Drain Tube Opening Effects on Drain Inflow

By Fawzi S. Mohammad[1] and R. Wayne Skaggs[2]

Abstract: Laboratory tests were conducted to determine the effects of total opening area, location of openings and gravel envelope on radial flow to 100 mm (4 in.) diam corrugated plastic drains. Radial flow theory was used to evaluate the effective drain tube radius, r_e, and the drainage transfer coefficient for the corrugated tubes. The effective radius increased with total perforation area as expected, but the location of the drain tube perforation had little effect on r_e. The greatest increase of effective radius for an increase in perforation area occurred between areas of 38–75 cm^2/m where r_e increased from 5 mm to about 21 mm. Use of a 50 mm thick gravel envelope resulted in an increase in the effective drain radius for a 100 mm diam pipe from 5–36 mm. Experimental results for the effective radius were compared to theoretical values obtained from an earlier solution for circumferential openings. The experimental results were in close agreement with predicted values for a 1.0 mm opening width.

Introduction

The purpose of this paper is to present results of a study to determine the effect of drain tube openings on inflow to drains. The relationship between effective drain radius and water entry area was evaluated experimentally for 100-mm (4-in.) diam drains and reported herein.

The research is intended to help quantify how many holes or what entrance area plastic tubes should have. The question of how the location of the holes affects the rate of drainage inflow was also investigated.

The U.S. Soil Conservation Service (14) requires a minimum water entry area of 21 cm^2/m (1 in.^{2}/ft) for corrugated tubing. The U.S. Bureau of Reclamation (2) requires the same minimum opening area. A wide range of total entry area was reported by FAO (4) for different European countries as follows: (1) Austria (7.7 cm^2/m–10.5 cm^2/m), Germany (F.R.G.) (7 cm^2/m–10 cm^2/m); (2) France (9.5–12.5 cm^2/m); (3) Netherlands (11.75–27.15 cm^2/m); (4) Sweden (14–21 cm^2/m); and (5) the United Kingdom (6–9.5 cm^2/m). For European tubing the requirement within the given range depends on drain radius and wall thickness. One U.S. manufacturer advertises an entrance area of 106 cm^2/m and claims significant advantages for the increased area, while another insists that 21 cm^2/m is more than sufficient.

Theory

Much work has been done to describe the effect of drain perforations on drainage rates. Kirkham and Schwab (7) developed an analytical expression to calculate the effect of number, size, and location of perforations in drain tubes on drainage rates under ponded surface con-

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ditions. The theoretical solutions of Kirkham and Schwab were verified with data from three-dimensional electric analog models used by Schwab and Kirkham. These analytical and analog solutions can be used to analyze the effect of drain tube openings on drainage rates for ponded surfaces. However, the most common drainage condition is one of water table drawdown, rather than a ponded surface. During water table drawdown, flow is approximately radial near subsurface drains. The flow rate for radial flow from a cylindrical source to a drain tube with completely permeable walls can be described as

$$Q = 2\pi l K \frac{(h_s - h_t)}{\ln\left(\frac{r_s}{r_t}\right)} \quad \text{(1)}$$

in which Q = flow rate (cm^3/hr); K = hydraulic conductivity of soil (cm/hr); l = length of tube (cm); h_s = hydraulic head of cylindrical source (cm); h_t = hydraulic head inside drain (cm); r_s = radius of source (cm); and r_t = radius of drain.

Eq. 1 assumes a completely open tube flowing full with the wall of the drain offering no resistance to the entry of water. In practice, drain tubes are not completely open; in fact, they have less than 2% of the wall open in most cases.

One method of evaluating the rate of flow into drains under radial flow conditions is to define an effective drain radius, r_e, such that the flow to a completely open tube with radius r_e would be the same as the flow into an actual tube. Then Eq. 1 becomes

$$Q = 2\pi l K \frac{(h_s - h_t)}{\ln\left(\frac{r_s}{r_e}\right)} \quad \text{(2)}$$

By conducting experiments with many different tubes with different numbers, sizes, and locations of perforations, the influence of perforations on the effective drain radius could be determined, and the results used to quantify both radial head loss and the effect of perforations on drain inflow.

