Walnut Gulch Supercritical Measuring Flume

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MEASUREMENT of the water flow in Walnut Gulch near Tombstone, Ariz., posed a difficult problem for the hydrographers studying the runoff from this area. The use of a current meter was impractical or impossible because flows are infrequent, flashy, and heavy laden with detritus. Conventional weirs or flumes were unsuited because transported material deposited in the approach to the weirs or flumes seriously affects their accuracy. A new type of flow meter that would accurately and reliably measure flows under these adverse conditions was developed by the Stillwater Hydraulic Laboratory. The meter is known as the Walnut Gulch supercritical measuring flume. Its development and performance are discussed in this paper.

The following criteria served as guiding principles in the development of a satisfactory design. The measuring device should:

1 Produce the necessary flow conditions within the meter that are amenable to measurement

2 Produce a rating relationship which is independent of the approach channel

3 Remain clean of detritus during and after each flow event

4 Be free of backwater effects

5 Have a unique rating; that is, a rating curve that gives identical values for all operating conditions

6 Have satisfactory accuracy under the operating conditions imposed upon it.

A study of earlier flumes was made to obtain additional guidance. The San Dimas critical-depth measuring flume (1)* was the first attempt to accomplish the measurement of debris-laden flows. This flume performs satisfactorily for certain field conditions; however, in common with other measuring flumes of rectangular cross section, it has some limitations. It does not measure low discharges with great accuracy because of the wide bottom. Also, the San Dimas has limited capacity if the width is reduced to secure accurate measurement of medium flows.

Natural channels are generally trapezoidal in shape and, therefore, a flume with a trapezoidal cross section would be more economical to construct. However, the use of a trapezoidal cross section was reported as unsatisfactory by Wilm, Cotton, and Storey (1). They state (1a) that surface waves were produced by overabruptness of the conical entrance section. This same conclusion was drawn by Bermel (2a). Nevertheless, trapezoidal flumes were used successfully by Robinson (3). Also the trapezoidal cross section would pass bulk debris more readily than the rectangular. However, large bulk debris was not a problem for the Walnut Gulch Watershed.

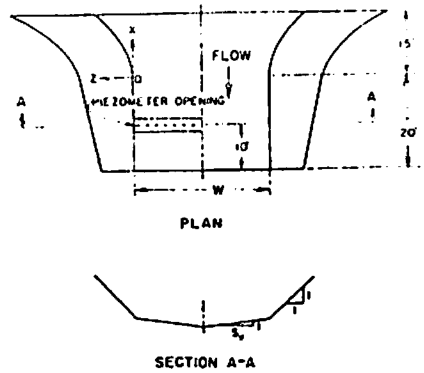

FIG. 1 Walnut Gulch supercritical measuring flume.

FLUME DESIGN

The basic hydraulic principles used to develop the Walnut Gulch supercritical measuring flume are:

1 Contract the stream. If the flow in the approach channel is supercritical, force a hydraulic jump to form well upstream of the flume. This is necessary to gain hydraulic control over the stream.

2 Pass the flow through a sloping, straight chute measuring section in which the flow will pass through critical depth near the entrance to this section.

3 Measure the head at the midlength of the straight section where the flow is at a supercritical velocity and the pressure on the floor of the flume is hydrostatic.

4 Dissipate the excess energy created by the flume if necessary.

Applying the hydraulic principles to the problem led to the final design shown in Fig. 1. The features of this design are a straight measuring section with a curved entrance. The curved approach provides a transition from the natural channel to the measuring section. This is accomplished by using the cylindroid surface over a 15-ft length. A perspective view of the surface is shown in Fig. 2. The surface is defined by the equation:

$$y = 0.03x + \left\{\frac{15}{0.04x^2 + 15}\right\}$$
$$(z - 0.03x^2)$$

where

x = horizontal coordinate positive in the upstream direction

y = vertical coordinate

z = horizontal coordinate normal to the center line of the flume.

The origin for these coordinates is at the intersection of the wall and floor at the entrance to the measuring section.

The developed surface is composed of straight-line elements between two parabolas. The smooth transition prevents undesirable wave formation within the measuring section.

The measuring section of the flume shown in Fig. 1 is a modified trapezoid with 1-on-1 side slopes. The floor of the flume is V-shaped to concentrate low flows into measurable depths. The cross sectional area of the measuring section should be equal to or less than one-half the natural channel area. This contraction ratio will aid in maintaining hydraulic control over the stream. The floor slope of 0.03 in the downstream direction insures supercritical flow within the measuring section. The length of the straight chute section should be approximately twice the maximum head. This length will assure hydrostatic pressure distribution on the floor at the midlength of the flume. If the straight chute section is shorter, the surface curvature from the overfall will extend upstream over the piezometer location, the piezometric pressures in the vertical will be nonhydrostatic, and the pressure on the floor will be reduced. The outfall should be high enough so that the tailwater surface is at no time higher than the static head at the piezometer. The measuring section should always contain supercritical flow.

