Lecture 9

Broad Crested Weirs

I. Introduction

- The broad-crested weir is an open-channel flow measurement device which combines hydraulic characteristics of both weirs and flumes
- Sometimes the name “ramp flume” is used in referring to broad-crested weirs
- As with related open-channel measurement devices, the broad-crested weir has an upstream converging section, a throat section, and a downstream diverging section
- The broad-crested weir can be calibrated for submerged flow conditions; however, it is desirable to design this device such that it will operate under free-flow conditions for the entire range of discharges under which it is intended to function

- When operating under free-flow conditions, critical flow will occur over the crest (sill), and the discharge is uniquely related to the upstream flow depth – in this case, the downstream conditions do not affect the calibration
- The broad-crested weir can be calibrated in the field or laboratory; however, a major advantage of the structure is that it can be accurately calibrated based on theoretical equations without the need for independent laboratory measurements
- The flow depth upstream of the measurement structure must always be higher than it would be in the absence of the structure because there is always some head loss
- Downstream of the structure the depth will not be affected; so, the required head loss is manifested (in one way) as an increase in the upstream depth
II. Transition Submergence

- The typical transition submergence ranges for modular flow are:

  Parshall flume ....................... 58 to 80%
  Cutthroat flume ..................... 55 to 88%
  Broad-crested weir............... 70 to 95%

- This means that the broad-crested weir can usually function as a free-flow measurement device with less increase in the upstream water depth, which can be a significant advantage

III. Advantages and Disadvantages

**Advantages**

1. the design and construction of the structure is simple, thus it can be relatively inexpensive to install
2. a theoretical calibration based on post-construction dimensions can be obtained, and the accuracy of the calibration is such that the discharge error is less that two percent (this is assuming correct design and installation of the structure)
3. as with other open-channel flow measurement structures operating under free-flow (modular) conditions, a staff gauge which is marked in discharge units can be placed upstream; this allows a direct reading of the discharge without the need for tables, curves, or calculators
4. the head loss across the structure is usually small, and it can be installed in channels with flat slopes without greatly affecting existing upstream flow depths
5. floating debris tends to pass over and through the structure without clogging

**Disadvantages**

1. for water supplies with sediment, there will be deposition upstream of the structure
2. the upstream water depth will be somewhat higher than it was without the structure
3. farmers and other water users tend to oppose the installation of this structure because they believe that it significantly reduces the channel flow capacity. Although this is a false perception for a correctly designed broad-crested weir, it
does represent an important disadvantage compared to some other flow measurement devices

IV. Site Selection

- The channel upstream of the broad-crested weir should be fairly straight and of uniform cross-section
- The flow regime in the upstream section should be well into the subcritical range so that the water surface is stable and smooth \( (F_r^2 < 0.20, \text{ if possible}) \). For this reason it is best to avoid locating the structure just downstream of a canal gate or turnout, for example, because the water surface is often not stable enough for an accurate staff gauge reading
- The use of a stilling well and float assembly (or other water level sensing device) to measure water level can partially compensate for fluctuating water levels, although it involves additional cost
- Preferably, there are no gates or channel constrictions downstream of the structure which would cause non-modular flow
- In fact, it is desirable to locate the structure just upstream of an elevation drop if possible
- The presence of adjustable gates downstream complicates the design even more than for fixed constrictions because the depth will depend on both discharge and gate setting
- Other factors involved in the site selection are the stability of the channel bed and side slopes in the upstream direction (in the case of earthen canals), and the accessibility for measurement readings and maintenance
- If the upstream channel is not stable, the calibration may change significantly, and sediment can accumulate rapidly at the structure, also affecting the calibration

V. Design Considerations

- One of the important advantages of the broad-crested weir is that it can be accurately calibrated according to theoretical and empirical relationships
- This means that it is not necessary to install "standard" structure sizes and rely on laboratory calibration data
- The ability to calibrate the structure using equations instead of measurements is based on the existence of parallel streamlines in the control section over the crest
- In many other open-channel flow measurement devices the streamlines are not straight and parallel in the control section, and although a theoretical calibration would be possible, it requires complex hydraulic modeling
- On the other hand, theoretical calibration of the broad-crested weir is relatively simple
- The broad-crested weir should be located and dimensioned so that the flow is modular over the full operating range of the device
- If there is a significant drop in the channel bed immediately downstream of the structure, then the height of the crest may not be important in achieving critical depth
• However, the relative dimensions of the structure are important to obtain "favorable" flow conditions over the crest, that is, flow conditions which conform to the inherent assumptions for accurate theoretical calibration
• Thus, the height and length of the crest are important dimensions with relation to the upstream flow depth
• In any case, adequate design of the structure dimensions is essentially a process of trial-and-error, and therefore can be greatly facilitated through use of a calculator or computer program

Sill Height

• One of the most important design parameters is the height of the sill above the upstream channel bed
• This height should be sufficient to provide modular flow for the entire range of discharges that the broad-crested weir is intended to measure; however, it should not be higher than necessary because this would cause undue increases in the upstream water level after installation
• Thus, a design objective is to determine the minimum crest height for which modular flow can be obtained, and not to exceed this minimum height
• Excessively tall broad-crested weirs are not a problem in terms of water measurement or calibration, they are only troublesome with respect to unnecessarily raising the upstream water level
• The lower limit on sill height is based on the Froude number in the upstream channel section \( F_r^2 < 0.20 \)