Bravo and Schwab (1977) used an electric analog model to determine the effect of openings on radial flow to corrugated drain tubes. They conducted experiments for tubes with different sizes of circumferential slots and complete circumferential openings. Skaggs (12) used the data of Bravo and Schwab to calculate the effective radius of the tube with circumferential slots. This value was then used to define the equivalent depth to the impermeable layer and to estimate water table drawdown from solutions to the Boussinesq equation. The equivalent depth concept was originated by Hooghoudt [van Schilfgaarde (15)] to account for head loss due to convergence of flow lines near subsurface drains. In a more direct approach, Skaggs and Tang (13) used the effective radius in numerical solutions to the two-dimensional Richard's equation for combined saturated-unsaturated flow. Neither approach can be used for a wide range of drain tube openings, however, because basic data for de-

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termining effective radii or other parameters characterizing radial flow to real drains are not available.

Analytical and numerical solutions have been obtained for a few special cases of radial flow. Kirkham (6) obtained an analytical solution for flow from a cylindrical source to a drain with complete circumferential openings or gaps. His solution may be used to define the drain flow rate lower bound (Q_l) and upper bound (Q_u) which may be expressed as

$$Q_l = \frac{2\pi l K(h_s - h_t)}{\ln \frac{r_s}{r_t} + \frac{2s^2}{r_t c^2} S_1} \quad \text{(3)}$$

and $$Q_u = \frac{2\pi l K(h_s - h_t)}{\ln \frac{r_s}{r_t} + \frac{2s^2}{r_t c^2} S_2} \quad \text{(4)}$$

in which S_1 and S_2 can be approximated as

$$S_1 = \sum_{n=1}^{\infty} \frac{1}{n^2} \sin \frac{n\pi c K_o\left(n \frac{r_t}{s}\right)}{s K_1\left(n \frac{r_t}{s}\right)} \quad \text{(5)}$$

and $$S_2 = \sum_{n=1}^{\infty} \frac{1}{n^2} \sin \frac{2n\pi c K_o\left(n \frac{r_t}{s}\right)}{s K_1\left(n \frac{r_t}{s}\right)} \quad \text{(6)}$$

in which K_o and K_1 = modified Bessel functions of the second kind and first and second order, respectively; $2s$ = distance between circumferential openings; c = opening width; and K, l, h_s, h_t, r_s and r_t are as previously defined. No flow rate for a given situation is taken as the average of the upper and lower bounds $(Q_l + Q_u)/2$.

Sneyd and Hosking (14) used numerical methods to solve an integral equation for the same problem considered by Kirkham. They also developed an asymptotic expansion to determine the flow rate as the gap width tends to zero. Nieuwenhuis and Wesseling (10) used numerical methods to solve the same problem and also considered the case of radial flow to a drain with continuous longitudinal slits. Longitudinal slots were also studied experimentally by Wesseling and Homma (16) who conducted sand tank tests to determine the entrance resistance for radial flow.

Another method of characterizing the effect of drain tube openings on radial flow is to define a surface transfer coefficient or an entrance resistance for calculating the head loss at the drain tube wall. Considering the head loss near the drain (Δh) to be the sum of a component due to radial flow and a component due to entrance resistance, the following equation can be written: $\Delta h = h_s - h_t = (h_s - h_r) + (h_r - h_t) = \Delta h_r + \Delta h_t$ in which h_s = hydraulic head at the cylindrical source; h_t = hydraulic

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head inside the drain; h_r = hydraulic head just outside the tube wall; Δh_r = head loss due to radial flow ($h_s - h_r$); and Δh_t = head loss due to entrance resistance at the drain. The head loss due to radial flow Δh_r can then be expressed as

$$\Delta h_r = h_s - h_r = \frac{Q \ln \frac{r_s}{r_t}}{2\pi l K} \quad (7)$$

In order to quantify Δh_t, a factor, α, analogous to the surface heat transfer coefficient, may be defined such that the flow rate through the tube wall may be expressed as

$$Q = \alpha A (h_r - h_t) \quad (8)$$

in which A = surface area of the tube; $\Delta h_t = h_r - h_t$ = head loss as the water moves through the tube wall; and α = surface transfer coefficient with units per hr. Rearranging Eq. 8 gives

$$h_r - h_t = \frac{Q}{A\alpha} \quad (9)$$

Combining Eqs. 7 and 9 and solving for α gives

$$\alpha = \frac{K}{r_t}\left[\frac{Q}{2\pi l K(h_s - h_t) - Q \ln \frac{r_s}{r_t}}\right] \quad (10)$$

The coefficient α can be defined for a given drain tube by measuring Q in an experimental setup where the other variables in Eq. 10 are known or measured.

