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Lloyd N. Austin

RECTANGULAR CUTTHROAT FLOW MEASURING FLUMES

By Gaylord V. Skogerboe[1] and M. Leon Hyatt,[2] Associate Members, ASCE

INTRODUCTION

Procedures and methods for more accurate measurement and improved management of water are continually being sought to make better use of our water resources. Of all the devices and structures developed for measuring water, measuring flumes are among the most widely accepted and used. The most common measuring flume is the Parshall flume[3] developed by Ralph Parshall at Colorado State University.

Common to most flumes is the basic geometry consisting of a converging inlet section, a throat, and a diverging outlet section. Occasionally, the diverging outlet section is removed under free flow conditions, and the water is allowed to jet directly from the throat section into the downstream channel. This is not always permissible, however, in unlined channels because of possible erosion problems.

In flat gradient channels, a flume may be installed to operate under conditions of submerged flow rather than free flow in order to (1) reduce energy losses, and (2) allow placement of the flume on the channel bed to minimize the increase in water surface elevation upstream from the flume. The purpose of the research effort reported herein was to develop a flume which

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[3] Parshall, R. L., "The Improved Venturi Flume," Transactions, ASCE, Vol. 89, 1926, pp. 841-851.

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would operate satisfactorily under both free flow and submerged flow conditions.

DEVELOPMENT OF FLUME

Previous studies by Robinson and Chamberlain[4] and Hyatt[5] indicate that a flume having a flat bottom is satisfactory for both free flow and submerged flow operation. The advantages of a level flume floor are that (1) it can be easily constructed, (2) it can be placed inside a concrete-lined channel, and (3) it can be placed on the channel bed.

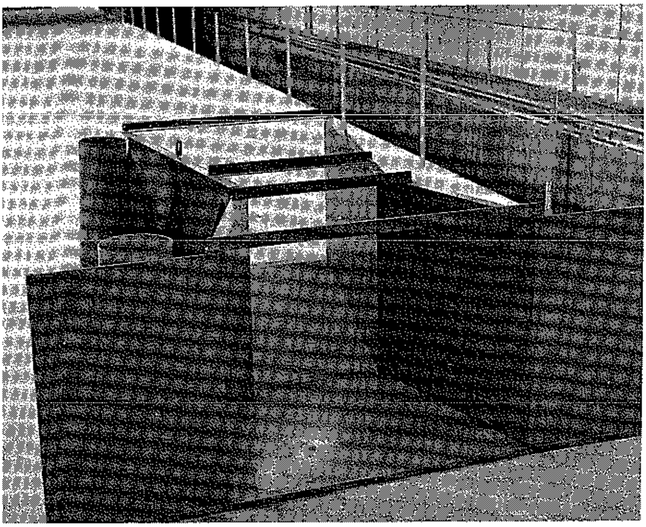

FIG. 1.—FINAL DESIGN OF 2-FT RECTANGULAR CUTTHROAT FLUME INVESTIGATED IN THE LABORATORY

Ackers and Harrison[6] recommend a maximum convergence of 3:1 for a flume inlet section. Experimental work by the writers[5,7] indicated that this

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[4] Robinson, A. R., and Chamberlain, A. R., "Trapezoidal Flumes for Open Channel Flow Measurement," Transactions, American Society of Agricultural Engineers, St. Joseph, Mich., Vol. 3, No. 2, 1960, pp. 120-124, 128.

[5] Hyatt, M. L., "Design, Calibration, and Evaluation of a Trapezoidal Measuring Flume by Model Study," thesis presented to the Utah State University, at Logan, Utah, in Mar., 1965, in partial fulfilment of the requirements for the degree of Master of Science.

[6] Ackers, P., and Harrison, A. J. M., "Critical-Depth Flumes for Flow Measurement in Open Channels," Hydraulics Research Paper No. 5, Hydraulics Research Station, Department of Scientific and Industrial Research, Wallingford, Berkshire, England, 1963.

[7] Skogerboe, G. V., Hyatt, M. L., and Eggleston, K. O., "Design and Calibration of Submerged Open Channel Flow Measurement Structures: Part 1, Submerged Flow," Report WG 31-2, Utah Water Research Laboratory, College of Engineering, Utah State University, Logan, Utah, Feb., 1967.

recommendation had merit, and consequently a 3:1 convergence was used in developing a flat-bottomed flume.

