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CALIBRATION OF WALNUT GULCH SUPERCRITICAL FLUMES

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INTRODUCTION

A new type of flume is being used to measure flows in Walnut Gulch and its tributaries near Tombstone, Arizona. The flume was developed to cope with the ephemeral, flashy, and sand- and gravel-laden flows conveyed by the steep streams in this watershed. Conventional weirs and flumes could not be used for flow measurement as their performance would be adversely affected by the deposition of sand and gravel in and around them. Yet, a precalibrated flow-measuring device was needed as the use of current meters to obtain field measurements was impractical or impossible. The Walnut Gulch supercritical measuring flume was developed to fill this need. These flumes have been described by the writer (1) and the field performance of the flumes has been reported by Osborn, Keppel and Renard (2). Since the publication of these earlier works, new information on these flumes has been obtained, particularly on model studies to calibrate them. Herein the writer presents the results of laboratory calibrations made on eight different flumes.

FLUME DESIGN

The flume has a straight portion, 20-ft length and a 10-ft depth, [the length of the straight portion of the flume should be about twice the maximum head (1)] preceded by a curved entrance approach portion 15 ft long. The straight portion has a shallow V-shaped floor and side walls of 1 on 1 slope (see Fig. 1). The curved approach has a cylindroid surface as shown in Fig. 2. The surface is defined by the equation

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$$y = 0.03x + \frac{z - 0.03x^2}{0.00267x^2 + 1} \quad \text{(1)}$$

in which x = horizontal coordinate positive in the upstream direction, in feet; y = vertical coordinate in feet; and z = horizontal coordinate normal to the center line of the flume, in feet. See Fig. 1 for the origin of coordinates.

The structure has a 3 % slope in the downstream direction to insure movement of sand and gravel through the flume. The invert of the flume is usually placed about 2 ft above the streambed to reduce backwater on the flume. The head is measured at the midpoint of the narrow, straight portion of the flume. Velocities are supercritical at the head measuring section, hence the name given to the flume. For additional information on the flume, see Ref. 1. All of

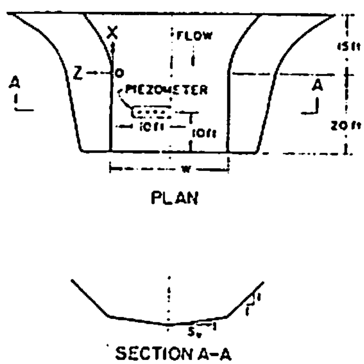

FIG. 1.—WALNUT GULCH SUPERCRITICAL MEASURING FLUME

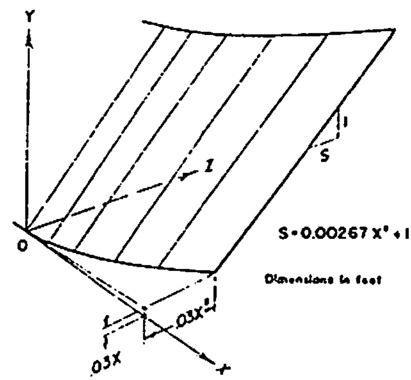

FIG. 2.—APPROACH CYLINDROID SURFACE

the flumes are 35 ft long and differ only in width, W, and floor cross slopes, S_v. See Table 1 for the dimensions of the flumes.

THEORY OF FLUME OPERATION

The flume contracts the stream cross section and causes the flow to pass through critical depth within the flume. The contraction ratio (measuring section flow area divided by the approach channel flow area) should be approximately 0.5 or less. A prediction of the capacity of the flume can be made by assuming that critical depth occurs at the junction of the straight and the curved entrance portions of the flume. The critical discharge at the junction section is given by

$$Q_c^2 = \frac{gA_c^3}{\alpha_c T_c} \quad \text{(2)}$$

in which Q_c = discharge; g = acceleration due to gravity; A_c = cross-sectional area of flow; α_c = velocity distribution constant; T_c = top width of flow; and c = a subscript relating to conditions at the critical section.

The total specific energy, H_c, in the flume at the junction section measured relative to the bottom of the V-shaped floor is given by

$$H_c = h_c + \frac{\alpha_c V_c^2}{2g} \quad (3)$$

or using Eq. 2 and $Q = AV$

$$H_c = h_c + \frac{A_c}{2T_c} \quad (4)$$

in which h_c = depth of flow above the V-shaped floor.