Experimental Procedure

Laboratory tests were conducted in a sand tank to determine the effect of total opening area and location of openings on the rate of inflow to 100-mm diam (4-in.) corrugated plastic drains under cylindrical flow conditions. An effective drain tube radius and a surface transfer coefficient were evaluated for corrugated tubes with different opening areas and opening locations. One test was conducted with the drain tube surrounded with a 50 mm thick gravel envelope. A summary of the experiments conducted is given in Table 1.

A drain tube was centered in a cylindrical sand tank 0.91 m long and 0.76 m in diameter. The tank was made of perforated metal with solid end plates that were fitted with ports for piezometers and with a 50 mm diameter pipe outlet for the drain tube (Fig. 1). The corrugated drain tube was radially centered in the sand tank, and mortar sand was packed to a uniform density in the space between the tank wall and the tube. The end plate was fastened, and the loaded cylinder hoisted into a submergence tank (1.2 m long × 1.2 m wide × 1.2 m deep) and placed in a horizontal position. The outlet from the drain tube was connected to the outlet of the submergence tank, which was in turn attached to a riser pipe. The outlet end of the riser could be adjusted in elevation to enable

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TABLE 1.—Summary of Tests Conducted for Corrugated Tube 10 cm in Diameter

Test number (1)	Number of perforations per meter (length) (2)	Shape and size of perforations (3)	Number of longitudinal rows of perforation (4)	Perforation area of test sample, in square centimeters (5)	Perforation area per unit length, in square centimeters per meter (6)	Perforation area as a percentage of tube wall area (7)
1	10	Circular (0.48 cm diam)	6	1.6	1.8	0.05
2	30	Circular (0.48 cm diam)	6	4.8	5.3	0.17
3	50	Circular (0.48 cm diam)	6	8.0	8.8	0.28
4	215	Circular (0.48 cm diam)	6	35.1	18.3	1.20
5	430	Circular (0.48 cm diam)	6	70.1	77.0	2.40
6	405	Slots (0.25 cm × 1.8 cm)	8	167.0	182.0	5.80
7[a]	215	Circular (0.48 cm diam)	6	35.2	38.5	1.20
8	30	Circular (0.48 cm diam)	1	4.8	5.3	0.17
9	50	Circular (0.48 cm diam)	2	8.0	8.8	0.28

[a]Standard tube (same as test number 4) with 5 cm thick gravel envelope.

adjustment of the hydraulic head inside the drain tube. Two sets of six piezometers were placed at 50 mm intervals along radii of the sand tank. Six additional piezometers were inserted through the side of the cylinder (Fig. 1). All the piezometers were connected by Tygon tubing through the wall of the submergence tank to manometer banks to measure the distribution of the hydraulic head in the radial direction. The experimental setup is shown schematically in Fig. 1.

