Energy Dissipation in Low Pressure Irrigation Pipelines: II Orifices

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ABSTRACT

EROSION caused by water discharged from gated pipe openings can be reduced by dissipating excess energy with orifices placed in the gated pipe couplings. Laboratory tests were conducted to determine graphical relationships and coefficients for estimating the head loss for orifices made from galvanized sheet metal. The loss coefficient, K_o, is a function of the orifice-to-pipe diameter ratio, β_o, and can be expressed by an equation of the form $K_o = a\beta_o^b$ where **a** and **b** are empirical constants determined from the tests. Comparisons made between machined, square edge orifices commonly used for flow measurement, and those made in sheet metal shops for irrigation showed that the irrigation orifices have a higher discharge coefficient and a lower head loss coefficient than do the square edge orifices. Square edge orifices placed in irrigation pipe couplings behaved similarly to those for flow measurement, particularly in the mid and lower ranges of the diameter ratio, β_o.

The head loss ratio, R, as defined by the ASME (1959) is the same for, (a) square edge orifices used for flow measurement, (b) square edge orifices installed in aluminum irrigation pipeline joint couplings, and (c) sheet metal orifices made for irrigation installed in pipe couplings. The ratio can be represented by the equation $R = 1\text{-}0.9\ \beta_o^{1.7}$.

INTRODUCTION

Gated irrigation pipe is often used on nonuniform and relatively steep slopes. When used on slopes that exceed the friction on hydraulic gradeline slope of the flowing water, pipeline pressures increase in downstream sections of pipe. The resulting high pressures can give nonuniform flow, make outlet gates difficult to adjust, and cause high velocity streams to be emitted from the pipe. These high velocity streams often cause excessive soil erosion, especially on erosive soils. Another problem encountered on steep slopes is that the pipe may not flow full and it is difficult to get sufficient flow from upstream outlets.

Orifice plates with concentric orifices, placed at intervals in the pipeline, can be used to dissipate excess energy. They can also "check" the water so that the pipe flows full. Pipe orifices are widely used for flow measurement, and discharge coefficients for these are readily available. However, when they are used for energy dissipation, velocity head recovery downstream from the orifice must be considered and information for this use is limited. Head loss information presented by the American Society of Mechanical Engineers (ASME, 1959) pertains to square edge orifices clamped between flanges at a pipeline joint with stringent installation requirements. An orifice for irrigation pipe is loosely installed inside the bell end of a pipe coupling and is held in place by the male end of a companion pipe. With this type coupling, there is a discontinuity in the pipeline at the joint. This is in contrast to ASME flow measurement conditions, where orifices are installed in a rigid joint having a uniform diameter. ASME orifices are also machined and honed to achieve a very exacting square edge. This degree of precision is not required for energy dissipating orifices and the cost of such orifices would be prohibitive. Orifices for irrigation pipelines were made by conventional tools normally used in sheet metal shops and their inside edges were not completely square.

Because of the different conditions noted, pressure loss data presented by the ASME would not be expected to apply exactly to sheet metal orifices used for irrigation. Therefore, laboratory tests were conducted to obtain energy or head loss coefficients for orifices used in gated irrigation pipe. The results of these tests are presented in this paper which also includes a comparison of the test results with the ASME data and presents coefficients with which the ASME data can be used to estimate energy dissipation in gated pipe systems.

PROCEDURE

Laboratory tests were conducted using 150 mm (6 in.), 200 mm (8 in.), and 250 mm (10 in.) aluminum conveyance pipe without gates or outlets to determine the head loss for different orifice sizes and discharge rates. Pipe lengths upstream from the orifice were 5 m (15 ft) and represented 30, 23, and 18 pipe diameters respectively for the three pipe sizes, while downstream lengths varied from 5 m to 9 m (15 to 30 ft). All pipe lengths were adequate for full downstream velocity head recovery. The orifice to be tested was installed inside the coupling which joined the two lengths of pipe. Pipe coupling losses were measured without an orifice in place and were found to be small (Humpherys, 1986). Since head loss for the couplings was small, all of the measured loss with an orifice installed was attributed to the orifice.

Orifices for the tests were made from 1.5 mm (16 gauge) galvanized sheet metal and were sized to fit inside the bell end of a gated pipe coupling as shown in Fig. 1. Guide pins were fastened to some of the orifice plates to position and hold them in place on the male end of the pipe while the pipe was inserted into the coupling.

