Lecture 26

Energy Dissipation Structures

I. Introduction

- Excess energy should usually be dissipated in such a way as to avoid erosion in unlined open channels
- In this context, “excess energy” means excess water velocity which causes erosion and or scouring in an open channel
- Erosive damage can occur even at low flow velocities when the water is swirling, although at a slower rate
- Energy dissipation structures and other protective infrastructure are used at locations that are prone to erosion

II. Locations of Excess Energy

- What are the locations of excess energy in open channels?
  1. Channel constrictions (such as gates, weirs, others)
  2. Steep longitudinal bed slopes
  3. Drops in elevation

- Energy dissipation is almost always needed downstream of supercritical flow sections
- Energy dissipation may also be desired in lined channels
- Energy dissipation structures are typically located at:
  1. Sudden drops in bed elevation
  2. Downstream ends of channel branches, flumes and chutes (especially where discharging into earthen sections)
  3. Outlets of culverts and inverted siphons
  4. Structures causing supercritical flow (e.g. underflow gates)
  5. Structures causing downstream turbulence and eddies

III. Energy Dissipation Structure Types

- Most energy dissipation structures in open channels are based on:
  1. the creation of a stable hydraulic jump
  2. head-on impact on a solid, immovable obstruction

- Both of these energy-dissipation structure classes can cause significant turbulence, reducing the hydraulic energy
- USBR publications state that the impact-type energy dissipation structures are more “efficient” than hydraulic-jump energy dissipaters (see Chapter VI in the Design of Small Canal Structures book by the USBR)
Here, a more “efficient” design is defined as one which results in a smaller and or cheaper structure for the same energy dissipation capacity.

- Design dimensions for energy dissipation structures are important because an inappropriate design can worsen an erosion and or scouring problem, as has been manifested in the field and in laboratory experiments.
- There have been cases in which the installation of an energy dissipation structure caused more erosion than that which occurred without it.

- The USBR has published design specifications for:
  1. baffled apron drops
  2. baffled pipe outlets
  3. vertical sleeve valve stilling wells

- The vertical sleeve structure is designed for energy dissipations at pipe-to-open channel interfaces (flow from a pipe into an open channel).
- All three of the above USBR energy dissipation structures are of the impact type.
- In practice, many variations of baffled energy dissipation structures can be found.

IV. Hydraulic Jumps for Energy Dissipation

- In open channels, a transition from subcritical to supercritical flow regimes results in very little localized hydraulic energy loss.
- But, the opposite transition, from supercritical to subcritical, involves a hydraulic jump and energy loss.
- The energy loss through a hydraulic jump can be significant, so jumps can be applied to energy dissipation applications in open channels.

**Figure 1.** Side view of a hydraulic jump (flow is from left to right)

- The energy loss across a hydraulic jump (upstream to downstream) is equal to the difference in specific energy:
\[ \Delta E = E_u - E_d \quad (1) \]

- Energy loss can be calculated based on measurements of depth and flow rate
- In designs, hydraulic jump energy loss is unknown, so you must apply the momentum function to determine a conjugate depth, then apply Eq. 1
- For a given Froude number, flow rate, and upstream depth:
  1. a rectangular cross section gives the least energy loss
  2. a triangular cross sections gives the greatest energy loss

- Cross sections with sloping sides provide more pronounced secondary currents (essentially orthogonal to the stream-wise direction), which also help dissipate hydraulic energy
- Thus, hydraulic jumps in trapezoidal cross sections give energy dissipation magnitudes somewhere between the extremes of rectangular and triangular cross-sectional shapes

- Some important hydraulic jump parameters, such as jump length and location, are determined experimentally, not theoretically
- Thus, design procedures for hydraulic jump energy dissipaters always include empirical equations
- The length of the “roller,” \( L_r \), is always less than the length of the jump, \( L_j \)

\[ L_j \approx 9.75h_u \left( F_u - 1.0 \right)^{1.01} \quad (2) \]

where \( F_u \) is the Froude number on the upstream side of the jump

- Small (weak) hydraulic jumps do not have a roller
- The length of a hydraulic jump in a rectangular cross section can be approximated by the following function:

\[ L_j \approx 9.75h_u \left( F_u - 1.0 \right)^{1.01} \quad (2) \]

- There are several classifications for hydraulic jumps

\[ \text{Figure 2. Another side view of a hydraulic jump (flow is from left to right)} \]

