CHAPTER 5

HYDRAULIC STRUCTURES

LEARNING OBJECTIVES

- Identify the various types and uses of hydraulic structures.
- Determination of channel flow using hydraulic structures
Introduction

Hydraulic structures are artificial or natural objects that can be used to divert, restrict, stop, or manage the flow of water. The structures can be made from a range of materials such as large rocks, concrete, wooden timbers or even tree trunks.

On the right is an example of a hydraulic structure that is built across a river to manage the natural flow of water in the river.

Introduction

Hydraulic structures can be grouped into two main categories:

- Hydraulic structures used for constant flow of pressure. Example: underflow sluice gates and pipes.
- Hydraulic structures used for flow in open channels with no pressure except atmospheric pressure. Example: weirs, spillways, and energy dissipator structures.
Introduction

- In this chapter, we will focus on four types of hydraulic structures, which are underflow sluice gates, spillways, weirs, and energy dissipator structures.
Underflow Sluice Gates

- Underflow sluice gate are used for controlling and measuring flow rates in open channels and rivers mainly in connection to hydro power plants.

\[ E_0 = \text{Specific energy} \]
\[ a = \text{height of gate opening} \]
\[ y_0 = \text{depth of flow at point 0} \]
\[ y_1 = \text{depth of flow at point 1} \]
Underflow Sluice Gates

- The flow under the vertical sluice gates is considered as rectangular orifice as long as the height of the opening below the gate, \( a \), is smaller compared to level of specific energy \( E_o \) and level of flow upstream, \( y_2 \) does not affect the flow.
- The minimum depth area at the opening of the sluice gate is called vena contracta.

Minimum flow depth → Minimum flow area → Maximum flow velocity

Underflow Sluice Gates

- The flow discharge equation can be derived from the Bernoulli theorem.
- The Bernoulli theorem states, energy per unit weight of fluid before and after flowing through a certain area or system is same.
- This is expressed by the equation below.

\[
\frac{V_o^2}{2g} + \frac{P_o}{\gamma} + y_o = \frac{V_1^2}{2g} + \frac{P_1}{\gamma} + y_1
\]
Underflow Sluice Gates

The following assumptions are also made:

- The pressure at point 0 and point 1 is atmospheric pressure, hence, $P_0 = P_1$
- The velocity at point 0 is too small compared to velocity at point 1.

Therefore, $v_0 \approx 0$ and $y_0 = E_0$

- Applying these two assumptions, we conclude that

$$y_0 - y_1 = \frac{v_1^2}{2g}$$

Thus, the simplified expressions for velocity and discharge for underflow gates are

$$v_1 = \sqrt{2g(y_0 - y_1)}$$

$$Q = baC_d\left(2g(y_0 - y_1)\right)^{1/2}$$

Where,

- $b$ = Width of gate
- $C_d$ = Coefficient of discharge - between 0.596 – 0.607
- $a$ = height of gate opening
**Underflow Sluice Gates**

- The simplified discharge equation for an underflow gate is valid if not influenced by the downstream water level $y_2$.
  
  In this case $(y_0 - y_1) > y_2$

- If downstream control occurs, $y_1$ submerges completely, and the calculation of discharge is based on $(y_0 - y_2)$. The flow discharge equation for this condition is
  
  $$Q = baC_d \left( 2g(y_0 - y_2) \right)^{1/2}$$

  When $(y_0 - y_1) \leq y_2$  **Case 2**

**Exercise 5.1**

An underflow gate is built in a rectangular channel with a bottom width $b$ of 2.5 m. Other values include $y_0 = 2$ m, $\psi = 0.625$, $C_d = 0.610$ and $a = 0.5$ m. Calculate the flow discharge if $y_2 = 1.8$ m.
Exercise 5.1

1. Find $y_1$
   \[ y_1 = \psi a = 0.625(0.5) = 0.313 \text{ m} \]

2. Determine $(y_0 - y_1)$
   \[ (y_0 - y_1) = (2 - 0.313) = 1.687 \text{ m} \]

Since $(y_0 - y_1) < y_2$, this means downstream control occurs.
Thus,
\[ Q = baC_d \left(2g(y_0 - y_2)\right)^{1/2} \]
\[ = 2.5(0.5)(0.61) \times \left[2(9.81)(2 - 1.8)\right]^{1/2} \]
\[ = 1.51 \text{ m}^3/\text{s} \]

Spillways

- A spillway is built in a reservoir to allow the flow of water to safely move downstream when the reservoir is full.
- A spillway is shaped as a rectangular concrete channel that connects the upstream and downstream regions of a weir.
- The best design for a spillway is following the lower nappe of the free fall of water and the best shape of the spillway surface is parabolic with inverted curve at the downstream.
The flow through a spillway can be seen in the graphic above. The flow shown here is a super-critical flow.

