TRANSITION SUBMERGENCE AND HYSTERESIS EFFECTS IN THREE-FOOT CUTTHROAT FLUMES

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ABSTRACT

New and detailed hydraulic laboratory measurements for a 3-foot Cutthroat flume with four different throat widths were collected and analyzed. It was found that there is no definitely observable transition submergence at which the regime changes from free to submerged, and vice versa. It was also found that no hysteresis effect on the calibration is observable in the 3-ft Cutthroat flume when moving from low to high submergence, or from high to low submergence.

The laboratory data demonstrate that previously published transition submergence, S_t, values do not accurately describe the hydraulic behavior of this Cutthroat flume because S_t is not constant for given flume dimensions – it varies with flow rate. Various criteria were applied to the laboratory data to define the curvilinear relationship of S_t with flow rate, thereby providing a more accurate application of the traditional free- and submerged-flow equations, in those cases where their continued use is desired. The observed S_t at the maximum discharge in each of the four throat widths was strongly correlated with the previously published S_t values.

INTRODUCTION

The methods and devices available for flow measurement in open channels are abundant, from procedures that only involve measure-at-a-glance, to complex structures inside canals. The selection of any of the many different methods and devices is contingent upon the required accuracy. One such device is a measurement flume. Flumes are often permanent structures and have the relative advantage of a low hydraulic head loss, compared to free-flow, sharp-crested weirs. Perhaps the most representative flume by its ubiquity is the Parshall flume (USBR 2001); nevertheless, the installation and construction of this flume can be complex, requiring a special calibration if the installed Parshall has a non-standard size.

On the other hand, the Cutthroat flume, so named because of its absence of a throat length in the structure (Skogerboe et al. 1993), presents some advantages compared to the Parshall flume due to its easy construction and installation, and its accuracy to measure discharge under free- and submerged-flow conditions.

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Cutthroat Flume Characteristics

The Cutthroat structural design can be described as a rectangular flat-bottom flume with a narrowing section (throat), but lacking a throat length (Fig 1). This device is composed of two sections: the inlet converging section and the outlet diverging section. The narrowing section creates the transition from subcritical to critical flow (under free-flow conditions), a situation required to define a unique head-discharge relationship in which the downstream hydraulic conditions do not affect either the upstream water depth or the discharge.

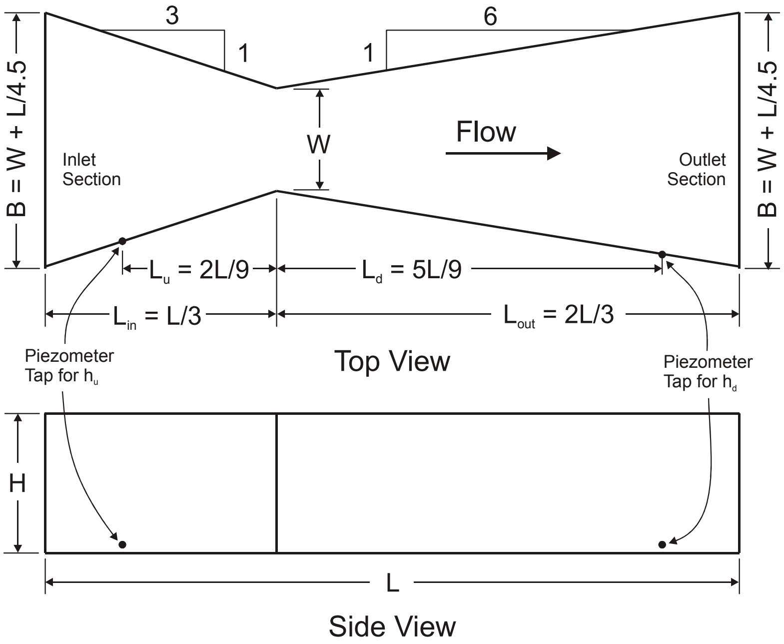


Figure 1. Cutthroat flume dimensions

Equation 1 relates water depth and discharge under free-flow conditions (Weber et al. 2006):

$$Q_f = C_f W h_u^{n_f} \tag{1}$$

where Q_f is the flow rate; C_f and n_f are calibration coefficients; and, h_u is the measured upstream water depth. The units of Q_f and h_u are typically m^3/s and m, or cfs and ft, respectively. The subscript “f” indicates free-flow conditions.

Under free-flow conditions, critical flow occurs in the vicinity of the flume throat, and any changes in downstream hydraulic conditions do not affect either the discharge or the upstream water depth. Under submerged-flow conditions, critical flow does not occur in the flume, and any change in the downstream water depth directly affects both the upstream depth and the discharge. Submerged-flow conditions require the measurement of both the upstream and downstream water levels, and the determination of the submergence value to estimate discharge. The measurement accuracy of the flume decreases under submerged-flow conditions.

Herein, submergence is defined as the ratio of downstream to upstream water depth. In equation form,

$$S = \frac{h_d}{h_u} \tag{2}$$

where S is submergence; h_d is downstream depth (m or ft); and, h_u is upstream depth (m or ft). The two depths are measured from a common elevation datum, and in the case of a Cutthroat flume this is the elevation of the floor (which should be level).

