DEPARTMENT OF CIVIL ENGINEERING

MILITARY INSTITUTE OF SCIENCE AND TECHNOLOGY

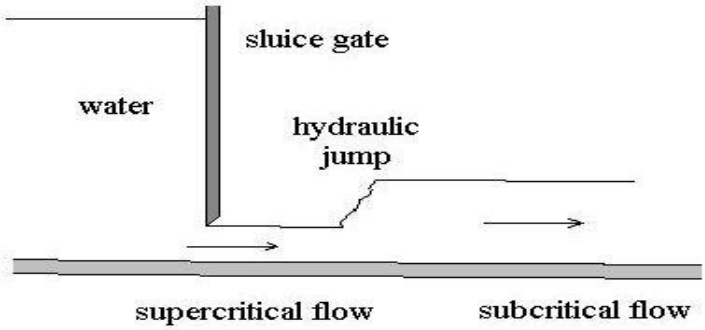
CE 362 Open channel flow sessional

Experiment No. 6

STUDY ON HYDRAULIC JUMP

6.1 General

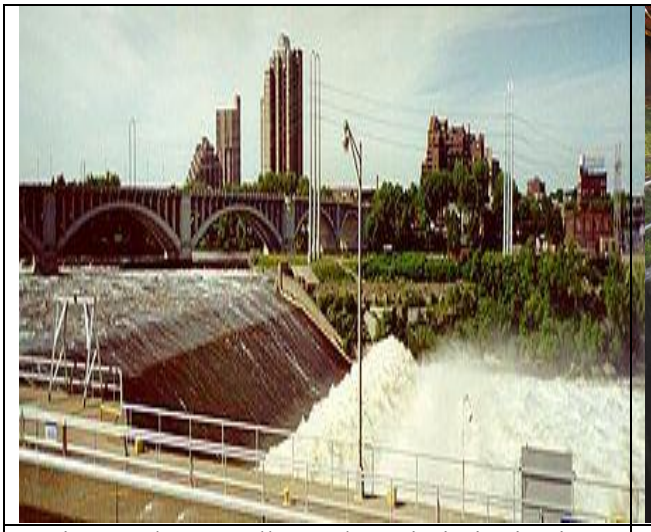
In open channel when a supercritical flow is made to change abruptly to subcritical flow, the result is usually an abrupt rise of the water surface. This feature is known as the hydraulic jump. It results when there is a conflict between u/s and d/s controls which influence the same reach of channel. For example, if the u/s control causes supercritical flow and d/s control dictates subcritical flow, then this conflict can be resolved by hydraulic jump, which pass the flow from one flow regime to other. This experiment deals with observation of hydraulic jump in horizontal rectangular channel and development of different relationship between height, length, efficiency and energy loss of jump. Hydraulic jump is useful in dissipation of excess energy in flows over dams, weirs, spillways and other hydraulic structure to prevent scouring; maintaining high WL in channels for irrigation and distribution purpose; increasing discharge of a sluice gate and thus increasing the effective head across the gate, mixing chemicals for water purification or wastewater treatment, increasing aeration of flows and declaration of waste water, identification of special flow condition.



6.2 Practical application:

Practical applications of the hydraulic jump in the field of open channel flow include-

1. The dissipation of kinetic energy in high velocity flows over weirs, spillways, gates and other hydraulic structures to prevent scouring downstream.
2. To increase of depth of water in channels for irrigation and water distribution purposes.
3. The increase of discharge of a sluice by repelling the tail water so that it works under free flow condition.
4. The reduction of uplift pressure under a structure by increasing weight of its apron.
5. The mixing of chemicals for water purification or waste water treatment.
6. The aeration of flows for city water supplies.
7. The removal of air pockets from water supply lines.

