Discussion of "Broad-Crested Weirs with Rectangular Compound Cross Sections" by M. Göğüş, Z. Defne, and V. Özkandemir

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The development of interactive, easy-to-use design and calibration software in the past two decades has made broad-crested weirs with streamlined approaches one of the best available structure types for measuring open channel flows. Advantages include excellent accuracy, minimal head loss, adaptability to many channel types, and the ability to measure wide flow ranges through the use of trapezoidal, V-shaped, and compound control sections.

The authors have presented a detailed set of experiments on weirs with rectangular compound cross sections. These weirs have a small inner rectangular section for measuring low flows and then, they broaden to a wide rectangular section at higher flow depths. The investigation considers the head-discharge ratings, discharge coefficients, velocity coefficients, and modular limits of the structures. Some of the work is compared to results from the WinFlume computer program (Wahl et al. 2000) developed by the discussers for the calibration and design of long-throated flumes and broad-crested weirs. Many of the results presented by the authors touch upon subjects previously investigated and documented in detail by the discussers and others. Specifically, comprehensive guides to the theory and practical application of long-throated flumes and broad-crested weirs were provided by the discussers in 1984 and 1993, and were most recently updated in 2001 to include new developments, notably the WinFlume computer program. However, only the 1984 work was cited by the authors. Some other notable works pertaining specifically to this class of structures are Bos (1985), Clemmens et al. (1993), Clemmens et al. (2001), and Wahl et al. (2005). In addition, the authors' reference to the WinFlume software is incorrect, giving only the incomplete name of a company distributing our book (Clemmens et al. 2001) in the United States. The first publication fully describing the software is actually Wahl et al. (2000), and the software is available for free download at www.usbr.gov/pmts/hydraulics_lab/winflume/.

The discussers believe that the authors' work creates misconceptions about the validity of the weir calibrations produced by the WinFlume software for both standard and compound weirs. This misconception may lead practitioners to adopt what we consider undesirable designs for compound weirs. Elaboration on these points, in the order the authors originally presented their results, follows.

Transition Zone in Head-Discharge Ratings

The authors discuss the fact that a discontinuity in the head-discharge relationship is expected as the flow transitions from the inner section to the outer section (the authors' Case 1 and Case 2), but then conclude that the transition zone is not evident in their data. Some distinction between the terms *discontinuity* and *transition* should be made. A discontinuity occurs because the section width suddenly changes shape. The area function for the throat is discontinuous, and thus the resulting discharge curve should also be discontinuous, experiencing a break in slope when the flow enters the outer section. The discontinuity in the rating of the $b_{18}z_5$ weir is clearly evident, because the $b_{18}z_5$ and $b_{18}z_{12}$ rating curves diverge from one another at about $h_1=7.5$ cm. If the rating for a weir with $z>12$ cm had been presented, the discontinuity in the b_{18z12} rating would also have been evident. Fig. 1 shows head-discharge relationships determined by WinFlume for compound weirs similar to those tested by the authors, and a weir with an inner section, where $z=24$ cm deep. As expected, the discontinuities in the ratings occur at about $h_1=1.5z$, where z is the depth of the inner section. This head corresponds to a critical depth, y_c, which completely fills the inner section.

What is not shown in the authors' data or in the ratings computed by WinFlume is the fact that the three-dimensional characteristics of the flow cause the rating to have higher uncertainty in the transition zone that spans the discontinuity. This would most likely have been revealed if repeated measurements were taken to evaluate the uncertainty of the ratings.

