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ORIFICE PLATES FOR FURROW FLOW MEASUREMENT

by

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United States Department of Agriculture
Agricultural Research Service
Soil and Water Conservation Research Division
Western Soil and Water Management Research Branch

in cooperation with the

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INTRODUCTION

At the request of the Soil Conservation Service, orifice plates which are used for the measurement of furrow flows were studied in the Hydraulic Laboratory at Colorado State University. The thought had been expressed that orifice plates would, in some instances, be better measuring devices for small flows in furrows rather than using small Parshall flumes or the volumetric method. To be usable, a measuring device for furrow flows must be easy to build, simple to install and relatively foolproof in operation. The accuracy must be within a range of ± 5 percent. Also the device should not materially change the flow conditions upstream. In essence, this would mean a minimum of ponding.

PROBLEMS FOR STUDY

A number of questions were listed which needed to be answered before recommendations could be made on the use of the orifice plates. Limitations in using the devices needed to be defined. The questions which were listed are as follows:

1/ Joint contribution from Soil and Water Conservation Research Division, Agricultural Research Service, U. S. Department of Agriculture, and Colorado Agricultural Experiment Station, Fort Collins, Colorado.

2/ Agricultural Engineer, Western Soil and Water Management Research Branch, U. S. Department of Agriculture, Agricultural Research Service, Soil and Water Conservation Research Division, and Colorado Agricultural Experiment Station, Fort Collins, Colorado.

1. The rating curves and charts which were available were of doubtful origin. It was requested that the plates be calibrated accurately so that dependable tables could be prepared. This was needed for both free flow and submerged flow conditions.
2. Are submerged flow measurements better than free flow, and if so, what minimum head differential will be needed?
3. What are the limits of free flow and/or submerged flow measurements, i.e., must the upstream water surface always be at some distance above the top of the orifice opening? In the case of submerged flow, is the elevation of the downstream water surface relative to the opening important?
4. In both free flow and submerged flow situations, how far must the edge of the orifice be kept from the approach channel? This, in effect, would delineate the effects of silting.
5. Do the plates need to be exactly vertical and at right angles to the direction of flow of the approach channel?
6. What is the effect of plate thickness on the discharge characteristics?

This study was designed to answer the foregoing problems as well as to find other operational techniques which would improve the dependability and accuracy of measurements using the plates.

EQUIPMENT AND PROCEDURE

The apparatus initially used for these tests consisted of a 2-foot wide laboratory channel to which water was supplied by a small 4-inch pump. A weir box utilizing a 90-degree V-notch weir was used to determine the discharges. This weir was calibrated in place by weighing the outflow.

The discharge through the flume was controlled by a valve in the pump discharge line and a bypass valve in the head box to the flume. The orifice plates were secured to a bulkhead and installed in the flume. A point gage mounted on a traveling carriage was used to determine the elevation of the water surface both upstream and downstream relative to the center of the orifice opening. The downstream water surface elevation was controlled by a flap gate so that any desired degree of submergence could be obtained.

For later tests a channel which was 8 inches wide and 1 foot deep was used. The plates with orifice openings of prescribed diameters were mounted near the mid-point of this flume. The bottom boundary of the approach section was maintained at 1 inch below the orifice opening. Measurement of depth and discharge was made as previously discussed.

The orifices used in the initial tests were made in aluminum plates that were 12 inches high, 18 inches wide, and 0.081 inch thick. The orifices were 3/4, 1, 1-3/8, 1-3/4, 2, and 2-1/2 inches in diameter with the centers 4-1/2 inches below the top of the plates. These were standard plates which were furnished by the Soil Conservation Service. Careful measurements of the diameters indicated that in the case of the 3/4-inch orifice the actual diameter was 0.76 inch and the 1-inch orifice had a diameter of 1.018 inches. The measured diameters of the other orifices were equal to their respective nominal diameters.

For further studies, additional plates were made which were 8 inches wide and 12 inches high. These had orifice diameters of 3, 3-1/2, and 4 inches. Plates with hole diameters of 1-3/8, 1-3/4, 2, and 2-1/2 inches, which had previously been calibrated in the larger flume, were cut to the smaller dimensions for retesting in the smaller flume.