Studies regarding the length of the throat section[7] showed that flow depths measured in the exit section of the flume resulted in more accurate submerged flow calibration curves than calibrations employing flow depth measurements in the throat section. The water surface profile fluctuates rapidly in the throat section as compared with the exit section where the water surface profile is more nearly horizontal. Consequently, a flow depth in the exit section of the flat-bottomed flume was selected for measurement.

Earlier studies[3] indicated that when the divergence of the flume exit section exceeded 6:1, flow separation would occur, and a major portion of the flow would adhere to one of the sidewalls. Although numerous angles of divergence and lengths of exit section were tested,[7] the 6:1 divergence proved most satisfactory as a balance between flow separation and fabrication costs.

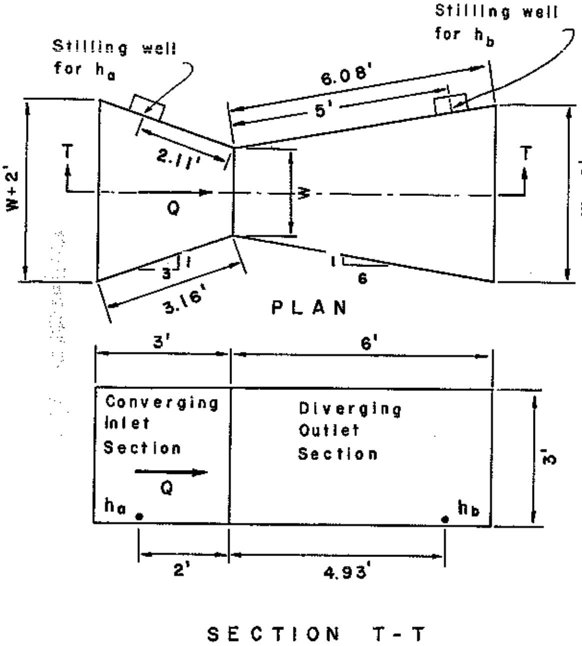

FIG. 2.—PLAN AND SECTIONAL VIEW OF RECTANGULAR CUTTHROAT MEASURING FLUMES

Since the downstream flow depth was to be measured in the exit section, there appeared no apparent advantage in having a throat section. Thus, testing was initiated with a flat-bottomed flume having only an entrance and an exit section.[8] The flume performed very well. One distinct advantage of re-

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[8] Skogerboe, G. V., Hyatt, M. L., Anderson, R. L., and Eggleston, K. O., "Design and Calibration of Submerged Open Channel Flow Measurement Structures: Part 3, Cutthroat Flumes," Report WG 31-4, Utah Water Research Laboratory, College of Engineering, Utah State University, Logan, Utah, Apr., 1967.

moving the throat section was improved flow conditions in the exit section. The converging inlet section tended to confine the flow into a jet which traveled along the flume center line, thus assisting in the prevention of flow separation.

The rectangular flat-bottomed flume that resulted from the testing program is shown in Fig. 1. Since the flume has no throat section (zero throat length), the flume was given the name "cutthroat" by the writers.

The most obvious advantage of a cutthroat flume is economy, since fabrication is facilitated by a flat bottom and removal of the throat section. Another advantage is that every flume size has the same wall lengths in both the entrance and exit sections, allowing the same forms or patterns to be used for any flume size. The use of a consistent geometric shape allows accurate predictions of discharge ratings for intermediate flume sizes.

