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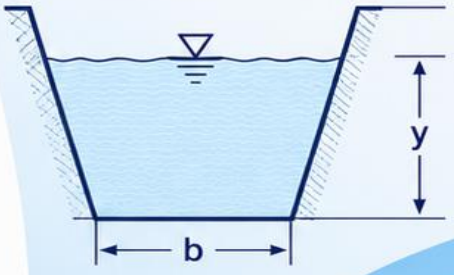
OPEN CHANNEL FLOW



THEORY • ANALYSIS • APPLICATION

- FLOW ANALYSIS
- ENERGY RELATIONSHIP
- UNIFORM FLOW
- RAPIDLY VARIED FLOW
- GRADUALLY VARIED FLOW

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OPEN CHANNEL FLOW

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Chapter – 1 Flow in Open Channel

1.1 Conduit: Conduit is a passage or medium through which a fluid flows.
Example - River, canal, sewer.

1.2. Types of Conduits

Conduits are of two types:

Open Conduits	Closed Conduits
a. Water flows with a free surface	a. Water does not flow with a free surface
b. The driving force is gravity	b. The driving force is pressure difference
c. **Example:** River, canals	c. **Example:** Pipe flow

Remember

1. Free surface is the interface where water meets air.
2. In open channel the top most layer of water is in contact with air.
3. At free surface, shear force is zero.

1.3 Open Channel

A conduit is said to be an open channel if it follows two conditions:

- Water flows with a free surface
- The driving force is gravity

Remember: Flow in an open channel is known as open channel flow.
Example: River, Canal

1.4 Type of open channel

1.4.1 Based on Channel Geometry

Based on channel geometry, open channel is of two types:

Prismatic channel	Non-Prismatic channel
a. The cross section and bed slope is constant along the length of the channel.	**a**. The cross section and bed slope are not constant along the length of channel.
b. Example: Canal	**b. Example**: River

1.4.2 Based on Mobility of the Channel Boundary

Based on mobility of channel boundary, open channels are of two types.

Mobile Boundary channel	Rigid Boundary channel
a. In such channel, the boundary of the channel moves with the flowing water.	**a.** In such channel, the boundary of the channel does not move with the flowing water.
b. Degree of freedom is 4.	**b**. Degree of freedom is 1.

Remember: In Rigid Boundary channels, only depth of flow changes, whereas in Mobile Boundary channels, depth of flow, area of flow, bed slope and layout change.

1.5 Type of Flow

Based on depth of flow, flow can be of following types

1.5.1 Steady Flow

In such flow, depth of flow remains constant at a location with respect to time.

Remember: In unsteady flow, depth of flow varies with respect to time at a location.

1.5.2 Uniform Flow

In such flow, depth of flow is constant along the length of the channel.

Remember:

- In non-uniform flow, depth of flow changes along the length of the channel.
- Uniform flow is possible in Prismatic channels only.

1.5.3 Steady Non-Uniform Flow

As the name suggests, the depth of flow in such case remains constant with respect to time but varies with respect to length of the channel.

This flow is further classified as:

Rapidly Varied Flow	Gradually Varied Flow
In RVF, the depth of flow changes rapidly over a short distance of the channel.	In GVF, the depth of flows changes gradually over a long distance of the channel.

Types of Flow

- **Steady**: y is constant wrt time.
- **Uniform**: y is constant wrt space.
- **Steady non-uniform**: y is constant wrt time but varies with space.
    - Classified into RVF and GVF.

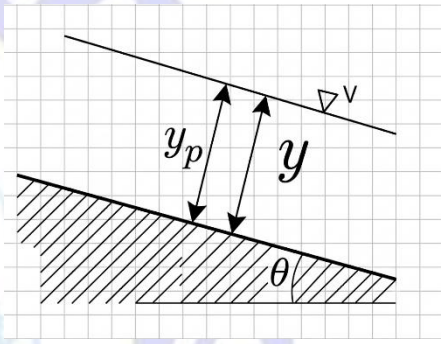
Remember

In Spatially Varied flow, either discharge is added or subtracted to a main flow.