Transition submergence, S_t, is the value of S at which a free-flow equation will yield exactly the same discharge value as a submerged-flow equation for a given structure. It is the threshold which distinguishes between application of one equation or the other to define the relationship between flow rate and depth(s). Thus, the definition of transition submergence is an important part of the complete calibration for a flow measurement structure in open channels.

In the case of submerged-flow, the traditional calibration equation is (Skogerboe et al. 1967):

$$Q_s = \frac{C_s W (h_u - h_d)^{n_f}}{(-\log_{10} S)^{n_s}} \tag{3}$$

where Q_s is the flow rate; C_s and n_f are free-flow calibration coefficients; n_s is submerged-flow calibration coefficient, h_u and h_d are the water depths, measured upstream and downstream of the flume, respectively; and, S is the submergence. As in Eq. 1, the values of Q_s and h_u are depend on the chosen units (e.g. m^3/s and m, or cfs and ft).

Equation 3 involves downstream conditions when the actual submergence is greater than or equal to the transition submergence. Thus, the conditions at the diverging outlet section of the flume affect the upstream water depth, having effects on the upstream depth and the flow rate.

The transition submergence is determined by equating Eqs. 1 and 3, where $Q_f = Q_s$. The equation to define S_t can be written by equating the discharge values from the free- and submerged-flow equations (Weber et al. 2006):

$$C_f \left(-\log_{10} S_t\right)^{n_s} = C_s \left(1 - S_t\right)^{n_f} \tag{4}$$

where all of the variables were defined in Eqs. 1 and 2. Using a trial-error procedure, an S_t value can be determined from Eq. 4. The value of S_t has been considered to be unique for a given Cutthroat flume size; and published calibration tables give S_t values exclusively as a function of throat width (Skogerboe et al. 1967). However, recent research (Weber et al. 2006) supports the idea that the S_t value actually manifests significant variability, not only with throat width and flume length, but also with discharge.

Hysteresis Phenomenon

The hysteresis phenomenon was defined by the USBR (2001) as the maximum difference between water measurement readings of a quantity, in this case discharge, for a given value of submergence. For the present purposes, hysteresis is the potential difference in flow rate for a given submergence, depending on whether the submergence value was arrived at by increasing or decreasing the downstream water depth. It has been reported that a hysteresis phenomenon occurs in some Parshall flumes, causing a variation of +3% to +5% in measurement accuracy (USBR 2001). A study of submerged flow in Parshall flumes (Peck 1988) found considerable difference among discharges by a 1-ft Parshall equation and laboratory data, as shown in Fig 2.

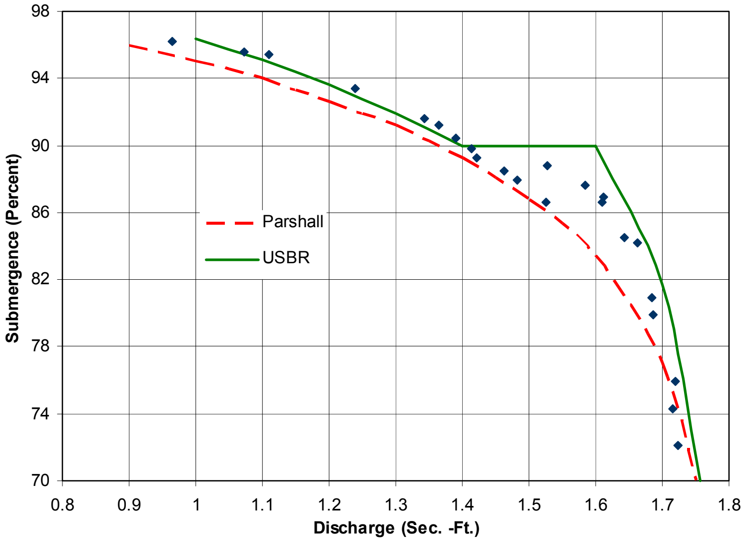


Figure 2**.** Relationship between discharge and submergence for a 1-ft Parshall flume (Peck 1988)

Figure 2 presents the relationship between the submergence and the discharge (cfs) for a given upstream water depth. The plotted data present a discharge discontinuity which is especially evident in the 0.78 and 0.88 submergence range, where hysteresis occurs (Q ≈ 1.52 cfs). This phenomenon has not been reported in the technical literature for a Cutthroat flume.

EXPERIMENTAL DESIGN

A 3-ft throat adjustable, acrylic Cutthroat flume was installed in a 24 x 3 x 3-ft rectangular flume at the Utah Water Research Laboratory, as seen in Fig. 3. The Cutthroat flume used in this research had a 3-ft length, with adjustable throat-width values of 4, 8, 12, and 16 inches. The Cutthroat flume also included piezometer taps located on the sidewalls. The piezometer taps were located 0.5 inches above the floor of the Cutthroat flume. The piezometric head at each tap was measured on a manometer board which was attached to the outside of the rectangular flume. Clear ¼-inch I.D. plastic tubes were installed from the taps to the manometer board.

