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Cutthroat Flow Measuring Flumes for Flat Gradient Channels

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CUTTHROAT FLOW MEASURING FLUMES FOR FLAT GRADIENT CHANNELS*

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SUMMARY

The cutthroat flume can operate either as a free or submerged flow structure. Submerged flow calibration curves and free flow equations have been developed. Rectangular cutthroat flume sizes of 1, 2, 3, 4, and 6 feet were studied and tested in the laboratory. Trapezoidal cutthroat flumes having zero (or V-shaped), 6-inch, and 12-inch throat widths were calibrated. The value of transition submergence is listed for each of the rectangular and trapezoidal cutthroat flumes.

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.

The dimensions and criteria for constructing cutthroat flumes are given. Proper installation and maintenance procedures are described, as well as techniques for measuring flow depths which will yield satisfactory results.

RESUME

Le jaugeur "cutthroat"‡ peut fonctionner soit comme jaugeur dénoyé soit comme jaugeur submergé. Les courbes de tarage pour les jaugeurs

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* Le jaugeur "Cutthroat" pour la mesure des débits dans les canaux à pentes faibles.

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‡ Jaugeur dont la section du col a été suppérimée.

submergés et les équations d'écoulement pour les jaugeurs dénoyés ont été développées. Des canaux "cutthroat" à section transversale rectangulaire de 1, 2, 3, et 4, 6 pieds ont été étudiés et testés au laboratoire. Des canaux "cutthroat" à section trapézoïdale ayant au col une largeur de base de zéro pouce (forme en V), 6 pouces et 12 pouces ont été étalonnés. Le rapport entre la hauteur d'eau aval et la hauteur d'eau amont (ou "submergence") est donné pour les jaugeurs "cutthroat" à section rectangulaire et trapézoïdale.

L' avantage le plus évident d'un jaugeur "cutthroat" est l'économie, parce que sa fabric tion est facilitée par un fond plat et l'élimination de la section du col. Un autre avantage est que la longueur des parois à l'amont et à l'aval est la même pour les canaux de toutes les dimensions, ce qui permet d'utiliser les mêmes coffrages pour des jaugeurs de dimensions différentes. L'emploi d'une forme géométrique semblable permet des prédictions exactes des courbes de débit pour les jaugeurs de dimensions intermédiaires.

Les dimensions et les critères pour la construction des jaugeurs "cutthroat" sont donnés. Les procédés d'installation et d'entretien sont décrits, aussi bien que les techniques pour mesurer les hauteurs d'eau qui donneront des résultats satisfaisants.

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

DEVELOPMENT OF FLUME

Previous studies by Robinson and Chamberlain(4) and Hyatt(2) 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.

Ackers and Harrison(1) recommend a maximum convergence of 3: 1 for a flume inlet section. Experimental work(2,5) indicated that this 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(5) showed that 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 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(5), the 6 : 1 divergence proved most satisfactory as a balance between flow separation and fabrication costs.

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(6). The flume performed very well. One distinct advantage of removing the throat section was improved flow conditions in the exit section. The converging inlet section tended to confine the flow into a jet which travelled 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 Figure 1. Since the flume has no throat section (zero throat length), the flume was given the name "cutthroat."

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.

The cutthroat flume can operate either as a free or submerged flow structure. Submerged flow calibration curves and free flow equations have been developed. The technique for preparing submerged flow ratings has been previously described(7). Explanation and examples 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 (Figures 2 and 3). The one varying dimension indicated in Figures 2 and 3 is the flume size or throat width, W. The

* All dimensions given in this paper are in units of the British system of measurement because the flumes were developed empirically using that system. Any conversions to the metric system should be made with caution because conversion constants may enter the transfer equations and the calibration tables may or may not retain the values given in this paper.

lengths of the converging and diverging sections are the same for each type of flume, whether rectangular or trapezoidal, as well as the location of the points for upstream depth measurement, h_a, and downstream depth measurement h_b, for each type. Rectangular cutthroat flume sizes of 1, 2, 3, 4, and 6 feet were studied and tested in the laboratory. Trapezoidal cutthroat flumes having zero (or V-shaped), 6-inch, and 12-inch throat widths were calibrated. 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.