Since a determination of the effects of various upstream approach conditions was one of the primary objectives of the study, the approach channel conditions were varied. The approach channel was trapezoidal in shape to simulate the furrow and was oriented in different locations relative to the orifice. This channel had a flat bottom, 5 inches in width, with sidewalls at 60 degrees from the horizontal and was constructed of plywood. The standard condition used for all plates was with the bottom of the approach channel on the centerline, 1 inch below the bottom of the orifice opening and oriented at a right angle to the plate. A second condition had the approach section on the centerline, but the floor was set at the bottom of the orifice. For the third condition, the approach was placed at a 15-degree angle to the centerline and the floor 1 inch below the bottom of the orifice. The final condition also utilized the approach at an angle of 15 degrees, but the approach floor was again set at the bottom of the orifice opening.

Because of the large number of tests necessary for each condition of approach, it was not possible to use all of these conditions for each of the orifice plates tested. For this reason, the 2-1/2 inch orifice was selected for a complete series since this orifice, with its higher discharge and correspondingly higher approach velocities, would be one of the most critical sizes as far as operating conditions were concerned. A complete range of free flow and submerged flow conditions using the standard approach was completed on all of the other orifices tested. Free flow is defined as the condition where the effluent jet is above the downstream water surface. For submerged flow, the downstream water surface is considered to be at some level above the bottom of the orifice opening.

In conducting a test, it was first necessary to set the flow to the desired discharge. A stabilization period of approximately 20 minutes was required to allow the flow to reach equilibrium. After equilibrium was reached, the water surface elevations were determined at five points on the upstream side of the plate. Three of these points were immediately upstream from the plate with one of them being over the orifice. The other two points were 0.5 and 1.0 feet upstream in the center. Readings of water levels were also taken using the marks engraved at 1/4-inch increments in the face of the plates. For those flows when the orifice was operating submerged, the elevation of the downstream water surface at several locations was also recorded. Determinations of discharge using the 90-degree V-notch weir were made immediately before and after the other readings were made.

ANALYSIS OF DATA

As was previously stated, the 2-1/2 inch diameter orifice was selected for a detailed study of the effect of upstream conditions and angle of plate. Figure 1 illustrates the relationship of depth and discharge for free flow discharge in the range of conditions tested. (The head was determined from the center of the opening.) The standard condition, for which discharge tables were prepared, was with the approach section previously described set perpendicular to the plate and the floor 1 inch below the orifice opening. Data are also shown for the orifice when the approach section was not used and the 2-foot