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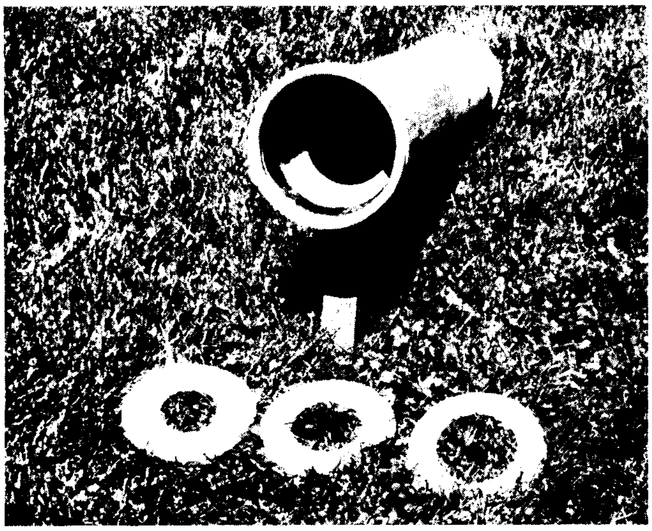

Fig. 1—Orifice plates used for energy dissipation in gated irrigation pipe.

However, subsequent tests indicated that this was not necessary. Plates with nominal orifice diameters ranging from 75 mm (3 in.) to 115 mm (4.5 in.) for the 150 mm pipe, 75 mm (3 in.) to 165 mm (6.5 in.) for the 200 mm pipe, and 125 mm (5 in.) to 190 mm (7.5 in.) for the 250 mm pipe were tested. These sizes represent orifice-to-pipe diameter ratios, β_o, ranging from 0.38 to 0.82 where $\beta_o = d_o/D$; d_o is the orifice diameter and D the inside pipe diameter. Most orifices were made using commercial shop procedures and circle cutters. The actual orifice diameters, which sometimes varied slightly from nominal, were used to determine β_o.

One series of tests was conducted using orifices made from the same sheet metal material but machined to provide a perfectly round orifice with a square edge. These were more nearly like the ASME orifices except that they fit loosely inside the pipe coupling.

Water for the tests was pumped from a laboratory sump and the flow measured with a 150 mm venturi-type flow meter. The test pipe was placed at zero slope in a flume and connected to a stilling head box at the inlet, so that the flow was free from swirls and eddies. Flow rates ranged from approximately 14 L/s (225 gpm) to 56 L/s (900 gpm). These flow rates represented a range of orifice Reynolds Numbers, N_R, from about 1.2 to 4.0 x 10^5 for the three pipe sizes with N_R based on d_o and the average orifice velocity. Piezometer taps were spaced 50 cm (20 in.) along the length of the test pipe with closer spacings down to 5 cm (2 in.) immediately downstream from the orifice. Piezometric head measurements were made with a water-column manometer. Head loss measurements were made for each orifice at different flow rates.

RESULTS AND DISCUSSION

The head loss, H_o, illustrated schematically in Fig. 2, is the elevation difference between the hydraulic gradelines extended upstream and downstream from the orifice. The downstream hydraulic gradeline was extrapolated upstream from the downstream section of pipe below the region where velocity head recovery was achieved. The head loss past an orifice can be expressed in the normal manner as a function of the velocity head $V_o^2/2g$ and a head loss coefficient as

$$H_o = K_o V_o^2/2g \quad \ldots\ldots\ldots\ldots [1]$$

where

- H_o = head loss representing the energy dissipated through an orifice, L
- K_o = dimensionless coefficient of head loss or energy dissipation through an orifice, a function of β_o
- V_o = orifice flow velocity = Q/A_o, L/T
- Q = flow discharge, L^3/T
- A_o = orifice area, L^2
- g = acceleration of gravity, L/T^2

Head loss coefficient

The head loss coefficient, K_o, was determined from the test data with a rearranged form of equation [1] where

$$K_o = 2g\, H_o/V_o^2 \quad \ldots\ldots\ldots\ldots [2]$$

The coefficient was found to be primarily a function of the diameter ratio β_o. It is nearly independent of flow rate and N_R in the higher ranges of N_R, where most irrigation flow rates fall, and in the mid and lower ranges of β_o as shown in Fig. 3. Published values of the discharge coefficient, C_d, for square edge orifices can be related to K_o, as noted later, and were used to compute K_o for square edge orifices for three diameter ratios. These are also shown in Fig. 3 to illustrate the variation of K_o with N_R.

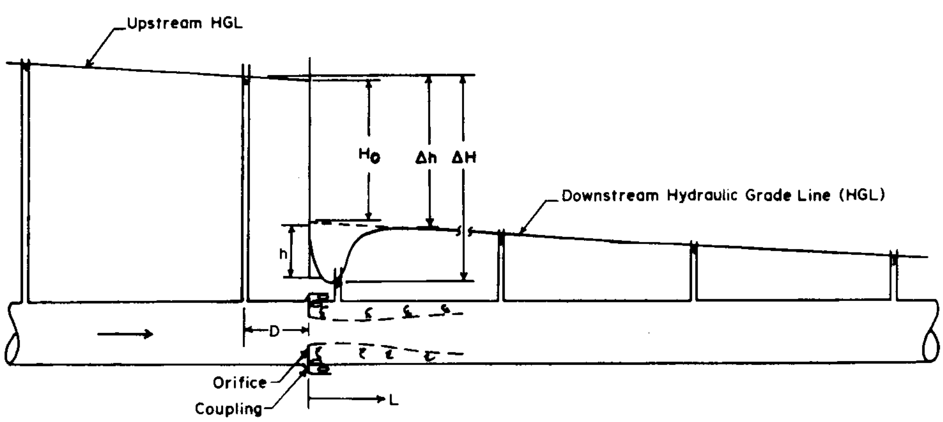

Fig. 2—Schematic diagram of the hydraulic gradeline for a pipeline with an energy dissipating orifice.