- Small (weak) hydraulic jumps do not have a roller
- The length of a hydraulic jump in a rectangular cross section can be approximated by the following function:

\[ L_j \approx 9.75h_u \left( F_u - 1.0 \right)^{1.01} \quad (2) \]

where \( F_u \) is the Froude number on the upstream side of the jump

- There are several classifications for hydraulic jumps
• Procedures exist to determine the type of jump that might occur in a given situation
• One classification groups hydraulic jumps into types “A” to “F”

V. Drop Spillways

• Drop spillways (also known as “drop structures”) are abrupt decreases in channel bed elevation with a downstream stilling basin, used to dissipate hydraulic energy in open channels
• Drop spillways often combine both hydraulic jump and impact features, although not all design situations are associated with a hydraulic jump
• Much research and experimentation has been done on drop spillways in efforts to adequately define design procedures and parameters
• Part of the reason for this is that, when incorrectly dimensioned, drop spillways can actually worsen an erosion problem in the downstream channel
• Most drop spillways have the following basic features:

  1. Inlet section
  2. Drop section
  3. Rectangular stilling basin
  4. Outlet section

• The flow through a drop spillway:

  1. Spills over a crest at a vertical headwall
  2. Falls on a horizontal (level) apron
  3. Impinges on floor blocks inside the basin
  4. Exits the stilling basin over an end sill

• Energy dissipation occurs via:

  1. Floor blocks
  2. End sill at DS of basin
  3. Turbulence in the “tail water”
  4. Hydraulic jump (in some cases)

• The following drop structure design elements are adapted principally from Donnelly & Blaisdell (1965) and involve mostly empirically-determined relationships

Stilling Basin Length

• How long does the stilling basin need to be for effective energy dissipation?
• According to experimental results, a series of simple iterative calculations are needed to answer this question
• Base dimensions on a design discharge and critical depth in a rectangular basin:
\[
h_c = \sqrt[3]{\frac{(Q/b)^2}{g}}
\]

where \( h_c \) is the critical depth of water in a rectangular open-channel section (m or ft); \( Q \) is the flow rate (m\(^3\)/s or cfs); \( b \) is the channel base width (m or ft); and \( g \) is the ratio of weight to mass (9.81 m/s\(^2\) or 32.2 ft/s\(^2\))

- In the present context, \( b \) represents the width of the stilling basin
- Note that Eq. 3 is based on the squared Froude number, set equal to unity
- Critical depth, \( h_c \), may or may not actually occur in the stilling basin (if it does not, there will be no hydraulic jump), but in any case the value of \( h_c \) is still used in the following design calculations

**Where the Nappe Hits the Floor**

- Consider the following figure where flow goes from left to right (note that the coordinate origin is located at the brink of the overfall):

![Diagram of a drop spillway showing the free and submerged nappes](image-url)

**Figure 3.** Side view of a drop spillway showing the free and submerged nappes (flow is from left to right)
• This is the equation for the “free nappe” is:

\[
\frac{x_f}{h_c} = -0.406 + \sqrt{3.195 - 4.386 \left( \frac{y_{\text{drop}}}{h_c} \right)}
\]  

(4)

where \( h_c \) is as defined in Eq. 3; and the other variables are defined in Fig. 3

• Note that \( y_{\text{drop}} < 0 \), and \( h_c > 0 \), in all cases
• This means that the ratio \( y_{\text{drop}}/h_c \) is always negative
• Thus, \( x_f \) increases with increasing absolute magnitude of \( y_{\text{drop}} \)
• Note also that \( x_f \) defines the upper nappe surface
• Each of the terms in Eq. 4 are dimensionless

• This is the equation for the “submerged nappe:”

\[
\frac{x_s}{h_c} = \frac{0.691 + 0.228 \left( \frac{x_t}{h_c} \right)^2 - \frac{y_{\text{drop}}}{h_c}}{0.185 + 0.456 \left( \frac{x_t}{h_c} \right)}
\]

(5)

again, where \( h_c \) is the critical depth, as defined in Eq. 3; \( x_t \) is defined by Eq. 6; and the other variables are defined in Fig. 3

• The variable \( x_t \) is the distance to where the upper nappe surface plunges into the tail water
• The nappe plunge location, \( x_t \), is defined by an equation which is similar to Eq. 4 for the free nappe:

\[
\frac{x_t}{h_c} = -0.406 + \sqrt{3.195 - 4.386 \left( \frac{h_t + y_{\text{drop}}}{h_c} \right)}
\]

(6)

where \( h_t \) is the tail water depth in the stilling basin, as seen in Fig. 3, and is referenced to the stilling basin floor