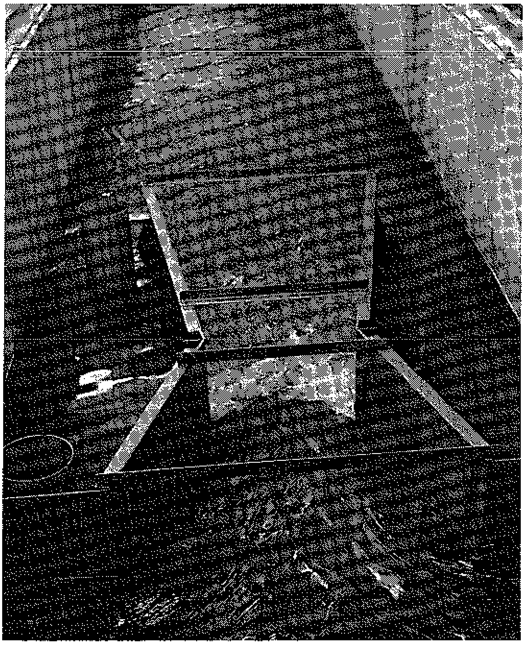

FIG. 3.—TWO-FOOT RECTANGULAR CUTTHROAT FLUME OPERATING UNDER FREE FLOW CONDITIONS

The cutthroat flume can operate either as a free or submerged flow structure as indicated herein. Submerged flow calibration curves and free flow equations are developed and their use illustrated for the rectangular cutthroat flumes studied. The technique for preparing submerged flow ratings has been previously described by the writers.[9] Explanation and examples

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[9] Skogerboe, G. V., and Hyatt, M. L., "Analysis of Submergence in Flow Measuring Flumes," Journal of the Hydraulics Division, ASCE, Vol. 93, No. HY4, Proc. Paper 5348, July, 1967, pp. 183-200.

regarding the practical aspects of installing, operating, and maintaining the structures are given.

FLUME DIMENSIONS

The cutthroat flume consists of a converging inlet section and a diverging outlet section (Fig. 2). The one varying dimension indicated in Fig. 2 is the flume size or throat width, W. The lengths of the converging and diverging sections are the same for each flume size, as well as the location of the points for upstream depth measurement, h_a, and downstream depth measurement, h_b. Rectangular cutthroat flume sizes of 1, 2, 3, 4, and 6 ft were studied and tested in the laboratory. The height used for a given structure would depend upon the stage-discharge relationship of the conveyance channel, and the flow conditions under which the flume would operate.

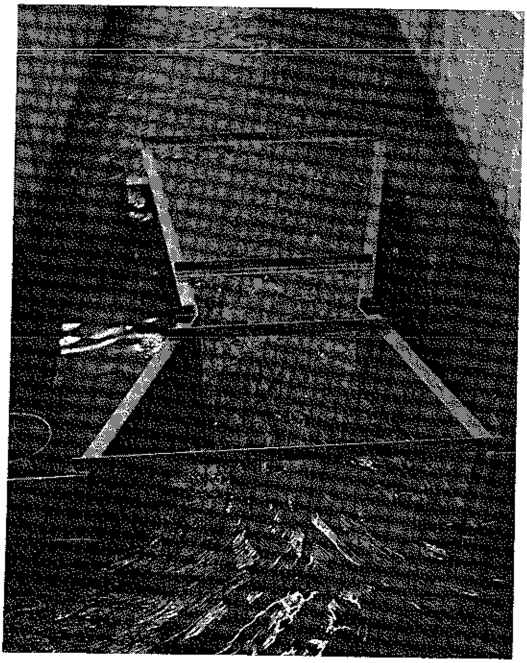

FIG. 4.—TWO-FOOT RECTANGULAR CUTTHROAT FLUME OPERATING UNDER SUBMERGED FLOW CONDITIONS

DEFINITION OF FLUME OPERATION

The two most significant flow regimes, or flow conditions, under which the flume may operate are free flow and submerged flow. The distinguishing difference between the two is the occurrence of critical depth in the vicinity of the flume neck for the free flow condition. This critical flow control requires only the measurement of a flow depth at some location upstream from the point of critical depth to obtain the free flow discharge. The location selected for measuring the upstream depth, h_a, is two-thirds the length of the converging section upstream from the flume neck (Fig. 2). A 2-ft rectangular cutthroat flume operating under free flow conditions is shown in Fig. 3.

When the downstream, or tailwater, depth is raised to the extent that the flow depths at every point through the structure become greater than critical depth, then the flume is operating under submerged (subcritical) flow conditions. With subcritical flow, an increase in tailwater depth will result in an increased upstream depth. A flume operating under submerged flow requires that two flow depths be measured, one upstream (h_a) and one downstream (h_b) from the flume throat (Fig. 2). The definition given to submergence, S, is the ratio, often expressed as a percentage, of the downstream depth to the upstream depth, $S = h_b/h_a$. Fig. 4 is a 2-ft rectangular cutthroat flume operating under submerged flow conditions.