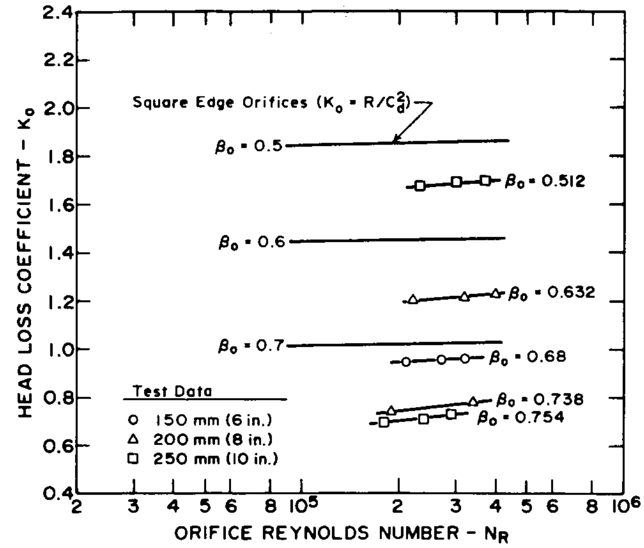

Fig. 3—Head loss coefficient K_o as a function of orifice Reynolds number for square edge orifices of three diameter ratios and representative data for irrigation sheet metal orifices from laboratory tests.

Values of K_o at different flow rates for a given orifice varied less than two percent from their average which, for practical purposes, is not significant. Therefore, average values of K_o for two or more test runs at different flow rates for a given orifice (Fig. 3) were plotted logarithmically as a function of $1\text{-}\beta_o$ as shown in Fig. 4. The factor $1\text{-}\beta_o$ was used rather than β_o so the data would plot as a straight line on a log-log plot. The head loss coefficient K_o approaches the coupling loss coefficient, K_c, as β_o approaches 1.0. Approximate values of K_c in the flow range of the tests were 0.15 for the 150 mm diameter pipe, 0.084 for the 200 mm pipe and 0.065 for the 250 mm pipe. As shown in Fig. 4, the head loss coefficient, K_o for 200 and 250 mm pipe can be represented by one curve while that for the 150 mm size is best represented by a separate curve. The function representing orifices for the 150 mm pipe ($r^2 = 0.995$) is

$$K_o = 3.5\,(1\text{-}\beta_o)^{1.2} \quad \text{[3]}$$

and for the 200 and 250 mm pipes ($r^2 = 0.997$) is

$$K_o = 4.85\,(1\text{-}\beta_o)^{1.38} \quad \text{[4]}$$

Combining each equation [3] and [4] with equation [1] gives the head loss for flow through orifices for 150 mm pipes as

$$H_o = 1.75\,(1\text{-}\beta_o)^{1.2}\,V_o^2/g \quad \text{[5]}$$

and for orifices in 200 and 250 mm pipe as

$$H_o = 2.42\,(1\text{-}\beta_o)^{1.38}\,V_o^2/g \quad \text{[6]}$$

Head loss curves such as those for 200 mm pipe shown in Fig. 5, can be constructed for different size orifices, flow rates, and pipe sizes from these equations for use in irrigation.

Comparisons with square edge orifices

As previously noted, a limited amount of information on head losses was presented by the ASME (1959) for flow measurement orifices which uses the basic orifice

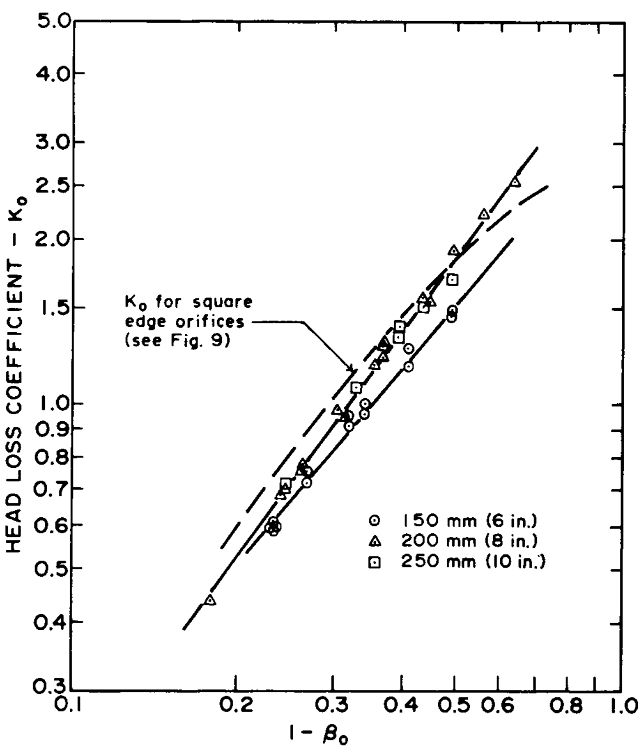

Fig. 4—Head loss coefficient K_o for energy dissipating sheet metal orifices used for irrigation as a function of the diameter ratio factor $1\text{-}\beta_o$.