The sand was saturated by slowly raising the water level in the sub-

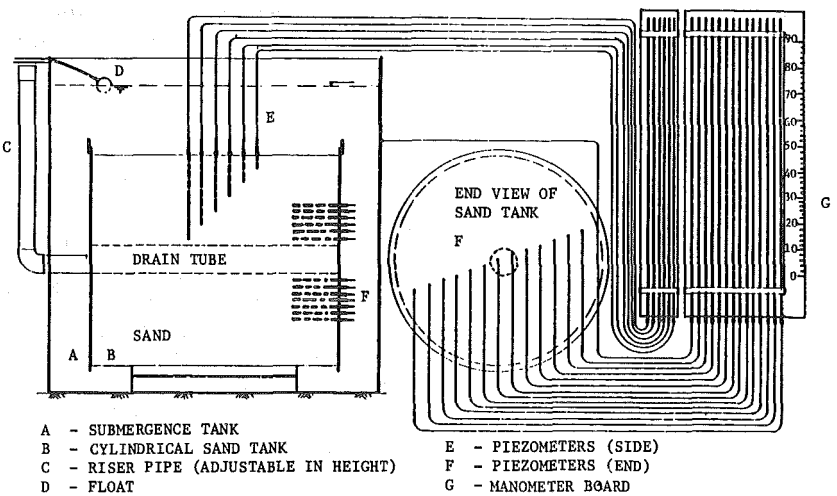

FIG. 1.—Schematic Diagram of Laboratory Setup

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mergence tank over a 24-hr period. After the water level reached the float cut off point in the tank, the outlet was lowered to the test position and flow began. The flow was allowed to continue for at least twenty-four hr to be certain that steady state conditions were attained. Then the flow rate was measured and manometers read. The outlet was lowered to another position and the test repeated. Each test was conducted under three different outlet elevations varying from 0.5 cm to 65.5 cm above the drain center. By testing drain tubes with different numbers of perforations, the effect of opening area and location on radial flow to the drain and on the head in the vicinity of the drain could be determined. Hydraulic conductivity of the sand was calculated for each test from the steady drain flow rate and radial hydraulic gradients measured at distances greater than 150 mm from the drain center.

The design criteria for the gravel envelope material was based on the U.S. Bureau of Reclamation procedure. All of the filter material (gravel) passed the 38 mm (1.5 in.) sieve; 90% passed the 19 mm (0.75 in.) sieve; and not more than 10% (actually 10%) passed the No. 60 sieve, which had openings of 0.3 mm (0.01 in.).

Sample Calculations

As an example, consider test 4, from Table 1. Experiments were conducted for three different outlet elevations. The measured hydraulic heads on the outside of the cylindrical tank, h_s, and inside the tube, h_t, referenced to the elevation of the center of the drain tube and the flow rate for each of the three flow rates for test 4 are given in Table 2.

The sand was packed to a density of 1.61 g/cm^3 and had a hydraulic conductivity of K = 0.575 m/hr. The tube length, l, was 0.910 m and r_s = 0.356 m. Solving for r_e in Eq. 2 for the results of test 4a (Table 2) gives a value of r_e = 5.0 mm. Repeating this procedure for experiments b and c gave r_e values of 4.5 mm, and 2.2 mm, respectively. The high hydraulic gradient of experiment c caused sand to move into the drain. For this reason, results for the experiments with the highest hydraulic gradients, the c experiments, were not used in determining the effective drain tube radii.

Substituting the same values as given above for experiment a into Eq. 10 with r_t = 50 mm gives α = 5.0 hr^{-1}.

Results and Discussion

Values of the effective drain tube radius, r_e, and the drainage transfer coefficient, α, are given in Table 3 for the various cases tested. Because

TABLE 2.—Measured Hydraulic Heads and Flow Rates for a 100 mm Corrugated Tube with Total Entry Area of 38.5 cm^2/m (Test 4)

Experiment (1)	Hydraulic head inside the tube, h_t, in meters (2)	Hydraulic head of the source (at the sand tank wall), h_s, in meters (3)	Steady state flow rate, in liters per minute (4)
a	0.465	0.655	2.45
b	0.299	0.654	4.42
c	0.005	0.650	6.95

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TABLE 3.—Effective Drain Tube Radius and Surface Transfer Coefficients as Calculated from Experimental Data

Test number (1)	Perforation area, in square centimeters per meter (2)	Perforation area as a percentage of tube wall area (3)	Number and Distribution of Perforations: Holes per meter (4)	Number and Distribution of Perforations: Rows (5)	$\Delta h(h_s - h_t)$, in meters (6)	Q, in liters per minute (7)	r_e, in millimeters (8)	α, in hour^{-1} (9)
1a	1.8	0.05	10	6	0.21	0.58	1.1×10^{-5}	0.6
1b		0.05			0.41	1.07	5.0×10^{-6}	0.6
2a	5.3	0.17	30	6	0.23	1.05	8.0×10^{-2}	1.2
2b		0.17			0.36	1.75	1.3×10^{-2}	1.3
3a	8.8	0.28	50	6	0.13	1.06	0.40	2.2
3b		0.28			0.30	2.0	0.10	1.8
4a	38.5	1.20	215	6	0.19	2.45	5.0	4.9
4b		1.20			0.35	4.42	4.3	4.7
5a	77.0	2.40	430	6	0.16	2.44	20.3	9.8
5b		2.40			0.31	4.91	21.3	10.3
6a	182.0	5.80	405 slots per meter	5	0.55	13.5	39.0	33.0
7a[a]	38.5	1.20	215	6	0.14	3.28	36.0	11.2
7b		1.20			0.26	6.10	73.6	11.5
8a	5.3	0.17	30	1	0.19	1.01	0.011	1.4
8b		0.17			0.32	1.46	0.036	1.2
9a	8.8	0.28	50	2	0.20	1.22	0.2	1.7
9b		0.28			0.31	1.91	0.2	1.7