The basic design has been used for five completed flumes plus a flume that is in an advanced stage of planning. All flumes have the cylindroid entrance and all have the same length. The only significant differences between the flumes are the widths, which were selected to provide capacity, and the floor cross slopes, which were selected to provide the desired accuracy of measurement of

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* Numbers in parentheses refer to the appended references.

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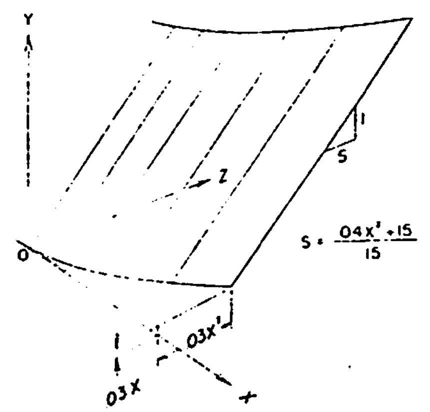

FIG. 2 The approach cylindroid surface.

low flows. The capacities of these structures range from 6,000 to 22,000 cfs, requiring widths ranging from 30 to 120 ft. Despite the similarities in the structures, the differences in structure proportions and in site characteristics made it inadvisable to generalize the design. Therefore, each flume was custom designed after a field survey and a hydraulic analysis of the site characteristics had been made. To illustrate the design approach, site No. 3 on Walnut Gulch has been chosen for discussion and presentation in this paper.

Flume Site No. 3 (Initial Study)

The proposed site for flume No. 3 was surveyed. Detailed topography was obtained for a distance of 700 ft upstream and 300 ft downstream. This survey provided the information on the topography to be reproduced in the model and also provided the data on the channel cross section and slope needed in order to make a preliminary hydraulic analysis.

The initial hydraulic study was made to estimate the water surface profile for the existing channel when conveying the assumed peak discharge rate. This estimate of water surface elevations at the flume site permitted selection of the elevation of the flume invert that would avoid backwater effects. A second profile calculation was made with the proposed flume assumed in place to determine if the flume would control the flow depth. This was necessary to comply with the principle that any hydraulic jump must be located well upstream from the flume. In this particular case the normal flow depth was found to be at or near critical; thus the backwater curve would tend to be horizontal and would join the normal water surface without a jump. A check was made also of the contraction ratio to make certain that the area of the flume cross section was equal to or less than half that of the area of the approach channel cross section throughout the depth range expected. All indicated adjustments in flume size and setting were made and the study proceeded to the model phase.

Model Studies

A model study is required for each flume. First, it provides a check on the overall hydraulic performance of the structure to make certain that undesirable waves or oblique approach currents do not exist. Second, and generally most important, it provides the calibration for the flume. Precalibration is essential because, as pointed out earlier, subsequent calibration by current meter would be nearly impossible except in the low flow range. Third, scour tests are needed to guide the design of a stilling basin or other protective works if the site indicates the need. Flume No. 3 was founded on a hard conglomerate and a stilling basin was not needed.

The selection of the model scale 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. A length scale of 1:32 was chosen in this case and an undistorted model of the flume and topography was constructed. Care was taken to include simulation of any trees or brush in the channel or on its banks.

The model operation and the data analysis were based on the Froude criterion; that is, gravitational forces alone are assumed to determine the relationship between head and discharge. However, it was recognized that the velocity of the approaching flow could influence the calibration. So particular attention was given to the friction factor for the approach channel. The initial channel was constructed of concrete mortar, which was finished with a wood float. This simulated in proper scale the estimated Manning's n value for the approach channel. To "bracket" this value, the channel was roughened by placing a ½-in. mesh hardware cloth over the bottom. This was followed by smoothing the channel surface with a concrete paint. Piezometer openings were placed at three stations in the approach channel to obtain the data needed for calculating the friction factor.

Head-Discharge Relationship

The resulting discharge rating is one with no objectionable flat portions or loops. The rating curve, shown on Fig. 3, is a calculated curve based on the experimentally determined discharge coefficients and on the actual dimensions of the prototype. For this reason no plotted data points are shown on this curve. No generalization of the data will be tried because each flume is custom rated. However, a reasonable approximation of the rating curve may be obtained using the following method:

1 Assume that flow will be at critical depth at the entrance to the straight chute section and calculate the velocity head for the given discharge.

2 Add the velocity head to the critical depth to obtain an estimate of the minimum specific energy of the flow at the entrance to the straight chute section.

3 Assume no loss of energy between the entrance to the straight section and the measuring section. Then, with a 10-ft distance between these two sections and a 0.03 slope in the direction of the flow, the specific energy of the flow at the measuring section will be equal to the specific energy at the entrance to the straight chute section plus 0.3 ft.

