Hydraulic performance of flumes for measurement of sediment-laden flash floods*

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Abstract. A network of 11 specially designed flumes has been established on the 155 km^2 Walnut Gulch Experimental Watershed, Arizona, specifically to monitor the size and propagation of flash floods typical to this region. Hydraulic problems of flash flood flow measurement are discussed, including high velocities, high sediment transport, alluvial instability, and extremely rapid increase in discharge rate (shock fronts). Several potential improvements for these flumes have been suggested from extensive model testing, prototype measurements now in progress, and several years of experience with flow peaks as large as 140 m^3/s.

Le fonctionnement hydraulique des canaux jaugeurs pour mesurer les crues brutales avec charges solides

Résumé. Un réseau de 11 points de mesures de débits a été construit sur le bassin versant expérimental de Walnut Gulch en Arizona (155 km^2), en vue de contrôler les crues brutales, typiques de cette région. On présente les problèmes de jaugeage des crues brutales, caractérisées par des vitesses rapides, des transports d'alluvions très importants et très instables et une croissance extrêmement rapide des débits (ondes de chocs). Des expériences nombreuses sur modèles réduits, ainsi que plusieurs années d'expérience pratique avec des débits atteignant 140 m^3/s conduisent à plusieurs possibilités d'amélioration de ces canaux jaugeurs.

INTRODUCTION

The Walnut Gulch Experimental Watershed, operated by the US Department of Agriculture, Agricultural Research Service, is in the upland Sonoran desert region, a semi-arid rangeland basin. Runoff is almost exclusively produced by scattered and isolated intense summer thunderstorms. Flash floods over dry, very porous, alluvium are nearly the only type of channel flow experienced in these inter-mountain basins which have a drainage area of less than several thousand square kilometres. On Walnut Gulch, there are 11 unique measuring flumes on a 155-km^2 watershed designed to collect data for evaluation of the hydraulic properties of the flood waves as well as the distribution and extent of alluvial extractions. The installation of the flumes began in 1958 and they were initially studied and calibrated by small scale model test (Gwinn, 1970). Presently, the calibration and performance of these flumes are being studied on a prototype scale with an electronic data collection system. Much is being learned concerning design for measuring flow under such adverse conditions.

Basic hydraulic criteria

There are three basic hydraulic characteristics to consider in measuring flows under the unique hydrological conditions of this region. First, a high sediment load is carried by the flash floods as a consequence of the hydrological pattern outlined above. Under these conditions, where natural Froude numbers are close to 1.0, common flumes calibrated for measurement in mild flow depths above a critical flow section are useless. Sediment accumulates and quickly alters the measurement section. For lighter sediment loads, some type of subcritical flume could be used with proper sediment suspension aids, such as artificial roughness elements (Replogle, 1974). For heavier sediment

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loads, however, one of the few alternatives is to accelerate the flow and calibrate using depths measured in a supercritical drawdown.

Second, the transient nature of the channel sections in loose, deep, alluvial material must be considered in the hydraulic design of flumes for this situation. The thalweg pattern may change from flow to flow; for each flow the previous sequence of floods determines a different initial bed pattern, surface material size distribution, and water content. Therefore, the hydraulic control of the flume for measurement must be complete.

Third, the rapid changes that occur in water stage of flash flood flows must be measured faithfully and accurately. The stage recording problem is compounded by the presence of large quantities of sediment which will quickly fill most common stilling well entrance configurations. Often, the measurement site is remote from available electric power, and stage must be recorded reliably without benefit of powered devices.

THE FLUMES AT WALNUT GULCH

The flumes at the Walnut Gulch Watershed have not dealt with these problems with uniform success. Much has been learned, however, which can be applied to flumes constructed in the future.

Figure 1 presents the general geometry of the Walnut Gulch Flume as designed (Gwinn, 1964). Mathematical descriptions of the approach 'transition' surfaces are