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.

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. The definition given to submergence, S, is the ratio, often expressed as a percentage, of the downstream depth to the upstream depth, $S=h_b/h_a$.

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(7).

Evaluation of the laboratory data for cutthroat flumes resulted in the S_t's listed in Tables I and II. When the submergence, h_b/h_a, for any given flume size exceeds the S_t given in Table I or II, 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 limits given in Table I or II, then critical depth (free flow) occurs in the flume and the free flow equations should be used to obtain the discharge.

The difference between free flow, S_t, and submerged flow water surface profiles for the cutthroat flume is illustrated in Figure 4. The discharge is constant. Water surface profile (a) illustrates free flow, whereas

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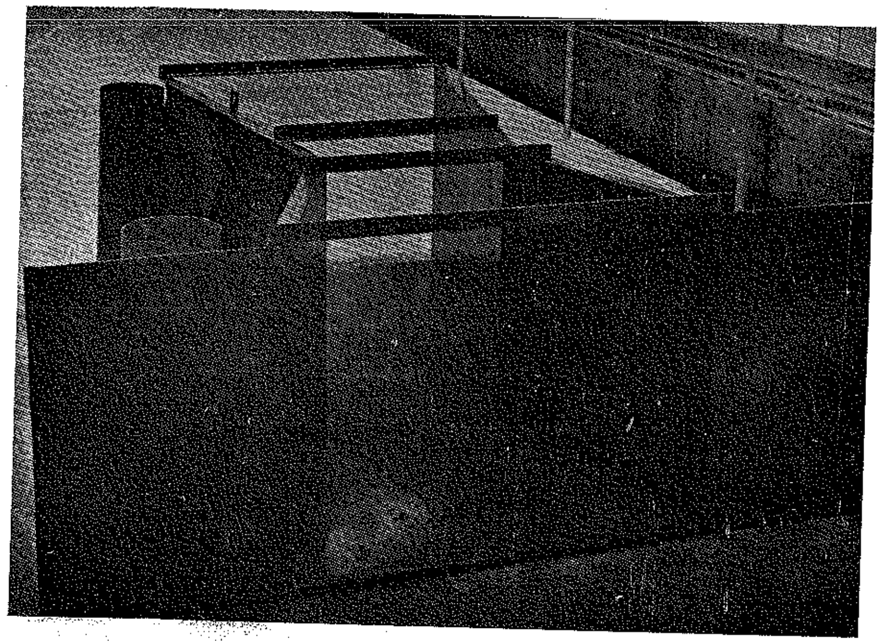

FIGURE 1 : Final design of 2-foot rectangular cutthroat flume.