• The term in parentheses in Eq. 6 will be positive in those cases in which the tail water is above the spillway crest
• To avoid a negative square root term in Eq. 6, limit \( (h_t + y_{\text{drop}})/h_c \) to a maximum of 0.7 when applying Eq. 6
• This is not a significant restriction because the required stilling basin length is not affected when:
\[
\frac{h_t + y_{\text{drop}}}{h_c} > 0.67
\]  

- All water depths (including \(h_c\) and \(h_t\)) are greater than zero
- All “x” values downstream of the spillway crest are greater than zero
- But all “y” values are negative below the spillway crest, positive above (this follows the convention introduced by Donnelly and Blaisdell), as seen in Fig. 3

- The average of the results from Eqs. 4 and 5 are used for drop structure design:

\[
x_a = \frac{(x_f + x_s)}{2}
\]  

where the value of \(x_a\) is can be determined mathematically (preferred) or graphically, as shown in the following plot (Fig. 4) of the above equations

- The stilling basin length, \(L\), will always be greater than \(x_a\) \((L > x_a)\)

**Figure 4.** Plot of drop spillway design equations for determining the value of \(x_a\)
Floor Blocks

- Floor blocks are usually included in drop structure designs to help dissipate hydraulic energy before the flow exits the stilling basin.
- There is a required minimum distance from $x_a$ to the blocks so the flow becomes parallel to the floor before impinging on the upstream face of the blocks.
- If the blocks are too close to the location of $x_a$, water splashes ("boils") off the blocks, and may go over the sides of the stilling basin.

![Diagram of a drop spillway showing the recommended location of floor blocks](image)

**Figure 5.** Side view of a drop spillway showing the recommended location of floor blocks (flow is from left to right)

- If $x_b < \frac{1}{2}h_c$, the floor blocks are mostly ineffective in terms of energy dissipation.
- Thus, for stilling basin design, let

$$x_b = 0.8h_c \quad (9)$$

- The recommended height of the floor blocks is 0.8 $h_c$.
- The recommended length of the floor blocks is 0.5 to 0.75 $h_c$.
- The recommended width of the floor blocks is also 0.5 to 0.75 $h_c$.
- Usually, make the floor blocks square (length = width).
- The upstream faces of the floor blocks should occupy from 50 to 60% of the basin width for effective energy dissipation.
- Use equal spacing of floor blocks across the width of the stilling basin, but make slight adjustments as necessary to accommodate the total width, $b$.

Longitudinal Sills

- Longitudinal sills are sometimes placed on the floor of the stilling basin, parallel to the basin walls, as seen in a plan-view (Fig. 6).
Figure 6. Plan view of a drop spillway showing longitudinal sills and square floor blocks (flow is from left to right)

- These sills are unnecessary if the floor blocks are properly:
  1. Proportioned
  2. Spaced

- Longitudinal sills are sometimes included in a design for structural reasons
- If they are included, they should pass through (not between) the floor blocks, as shown in Fig. 6

End Sill Location

- There is a minimum distance from the floor blocks to the end sill, which is located at the downstream end of the stilling basin
- This minimum distance is intended to maximize the energy dissipation from both the floor blocks and the end sill
- For design purposes, let:

$$x_c \geq 1.75h_c$$

where $x_c$ is defined in Fig. 7
Figure 7. Side view of a drop spillway showing the location of the end sill and the total basin length (flow is from left to right)

- However, in most design cases, $x_c$ is set equal to $1.75 h_c$
- In other cases, it may be necessary to provide a longer stilling basin length to accommodate the site-specific conditions

Stilling Basin Length

- In summary, the stilling basin length is:

$$L = x_a + x_b + x_c$$  \hspace{1cm} (11)

or,

$$L = x_a + 2.55 h_c$$ \hspace{1cm} (12)

End Sill Height

- The end sill height is:

$$y_{end} = 0.4 h_c$$ \hspace{1cm} (13)

where $y_{end}$ is the end sill height, as shown in Fig. 8

- Observe that $y_{end} > 0$ in all cases
Figure 8. Side view of a drop spillway showing the height of the end sill

- The top of the end sill should be at or slightly above the invert (bottom) elevation of the downstream channel (or downstream channel transition), as shown in the following figure.

Figure 9. Side view of a drop spillway showing the downstream channel invert

Tail Water Depth

- A minimum tail water depth is required in the design of a drop spillway.
- To prevent downstream scouring, the tail water depth should be “about the same” as the depth in the stilling basin.
- If this is true, the hydraulic jump is submerged inside the basin length.
- For design, let

\[ h_t \geq 2.15h_c \]  \hspace{1cm} (14)

where \( h_t \) is from the downstream water surface to the stilling basin floor, as seen in Fig. 9.
• In most drop spillway designs, let

\[ h_t = 2.15h_c \]  \hspace{1cm} (15)  

• Note that the recommended ratio of \( h_t/h_c \) (= 2.15) is independent of the drop height, \( y_{\text{drop}} \).