Figure 3. Photograph of the laboratory setup

The 12- and 4-inch water supply pipes had sharp-edged, circular orifice plates connected to a differential manometer to measure the discharge entering the 3-ft rectangular flume during operation. The bed slope of the rectangular flume was measured and leveled to zero in the longitudinal and transverse directions. A tailgate at the end of the rectangular flume was used to change the water depth downstream. Four throat widths (W) were used, beginning with the 16-inch width, and progressively decreasing to 12, 8, and 4 inches. Fifteen different free-flow upstream depths, h_{uf}, (initial condition) were used for each throat width:

0.13, 0.20, 0.26, 0.33, 0.39, 0.46, 0.52, 0.59, 0.66, 0.72, 0.79, 0.85, 0.92, 0.98, 1.02 ft

Each series of measurements for a constant flow rate began with the tailgate in the completely lowered position: this provided free-flow conditions. The initial information was recorded: flume throat, water temperature, and supply water pipe used. Measurements of h_u and h_d were taken from a water manometer attached to the flume taps and additional manometer readings were taken from the supply pipe orifice plate to determine the flow rate after the 10-min time lag. Following this, the tail gate was raised slightly, and a new set of measurements were taken after observing that steady-state conditions have been reestablished. This process was continued for the given flow rate (which was constant) until the regime became submerged, at which point the tail gate continued to be raised, taking additional measurements until the upstream depth was nearly equal to the Cutthroat flume wall height, and/or the submergence exceeded 0.995.

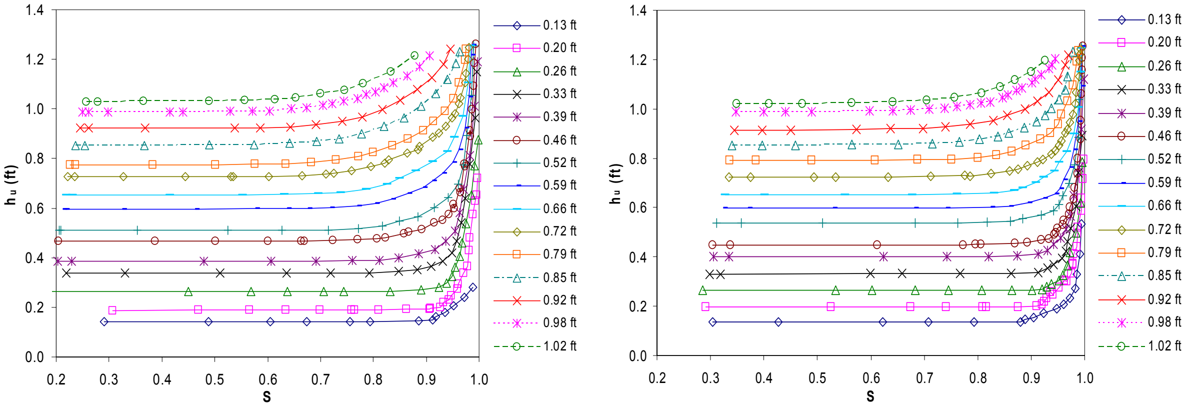
For h_{uf} values of 0.13, 0.46, 0.72, and 0.98 ft, once the maximum submergence value was reached, the tail gate was incrementally lowered, taking the same manometer measurements described above, until the regime was obviously free flow (it was never necessary to lower the tail gate completely to return to free-flow conditions). After completing measurements for all of the free-flow upstream depth, h_{uf}, values for a given throat width, the throat width was changed to the next smaller value and the same procedure was repeated. This was continued until the required measurements had been taken for all four throat widths on the 3-ft Cutthroat flume.

All measurements were taken under steady-state flow conditions. Thus, after a change in the tail gate position, a waiting period of at least ten minutes was found to be necessary to ensure steady-state hydraulic conditions before recording manometer readings. The 4-inch or 12-inch supply pipe to the 3-ft rectangular flume was used, as appropriate, depending on the flow rate.

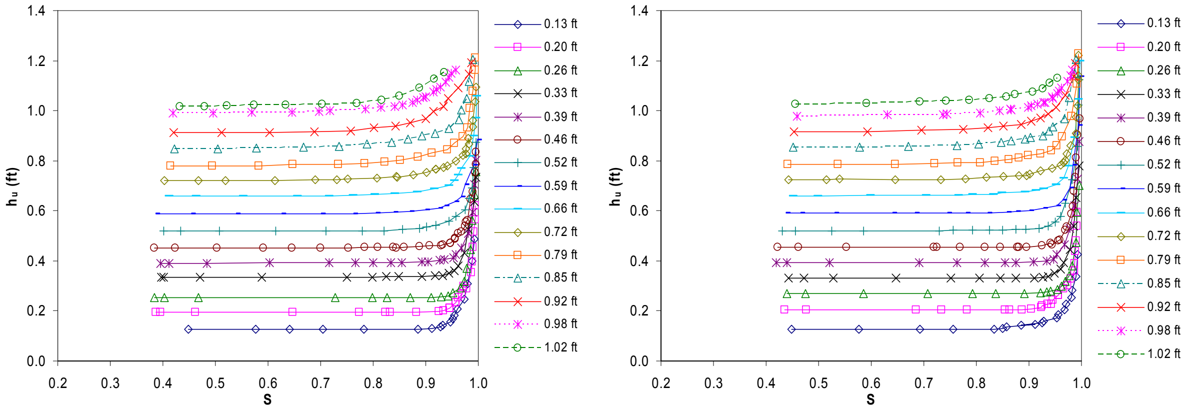
RESULTS

Cutthroat Flume Hydraulic Data

The data obtained for each throat size are shown in Fig. 4. Each curve can be identified by the initial upstream water depth (h_{uf}) initially considered (0.13, 0.20, 0.26, 0.33, 0.39, 0.46, 0.52, 0.59, 0.66, 0.72, 0.79, 0.85, 0.92, 0.98, 1.02 ft). Some characteristics related to the data shown in Fig. 4 are listed below:



(a) W = 4 inch (b) W = 8 inch



(c) W = 12 inch (d) W = 16 inch

Figure 4. Measured upstream water depth (h_u) and submergence (S)

- Each curve showed in the plots corresponds to a fixed and unique steady-state discharge. The “curves” in these plots are actually straight line segments which connect the data points;
- Each curve is composed of two sub-curves: one that describes a horizontal line (constant h_u value with respect to submergence, S) corresponding to free-flow conditions; and another sub-curve that shows an h_u increment related to the increase in submergence (submerged-flow condition);
- The threshold (transition) submergence between the horizontal and curved segments is different for each constant-discharge curve;
- The change from horizontal to curved lines in the curves is smooth and gradual, not presenting an abrupt change (i.e. no sudden change from free to submerged flow);
- Low-discharge curves (h_{uf} values of 0.13 and 0.20 ft) behave differently compared to the other curves for higher discharges for each of the four Cutthroat flume widths; and,
- Above a submergence of 0.95, the h_u values increase rapidly with submergence.

These characteristics help to define the data to be used in a transition submergence analysis:

- Omission of 0.13- and 0.20-ft data; and,
- Use of the rest of the data up to a maximum submergence of 0.95.

Traditional Free- and Submerged-Flow Equation Calibrations

With the collected data and the two constraints mentioned above, the calibration of the traditional free- and submerged-flow equation was accomplished. For the free-flow equation, the first upstream water depth measured per discharge and throat width was taken, giving 15 pairs of points (Q and h_u) per throat width. Subsequently, a logarithmic transformation and a linear regression were performed, whose resultant parameters were appropriately transformed in order to obtain the coefficients for the free-flow equation (Eq. 1).

The calibration of the submerged-flow equation was performed similar to the free-flow procedure. In this case, a logarithmic transformation of Eq. 3 was performed, giving Eq. 5:

$$-n_s \log_{10}(-\log_{10} S) + \log_{10}\left(C_s\right) = \log_{10}(Q_s) - n_f \log_{10}(h_u - h_d) \qquad (5)$$

The data used to obtain the submerged-flow equation parameters were: discharge, submergence, and difference between upstream and downstream water levels (head differential), all with an $S \leq 0.95$ constraint. Based on the concepts and equations presented in the Introduction section, the coefficient values for the free- and submerged-flow equations were found.

Transition Submergence from the Free- and Submerged-Flow Equations

The estimation of transition submergence between these two flow conditions was accomplished using Eqs. 1 and 3. For the traditional equation forms, the transition submergence was found using a procedure described by Skogerboe et al. (1993). Nevertheless, it cannot be assumed that

S_t takes a single value for a given Cutthroat flume size, as can be seen in Fig. 4. Thus, despite the logical procedure followed for the traditional equations to obtain the submergence threshold value, the results do not correctly interpret the submergence threshold between free- and submerged-flow conditions. The estimated S_t values from the traditional and modified equations are presented in Table 2.

Table 2. Transition Submergence Values from the Free- and Submerged-Flow Equations

Equations	**W (inch)**			
	4	**8**	**12**	**16**
Published Values	0.58	0.67	0.75	0.82
Traditional FF and SF	0.65	0.73	0.79	0.77

Note: FF = free flow; SF = submerged flow

Equation Development

As seen in Fig. 4, the transition submergence cannot be defined as a single value as in traditional practice, given the visual difference among the laboratory data and a constant S_t value. This situation invites the development of new way to describe free- and submerged- flow conditions. The characteristics that the new equation must describe are:

- A horizontal line (constant h_u) for any submergence value in the free-flow range; and,
- A concave curve, where the h_u value increases as a function of the submergence and discharge in the submerged-flow range, approaching the vertical at S = 1.0.

Given the characteristics that the new flow equation must account for, the empirical equation selected (among several alternatives) for this research is:

$$h_u = h_{uf} + \left(\frac{aQ + b}{\left[\ln\left(cQ + dS^e \right) \right]^f} \right) \tag{6}$$

The values of h_u and Q were described by Eqs. 1 and 3, h_{uf} is the upstream water depth for free-flow conditions; and, the letters a, b, c, d, e, and f represent fitted equation parameters. The value of h_{uf} is defined by Eq. 1. The results from the statistical analysis are shown in Table 3, and the calibration parameters for Eq. 6 are given in Table 4.