[a]Standard tube with 50 mm thick graded gravel envelope.

sand moved into the drains under the highest gradient (e.g., test c in Table 2), only results for the two lower gradients (the two higher values of h_t) were considered valid and are reported. These tests had constant h_s values of 0.65 m and h_t values varying from 0.095 m to 0.55 m, above the center of the drain tube.

The r_e values obtained for the 100 mm diam corrugated tubes are plotted as a function of entry area in Fig. 2. As expected, the effective radius increases with total perforation area. The greatest response of the effective radius to increase in perforation area occurred from perforation areas of 38 to 75 cm^2/m in which r_e increased from 5 mm to about 21 mm.

Total water entry areas of less than 6 cm^2/m (0.19% of total wall area) gave extremely small r_e values (e.g. 1.1×10^{-5} mm for a perforation area of 1.8 cm^2/m and 1.3×10^{-2} cm for an area of 5.3 cm^2/m, Table 3). Such small r_e values seem unrealistic when compared with the individual perforations with diameters of 4.8 mm. However, the flow rate is dependent on the log of the effective radius. Inflow resistance at the tube wall due to a small number of perforations requires an exponential decrease

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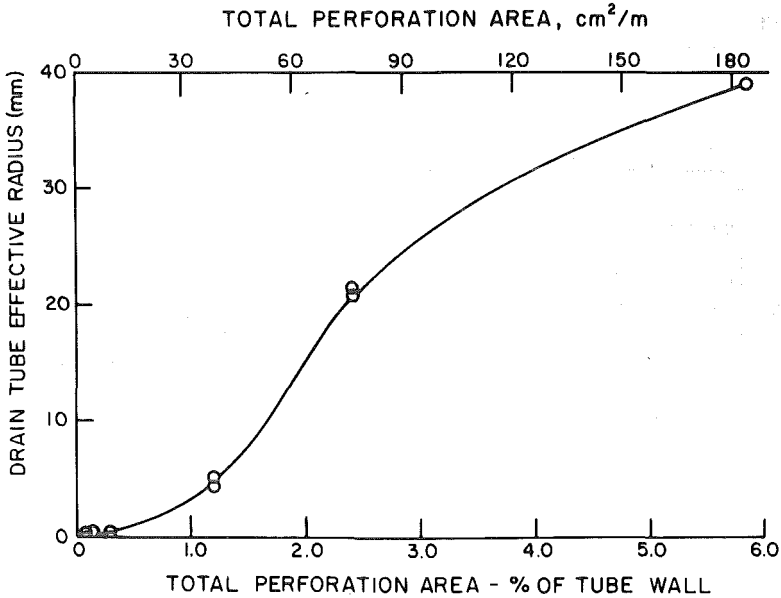

FIG. 2.—Effective Radius of a 10-cm Diameter Corrugated Plastic Drain Tube as Affected by Total Perforation Area

in r_e to account for head losses due to convergence and the consequent decrease in flow.

Once the effective radius is defined, it can conveniently be used in equations presented by Moody (9) to determine the equivalent depth to the impermeable layer. This value may be used, in turn, in solutions to the Boussinesq equation to predict water table drawdown and drain outflow rates for a given drain spacing and depth (12).

The circumferential location of the drain perforations had little effect on the effective radius of the drain tube. The average effective radius for the 10 cm diam tube with a total entrance area of 8.8 cm^2/m distributed in six rows was 0.025 mm (test 3) compared with an average effective radius of 0.020 mm for the same entrance area when all the holes were in one row at the bottom of the tube (test 9). These results disagree with those obtained by Luthin and Haig (8) who compared results of tests on 150-mm (6-in.) drain tube with drain holes on top with holes on the bottom. Luthin and Haig's tube had one row of 3-mm (1/8-in.) holes on 6-mm (1/4-in.) centers in a line along the drainpipe, and a strip of fiberglass taped over the row of holes to keep sand from entering them. They found that the discharge rate from the drain was greater when the drain tube holes were on the bottom because of the increased head drop between the water table level and the entry points in the pipe. In their case the tube did not run full so flow was not completely radial. Whereas, in the tests reported here, the tube was full of water so the position of the holes did not change the head.