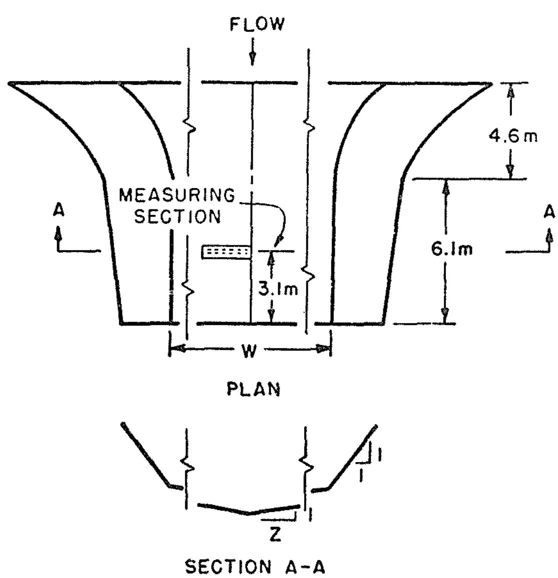

FIGURE 1. Walnut Gulch supercritical flow-measuring flume.

given in the original description (Gwinn, 1964). The width, W, of constructed flumes varies from 1.5 to 36.6 m.

The design is not particularly unique, but rather is a more complex version of the trapezoidal supercritical flumes studied by Robinson (1959). The floor is V-shaped in cross section, with cross slopes typically 10 per cent. The flume was designed for critical flow to occur at the section where the side walls become straight, downstream of the curving transition walls.

Hydraulic control

In prototype operation, however, most flows are confined to the floor, in which case the critical section is at the upstream edge of the floor. Only after water is some height above the floor–wall intersection elevation does the control section appear to move downstream to its 'design' location. At these deeper flows, however, the higher approach velocities often cause waves to emanate from the entrance walls, indicating the need for contraction to occur upstream of the critical section. Another variance between design and field performance results from the insufficient lateral control exercized by the structure on the flows which are confined by the alluvial bed. In this case, neither the natural channel sides nor the flume walls control flow, and dynamic

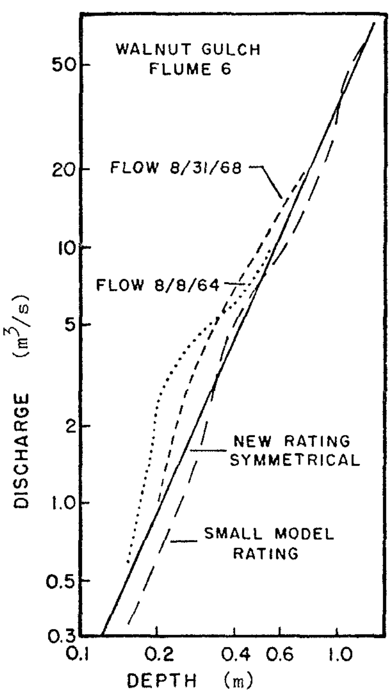

FIGURE 2. Comparison of flume depth discharge ratings for symmetrical and asymmetrical flow.

sinuosity – building and reshaping of sand bars – causes serious lateral unbalance in flow patterns across the depth measuring section. Differences from the model derived depth–discharge relationship may be as much as 200 per cent depending upon the flow pattern in the approach channel, with variation being diminished at large flows. Figure 2 illustrates the problem experienced.

All the flumes in use were constructed with a similar depth sensing apparatus. A 0.6 m × 2.54 m metal plate with slots approximately 1.5 cm × 15 cm in size leads to a 1 m diameter stilling well through a tunnel of approximately 0.3 m^2 cross section. This configuration allows material from the moving sediment load to fill the tunnel and seal the slots before all but the shorter floods have passed. This arrangement can be considerably improved by several methods, principally by minimizing overall intake volumes except that necessary to trap sand entering the intake slots of a minimum area. Such improvements are now undergoing field evaluation.

Corrective measures

Limited space here prohibits a comprehensive discussion of the various types of analyses made to determine the rating relations for these flumes, or to elaborate on the remedial measures taken to improve their utility, barring reconstruction. The flumes were originally rated by an extensive series of model tests at scales of 1:30 to 1:40 (Gwinn, 1970). After the experience indicated an overwhelming proportion of the flow volume was measured in the floor section, additional tests were conducted using a 1:5 scale hydraulic model of the floor alone with a moveable sand bed upstream. The original model tests which were for fixed bed conditions did not yield data for this range of flows.