Table 3. Statistical Equation Analysis Summary (all throat widths)

			Percentage of total data fitted		
Total data points	**Mean r^2**	**SSR**	**Error < 1%**	**Error < 3%**	**Error < 5%**
706	0.999	0.032	75%	97%	99%

Notes: r^2 is the coefficient of determination. SSR is the sum square of residuals

Table 4. Calibration Parameters for Eq. 6

	Equation 6 Parameters					
W (in)	**a**	**b**	**c**	**d**	**e**	**f**
4	5.47	-0.29	10.60	3.54	-20.15	2.66
8	13.50	-2.59	0.05	13.61	-10.65	4.32
12	8.11	-0.11	0.03	26.05	-15.77	3.94
16	0.89	0.03	0.04	13.58	-19.72	3.09

Transition Submergence from the Newly Proposed Equation

Once the proposed equation was calibrated for each of the four throat widths, it was possible to define the transition submergence for each. The value of the submergence that was considered as the threshold between free- and submerged-flow conditions was specified as the submergence value that, when used in the derivative of the equation, gives a specified slope value (Eq. 7).

$$S_0 = S_t \Leftrightarrow f'(S)\Big|_{S=S_0} = m \tag{7}$$

where S_o is the submergence value to be considered as the transition submergence (S_t), considering that when S_o is used in the first derivative of the equation, the result is a fixed slope value, m. One important parameter at this point is the derivative value of the equation. This value should be constant for all the equations regardless of the Cutthroat flume throat width, and must accurately define the submergence threshold for all the curves to be considered as the transition submergence. Furthermore, the value of the slope to be selected should improve the accuracy of the traditional free- and submerged-flow equations by the use of the submergences estimated based on the selected slope.

To determine the most appropriate slope for the definition of transition submergence, five different values were considered: 5.0%, 7.5%, 10.0%, 12.5%, and 15.0%. Based on the submergence values obtained using these slope values, SSR values from the traditional free- and submerged-flow equations were calculated. The results are shown in Figs. 5 and 6.

From Fig. 5, it is evident that the SRR values increases for the minimum slope value (right side of Fig. 5) since the submerged-flow equation is in the free-flow range. The SSR values indicate that the traditional free- and submerged-low equations reach a minimum SSR value with a slope value of 10%. This indicates the appropriateness of Eq. 6 as model that adequately represents the measured data. From these results (Fig. 6), it is evident that Eq. 6 more accurately describes the location where transition submergence occurs along the curves described by the laboratory data. This characteristic, plus the high correlation among predicted and measured S versus h_u and discharge data, indicates the advantage of applying Eq. 6 instead of the separate free- and submerged-flow equations which have been traditionally used to calibrate 3-ft Cutthroat flumes.

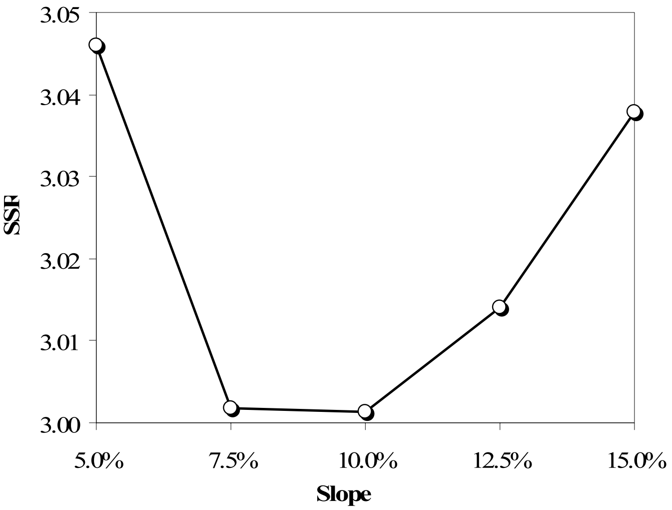


Figure 5. Accumulated SSR from the proposed equation per slope value (all throat widths)

Hysteresis

Based on the data collected during this research, it was possible to analyze the existence (or lack thereof) of the hysteresis phenomenon, considering data of those discharges for which the tailgate at the end of the rectangular flume was raised and lowered. These discharges, expressed by the upstream water depth, are the following for each of the four throat widths: 0.20, 0.46, 0.72, and 0.98 ft. The criterion behind this 4 discharge selection was to adequately distribute the data collection for hysteresis among all 15 upstream water depths considered for the research, in order to accurately describe the hysteresis effects, in case this phenomenon really occur in Cutthroat flumes. The data are given in Fig. 7.

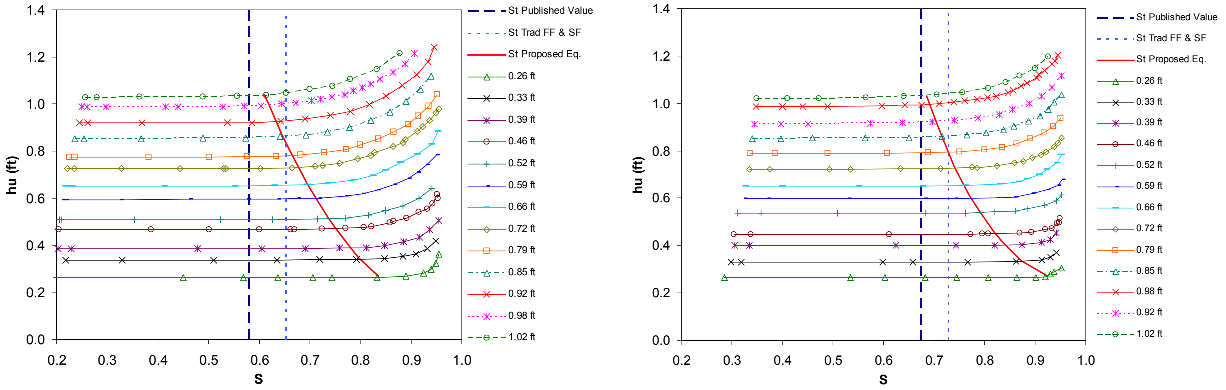
It is easy to observe (Fig. 7) that a detectable hysteresis phenomenon does not occur for any of the data values collected for the 3-ft Cutthroat flume. The minimal differences that appear at the data plots are related to the water movement by effect of the hydraulic jump downstream of the Cutthroat flume, and to the accuracy of the readings done, being these differences not significant to assure in a definitive way that this phenomenon should be considered present at Cutthroat flumes.