The influence of the gravel filter on r_e is large. The effective radius of

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the standard tube with a perforation opening area of 38.5 cm^2/m was increased from 5 mm to 55 mm by a 5 cm gravel thickness. This conclusion is in agreement with Young's (17) results which concluded that the hydraulic effect of a filter surround greatly increases the effective radius of a non-ideal drain. It can be seen, however, that the gravel envelope did not increase the effective radius to that of the envelope itself, the outside of which was 100 mm from the center of the tube. This indicates some loss of hydraulic head within the gravel envelope as the water converges to the tube openings. The effective radius is expected to increase with greater envelope thickness and higher hydraulic conductivity of the envelope.

Experimental results for the effective radius are compared in Fig. 3 to theoretical values obtained from Kirkham's (6) solution. Kirkham's solution (Eqs. 3 and 4) assumes that the openings are circumferential of

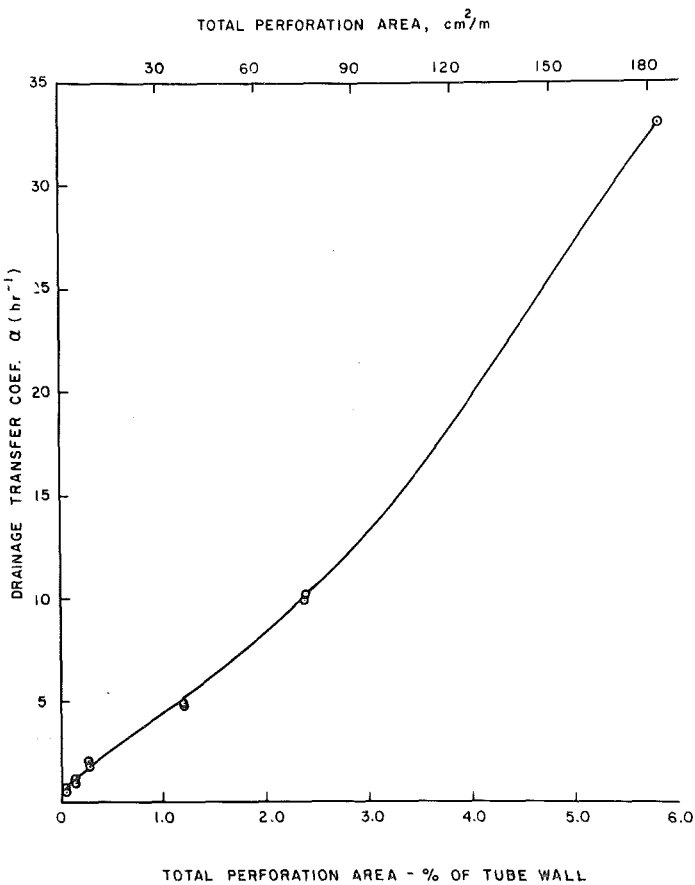

FIG. 4.—Drainage Transfer Coefficient, α, versus Perforation Area of Drain Tube

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width c and spaced a distance $2s$ apart. By assuming an opening width, the distance $2s$ between openings can be adjusted to give any desired opening area per unit length. This was done for a 100 mm diam tube for opening widths of 1, 1.5, 2 and 3 mm and the results are plotted in Fig. 3. The assumed radius of the cylindrical source was the same as in the experiments, 35.6 cm. The results show that, for a constant opening area, the effective radius r_e decreases as the width of the opening increases. The experimental results obtained in this study are in close agreement with the predicted relationship for a 1.0 mm circumferential opening width. Although there is no apparent explanation for this agreement, the predicted curves can be used to interpolate between measured points and to estimate r_e values for larger perforation areas.