TABLE 1.—SUMMARY OF LABORATORY-CALIBRATED WALNUT GULCH FLUMES

Flume number (1)	Floor cross slope (S_y) (4)	Flume width, in feet (3)	Maximum discharge, in cubic feet per second (4)	Model length scale (5)	Contraction ratio (h_p = 10 ft) (6)	Data on Figure number (7)
1	15	120	26,000	1:40	0.48	3(*a*)
3	7.5	30	6,000	1:32	0.56	3(*b*)
4	10	5	1,260	1:30	0.13	3(*c*)
6	10	70	16,500	1:30	0.70	3(*d*)
7	10	40	8,600	1:30	0.40	3(*e*)
8	10	40	8,600	1:30	0.80	3(*f*)
11	10	30	6,000	1:30	0.36	3(*g*)
15	10	40	8,300	1:30	0.23	3(*h*)

The total specific energy, H_p, above the flume zero at the point of head measurement, assuming no energy loss between the junction section and the head measurement section, would be

$$H_p = h_c + \frac{A_c}{2T_c} + 0.03L \quad (5)$$

in which L = horizontal length between critical section and point of head measurement (10 ft). Also,

$$H_p = h_p + \frac{Q_c^2}{2gA_p^2} \quad (6)$$

in which p = a subscript relating to conditions at the point of head measurement.

If we subtract Eq. 6 from Eq. 5, one obtains

$$h_p = h_c + \frac{A_c}{2T_c} + 0.03L - \frac{Q_c^2}{2gA_p^2} \quad (7)$$

To obtain a computed rating of h_p versus Q involves solving Eq. 7 using a trial value of h_p and a computed value of Q for a given h_c. The initial trial value h_p is assumed too low and incremented until the equation balances. This iteration is readily accomplished with an electronic computer.

Sediment approaching the measuring structure must be allowed to pass through the structure. This means that approach velocities will be relatively high and may influence the depth of flow at the measuring section. Since the approach velocity and direction will be different for each flume site, it was thought necessary to calibrate each structure individually by model studies in a hydraulic laboratory. In addition to providing the calibration, the model studies provided a check on the overall performance of the structure by revealing whether undersirable waves or oblique currents exist.

MODEL STUDIES

The proposed site for each flume was surveyed. Detailed topographic data were obtained for a distance of 500 ft to 1,000 ft upstream and about 300 ft

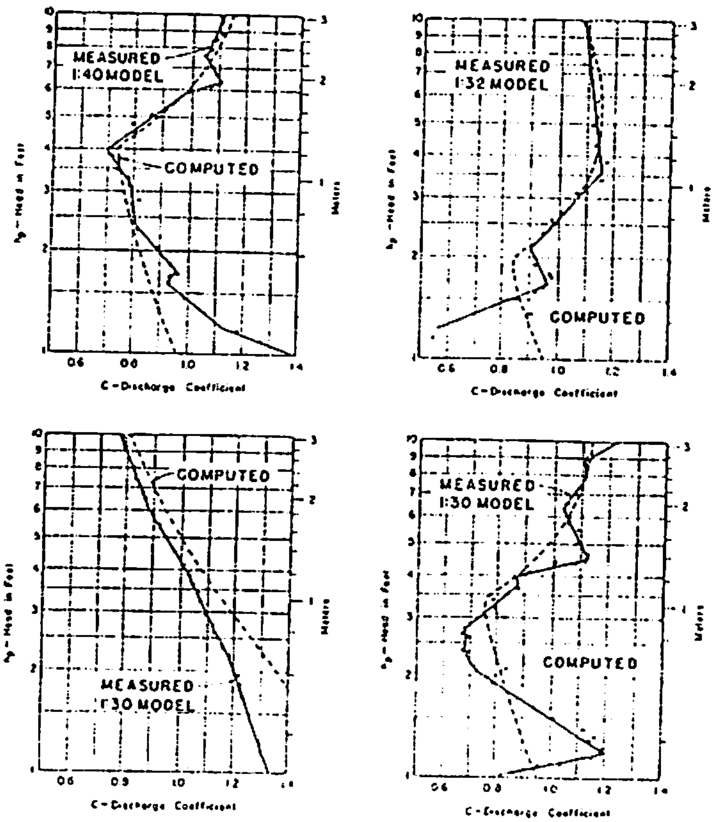

FIG. 3.—DISCHARGE COEFFICIENTS FOR WALNUT GULCH FLUME: (*a*) NO. 1; (*b*) NO. 3; (*c*) NO. 4; (*d*) NO. 6; (*e*) NO. 7; (*f*) NO. 8; (*g*) NO. 11; (*h*) NO. 15

downstream. The location, density and height of any vegetation in the channel was determined and the approximate particle size of the bed material noted. These data were used to estimate the friction factor. The obstructions were built to scale and properly placed in the model.