The figure shows an ogee spillway as a section of dam designed to permit water to pass over its crest.
Spillways

- Ogee spillway also known as the overflow spillway (widely used on gravity, arch and buttress dams) and the most extensively used spillway to safely pass the flood flow out of reservoir.

Spillways

- The characteristics of ogee shape are based on the underside shape of the sharp-crested weir nappe.
**Spillways**

- In the high overflow spillway ($H_1/P \approx 0$ or $H_1 > H_d$), the discharge corresponding to the maximum designed capacity of the spillway, and the crest of ogee spillway rises up from point A (sharp-crested crest) to maximum rise of 0.115 $H_1$ then falls in parabolic form.

- Discharge coefficient for ogee spillway is about 20% higher than discharge coefficient for weir.

**Weir**

- A weir is an overflow structure built across an open channel to measure the rate of flow.

- The weir offers a simple and reliable method of measuring the stream flow.
Weir

- There are several types of weirs, depending on crest width and channel openings.

<table>
<thead>
<tr>
<th>Based on Crest Width</th>
<th>Based on Channel Openings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broad-crested Weir</td>
<td>Rectangular Weir</td>
</tr>
<tr>
<td>Sharp-crested Weir</td>
<td>Trapezoidal Weir</td>
</tr>
<tr>
<td></td>
<td>Triangular Weir</td>
</tr>
</tbody>
</table>

Broad - When thick of crest more than 60% of nappe’s thick

Weir

- Weirs are categorised into rectangular, triangular, trapezoidal and submerged weirs.
- The formulas and example calculations on the flow discharge for each type of weir are presenting below.
Rectangular Weir

- Rectangular weirs are divided into suppressed weirs and contracted weirs.
- A weir is suppressed when the weir spans the full width of a rectangular channel and usually require ventilation downstream.

\[ Q = \frac{2}{3} C_d \sqrt{2g LH_1^{3/2}} \]

where
- \( C_d \) - coefficient of discharge
- \( L \) - width of weir
- \( H_1 \) - head over the weir
Rectangular Weir

- The Rehbock formula to determine the value of $C_d$:
  \[ C_d = 0.611 + 0.075 \frac{H_1}{P} \]

Where,

$H_1$ = Head over the weir
$P$ = height of the weir crest above the channel bottom.

Note: This expression for $C_d$ is valid if $H_1/P \leq 5$

- Syarat kes 1: $H_1/P \leq 5$
  $Cd = 1.06 \times [1 + (P/H_1)]^{3/2}$

- Syarat kes 2: $H_1/P \geq 20$

Exercise 5.2

Consider a rectangular weir 0.75 m high and 1.5 m long as below. The weir is being used for discharging water from a tank under a head of 0.5 m. Estimate the discharge for suppressed weir.
**Exercise 5.2**

**Coefficient of Discharge**

Using Rehbock Formula, calculate $C_d$

Given, $H = 0.5$ m and $P = 0.75$ m. Thus,

$$C_d = 0.611 + 0.075 \left( \frac{H_1}{P} \right)$$

$$C_d = 0.611 + 0.075 \left( \frac{0.5}{0.75} \right) = 0.661$$

**Exercise 5.2**

Known values, $C_d = 0.661$; $H = 0.5$ m; $L = 1.5$ m; $g = 9.81$ m/s. Thus,

$$Q = \frac{2}{3} C_d \sqrt{2gLH_1^{3/2}}$$

$$Q = \frac{2}{3} (0.661) \sqrt{2(9.81)(1.5)(0.5)^{3/2}}$$

$$Q = 1.035 m^3/s$$
Rectangular Weir

- Meanwhile, contracted weirs have weirlengths that are less than the width of a channel. Due to the presence of the end contractions, the effective length of the weir is smaller than the actual length of the weir.

\[ L_e = L - (0.1nH) \]

\[ n = \text{Number of end contractions} \]

\[ H_1 = \text{Head over the weir} \]

\[ C_d = \text{Coefficient of discharge}, \quad C_d = C_v \times C_c \]

\[ Q = \frac{2}{3} C_d \sqrt{2gL_eH_1^{3/2}} \]

Where:

- \( L \) = Length of the weir
- \( L_e \) = \( L - (0.1nH) \)
- \( n \) = Number of end contractions
- \( H_1 \) = Head over the weir
- \( C_d \) = Coefficient of discharge, \( C_d = C_v \times C_c \)