4 Calculate the depth of the supercritical velocity flow for this estimated specific energy at the measuring section for the selected flow. Trial and error methods must be used to make this computation.

5 The depth calculated in step 4 is the estimated head for the given discharge.

The estimating procedure described in the foregoing five steps is valid only for flows controlled by the entrance to the straight chute section. These are assumed to be all flows with critical depths within the 1-on-1 side slopes of the flume. Flows smaller than this will be controlled by entrance conditions at the upper end of the flume and by chan-

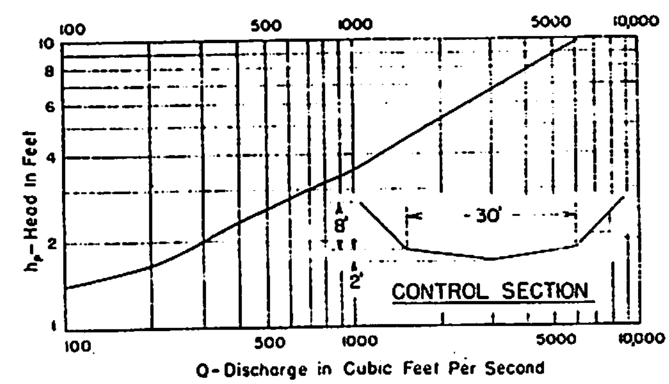

FIG. 3 Discharge rating for Walnut Gulch flume No. 3.

nel flow in the V-section of the flume floor.

A comparison of the actual and the estimated rating curves was made by a study of the discharge coefficients. The values of the coefficient C in the following formula were computed both for the actual tests and for the estimated ratings:

$$Q = C \frac{t}{2} \sqrt{2g}\, h_p^{3/2}$$

where

Q = discharge in cubic feet per second

C = discharge coefficient

t = width in the measuring section at elevation h_p above the flume zero

g = acceleration due to gravity

h_p = piezometer head above the flume zero, the bottom of the V at the measuring section

The agreement between the estimated and the experimentally determined discharge coefficients shown in Fig. 4 is good. The maximum difference is about 5 percent.

Effect of Approach Channel Friction

The rating reported is that obtained with "normal" friction in the approach channel. Placing the hardware cloth in the channel increased the Manning's n, in prototype terms, from 0.034 to 0.045 for an average hydraulic radius of 6.5 ft. Yet the discharge rate was reduced by only 3.8 percent for this 32-percent increase in approach channel friction.

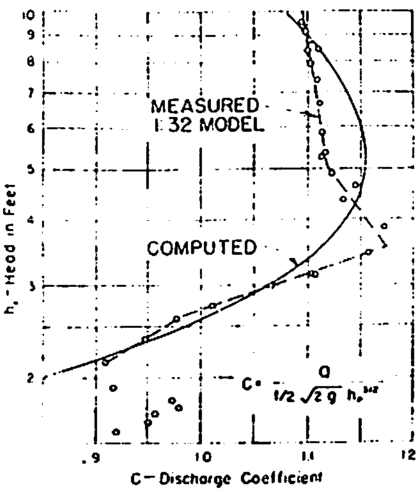

FIG. 4 Discharge coefficients for Walnut Gulch flume No. 3.

Painting the channel surface did not lower the friction factor. Therefore, a test was not obtained for a condition smoother than "normal." However, since a large increase in channel friction had but small effect on the discharge, it is thought that a decrease in friction would also have but small effect on discharge, and the failure to achieve a smoother condition did not invalidate the experiment.

Prototype Performance

Two flumes with rated capacities of 6,000 and 18,500 cfs are in operation. These were built in 1958 and 1959. Some flows have occurred since then and despite their heavy sediment loads, no detrital material was deposited in the flumes. Continuous stage records were obtained for all flows and the general evidence is that the flumes functioned as designed.

Summary

The Walnut Gulch supercritical measuring flume was developed for measuring the flow in detritus-laden ephemeral streams of southwest United States. This flume has curved entrance walls to provide a smooth transition from the stream channel to the straight measuring section. A 3-percent floor slope maintains velocities high enough to prevent sediment deposition in the flume. Sensitivity needed for low-flow measurement is obtained by a V-shaped floor. Capacity requirements are met by sloping the side walls of the measuring section 1-on-1. Each flume is custom designed to fit the site and is calibrated by model tests. Observations on two field installations, one with a 6,000 cfs capacity and the other with a 18,500 cfs capacity, have indicated highly satisfactory performances.

References

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3 Robinson, A. R. Trapezoidal measuring flumes for determining discharges in steep ephemeral streams. Colorado State University Research Foundation, Civil Engineering Section, No. CER59ARR1, Fort Collins, Colo., February 1959.