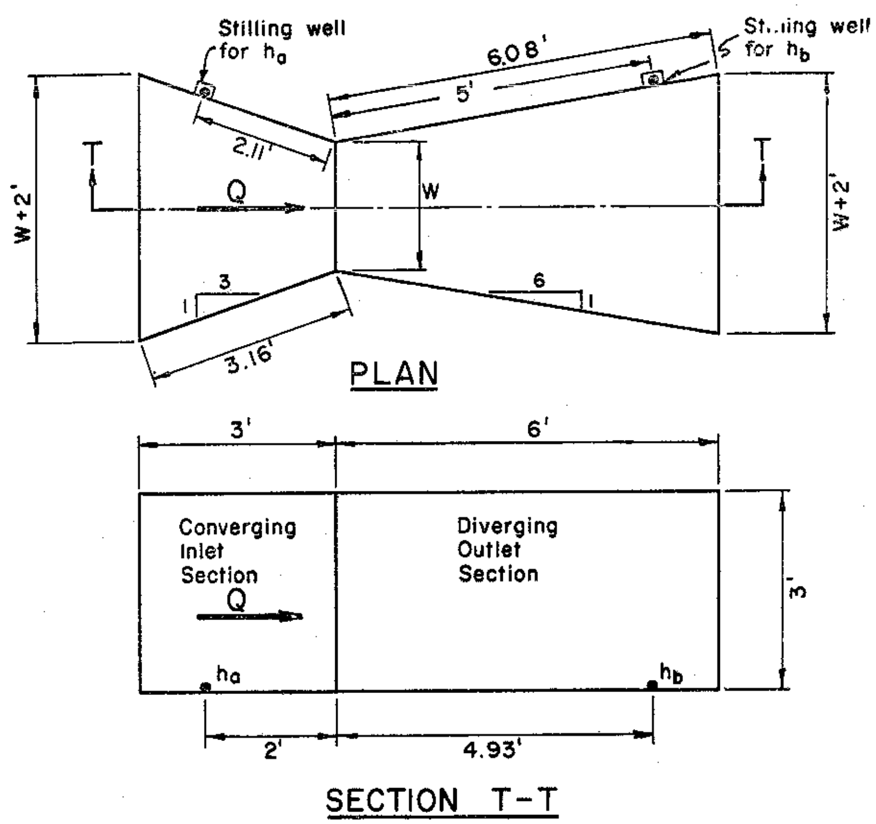

FIGURE 2: Plan and sectional view of rectangular cutthroat measuring flumes.