TABLE 1.—TRANSITION SUBMERGENCES FOR RECTANGULAR CUTTHROAT FLUMES

Flume Size, W, in feet (1)	Transition Submergence, S_t, in percentage (2)	Flume Size, W, in feet (3)	Transition Submergence, S_t, in percentage (4)
1	79	3	85
1.5	81	4	86
2	83	5	87
2.5	84	6	88

Upon occasion, flumes designed initially to operate under free flow conditions become submerged, either due to unusual operating conditions downstream or the accumulation of moss and/or vegetation in the channel. Care always should be taken to note the operating condition of the flume in order to determine whether the free flow equation or the submerged flow curves should be used. The value of submergence at which free flow changes to submerged flow, or vice versa, is referred to as the transition submergence, S_t. At this transition state, the discharge given by the free flow equation is exactly the same discharge as that given by the submerged flow calibration curves or equation, if such is known. Hence, if discharge equations are known for both the free and submerged flow conditions, a definite value of the transition submergence can be obtained by setting the equations equal to one another.[9]

Evaluation of the laboratory data for rectangular cutthroat flumes ranging in size from 1 to 6 ft resulted in the S_t's in Table 1. When the submergence, h_b/h_a, for any given flume size exceeds the S_t given in Table 1, the flow is subcritical (submerged) and the submerged flow calibration curves must be used to determine the discharge. When the submergence value does not exceed the limit given in Table 1, then critical depth (free flow) occurs in the flume and the free flow equation (Eq. 3) should be used to obtain the discharge.

The difference between free flow, S_t, and submerged flow water surface

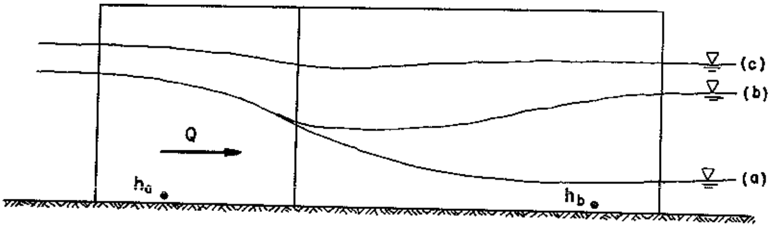

FIG. 5.—ILLUSTRATION OF FLOW REGIMES IN A RECTANGULAR CUTTHROAT FLUME

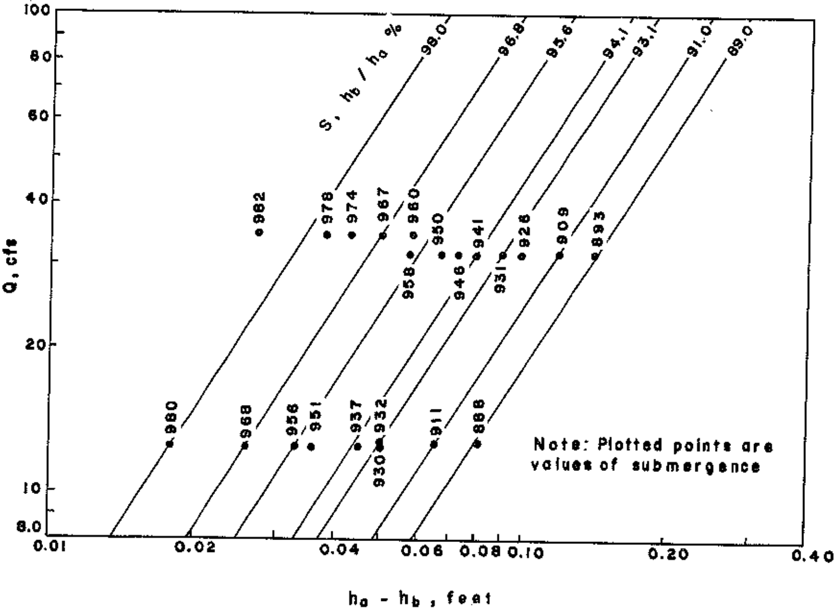

FIG. 6.—SUBMERGED FLOW DATA AND CALIBRATION CURVES FOR 6-FT RECTANGULAR CUTTHROAT FLUME

profiles for the cutthroat flume is illustrated in Fig. 5. The discharge is constant. Water surface profile (a) illustrates free flow, whereas profile (b) indicates the S_t condition. Both profiles have the same upstream depth of flow. Profile (b) has a maximum submergence value for which the free flow condition can exist in the flume. The submerged flow condition is illustrated by profile (c), where an increase in the tailwater depth has also increased the depth of flow upstream from the flume.

