January 1967

Design and Calibration of Submerged Open Channel Flow Measurement Structures: Part 3 - Cutthroat Flumes

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Design and Calibration of Submerged

Open Channel Flow Measurement Structures

Part 3

CUTTHROAT FLUMES

OWRR Project No. B-006-UTAH

Matching Grant Agreement No. 14-01-0001-717

Investigation Period — April 1, 1965 to June 30, 1967

Partial technical completion report prepared for

Office of Water Resources Research

United States Department of the Interior

and

Utah Center for Water Resources Research

Utah State University

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April 1967 Report WG31-4

ABSTRACT

DESIGN AND CALIBRATION OF SUBMERGED OPEN CHANNEL FLOW MEASUREMENT STRUCTURES

PART 3, CUTTHROAT FLUMES

Cutthroat flumes having a rectangular or trapezoidal shape have been developed, and their role in water measurement, along with the advantages of their use are discussed. The dimensions and criteria for constructing cutthroat flumes are given. The differences between free flow and submerged flow conditions are discussed, along with the necessary criteria for determining which flow regime exists. The value of transition submergence is listed for each of the rectangular and trapezoidal cutthroat flumes which were investigated in the laboratory. The free flow analysis and tables are presented for the cutthroat flumes studied as are the three-dimensional calibration curves which are used when submerged flow exists in the flumes. Examples are given which illustrate the free and submerged flow operation. Proper installation and maintenance procedures for cutthroat flumes are described, as well as techniques for measuring flow depths which will yield satisfactory results.

Skogerboe, Gaylord V., M. Leon Hyatt, Ross K. Anderson, and Keith O. Eggleston. DESIGN AND CALIBRATION OF SUBMERGED OPEN CHANNEL FLOW MEASUREMENT STRUCTURES: PART 3, CUTTHROAT FLUMES. Research Project Partial Technical Completion Report to Office of Water Resources Research, Department of Interior, and Utah Center for Water Resources Research. Report WG31-4, Utah Water Research Laboratory, College of Engineering, Utah State University, Logan, Utah. April 1967.

KEYWORDS — flow measurement *flow measuring flumes hydraullics hydraulic structures open-channel flow *subcritical flow *submerged flow

ACKNOWLEDGMENTS

The existence of this publication is based on support in part from funds provided by the United States Department of the Interior, Office of Water Resources Research, as authorized under the Water Resources Research Act of 1964, Public Law 88-379. The project providing the information used in this report is a part of the program of the Utah Center for Water Resources Research, Utah State University, Logan, Utah. Thanks and appreciation for this support is here acknowledged.

The cooperation and services of the Utah Water Research Laboratory were invaluable in the publication of this report. Sincere thanks are given Miss Donna Higgins for editing and Mrs. Linda Williams for typing this manuscript.

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NOMENCLATURE

Symbol	Definition
C	coefficient in free flow equation
$C_{0.1}$	the discharge intercept for a particular submergence when h_a - h_b is equal to 0.1
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
h_m	minimum depth of flow in flume
Q	flow rate or discharge
S	submergence, which is the ratio of a downstream to an upstream depth where both depths are referenced to a common elevation
S_t	transition submergence
W	throat width at cutthroat flume neck
π_2	submergence, S
π_3	$(h_a - h_b)/h_m$

APPROACH TO STUDY

Procedure and methods for more accurate measurement and improved management of water are continually being sought for better utilization of our water resources. Many devices and structures have been developed for measuring water, but measuring flumes are one of the most widely accepted and used. The most common measuring flume is the Parshall flume which is discussed in a preceding report (Skogerboe, Hyatt, England, and Johnson, 1967).

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, because of possible erosion problems.

In flat gradient channels, it may be desirable to install a flume to operate under conditions of submerged flow rather than free flow in order to: (1) reduce energy losses, and (2) place 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 (1960) and Hyatt (1965) 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, as opposed to the Parshall flume with an inclined floor in the throat and exit sections, are: (1) it is easy to construct, (2) it can be placed inside a concrete-lined channel, and (3) it can be placed on the channel bed.

Ackers and Harrison (1963) recommend a maximum convergence of 3:1 for a flume inlet section. Experimental work by the writers 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, discussed in a preceding report (Skogerboe, Hyatt and Eggleston, 1967), 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 changes 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.

The earlier study by Hyatt (1965) 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 divergences and lengths of exit section were tested, 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 to be no apparent advantage in having a throat section. Consequently, testing was initiated with a flat-bottomed flume having only an entrance and an exit section. 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 traveled along the flume centerline, thus assisting in the prevention of flow separation.

The rectangular flat-bottomed flume, which resulted from the testing program, is illustrated 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, which allows the same forms or patterns to be used for any flume size.

The cutthroat flume can operate either as a free or submerged flow structure as indicated in this report. Submerged flow calibration curves and free flow tables are developed and their use illustrated for the rectangular and trapezoidal cutthroat flumes studied. Discussion and examples regarding the practical aspects of installing, operating, and maintaining the structures are given.

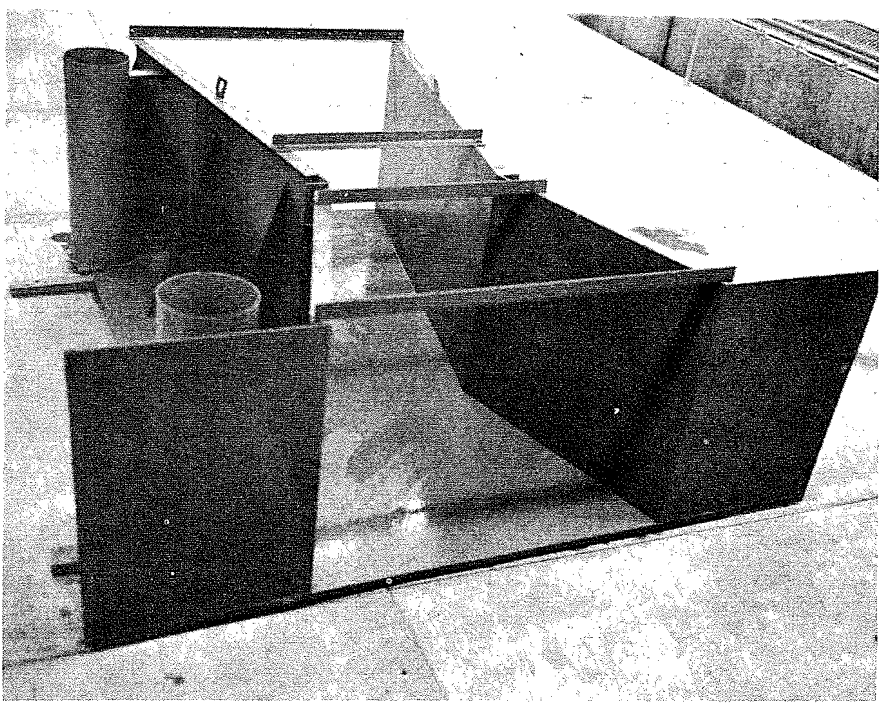


Fig. 1. Rectangular cutthroat flume.

DIMENSIONS OF RECTANGULAR CUTTHROAT FLUMES

The cutthroat flume consists of only a converging inlet section and a diverging outlet section. Fig. 2 is a plan and sectional view of a rectangular cutthroat flume. The one varying dimension indicated in Fig. 2 is the flume size or throat width, W. The length 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 feet were studied and tested in the laboratory. Although a wall height of 3 feet was maintained for the flumes studied, the height used for any particular structure would be dependent upon the stage-discharge relationship of the conveyance channel and the desired flow conditions under which the flume would operate. The rectangular cutthroat flumes studied in the laboratory were constructed of steel plate, but any field structure could be constructed of wood, concrete, or any other material depending on existing conditions, desired use, and durability.

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. Figs. 2 and 3 show the location selected for measuring the upstream depth, h_a, which is two-thirds the length of the converging section upstream from the flume neck.

When the flow conditions are such that 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, resulting in a change in the upstream depth, then the flume is operating under submerged flow conditions. 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 as shown in Fig. 2. The definition given to submergence, designated by S, is the ratio, often expressed as a percentage, of the downstream depth to the upstream depth ($S = h_b/h_a$).

Ofttimes, flumes designed initially to operate under free flow conditions become submerged upon occasion, 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 tables 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, symbolized by S_t. At this transition state, the discharge given by the free flow tables or 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. Thus, the proper method for determining the operating conditions of a flume is to compute the submergence after measuring h_a and h_b. If the submergence is less than the transition submergence, the flume is operating under free flow conditions. The flume is operating under submerged flow conditions when the submergence is greater than the transition submergence.

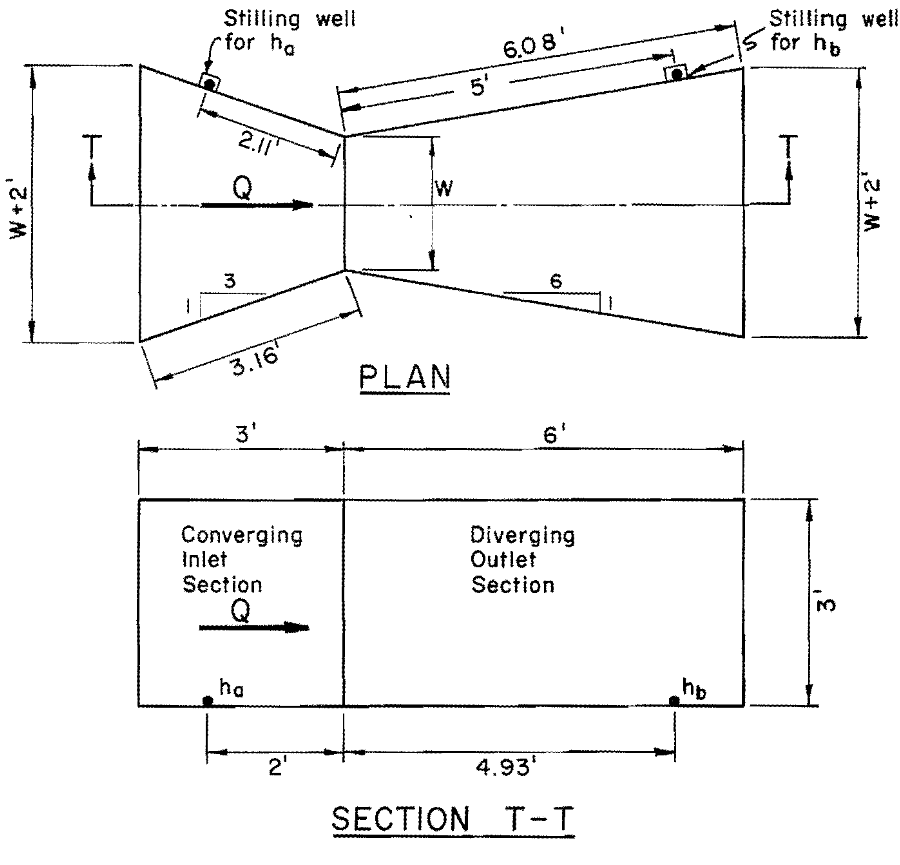


Fig. 2. Plan and sectional view of rectangular cutthroat measuring flume.

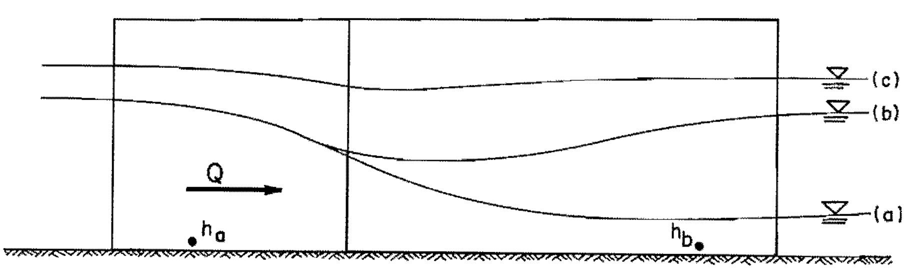


Fig. 3. Illustration of flow conditions in a rectangular cutthroat flume.

Evaluation of the laboratory data for rectangular cutthroat flumes ranging in size from 1 to 6 feet resulted in the transition submergences

Table 1. Transition submergences for rectangular cutthroat flumes.

Flume Size, W	Transition Submergence, S_t	Flume Size, W	Transition Submergence, S_t
1'	79%	3'	85%
1.5'	81%	4'	86%
2'	83%	5'	87%
2.5'	84%	6'	88%

listed in Table 1. When the submergence, h_b/h_a, for any given flume size exceeds the transition submergence 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 table (Table 2) should be used to obtain the discharge.