The model scale selection was based on the size of the area to be modeled, the size of the laboratory basin, the available water supply, and the approximate roughness of the field channel. Model scales used are given in Table 1.

The topography of the approach channel was modeled in the laboratory test basin with Portland cement mortar with all topographic details carefully reproduced. A model of the proposed flume was constructed of redwood and installed in the model basin at the chosen location.

Flush-mounted piezometers were installed at several points in the bed of the model channel to obtain the data needed for calculating the friction factor in the model approach channel.

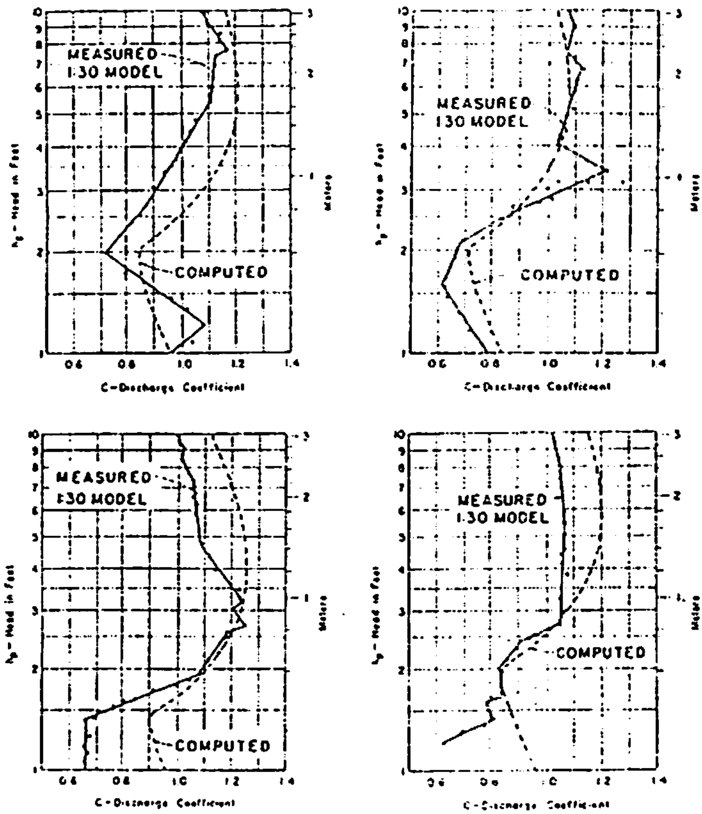

FIG. 3.—*CONTINUED*

Approximately 50 test flows were used in calibrating each model, or each variation of the particular model. Head, discharge rates, water temperature, and general flow conditions were determined for each test flow.

DATA ANALYSIS

The discharge coefficient was calculated for each test flow from the formula:

$$Q = C \frac{l}{2} \sqrt{2g}\ h_p^{1.5} \qquad (8)$$

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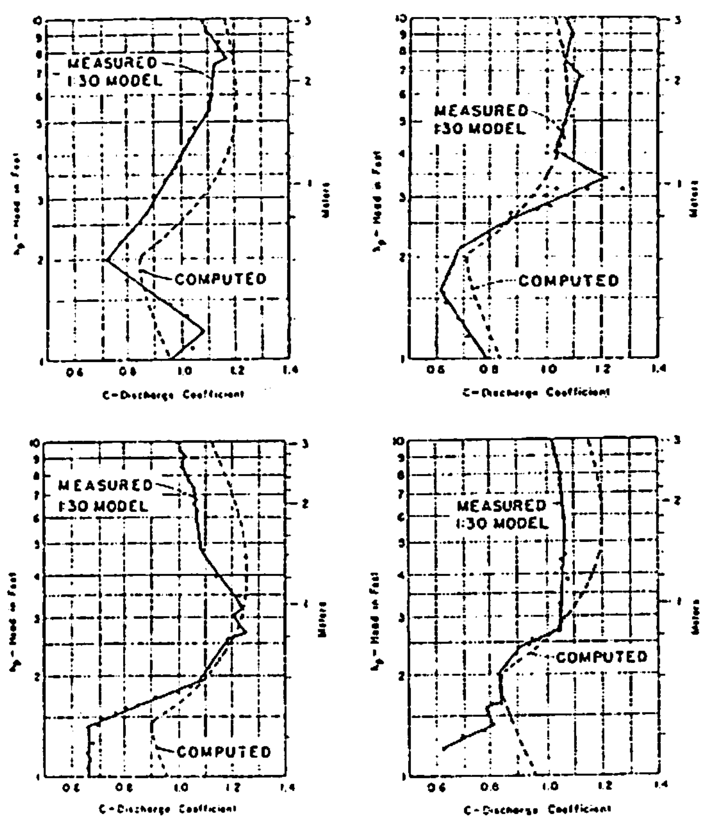