FREE FLOW OPERATION

Under free flow conditions, the discharge, Q, through a cutthroat flume depends only upon the upstream depth of flow. Analysis of the free flow data collected in the laboratory for rectangular cutthroat flumes resulted in the following basic form of the free flow equation

$$Q = C\,h_a^{1.56} \qquad (1)$$

The value of C for each size of flume may be obtained from

$$C = 3.50\,W^{1.025} \qquad (2)$$

where W is the throat width in feet. By combining Eqs. 1 and 2, the free flow discharge in second-feet (cfs) can be obtained for rectangular cutthroat flumes having throat widths between 1 ft and 6 ft.

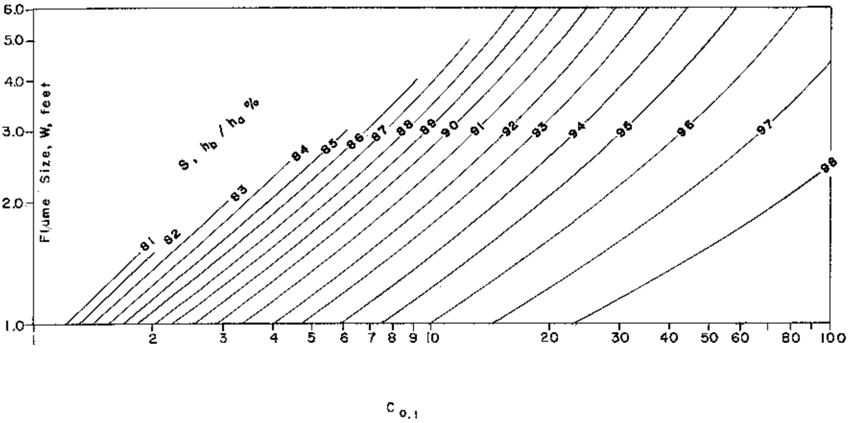

FIG. 7.—RELATION BETWEEN FLUME SIZE AND SUBMERGENCE FOR RECTANGULAR CUTTHROAT FLUMES

$$Q = 3.50\,W^{1.025}\,h_a^{1.56} \qquad (3)$$

SUBMERGED FLOW OPERATION

When submerged flow conditions exist, the rate of discharge depends upon both h_a and h_b. The submerged flow calibration curves for the rectangular cutthroat flumes are developed by making a three-dimensional plot of the parameters that describe submerged flow.[9] The calibration curves are developed on logarithmic paper with Q plotted on the ordinate; change in water surface elevation, $h_a - h_b$, plotted along the abscissa; and the submergence,

h_b/h_a, as the varying parameter. A typical submerged flow rating is illustrated in Fig. 6 in which the laboratory data for the 6-ft rectangular cutthroat flume has been plotted. The lines of constant submergence were drawn to best fit the data and resulted in slopes of 1.56, the same slope as given by the free flow equation (Eq. 1).

Submerged flow calibration curves were developed from the collected data for the rectangular cutthroat flumes of throat width of 1 ft, 2 ft, 3 ft, 4 ft, and 6 ft.[8] By interpolation, calibration curves were obtained for flume widths of 1.5 ft, 2.5 ft, and 5 ft.[8]