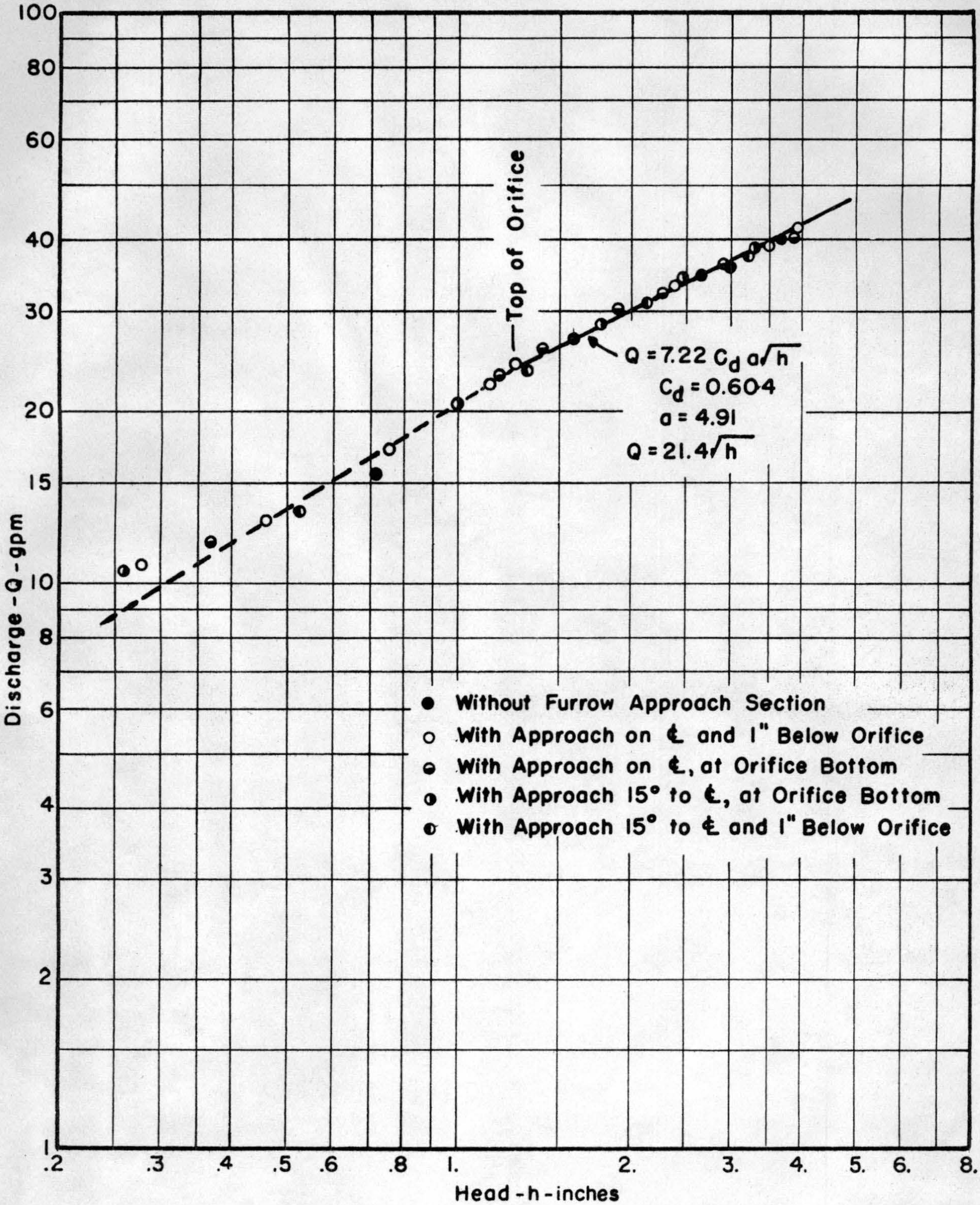

Fig. 1 Calibration of 2-1/2" Furrow Orifice Under Free Flow Conditions.

wide channel served as the approach. There was generally very little deviation of any of the data from that using the standard condition. In fact, the maximum deviation from the standard equation was about 4 percent when the upstream water surface was above the top of the orifice. Slightly lower discharges for a given head were determined for the orifice without the furrow approach indicating a lower coefficient of discharge. The head-discharge relationship when the approach was on centerline but with the floor at the orifice bottom was the same as the standard condition. Likewise, with the approach at a 15-degree angle and the floor again at the bottom of the orifice opening, the discharge was the same as the standard condition. As would be expected, the relationship was not the same when the water surface was below the top of the opening and there was more scatter of data. However, the indications are that the water surface can be exactly at this point before this change occurs.

The results of the calibrations on the 2-1/2 inch orifice when the opening was submerged are shown in figure 2. Except for those flows below 22 gpm. the head-discharge relationships were very nearly the same for all conditions of the approach. The maximum deviation for the higher flows was again about 4 percent. For flows below this amount the relationship is not so well defined as there was more scatter of the data. In general, when the approach floor was at the bottom of the opening, slightly greater flows for a given difference in head were noted. However, the differences were so slight that the standard equation could be used with a maximum deviation of not over 3 percent.