The difference between free flow, transition submergence, and submerged flow water surface profiles for the cutthroat flume is illustrated in Fig. 3. The discharge is constant. Water surface profile **a** illustrates free flow, whereas profile **b** indicates the transition submergence condition. Both profiles **a** and **b** have the same upstream depth of flow. Profile **b** has

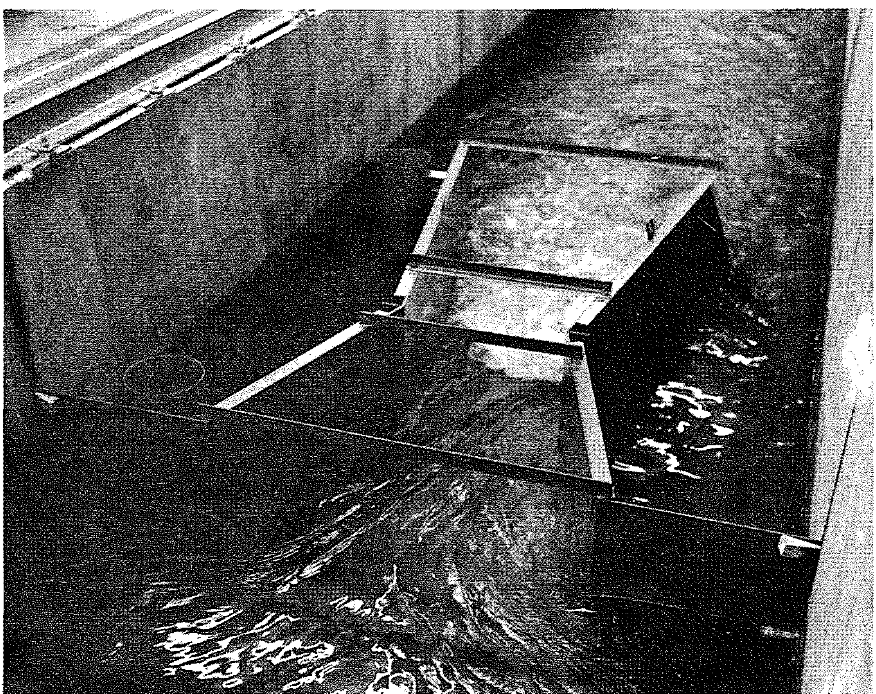


Fig. 4. Rectangular cutthroat flume operating under free flow conditions.

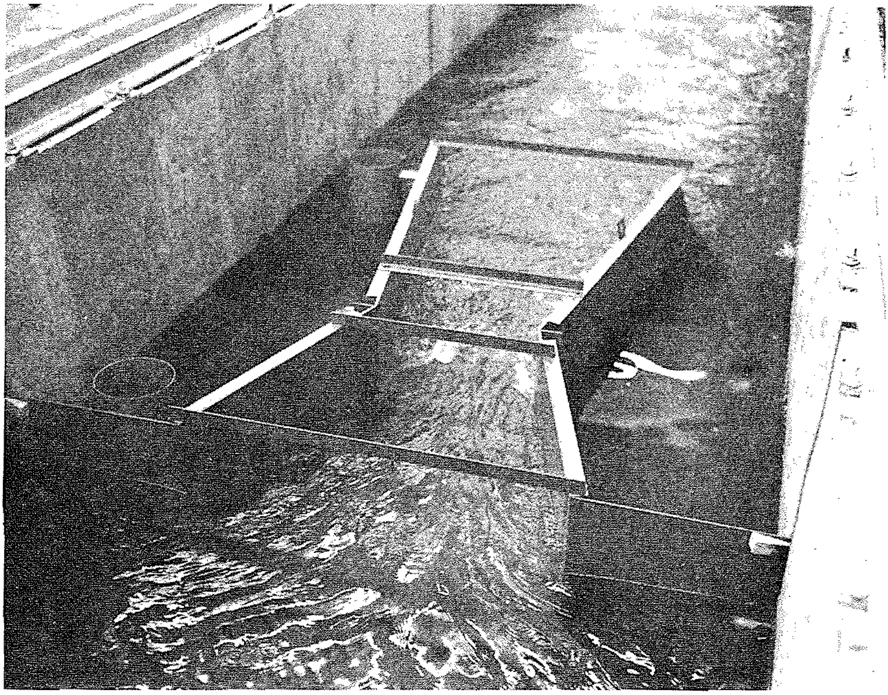


Fig. 5. Rectangular cutthroat flume operating under submerged flow conditions.

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, h_a. 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

$$Q = C h_a^{1.56} \quad \text{. 1}$$

The value of C for each size of flume may be obtained from the following equation,

$$C = 3.50\ W^{1.025} \quad \text{. . . . . 2}$$

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 the rectangular cutthroat flume sizes listed in Table 1. The free flow discharge for cutthroat flumes is listed in Table 2 for h_a values between 0.20 and 2.60 feet.

Example 1: For illustration of the use of Table 2, a 4-foot rectangular cutthroat flume known to be operating free flow

Table 2. Free flow calibration tables for rectangular cutthroat flumes.

Upper Head h_a	Throat Width							
	1'	1.5'	2'	2.5'	3'	4'	5'	6'
Feet	Flow in cubic feet per second							
0.20	0.29	0.43	0.58	0.72	0.87	1.18	1.48	1.78
0.21	0.31	0.46	0.62	0.79	0.95	1.27	1.61	1.93
0.22	0.33	0.50	0.67	0.84	1.01	1.37	1.71	2.07
0.23	0.35	0.54	0.72	0.90	1.09	1.46	1.84	2.22
0.24	0.38	0.57	0.77	0.96	1.17	1.56	1.96	2.38
0.25	0.40	0.61	0.82	1.03	1.24	1.67	2.09	2.53
0.26	0.42	0.65	0.87	1.10	1.32	1.76	2.22	2.69
0.27	0.45	0.69	0.92	1.16	1.40	1.88	2.36	2.85
0.28	0.48	0.72	0.98	1.22	1.48	1.98	2.49	3.01
0.29	0.51	0.76	1.03	1.30	1.57	2.10	2.65	3.19
0.30	0.53	0.81	1.09	1.37	1.65	2.22	2.79	3.37
0.31	0.56	0.85	1.14	1.43	1.74	2.33	2.93	3.55
0.32	0.59	0.89	1.20	1.51	1.82	2.45	3.08	3.71
0.33	0.61	0.95	1.27	1.59	1.92	2.58	3.24	3.92
0.34	0.64	0.98	1.32	1.66	2.00	2.70	3.39	4.10
0.35	0.67	1.02	1.38	1.74	2.10	2.81	3.53	4.26
0.36	0.71	1.08	1.44	1.82	2.19	2.94	3.70	4.45
0.37	0.74	1.12	1.51	1.90	2.29	3.07	3.87	4.66
0.38	0.77	1.17	1.58	1.98	2.38	3.20	4.03	4.86
0.39	0.81	1.22	1.64	2.06	2.48	3.34	4.20	5.05
0.40	0.84	1.26	1.70	2.14	2.58	3.47	4.35	5.25
0.41	0.87	1.31	1.78	2.23	2.69	3.61	4.54	5.48
0.42	0.90	1.37	1.84	2.30	2.78	3.74	4.70	5.67
0.43	0.94	1.42	1.91	2.40	2.89	3.89	4.88	5.90
0.44	0.97	1.48	1.98	2.49	3.00	4.03	5.07	6.11
0.45	1.00	1.53	2.05	2.58	3.10	4.18	5.25	6.33
0.46	1.04	1.58	2.12	2.67	3.22	4.32	5.43	6.56
0.47	1.07	1.63	2.20	2.76	3.32	4.46	5.61	6.77
0.48	1.11	1.68	2.26	2.85	3.44	4.61	5.79	7.00
0.49	1.15	1.73	2.34	2.94	3.54	4.75	5.98	7.21
0.50	1.19	1.80	2.42	3.03	3.65	4.91	6.18	7.45
0.51	1.23	1.85	2.50	3.13	3.78	5.08	6.38	7.70
0.52	1.26	1.91	2.56	3.22	3.88	5.22	6.56	7.92
0.53	1.30	1.96	2.64	3.32	4.00	5.38	6.76	8.16
0.54	1.34	2.02	2.72	3.41	4.12	5.53	6.96	8.41
0.55	1.38	2.08	2.80	3.51	4.24	5.70	7.16	8.65
0.56	1.42	2.14	2.88	3.62	4.36	5.86	7.36	8.89
0.57	1.45	2.21	2.96	3.72	4.49	6.03	7.58	9.15
0.58	1.49	2.27	3.05	3.83	4.62	6.21	7.80	9.41
0.59	1.53	2.33	3.13	3.93	4.73	6.36	8.00	9.66

Table 2. Continued.

Upper Head h_a	Throat Width							
	1'	2.5'	2'	2.5'	3'	4'	5'	6'
Feet	Flow in cubic feet per second							
0.60	1.58	2.39	3.21	4.03	4.87	6.54	8.22	9.92
0.61	1.62	2.44	3.30	4.14	4.98	6.70	8.42	10.16
0.62	1.66	2.51	3.38	4.24	5.11	6.88	8.64	10.43
0.63	1.70	2.57	3.46	4.35	5.25	7.05	8.85	10.69
0.64	1.74	2.64	3.55	4.45	5.37	7.21	9.08	10.95
0.65	1.78	2.70	3.63	4.56	5.50	7.39	9.29	11.21
0.66	1.83	2.77	3.73	4.68	5.65	7.59	9.53	11.50
0.67	1.87	2.83	3.82	4.79	5.77	7.75	9.75	11.76
0.68	1.91	2.91	3.91	4.90	5.91	7.95	9.99	12.05
0.69	1.95	2.97	3.99	5.02	6.04	8.11	10.20	12.31
0.70	2.01	3.04	4.09	5.13	6.18	8.31	10.45	12.60
0.71	2.05	3.10	4.17	5.24	6.32	8.50	10.69	12.89
0.72	2.10	3.18	4.27	5.36	6.46	8.68	10.92	13.17
0.73	2.14	3.24	4.36	5.48	6.60	8.87	11.16	13.46
0.74	2.19	3.31	4.45	5.59	6.75	9.06	11.40	13.75
0.75	2.23	3.38	4.55	5.71	6.88	9.25	11.63	14.03
0.76	2.28	3.46	4.65	5.83	7.03	9.46	11.88	14.34
0.77	2.32	3.52	4.74	5.95	7.17	9.64	12.12	14.63
0.78	2.37	3.60	4.83	6.07	7.32	9.83	12.35	14.92
0.79	2.42	3.66	4.93	6.19	7.47	10.28	12.61	15.23
0.80	2.47	3.74	5.03	6.32	7.62	10.24	12.87	15.53
0.81	2.52	3.81	5.13	6.44	7.77	10.44	13.12	15.84
0.82	2.57	3.89	5.23	6.56	7.91	10.65	13.38	16.15
0.83	2.62	3.96	5.33	6.69	8.07	10.84	13.63	16.46
0.84	2.67	4.04	5.43	6.81	8.22	11.04	13.89	16.77
0.85	2.71	4.11	5.53	6.95	8.37	11.25	14.15	17.07
0.86	2.76	4.19	5.63	7.07	8.52	11.45	14.40	17.38
0.87	2.81	4.27	5.74	7.21	8.68	11.67	14.67	17.71
0.88	2.86	4.34	5.84	7.33	8.83	11.87	14.93	18.02
0.89	2.92	4.42	5.93	7.46	9.00	12.08	15.20	18.34
0.90	2.97	4.49	6.04	7.59	9.15	12.29	15.46	18.65
0.91	3.02	4.58	6.15	7.72	9.31	12.50	15.73	18.99
0.92	3.07	4.65	6.26	7.85	9.47	12.72	16.01	19.31
0.93	3.12	4.73	6.36	7.99	9.63	12.95	16.28	19.65
0.94	3.17	4.81	6.47	8.12	9.79	13.17	16.55	19.97
0.95	3.23	4.89	6.58	8.26	9.95	13.38	16.82	20.30
0.96	3.28	4.98	6.68	8.40	10.12	13.60	17.10	20.64
0.97	3.34	5.05	6.80	8.53	10.29	13.82	17.38	20.97
0.98	3.39	5.14	6.91	8.67	10.46	14.04	17.66	21.32
0.99	3.45	5.21	7.02	8.81	10.62	14.27	17.95	21.65

Table 2. Continued

Upper Head h_a	Throat Width							
	1'	1.5'	2'	2.5'	3'	4'	5'	6'
Feet	Flow in cubic feet per second							
1.00	3.50	5.30	7.13	8.95	10.79	14.50	18.23	22.00
1.01	3.55	5.39	7.24	9.08	10.96	14.72	18.51	22.34
1.02	3.61	5.46	7.35	9.23	11.13	14.95	18.80	22.69
1.03	3.66	5.55	7.46	9.37	11.29	15.18	19.09	23.04
1.04	3.72	5.63	7.57	9.51	11.46	15.41	19.38	23.38
1.05	3.78	5.72	7.69	9.66	11.65	15.65	19.68	23.75
1.06	3.84	5.81	7.81	9.80	11.82	15.88	19.97	24.09
1.07	3.89	5.89	7.92	9.94	11.99	16.11	20.25	24.43
1.08	3.95	5.98	8.04	10.09	12.18	16.35	20.56	24.82
1.09	4.00	6.06	8.15	10.24	12.35	16.59	20.85	25.16
1.10	4.06	6.15	8.27	10.38	12.52	16.82	21.15	25.52
1.11	4.11	6.24	8.39	10.53	12.70	17.07	21.46	25.89
1.12	4.17	6.32	8.51	10.68	12.87	17.30	21.75	26.24
1.13	4.24	6.41	8.63	10.82	13.06	17.55	22.06	26.62
1.14	4.30	6.57	8.75	10.98	13.24	17.79	22.37	26.99
1.15	4.35	6.59	8.87	11.13	13.42	18.04	22.67	27.36
1.16	4.41	6.68	8.99	11.28	13.60	18.27	22.97	27.72
1.17	4.47	6.77	9.11	11.44	13.79	18.53	23.30	28.11
1.18	4.52	6.86	9.23	11.58	13.96	18.76	23.58	28.46
1.19	4.59	6.95	9.35	11.74	14.16	19.02	23.92	28.87
1.20	4.65	7.03	9.47	11.89	14.33	19.25	24.21	29.21
1.21	4.71	7.13	9.59	12.05	14.52	19.52	24.53	29.61
1.22	4.77	7.23	9.73	12.20	14.72	19.78	24.86	30.00
1.23	4.83	7.31	9.85	12.36	14.90	20.02	25.17	30.38
1.24	4.89	7.41	9.97	12.52	15.10	20.29	25.50	30.78
1.25	4.95	7.51	10.09	12.67	15.28	20.53	25.81	31.15
1.26	5.02	7.60	10.23	12.84	15.49	20.80	26.16	31.59
1.27	5.09	7.69	10.35	12.99	15.67	21.05	26.47	31.95
1.28	5.14	7.79	10.48	13.15	15.86	21.32	26.80	32.34
1.29	5.21	7.88	10.60	13.31	16.06	21.57	27.12	32.74
1.30	5.27	7.97	10.73	13.47	16.24	21.82	27.44	33.11
1.31	5.33	8.08	10.86	13.64	16.45	22.10	27.78	33.52
1.32	5.39	8.18	10.99	13.80	16.64	22.36	28.11	33.92
1.33	5.45	8.26	11.12	13.95	16.83	22.61	28.43	34.31
1.34	5.53	8.42	11.26	14.14	17.04	22.88	28.72	34.84
1.35	5.59	8.47	11.42	14.29	17.23	23.15	29 11	35.12
1.36	5.65	8.56	11.52	14.45	17.42	23.42	29.44	35.53
1.37	5.72	8.66	11.65	14.62	17.63	23.69	29.79	35.95
1.38	5.78	8.76	11.78	14.79	17.83	23.97	30.13	36.37
1.39	5.84	8.85	11.92	14.95	18.03	24.22	30.46	36.76

