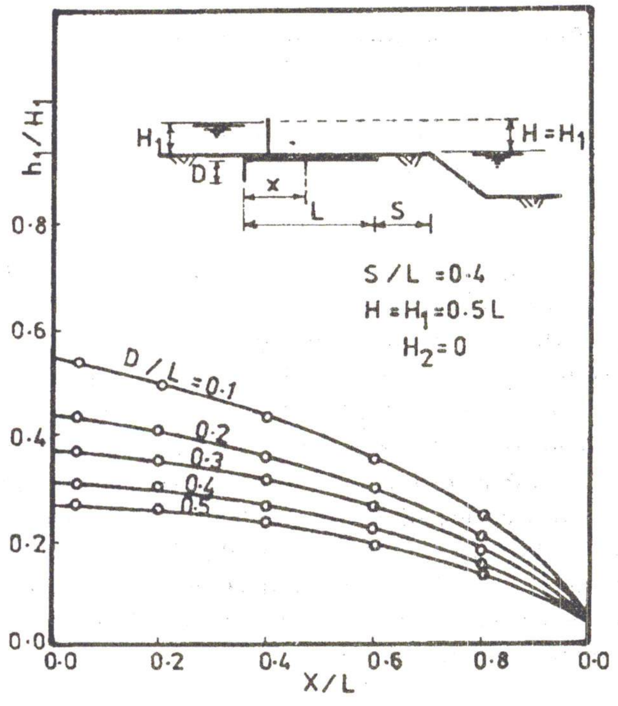

Figure 12. Effect of variation of sheet pile length on the maximum uplift pressure for S/L =0.4.

Table 1. Comparison between measured and calculated values of the depth H_o and the discharge Q.

S/L	D/L	H_2/L	H_o meas. in cms	H_o cal. in cms	% dev.	$Q_{meas.}$ $Cm^2/sec.$	$Q_{cal.}$ Cm^2/sec	% dev.
0.0	0.3	1.25	57.84	58.0	0.28	6.06	7.4	22.2
		1.501	57.671	57.85	0.30	6.29	7.58	20.6
		1.75	57.59	57.73	0.24	6.67	7.73	16.0
		2.0	57.59	57.59	0.0	6.95	7.90	13.7
	0.4	0.50	57.94	58.71	1.3	4.45	6.3	41.7
		0.75	57.38	58.08	1.2	5.05	7.06	40.0
		1.00	57.13	57.69	1.0	5.65	7.52	33.2
		1.25	56.81	57.60	1.4	6.17	7.87	27.5
		1.50	56.75	57.31	1.0	6.67	8.36	25.4
		1.75	56.70	57.19	0.9	7.09	8.66	22.0
		2.00	56.70	57.02	0.6	7.26	8.86	22.0
	0.5	0.50	57.60	58.63	1.8	4.63	7.02	51,6
		0.75	57.10	57.98	1.5	4.83	7.47	54.6
		1.0	56.8	57.56	1.3	5.65	8.26	46.3
		1.25	56.65	57.22	1.0	6.39	8.95	40.0
		1.50	56.55	57.10	1.0	6.80	9.10	34
		1.75	56.50	56.94	0.8	7.24	9.33	29
		2.0	56.56	56.75	0.40	7.4	9.56	29
0.2	0.4	0.75	57.88	58.37	0.85	5.13	7.14	39.4
		1.0	57.63	57.99	0.60	5.75	7.65	33.0
		1.25	57.50	57.80	0.50	6.17	7.86	27.4
		1.50	57.38	57.60	0.40	6.53	8.12	24.0
		1.75	57.25	57.50	0.40	6.95	8.27	19.0
		2.0	57.25	57.34	0.15	7.17	8.47	180
	0.5	0.50	57.90	58.91	1.7	4.47	6.52	46
		0.75	57.50	58.29	1.4	5.13	7.32	42.7
		1.00	57.25	57.87	1.1	5.65	7.86	39.3
		1.25	57.10	57.54	0.8	6.11	8.28	35.4
		1.50	57.0	57.43	0.75	6.47	8.43	30
		1.75	56.95	57.25	0.5	6.87	8.64	26
		2.0	56.95	57.07	0.2	7.09	8.87	25
0.4	0.4	1.50	57.94	57.88	-0.1	6.47	8.04	24
		1.75	57.81	57.75	-0.1	6.67	8.21	23
		2.0	57,.81	57.62	-0.3	6.97	8.38	23.4
	0.5	0.75	57.95	58.55	1.0	4.83	6.74	40
		1.0	57.70	58.14	0.75	5.37	7.25	35
		1.25	57.55	57.83	0.5	5.85	7.77	33
		1.50	57.40	57.69	0.5	6.23	7.94	27
		1.75	57.35	57.54	0.3	6.53	8.02	23
		2.0	57.35	57.34	0.0	6.67	8.26	24
0.6	0.5	1.0	58.10	58.37	0.5	4.97	6.76	36
		1.25	57.95	58.06	0.2	5.37	7.12	32.6
		1.50	57.90	57.92	0.0	5.75	7.30	27
		1.75	57.85	57.74	-0.2	5.95	7.51	26.2
		2.0	57.85	57.58	-0.5	6.17	7.71	25.0
0.8	0.5	1.5	58.10	58.12	0.0	5.55	7.16	29
		1.75	58.0	57.98	0.0	5.85	7.35	25.6
		2.0	57.95	57.79	-0.3	6.06	7.57	24.9
1.0	0.5	2.0	58.05	57.95	-0.2	5.75	7.14	24.2