The equation for flow through an orifice usually is given as:

$$Q = C_d A \sqrt{2gH} \qquad (1)$$

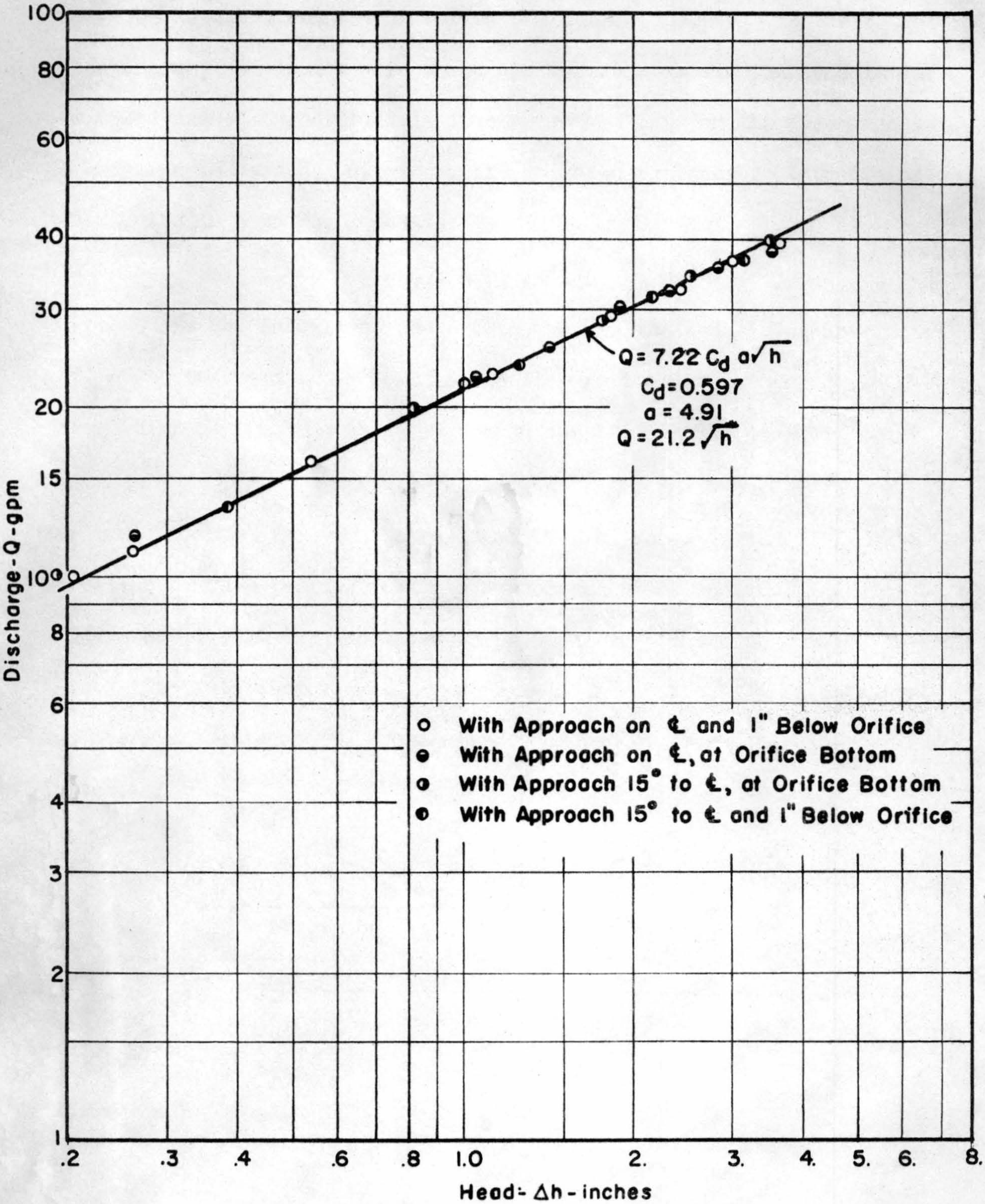

Fig. 2 Calibration of 2-1/2" Furrow Orifice Under Submerged Flow Conditions.