Table 2. Continued

Upper Head h_a	Throat Width							
	1'	1.5'	2'	2.5'	3'	4'	5'	6'
Feet	Flow in cubic feet per second							
1.40	5.91	8.95	12.05	15.12	18.23	24.50	30.81	37.18
1.41	5.98	9.06	12.18	15.29	18.44	24.78	31.15	37.60
1.42	6.05	9.17	12.33	15.47	18.65	25.06	31.52	38.04
1.43	6.11	9.25	12.45	15.62	18.84	25.31	31.82	38.41
1.44	6.18	9.36	12.59	15.81	19.06	25.60	32.19	38.85
1.45	6.24	9.46	12.73	15.98	19.25	25.88	32.53	39.27
1.46	6.31	9.56	12.87	16.16	19.47	26.17	32.90	39.71
1.47	6.37	9.66	12.99	16.32	19.67	26.43	33.23	40.10
1.48	6.45	9.76	13.14	16.49	19.87	26.71	33.57	40.51
1.49	6.51	9.87	13.27	16.66	20.08	26.98	33.93	40.94
1.50	6.58	9.96	13.41	16.84	20.30	27.27	34.28	41.38
1.51	6.65	10.07	13.55	17.02	20.51	27.56	34.65	41.82
1.52	6.72	10.18	13.69	17.19	20.73	27.85	35.02	42.25
1.53	6.79	10.29	13.84	17.37	20.94	28.15	35.38	42.70
1.54	6.86	10.38	13.97	17.54	21.14	28.41	35.72	43.11
1.55	6.93	10.49	14.11	17.72	21.36	28.71	36.09	43.56
1.56	7.00	10.60	14.26	17.90	21.58	29.00	36.49	44.00
1.57	7.07	10.21	14.40	18.08	21.80	29.29	36.82	44.44
1.58	7.14	10.81	14.55	18.26	22.01	29.58	37.19	44.88
1.59	7.20	10.91	14.68	18.43	22.23	29.86	37.55	45.31
1.60	7.28	11.03	14.84	18.62	22.45	30.18	37.94	45.78
1.61	7.35	11.14	14.98	18.80	22.67	30.46	38.30	46.22
1.62	7.42	11.23	15.11	18.97	22.87	30.74	38.65	46.64
1.63	7.50	11.35	15.27	19.16	23.11	31.05	39.05	47.13
1.64	7.56	11.45	15.40	19.33	23.32	31.33	39.39	47.54
1.65	7.63	11.56	15.55	19.51	23.54	31.62	39.76	47.97
1.66	7.72	11.68	15.71	19.73	23.78	31.95	40.18	48.49
1.67	7.79	11.79	15.86	19.91	24.01	32.25	40.56	48.94
1.68	7.86	11.89	16.00	20.09	24.22	32.55	40.93	49.38
1.69	7.93	12.01	16.16	20.28	24.45	32.87	41.33	49.87
1.70	8.01	12.13	16.32	20.49	24.69	33.19	41.73	50.35
1.71	8.08	12.24	16.47	20.67	24.92	33.49	42.11	50.82
1.72	8.16	12.34	16.61	20.85	25.14	33.78	42.48	51.26
1.73	8.23	12.46	16.76	21.04	25.37	34.09	42.85	51.71
1.74	8.30	12.56	16.90	21.22	25.58	34.38	43.22	52.15
1.75	8.37	12.67	17.06	21.40	25.81	34.68	43.60	52.62
1.76	8.45	12.79	17.21	21.61	26.05	35.00	44.00	53.11
1.77	8.52	12.90	17.37	21.80	26.29	35.31	44.40	53.59
1.78	8.61	13.03	17.53	22.01	26.54	35.66	44.84	54.11
1.79	8.68	13.14	17.68	22.19	26.76	35.96	45.21	54.55

Table 2. Continued.

Upper Head h_a	Throat Width							
	1'	1.5'	2'	2.5'	3'	4'	5'	6'
Feet	Flow in cubic feet per second							
1.80	8.75	13.25	17.82	22.37	26.97	36.25	45.57	55.00
1.81	8.82	13.36	17.97	22.57	27.20	36.55	45.95	55.46
1.82	8.90	13.48	18.13	22.77	27.44	36.89	46.38	55.96
1.83	8.97	13.58	18.28	22.95	27.66	37.19	46.74	56.41
1.84	9.05	13.70	18.43	23.14	27.90	37.50	47.15	56.88
1.85	9.14	13.83	18.61	23.36	28.16	37.85	47.58	57.42
1.86	9.22	13.96	18.79	23.58	28.43	38.21	48.03	57.97
1.87	9.29	14.08	18.93	23.76	28.66	38.51	48.41	58.42
1.88	9.37	14.20	19.10	23.98	28.91	38.84	48.84	58.94
1.89	9.44	14.30	19.24	24.16	29.13	39.14	49.21	59.39
1.90	9.52	14.41	19.39	24.34	29.34	39.43	49.58	59.83
1.91	9.59	14.53	19.54	24.53	29.57	39.74	49.97	60.30
1.92	9.67	14.64	19.69	24.71	29.80	40.04	50.35	60.77
1.93	9.76	14.79	19.89	24.97	30.10	40.45	50.85	61.37
1.94	9.84	14.90	20.04	25.16	30.34	40.77	51.26	61.86
1.95	9.93	15.03	20.22	25.38	30.59	41.12	51.70	62.39
1.96	10.01	15.16	20.39	25.59	30.86	41.47	52.13	62.92
1.97	10.08	15.26	20.53	25.77	31.07	41.76	52.50	63.36
1.98	10.15	15.37	20.68	25.97	31.29	42.06	52.88	63.82
1.99	10.22	15.49	20.83	26.15	31.52	42.36	53.27	64.28
2.00	10.30	15.61	21.00	26.35	31.77	42.70	53.68	64.79
2.01	10.40	15.75	21.19	26.60	32.07	43.09	54.18	65.38
2.02	10.50	15.89	21.38	26.84	32.36	43.49	54.66	65.97
2.03	10.57	16.01	21.53	27.03	32.59	43.79	55.05	66.44
2.04	10.64	16.11	21.68	27.21	32.80	44.08	55.42	66.88
2.05	10.71	16.22	21.83	27.40	33.03	44.40	55.82	67.36
2.06	10.82	16.37	22.03	27.65	33.34	44.75	56.33	67.98
2.07	10.89	16.48	22.17	24.83	33.56	45.08	56.70	68.42
2.08	10.98	16.63	22.38	28.08	33.86	45.49	57.21	69.03
2.09	11.06	16.75	22.53	28.28	34.10	45.82	57.60	69.52
2.10	11.13	16.85	22.68	28.46	34.32	46.11	57.97	69.96
2.11	11.20	16.97	22.83	28.66	34.54	46.43	58.36	70.44
2.12	11.31	17.12	23.03	28.90	34.84	46.84	58.88	71.06
2.13	11.40	17.27	23.23	29.15	35.15	47.23	59.39	71.67
2.14	11.48	17.39	23.39	29.36	35.39	47.55	59.80	72.16
2.15	11.55	17.49	23.53	29.54	35.61	47.85	60.16	72.60
2.16	11.62	17.60	23.69	29.73	35.84	48.17	60.55	73.08
2.17	11.73	17.75	23.89	29.98	36.15	48.57	61.07	73.70
2.18	11.82	17.90	24.09	30.23	36.45	48.97	61.58	74.31
2.19	11.90	18.02	24.24	30.43	36.69	49.30	61.98	74.80

Table 2. Continued.

Upper Head h_a	Throat Width							
	1'	1.5'	2'	2.5'	3'	4'	5'	6'
Feet	Flow in cubic feet per second							
2.20	11.97	18.13	24.39	30.61	36.92	49.60	62.36	75.25
2.21	12.05	18.25	24.55	30.83	37.16	49.93	62.79	75.77
2.22	12.15	18.39	24.74	31.05	37.44	50.31	63.26	76.34
2.23	12.24	18.54	24.94	31.30	37.74	50.71	63.77	76.95
2.24	12.32	18.66	25.10	31.50	37.98	51.04	64.17	77.43
2.25	12.39	18.76	25.24	31.68	38.20	51.33	64.54	77.88
2.26	12.48	18.89	25.42	31.91	38.47	51.70	65.01	78.45
2.27	12.58	19.05	25.63	32.17	38.78	52.12	65.53	79.09
2.28	12.67	19.18	25.81	32.40	39.06	52.49	65.99	79.64
2.29	12.75	19.31	25.97	32.61	39.32	52.84	66.43	80.16
2.30	12.83	19.44	26.15	32.83	39.57	53.19	66.86	80.69
2.31	12.93	19.58	26.35	33.07	39.87	53.58	67.37	81.31
2.32	13.02	19.71	26.52	33.29	40.13	53.93	67.81	81.83
2.33	13.10	19.83	26.67	33.49	40.37	54.26	68.21	82.32
2.34	13.17	19.95	26.83	33.68	40.62	54.58	68.61	82.80
2.35	13.26	20.09	27.02	33.92	40.89	54.95	69.09	83.37
2.36	13.36	20.24	27.23	34.18	41.20	55.37	69.62	84.02
2.37	13.45	20.36	27.40	34.39	41.45	55.71	70.03	84.52
2.38	13.52	20.48	27.54	34.57	41.68	56.01	70.42	84.99
2.39	13.65	20.67	27.81	34.91	41.99	56.42	71.10	85.62
2.40	13.72	20.78	27.95	35.09	42.30	56.84	71.46	86.24
2.41	13.79	20.89	28.11	35.29	42.53	57.16	71.87	86.72
2.42	13.90	21.04	28.31	35.53	42.84	57.56	72.37	87.34
2.43	14.00	21.20	28.52	35.80	43.16	58.00	72.92	88.00
2.44	14.08	21.33	28.69	36.02	43.42	58.36	73.37	88.54
2.45	14.17	21.46	28.87	36.25	43.70	58.72	73.83	89.09
2.46	14.26	21.60	29.05	36.46	43.97	59.08	74.29	89.64
2.47	14.35	21.73	29.23	36.69	44.23	59.44	74.74	90.19
2.48	14.44	21.87	29.42	36.93	44.52	59.82	75.21	90.77
2.49	14.53	22.00	29.59	37.15	44.78	60.18	75.67	91.32
2.50	14.61	22.14	29.77	37.37	45.06	60.55	76.12	91.86
2.51	14.69	22.25	29.94	37.58	45.31	60.89	76.56	92.39
2.52	14.81	22.42	30.16	37.85	45.64	61.33	77.11	93.06
2.53	14.91	22.58	30.37	38.13	45.96	61.77	77.66	93.72
2.54	14.99	22.71	30.55	38.35	46.23	62.13	78.11	94.27
2.55	15.08	22.84	30.73	38.57	46.50	62.49	78.57	94.81
2.56	15.18	23.00	30.94	38.84	46.82	62.92	79.11	95.47
2.57	15.26	23.11	31.08	39.02	47.04	63.21	79.48	95.91
2.58	15.36	23.27	31.29	39.29	47.36	63.65	80.02	96.57
2.59	15.47	24.43	31.52	39.56	47.69	64.09	80.58	97.24

and with an upstream depth of flow, h_a, equal to 1.77 feet is considered. Enter Table 2 at the left side with a value of h_a equal to 1.77 feet, then under the column headed by throat width of four feet, observe the rate of flow which is 35.31 cfs.

SUBMERGED FLOW OPERATION

Fundamental Theory

Utilizing momentum principles, a theoretical submerged flow discharge equation could be developed for the rectangular cutthroat flume. Such an equation has been written (Skogerboe, Hyatt, and Eggleston, 1967) for a rectangular flume assuming uniform velocity distribution, hydrostatic pressure distribution, steady flow, and neglecting friction forces. The theoretical equation strengthens the results of dimensional analysis applied to any particular flume geometry.

When dimensional analysis is applied to submerged flow through a specified flume geometry, three pi-terms are obtained. The first pi-term (π_1) is the Froude number evaluated at the section of minimum flow depth, h_m. The submergence, S, is the second pi-term (π_2). The change in water surface elevation, h_a - h_b, divided by the minimum flow depth, h_m, is the third pi-term (π_3). The logarithm of π_2 plotted against π_3 (Fig. 6) yields the distribution of the lines of constant submergence for the submerged flow calibration curves (Skogerboe, Hyatt, and Eggleston, 1967). The true distribution of the lines of constant submergence is given by the curved line in Fig. 6 which best fits the data, whereas, the straight line is an approximation of the relationship over a large range of submergence. The distribution of the lines of constant submergence obtained from the straight line relationship in Fig. 6 has merit because of the approximate submerged flow equation which can be obtained. The approximate submerged flow equation obtained from the straight line relationship will usually produce reasonable accuracy for submergence values less than 96 percent. The true distribution has been used in developing submerged flow calibration curves for cutthroat flumes.