Upstream and Downstream Ramps

• The converging upstream ramp should have a slope of between 2:1 and 3:1 (H:V). If flatter, the ramp is longer than necessary and there will be additional hydraulic losses which detract from the calibration accuracy
• If the ramp is steeper than 2:1, unnecessary turbulence may be created in the converging section, also causing addition head loss
• The diverging ramp at the downstream end of the crest should have a slope of between 4:1 and 6:1 (H:V), or should be truncated (non-existent). The 6:1 ratio is preferred in any case, and this same ratio is used in the diverging sections of other flow measurement devices, in both open-channel and pipe flow, to minimize head losses from turbulence
• If the 6:1 ratio causes an excessively long downstream ramp, then the length should be abruptly truncated (see the figure below), not rounded off
Many broad-crested weirs do not have a downstream ramp — the structure is terminated with a vertical wall just downstream of the throat section. In many cases, the energy that could be "recovered" by the inclusion of a downstream ramp is not enough to justify the additional expense. Also, the benefits of a downstream ramp are more significant in large broad-crested weirs (more than 1 m high).

Most of the head loss across the structure occurs due to turbulence in the diverging section, and in many cases the losses in the converging and throat sections may be neglected in calibration calculations.

Lateral Flow Contraction

- The side slope in the throat section of the broad-crested weir is usually the same as that in the upstream section, but it does not need to be the same.
- In very wide and earthen channels it is common practice to reduce the width of the throat section and design for a zero side slope (i.e. a rectangular section).
- When the side slope is reduced it is usually because the vertical flow contraction obtained by the crest height is insufficient to induce modular flow conditions. Therefore, in some cases lateral flow contraction is also required.

**Ratio of \( h_u / L \)**

- The ratio of upstream head to crest length is limited by a maximum of approximately 0.75, and a minimum of approximately 0.075.
- The lower limit is imposed to help maintain a reasonably small ratio of head loss to total upstream head (relative to the crest elevation).
- The upper limit is meant to avoid a non-hydrostatic pressure distribution on the crest.
- The calibration procedure is valid only for horizontal, parallel streamlines in the control section in the throat. When the ratio is between these limits, the theoretical calibration should be accurate to within two percent of the actual discharge.
- The ratio of upstream flow depth (referenced from the sill elevation) to the throat length is approximately 0.5 for the average discharge over a correctly-designed broad-crested weir.
- The figure below shows dimensions for a sample BCW design.
VI. Modular Limit

- The modular limit is defined as the ratio of specific energies in the downstream and upstream sections \((E_d/E_u)\) at which transitional flow exists.
- The velocity heads in the upstream and downstream sections will normally be small compared to the flow depths, so this ratio may be approximated by the transition submergence, \(S_t = h_d/h_u\) for \(Q_f = Q_s\).
- When the ratio is greater than the modular limit, the structure is submerged and the flow is non-modular.
• Under non-modular conditions the theoretical calibration is invalid since it assumes that critical flow occurs somewhere over the crest in the throat section.

• Field calibration of the structure for submerged-flow conditions is possible, but the results will be less accurate and the structure's use as a measurement device will be less convenient.

**Determining Downstream Depth**

• For existing channels with a straight section downstream of the broad-crested weir, and without hydraulic controls such as sluice gates, the value of \( h_d \) can be determined according to normal flow conditions. That is, for a given discharge, the value of \( h_d \) can be calculated using the Manning or Chezy equations.

• In the case of a downstream control which causes a backwater effect at the broad-crested weir, the issue becomes complicated since the actual submergence ratio across the structure depends not only on the discharge, but also on the control setting (which creates an M1 profile upstream toward the broad-crested weir). This is a common situation because the water surface profile in most irrigation channel reaches is affected by downstream flow control structures.

• For this reason, it is preferable to have a drop in elevation immediately downstream of the broad-crested weir, or to have a straight canal section without any nearby control structures in the downstream direction.

**Energy Balance and Losses**

• Given an upstream depth and its associated discharge (according to the calibration), the value of downstream specific energy, \( E_d \), for the modular limit is calculated by subtracting estimated head losses from the upstream specific energy, \( E_u \).

• These head losses include friction and turbulence across the broad-crested weir, and equations exist to approximate the respective values according to cross-sectional geometry, expansion ratios, and roughness coefficients (Bos, et al. 1984).

• Computer programs for developing the theoretical calibration contain these equations; however, it is worth noting that the losses due to wall friction are very minimal, and accurate estimation of roughness coefficients is not necessary for calibration.

• The majority of the losses occur due to the sudden expansion downstream of the throat section, and these losses are either estimated or calculated (using empirical relationships) depending on the downstream ramp dimensions.

**Calculating the Modular Limit**

• The modular limit will vary according to discharge for a given installation, and its calculation can be summarized as follows:

1. Given an upstream depth, channel cross-section, and weir calibration, calculate the discharge (assuming modular flow), and add depth plus velocity head to produce \( E_u \).
2. Calculate head losses due to wall friction in the converging and throat sections, then estimate the expansion loss downstream of the throat, and add these two values
3. Subtract the combined losses from $E_u$, giving the value of $E_d$. The modular limit is, then, $E_d/E_u$
4. Determine the downstream depth for the given discharge. This can be done using the Manning equation for uniform flow, or by another equation when a backwater profile exists from a downstream control
5. Compare the calculated downstream water level with the value of $h_d$, which is equal to $E_d$ minus the corresponding downstream velocity head. If the calculated water level is less than or equal to $h_d$, the flow will be modular because the actual head loss is greater than that required for modular flow