Effective drain tube radii were calculated from the electrical analog results of Bravo and Schwab (1) and are also plotted in Fig. 3. Their cases 3, 5 and 6 were in close agreement with predictions using Kirkham's equations for a circumferential opening of 3 mm. This is logical for Bravo and Schwab's case 6 which represented 3 mm wide circumferential openings and for case 3 which was for 5 rows of 3 mm wide, 36 mm long circumferential slots. Their cases 4 and 5 had 5 rows of 1.6 mm wide, 27 mm long slots. The reduced r_e values for cases 3, 4 and 5, as compared to Kirkham's predictions, due to the fact that the openings were not completely circumferential.

The drainage transfer coefficients, α, were calculated for all cases using Eq. 10 and are plotted in Fig. 4. Calculation of convergence head losses with the α coefficient avoids use of the seemingly unrealistically small values for effective radius corresponding to small perforation area.

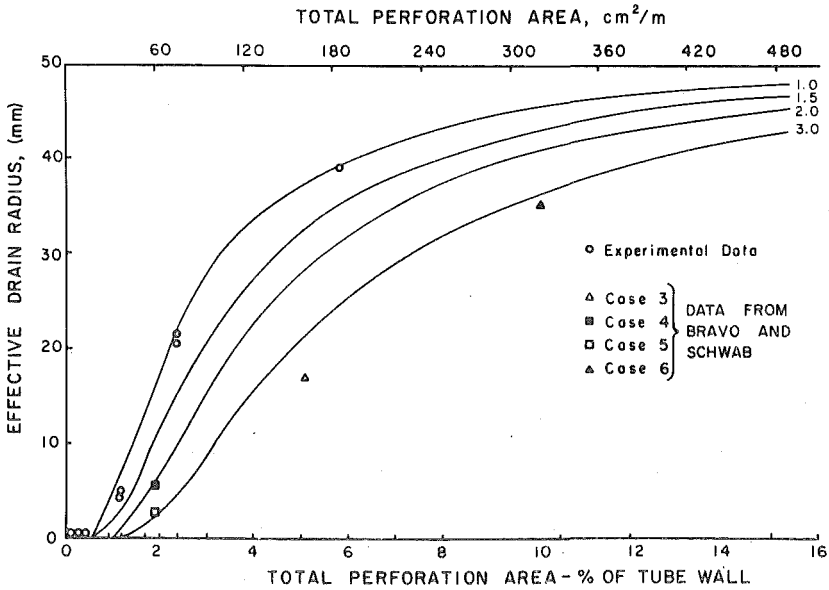

FIG. 3.—Effective Drain Tube Radius as a Function of Perforation Area as Calculated by Kirkham's (6) Equation (Solid Curves) and as Measured Experimentally in this Study and by Bravo and Schwab (1) (Δ, , ,Δ)

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The α values increased with entry area from less than 1 hr^{-1} for a total entry area of 1.8 cm^2/m to 33 hr^{-1} for an entry area of 182 cm^2/m.

Summary and Conclusions

Laboratory tests were conducted to determine the effect of total area of openings and location of openings on the rate of inflow to 100-mm diam (4 in.) corrugated plastic drains. An effective drain tube radius and a surface transfer coefficient were evaluated for corrugated tubes with different opening areas and opening locations. One test was conducted with the drain tube surrounded with a 50 mm thick gravel envelope. Radial flow theory was used to evaluate the effective drain tube radius and the drainage transfer coefficient for the corrugated tubes.

The r_e values obtained for the 100-mm diameter corrugated tubes are plotted as a function of entry area in Fig. 2. As expected, the effective radius increases with total perforation area. The greatest response of the effective radius to increase in perforation area occurred between areas of 38 to 75 cm^2/m in which r_e increased from 5 mm to about 21 mm.

The location of the drain perforations had little impact on the effective radius of the drain tube. The influence of a gravel envelope on r_e is large; the effective radius of the standard tube with 38.5 cm^2/m opening area was increased from 5 mm to 36 mm with the use of a 50 mm thick gravel envelope.

Experimental results for effective radius were compared to theoretical values obtained from Kirkham's (6) solution. The experimental results were in close agreement with the predicted relationship for a 1.0 mm circumferential opening width.

The drainage transfer coefficients, α, were calculated for all cases using Eq. 10 and are plotted in Fig. 4. The α values increase with the entry area from less than 1 hr^{-1} for a total entry area of 1.8 cm^2/m to 33 hr^{-1} for an entry area of 182 cm^2/m.

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