Suppressed weirs span the entire width of a channel, whereas contracted weirs normally have lengths that are less than the width of a channel.
Cd for contracted:

Using Bazin’s formula:

\[ Cd = \left[ 0.507 + \frac{0.00451}{H_1} \right] \left[ 1 + 0.55 \left( \frac{H_1}{P + H_1} \right)^2 \right] \]

Rectangular Weir

Another equation for contracted weirs, known as the Francis formula.

\[ Q = \frac{2}{3} C_c \sqrt{2g(L - 0.1nH_1)} \left( H_1 + \frac{V_o^2}{2g} \right)^{3/2} - \left( \frac{V_o^2}{2g} \right)^{3/2} \]

for \( L > 3H_1, H_1 / P < 1.0 \)

where

\( V_o \) = Velocity of approach
\( n \) = Number of end contractions
\( C_c \) = Coefficient of contraction, usually taken as 0.622
Rectangular Weir

- The following table shows the values of $n$ for different number of end contractions.

<table>
<thead>
<tr>
<th>Two end contraction</th>
<th>One end contraction</th>
<th>Zero end contraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n = 2$</td>
<td>$n = 1$</td>
<td>$n = 0$</td>
</tr>
</tbody>
</table>

Exercise 5.3

Consider a rectangular weir 0.75 m high and 1.5 m long as below. The weir is being used for discharging water from a tank under a head of 0.5 m. Estimate the discharge for a contracted weir, where $n = 2$. 
Exercise 5.3

Coefficient of Discharge
Using Rehbock Formula, calculate $C_d$

Given, $H = 0.5$ m and $P = 0.75$ m. Thus,

$$C_d = 0.611 + 0.075 \left( \frac{H}{P} \right)$$

$$C_d = 0.611 + 0.075 \left( \frac{0.5}{0.75} \right) = 0.661$$

Exercise 5.3

Known values, $C_d = 0.661$; $H = 0.5$ m; $L = 1.5$ m; $g = 9.81$ m/s. Thus,

$$L_e = L - (0.1nH)$$

$$L_e = 1.5 - (0.1 \times 2 \times 0.5) = 1.4$$ m

$$Q = \frac{2}{3} C_d \sqrt{2g L_e H^3}$$

$$Q = \frac{2}{3} (0.661) \sqrt{2(9.81)(1.4)(0.5)^{3/2}}$$

$$Q = 0.966 m^3 / s$$
**Triangular Weir**

- The flow discharge formula for a triangular weir with a central angle $\theta$, under a head $H_1$ is expressed as,

$$Q = C_d \frac{8}{15} \sqrt{2g} \tan \frac{\theta}{2} H_1^{5/2}$$

Where

- $C_d = \text{coefficient of discharge}$ is a function of $\theta$ with a value of 0.58.

**Exercise 5.4**

Calculate flow discharge through a triangular notch with a vertex angle of 60° and a head ($H_1$) over vertex of 0.5 m. The coefficient of discharge is assumed to be 0.58.
**Exercise 5.4**

\[
Q = C_d \frac{8}{15} \sqrt{2g} \tan \frac{\theta}{2} H_1^{5/2}
\]

\[
Q = \left( \frac{8}{15} \times 0.58 \times \sqrt{2(9.81)} \tan \frac{60}{2} \times (0.5)^{5/2} \right)
\]

\[
Q = 0.247 \text{ m}^3 / \text{s}
\]

**Trapezoidal Weir**

- The flow from a trapezoidal weir with the side slope \( m: 1 \) is a combination of flow from a suppressed rectangular weir with \( L = B \), and a triangular weir with a central angle of \( 2\theta \), where \( \tan \theta = m \).

The flow discharge can be calculated by using the formula given below.

\[
Q = \frac{2}{3} C_d \sqrt{2g} \frac{H_1^{3/2}}{L + \frac{4}{5} H_1 \tan \theta}
\]
Trapezoidal Weir

- The trapezoidal weir with side slope of 1 horizontal to 4 vertical is known as a Cippoletti weir. The flow discharge for a Cippoletti weir can be calculated by using the formula given below.

\[ Q = \frac{2}{3} C_d \sqrt{2g LH_{1}^{3/2}} \]

Where the coefficient of discharge has a constant value of 0.63.