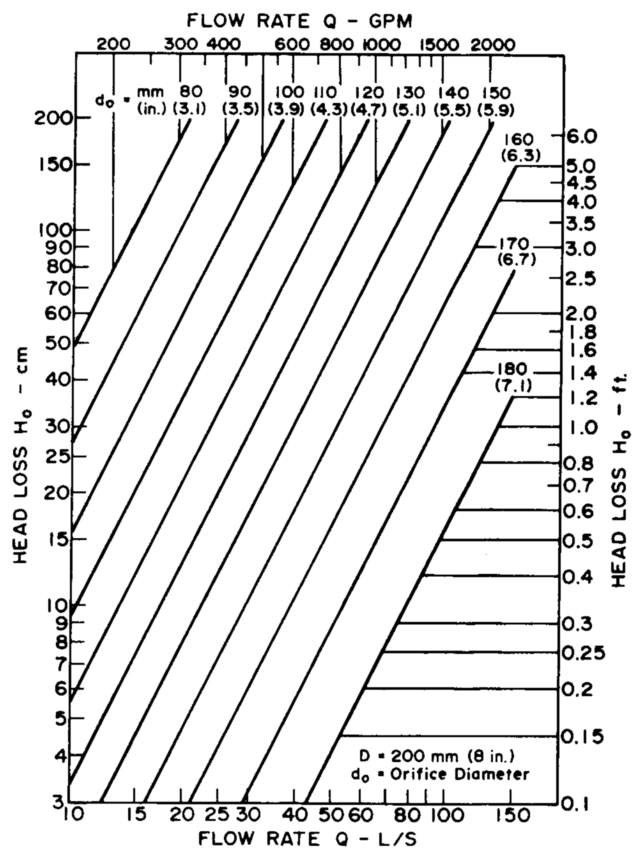

Fig. 5—Representative diagram of the head loss for energy dissipating orifices in a 200 mm (8 in.) irrigation pipe for different size orifices and flow rates.

flow equation

$$V_o = C_d(2g\,\Delta H)^{0.5} \quad [7]$$

where

C_d = coefficient of discharge for orifices,
ΔH = differential pressure head measured by pressure taps located upstream and downstream from the orifice.

Several types of pressure taps are used for measuring the differential head ΔH. This discussion and the ASME data are based upon vena contracta taps. As illustrated in Fig. 2, the high-pressure tap is located one pipe diameter upstream from the face of the orifice plate and the low pressure tap at the vena contracta which is the point of minimum downstream pressure (Brater and King, 1976).

Head loss ratio: The ASME (1959) defines a pressure head loss ratio as

$$R = \Delta h/\Delta H \quad [8]$$

where

Δh = difference between the minimum pressure head upstream from the orifice and the maximum head downstream from the orifice.
ΔH = difference between the minimum pressure head upstream and the minimum head downstream from the orifice.

The differential pressure heads as defined above are shown in Fig. 2. As shown in Fig. 2, Δh is nearly the same as the head loss, H_o. The difference between Δh and H_o is small compared to the loss and represents the pipe friction loss between the upstream tap and the point of maximum downstream pressure. This difference was generally less than 12 mm (0.5 in.) and for energy dissipating purposes can be neglected. Thus, if H_o is substituted for Δh, from equation [8], the head loss is

$$H_o = R\Delta H \quad [9]$$

From equation [7],

$$\Delta H = 1/C_d^2\,(V_o^2/2g) \quad [10]$$

and combining equations [9] and [10] gives

$$H_o = R/C_d^2\,(V_o^2/2g) \quad [11]$$

from which

$$K_o = R/C_d^2 \quad [12]$$

As noted previously, a series of laboratory tests was conducted using machined square edge orifices installed in the irrigation pipe couplings. These tests were made to compare results between machined and non-machined orifices made from sheet metal and the precision-made ASME orifices. Some runs were made during the laboratory tests with both groups of sheet metal orifices to obtain Δh and ΔH data from which the pressure head loss ratio could be determined. The head loss ratio for these tests, expressed as (1-R), is plotted logarithmically as a function of β_o in Fig. 6. The data for both groups of sheet metal orifices fit the same curve. Individual data points taken from Fig. 26 of the ASME publication for square edge flow measuring orifices are also shown in Fig. 6 and fit the same curve. The head loss ratio R can be expressed by an equation of the form