Model tests at 1:5 scale were also used to develop a means to provide upstream stabilization against natural alluvial sinuosity at low flows. Figure 3 shows the typical arrangement of the porous low dikes now being used to increase positive control for the flashy, heavy sediment flows. The dike tops protrude only 15–50 cm above the sand bed. The hydraulic model not only helped develop this remedial solution, but also gave insight into the extent of probable bias in the records from uncontrolled flows. With increased confidence in the straight-through flow rating relations, notes on degree of flow asymmetry are now being used to re-estimate flow records. Further improvement in the records of rapidly rising wave fronts is being made by application of the simple differential equation for flow through the depth recording system. Considering the entrance plate as an orifice, and knowing the water volume within the tunnel and the depth in the stilling well, it can be shown that

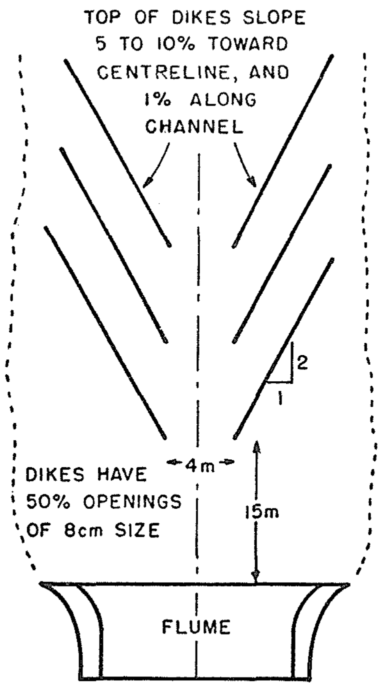

FIGURE 3. Porous control dike arrangement added to control sinuosity.

$$h_s - h_w = \frac{1}{2} g \left(\frac{dh_w}{dt} \frac{dV_w}{dh_w} \frac{1}{CA_s} \right)^2 \qquad (1)$$

where

g = gravitational constant;
h_s = depth of water in channel;
h_w = depth of water in stilling well;
V_w = volume of water in intake chamber;
C = orifice coefficient of plate;
A_s = area of orifice in plate.

This equation may be solved successively for the record of stilling well depth versus time to yield a record of actual flow stage versus time. Such an analysis may also be used to help design and evaluate an optimum intake arrangement. Experimental intake configurations and depth sensors are currently being evaluated in prototype installations; the difficult field conditions require rigorous design testing.

An electronic data collection system has recently been installed in an intensive study of full scale hydraulic relations at one flume site, which has available electrical power. An instrument carriage has been constructed on a footbridge over the flume which allows lateral and vertical traverse across the flow. Depth profiles in cross section are obtained by sonar transducer, and velocity may be measured at any point with a rather unique electromagnetic velocity meter. In addition, fixed sensors (both sonar and pressure) record instantaneous centreline depth free from hydraulic lag. The major objectives are to obtain the first full scale flume rating relations, to evaluate quantitative effects of asymmetry, and to compare practical utility of several electronic depth measuring methods. One early test result is illustrated in Fig.4, comparing actual depths at centreline from sonar and pressure transducers with depth recorded in the stilling well. This figure indicates the typical extent of variation in elevations across the measuring section. The stilling well records depths averaged in some manner across the lateral extent of its openings. This flume was deliberately left without upstream porous control dikes to observe control performance of an unaided flume. It also indicates the lag in response of the stilling well to the rapidly rising wave front.

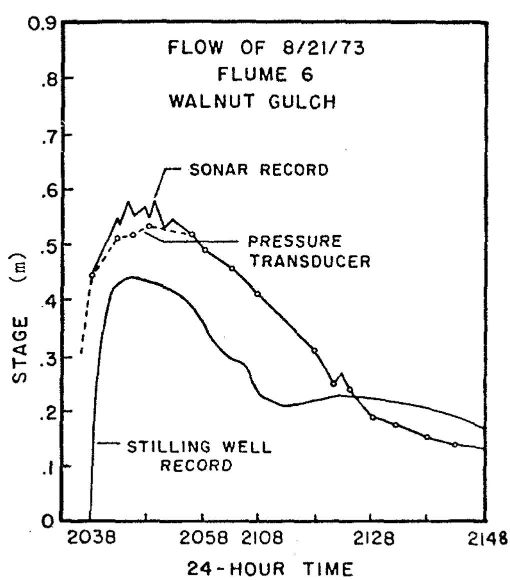

FIGURE 4. Comparative records from old and new stage sensors for one event in 1973.

SUMMARY

In the short space available, we have indicated the comprehensive nature of problems involved in measurement of flash flood waves, as well as suggestions for practical flume design improvements for such measurement. With improvements implemented, the Walnut Gulch type flume is providing relatively accurate data on this rather extreme type of flow event.

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