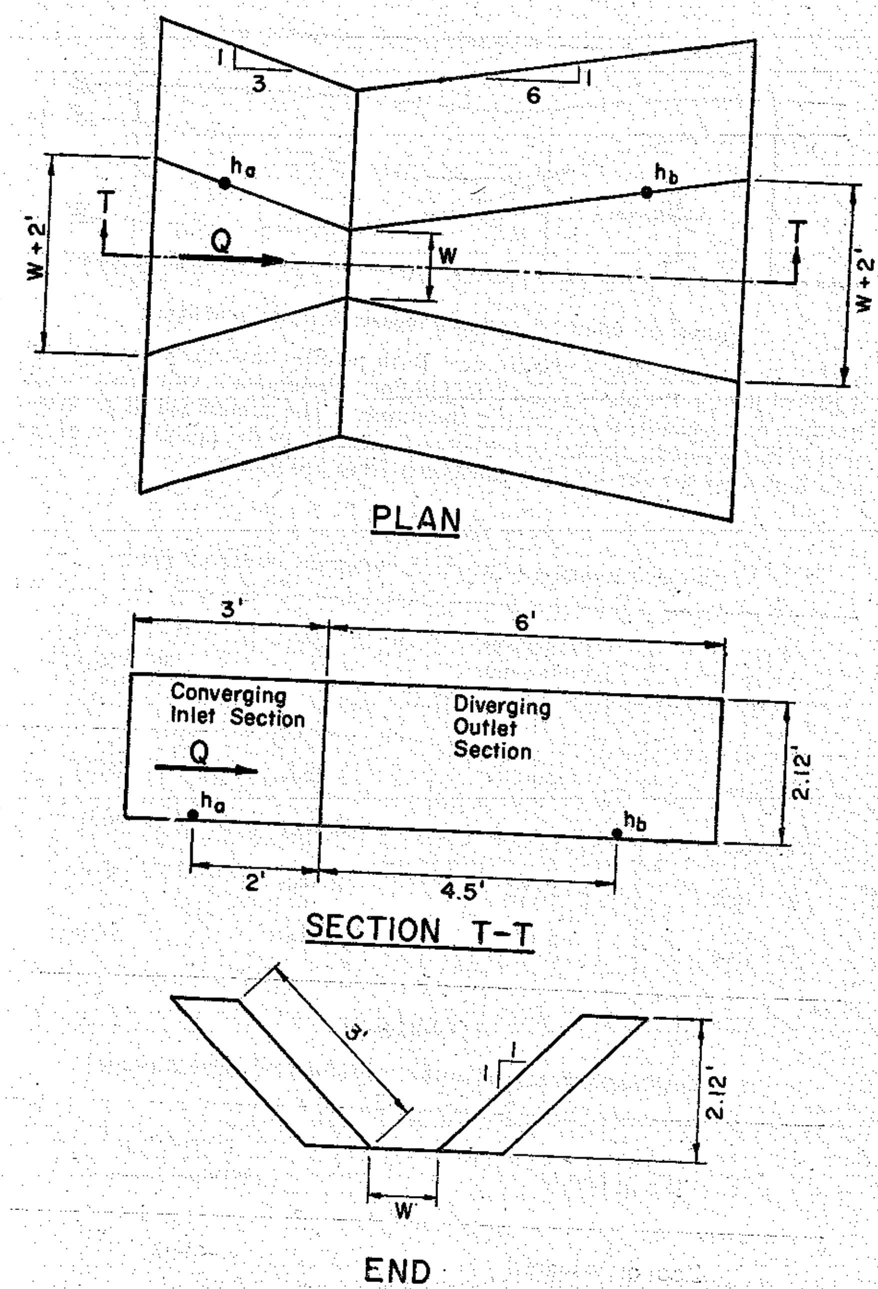

FIGURE 3: Plan, sectional, and end view of trapezoidal cutthroat measuring flume

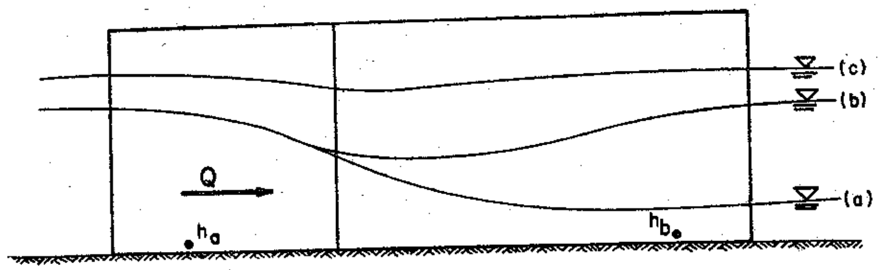

FIGURE 4: Illustration of flow regimes in a cutthroat flume

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.

TABLE I

Transition submergences for rectangular cutthroat flumes

Flume size, W	Transition submergence, S_t	Flume size, W	Transition submergence, S_t
1.0 foot	79%	3 feet	85%
1.5 feet	81%	4 feet	86%
2 feet	83%	5 feet	87%
2.5 feet	84%	6 feet	88%

TABLE II

Transition submergences for trapezoidal cutthroat flumes

Flume throat width	Transition submergence, S_t
Zero or V-shaped	60%
6-inch	76%
12-inch	79%

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

$$Q = C h_a^{1.56} \quad \ldots(1)$$

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

$$C = 3.50\ W^{1.025} \quad \ldots(2)$$

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

$$Q = 3.50\ W^{1.025} h_a^{1.56} \quad \ldots(3)$$

Free flow equations have been developed from laboratory data for the three trapezoidal cutthroat flumes listed in Table II. The free flow equation for the V-shaped flume is

$$Q = 2.57 h_a^{2.53} \quad \ldots(4)$$

For the 6-inch flume, the free flow equation is

$$Q = 3.98 h_a^{2.26} \quad \ldots(5)$$

The free flow equation for the 12-inch flume is

$$Q = 5.48 h_a^{2.02} \quad \ldots(6)$$

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 cutthroat flumes are developed by making a three-dimensional plot of the parameters that describe submerged flow(7). 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.

