Orifice Plates for Furrow Flow Measurement: Part I - Calibration

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ABSTRACT

ORIFICES, due to their discharge sensitivity to head, are potentially the most accurate open channel flow measurement device and consequently, the best device for determining furrow infiltration rates by the inflow-outflow method. Laboratory calibration determined that orifices under submerged flow conditions are insensitive to boundaries as close as one-half diameter from an edge, allowing practical field use of multi-holed orifice plates in furrows. Submerged flow discharge coefficient for square-edged orifices with the plate thickness less than one-third of the diameter is 0.625. Free flow coefficients vary both with orifice size and head.

INTRODUCTION

Inflow-outflow measurement of furrow infiltration rates is perferable because the measurement is made under near normal operational conditions. However, the infiltration determination is sensitive to flow measurement errors, especially if the measurement is made over short furrow sections in which less than half the inflow is infiltrated (Trout and Mackey, 1985). Accurate flow measurement is thus critical.

The accuracy with which measurement device readings can be made will often limit the accuracy of the flow measurement. Consequently, important factors in choosing an accurate furrow flow measurement device will include the accuracy with which the head can be measured and the sensitivity of the measurement to error in the head reading. The head-discharge relationship of most flow measurement devices is a power function of the form:

$$Q = aH^u \quad [1]$$

where Q = the flow rate (L^3/T)
H = the total head at the gauging point (L)
a and u = empirical coefficients.

By differentiating equation [1], the sensitivity of the predicted flow to head measurement error is determined. In relative terms:

$$dQ/Q = u(dH/H) \quad [2]$$

or the relative error in predicted flow is proportional to the relative error in head reading with the exponential coefficient, u, being the proportionality constant. The value of this exponent depends on the geometry of the device constriction. Fixed area constrictions (orifice) have an exponent of 0.5. Free surface devices (weirs and flumes) will have exponents from near 1.5 for vertical to about 2.5 for sloping-sided control sections. For example, V-notch flumes (Robinson and Chamberlain, 1960) have an exponent of 2.58 and Parshall flumes, about 1.55. Consequently, orifices are only 20 to 30% as sensitive to relative errors in head readings as are flumes and weirs.

A further advantage of orifices is that, due to the large flow constriction, head can be measured close to the constriction and in relatively still water, allowing simple and accurate head measurement without stilling wells or precise leveling. Consequently, orifices are potentially more accurate than other open channel flow measurement devices.

The objective of this study is to extend the previous work of Robinson (1959) to determine whether orifice plates are practical furrow flow measurement devices and whether they maintain their potential accuracy under field conditions. This paper describes the laboratory calibration results. A companion paper (Trout, 1986) discusses design and field use.

ORIFICE FLOW

The discharge equation for orifices is:

$$Q = C_d\, A \sqrt{2g\,(h + h_v)} \quad [3]$$

where Q = flow rate (L^3/T)
C_d = the orifice discharge coefficient
A = orifice cross-sectional area (L^2)
g = acceleration of gravity (L/T^2)
h = piezometric head acting on the orifice (L)
h_v = velocity head acting on the orifice (L)

The piezometric head is the upstream water surface elevation relative to the orifice centerline when the downstream jet flows free, and the water surface elevation drop across the constriction when the jet is submerged.

Velocity head, h_v, is given by:

$$h_v = V_1{}^2/2g = \frac{Q^2}{2g\,A_1{}^2} \quad [4]$$

where V_1 is the velocity immediately upstream of the orifice (L/T) and A_1 is the cross-sectional area immediately usptream of the orifice (L^2).

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Equations [3] and [4] can be combined to give

$$Q = \frac{C_d A \sqrt{2gh}}{\sqrt{1 - C_d^2 (A/A_1)^2}} \quad \ldots\ldots\ldots\ldots [5]$$

Consequently, the effect of the velocity head on the discharge depends upon the ratios of the upstream area, A_1, to the orifice area, A. As long as A_1/A is greater than 6, the effect on discharge will be less than 0.5% and the velocity head can be ignored. This ratio is usually exceeded in furrows.