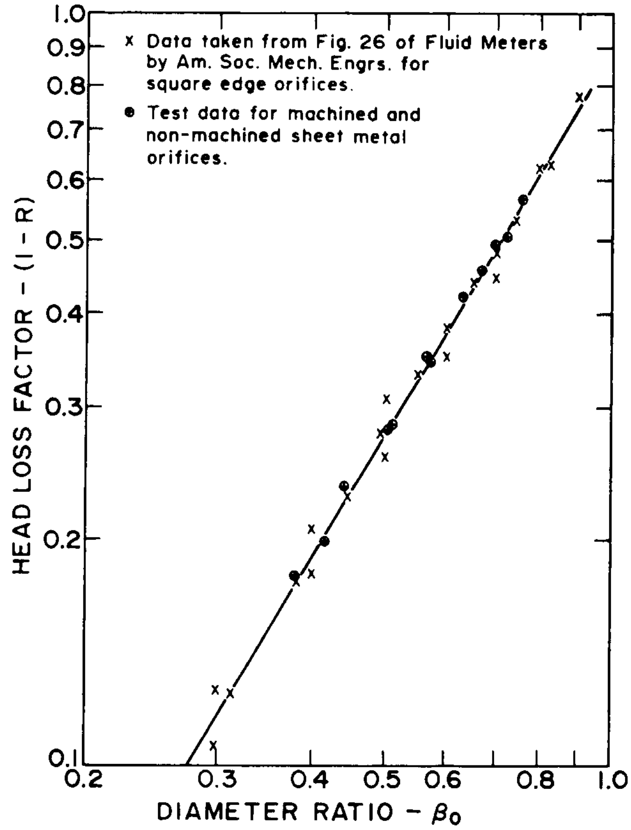

Fig. 6—Head loss factor (1-R) as a function of the diameter ratio β_o for common and square edge sheet metal orifices in irrigation pipe couplings and for ASME square edge flow measurement orifices.

$$(1-R) = a\,\beta_o^{\,b} \quad [13]$$

where **a** and **b** are constants and are shown in Table 1 for regressions on each set of data individually and combined.

As shown in Fig. 6 and Table 1, the head loss ratio is the same for all orifices and can be expressed as

$$(1-R) = 0.9\,\beta_o^{\,1.7} \quad [14]$$

from which

$$R = 1-0.9\,\beta_o^{\,1.7} \quad [15]$$

Since K_o is a function of R and C_d as shown by

TABLE 1. CONSTANTS FOR THE GENERAL EQUATION EXPRESSING R AS A FUNCTION OF β_o FOR TWO SETS OF DATA

Data set	a	b	r^2
Laboratory tests w/square edge and common orifices	0.899	1.68	0.999
Data from ASME Figure 26	0.887	1.69	0.997
Both data sets combined	0.893	1.69	0.997

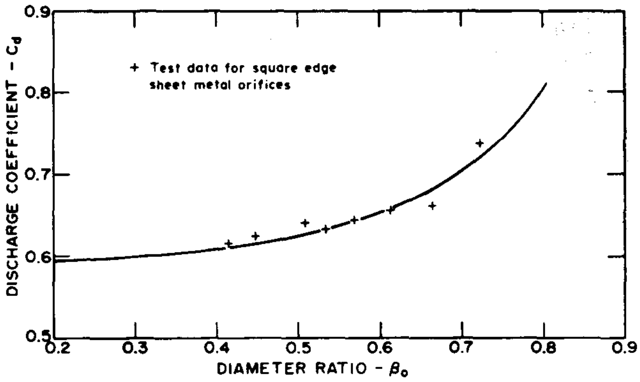

Fig. 7—Published values of the discharge coefficient C_d as a function of β_o for square edge orifices in the orifice N_R range from 2 to 2.5 x 10^5 with data from the laboratory tests for square edge sheet metal orifices superimposed.

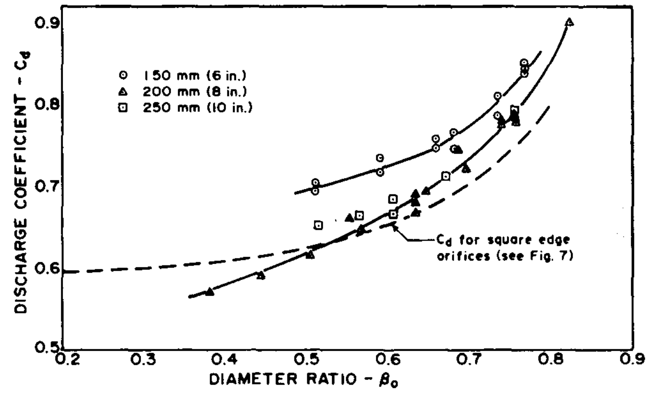

Fig. 8—Discharge coefficient C_d for irrigation sheet metal orifices tested in the laboratory as a function of β_o; the curve for square edge orifices is shown for comparison.

equation [12], and since R is apparently the same for all orifices, any differences between K_o for square edge orifices and those made for irrigation energy dissipation must result from differences in the discharge coefficient C_d.