Discharge Coefficients

The authors present discharge coefficients for the base case of a broad-crested weir without an inner section (weir model Bz_0), and then compare discharge coefficients of their compound weirs to the base case. Their Fig. 6 compares the discharge coefficients of the Bz_0 weir to results obtained from WinFlume and from an analysis using equations and data provided by Bos (1989). The results from the latter two sources are in perfect agreement, but differ markedly from the authors' results. The authors' observed discharge coefficients are as much as 20% lower at the smallest values of H_1/L (approx. 0.1). The authors speculate that the differences might be due to high friction in the models or a non-streamlined approach, or possibly inherent uncertainty in the ability to determine the discharge coefficient, C_d. The authors cite Bos (1989) in stating that an uncertainty of ±4 to 5% is possible in the determination of C_d. The discussers are convinced that such an uncertainty cannot explain such a large discrepancy, and that the quoted uncertainty is associated with C_d values that are deter-

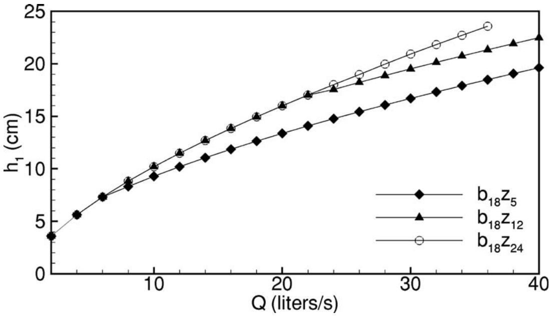

Fig. 1. Head-discharge ratings of compound weirs

mined experimentally. When C_d values are determined analytically using WinFlume, the inherent uncertainty is less than ±2% (Clemmens et al. 2001).

The effect of friction losses caused by surface roughness can be evaluated using WinFlume. Analyzing the Bz_0 weir using different roughness coefficients—even unreasonably high values—shows that variations in roughness cannot produce agreement with the authors' results. A 300-fold increase in roughness causes no change in the discharge coefficients of the Bz_0 weir, because the length of the crest in the flow direction is too short to allow a turbulent boundary layer to develop. The boundary layer is entirely laminar, and as a result, the friction loss through the structure is independent of the surface roughness. Even if the crest were lengthened from 35 to 100 cm (allowing a turbulent boundary layer to develop), the change in discharge coefficient corresponding to a 300-fold increase in the surface roughness is only about 5% at low values of H_1/L.

The effect of a non-streamlined approach can also be discounted, because the authors' C_d values are even lower than those of broad-crested weirs with a blunt upstream face. This contradicts more than 100 years of research dating back to Bazin (1896), even at low heads when the section is a simple rectangle (Replogle 1978). The authors' tested devices are very similar to those documented by the British Standards Institute (1969), but again with quite different discharge coefficients.

These unexplainable differences suggest a serious flaw in the experiments. The most likely problem is an error in the independent flow measurements used to evaluate the tested weirs. Unfortunately, a primary standard, such as a weight tank, was not used as the comparison flow measurement. Instead, a sharp-crested weir was used, which has its own inherent inaccuracy and possibilities for error. The authors provide essentially no detail on this weir or how measurements were taken to assure high accuracy. One possible explanation for the differences is that the sharp-crested weir appears to be partially contracted, for it is described as 26 cm wide, but is placed in a 29-cm wide channel. The authors do not state how this weir was calibrated or what rating was used, but if a standard rating for a fully contracted rectangular weir was used, the indicated flow rates would be significantly lower than the actual flows; the errors would have been more than large enough to explain the differences observed between the authors' results and established ratings and theory.

Velocity Coefficients

The authors' Fig. 8 confirms a result shown in the discussers' books (Clemmens et al. 2001, Bos 1989, Bos et al. 1984) that C_v

Fig. 2. Broad-crested weir with complex trapezoidal throat section on the Croke Canal, Colo.

is related to the area ratio as first defined by Bos (1977). The authors' data show no discernible variation of C_v as a function of the inner weir crest width or step height. Work by the discussers over a broader range of shapes has shown that there is a slight variation of C_v as a function of the throat shape, quantified in the exponent of the head-discharge equation.

Modular Limits

The scatter of the authors' data prevents drawing any significant conclusions, except that compound control sections reduce the modular limit. The WinFlume model reproduces this result, although the reduction of the modular limit is generally smaller than that shown by the authors (Bos and Reinink 1981).