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DATA ANALYSIS

The discharge coefficient was calculated for each test flow from the formula:

$$Q = C \frac{l}{2} \sqrt{2g}\ h_p^{1.5} \quad \text{. . . . . (8)}$$

in which Q = discharge, in feet per second; C = discharge coefficient; l = width, in feet, at the measuring point at elevation h_p above the flume zero; and h_p = piezometric head, in feet above the flume zero, the bottom of the V-shaped floor.

The measured coefficient, C, values are plotted (solid line) against the corresponding values of head, h_p, for each flume on Fig. 3. Also plotted on these same figures are C values derived from the theoretical relationship between head and discharge calculated as explained earlier (broken line).

Manning's n values were calculated for each test with the following:

$$V = \frac{1.486}{n} R^{2/3} S^{1/2} \quad \text{. . . . .} \quad (9)$$

in which V = velocity, in feet; R = hydraulic radius, in feet; S = slope of the energy line; and n = Manning's n.

Values of Manning's n were expressed in prototype scale by applying a multiplier equal to the one-sixth power of the length scale ratio. They ranged from 0.02 to 0.04 for the wood float, finished mortar surface of the model. These values were generally within the range of estimates of the prototype values.

ANALYSIS

An examination of the C versus h_p curves shows good agreement in trend between the measured values and the computed curves, particularly for values of h_p above the reversal point of the computed "C" curves. This point on the computed C curve corresponds to the head at which contraction begins at the junction section. This head is equal to the vertical distance from the flume zero to the point of intersection of the wall with the floor of the flume. For example, flume 1 [Figs. 3(a) and 4] has a half-width of 60 ft and a floor cross slope of 1 on 15. Therefore, there is a rise of 4 ft in the floor from the bottom of the V to the intersection of the floor and the wall. This rise corresponds to the value of h_p at the reversal of the direction of the computed C line.

The measured C values for heads above the control point to flume 8 [Fig. 3(f)] show the greatest departure from the computed values, with the maximum deviation occurring at a head of about 3.5 ft. This is caused by a wave formation at the measuring section at this head resulting from improper alignment of the flume with the approach channel and insufficient contraction. This flume was constructed before the model studies and may account for any incorrect positioning of the flume. Experience indicates the desirability of preconstruction model studies for these flumes.

Below the head corresponding to the control point at the junction section, the measured C values exhibit various tendencies. Some closely conform to the computed values (flume 8). Some are greater (flume 1) and some are less (flumes 3, 11 and 15). In this lower head range, the velocity of the flow approaching the flume may be the control influencing the depth at the measuring section. Or in some instances, a control contraction may occur at the entrance to the flume and conformance to the computed curve can then be expected. If the approach channel conditions remain stable, and if the model accurately reflected the influence of the approach condition, the C values observed in this lower head range are believed to be satisfactory. If the approach channel changes, it would be desirable to make field determinations of the C values in this lower head range.

The agreement between the trends of the measured and computed C values is good in the upper head range. For some flumes, the coefficients also closely agree in value (flumes 1, 3, 6, and 8). For other flumes, the measured values of C are less than computed (flumes 4, 7, 11, and 15). In seeking the reason for this behavior of the C value, it was observed that the contraction ratio of the flume cross section to the stream cross section appeared to be significant. For contraction ratios of 0.40 and < the measured C values were < computed. Whereas for ratios > 0.40, the measured C values closely approximated the computed.