Exercise 5.5

Consider a Cippoletti weir with width of 0.5 cm installed at a section of a channel. Calculate for the discharge in the channel when the head over the weir crest is 0.25 cm. Assume \( C_d = 0.63 \).
Exercise 5.5

\[ Q = \frac{2}{3} C_d \sqrt{2g LH}^{3/2} \]

\[ Q = \frac{2}{3} (0.63) \sqrt{2(9.81)(0.5)(0.25)}^{3/2} \]

\[ Q = 0.1163 \text{ m}^3 / \text{s} \]

Energy Dissipator Structure

- Energy dissipator structures are built at the lower end of a spillway to decrease the kinetic energy of flow. These structures are built to reduce the damages caused by high kinetic energy of flows.
- Example of energy dissipator is Stilling Basin Type III.
**Energy Dissipator Structure**

- When designing an energy dissipator for a given location or site, you must consider the matters related to site location, dissipator structures and the discharge flow through the dissipator.
- As such, the experience of an energy dissipator designer would be valuable and useful in designing an energy dissipator structure.

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**USBR Stilling Basin Designs**

**Type I:** $1.7 < F_1 < 2.5$

- Weak jump; no special structures needed

**Type II:** $4.5 < F_1$ and $V_1 > 60$ ft/s

(Figure 3.13 – dentated end sill, no baffle blocks)

**Type III:** $4.5 < F_1$ and $V_1 < 60$ ft/s

(Figure 3.12 – Solid end sill, baffle blocks)

**Type IV:** $2.5 < F_1 < 4.5$

- Oscillating jump, unstable
- No baffle blocks because of wave action
Energy Dissipator Structure

- The stilling basin type III is very stable with a steep jump front and less wave action downstream than either stilling basin type II or free hydraulic jump.
- It is recommended for discharges up to 18.58 m²/s per basin width with the Froude number (Fr) in range between 4.5 to 17 and a velocity of flow $v_1$ up to 15.2 m/s to 18.3 m/s.

Energy Dissipator Structure

- Stilling Basin Type III. There are three component blocks for the shown energy dissipator structure.

Block A are chute blocks.
Block B are baffle piers.
Block C are end sills.
Energy Dissipator Structure
Sizing for Stilling Basin Type III

<table>
<thead>
<tr>
<th>Block A</th>
<th>Block B</th>
<th>Block C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_1 = y_1$</td>
<td>$h_3 \rightarrow$ use formula $t = h_3/5$</td>
<td>$h_4 \rightarrow$ use formula $z_2 = 2.0$</td>
</tr>
<tr>
<td>$w_1 = y_1$</td>
<td>$s_3 = w_3 = 3h_3/4$</td>
<td></td>
</tr>
<tr>
<td>$h_1 = y_1$</td>
<td>$z_1 = 1.0$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$L_1 = 4y_2/5$</td>
<td></td>
</tr>
</tbody>
</table>

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Energy Dissipator Structure

- List of equations used to calculate the height of blocks A, B and C of an energy dissipator structure. The block heights are labelled as $h_1$, $h_3$ and $h_4$ respectively.

<table>
<thead>
<tr>
<th>Block</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$h_1 = y_1$</td>
</tr>
<tr>
<td>B</td>
<td>$h_3 = y_1(0.168Fr_1 + 0.63)$</td>
</tr>
<tr>
<td>C</td>
<td>$h_4 = y_1\left(\frac{Fr_1}{18} + 1\right)$</td>
</tr>
</tbody>
</table>
Energy Dissipator Structure

The depth $y_1$ used in all three equations above can be determined using

$$y_1 = \frac{Q}{Bv_1}$$

Where,

- $B$ = width of the spillway
- $v_1$ = velocity of flow in the spillway

The mean velocity $v_1$ at the toe of spillway can be determined using this equation.

$$v_1 = \sqrt{2g\left[H_1 - \frac{H_2}{2}\right]}$$

Where the positions of heights $H_1$ and $H_2$ are shown below.

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Energy Dissipator Structure

The depth of flow is used to estimate the length of the structure $L$. Basically, $y_2$ is determined by using the hydraulic jump equation with $y_1$ as the conjugate depth.
**Energy Dissipator Structure**

When the values of $L/y_2$ are plotted against $Fr_1$, you get the $L/y_2$ curve.