SAMPLE APPLICATIONS

The following are examples of the recommended use of these research results in practical flow measurement applications. The example is for the traditional forms of the free- and submerged-flow equations using transition submergence values from Eq. 6 as threshold between free- and submerged-flow conditions.

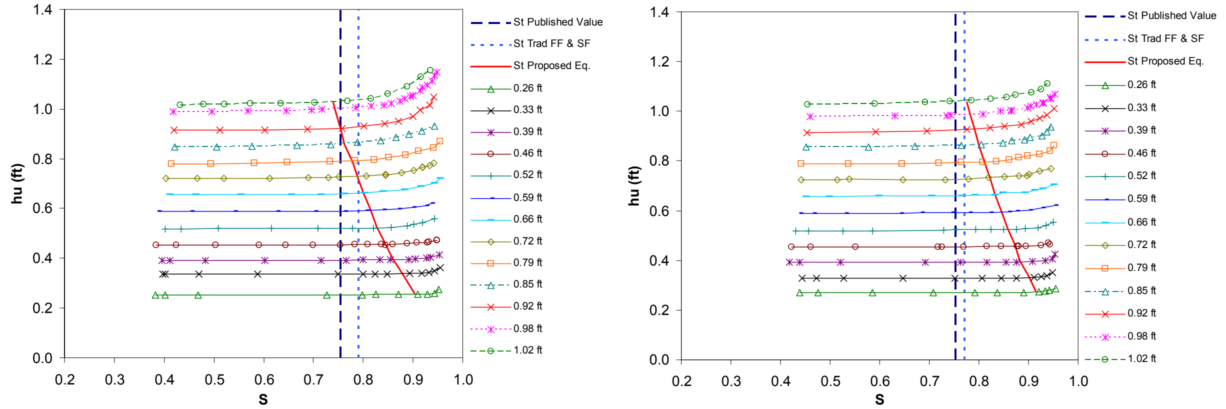
Use of Submergence Values from Eq. 6

The initial condition for this procedure is the data collection under free- and submerged-flow conditions as described in the Introduction section. Based on these data, the calibration of the traditional free- and submerged-flow equations and Equation 6 can be done. In this example, data from the 4-inch Cutthroat flume throat width will be used. Based on the results of the calibration previously done, transition submergence values from Eq. 6 are obtained using a fixed slope of 0.10 and several upstream water depths, h_u, creating an S_t range from small to the large discharges, and obtaining a graph similar to that shown in Fig. 8.