When head, h, and the diameter, d, of a circular orifice are measured in millimeters, the discharge, Q, is desired in liters per minute and the velocity head is negligible, equation [3] will be:

$$Q = 0.00660 C_d\, d^2 \sqrt{h} \quad \ldots\ldots\ldots\ldots [6]$$

The discharge coefficient, C_d, depends upon the shape and condition of the constriction and the degree of the upstream contraction. Shape factors include the edge width-to-diameter ratio, t/d, where t is the orifice edge width or plate thickness and d is the diameter of the orifice; and the sharpness of the upstream edge described by r/d, where r is the radius of rounding of the front corner.

The edge width (or plate thickness if the edge is not tapered) will not affect C_d as long as the orifice jet does not cling to edges. Edge attachment will occur somewhere between an edge width/diameter ratio of 1/8 and 1/3, beyond which C_d will increase (ASME, 1959).

According to Albertson, et al. (1960), the effect of rounding the upstream orifice edge is:

$$C_d = 0.61 + 1.86\, r/d \quad \ldots\ldots\ldots\ldots [7]$$

up to a limit of $C_d = 0.8$ ($r/d = 0.1$). This relationship implies that even a 0.01 rounding ratio, or a 0.3 mm radius rounding of a 30 mm hole, would cause a 3% increase in the discharge coefficient. This is comparable to a 0.3 mm increase in the hole radius (or a diameter increase from 30 to 30.6 mm) which would cause a 4% area increase and thus a 4% discharge increase. Thus, the discharge relationship is nearly as sensitive to rounding the front edge as to hole diameter errors. However, the edge rounding is much more difficult to measure.

According to the USBR *Water Measurement Manual* (USBR, 1981), for fully contracted operation, "the distance from the orifice edges to the bounding surfaces, both on the upstream and downstream sides, should be greater than twice the least dimension of the orifice." This implies that the furrow wetted perimeter and the water surface must be at least two diameters from the edge of a circular orifice. The Manual further states that the discharge coefficient will increase by 1.5% for every 10% of the orifice perimeter over which the contraction is fully suppressed. This relationship will obviously underestimate the discharge at complete suppression when the coefficient will approach 1.0.

The only quantification of the effects of incomplete orifice contraction found in the literature is given for concentric orifices in pipes (ASME, 1959; Albertson et al., 1960). For this configuration the coefficient increases only slightly until the pipe boundary is within one orifice diameter from the orifice edge (or $d/D = 0.33$ where d is the orifice diameter and D is the pipe diameter), and rapidly when the distance to the boundary is less than 1/4 d, ($d/D = 0.67$). Table 1 shows predicted C_d increases for several boundary distances.

TABLE 1. VARIATION IN THE CIRCULAR ORIFICE DISCHARGE COEFFICIENT, C_d, WITH RELATIVE DISTANCE FROM THE ORIFICE EDGE TO THE UPSTREAM AND DOWNSTREAM CONCENTRIC BOUNDARY (ADAPTED FROM FIG. 3-24 IN ALBERTSON ET AL. 1960).

Boundary distance	C_d	Increase in C_d(%)
> 10 diameters	0.61	—
1 diameter	0.62	1%
1/2 diameter	0.65	6%
1/4 diameter	0.68	11%

Using these two estimates of contraction suppression effects, if the furrw bed were to aggrade to within 1/4 diameter of the orifice edge (causing an 11% coefficient increase) over 1/3 of the orifice perimeter (causing a 4.5% coefficient increase), a 0.5% increase in discharge coefficient would be expected ($0.11 \times 0.045 = 0.005$).