<table>
<tr><td></td><td></td></tr>
<tr><td>Saint Anthony Falls on the Mississippi River showing a pronounced hydraulic jump.</td><td>Hydraulic jump using sluice gate</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Hydraulic jump at the end of a spillway</td><td>Man-made hydraulic jumps</td></tr>
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Hydraulic Jump Characteristic

Amount upstream flow is supercritical (i.e., pre jump Froude Number)	Ratio of height after to height before jump	Descriptive characteristics of jump	Fraction of energy dissipated by jump
≤1.0	1.0	No jump; flow must be supercritical for jump to occur	None
1.0–1.7	1.0–2.0	Standing or undulating wave	<5%
1.7–2.5	2.0–3.1	Weak jump (series of small rollers)	5% – 15%
2.5–4.5	3.1–5.9	Oscillating jump	15% – 45%
4.5–9.0	5.9–12.0	Stable clearly defined well-balanced jump	45% – 70%
>9.0	>12.0	Clearly defined, turbulent, strong jump	70% – 85%

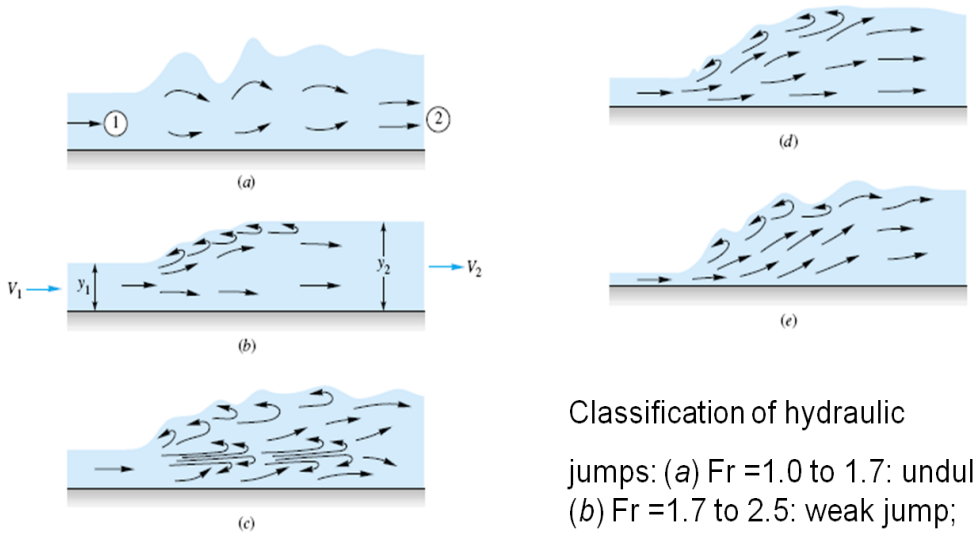
NB: the above classification is very rough. Undular hydraulic jumps have been observed with inflow/pre jump Froude numbers up to 3.5 to 4

6.3 Theory

Type of hydraulic jump:

The hydraulic jumps in horizontal rectangular channels have been most extensively studied and are known as the classical jumps. Based on the results of extensive studies, the United States Bureau of Reclamation **(USBR)** classified the hydraulic jumps in horizontal rectangular channels in the following five categories according to the Froude number Fr1 of the incoming flow**:**

1. **For $1< F_{r1} < 1.7$**, the water surface shows undulations and the change from initial to sequent depth is small and gradual. This jump is called an **undular jump.**
2. **For $1.7< F_{r1} < 2.5$**, a series of small rollers appear on the jump surface, but the downstream water surface remains smooth. This type of jump is known **weak jump.**
3. **For $2.5< F_{r1} < 4.5$**, the incoming jet oscillates between the bed and the bottom of the surface roller. Each oscillation produces a large surface wave of irrigation period which may persist for a considerable distance downstream causing unlimited damage to earth banks and riprap. This jump is known as an **oscillating jump.**
4. **For $4.5 < F_{r1} < 9.0$**, a steady jump with appreciable energy dissipation and fairly smooth water surface downstream is formed. The action and position of the jump is least sensitive to the tail water fluctuation. This type of jump is as a **steady jump**.
5. **For $F_{r1}> 9.0$**, the jump surface and the water surface downstream become very rough and high-velocity jet generates waves downstream. The jump is effective since the energy dissipation is high. This jump is known as a **strong jump.**



Classification of hydraulic jumps: (*a*) Fr =1.0 to 1.7: undular jumps; (*b*) Fr =1.7 to 2.5: weak jump; (*c*) Fr =2.5 to 4.5: oscillating jump; (*d*) Fr =4.5 to 9.0: steady jump; (*e*) Fr =9.0: strong jump.