where Q is the discharge in cubic feet per second, C_d is the coefficient of discharge, A is the area in square feet and H is the head in feet. For field use of the orifice it is more convenient for the discharge to be measured in gallons per minute and the head in inches. Introducing these units in equation 1 results in:

$$Q = 0.900\ C_d\ a\sqrt{2gh} \qquad (2)$$

where Q is now in gallons per minute, a is the area in square inches and h is the head in inches. Since the gravitational term g is essentially constant, equation 2 can be further simplified to:

$$Q = 7.22\ C_d\ a\sqrt{h}\ . \qquad (3)$$

For the submerged case h is replaced by Δh which is the difference in elevation between the upstream and downstream water surfaces. From equation 3 it is noted that the discharge is proportional to the square root of the head. This relationship was found to exist for all of the calibrations. The average values of C_d determined from the experimental data are shown in table 1.

Table 1.--Average coefficients of discharge
Furrow orifices

Orifice Diameter (Inches)	C_d Free Flow	C_d Submerged Flow
3/4	0.61	0.57
1	.62	.58
1-3/8	.64	.61
1-3/4	.63	.61
2	.62	.61
2-1/2	.61	.60
3	.60	.60
3-1/2	.60	.60
4	.60	.60

The values for the coefficient of discharge shown in table 1 represent averages of a number of tests for each size. For the submerged conditions, the coefficients varied from 0.57 for the 3/4 inch to 0.61 for the 1-3/8, 1-3/4, and 2 inch sizes. For free flow, a maximum coefficient of 0.64 was found for the 1-3/8 inch orifice and minimum values of 0.60 for the 3, 3-1/2, and 4 inch sizes. For those sizes below 2-1/2 inches, the coefficient under submergence was below that for free flow. A search of literature indicated that very little attention has been given to the effect of submergence on the coefficient of discharge. In fact, no comparison was found between the free flow and submerged flow cases. It should be emphasized that the coefficients shown on table 1 were determined for the previously discussed boundary conditions and the values were effected to some extent by these boundaries. Theoretically, the value of C_d should approach a limiting value of 0.611 for the free flow case.

No explanation can be given at this time for the higher coefficient for the 1-3/8 inch orifice when operating under free flow conditions. An examination of this orifice showed it to be the exact diameter as indicated and that the edges were sharp. Any tendency for rounding of the orifice edges would in turn increase the coefficient of discharge. The tests on both the 1-3/8 and 2-1/2 inch orifices were repeated with different experimental setups and essentially the same values of C_d were determined as found in the previous tests.

An even greater variation in the coefficient of discharge was noted for those data which were previously furnished by the Soil Conservation Service. A value for C_d of 0.680 was used for 3/4-inch orifices under free flow conditions. In a later communication (1), a coefficient of discharge of 0.555 was given for orifices of 1-3/4, 2-1/2, and 3-1/2 inch sizes operating under submergence.

Based on the experimentally determined coefficients for each plate and an orifice of exact size, tables 2 and 3 were prepared giving the free flow and submerged flow calibrations. The tabulation for the free flow relationship begins with a head which is slightly greater than the radius of the orifice. It would seem undesirable to use these plates under conditions where the upstream water surface would be below the top of the opening.

During the tests of submergence, a number of runs were made where the downstream water surface was within the area of the hole. However, the values in table 3 were determined for the case when the downstream water surface was above the top of the hole. When the downstream water surface was within the hole, there was a transition zone in which a single determination of h or Δh would not give a true indication of discharge. In this zone, for the correct determination of discharge, it would be necessary to use both an h and Δh reading. Although this relationship was determined, it is not included in this report since it would tend to complicate the use of the orifice plate. From these observations it can be definitely stated that the downstream water surface must be either below the bottom (free flow) or above the top of the opening (submerged flow) in order for correct determinations of discharge to be made from

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(1) Memorandum from P. M. Price, State Conservation Engineer, Soil Conservation Service, Temple, Texas to Area Conservationists - Texas, June 3, 1957, Subject: Engineering Plans and Calibration Curves for Submerged Orifice Plate.