Submerged flow calibration curves were developed from the collected data for the rectangular cutthroat flumes of throat width of 1 foot, 2 feet, 3 feet, 4 feet, and 6 feet(6). Submerged flow calibration curves can also be developed for any width, W, between 1 foot and 6 feet by using a three-dimensional logarithmic plot (Figure 5). The quantity $C_{0 \cdot 1}$ is the numerical value of Q at the intercept of S and $h_a - h_b$ equal to 0.10 foot. Development of submerged flow calibration curves from Figure 5 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 feet. The value of $C_{0 \cdot 1}$ corresponding to each of the lines of constant submergence in Figure 5 is tabulated in Figure 6. The values of $C_{0 \cdot 1}$ (Q) are plotted on a vertical line in Figure 6 for $h_a - h_b$ equal to 0.10 foot. 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 feet rectangular cutthroat flume.

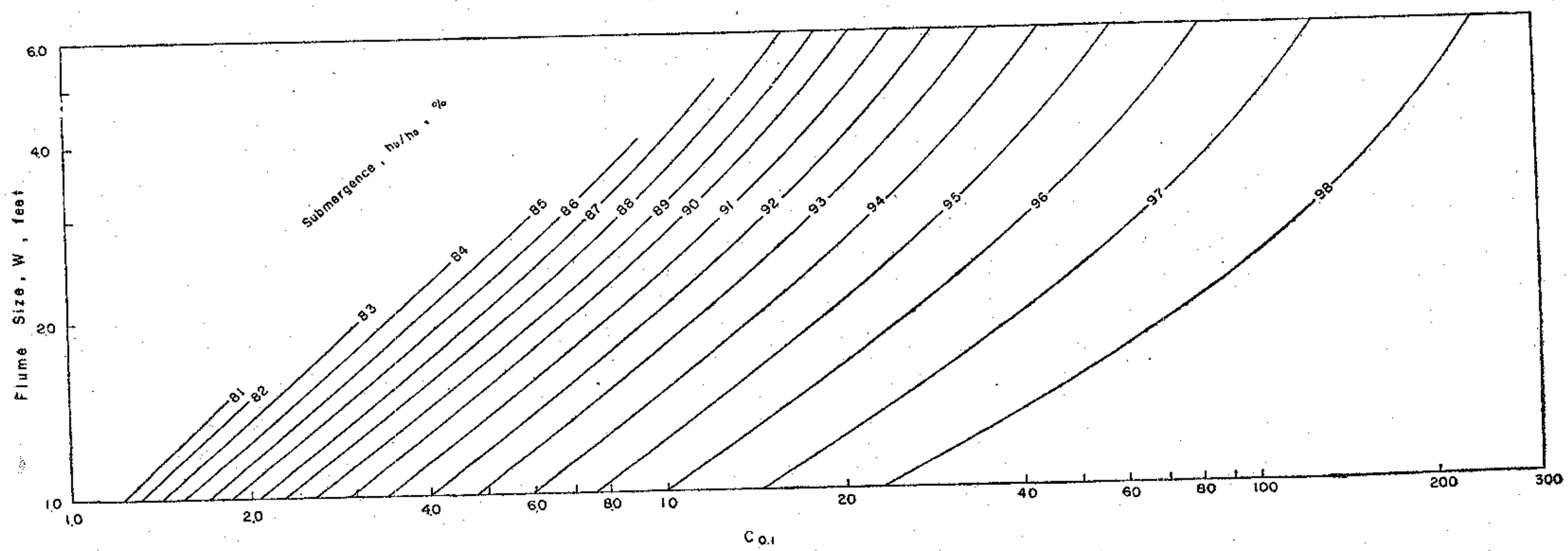

FIGURE 5 : Relation between flume size and submergence for rectangular cutthroat flumes