At the request of the U. S. Soil Conservation Service, A. R. Robinson studied the use of orifices for furrow flow measurement (Robinson, 1959). His objectives were similar to those of this study. However, his primary measuring device was a V-notch weir and he aimed for an accuracy of only ±5%. He tested circular orifices from 19 to 102 mm (3/4 to 4 in.) diameter cut in 2.06 mm (0.081 in.) aluminum plates. Approach conditions tested included placing the orifice 25 mm (1 in.) above and at the bed of a trapezoidal channel, and perpendicular to and 15 deg off perpendicular to the channel. Some of the conclusions of that study are:

1. Upstream approach conditions exert a very minor effect (< ± 3%) on the head-discharge relationship.
2. The upstream water surface can be as low as the top of the opening without affecting free flow measurements.
3. The downstream water surface must be either below the opening for free flow conditions or above the opening for submerged flow conditions.
4. Angling the orifice as much as 15 deg from perpendicular to the flow does not affect the discharge coefficient.
5. The discharge coefficient varies with orifice diameter and free or submerged flow as given in Table 2.

Based on Robinson's findings, the USDA Soil Conservation Service (SCS, 1962) recommends the use of a three section, 20 gauge (1 mm thick) orifice plate with clear plastic viewing slots to determine the head loss. They use Robinson's discharge coefficients, which are also listed in Bos (1976), Table 8.1.

CALIBRATION METHODOLOGY

Square-edged circular orifices, cut in clear acrylic sheets, were calibrated either in a 300 mm (12 in.) wide semicircular flume made by cutting a section of PVC pipe in half longitudinally, or in a 400 mm wide by 300 mm deep rectangular wooden flume. The orifice plates were positioned perpendicular to the flume boundaries. The orifice edges were at least 100 mm from the nearest boundary in the rectangular flume and 1 diameter from the bottom of the semicircular flume. Steady inflows

TABLE 2. AVERAGE DISCHARGE COEFFICIENTS FOR FURROW ORIFICES MEASURED BY ROBINSON (1959)

Orifice diameter		C_d submerged flow	C_d free flow
mm	(inches)		
19.1	(3/4)	0.57	0.61
25.4	(1)	0.58	0.62
34.9	(1 3/8)	0.61	0.64
44.5	(1 3/4)	0.61	0.63
50.8	(2)	0.61	0.62
63.5	(2 1/2)	0.60	0.61
76.2	(3)	0.60	0.60
88.9	(3 1/2)	0.60	0.60
101.6	(4)	0.60	0.60

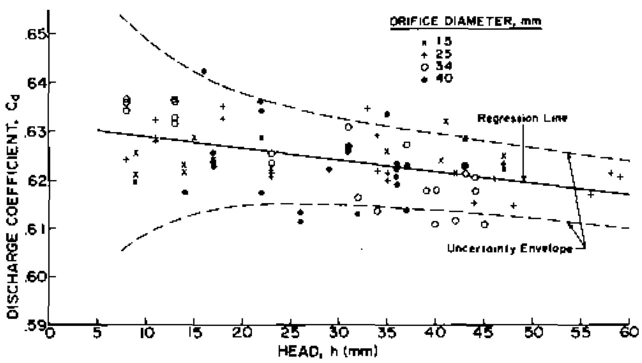

Fig. 1—Calculated discharge coefficients for submerged square-edged orifices.

were delivered from a constant head tank. Flow rates were determined with a weighing tank. Submerged flow piezometric head was measured with a differential point gauge, described in Trout (1986), with 1 mm resolution. For free flow conditions, the downstream gauge point was placed at the orifice horizontal centerline. The A_1/A ratio was always greater than 10 during calibration.

In the semicircular flume, four sizes of orifices (15 mm, 25 mm, 34 mm, and 40 mm diameter) cut in 4.8 mm thick plates were calibrated at several flow rates under free flow, submerged flow, and transitional conditions. The discharge coefficient for each test was calculated by solving equation [6] for C_d. Variations in the discharge coefficient with head and downstream water level were determined.