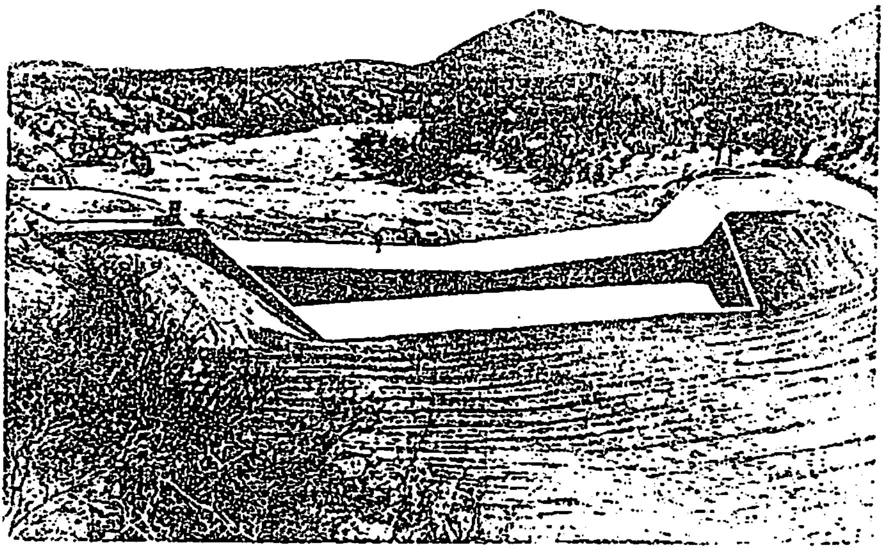

FIG. 4.—WALNUT GULCH FLUME NO. 1 NEAR TOMBSTONE, ARIZONA

A study has been started to learn if, for those flumes having measured C values less than computed values, a method of yielding a better prediction of the C value could be developed. In one calculation, it was assumed that the critical depth occurred at a point midway between the junction and the measuring sections. This trial calculation produced computed C values that were quite close to the measured values. Since the analytical basis for this finding has not been developed, further comment on this finding is not offered.

CONCLUSIONS

The Walnut Gulch supercritical-flow measuring flume is used to measure flows in Walnut Gulch and its tributaries near Tombstone, Arizona. Model tests are required to calibrate the flumes through the major portion of th depth of flow range (including the greater depths). The model results are por trayed in relationships of discharge coefficients to piezometric head in th supercritical-flow portion of the flume. Discharge coefficients computed c the assumptions that critical depth occurs at the entrance of the narrow por tions of the flume and that no energy loss occurs in the flume predicted th shape of the discharge coefficient versus piezometric head curve.

ACKNOWLEDGMENT

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APPENDIX I.—REFERENCES

1. Gwinn, W. R., "Walnut Gulch Supercritical Measuring Flume," *Transactions*, ASAE, Vol. 7 No. 3, 1964, pp. 197-199.
2. Osborn, H. B., Keppel, R. V., and Renard, K. G., "Field Performance of Large Critical-Dept Flumes for Measuring Runoff from Semiarid Rangeland," United States Department of Agri culture, Agricultural Research Service, ARS 41-69, March, 1963.

APPENDIX II.—NOTATION

The following symbols are used in this paper:

A_c = cross-sectional area of flow, in square feet;
c = subscript relating to conditions at critical section;
C = discharge coefficient;
g = acceleration due to gravity, in feet per second per second;
h_c = depth of flow above the V-shaped floor, in feet;
h_p = piezometric head above flume zero, bottom of V-shaped floor, in feet;
H_c = total specific energy, in feet;
H_p = total specific energy, if feet;
L = horizontal length between critical section and point of head measure ment, in feet;
n = Manning's n;
p = subscript relating to conditions at point of head measurement;

Q = discharge, in cubic feet per second;
Q_c = discharge, in cubic feet per second;
R = hydraulic radius, in feet;
S = slope of the energy line;
S_v = floor cross slopes;
T = width at measuring point at elevation h_p above flume zero, in feet;
T_c = top width of flow, in feet;
V = velocity, in feet per second;
W = width, in feet;
x = horizontal coordinate positive in upstream direction, in feet;
y = vertical coordinate, in feet;
z = horizontal coordinate normal to center line of flume, in feet; and
c = velocity distribution constant.

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KEY WORDS: channels; discharge; floods; flumes; hydraulics; hydrology; measurement; models; runoff; sediments; stream gages; water flow

ABSTRACT: A new supercritical measuring flume is being used to gage sediment-laden ephemeral flows in steep channels. The transition from the natural channel to the straight modified trapezoidal measuring section of the flume consists of a cylindroid surface. The flume is kept free of deposition by a V-shaped floor which slopes in the direction of the flow. The head is measured at the midpoint of the straight section. Ten of these concrete flumes have been installed in the Walnut Gulch Watershed near Tombstone, Arizona. Eight of the flumes have already been calibrated with models in the laboratory. The largest has a bottom width of 120 ft and a capacity of about 26,000 cfs. This structure is the largest known pre-calibrated flume now in operation. The design of the flumes, the laboratory calibration data and some observations of their field operation are analyzed.

REFERENCE: Gwinn, Wendell R., "Calibration of Walnut Gulch Supercritical Flumes," Journal of the Hydraulics Division, ASCE, Vol. 96, No. HY8, Proc. Paper 7479, August, 1970, pp. 1681-1689.