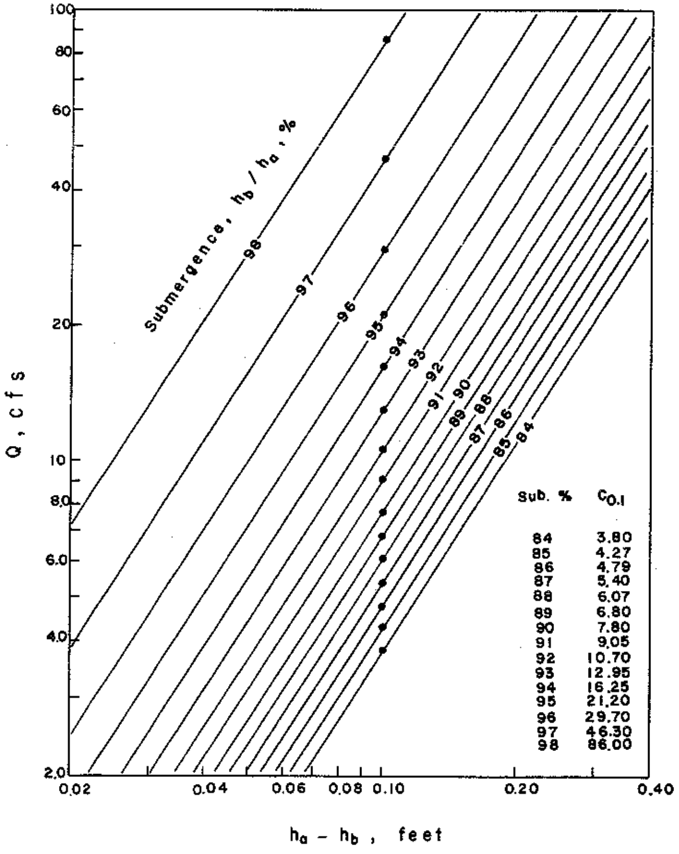

FIG. 8.—DEVELOPMENT OF SUBMERGED FLOW CALIBRATION CURVES FOR 2.2-FT RECTANGULAR CUTTHROAT FLUME

Submerged flow calibration curves can also be developed for any width, W, between 1 ft and 6 ft by using a three-dimensional logarithmic plot (Fig. 7). The quantity $C_{0.1}$ is the numerical value of Q at the intercept of S and h_a - h_b equal to 0.10 ft. Development of submerged flow calibration curves from Fig. 7 can best be illustrated by an example.

Example.—A set of submerged flow calibration curves is desired for a rectangular cutthroat flume with a width, W, of 2.20 ft. The value of $C_{0.1}$ corresponding to each of the lines of constant submergence in Fig. 7 is tabulated in Fig. 8. The values of $C_{0.1}$ (Q) are plotted on a vertical line in Fig. 8 for h_a - h_b equal to 0.10 ft. The lines of constant submergence are drawn through the points at a slope of 1.56 and labeled with the corresponding submergence value to complete the submerged flow calibration curves for the 2.2-ft rectangular cutthroat flume.

FLUME INSTALLATION

Any water measuring device must be properly installed to yield adequate results. The first consideration prior to installing a flume is the location or site of the structure. The flume should be placed in a straight section of channel. Proper installation requires that the flume be aligned straight with the channel and should be level longitudinally and laterally. If operating conditions require frequent changing of the discharge, the flume may be conveniently located near a point of diversion or regulating gate.

After the site has been selected for the flume, it is necessary to determine certain design criteria. The maximum quantity of water to be measured, the depth of flow necessary to obtain this discharge, and the allowable head loss through the flume must be determined. For design purposes, the head loss may be taken as the change in water surface elevation between the flume entrance and exit, h_a - h_b. The downstream depth of flow will remain essentially the same after installation of the flume as it was prior to installation, but the upstream depth will increase by the amount of head loss. The allowable increase in upstream depth may be limited by the height of canal banks upstream from the flume. Such a limiting condition may require increasing the flume size, or operating the flume as a submerged flow structure. Economic factors usually play a determining role in the flume size selected.

Measurements may be made in the flume by the use of staff gages or stilling wells. The use of staff gages under submerged flow conditions will usually result in accuracies worse than 5%. When used, a staff gage should be set vertically at the specified location for h_a and h_b along the converging or diverging wall. The staff gage must be carefully referenced to the elevation of the flume bottom. Use of stilling wells is recommended, however, for accuracies within 5%. Stilling wells have the advantage of providing a calm water surface compared with the fluctuation or "bounce" of the water surface that may exist within the flume. Stilling wells are also necessary if continuous recording instruments are to be used. Under submerged flow conditions, two stilling wells placed adjacent to each other are very desirable and facilitate the use of a double head recording instrument for obtaining a continuous record with time of h_a and h_b.

Free Flow Installation.—If circumstances allow, it is preferable to have a flow measuring device operate under free flow conditions. The obvious advantage is that only an upstream flow depth need be measured to determine the discharge. The procedure to follow for installing a cutthroat flume to operate under free flow conditions is listed below.

1. Ascertain the maximum flow rate to be measured.

2. At the site selected for installing the flume, locate the high water line on the canal bank and determine the maximum depth of flow.