(a) W = 4 inch

(b) W = 8 inch



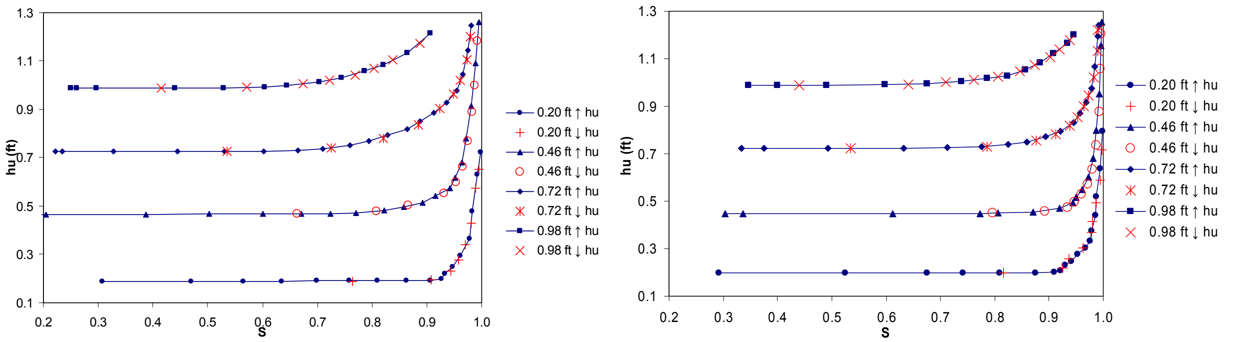
(c) W = 12 inch

(d) W = 16 inch

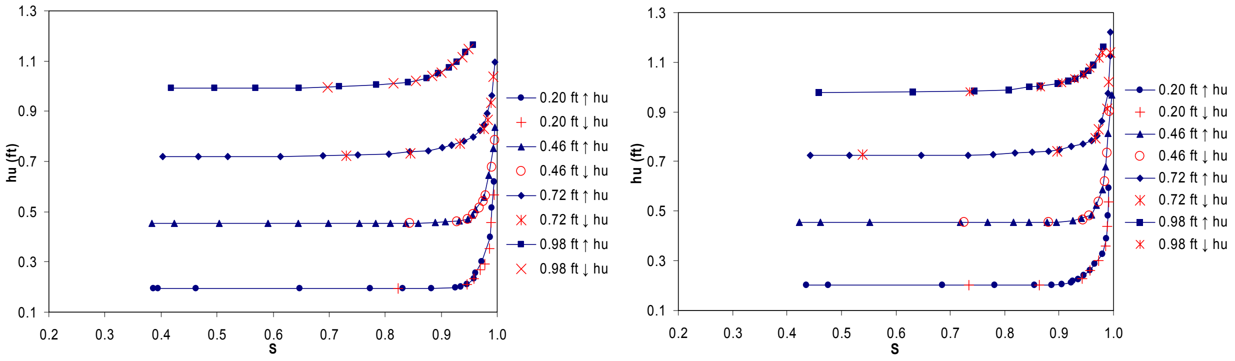
Figure 6. S_t behavior from published values and traditional and proposed equations

In Fig. 8, the S_t - h_u curve for a 4-inch throat width allows the differentiation between free- and submerged-flow regions where the respective traditional equations (Eqs. 1 and 3) can be applied. Also, it is possible to establish an accurate mathematical relationship between S_t and h_u, as shown in Fig. 8, obviating the need for a graphical determination of S_t and the water flow condition to consider.

To estimate the discharge in the 4-inch throat width using the S_t values from Eq. 6, it is necessary to measure the water depth both upstream and downstream in the Cutthroat flume. In this example, the data obtained for two Cutthroat flumes with W = 4 inches were:



(a) W = 4 inch (b) W = 8 inch



(c) W = 12 inch (d) W = 16 inch

Figure 7. S-h_u curves - increasing (↑) –decreasing (↓) submergence

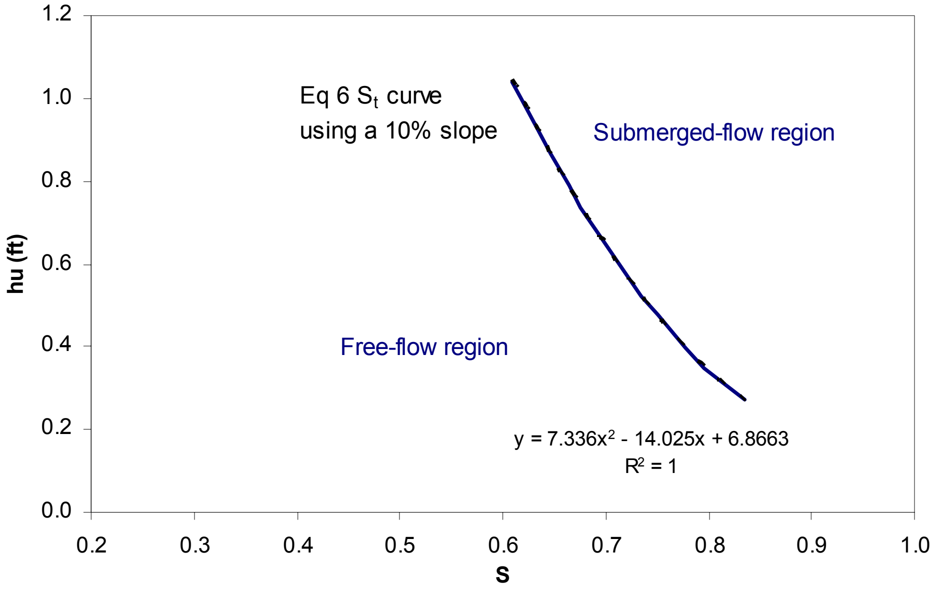


Figure 8. Equation 6 S_t values and correlation (W = 4 inches)

Cutthroat 1	Cutthroat 2
h_u : 0.56 ft, h_d : 0.24 ft	h_u: 0.70 ft, h_d: 0.60 ft

Then, the submergence is calculated for each are:

S : 0.43	S: 0.86

Figure 9 is obtained by plotting these two points on Fig. 8. It can be observed that the flow condition for Cutthroat flume 1 is free-flow, and the second flume is in a submerged-flow condition. Thus, it is possible to apply the respective equations to determine the discharge in each case:

For Cutthroat flume 1:

$$Q_f = C_f W h_u^{n_f} = 4.197(0.333)(0.56)^{1.685} = 0.527 \text{ cfs} \tag{8}$$

For Cutthroat flume 2:

$$Q_s = \frac{C_s W (h_u - h_d)^{n_f}}{(-\log_{10} S)^{n_s}} = \frac{2.595(0.333)(0.70 - 0.60)^{1.685}}{(-\log_{10} 0.86)^{1.335}} = 0.660 \text{ cfs} \tag{9}$$