Practical Considerations

The authors focus their conclusions primarily on the variation of the discharge coefficients, velocity coefficients, and modular limits in relation to the depth and width of the inner channel. These details are of little practical concern to a designer. As long as discharge coefficients of structures are predictable and stable, whether they are higher or lower than those of other structures is unimportant, because structure sizes can be varied during design to obtain any desired head-discharge rating. Furthermore, today these results are of little use to researchers, as the behaviors observed by the authors are already accurately modeled by the WinFlume software.

The WinFlume program does not offer the ability to analyze a structure exactly like that tested by the authors, only because it is an impractical design. At the transition from flow in only the inner channel to flow in both the inner and outer channels, small errors in head measurement indicate large changes in flow. WinFlume requires that the shoulders of the compound cross section have a slope toward the center of the channel. This reduces the extent of the transition zone in which the flow is just barely deep enough to create a shallow flow across the entire shoulder area. Head-discharge relationships are also unpredictable in this zone because the flow in the shoulder areas is unduly influenced by friction and because the flow depth at the downstream end of the inner section may be low enough that the flow in the inner section is hydraulically disconnected from the shoulder flow. Maintaining a slope toward the center of the channel minimizes all of these problems. For practical purposes, WinFlume can model the authors' weirs if this slope is made very slight.

Broad-crested weirs with compound control sections are effective measurement structures when a wide range of flows must be measured (Fig. 2). Such structures have been in use successfully for more than 30 years (Replogle 1975; Bos et al. 1984). In many cases, simpler structures with trapezoidal or V-shaped control sections may provide adequate measurement range, but when a compound control section is necessary, the WinFlume computer program is an effective tool for their design and calibration. The WinFlume software can determine accurate head-discharge ratings and compute the required head loss and associated modular limit for any combination of prismatic upstream, downstream, and control section shapes.

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Closure to "Broad-Crested Weirs with Rectangular Compound Cross Sections" by M. Göğüş, Z. Defne, and V. Özkandemir

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The aim of this study was to present a detailed set of experiments on weirs with rectangular compound cross section. These weirs have a small inner rectangular section for measuring low flows and then, they broaden to a wide rectangular section at higher flow depths. Although there is much research presenting the theory and practical application of this class of structures—most of it conducted by the discussers—the experimental data pertaining specifically to broad-crested weirs with rectangular compound cross sections were not found in the literature. Therefore, in the paper we tried to describe, specifically, the results of a series of experiments to evaluate the effects of step height and width on the discharge coefficients and modular limits of such weirs.

In light of the previous works, the results of the experimental data of this study were analyzed and presented. Lack of access to Clemmens et al. (1993), Clemmens et al. (2001)—both ILRI publications—and, Wahl et al. (2005) (published after this paper had been accepted for publication) while this paper was being prepared, led to them not being cited in the paper. However, two major references, viz, Bos et al. (1984) and Bos (1989) were cited. The basic theory and information presented in these two references in relation to the broad-crested weirs were found to be sufficient to analyze our experimental data. Since the work done by Wahl et al. (2000) was not available at the time, the WinFlume program was downloaded from the related webpage and cited in the reference list.

The discussers have expressed that our work creates misconceptions about the validity of the weir calibrations produced by the WinFlume software for both standard and compound weirs. It should be clearly pointed out that the writers do not claim anything in their paper regarding the validity of the weir calibrations produced by the WinFlume software. We have compared our experimental results, C_d versus H_1/L, with those of the WinFlume software only for the model of Bz_0. Based on the comparison of these data, one cannot conclude against the accuracy of the results obtained using WinFlume.

Regarding the transition zone in head-discharge ratings, the writers have stated, "…the transition zones can not be shown clearly on the curves," referring to the small-scale $h1$ versus Q curves presented in the paper; not, "the transition zone is not evident" as the discussers expressed. In reality, of course, there will be a discontinuity as a function of the step height due to the sudden change in section width. As stated by the discussers, three-dimensional characteristics of the flow cause the rating to have higher uncertainty in the transition zone that can only be evaluated by repeated measurements.