Table 2.--Discharge through free flow orifices

Head Inches	Diameter of Orifice (Inches) 3/4	1	1-3/8	1-3/4	2	2-1/2	3	3-1/2	4
	Flow in GPM								
0.4	1.24								
0.5	1.39	2.49							
0.6	1.52	2.73							
0.7	1.64	2.94	5.71						
0.8	1.75	3.15	6.11						
0.9	1.86	3.34	6.48	10.34					
1.0	1.96	3.52	6.83	10.90					
1.1	2.06	3.69	7.16	11.43	14.83				
1.2	2.15	3.86	7.48	11.94	15.49				
1.3	2.23	4.01	7.78	12.43	16.12	24.8			
1.4	2.32	4.16	8.08	12.90	16.73	25.8			
1.5	2.40	4.31	8.36	13.35	17.32	26.7			
1.6	2.48	4.45	8.63	13.79	17.89	27.5	38.7		
1.7	2.55	4.59	8.90	14.21	18.44	28.4	39.9		
1.8	2.63	4.72	9.16	14.62	18.97	29.2	41.1		
1.9	2.70	4.85	9.41	15.03	19.49	30.0	42.2	57.5	
2.0	2.77	4.98	9.66	15.42	20.0	30.8	43.3	59.0	
2.1	2.84	5.10	9.89	15.80	20.5	31.5	44.4	60.5	
2.2	2.91	5.22	10.13	16.17	21.0	32.3	45.4	61.9	
2.3	2.97	5.34	10.35	16.53	21.4	33.0	46.4	63.3	82.5
2.4	3.04	5.45	10.54	16.89	21.9	33.7	47.4	64.6	84.3
2.5	3.10	5.57	10.79	17.23	22.3	34.4	48.4	65.9	86.0
2.6	3.16	5.68	11.01	17.58	22.8	35.1	49.4	67.2	87.6
2.7	3.22	5.79	11.22	17.91	23.2	35.8	50.3	68.5	89.3
2.8	3.28	5.89	11.42	18.24	23.7	36.4	51.2	69.8	91.0
2.9	3.34	5.99	11.63	18.56	24.1	37.1	52.1	71.0	92.6
3.0	3.40	6.09	11.82	18.88	24.5	37.7	53.0	72.2	94.2
3.1	3.45	6.19	12.02	19.19	24.9	38.3	53.9	73.4	95.7
3.2	3.50	6.29	12.21	19.50	25.3	38.9	54.8	74.6	97.2
3.3	3.56	6.39	12.40	19.77	25.7	39.5	55.6	75.7	98.7
3.4	3.61	6.49	12.59	20.1	26.1	40.1	56.5	76.8	100.1
3.5	3.67	6.59	12.77	20.4	26.4	40.7	57.3	77.8	101.6
3.6	3.72	6.68	12.95	20.7	26.8	41.3	58.1	78.9	103.1
3.7	3.77	6.77	13.13	21.0	27.2	41.9	58.9	80.0	104.6
3.8	3.82	6.86	13.31	21.3	27.6	42.4	59.7	81.1	106.0
3.9	3.87	6.95	13.48	21.5	27.9	43.0	60.5	82.2	107.4

Table 2.--Discharge through free flow orifices (con.)

Head Inches	Diameter of Orifice (Inches)								
	3/4	1	1-3/8	1-3/4	2	2-1/2	3	3-1/2	4
	Flow in GPM								
4.0	3.92	7.04	13.65	21.8	28.3	43.5	61.3	83.2	108.7
4.1			13.82	22.1	28.6	44.1	62.0	84.2	110.0
4.2			13.99	22.3	29.0	44.6	62.8	85.3	111.4
4.3			14.16	22.6	29.3	45.1	63.5	86.3	112.7
4.4			14.32	22.9	29.7	45.6	64.2	87.3	114.0
4.5			14.48	23.1	30.0	46.2	65.0	88.3	115.3
4.6			14.64	23.4	30.3	46.7	65.7	89.3	116.6
4.7			14.80	23.6	30.7	47.2	66.4	90.2	117.9
4.8			14.96	23.9	31.0	47.7	67.1	91.1	119.2
4.9			15.11	24.1	31.3	48.2	67.8	92.1	120.4
5.0			15.27	24.4	31.6	48.6	68.5	93.1	121.6