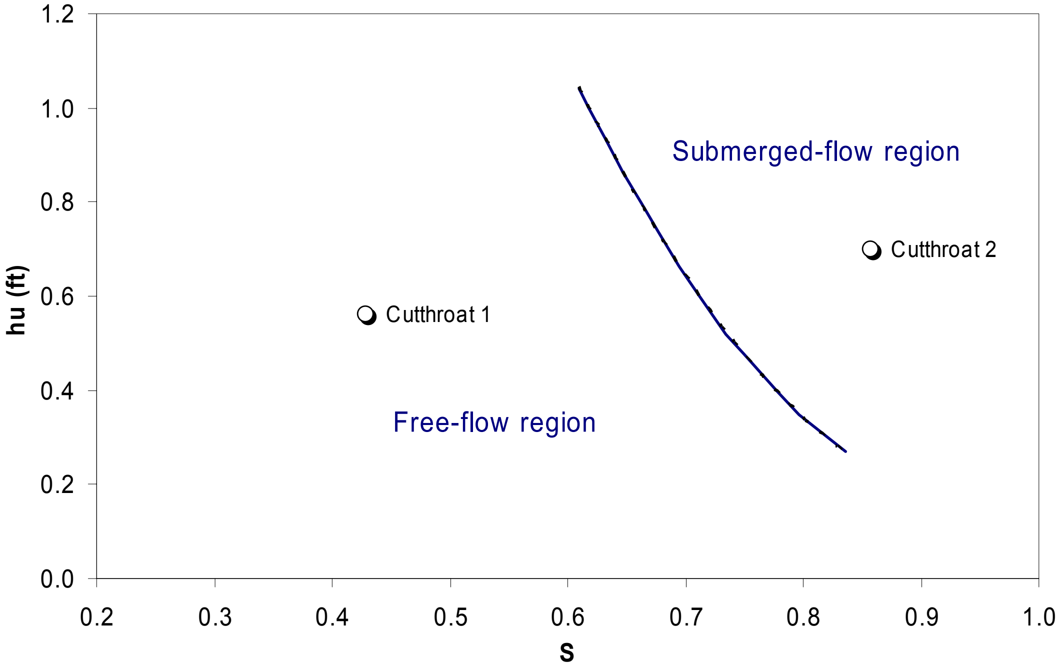


Figure 9. Equation 6 S_t values and sample Cutthroat flume data (W = 4 inches)

CONCLUSIONS

The analysis of the 3-ft Cutthroat flume collected data suggests several notable conclusions: first, observation and analysis did indicate that transition submergence, S_t, varies with discharge for a given Cutthroat flume length and width, thereby refuting the assumption of a single S_t value for each flume size, as previously believed. The transition submergence values are higher for small discharges, decreasing with and increase in flow rate. It was also noted that the transition submergence decreases at very small flow rates. The range of transition submergence values was found to be different for each Cutthroat flume throat width. Previously published transition submergence values are mathematical solutions for the intersection of traditional free- and submerged-flow equations, and do not accurately represent the hydraulic behavior of the S_t parameter, in general.

Second, a transition submergence accuracy analysis for the existing free- and submerged-flow equations was performed. The traditional equations demonstrated their inability to accurately describe the expected threshold submergence.

Third, based on the previous results, it became necessary to develop a new equation that can describe adequately the S versus h_u behavior for free- and submerged-flow conditions. From several alternatives, Eq. 6 provides an excellent S_t fit. Using the first derivative of the Eq. 6, and analyzing several slopes, it was determined that the best slope value is 0.10 (10%), gives the minimum error for the free- and submerged-flow equation using the data collected.

Fourth, given the excellent fit obtained among the values from Eq. 6 and laboratory data (discharge, submergence, and water depths), it is possible to use this equation to calculate the flow rate without the need to apply separate free- and submerged-flow equations, and without the need to determine transition submergence.

Fifth, an analysis of the hysteresis phenomenon was performed, whereby it was determined that there is no observable presence of this phenomenon in the Cutthroat flume sizes considered in this experiment. The absence of this phenomenon indicates that the water depth measurements in Cutthroat flumes will have a unique discharge correspondence regardless of whether the submergence may be increasing or decreasing, provided the flow conditions are steady.

Lastly, the results of this study are for 3-ft Cutthroat flumes, but the same hydraulic analysis is likely to be valid for Cutthroat flumes of different lengths and throat widths, at least within the size ranges for which calibration data are already available. This analysis will probably also be valid for various other open-channel measurement flumes, such as Parshall flumes, because the same traditional free- and submerged-flow equations have been used to calibrate this and other flume geometries.

RECOMMENDATIONS

First, it is recommended to repeat this experiment under non-laboratory conditions (e.g. Cutthroat flumes installed in irrigation canals), regardless of the materials used for their constructions (concrete, metal, bricks, others) in order to have a better understanding of the hydraulic behavior of the transition submergence. Second, based on the methodology followed in this research, similar experiments should be done with other type of flumes and weirs (e.g. Parshall flumes, broad- and sharp-crested weirs) to determine whether the transition submergence has the same or different behavior than the reported in this research. The same forms of the free- and submerged-flow equations which have traditionally been used to calibrate Cutthroat, Parshall, and other open-channel measurement flumes suggest that the curve-fitting analysis presented herein could also apply to the accurate calibration of other flume sizes and shapes. Also, it would be useful to determine whether Eq. 6 is also applicable to the calibration of other Cutthroat flume sizes, and of different flume geometries, such as those of Parshall flumes.

Finally, it is necessary to develop a new unique discharge versus water depth equation that can accurately describe the relationship among flow rate, submergence, and water depths, avoiding the need to use two equations and regardless the free- or submerged-flow condition or the value of transition submergence. Equation 6, proposed in this research, appear to be an excellent starting point in both the development of improved and simplified equations for measurement flume discharge calibrations, but it is envisioned that there may be other equation forms which can fit the data even better, perhaps up to submergence values beyond 95%.

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