• There may be a hydraulic jump up to the tail water depth, in some cases.

• If the tail water depth, \( h_t \), is too low (i.e. \( h_t < 2.15h_c \))
  1. Increase the stilling basin width, \( b \), which will decrease \( h_c \); or,
  2. Increase \( |y_{\text{drop}}| \), deepening the stilling basin floor.

• An increase in \( |y_{\text{drop}}| \) and or \( b \) may increase construction and maintenance costs.

• An increase in \( |y_{\text{drop}}| \) also increases the end sill height.

• Note that the depth from the spillway crest to the stilling basin floor can be increased not only by deepening the basin floor, but also by providing a weir at the overfall location.

• This solution can be convenient for the drop structure design, but care must be taken with the freeboard in the upstream channel because increasing the spillway crest height will result in a corresponding upstream water depth increase.

• How to determine the value of tail water depth, \( h_t \)?

• If uniform flow conditions prevail in the downstream channel, use the Manning or Chezy equation to calculate \( h_{ds} \).

• Otherwise, apply gradually-varied flow analysis for subcritical conditions to determine \( h_t \).

• Thus, \( h_{ds} \) is calculated independently of the drop structure dimensions.

• Finally,

\[ h_t = h_{ds} + y_{\text{end}} \]  \hspace{1cm} (16)  

**Side and Wing Walls**

• The tops of the sidewalls should be at least 0.85\( d_c \) above the tail water surface.

• Wing walls are DS of the end sill, at 45° angle, and with a top slope of 1:1.

• Wing wall length depends on the width of the DS channel section.

• Wing walls are not necessary if the DS channel is a lined canal.
Drop Spillway Construction

- Construction is usually of steel-reinforced concrete
- The basin floor should be level, both longitudinally and transversely
- Upstream and or downstream channel transitions may be needed
- Concrete floor and wall thickness is usually 5-8 inches (12-20 cm)
- The depth of the concrete footings should be 2-3 ft for most designs in small- and medium-size channels
- May need riprap or other form of erosion protection upstream and downstream of the drop structure where earthen channels exist
- The approach channel bed elevation should be the same as the spillway crest elevation at the headwall
- The required headwall height at the crest location depends on the expected upstream depth at the design discharge, plus freeboard
- The side walls slope down from the top of the headwall to the top of the wing walls at the end sill location (see Fig. 10)
- In some cases it is convenient and appropriate to make the stilling basin width, b, equal to the width of the upstream or downstream channel (may eliminate the need for transitions)

VI. Drop Spillway Design Procedure

- The best design procedure depends on the given site conditions and requirements for a particular location
- However, in general, the following procedure can be applied
  
  1. Define the total available bed elevation change at the proposed drop structure location.
  2. Define the design discharge, Q.
3. Calculate $h_{ds}$ based on the downstream channel conditions (cross section, bed slope, roughness) using a uniform-flow equation, or the gradually-varied flow equation, as appropriate.

4. Choose a reasonable value for the stilling basin width, $b$.

5. Calculate critical depth in the stilling basin, $h_c$ (Eq. 3).

6. Calculate $y_{end}$ (Eq. 13).

7. Calculate $h_t$ (Eq. 16).

8. Is Eq. 14 satisfied? If not, use Eq. 14 to recalculate the stilling basin width, $b$, then go back to Step 5.

9. Calculate $y_{drop}$ based on the total available bed elevation change and $y_{end}$ (see Fig. 9), where $y_{drop}$ should be less than zero. If $y_{drop} \geq 0$, consider raising the spillway crest by including a weir.

10. Calculate $x_f$ (Eq. 4).

11. Calculate $x_t$ (Eq. 6).

12. Calculate $x_s$ (Eq. 5).

13. Calculate $x_a$ (Eq. 8).

14. Calculate $x_b$ (Eq. 9).

15. Calculate $x_c$ (Eq. 10).

16. Calculate the stilling basin length, $L$ (Eq. 11). If the length is not acceptable, adjust $b$ and go back to Step 5.