Application Principles

Submerged flow calibration curves for the rectangular cutthroat flumes were obtained by preparing three-dimensional plots of the parameters describing submerged flow. Each plot is made on log-log paper with the discharge, Q, as the ordinate; difference in upstream and downstream depths of flow, h_a - h_b, as the abscissa; and the submergence, h_a/h_b as the varying parameter.

Laboratory data were collected for rectangular cutthroat flumes having throat widths of 1, 2, 3, 4, and 6 feet. The submerged flow calibration curves for these flumes are shown in Figs. 7, 9, 11, 12, and 14. The calibration curves for the 1.5-, 2.5-, and 5 foot flumes (Figs. 8, 10, and 13) were obtained by interpolating between the curves developed from the collected data. The distribution of the lines of constant submergence follow the true distribution rather than an approximate distribution (Fig. 6).

One incidental point of interest is that the slope of the lines of constant submergence is the same for all the submerged flow calibration curves

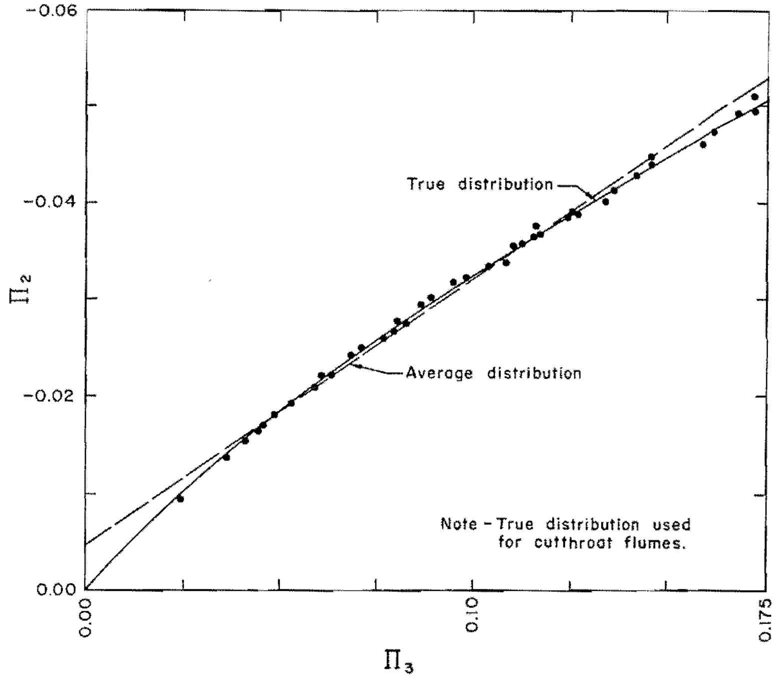


Fig. 6. Relationship between π_2 and π_3.

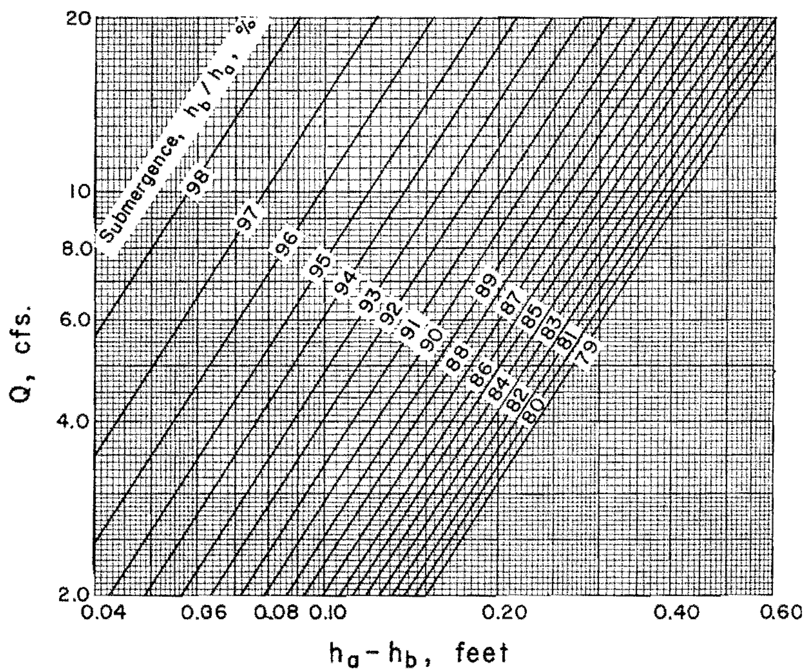


Fig. 7. Submerged flow calibration curves for 1-foot rectangular cutthroa flume.

(Figs. 7 through 14). The slope is 1.56, which corresponds to the power of h_a in the free flow equation (Eq. 1) for rectangular cutthroat flumes.

To obtain the discharge under submerged flow conditions, the upstream, h_a, and downstream, h_b, depths of flow are first measured. Next, using these depths, the submergence ratio, h_b/h_a, is computed as is the difference in the depths, h_a - h_b. With the two computations completed, the proper set of calibration curves are selected, from which the discharge is obtained. To illustrate the use of the submerged flow calibration curves, an example will be selected using a 2-foot rectangular cutthroat flume.

Example 2: Assume the measured values of h_a and h_b in a 2-foot flume are 1.94 and 1.55 feet, respectively. The submergence ratio is computed to be 80 percent (1.55 ÷ 1.94 = 0.80) and the difference in depths is 0.39 foot (1.94 - 1.55 = 0.39). Checking Table 1, the transition submergence ratio for the 2-foot flume is found to be 83 percent which is greater than the 80 percent submergence measured for this situation. Hence, the flow condition is free flow and the discharge is obtained from Table 2. Here, for an h_a heading of 1.94 feet, the free flow discharge is

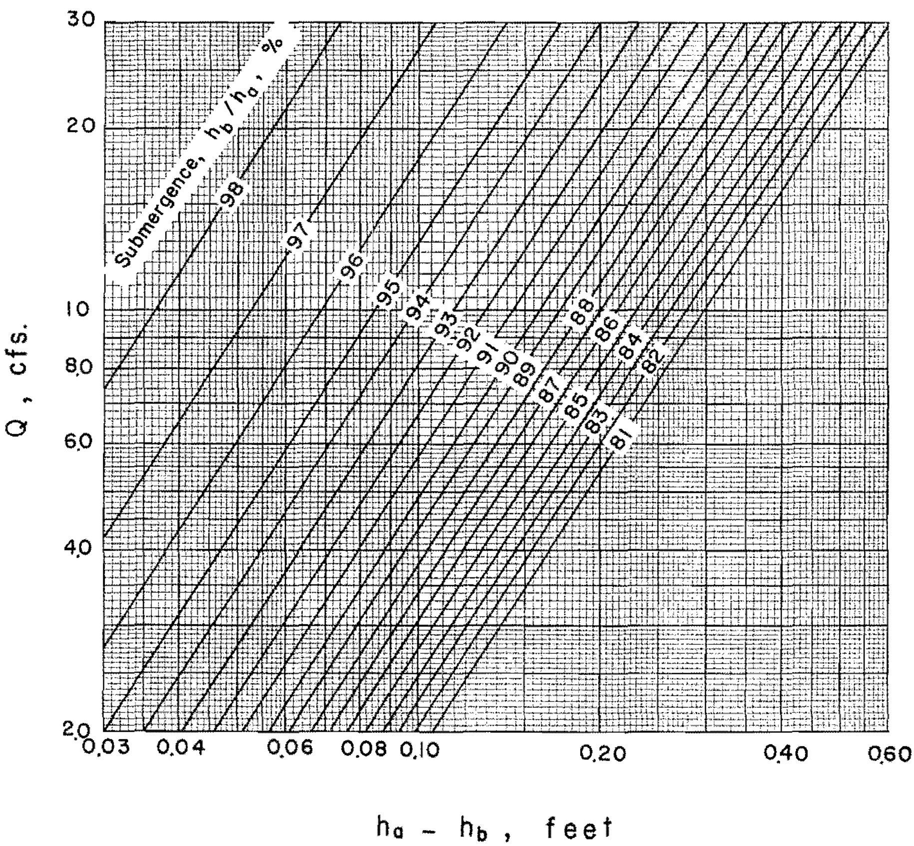


Fig. 8. Submerged flow calibration curves for 1.5-foot rectangular cutthroat flume.

found to be 20.04 cfs for a 2-foot rectangular cutthroat flume.

Suppose now that in the same 2-foot flume, conditions change such that h_a and h_b are measured as 2.14 and 1.93 feet, respectively. The submergence ratio is 90 percent and the difference in depths is 0.21 foot. The calibration curve for the 2-foot flume (Fig. 9) is entered from below with an h_a - h_b value of 0.21. Then, move vertically upward to the 90 percent submergence line. At this point of intersection, move horizontally to the left and read the discharge as 21.65 cfs on the vertical scale.

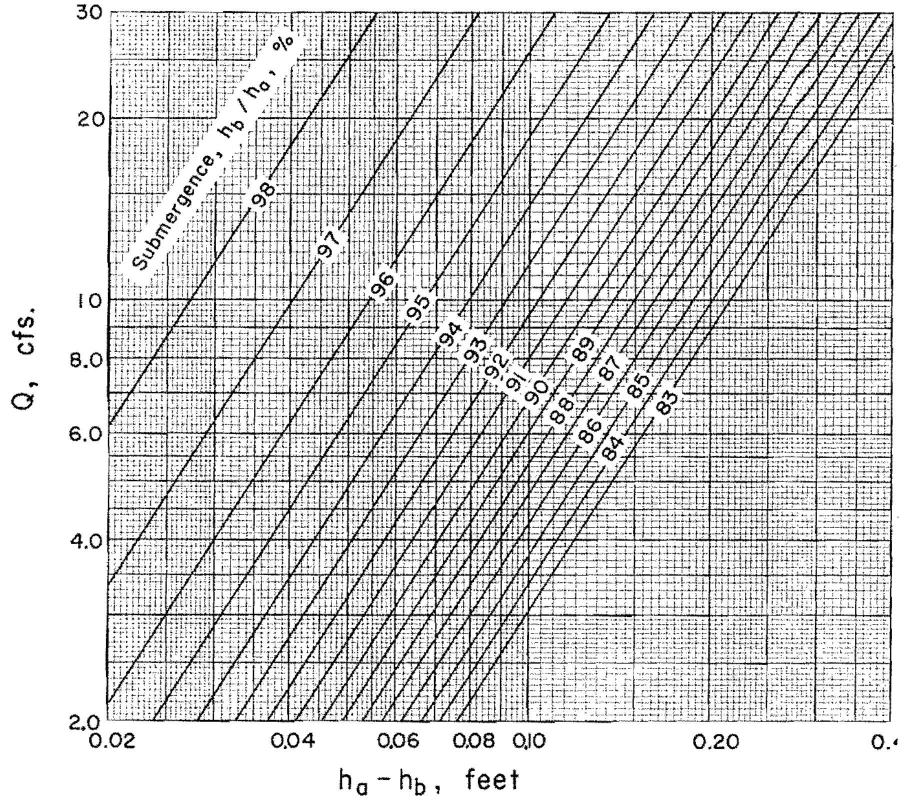


Fig. 9. Submerged flow calibration curves for 2-foot rectangular cutthroat flume.