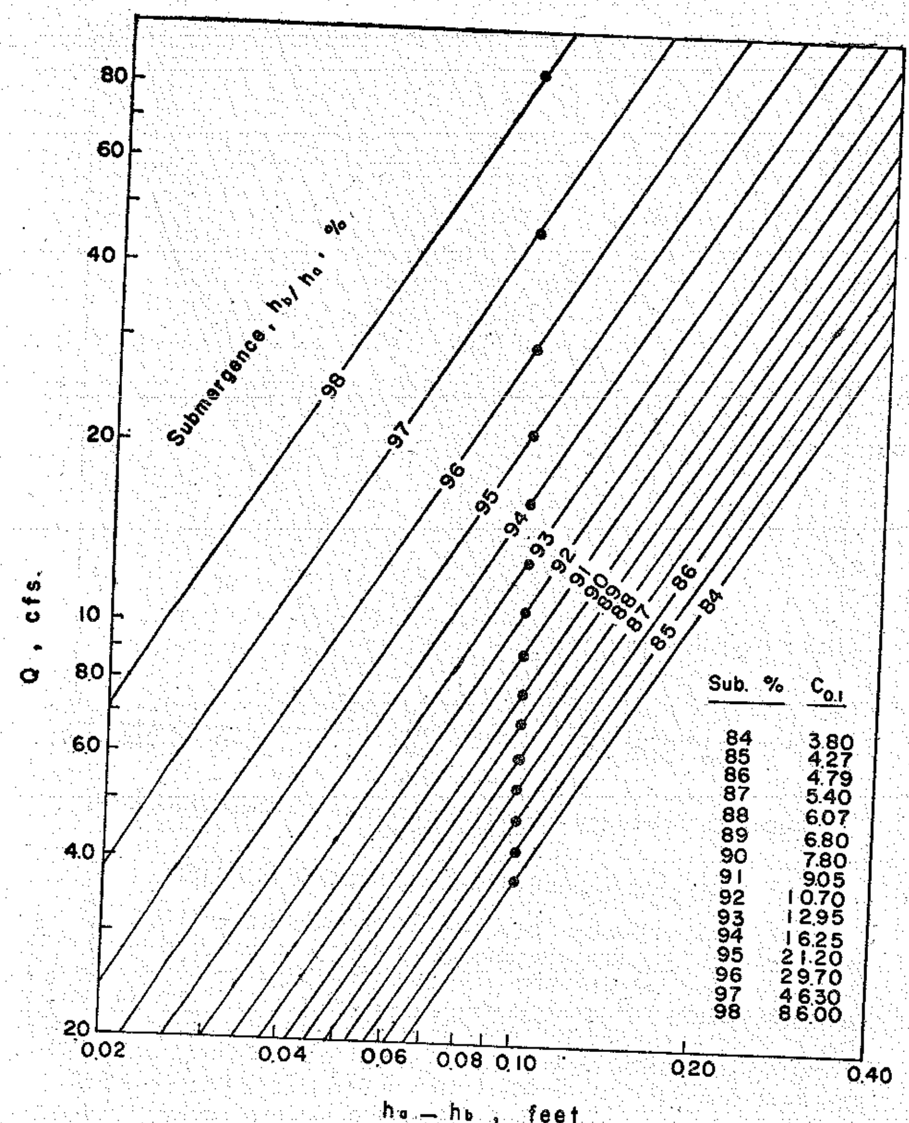

FIGURE 6: Development of submerged flow calibration curves for 2.2 feet rectangular cutthroat flume

Submerged flow calibration curves were developed from laboratory data for the trapezoidal cutthroat flumes listed in Table II. A three-dimensional plot was made of the discharge, Q, plotted as the ordinate; the difference in upstream and downstream depths, h_b/h_a, plotted as the varying parameter. The calibration curves developed for the V-shaped, 6-inch, and 12-inch trapezoidal cutthroat flumes are found in Figures 7, 8, and 9 respectively.