1.6 Geometrical Parameters in open channel

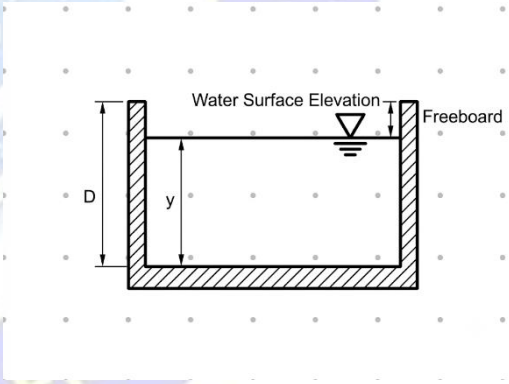
1.6.1 Depth of flow (y)

y is the perpendicular distance from the water surface to the channel bed.



1.6.2 Area of flow (A)

A is the cross-sectional area of the channel in contact with water.



1.6.3 Wetted Perimeter (P)

P is that perimeter of the channel in contact with water.

1.6.4 Top width (T)

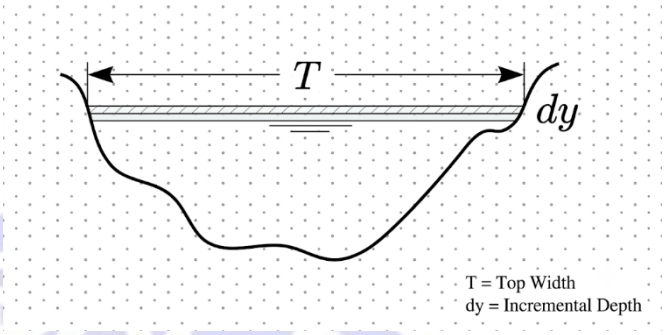
T is the width of the channel which is seen from the top view.

Remember:

From the figure:

$$dA = Tdy$$

$$\Rightarrow T = \frac{dA}{dy}$$



1.6.5 Hydraulic Radius (R)

It is given as

$$R = \frac{\text{Area of flow}}{\text{Wetted Perimeter}}$$

$$R = \frac{A}{P}$$

1.6.6 Hydraulic Depth (D)

It is given as

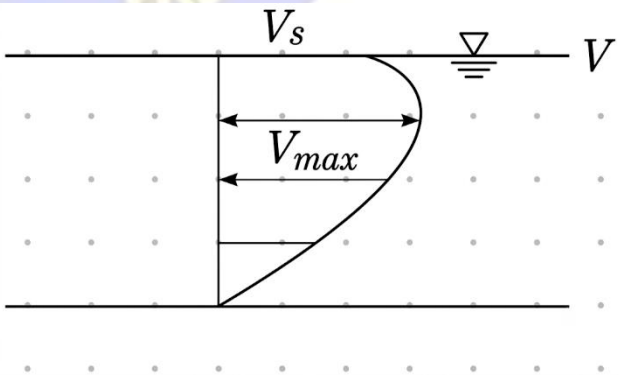
$$D = \frac{\text{Area of flow}}{\text{Top width}}$$

$$\Rightarrow D = \frac{A}{T}$$

1.7 Flow Parameters

- These are the parameters which describe the flow in order to analyses them.
- Depth of flow, velocity of flow and discharge are the examples of flow parameters.

1.8 Velocity Distribution in an open channel



As shown in the figure, velocity is not maximum at the surface but some depth below it.

This is due to the formation of secondary currents.