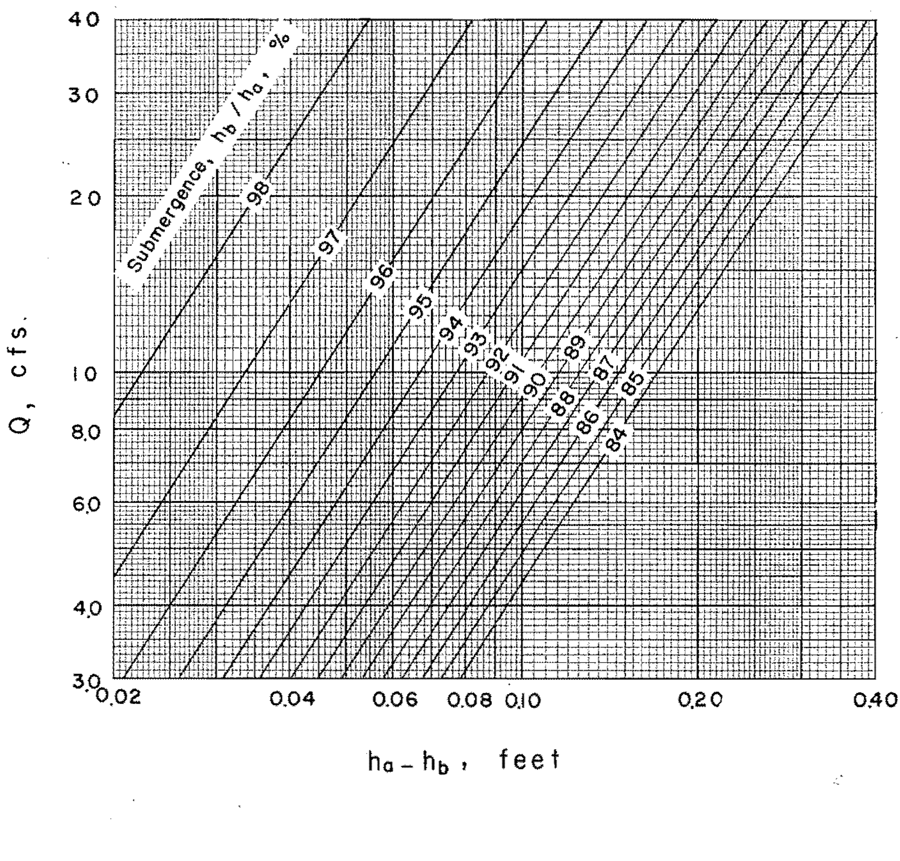
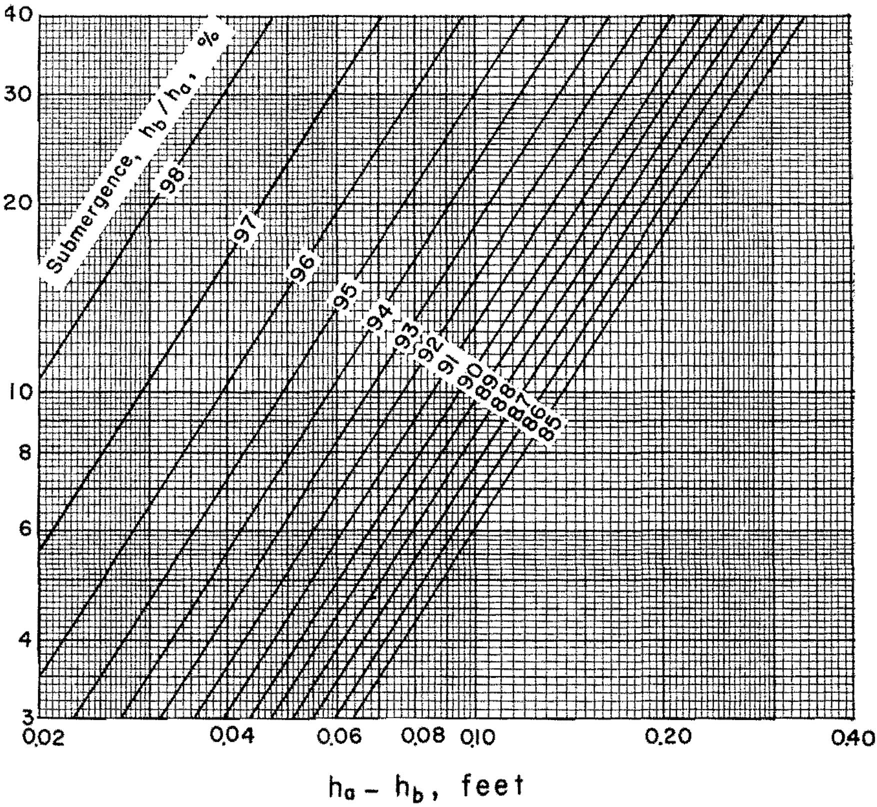


Fig. 10. Submerged flow calibration curves for 2.5-foot rectangular cutthroat flume.



;. 11. Submerged flow calibration curves for 3-foot rectangular cutthroat flume.

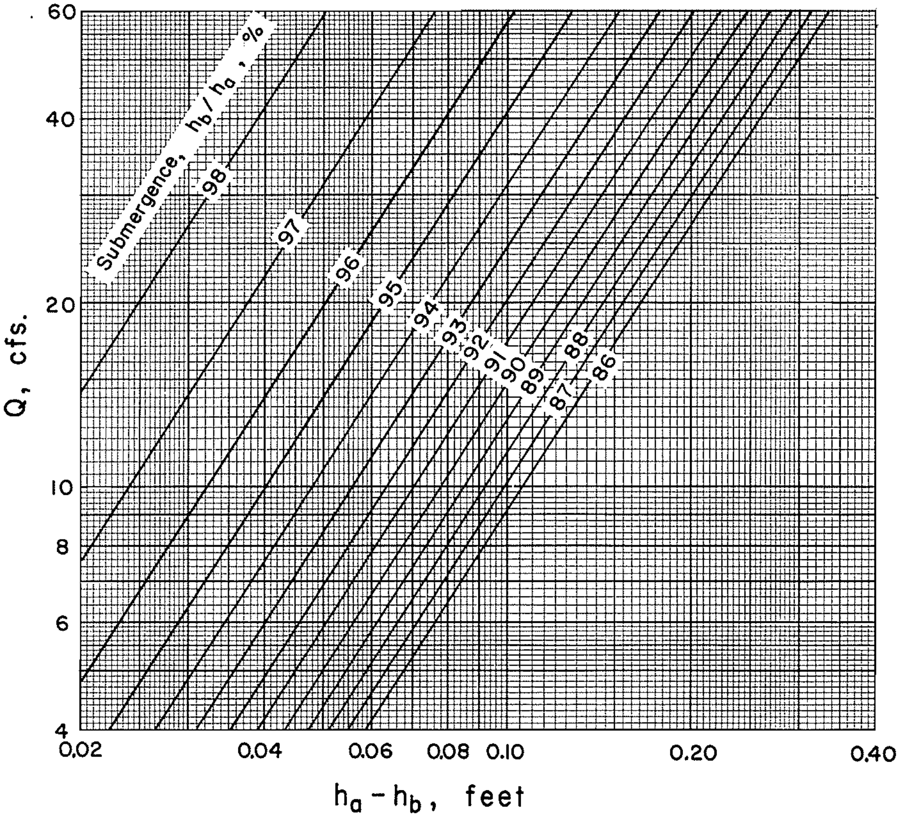
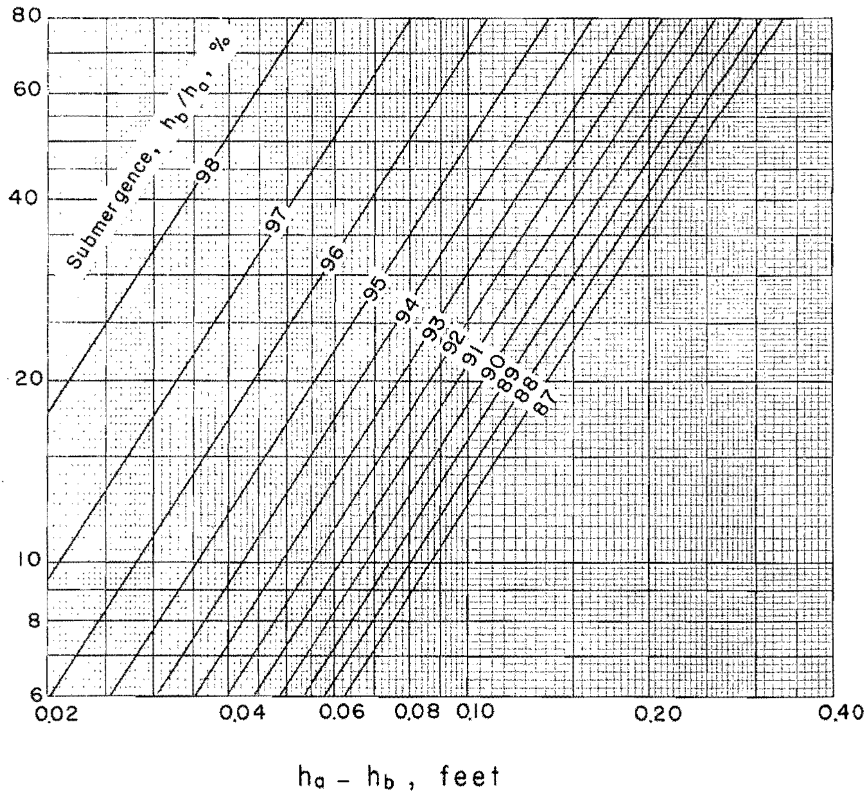


Fig. 12. Submerged flow calibration curves for 4-foot rectangular cutthroat flume.



13. Submerged flow calibration curves for 5-foot rectangular cutthroat flume.

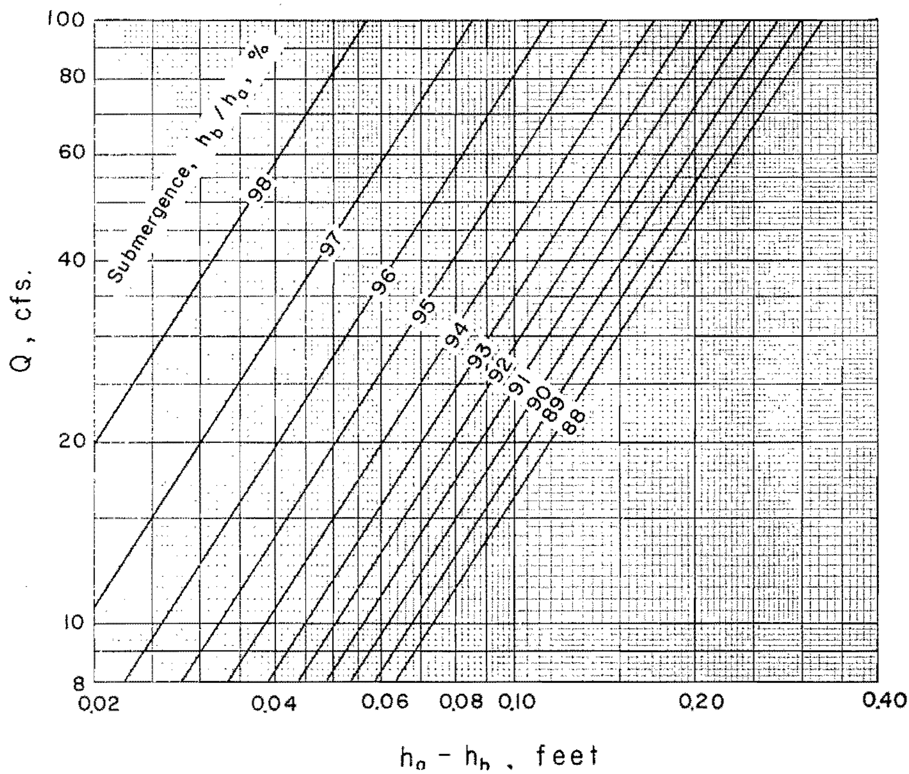


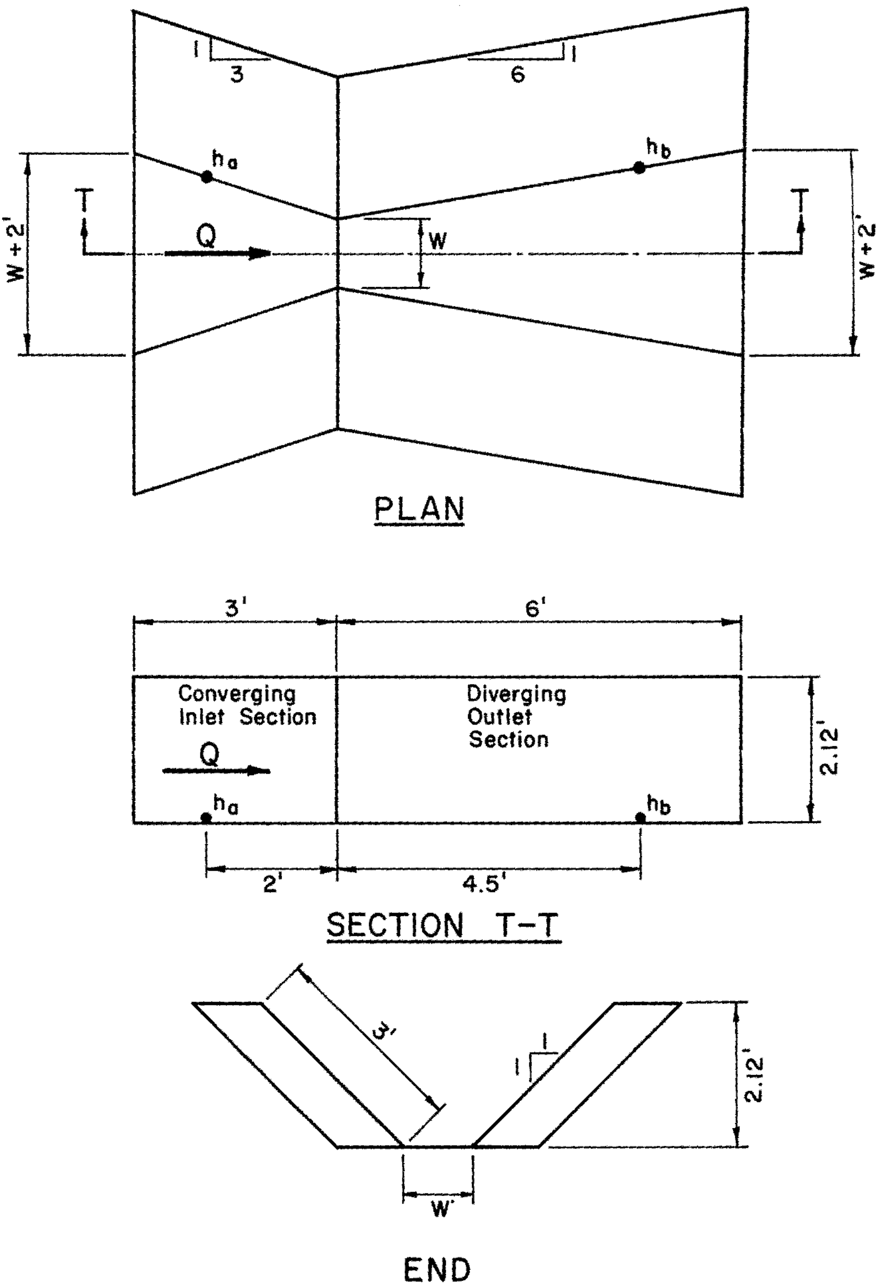
Fig. 14. Submerged flow calibration curves for 6-foot rectangular cutthroat flume.