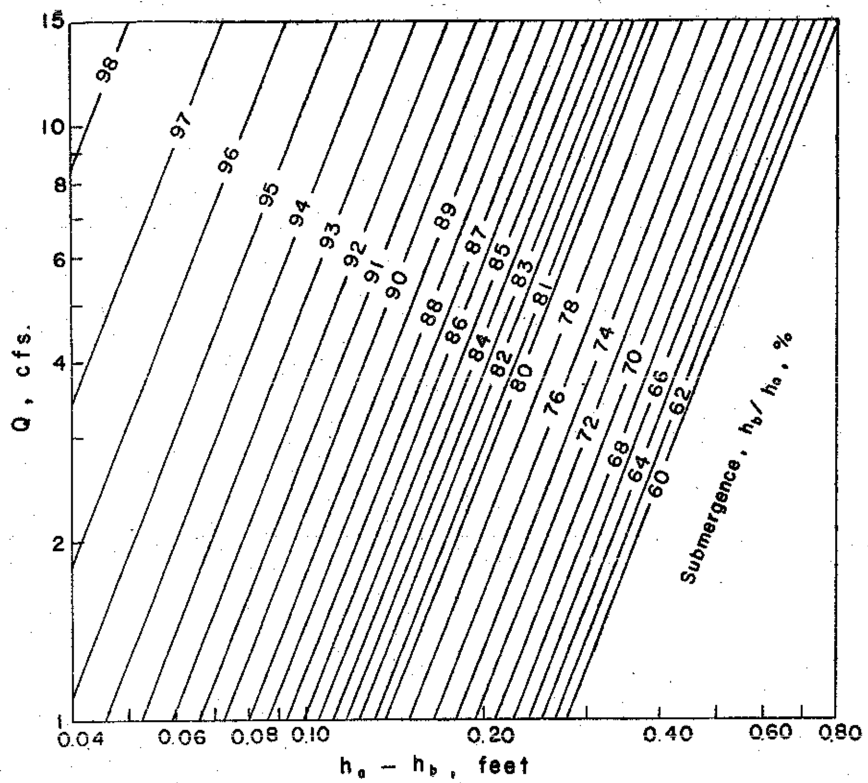

FIGURE 7: Submerged flow calibration curves for V-shaped trapezoidal cutthroat flume.

INSTALLATION OF CUTTHROAT FLUMES

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

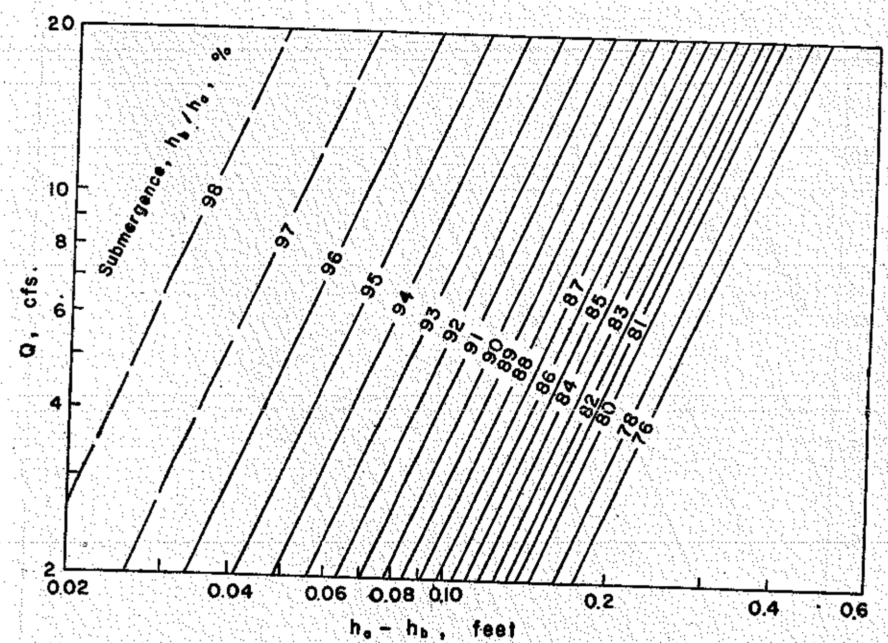

FIGURE 8 : Submerged flow calibration curves for 6-inch trapezoidal cutthroat flume.

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 per cent. 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 per cent. 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.