4.5. *Seepage discharge*

Experimental results showed that, variation of both the total head H ($H=H_1+H_2$), and the horizontal distance S have a remarkable influence on the seepage flux as shown in Figure (13). However, smaller effect on the seepage flux is obtained due to the variation of sheet pile depth, as shown in Figure (14).

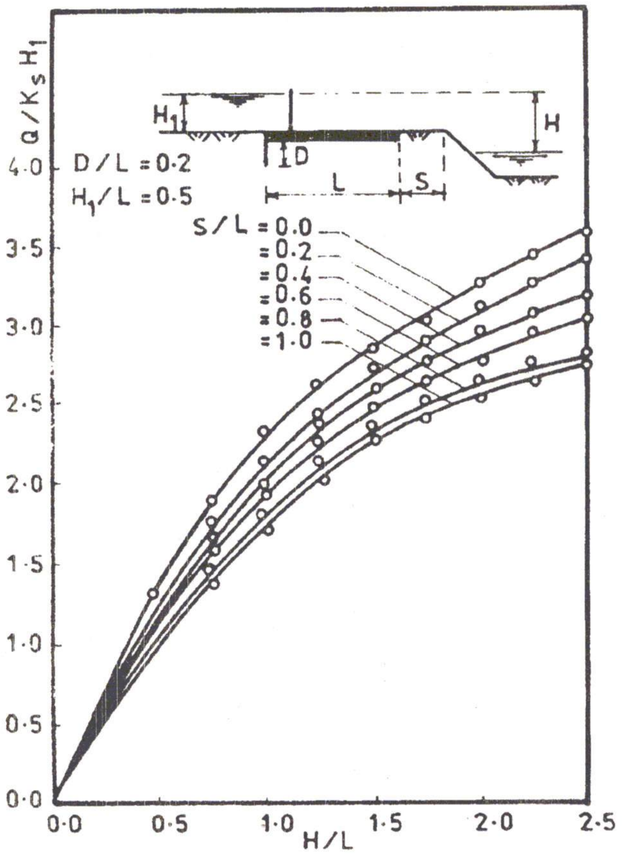

Figure 13. The effect of distance S on seepage quantity for D/L=0.2 and H_1 = 0.5 L.