Discharge coefficient: Published values of the coefficient of discharge C_d for orifice Reynolds numbers N_R in the range from 2 to 2.5 x 10^5 (Baumeister, 1967; Brater and King, 1976 and Rouse, 1950) are shown by the curve in Fig. 7 as a function of β_o. These coefficients all include the velocity of approach factor $1/[1-\beta_o^4]^{0.5}$. The coefficient C_d for the square edge orifices tested in the laboratory was determined from a rearranged form of equation [7] where

$$C_d = V_o/(2g\Delta H)^{0.5} \quad [16]$$

These data superimposed upon the curve in Fig. 7 show that the discharge coefficient for square edge orifices placed in irrigation couplings is similar to that for square edge orifices installed under more exacting conditions. The effects of coupling geometry and pipe discontinuity at the couplings are apparently relatively small, particularly, at low values of β_o. They would be expected to increase as β_o increases such that the flow streamlines are closer to the coupling boundary in the vicinity of the orifice plate.

A discharge coefficient, C_d, for the irrigation orifice plates was determined from equation (12) where

$$C_d = (R/K_o)^{0.5} \quad [17]$$

which combined with equation [15] gives

$$C_d = [(1-0.9\beta_o^{1.7})/K_o]^{0.5} \quad [18]$$

Equation [18] was used rather than equation [16] for the irrigation orifices because ΔH was not available from the test data for many of the runs. The discharge coefficient for the irrigation orifices is shown in Fig. 8 along with the curve for square edge orifices from Fig. 7 for comparison. As noted in the figure, the coefficient for 150 mm pipes was different from that for the 200 and 250 mm pipes. Except for three data points for small orifices, the coefficient is generally higher than for square edge orifices. This is as expected because the slight rounding of the edge of the orifice opening resulting from shop construction compared to an exact square edge, decreases the flow contraction through the orifice, and results in a higher discharge coefficient. For irrigation applications, orifices with β_o values less than about 0.5, would seldom be used because of their severe flow restriction.

The head loss coefficient K_o for square edge orifices calculated from published values of C_d with a rearrangement of equation [18] is shown in Fig. 9 where

$$K_o = (1-0.9\beta_o^{1.7})/C_d^2 \quad [19]$$

Correspondingly, coefficients from the laboratory tests for square edge orifices are also shown. This shows the close agreement between the loss for square edge orifices installed in irrigation couplings and that for flow measurement orifices. The curve from Fig. 9 is also shown in Fig. 4 for comparison. Fig. 4 shows that the

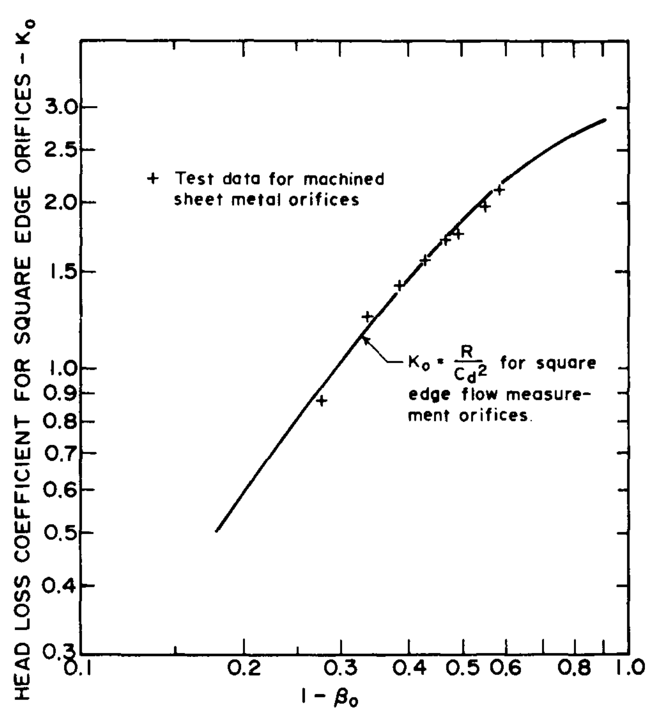

Fig. 9—Head loss coefficient K_o for square edge orifices determined from published values of C_d in the orifice N_R range from 2 to 2.5 x 10^5 with data from the laboratory tests for square edge orifices superimposed.

head loss for orifices that are not square edged, such as the irrigation orifices, can vary significantly from that for square edge orifices. Values of C_d from Fig. 8 can be used with the diameter ratio as in equation [19] to estimate the head loss coefficient for commonly-made sheet metal orifices.

Hydraulic Gradeline Depression

Orifice plates convert pressure head to velocity head as water flows through the orifice openings. Consequently, the pipe pressure immediately downstream from an orifice, near the vena contracta, is reduced beyond that represented by the head loss and is lower than that further downstream, as shown in Fig. 2. This reduces the flow from outlets or gates that may be located in this section of pipe. To minimize this effect, it is best to use orifices with either relatively large or relatively small diameter ratios. A greater number of orifices with large β_0 values will be required, but they are relatively easy to install and their cost is nominal.