17. Calculate the floor-block dimensions and spacing.

18. Calculate the head wall height based on the upstream depth at $Q_{max}$, plus freeboard.

19. Calculate the height of the wing walls at the end sill ($0.85 h_c$).

20. Prepare side view and plan view drawings of the drop spillway structure.

**VII. Example Drop Spillway Design**

**Given:**

- The design flow rate is $Q_{max} = 9.0 \text{ m}^3/\text{s}$
- There is a drop of 2.25 m in channel bed invert at this location
- The upstream channel is earthen, as is the downstream channel
- The upstream channel has a base width of approximately 5 m
- The downstream channel has an approximately trapezoidal cross section: base width is $b = 5$ m, side slopes have $m = 1.64$, and the bed slope is $S_o = 0.000112$
- For the downstream channel, use a Manning $n$ value of 0.019
- The depth in the downstream channel is at the uniform flow depth at $Q_{max}$

**Solution:**

1. The total available bed elevation change is given as 2.25 m.
2. The design discharge is given as 9 m$^3$/s
3. Uniform flow conditions are expected in the downstream channel. Using the *ACA* program, the normal depth in the downstream channel is 1.80 m at the design capacity of 9 m$^3$/s, with a Manning roughness of $n = 0.019$.
4. Try a stilling basin width of $b = 5$ m, matching the upstream channel base width
5. Critical depth in the stilling basin (Eq. 3):

\[ h_c = \sqrt[3]{\frac{(9/5)^2}{9.81}} = 0.691 \text{ m} \]

6. The end sill height will be (Eq. 13):

\[ y_{\text{end}} = 0.4(0.691) = 0.276 \text{ m} \]

7. The tail water depth will be (Eq. 16):

\[ h_t = 1.80 + 0.276 = 2.076 \text{ m} \]

8. Check to see if Eq. 14 is satisfied:

\[ h_t = 2.076 \text{ m} \]

\[ 2.15h_c = 2.15(0.691) = 1.486 \text{ m} \]

Thus,

\[ h_t > 2.15h_c \]

and Eq. 14 is satisfied.

9. The value of \( y_{\text{drop}} \) will be:

\[ y_{\text{drop}} = -2.25 - 0.276 = -2.526 \text{ m} \]

Notice that \( y_{\text{drop}} \) is negative (as required).

10. Calculate \( x_f \) (Eq. 4):

\[ x_f = 0.691 \left[-0.406 + \sqrt{3.195 - 4.386 \left(\frac{-2.526}{0.691}\right)}\right] = 2.75 \text{ m} \]

11. Calculate \( x_t \) (Eq. 6):

\[ x_t = 0.691 \left[-0.406 + \sqrt{3.195 - 4.386 \left(\frac{2.076 - 2.526}{0.691}\right)}\right] = 1.42 \text{ m} \]

12. Calculate \( x_s \) (Eq. 5):
13. Calculate $x_a$ (Eq. 8):

$$x_a = \frac{(2.75 + 3.27)}{2} = 3.01 \text{ m}$$

14. Calculate $x_b$ (Eq. 9):

$$x_b = 0.8(0.691) = 0.553 \text{ m}$$

15. Calculate $x_c$ (Eq. 10):

$$x_c = 1.75(0.691) = 1.209 \text{ m}$$

16. Calculate the stilling basin length (Eq. 11):

$$L = x_a + x_b + x_c = 4.77 \text{ m}$$

Notice that $L < b$ in this design.

17. Floor block dimensions and spacing:

Floor block height: $0.8 h_c = 0.8(0.691) = 0.55 \text{ m}$
Floor block width: $0.5 h_c = 0.8(0.691) = 0.35 \text{ m}$
Floor block length: $0.5 h_c = 0.8(0.691) = 0.35 \text{ m}$

At 50% basin width, the required number of floor blocks is:

$$N = \frac{0.5b}{0.35} = \frac{2.5}{0.35} = 7.1 \text{ blocks}$$

Round up to $N = 8$ blocks, giving a percent area of 56%. Placing a block against each side wall of the stilling basin, the uniform spacing between the blocks will be:

$$\text{spacing} = \frac{b - 0.35N}{N - 1} = 0.314 \text{ m}$$

18. The height of the headwall, from the basin floor to the top, should be:
\[-y_{\text{drop}} + 1.1(h_{\text{ds}}) = 2.526 + 1.1(1.80) \approx 4.50 \text{ m}\]

where the coefficient 1.1 is to allow for freeboard.

19. Wing wall height at end sill:

\[0.85h_c = 0.85(0.691) = 0.587 \text{ m}\]

20. Design notes:

- Complete the design by specifying wall & floor thickness
- Specify the depth of footings (see Fig. 10)
- Specify the length of the wing walls (they should be at least long enough to meet the side slopes of the downstream channel)
- Make design drawings (side and plan views)
- A more iterative design approach could be used to minimize the size (b x L) of the drop spillway, thereby reducing its cost

References & Bibliography