As for the differences observed in Fig. 6 of the paper between the experimental data and those obtained from the WinFlume, and from the analysis using equations and data provided by Bos (1989), we agree with all the explanations given by the discussers regarding the effect of friction, non-streamlined approach, and inherent uncertainties. However, it should be stated that the WinFlume design software assumes that streamlining is obtained by the use of an inclined approach ramp, rather than the rounded upstream sill used by the writers. Therefore, the approach may not be sufficiently streamlined on the broad-crested weir having a rounded upstream sill edge. It is obvious that better streamlining over the weir can be achieved by providing sloping upstream face to the weir. The discharge coefficient of a broad-crested weir with a vertical upstream face can be increased by providing a sloping upstream face (Ackers et al. 1980). For sharp-edged rectangular profile weirs, Singer and Crabbe defined the following operating conditions for which the discharge coefficient is constant; $0.08\langle h1/L\langle 0.33$ and $0.18\langle h1/(h1+P)\langle 0.36$ (Ackers et al. 1980; Bos 1989). Singer and Crable suggested $C_d=0.848$ and 0.855, respectively, in this region. For the aforementioned ranges of h_1/L and $h_1/(h_1+P)$, there are various experimental data, where the C_d values are between 0.80 and 0.85. When h_1/L exceeds 0.33 and/or $h_1/(h_1+P)$ exceeds 0.36, the coefficient of discharge rises.

A small degree of rounding of the upstream corner of a rectangular-profile weir produces a considerable increase in the discharge coefficient. The radius of the nose, r_2, influences the flow characteristics of the round-nosed horizontal-crested weir in two ways, first, if it is too sharp, separation can occur at the upstream end of the crest and the boundary layer will not develop in the way assumed in the derivation of the theoretical discharge equation; second, the depth of water h_1, at the upstream end of the weir is influenced by the radius (Ackers et al. 1980). Therefore, for a known discharge passing over the weir, if h_1 value is recorded with ±0.5–1.00 mm difference as a function of the nose radius, this can result in significant variation on the corresponding C_d value.

Because of these effects, not being provided a streamlined approach due to the used nose radius $r_2=5$ cm, short weir length $L=35$ cm, and small weir height $P=10$ cm, we believe that the observed discharge coefficients are as much as 20% lower at the smallest values of H_1/L (approx 0.1) than those obtained from WinFlume and provided by Bos (1989). The suggested values of the above mentioned parameters by the "design specifications" are as follows; while the lower limit of 6 cm or 0.08 L (whichever is greater) is recommended for h_1, $r_2\geq 0.2H_{max}$, $L\geq 1.50H_{max}$ and $P\geq 15$ cm (Bos 1989; Ackers et al. 1980).

In the experiments, a rectangular sharp-crested weir, 26 cm wide and 29 cm high, mounted in the inlet box of the laboratory flume with a width of 26 cm was used. It was not contracted. Since the inlet box, which was a rectangular channel 5.0 m long, was installed about 0.80 m above the main channel, it was possible to measure the flow rate passing over this weir volumetrically. Before starting the experiments, Kinsvater and Carter's discharge equation was calibrated with volumetrically determined discharges. For a given water-head over the sharp-crested weir, the corresponding volumetric flow rate was determined three times and their average taken. Therefore, it can clearly be stated that all the flow measurements were conducted with high accuracy.

Given the practical considerations, it is obvious that the shoulders of the compound cross section should have a slope toward the center of the channel for the reasons stated by the discussers; that had been clearly expressed in the paper under the subsection of "Head-Discharge Rating." In the models tested, we took the above mentioned slopes as $\theta=\theta°$ to not have another slope parameter among the variables affecting the flow.

As stated by the discussers, we focused our conclusions primarily on the variation of the discharge coefficients, velocity coefficients, and modular limits in relation to the depth and width of the inner channel. The C_d values determined for the base case of the broad-crested weir without an inner section, weir model Bz_0, were used only to compare them with those of the weir models with inner sections. Since the percentage of uncertainty in the determination of C_d is almost in the same order of magnitude for each weir model tested, the conclusions made regarding the depth and width of the inner channel will not be wrong.

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