TRAPEZOIDAL CUTTHROAT FLUMES

Dimensions

The trapezoidal cutthroat flume is similar to the rectangular cutthroat flume in that both consist of only a converging inlet section and a diverging outlet section, with no throat section. Fig. 15 is a plan, sectional, and end view of the type of trapezoidal flume investigated. In the testing program, only the flume width, W, was varied with the length of the converging and diverging sections and the side slope kept as a constant value (Fig. 15). Measurement of the upstream, h_a, and downstream, h_b, depths of flow were made at the points shown in Fig. 15. Steel plate was used in construction, but other materials could be used as discussed earlier in this report.

Trapezoidal cutthroat flumes having throat widths, W, of zero (V-shaped), 6 inches, and 12 inches were selected for laboratory investigation. Development of intermediate sizes, or larger sizes, was not attempted because of the great diversity of possible trapezoidal geometries. To test such a variety of possible shapes was considered beyond the resources of this study.



5. **Plan, sectional, and end view of trapezoidal cutthroat measuring flume.**

Operation

The previous discussion given to the free and submerged flow operation of the rectangular cutthroat flumes applies equally well to the trapezoidal flumes. The rate of discharge under the free flow condition depends only upon the upstream depth of flow, h_a, whereas under submerged flow conditions, the discharge requires the measurement of the upstream and downstream depths of flow, h_a and h_b. The transition from the free flow condition to the submerged flow condition occurs when a change in the downstream, or tailwater, depth results in an increased upstream flow depth. Table 3 indicates the value of transition submergence for the trapezoidal cutthroat flumes which were studied.

Table 3. Transition submergences for trapezoidal cutthroat flumes.

Flume Throat Width	Transition Submergence, S_t
Zero or V-shaped	60%
6 inch	76%
12 inch	79%

Hence, when the submergence ratio, h_b/h_a, is less than the value given in Table 3 for a particular trapezoidal cutthroat flume, the free flow tables (Tables 4, 5, and 6) should be used, and when h_b/h_a is greater than S_t, the submerged flow calibration curves should be used for determining the discharge.

When the trapezoidal flumes are operating under free flow conditions, only the upstream depth of flow, h_a, is required for obtaining the discharge. Free flow equations have been developed from laboratory data for the three trapezoidal cutthroat flumes listed in Table 3. The free flow equation for the V-shaped flume is

$$Q = 2.57\, h_a^{2.53} \quad \ldots \quad 3$$

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

$$Q = 3.98\, h_a^{2.26} \quad \ldots \quad 4$$

The free flow equation for the 12-inch flume is

$$Q = 5.48\, h_a^{2.02} \quad \ldots \quad 5$$

Tables 4, 5, and 6, are the free flow calibration tables corresponding to Eqs. 3, 4, and 5, respectively. The tables give the free flow discharge in cfs for values of h_a between 0.10 and 2.09 feet.

The submerged flow calibration curves for the trapezoidal cutthroat flumes were developed from the collected data in the same manner as were the rectangular flume curves. A three-dimensional plot was made of the discharge, Q, plotted as the ordinate; the difference in upstream and downstream depths, $h_a - h_b$, plotted as the abscissa; and the submergence, h_b/h_a, plotted as the varying parameter. The distribution of the lines of constant submergence is the true distribution rather than the approximate distribution as illustrated by the curved plot in Fig. 6. The

Table 4. Free flow calibration table for V-shaped trapezoidal cutthroat flume.

Upper head h_a feet	Discharge Q cfs	Upper head h_a feet	Discharge Q cfs	Upper head h_a feet	Discharge Q cfs	Upper head h_a feet	Discharge Q cfs	Upper head h_a feet	Discharg Q cfs
0.10	0.007	0.50	0.45	0.90	1.97	1.30	4.99	1.70	9.83
0.11	0.010	0.51	0.47	0.91	2.02	1.31	5.09	1.71	9.99
0.12	0.012	0.52	0.49	0.92	2.08	1.32	5.19	1.72	10.13
0.13	0.015	0.53	0.52	0.93	2.14	1.33	5.29	1.73	10.20
0.14	0.018	0.54	0.54	0.94	2.20	1.34	5.39	1.74	10.43
0.15	0.021	0.55	0.57	0.95	2.26	1.35	5.49	1.75	10.59
0.16	0.025	0.56	0.59	0.96	2.32	1.36	5.59	1.76	10.74
0.17	0.029	0.57	0.62	0.97	2.38	1.37	5.70	1.77	10.90
0.18	0.033	0.58	0.65	0.98	2.44	1.38	5.81	1.78	11.05
0.19	0.038	0.59	0.67	0.99	2.50	1.39	5.91	1.79	11.21
0.20	0.044	0.60	0.70	1.00	2.57	1.40	6.02	1.80	11.37
0.21	0.050	0.61	0.73	0.01	2.63	1.41	6.13	1.81	11.53
0.22	0.056	0.62	0.77	1.02	2.70	1.42	6.24	1.82	11.69
0.23	0.062	0.63	0.80	1.03	2.77	1.43	6.35	1.83	11.86
0.24	0.069	0.064	0.83	1.04	2.84	1.44	6.47	1.84	12.02
0.25	0.077	0.65	0.86	1.05	2.90	1.45	6.58	1.85	12.19
0.26	0.085	0.66	0.90	1.06	2.98	1.46	6.69	1.86	12.35
0.27	0.094	0.67	0.93	1.07	3.05	1.47	6.81	1.87	12.52
0.28	0.103	0.68	0.97	1.08	3.12	1.48	6.93	1.88	12.69
0.29	0.112	0.69	1.00	1.09	3.19	1.49	7.05	1.89	12.86
0.30	0.12	0.70	1.04	1.10	3.27	1.50	7.17	1.90	13.04
0.31	0.13	0.71	1.08	1.11	3.34	1.51	7.28	1.91	13.21
0.32	0.14	0.72	1.12	1.12	3.42	1.52	7.41	1.92	13.38
0.33	0.15	0.73	1.16	1.13	3.50	1.53	7.54	1.93	13.57
0.34	0.17	0.74	1.20	1.14	3.58	1.54	7.66	1.94	13.74
0.35	0.18	0.75	1.24	1.15	3.66	1.55	7.79	1.95	13.92
0.36	0.19	0.76	1.28	1.16	3.74	1.56	7.92	1.96	14.11
0.37	0.21	0.77	1.33	1.17	3.82	1.57	8.04	1.97	14.29
0.38	0.22	0.78	1.37	1.18	3.91	1.58	8.18	1.98	14.47
0.39	0.24	0.79	1.41	1.19	3.99	1.59	8.31	1.99	14.66
0.40	0.25	0.80	1.46	1.20	4.08	1.60	8.44	2.00	14.84
0.41	0.27	0.81	1.51	1.21	4.16	1.61	8.57	2.01	15.03
.42	0.29	0.82	1.56	1.22	4.25	1.62	8.71	2.02	15.23
.43	0.30	0.83	1.60	1.23	4.34	1.63	8.85	2.03	15.41
.44	0.32	0.84	1.65	1.24	4.43	1.64	8.98	2.04	15.60
.45	0.34	0.85	1.70	1.25	4.52	1.65	9.12	2.05	15.80
46	0.36	0.86	1.75	1.26	4.61	1.66	9.26	2.06	16.00
47	0.38	0.87	1.81	1.27	4.71	1.67	9.40	2.07	16.20
48	0.38	0.88	1.86	1.28	4.80	1.68	9.55	2.08	16.39
49	0.42	0.89	1.91	1.29	4.89	1.69	9.69	2.09	16.58

Table 5. Free flow calibration table for 6-inch trapezoidal cutthroat flume.

Upper head h_a feet	Discharge Q cfs	Upper head h_a feet	Discharge Q cfs	Upper head h_a feet	Discharge Q cfs	Upper head h_a feet	Discharge Q cfs	Upper head h_a feet	Discharge Q cfs
0.10	0.022	0.50	0.83	0.90	3.14	1.30	7.20	1.70	13.20
0.11	0.027	0.51	0.87	0.91	3.22	1.31	7.33	1.71	13.38
0.12	0.033	0.52	0.91	0.92	3.29	1.32	7.46	1.72	13.56
0.13	0.039	0.53	0.95	0.93	3.38	1.33	7.58	1.73	13.73
0.14	0.047	0.54	0.99	0.94	3.46	1.34	7.71	1.74	13.91
0.15	0.05	0.55	1.03	0.95	3.54	1.35	7.84	1.75	14.10
0.16	0.06	0.56	1.07	0.96	3.63	1.36	7.97	1.76	14.28
0.17	0.07	0.57	1.12	0.97	3.71	1.37	8.10	1.77	14.47
0.18	0.08	0.58	1.16	0.98	3.80	1.38	8.24	1.78	14.65
0.19	0.09	0.59	1.21	0.99	3.89	1.39	8.38	1.79	14.84
0.20	0.10	0.60	1.26	1.00	3.98	1.40	8.51	1.80	15.03
0.21	0.12	0.61	1.30	1.01	4.06	1.41	8.65	1.81	15.21
0.22	0.13	0.62	1.35	1.02	4.16	1.42	8.79	1.81	15.41
0.23	0.14	0.63	1.40	1.03	4.25	1.43	8.93	1.82	15.60
0.24	0.16	0.64	1.45	1.04	4.34	1.44	9.07	1.84	15.79
0.25	0.17	0.65	1.50	1.05	4.43	1.45	9.22	1.85	15.99
0.26	0.19	0.66	1.56	1.06	4.54	1.46	9.36	1.86	16.18
0.27	0.21	0.67	1.61	1.07	4.63	1.47	9.51	1.87	16.37
0.28	0.22	0.68	1.66	1.08	4.73	1.48	9.65	1.88	16.58
0.29	0.24	0.69	1.72	1.09	4.83	1.49	9.80	1.89	16.78
0.30	0.26	0.70	1.77	1.10	4.93	1.50	9.95	1.90	16.98
0.31	0.28	0.71	1.83	1.11	5.03	1.51	10.10	1.91	17.18
0.32	0.30	0.72	1.89	1.12	5.15	1.52	10.25	1.92	17.38
0.33	0.32	0.73	1.95	1.13	5.25	1.53	10.40	1.93	17.60
0.34	0.35	0.74	2.01	1.14	5.35	1.54	10.56	1.94	17.79
0.35	0.37	0.75	2.08	1.15	5.46	1.55	10.72	1.95	18.04
0.36	0.39	0.76	2.14	1.16	5.57	1.56	10.87	1.96	18.22
0.37	0.42	0.77	2.20	1.17	5.67	1.57	11.03	1.97	18.43
0.38	0.45	0.78	2.27	1.18	5.79	1.58	11.19	1.98	18.63
0.39	0.47	0.79	2.33	1.19	5.89	1.59	11.35	1.99	18.85
0.40	0.50	0.80	2.40	1.20	6.01	1.60	11.51	2.00	19.06
0.41	0.53	0.81	2.47	1.21	6.12	1.61	11.68	2.01	19.28
0.42	0.56	0.82	2.54	1.22	6.24	1.62	11.84	2.02	19.50
0.43	0.59	0.83	2.61	1.23	6.36	1.63	12.02	2.03	19.71
0.44	0.62	0.84	2.68	1.24	6.47	1.64	12.17	2.04	19.93
0.45	0.65	0.85	2.75	1.25	6.59	1.65	12.34	2.05	20.16
0.46	0.69	0.86	2.83	1.26	6.71	1.66	12.51	2.06	20.39
0.47	0.72	0.87	2.90	1.27	6.83	1.67	12.68	2.07	20.61
0.48	0.76	0.88	2.98	1.28	6.95	1.68	12.85	2.08	20.83
0.49	0.80	0.89	3.06	1.29	7.08	1.69	13.03	2.09	21.05

Table 6. Free flow calibration table for 12-inch trapezoidal cutthroat flume.