Each run was duplicated with a PVC plate lying in the bottom of the flume both usptream and downstream of the orifice plate, which created a lower horizontal boundary about one-half orifice diameter from the orifice lower edge. With the 25 mm orifice, lower boundaries were similarly created d/4 below and at the lower orifice edge to determine the effect of a planar boundary on the discharge coefficient.

The effect of orifice edge width was tested in the rectangular flume both by calibrating a 20 mm orifice cut in 2.4, 3.2, 4.8, and 6.4 mm thick plates, and by calibrating a 20 mm orifice cut in a 4.8 m thick sheet before and after beveling the back edge of the orifice to an edge thickness of 3.2 and 1.2 mm.

The effect of orifice spacing was checked in the rectangular flume by variably spacing five 29 mm holes across a plate such that the distance between hole edges ranged from 20 to 50 mm, and by plugging unused holes with rubber stoppers, calibrating the holes individually and in pairs.

CALIBRATION RESULTS

Fig. 1 shows the discharge coefficient calculated from the submerged flow calibration data for four orifice sizes. The values fall in a band about 0.02 wide which decreases with head. A best fit linear regression line (significant at 99%), drawn on the figure, decreases from 0.629 at h=10 mm to 0.620 at h=50 mm. No consistent differences with orifices sizes are evident.

Also drawn on the figure are 95% confidence interval boundaries for the calibration process. Calibration uncertainty included head and flow measurement. Differential point gauge resolution was ±0.5 mm. Assuming a uniform distribution within this resolution, the head measurement standard deviation would be about 60% of the resolution or 0.3 mm. The effective coefficient of variation, CV, in terms of flow was calculated by equation [2]. Constant flow weighing tank data had a CV of about 0.5%. Since the discharge coefficient is calculated from the ratio of these values, the confidence interval, E, of the coefficient can be estimated from (Cochran, 1963):

$$E = \overline{C}_d\ (1 \pm t\sqrt{CV_1{}^2 + CV_2{}^2 - t^2\ CV_1{}^2\ CV_2{}^2})/(1-t^2 CV_1{}^2)$$

$$\cong \overline{C}_d\ (1 \pm 1.96\ ((0.3u/h)^2 + (0.005)^2)^{1/2})\ \ldots\ldots [8]$$

where: $\overline{C}_d$ = the mean coefficient value at h
t = the student t statistic = 1.96 for a 95% probability with large samples
CV_1 = the head measurement-caused flow rate coefficient of variation = 0.3 u/h
CV_2 = the flow measurement coefficient of variation = 0.005.

Most of the data points (85%) fall within this uncertainty envelope and no point is more than 0.004 or 0.6% of $\overline{C}_d$ outside the envelope. Consequently, it is concluded that the orifices are at least as accurate as the calibration process, which varied from ±3.6% at h=10 mm to ±1.2% at h=50 mm, and the discharge coefficients vary between orifices of different sizes by less than 1%.

Since the discharge coefficient decreases only 1.5% over a 10 to 50 mm head range, use of a constant C_d value of 0.625 will be more convenient and introduce less than a 1% error from the linear best estimate. This coefficient is higher than the often cited value of 0.61.

Fig. 1 includes data for downstream water depths varying from the top edge of the orifice to three diameters above the edge. No consistent variation in C_d with downstream submergence depth was found. In fact, as Fig. 2 shows, the orifice head deviated little from the constant submerged flow head loss until the downstream depth lowered to near the orifice centerline.

Fig. 2 shows measured elevation drop across the orifice plate at constant flow rates as the downstream water level is lowered from above to below a 25 mm orifice, thus changing from submerged to free flow conditions. If the discharge coefficient remained constant, the constant head loss (horizontal line) during submerged flow should intersect at the orifice centerline with the 45 deg line