Initial and sequent depth:

The depth of flow before the jump is known as the initial depth y_1 and that after the jump as the sequent depth y_2. Since a hydraulic jump is accompanied by considerable energy dissipation, the energy principle cannot be used initially for its analysis. However, as the jump takes place in a short distance so that the external friction force F_f can generally be neglected, the computation of hydraulic jumps always begins with the momentum equation

$$\rho Q (\beta_2 U_2 - \beta_1 U_1) = Fp_1 - Fp_2 + W \sin\theta - F_f$$

Consider a hydraulic jump occurring in a horizontal ($\theta = 0$) rectangular channel. Since the jump takes place in a short reach of channel, $F_f = 0$, and since the prismatic, $\beta_1 = \beta_2 = 1$.
The hydrostatic forces Fp_1 and Fp_2 may expressed as

$$Fp_1 = \gamma Z_1 A_1$$
And
$$Fp_2 = Fp_1 = \gamma Z_2 A_2$$

Where, Z_1 and Z_2 are the vertical distances of the cancroids of the respective water areas A_1 and A_2 from the free surface. Now applying momentum equation between section 1 and section 2 one can find,

$$Q_2/ (gA_1)+ z_1 A_1 = Q_2 / (gA_2) + z_2 A_2 \quad \text{.....(6.1)}$$
or
$$F_1 = F_2$$
where

$$F = Q_2/ (gA)+ zA$$

And is known as the **specific force or specific momentum.** The term $Q_2/ (gA)$ represent the momentum of flow passing through the channel section per unit time per unit weight of water and the term zA represents the pressure force per unit weight of water. Thus the specific force represents the force per unit weight of water.

Since for a rectangular channel $Q = A_1U_1 = A_2U_2$, $A_1 = By_1$, $A_2 = By_2$, $z_1 = y_1/2$, $z_2 = y_2/2$, So equation 6.1 yields,

$$q_2/g (1/y_1 - 1/y_2) = 1/2 (y_2^2 - y_1^2) \quad \text{.....(6.2)}$$

Where $q = Q/ B$. Using $q = y_1U_1 = y_2U_2$ Eq. 6.2 may be respect as,

$$U_1^2/gy_1 = F_1^2 = 1/2\ y_2/y_1 (y_2/y_1+1) \quad \text{..... (6.3)}$$

Eq. 6.3 may be solved to yield,

$$y_2/ y_1 = (1/2) * (\sqrt{} (1+ 8F_1^2) - 1) \quad \text{..... (6.4)}$$

Where y_2/y_1 **is known as the ratio between sequent depth and initial depth.**

This equation contains three independent variables and two of them must be known before the third may be computed. Normally the upstream conditions, i.e. h_1 and F_{r1} will be known and downstream depth h_2 can be determined by using this equation. It must be realized, however, that the downstream control produces the required depth h_2, and then the jump will form.

The depth produced by a downstream control the tail water depth h. When a jump is formed $h_2 = h_1$. If the tail water depth is increased, the jump moves upstream and if the tail water depth is decreased, the jump moves downstream.

Length of the jump

The length of a hydraulic jump is the horizontal distance from the front of face of the jump to a point immediately downstream from the roller. It is an important design parameter, but it cannot be determined theoretically. For jumps occurring in horizontal rectangular channels, the length of the jump is preferably estimated from the Bradley and Paterka (1957) curve which is a plot of Fr1 vs. $L_j/h_2 = 6.0$ to 6.1 in the range of the froude numbers, ($Fr_1 = 5$ to 13) yielding the best performance. Silverster (1964) demonstrated that for free hydraulic jump in horizontal rectangular channels

$L/y_1 = 9.75 (F_1 - 1)1.01$ .... (6.5)

Energy loss in jump

The loss of total energy in the jump is equal to the differences in specific energies before and after the jump. It can be shown that, the total loss is,

$E_{total} = E_1 - E_2 = (y_2 - y_1)^3 / 4y_1y_2$ .... (6.6)

Where, E_1 = specific energy before the jump
E_2 = Specific energy after the jump

However the kinetic energy loss in jump is given by the difference in velocity head before and after jump. Thus,

$E_{kE} = (1/(2g))* (V_1^2 - V_2^2)$ .... (6.7)

Where,
V_1 = Velocity before the jump
V_2 = Velocity after the jump

Efficiency of jump

The ratio of the specific energy after the jump to before the jump is defined as the efficiency of the jump. It can be shown that the efficiency of the jump is given by,