Upper head h_a feet	Discharge Q cfs	Upper head h_a feet	Discharge Q cfs	Upper head h_a feet	Discharge Q cfs	Upper head h_a feet	Discharge Q cfs	Upper head h_a feet	Discharge Q cfs
0.10	0.05	0.50	1.35	0.90	4.43	1.30	9.30	1.70	16.00
0.11	0.06	0.51	1.41	0.91	4.53	1.31	9.46	1.71	16.20
0.12	0.08	0.52	1.46	0.92	4.63	1.32	9.60	1.72	16.38
0.13	0.09	0.53	1.52	0.93	4.73	1.33	9.75	1.73	16.58
0.14	0.10	0.54	1.58	0.94	4.83	1.34	9.90	1.74	16.77
0.15	0.12	0.55	1.64	9.95	4.94	1.35	10.04	1.75	16.97
0.16	0.14	1.56	1.70	0.96	5.05	1.36	10.20	1.76	17.16
0.17	0.15	0.57	1.76	0.97	5.15	1.37	10.35	1.77	17.37
0.18	0.17	0.58	1.82	0.98	5.26	1.38	10.50	1.78	17.56
0.19	0.19	0.59	1.89	0.99	5.37	1.39	10.66	1.79	17.77
0.20	0.21	0.60	1.95	1.00	5.48	1.40	10.81	1.80	17.96
0.21	0.23	0.61	2.02	1.01	5.58	1.41	10.97	1.81	18.17
0.22	0.26	0.62	2.08	1.02	5.70	1.42	11.13	1.82	18.37
0.23	0.28	0.63	2.15	1.03	5.80	1.43	11.28	1.83	18.58
0.24	0.31	0.64	2.22	1.04	5.92	1.44	11.45	1.84	18.78
0.25	0.33	0.65	2.30	1.05	6.04	1.45	11.61	1.85	18.99
0.26	0.37	0.66	2.37	1.06	6.16	1.46	11.77	1.86	19.19
0.27	0.39	0.67	2.44	1.07	6.28	1.47	11.93	1.87	19.39
0.28	0.42	0.68	2.51	1.08	6.40	1.48	12.10	1.88	19.68
0.29	0.45	0.69	2.59	1.09	6.51	1.49	12.27	1.89	19.86
0.30	0.48	0.70	2.66	1.10	6.64	1.50	12.43	1.90	70.05
0.31	0.51	0.71	2.74	1.11	6.76	1.51	12.60	1.91	20.27
0.32	0.55	0.72	2.82	1.12	6.88	1.52	12.76	1.92	20.49
0.33	0.58	0.73	2.90	1.13	7.01	1.53	12.94	1.93	20.69
0.34	0.61	0.74	2.98	1.14	7.14	1.54	13.11	1.94	20.91
0.35	0.66	0.75	3.07	1.15	7.27	1.55	13.28	1.95	21.11
0.36	0.69	0.76	3.14	1.16	7.40	1.56	13.46	1.96	21.34
0.37	0.73	0.77	3.23	1.17	7.53	1.57	13.63	1.97	21.56
0.38	0.78	0.78	3.32	1.18	7.66	1.58	13.81	1.98	21.78
0.39	0.82	0.79	3.40	1.19	7.79	1.59	13.98	1.99	22.01
0.40	0.84	0.80	3.49	1.20	7.92	1.60	14.16	2.00	22.22
0.41	0.91	0.81	3.58	1.21	8.06	1.61	14.34	2.01	22.46
0.42	0.95	0.82	3.67	1.22	8.19	1.62	14.52	2.02	22.68
0.43	1.00	0.83	3.77	1.23	8.32	1.63	14.70	2.03	22.90
0.44	1.04	0.84	3.85	1.24	8.46	1.64	14.88	2.04	23.13
0.45	1.09	0.85	3.95	1.25	8.60	1.65	15.07	2.05	23.37
0.46	1.14	0.86	4.04	1.26	8.74	1.66	15.26	2.06	23.60
0.47	1.19	0.87	4.13	1.27	8.88	1.67	15.44	2.07	23.83
0.48	1.24	0.88	4.23	1.28	9.02	1.68	15.63	2.08	24.06
0.49	1.30	0.89	4.33	1.29	9.17	1.69	15.82	2.09	24.29

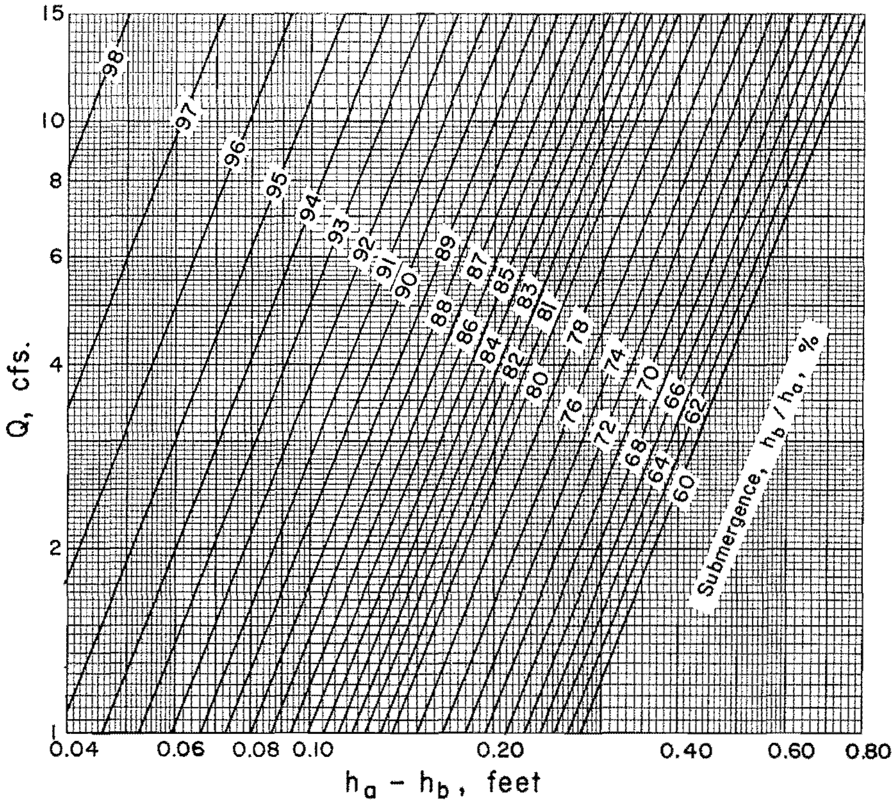


Fig. 16. Submerged flow calibration curves for V-shaped trapezoidal cutthroat flume.

calibration curves developed for the V-shaped, 6-inch, and 12-inch trapezoidal cutthroat flumes are found in Figs. 16, 17, and 18, respectively.

As an illustrative example of the trapezoidal cutthroat flume submerged flow calibration curves, the following example has been selected.

Example 3: Assume that an h_a and h_b value of 1.50 feet and 1.38 feet, respectively, are measured in a 6-inch trapezoidal cutthroat flume. The submergence ratio of 92 percent (1.38/1.50 = 0.92) and the difference in depths of 0.12 foot (1.50 - 1.38 = 0.12) are first computed. By first entering Table 3, a transition submergence of 76 percent is obtained for this particular flume, which is less than the submergence ratio of 92 percent. Thus, a submerged flow condition exists. Entering Fig. 17 from below with an h_a - h_b value of 0.12 foot, move vertically upward until the submergence line of 92 percent is intersected. From this point of intersection, move horizontally to the left and read a discharge value of 8.25 cfs on the vertical scale.

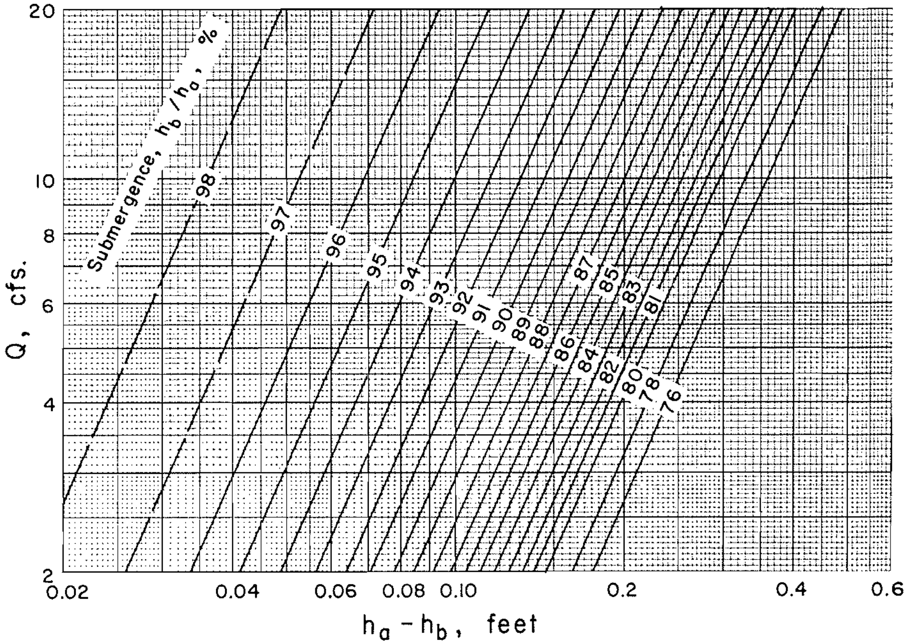


Fig. 17. Submerged flow calibration curves for 6-inch trapezoidal cut-throat flume.

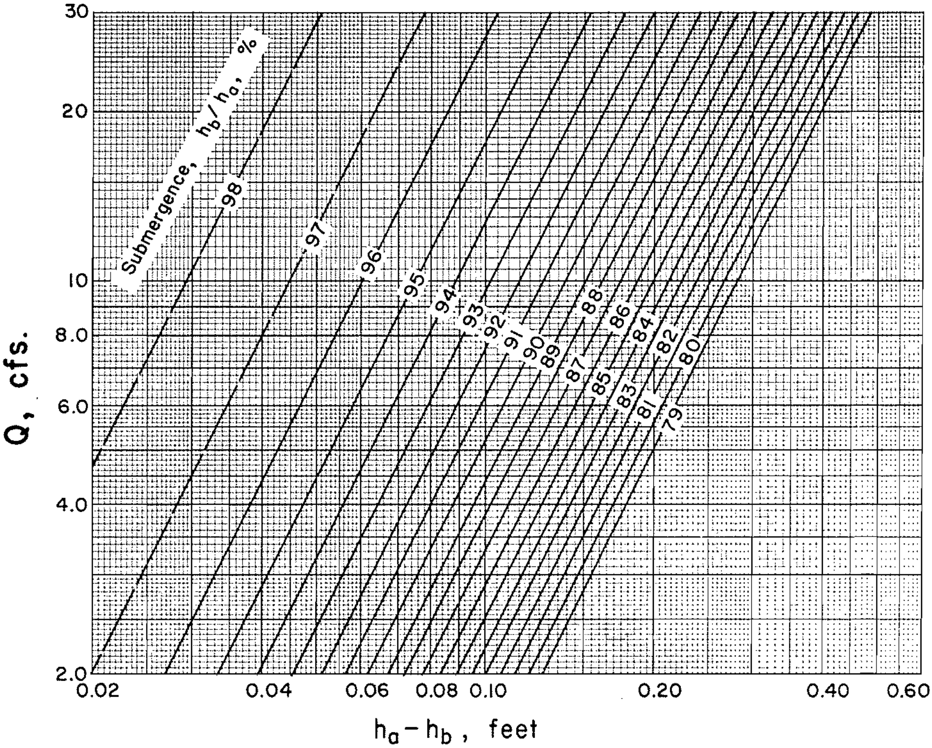


Fig. 18. Submerged flow calibration curves for 12-inch trapezoidal cut-throat flume.

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. If operating conditions require frequent changing of the discharge, the flume may be conveniently located near a point of diversion or regulating gate. However, care should be taken to see that the flume is not located too near a gate because of unstable or surging effects which might result from the gate operation.

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. 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 play a determining role in the flume size selected. The following example is illustrative of the installation factors discussed above.

Example 4: Suppose the logical rectangular cutthroat flume size necessary to measure a maximum discharge of 12.5 second-feet under free flow conditions must be found. Presently, the maximum flow depth in the canal is 0.95 foot and the head loss is not to exceed 3 inches (0.25 foot). Under these conditions, the maximum downstream flow depth would be 0.95 foot and the maximum upstream flow depth 1.20 feet ($0.95 + 0.25 = 1.20$). The submergence would be 79 percent ($0.95 \div 1.20 = 0.79$). Checking Table 1, we find that the transition submergence for all the rectangular cutthroat flumes is equal to, or greater than, 79 percent. Hence, any one of the flumes could be selected. However, the transition submergence for the 1-foot flume is 79 percent, and caution should be used in selecting this flume size since any future changes in the canal system could result in submerged flow conditions. To select the proper flume size, enter Table 2 under 1.5-foot flume to obtain the value of h_a corresponding to a discharge of 12.5 cfs. For this discharge value, the upstream depth is 1.74 feet which is greater than the allowable maximum upstream depth of 1.20 feet. Hence, the 1.5 flume will have the capacity to measure the desired discharge, but will produce too great a head loss ($1.74 - 0.95 = 0.79$ foot). Consequently, a larger flume size is necessary to satisfy the imposed conditions. The 2- and 2.5-foot flumes have h_a values of about 1.44 feet and 1.24 feet, respectively, for a discharge of 12.5 cfs, both of which are greater than the allowable depth of 1.20 feet. The 3-foot flume has an upstream depth of 1.18 feet for a discharge of 12.5 cfs, and since this value is less than the restrictive depth of 1.20, it would be selected for use in this particular situation. The 4-foot and larger flumes could also be used but the economic factors would make their selection undesirable.

Example 5: Suppose in the preceding example the present conditions are such that placement of a 2-foot rectangular cutthroat flume is a necessity. Entering Table 2 under a 2-foot flume, the upstream depth which corresponds to the discharge value of 12.5 cfs is about 1.44 feet. The maximum downstream depth of flow is given as 0.95 foot. The head loss resulting from operating this flume under the imposed conditions is 0.49 foot (1.44 - 0.95 = 0.49). The previous example states the head loss must not exceed 3 inches, but placing the 2-foot flume will exceed this by 0.24 foot (0.49 - 0.25 = 0.24). Hence, to place this particular flume into the canal under these conditions, it will be necessary to raise the canal banks upstream from the flume. The canal banks must be raised 0.24 foot plus whatever freeboard allowance is considered desirable. As mentioned before, the only other alternative would be the use of a larger flume which would produce a resulting decrease in head loss.

Proper installation requires the flume be placed level in the channel. The flume should be aligned straight with the channel and should be level longitudinally and laterally. Note that with time the tendency is for the flume to settle with the exit becoming lower than the entrance.

For a rectangular cutthroat flume whose width, W, does not conform with the standard sizes listed in this report, the free flow discharge table or curve can be obtained from Eqs. 1 and 2. An example will illustrate the technique.

Example 6: Assume a free flow calibration is needed for a rectangular cutthroat flume with a width, W, of 2.20 feet. The value of C required in Eq. 1 can be computed by substituting 2.20 for W in Eq. 2

$$C = 3.50\ (2.2)^{1.025} = 3.50\ (2.224) = 7.85 \quad . \quad . \quad . \quad 6$$

Substituting 7.85 for C in Eq. 1, the free flow equation becomes

$$Q = 7.85\ h_a^{\ 1.56} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 7$$

From Eq. 7, the calibration tables for the 2.2-foot flume can be obtained. Thus, if the h_a gage reading were 1.87 feet, then the discharge, Q, could be computed.

$$Q = 7.85\ (1.87)^{\ 1.56} = 7.85 \times 2.65 = 20.80 \text{ cfs.}$$

The procedure to follow for obtaining the submerged flow calibration curves for a rectangular cutthroat flume of width, W, is as follows.