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**Energy Dissipator Structure**

- The steps to design an energy dissipator structure is shown below

<table>
<thead>
<tr>
<th>STEP</th>
<th>ACTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td>Find $y_1$, $y_1$, $Fr_1$, and $y_2$</td>
</tr>
<tr>
<td>Step 2</td>
<td>Determine length of structure, $L$</td>
</tr>
<tr>
<td>Step 3</td>
<td><strong>Determine $s_1$, $w_1$, $h_1$, and the quantity of Block A</strong>&lt;br&gt;$Block A = \frac{b}{(s_1 + w_1)}$</td>
</tr>
<tr>
<td>Step 4</td>
<td><strong>Determine $h_3$, $t$, $s_3$, $w_3$, $L_1$ and the quantity of Block B</strong>&lt;br&gt;$Block B = \frac{b}{(s_3 + w_3)}$</td>
</tr>
<tr>
<td>Step 5</td>
<td>Determine $h_4$ for Block C</td>
</tr>
</tbody>
</table>

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**Diagram:**

- Graph showing $L/y_2$ vs. $Fr_1$ with data points

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**Text in yellow:**

- *Mencari panjang Lembangan, L*
Exercise 5.6

A weir is built with $H_1 = 30$ m and $H_0 = 5$ m. The flow discharge for the weir is $80$ m$^3$/s, which passes through a spillway with the width of 8 m. Design a stilling basin at the downstream of the spillway in order to dissipate energy and thus protects the structure of the spillway by involving the design of block A, B and C for a stilling basin type III structure.

Exercise 5.6

Step 1: Find $v_1$, $y_1$, $F_{r1}$ and $y_2$

\[
v_1 = \left[2g(H_1 - H_0/2)\right]^{1/2}
= \left[2(9.81 \times 30 - 5/2)\right]^{1/2}
= 23.23 \text{ m/s}
\]

\[
y_1 = \frac{Q}{bv_1}
= \frac{80}{(8 \times 23.23)}
= 0.43 \text{ m}
\]

\[
F_{r1} = \frac{v_1}{(gy_1)^{1/2}}
= \frac{23.23}{[(9.81 \times 0.43)^{1/2}}
= 11.31
\]

\[
y_2 = \left(\frac{y_1}{2}\right)^{1/2} - 1 + \left[1 + 8F_{r1}^2\right]^{1/2}
= \left(\frac{0.43}{2}\right)^{1/2} - 1 + \left[1 + 8(11.31)^2\right]^{1/2}
= 6.67 \text{ m}
\]
Exercise 5.6

Step 2: Determine length of structure, $L$

Referring to the $L/y_2$ curve for stilling basin type III for $Fr_1 = 11.31, L/y_2 = 2.7$

$\therefore L = 2.7(6.87)$

$= 18 \text{ m}$

Exercise 5.6

Step 3: Determine $s_1, w_1, h_1$ and the quantity of Block A

Block A = $b/(s_1 + w_1)$

$s_1 = y_1 = 0.43 \text{ m}$

$w_1 = y_1 = 0.43 \text{ m}$

$h_1 = y_1 = 0.43 \text{ m}$

Thus, the quantity of Block A

$= b/ (s_1 + w_1)$

$= 8/ (0.43 + 0.43)$

$= 9$
Exercise 5.6

Step 4: Determine $h_3$, $t$, $s_3$, $w_3$, $L_1$ and the quantity of Block B

Block $B = \frac{b}{5} (s_3 + w_3)$

\[ h_3 = y_3 (0.166F_{13} + 0.63) \]
\[ = 0.43 (0.166 (11.31) + 0.63) \]
\[ = 1.09 \text{ m} \]

\[ t = \frac{h_3}{5} = 1.09/5 = 0.22 \text{ m} \]

\[ s_3 = \frac{3h_3}{4} = 3 (1.09)/4 = 0.818 \text{ m} \]

\[ w_3 = \frac{3h_3}{4} = 3 (1.10)/4 = 0.918 \text{ m} \]

Thus, the quantity of Block B

\[ L_1 = \frac{4y_3}{5} = 4 (6.67)/5 = 5.34 \text{ m} \]

\[ z_1 = 1.0 \]

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Exercise 5.6

Step 5: Determine $h_4$ for Block C

\[ h_4 \geq \gamma_4 \left[ \frac{R_{13}}{15} + 1 \right] \]

\[ h_4 = 0.43 \left[ \frac{11.33}{15} + 1 \right] = 0.70 \text{ m} \]

and;

\[ z_2 = 2.0 \]
Assignment No. 5

Q1. Explain the functions of the following hydraulic structures:
   a. sluice gate
   b. weir
   c. spillway
   d. energy dissipator structures

Q2. A 1.5-m wide sluice gate with an opening of 10 cm is discharging water at a rate of 3 m/s. Calculate the flow discharge of the flow if the flow depth behind the sluice gate is 3 m and the downstream flow depth is 2 m. Given $C_D = 0.585$.

Q3. A trapezoidal weir with side slope 1:4 and width 0.5 m is used to measure flow rate of a river. Compute the discharge if the head above the weir is 25 cm and $C_D = 0.675$. 