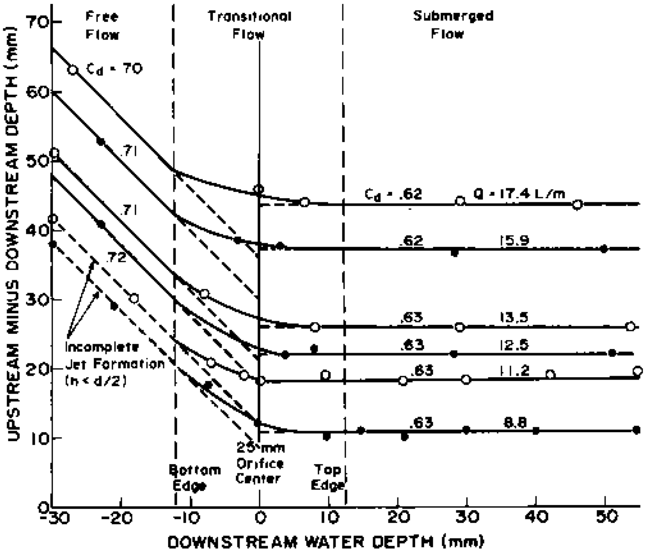

Fig. 2—Upstream minus downstream water elevations vs. downstream elevation relative to the orifice centerline for a 25 mm orifice at six constant flow rates (open circle designate alternate runs).

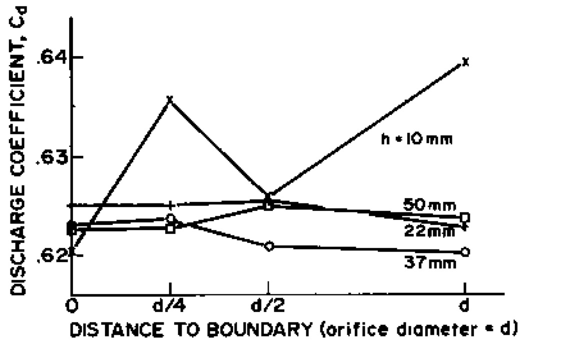

Fig. 3—Calculated discharge coefficient of a 25 mm orifice with a lower horizontal boundary.

resulting from the constant upstream head during free flow. As the figure shows, free flow head is always less than submerged flow, implying a larger discharge coefficient.

In free flow calibrations of nine orifice sizes varying from 15 to 45 mm, the discharge coefficients varied inversely with both head and orifice size. A summary of the free flow coefficients is given in Table 3. The coefficients appear to approach the submerged flow coefficient at both high heads and large sizes. An explanation for this coefficient variation was not found. The jet was observed to fully detach from the orifice edges at upstream depths greater than 2 to 4 mm above the top orifice edge ($h=d/2+2$ to $d/2+4$). Neither a reference elevation adjustment or allowance for incomplete jet energy dissipation can explain both the variation with head and size. Robinson (1959) also found free flow coefficients of orifices in this size range larger than submerged flow coefficients, although no variation with head was reported. Until this variation is understood, furrow orifices should not be used under free flow conditions.

Fig. 3 shows the effect of an upstream and downstream horizontal lower boundary on the submerged flow discharge coefficient of a 25 mm orifice. The coefficient does not vary consistently with boundary distance between one diameter from and at the lower edge at any head between 10 and 50 mm. Analysis of 60 pairs of calibration points from four orifice sizes with a lower boundary both about d/2 and farther than d from the orifice edge indicated no significant difference in the discharge coefficients at the 99% level of probability. Calibration data with both 1:1 sloped sides and a bottom boundary indicated a boundary effect began when all three boundaries were about one-half diameter distance and increased to about $1.02C_d$ at about 0.2 d distance. The effects of a furrow perimeter within d/2 of the orifice edge or a planar boundary at the edge is thus concluded to be less than 1%.

TABLE 3.
FREE FLOW DISCHARGE COEFFICIENTS.