The measured values of seepage flux, in the case of separation from the floor only, are analyzed. As a result, an empirical equation to evaluate the seepage flux is obtained in the form,

$$Q = \lambda K_s \frac{(T^2 - Z_1^2)}{2\ell'_2} \tag{9}$$

where,

$$\lambda = 0.57 \sqrt{\frac{H_2 - \delta H}{H_1}} - 1.5\left(\frac{D}{L}\right)^3 - 0.15\left(\frac{S}{L}\right), \tag{10}$$

$$\ell'_2 = L - \ell'_1 + S + (H_2 - \delta H) \cot \theta, \text{ and} \tag{11}$$

$$\ell'_1 = 0.6 \quad L \sqrt{\frac{H_1}{H_2 - \delta H}} - D + 0.6\ S \tag{12}$$

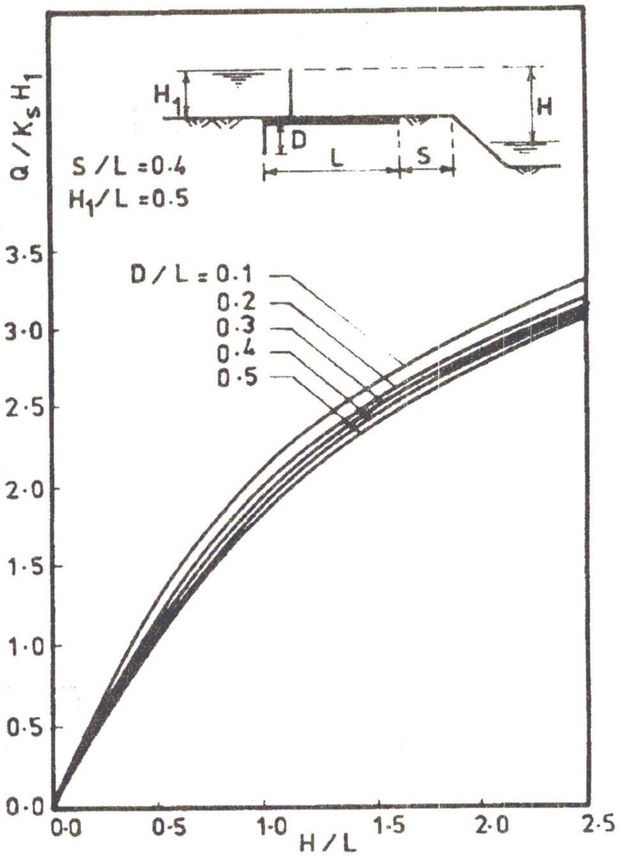

Figure 14. The effect of sheet pile depth D on seepage quantity for S/L =0.4 and H_1 = 0.5 L.

5. CONCLUSIONS

Using the experimental measurements, the theoretical equations are verified and adjusted to be used in:

1. Estimation of the initial depth of the seepage flow H_o., using Eq (2).
2. Determination of seepage flux Q. Thus, Eqs. (6)

and (7) are used to compute the seepage flux for the case of separation from both floor and sheet pile. Eq (9) is used to determine the seepage discharge for the case of separation from the floor only.

Analyzing the experimental data, empirical equations are obtained. Eq (5) is used to find the height of seepage face δH. Eq (8) is used to obtain the unseparated length of floor ℓ'_1.

From the analysis of the experimental results, it can be concluded that, the involving parameters, in the combined seepage problem, have a sensitive effect on the seepage characteristics beneath the floor of a hydraulic structure which may be summarized as follows;

1. Separation of seepage flow may occur. When D/L < 0.3, the flow separates from the floor only.
2. Length of separation from the floor increases when both the upstream depth of flow, H_1, and the horizontal distance behind the floors, S decrease.
3. The uplift pressure on the floor decreases when both the drain free board, H_2, and the sheet pile depth, D, increase. The uplift pressure increases as both H_1 and S increase.
4. The seepage flux increases as the total head H increases, while it decreases when S increases. The variation of sheet pile depth has a poor effect on the seepage quantity.

For storage structures (Dams), where the seepage flux is more significant, it is preferable to be constructed as far as possible from the dropped site. A distance of two times the base width at least is considered sufficient, i.e $S = 2L$.

For weirs and regulators, where the uplift pressure is more important, it is advisable to be constructed closer to the drop as possible.

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