$E_2/E_1 = ((8F_1^2 + 1)(3/2) - 4F_1^2 + 1) / ((8F_1^2) (2+ F_2))$. ..... (6.8)

Height of the jump

The height of the jump is the difference between the sequent depth and initial depth, i.e. $h_j = h_2 - h_1$. ..... (6.9)

The ratio h_j / E_1 is known as the relative height. It can be shown that

$h_j/h_1 = (1/2)* (\sqrt{}(1+ 8 Fr_1^2) -3)$

Then we get

$h_j/E_1 = (\sqrt{}(1+ 8 Fr_1^2) -3)/ (2 + Fr_1^2)$ ..... (6.10)

6.4 Objectives

1. To determine the type of the jump according to USBR classification
2. To measure the initial depth y_1 sequent depth y_2, length L and height h_1 of the jump and compare them with them with the theoretical value.
3. To determine the total energy loss, kinetic energy and efficiency of jump compare them with the theoretical value.
4. To develop the theoretical characteristics curve of hydraulic jump

6.5 Procedure:

1. Measure the depth of flow before the jump at three points and average them to get initial depth y_1
2. Measure the depth of flow after the jump at three points and average them to get sequent depth y_2
3. Determine the velocity before the jump V_1, hence calculate F_1 and find the type of jump
4. Measure the length of the jump L, then find L/y_1 and verify the Eq 6.5
5. Compute height of jump h1 from Eq. 6.9, hence find the value of h_j/E_1 and verify the Eq. 6.10
6. Compute E_1 and E_2 then find the total energy loss E_1-E_2 and verify Eq. 6.6
7. Compute kinetic energy loss from Eq. 6.7
8. Compute efficiency of jump E2/E1 and verify Eq. 6.10
9. Plot E_2/E_1, h_1/E_1, y_1/E_1, y_2/E_1 vs. F_1 to get the characteristics curve.

Typical shape of graph

Characteristics graph of hydraulic jump is a combination of four graphs.

1. E_2/E_1 vs. F_1 graph: From eq. 6.8, at $F_1 = 1$, E_2/E_1. So the curve will start from ordinate (1,1) and decreases with increases in F_1
2. h_j/E_1 vs. F_1 graph: From eq. 6.10 , at $F = 1$, $h_j/E_1 = 0$, so the curve will start from ordinate (1,0) and increases up to a value of $h_j/E_1 = 0.507$ at $F_1 = 2.77$ then decreases with F_1

3. y_1/E_1 and y_2/E_1 vs. F_1 graph: At critical state i.e. at $F_1 = 1$, from eq. 6.4 $y_1 = y_2$. So both curve will be start from a common point at F1 = 1. Now at critical state, E = 1.5 y so, $y_1/E_1 = y_2/E_1 = 2/3$ at this state. Hence both the curve will start from the ordinate (1, 2/3). The y_1/E_1 vs. F_1 curve decrease with higher F_1 but y_2/E_1 vs. F_1 curve increases up to a value of 0.8 at $F_1 = 1.73$ then decrease with higher F_1.

6.6 DATA SHEET

STUDY ON HYDRAULIC JUMP

Depth				**Velocity**		**F_1**	**Type of jump**
y_1 (m)		y_2 (m)		V_1	V_2		

Verification of total Energy Loss					**Kinetic Energy Loss (m)**	**Verification of Efficiency**		
E_1 (m)	E_2 (m)	E_2-E_1	RHS of Eq (6.6)	Comment		E_2/E_1	RHS of Eq (6.8)	Comment

Verification of Length of The Jump				**Verification Of Height of The Jump**			
L (m)	L/y1	RHS of Eq (6.5)	Comment	hj (m)	hj/E1	RHS of Eq (6.10)	Comment

Level / Term : **Dept. :**
Reg No. : **Section:**
Group No. : **Date :**

Signature of the Teacher

6.7 Calculation and Graph

Sample calculation:

6.8 Discussion

Comments on Result:

Comments on Graph:

Sources of Error:

6.9 Assignment

1. What are the different types of hydraulic jumps according to USBR classification?

2. Why does energy loss occur in hydraulic jumps? Is it really an energy loss?

3. What is tail water depth? Explain why a hydraulic jump moves upstream or downstream when the tail water depth is greater or smaller than the sequent depth.