Table 3.--Discharge through submerged flow orifices

Head Inches	Diameter of Orifice (Inches) 3/4	1	1-3/8	1-3/4	2	2-1/2	3	3-1/2	4
	Flow in GPM								
0.3	1.00	1.80	3.58	5.80	7.56	11.71	16.8	22.8	29.8
0.4	1.15	2.07	4.14	6.70	8.73	13.52	19.4	26.4	34.6
0.5	1.29	2.32	4.62	7.49	9.76	15.11	21.7	29.5	38.4
0.6	1.41	2.55	5.07	8.20	10.69	16.55	23.7	32.3	42.2
0.7	1.52	2.75	5.47	8.86	11.55	17.88	25.6	34.9	45.6
0.8	1.63	2.94	5.85	9.47	12.34	19.11	27.4	37.2	48.6
0.9	1.73	3.12	6.20	10.05	13.09	20.3	29.1	39.6	51.6
1.0	1.82	3.29	6.54	10.60	13.80	21.4	30.6	41.7	54.5
1.1	1.91	3.45	6.86	11.11	14.48	22.4	32.1	43.7	57.1
1.2	2.00	3.60	7.16	11.60	15.12	23.4	33.6	45.6	59.6
1.3	2.08	3.75	7.46	12.08	15.74	24.3	34.9	47.5	62.0
1.4	2.16	3.89	7.74	12.53	16.33	25.2	36.2	49.2	64.3
1.5	2.23	4.03	8.01	12.97	16.90	26.2	37.5	51.1	66.7
1.6	2.30	4.16	8.27	13.40	17.45	27.0	38.7	52.7	68.8
1.7	2.37	4.29	8.53	13.81	17.99	27.8	39.9	54.3	70.9
1.8	2.44	4.41	8.77	14.21	18.52	28.6	41.1	55.9	72.9
1.9	2.51	4.53	9.02	14.60	19.02	29.4	42.2	57.5	75.0
2.0	2.58	4.65	9.25	14.98	19.52	30.2	43.3	59.0	76.9
2.1	2.64	4.76	9.48	15.35	20.0	30.9	44.4	60.5	78.8
2.2	2.70	4.88	9.70	15.71	20.4	31.7	45.4	61.9	80.7
2.3	2.76	4.99	9.92	16.06	20.9	32.3	46.4	63.3	82.5
2.4	2.82	5.09	10.13	16.41	21.3	33.0	47.4	64.6	84.3
2.5	2.88	5.20	10.34	16.74	21.8	33.6	48.4	65.9	86.0
2.6	2.94	5.30	10.55	17.08	22.2	34.3	49.4	67.2	87.6
2.7	3.00	5.40	10.75	17.40	22.7	35.0	50.3	68.5	89.3
2.8	3.05	5.50	10.94	17.72	23.1	35.7	51.2	69.8	91.0
2.9	3.10	5.60	11.14	18.03	23.5	36.3	52.1	71.0	92.6
3.0	3.15	5.69	11.33	18.34	23.9	37.0	53.0	72.2	94.2
3.1	3.20	5.79	11.52	18.65	24.3	37.6	53.9	73.4	95.7
3.2	3.25	5.88	11.70	18.94	24.7	38.2	54.8	74.6	97.2
3.3	3.30	5.97	11.88	19.24	25.1	38.7	55.6	75.7	98.7
3.4	3.35	6.06	12.06	19.53	25.4	39.3	56.5	76.8	100.1
3.5	3.40	6.15	12.24	19.81	25.8	39.9	57.3	77.8	101.6
3.6	3.45	6.24	12.41	20.1	26.2	40.5	58.1	78.9	103.1
3.7	3.50	6.32	12.58	20.3	26.5	41.1	58.9	80.0	104.6
3.8	3.54	6.41	12.75	20.6	26.9	41.6	59.7	81.1	106.0
3.9	3.59	6.49	12.92	20.9	27.3	42.2	60.5	82.2	107.4

Table 3.--Discharge through submerged flow orifices (con.)