Orifice diameter, mm	d/2	Head, h mm 25	50	80
15.2	0.76	0.72	0.69	
20.1	0.74	0.68	0.66	0.64
25.3	0.73	0.71	0.67	
25.7	0.69	0.67	0.64	0.63
33.7	0.69	0.68	0.65	0.63
33.9	0.69	0.68	0.64	
34.9	0.63	0.63	0.63	0.63
40.7	0.65	0.64	0.63	0.63
45.1	0.62	0.62	0.62	0.61

Fig. 2 shows that, even when the upstream water surface is within 11 mm of the orifice top edge, the submerged flow discharge coefficient is not affected. No water surface boundary effect was found with any size when the surface was greater than 10 mm from the upper edge, or about d/4 distance from the 40 mm orifice edge.

When two closely-spaced orifices with diameters d_1 and d_2 flow concurrently, the submerged flow will be divided proportionally to their areas and an effective boundary will be created between the orifices, located $d_1/(d_1+d_2)$ times the spacing from the d_1-sized orifice. When orifices at the closest spacing tested ($0.34\,(d_1+d_2)$) were calibrated concurrently, the discharge coefficient of the combination was always within 0.5% of the coefficient of the individual orifices. Consequently, no effects from an interference boundary as close as 0.34 d is expected.

Plate thickness had no significant effect on the submerged flow discharge coefficient up to the largest tested edge width-to-diameter ratio of 1/3 (a 20 mm hole in a 6.4 mm [1/4 in.] plate), even at heads as low as 10 mm. Beveling a 20 mm orifice in a 4.8 mm plate to 1.2 mm edge thickness also did not effect the coefficient.

SUMMARY

These results show that small orifices with square front edges accurately measure submerged flows, and that flows through these orifices are not significantly affected by wetted perimeter boundaries within 1/2 diameter of their edge and only slightly by a boundary as close as sediment will deposit to an orifice hole. The discharge relationship is also not affected by the upstream water surface coming as close as 10 mm from the hole. Consequently, submerged orifices are a viable means of precisely measuring furrow flow. Edge width within the practical range ($t/d<1/3$ and $h>10$ mm) did not effect the discharge coefficient, so there is no need to bevel the back edge of furrow orifices.

The submerged flow discharge coefficient decreases

(continued on page 111)

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slightly over the head range. A C_d value of 0.625 is within 1% of the linear best estimate over a 10 to 50 mm head range. The free flow discharge coefficient varied with head and orifice size, so free flow use is not recommended.

References

1. Albertson, Maurice L., James R. Barton, and Daryl B. Simons. 1960. Fluid mechanics for engineers. Prentice Hall, Inc., Englewood Cliffs, NJ, pp 133 and 136.
2. American Society of Mechanical Engineers (ASME). 1959. Fluid meters—their theory and application. American Society of Mechanical Engineers 5th Edition. 19 West 39th St., New York, pp. 69-77.
3. Bos, M. G. 1976. Discharge measurement structures. Publication No. 20, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.
4. Cochran, William G. 1963. Sampling techniques, 2nd Ed. John Wiley, p. 164.
5. Robinson, A. R. 1959. Orifice plates for furrow flow measurement. Unpublished report of the USDA-ARS Soil and Water Conservation Research Division and Colorado Agric. Exp. Station, Fort Collins, CO.
6. Robinson, A. R., and A. R. Chamberlain. 1960. Trapezoidal flumes for open channel flow measurement. TRANSACTIONS of the ASAE 3(2):120-124, 128.
7. Trout, Thomas J. 1986. Orifice plates for furrow flow measurement: Design and field use. TRANSACTIONS of the ASAE 29(1):107-111 (this issue).
8. Trout, Thomas J., and Bruce E. Mackey. 1985. Inflow-outflow infiltration measurement accuracy. Unpublished report to be submitted to TRANSACTIONS of the ASAE.
9. U. S. Bureau of Reclamation (USBR). 1981. Water Measurement Manual 2nd Edition, Revised reprint. U. S. Govt. Printing Office. Denver, CO.
10. USDA Soil Conservation Service. 1962. Measurement of Irrigation Water. SCS National Engineering Handbook, Section 15, Chapter 9, pp. 9-5 to 9-9.