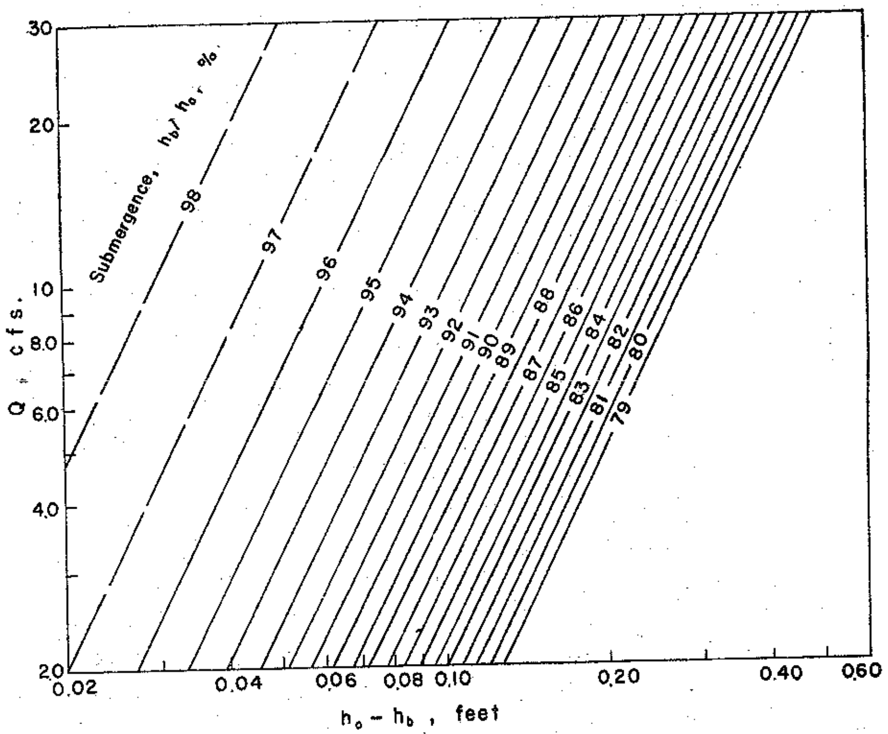

FIGURE 9 : Submerged flow calibration curves for 12-inch trapezoidal cutthroat flume

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 [Equations (3), (4), (5) or (6)], 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 $S_t \times h_a$, the transition submergence multiplied by 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.

SUBMERGED FLOW INSTALLATIONS

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 principal 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 free-board in the canal at maximum discharge and maximum 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 (Figure 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 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.

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. A flume wall 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 and h_b or h_a 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.

ACKNOWLEDGMENTS

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REFERENCES

(1) ACKERS, P., and HARRISON, A. J. M., "Critical-depth flumes for flow measurement in open channels," 1963 Hyd. Res Sta., Deptt of Sci. and Indus. Res., Wallingford, Berkshire, England, Hydr. Res. Paper, No. 5.

(2) HYATT, M. L., "Design, calibration, and evalution 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.

(3) PARSHALL, R. L., "The improved Venturi Flume". ASCE Trans 1926, v. 89, p 841-851.

(4) ROBINSON, A. R., and CHAMBERLAIN, A. R., "Trapezoidal flumes for open channel flow measurement," American Society of Agricultural Engineers Trans. St. Joseph, Mich., 1960, v. 3, n 2, 1960, p 120-124, 128.

(5) 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, Feb., 1967, Utah Water Research Laboratory, College of Engineering, Utah State Uuiversity, Logan, Utah.

(6) SKOGERBOE, G.V., HYATT, M. L., ANDERSON, R. L., and EGGLESTON K. O., "Design and calibration of submerged open channel flow measurement structures: Parts 3, Cutthroat Flumes," Report WG 31-4, Apr. 1967, Ut. Wtr. Res. Lab. College of Engineering, Utah State University, Logan, Utah.

(7) SKOGERBOE, G. V., and HYATT, M. L., "Analysis of submergence in flow measuring flumes," ASCE Journal of the Hydraulics Division, July 1967, v 93, n HY4, Proc. Paper 5348, p 188-200.