3. Using the free flow equation (Eq. 3), compute the depth of water that corresponds to the maximum discharge capacity of the canal.

4. Place the floor of the flume at a depth which does not exceed the transition submergence multiplied by h_a ($S_t \times h_a$) below the high water line. Generally, the flume bottom should be placed as high in the canal as grade and other conditions permit to insure free flow.

Example.—Placement of the 2.2-ft flume (Fig. 9) to operate free flow is desired in a canal with a maximum discharge of 26.0 cfs. The corresponding value of h_a is 2.15 ft. Multiplying h_a by S_t (0.83 from Table 1) gives a depth to the flume floor of 1.78 ft. Hence, the flume floor should be set no lower than 1.78 ft below the original maximum water surface (Fig. 9) and the head loss is 0.37 ft. A larger flume can be used if the head loss is too great.

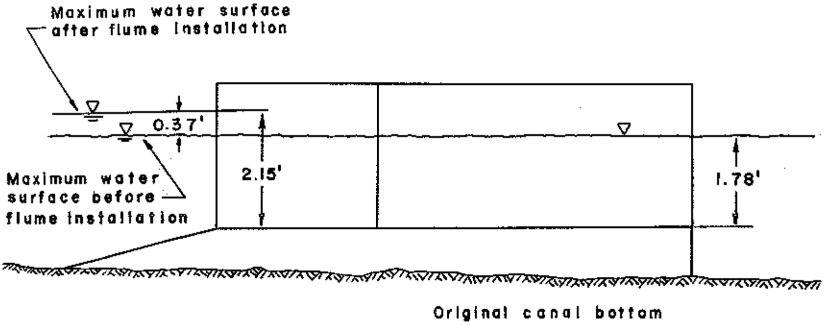

FIG. 9.—INSTALLATION OF 2.2-FT RECTANGULAR CUTTHROAT FLUME TO OPERATE UNDER FREE FLOW CONDITIONS

Submerged Flow Installation.—The existence of certain conditions, such as insufficient grade or the growth of moss and vegetation, sometimes makes it impossible or impractical to install a flume to operate under free flow conditions. Where such situations exist, a flume may be set in the canal to operate under submerged flow conditions. The prinicpal advantage of submerged flow operation is the smaller head loss which occurs in the flume as compared with free flow. When the flat-bottomed cutthroat flumes are installed to operate under submerged flow conditions, the flume floor may be placed level on the canal bottom. This placement will allow quicker drainage of the canal section and reduced seepage losses upstream from the flume, particularly for the flow rates which are less than the maximum discharge. The following is illustrative of the procedure to follow in placing a cutthroat flume to operate under submerged flow conditions.

1. Establish the maximum flow rate to be measured.

2. On the canal bank, where the flume is to be installed, locate the high water line to determine the maximum flow depth.

3. Giving consideration to the amount of freeboard in the canal at maximum discharge and maximum flow depth, determine how much higher the

water surface can be raised in the canal upstream from the flume location.

4. Select the required size of flume from the general submerged flow curves (Fig. 7). With the floor of the flume being placed at essentially the same elevation as the bottom of the canal, the maximum depth of flow (item 2) becomes h_b, and the additional amount that the water surface in the canal can be raised (item 3), becomes $h_a - h_b$. Using this information, the submergence, h_b/h_a, can be computed. Knowing $h_a - h_b$ and h_b/h_a, the flume size can be selected from the submerged flow curves. The procedure for selecting the flume size can be illustrated with the following example.

Example.—The site selected for a rectangular cutthroat flume is a canal with a maximum discharge of 28 cfs. The maximum depth of water in the canal corresponding to this flow rate is 1.8 ft. With the amount of existing freeboard in the canal, it is felt that the water surface should not be raised more than 0.2 ft, thereby resulting in a maximum flow depth of 2.0 ft (1.8 + 0.2 = 2.0) upstream from the flume after installation. Therefore, for purposes of selecting the flume size, $h_b = 1.8$ ft; $h_a = 2.0$ ft; $h_a - h_b = 0.20$ ft; $h_b/h_a = 1.8/2.0 = 0.90 = 90\%$. The equation for a line of constant submergence in a submerged flow calibration plot (e.g. Fig. 6) can be written as