1. Determine the throat width, W, at the flume neck.

2. Enter Fig. 19 on the left with the flume size, W, obtained in step 1 and move horizontally to the right across the lines of constant submergence. Note in Fig. 19 that the lines of constant submergence, up to a value of 88 percent, terminate on the flume size which has a corresponding value of transition submergence.

3. At the intersection of each line of submergence, move vertically downward and obtain the $C_{0.1}$ intercept corresponding to each submergence. The $C_{0.1}$ intercept is the value of Q when h_a - h_b is equal to 0.10 foot.

4. On log-log paper, enter the horizontal axis with an h_a - h_b value

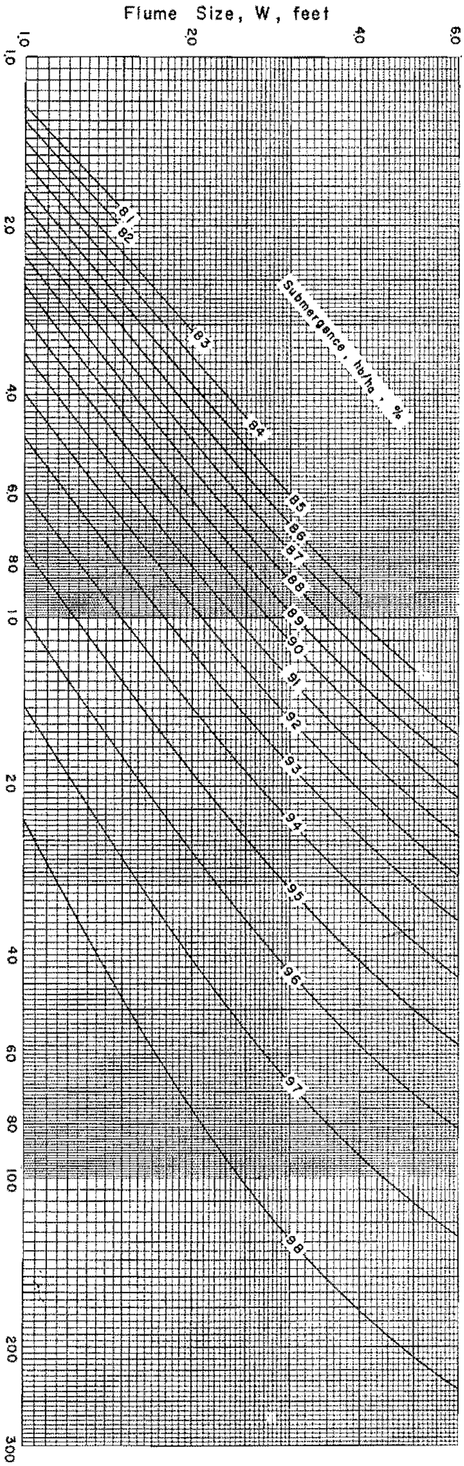


Fig. 19. Relation between flume size and submergence for rectangular cutthroat flumes.

of 0.10 and move vertically upward plotting each $C_{0.1}$ as Q. List the value of submergence on each plotted point.

5. Draw a line with a slope of 1.56 through each plotted point to obtain a complete set of calibration curves.

The following example will further illustrate and explain the above procedure.

> **Example 7:** Assume now a set of submerged flow calibration curves is desired for a rectangular cutthroat flume with a width, W, of 2.20 feet. Fig. 19 is entered from the left with a flume size of 2.2. Moving horizontally to the right, the $C_{0.1}$ values are obtained for each submergence value and are tabulated in the corner of Fig. 20. With the range of ordinate and abscissa values obtained, comparable to those in Figs. 7 through 14, the $C_{0.1}$ values are placed on Fig. 20 by moving vertically upward on the h_a - h_b line of 0.10. The line of constant submergence is drawn through each $C_{0.1}$ point at a slope of 1.56 and the corresponding submergence value is labeled on the line. The complete family of parallel lines constitute the submerged flow calibration curves for the 2.2-foot rectangular cutthroat flume.

Measurements may be made in the flume by the use of staff gages or stilling wells. Only fair accuracy is obtained from the use of staff gages. 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 accuracy. 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.

Flume Installation to Insure Free Flow

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 discharge tables (Tables 2, 4, 5, and 6), select the proper 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 x h_a) below the high water

line (Fig. 21). Generally, the flume bottom should be placed as high in the canal as grade and other conditions permit to insure free flow.

Example 8: The 12-inch trapezoidal flume shown in Fig. 21 has a transition submergence of 79 percent. The maximum discharge in the canal is 20 cfs, which for free flow conditions corresponds to an h_a value of 1.90 feet. Multiplying h_a (1.90) by the transition submergence (0.79), gives a depth to the flume floor of 1.50 feet (1.90 x 0.79 = 1.50). Therefore, the flume crest should be set no lower than 1.50 feet below the

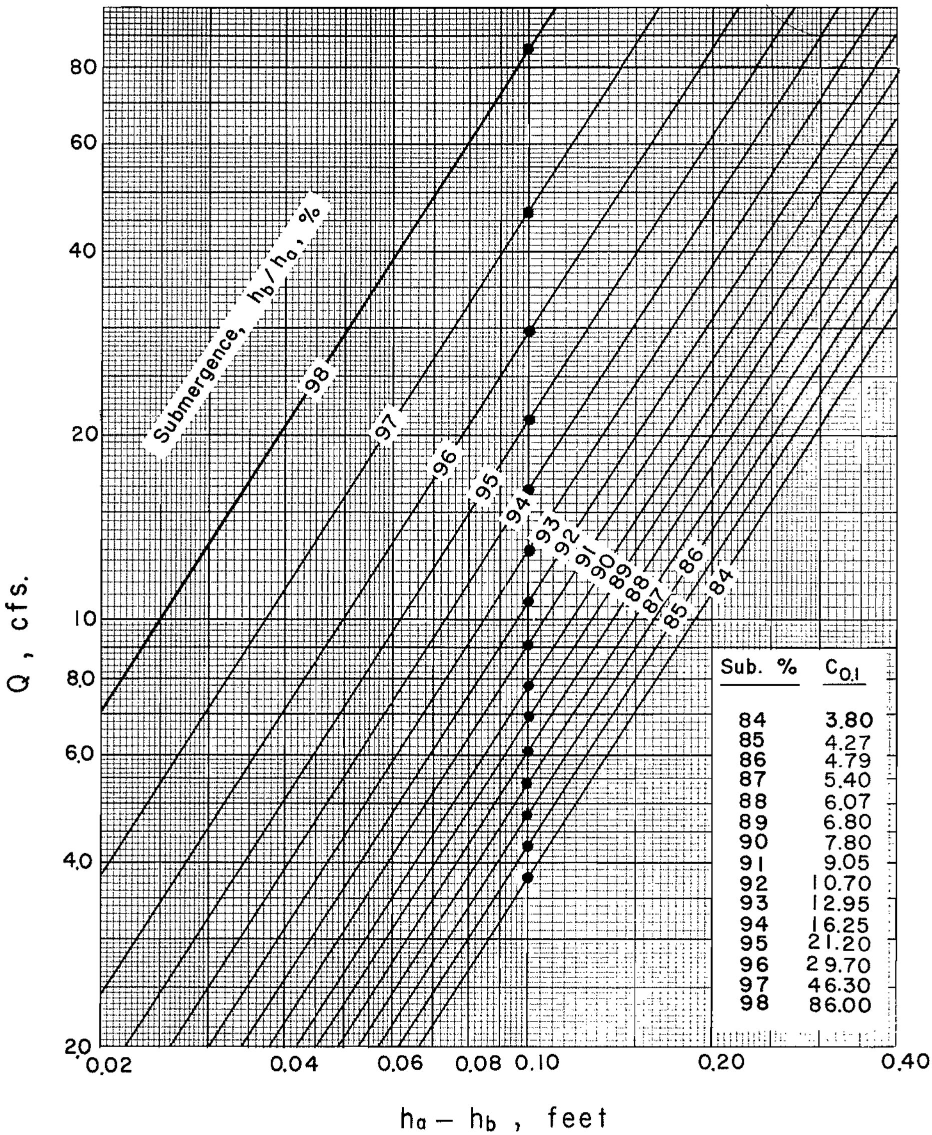


Fig. 20. Development of submerged flow calibration curves for 2.2-foot rectangular cutthroat flumes.

original maximum water surface (Fig. 21) that existed prior to installing the flume. The loss of head through the structure will be the difference between 1.90 feet and 1.50 feet, which is 0.40 foot, as shown in Fig. 21. A larger flume can be used if the head loss is too great.

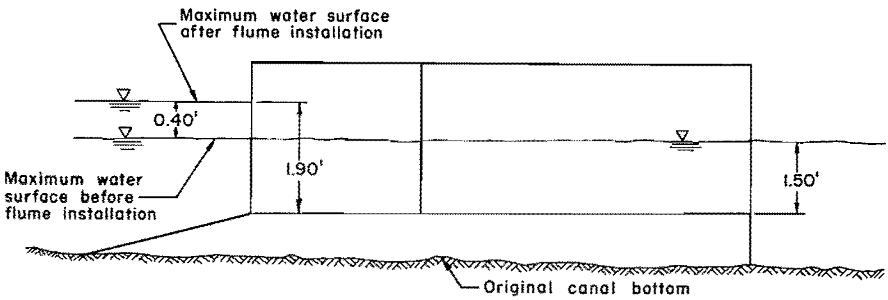


Fig. 21. Illustration of the installation of a 12-inch trapezoidal cutthroat flume to operate under free flow conditions.

Flume Installation for Submerged Flow

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. This reduction in head loss may mean that the canal banks upstream from the flume do not have to be raised to enable the same maximum flow capacity in the canal that existed prior to the installation of the flume. 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 upstream from the flume, 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 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 submerged flow calibration curves by trial and error. 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 calibration curves. The trial and error procedure for selecting the size of flume can be illustrated with the following example.

Example 9: 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 feet. With the amount of existing freeboard in the canal, it is felt that the water surface should not be raised more than 0.2 foot, thereby resulting in a maximum flow depth of 2.0 feet (1.8 + 0.2 = 2.0) upstream from the flume after installation. Therefore, for purposes of selecting the flume size,

h_b = 1.8 feet
h_a = 2.0 feet
h_a - h_b = 0.20 foot
h_b/h_a = 1.8/2.0 = 0.90 = 90%

As a beginning point, enter the submerged flow calibration curves of a 2-foot rectangular cutthroat flume (Fig. 9). With the h_a - h_b value of 0.20 foot, move vertically to the submergence line of 90 percent, and then read the discharge to the left as 20.1 cfs. Since this flow rate (20.1 cfs) is less than the maximum flow rate (28 cfs), a larger flume is required.

Entering the submerged flow calibration curves for a 2.5-foot rectangular cutthroat flume (Fig. 10) with h_a - h_b = 0.20 foot, move vertically to the 90 percent submergence line, and read the discharge as 26.5 cfs. Again, the flow rate is less than the design maximum flow rate of 28 cfs, and a larger cutthroat flume is required.

Entering the submerged flow calibration curves for a 3-foot rectangular cutthroat flume (Fig. 11) with h_a - h_b = 0.20 foot, move vertically to the 90 percent submergence line, and read the discharge as 32.0 cfs. Since this flow rate (32.0 cfs) is larger than the maximum flow rate in the canal (28 cfs), a 3-foot rectangular cutthroat flume may be used.

Example 10: Suppose a trapezoidal cutthroat flume were desired for placement in the canal instead of the rectangular flume. The same conditions as given in Example 9 exist. The solution to this problem is found by entering submerged flow calibration curves for the 12-inch trapezoidal cutthroat flume (Fig. 15) with h_a - h_b = 0.20 foot. Move vertically to the 90 percent submergence line and then read the discharge to the left as 20.7 cfs. This flow rate (20.7 cfs) is less than the maximum flow rate expected in the canal (28 cfs), so a larger trapezoidal cutthroat flume would be required for this situation. Since no calibration curves are available for larger trapezoidal cutthroat flumes, placement of the trapezoidal flume would be impossible unless the existing design conditions were altered in some way or testing was conducted on larger trapezoidal flumes. Worthy of note, a 12-inch trapezoidal cutthroat flume has a discharge capacity greater than the 2.0-foot rectangular cutthroat flume (20.7 cfs as opposed to 20.1 cfs) for the same given set of conditions.

MAINTENANCE OF CUTTHROAT FLUMES

Once proper installation has been assured, periodic maintenance will insure continued satisfactory operation. Moss which may have collected 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 any further encrustation.

After a few months of operation, and at the end of the season or year, it is wise to check the flume bottom 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 with fair accuracy. For the flume tilting sideways, the adjustment is made by taking the average of the depths of flow measured on each side of the flume for use in the rating tables or 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 caused by 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.

SUMMARY

Cutthroat flumes having a rectangular or trapezoidal shape have been developed, and their role in water measurement, along with the advantages of their use are discussed. The dimensions and criteria for constructing cutthroat flumes are given. The differences between free flow and submerged flow conditions are discussed, along with the necesasry criteria for determining which flow regime exists. The value of transition submergence is listed for each of the rectangular and trapezoidal cutthroat flumes which were investigated in the laboratory. The free flow analysis and tables are presented for the cutthroat flumes studied as are the three-dimensional calibration curves which are used when submerged flow exists in the flumes. Examples are given which illustrate the free and submerged flow operation. Proper installation and maintenance procedures for cutthroat flumes are described, as well as techniques for measuring flow depths which will yield satisfactory results.

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