The piezometric head depression, h, is the elevation difference between the actual depressed hydraulic gradeline at a given point downstream from the orifice and its projected elevation at that point when extrapolated upstream from the downstream section of pipe where full velocity head recovery is achieved. By minimizing h when designing energy dissipating orifices, near uniform flow rates from the openings can be achieved with a small adjustment of the pipe gates.

The piezometric head depression is affected by the diameter ratio β_0, velocity head $V_0^2/2g$, distance downstream from the orifice, and to a lesser extent, pipe size. The depression, expressed as the ratio h/H_0 is shown in Fig. 10 for different diameter ratios, β_0. The curves represent average values for all pipe sizes developed for even values of β_0 from cross plottings of the laboratory test data. Distance downstream from the orifice is expressed in pipe diameters. As seen from the figure, the depression can be significant in relation to the head loss up to a distance of about 2½ to 3 pipe diameters downstream where it exceeds about one tenth of the head loss. The depression was related to H_0 for ease of estimation. For practical purposes, a high degree of accuracy is not necessary when estimating h. The depression at the first downstream outlet or gate, which is the primary point of interest, can be estimated by using the curves in Fig. 10 to determine the ratio h/H_0. The depression is calculated from this ratio for a given orifice ratio and distance with H_0 estimated from head loss curves such as those shown in Fig. 5.

Design Procedure

An elevation profile along the pipeline is needed to determine the number, size, and location of orifices to be used in the field. The desirable pressure head along the length of a gated pipe is between 0.3 and 0.7 m (1 to 2 ft). Orifices are selected to maintain this pressure head range. The pressure should be reduced to the required level in the first gated pipe section by using orifices in the conveyance pipe preceding the distribution section. This can be done, if necessary, with orifices having relatively small β_0 values. Using small orifices here minimizes the number needed to maintain the optimum operating pressure at the upstream end of the distribution pipe and also helps to minimize h in the downstream gated pipe sections.

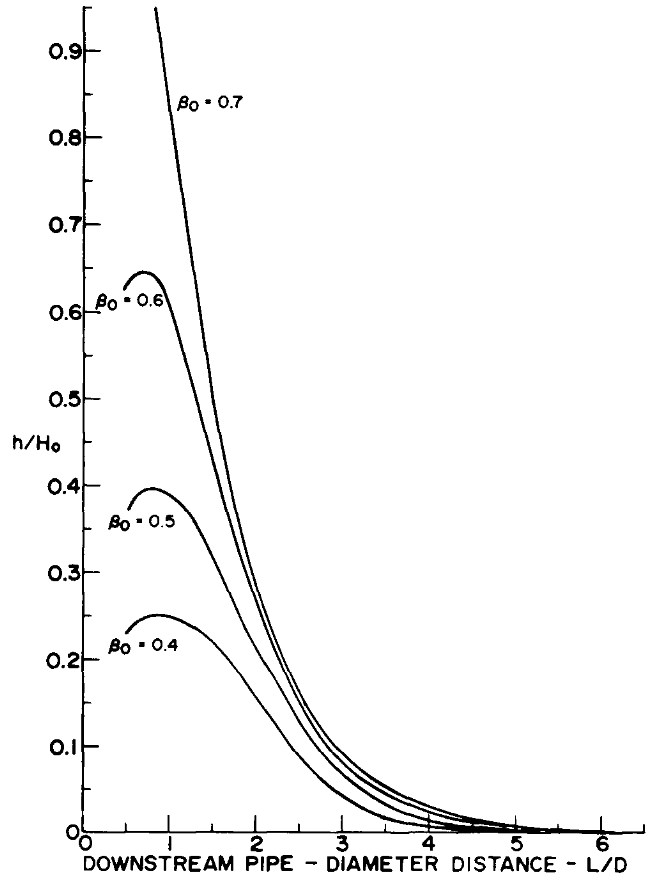

Fig. 10—Piezometric head depression ratio h/H_0 for different diameter ratios β_0 as a function of pipe-diameter distance L/D downstream from an orifice in irrigtion pipelines.

A design example is illustrated in Fig. 11. This is for a design flow of 34 L/s (540 gpm) in 200 mm gated pipe. The hydraulic gradient or slope of the pipe at the design flow is shown with the elevation profile of the pipeline. The design can be accomplished graphically by using a cardboard or plastic template with the upper side sloped to match the hydraulic gradient. The left side is vertical, to correspond to elevation, with marks representing the head loss for several orifices in the size range needed. The range of possible orifice sizes for a particular site or condition can be determined by estimating the head loss desired for one orifice (Fig. 5). Since the orifices are installed in the pipe joints, the loss represented by one orifice must be for a distance represented by a whole number of pipe lengths usually some multiple of 9 m. A trial set of orifice sizes is selected and the hydraulic gradeline depression, h, at the first downstream outlet from the orifice is estimated using Fig. 5 and 10 for the design flow. The larger the orifice sizes, the smaller h will be and the greater the number that will be required. In the example, if h is arbitrarily limited to about 10 cm (0.33 ft) at the first opening, which is 2.5 diameters downstream, then all orifices 120 mm and larger will be satisfactory. When a set of orifice sizes has been selected, their head loss for the design flow is marked on the template. The template is moved downstream from the inlet and parallel to the pipe hydraulic slope line until the accumulated excess elevation head at a pipe joint matches the loss for one of the selected orifices. The hydraulic gradeline is then reduced by that amount and drawn on the chart. This process is repeated such that