$$Q = K(h_a - h_b)^{1.56} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where K is a function of both submergence and flume size. For the specified conditions listed above, $K = Q/(h_a - h_b)^{1.56} = 28/(0.20)^{1.56} = 344.8$. In order to use Fig. 7, $C_{0.1}$ must be computed. By definition, $C_{0.1}$ is the discharge intercept for $h_a - h_b$ equal to 0.10 ft. Hence, $Q = 344.8\ (h_a - h_b)^{1.56}$; $C_{0.1} = 344.8\ (0.10)^{1.56} = 9.52$. Thus, enter Fig. 7 with $C_{0.1}$ equal to 9.52 and move vertically upward to the submergence line of 90%, and read the flume size to the left as 2.6.

MAINTENANCE OF CUTTHROAT FLUMES

Once proper installation has been assured, periodic maintenance will insure continued satisfactory operation. Moss which may collect on the flume walls should be removed. Any debris which may collect on the flume floor should be removed. Flume walls of steel may become encrusted and the encrustation should be removed with a steel-wire brush. Once the steel walls are scraped clean, application of asphaltic paint will delay further encrustation.

After a few months of operation, and at the end of the season or year, the flume bottom should be checked to be sure it is still level. Flumes may "settle" or tilt sideways due to improper installation or flume operation. When the settling is minor, the discharge can still be estimated, but with a corresponding decrease in accuracy. For the flume tilting sideways, the adjustment can be made by taking the average of the depths of flow measured on each side of the flume for use in the free flow equation or submerged flow calibration curves.

The usual place for settlement to occur is the exit section because of the channel erosion which occurs immediately downstream from the flume due to the jetting action of the water. In this case, the value of discharge obtained from the h_a or h_a and h_b values will be less than the true discharge. The greater the settlement, the greater the discrepancy between the estimated and true discharge. Satisfactory solutions to this problem include: raising the lower end of the flume so it is again level; placing a new level floor in the flume; or placing a liner in the existing flume and then grouting it into place.

CONCLUSIONS

The dimensions and criteria for constructing rectangular cutthroat flumes are given, and their role in water measurement, along with the advantages of their use are analyzed. The most obvious advantage of a cutthroat flume is economy, since fabrication is facilitated by the flat-bottom and removal of the throat section. Another advantage is that every flume size has the same convergence, divergence, and wall lengths, allowing the same forms or patterns to be used for any flume size. The differences between free flow and submerged flow conditions are described, together with the necessary criteria for determining which flow regime exists. The transition submergences are listed for flume sizes between 1 and 6 ft. The use of a consistent geometric shape has facilitated the development of a general free flow discharge equation for rectangular cutthroat flumes. For this same reason, it has been possible to develop general submerged flow curves for these same flumes.

ACKNOWLEDGMENTS

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APPENDIX.—NOTATION

The following symbols are used in this paper:

C = coefficient in free flow equation;
$C_{0.1}$ = the discharge intercept for a particular submergence value when $h_a - h_b$ is equal to 0.10 ft;
h_a = flow depth at specified location in entrance section of cutthroat flume;
h_b = flow depth at specified location in exit section of cutthroat flume;
K = constant relating discharge and change in water surface elevation;
Q = flow rate or discharge;
S = submergence, which is the ratio of a downstream to an upstream flow depth, where both depths are referenced to a common elevation;
S_t = transition submergence; and
W = throat width.

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KEY WORDS: drainage; flow measurement; flumes; hydraulics; hydraulic structures; irrigation; measuring instruments; open-channel flow; subcritical flow

ABSTRACT: The dimensions and criteria for constructing rectangular cutthroat flumes, their role in water measurement, and the advantages of their use are examined. The differences between free flow and submerged flow conditions are described along with the necessary criteria for determining which flow regime exists. The transition submergences are listed for flume sizes between 1 ft and 6 ft. The general free flow equation and the curves which are used when submerged flow exists in the flumes are presented. Proper installation and maintenance procedures for cutthroat flumes and techniques for measuring flow depths which yield satisfactory results are described.

REFERENCE: Skogerboe, Gaylord V., and Hyatt, M. Leon, "Rectangular Cutthroat Flow Measuring Flumes," Journal of the Irrigation and Drainage Division, ASCE, Vol. 93, No. IR4, Proc. Paper 5628, December, 1967, pp. 1-13.