Head Inches	Diameter of Orifice (Inches) 3/4	1	1-3/8	1-3/4	2	2-1/2	3	3-1/2	4
	Flow in GPM								
4.0	3.64	6.57	13.08	21.1	27.6	42.7	61.3	83.2	108.7
4.1			13.24	21.4	27.9	43.2	62.0	84.2	110.0
4.2			13.40	21.7	28.3	43.7	62.8	85.3	111.4
4.3			13.56	21.9	28.6	44.2	63.5	86.3	112.7
4.4			13.72	22.2	28.9	44.7	64.2	87.3	114.0
4.5			13.87	22.4	29.3	45.2	65.0	88.3	115.3
4.6			14.03	22.7	29.6	45.7	65.7	89.3	116.6
4.7			14.18	22.9	29.9	46.2	66.4	90.2	117.9
4.8			14.33	23.1	30.2	46.7	67.1	91.1	119.2
4.9			14.48	23.4	30.5	47.2	67.8	92.1	120.4
5.0			14.62	23.6	30.8	47.7	68.5	93.1	121.5

one reading of head. When used in a furrow, this would mean either cleaning the downstream channel to lower the water surface or throwing in additional material in order to retard the flow.

SUMMARY AND RECOMMENDATIONS

Based on this study, the following statements can be made concerning the use of the orifice plate for furrow measurement:

1. Either free flow or submerged flow conditions will give satisfactory results and the discharge determined using the attached tables should have an accuracy within $\pm$ 5 percent. The downstream water surface must either be below the opening for free flow conditions or above the opening for submerged conditions.
2. Free flow measurements can be made down to the limit where the upstream water surface is just above the top of the opening. When the water surface drops below this point, it would be desirable to remove the plate and insert one with a smaller opening.
3. It is recommended that scribe marks on the face of the plates should not be used to determine the head. A portable hook gage resting on top of the plate and slightly to one side of the opening is more desirable. It was found that there was very little difference in measuring the head at the plate or at points up to 1 foot upstream. However, precise measurements of head are mandatory if desired accuracy limits are not to be exceeded. For example at minimum heads, a measurement

error of 0.05 inch may introduce an error as great as 7 percent in the discharge. It would also be desirable to have a scribed mark on the plate to indicate the exact center of the orifice opening since the head for free flow discharges is determined from this point.

4. The upstream approach conditions exerted a very minor effect on the head-discharge relationship. The difference when the boundary was at the edge of the opening as compared to that an inch below was insignificant. Also, there was no discernible effect when the plate was set at an angle of 15 degrees to the direction of flow. By analogy, an angle of 15 degrees from the vertical should also exert a minor effect. Any differences would probably be in the order of 3 percent or less, which would be within the allowable error of measurement. It is recommended, however, that the plate be set nearly perpendicular to the flow and that some distance always be maintained between the bottom and sides of the orifice opening and the furrow boundary. If it is found that during operation the furrow has silted up near the opening, this material should be shoveled out and a short period allowed for the flow to restabilize.

5. It is important that the opening diameter be held within close tolerances. Since the discharge is directly proportional to area, a variation of $\pm$ 0.01 inch in the 3/4-inch orifice diameter would result in approximately a 3 percent error in discharge when using the rating table prepared for a 3/4-inch

orifice of exact dimensions. Also, the upstream edge of the orifice opening must be sharp and care must be exercised that it does not become battered or rounded.

6. Although no tests were made on the effect of plate thickness, this should have no effect on the discharge through the orifice provided the thickness is not greater than the distance to the vena contracta of the jet. This is the portion of the jet which has the smallest diameter. The approximate distance to the vena contracta from the upstream edge of the plate is one-half the diameter of the orifice. For the 3/4-inch orifice this would indicate a plate which was greater than 3/8 inch in thickness. Since this thickness is impractical, the statement can be made that plate thickness will have no effect.

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