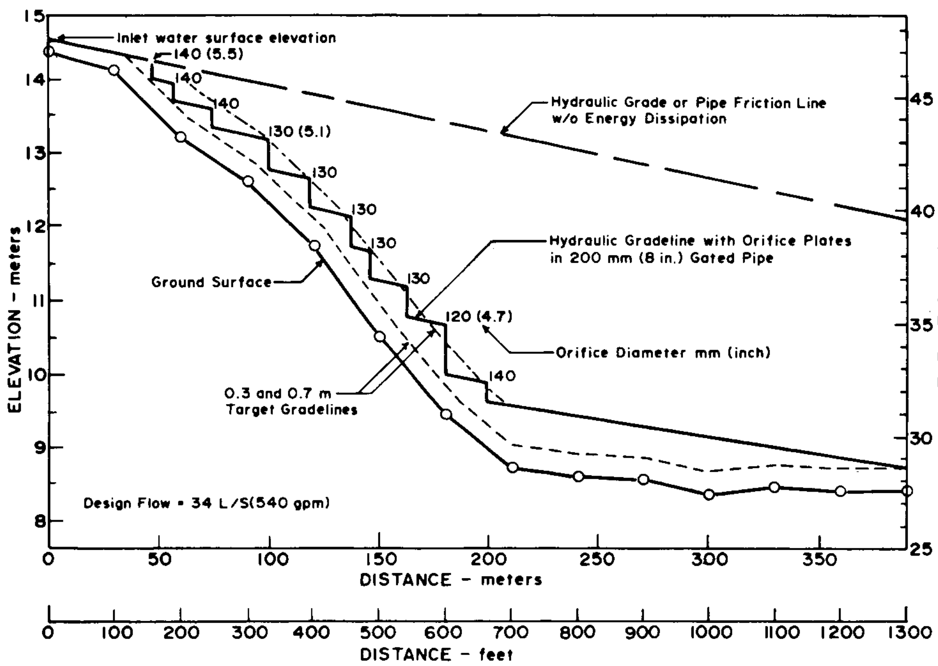

Fig. 11—Design example illustrating hydraulic gradeline reduction in steps or increments with energy dissipating orifices.

the hydraulic gradeline is reduced in steps to within the desired range after each orifice as illustrated in Fig. 11. The graphic design can be quickly checked by numerically summing the loss increments and comparing the elevation of the resulting gradeline to the pipeline elevation at its downstream end.

Maintenance

To minimize rusting of the orifice edge, pipelines should be permitted to drain after each irrigation (this will usually occur naturally with gated pipe) and the orifices stored in a dry place during the off-season.

SUMMARY AND CONCLUSIONS

Orifices placed at intervals in gated pipe couplings can be used to dissipate excess energy and thus minimize erosion caused by high velocity streams discharged from the pipe. The orifice can be made from galvanized sheet metal at most sheet metal shops. Head loss relationships for orifices used in irrigation pipelines for energy dissipation were obtained from laboratory tests. Comparisons were made between the head loss and discharge coefficients for machined square edge orifices and those made for irrigation in sheet metal shops. General conclusions are:

1. Head loss for sheet metal orifices made for irrigation can be predicted using coefficients determined from this study.

2. The head loss coefficient, K_o, can be expressed by an equation of the form $K_o = a\beta_o^b$ where **a** and **b** are empirical constants determined from laboratory tests. K_o is nearly independent of orifice Reynolds number in the range normally encountered in the field (1.2 to 4.0×10^5) and in the mid and lower ranges of the diameter ratio β_o. The coefficient varied less than two percent from the average in the range of Reynolds numbers for the tests.

3. Sheet metal orifices made in sheet metal shops have a slightly rounded edge which results in a higher coefficient of discharge, and a lower head loss coefficient than for machined square edge orifices.

4. The head loss ratio, R, as defined by the ASME (1959) is the same for, (a) square edge orifices used for flow measurement, (b) square edge orifices installed in aluminum irrigation pipeline joint couplings and (c) sheet metal orifices made for irrigation installed in pipe couplings. The ratio can be represented by the equation $R=1\text{-}0.9\,\beta_o^{1.7}$.

5. Square edge orifices in aluminum irrigation pipe couplings behave similarly to those for flow measurement, particularly in the mid and lower ranges of the diameter ratio, β_o. Both the discharge and the head loss coefficients for square edge sheet metal orifices installed in pipe couplings fit the calculated curves for these parameters determined from published values of the discharge coefficient for square edge orifices.

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