Due to the presence of the boundary the velocity varies along the depth of the channel. To determine discharge, average velocity is required which is given as:

$$\textbf{Average Velocity} = V = \frac{1}{A}\int v\, dA$$

Where,

- A = cross sectional area
- v = random velocity at any depth

1.9 Kinetic Energy Correction Factor (α)

To analyses open channels, sometimes kinetic energy is used which shows error due to the use of average velocity in place of actual velocity.
This error is accommodated by α and is given as:

$$\alpha = \frac{\int v^3\, dA}{V^3 A}$$

1.10 Momentum correction factor

Sometimes to analyses an open channel, momentum equation is used which may show error due to the use of average velocity in place of actual velocity.
This error is accommodated by β and is given by.

$$\beta = \frac{\int v^2\, dA}{V^2 A}$$

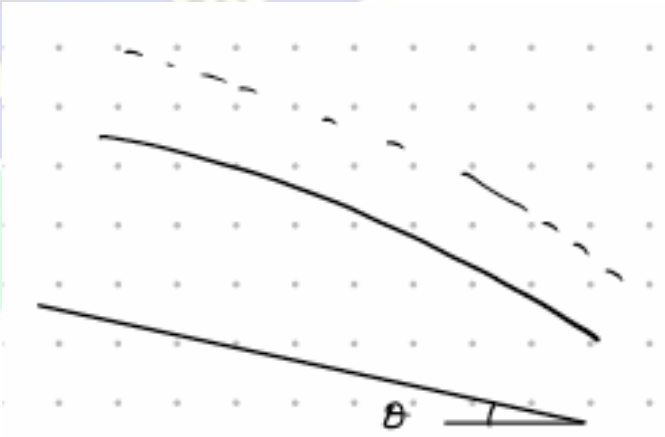
Remember

1. $\alpha > \beta > 1$
2. If the velocity distribution at a section is uniform i.e. $V = v$, then $\alpha = \beta = 1$
3.

1.11 Total Energy Head, *H*

In an open channel, the total energy head is the summation of three heads which are:

1. Datum Head, z
2. Pressure Head, $y\cos\theta$
3. Kinetic Head, $\alpha\frac{v^2}{2g}$



Thus,

$$H = z + y\cos\theta + \alpha\frac{v^2}{2g}$$

If the channel is horizontal and velocity at a section is uniform then

$$H = z + y + \frac{v^2}{2g}$$

1.12 Specific Energy Head, *E*

If the datum of the channel is assumed to be at the bed of the channel then $z = 0$.

Now, putting this in the equation of Total energy head, we get a new term which is:

$$E = y + \frac{v^2}{2g}$$

where, E is known as specific energy head.

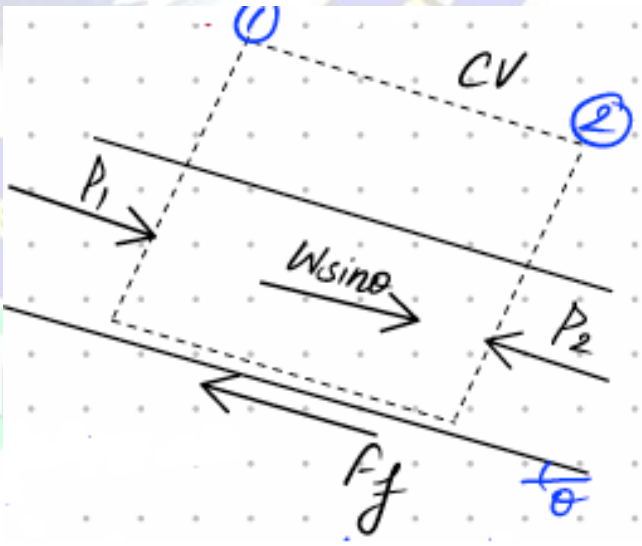
1.13 Momentum Equation

- This is based on Newton's second law of motion which states:
- the summation of all forces in a given direction is equal to rate of change of momentum in that direction.

Applying momentum equation in the given figure:

$$\sum F = \frac{dp}{dt}$$

$$P_1 - P_2 + W\sin\theta - F_f = M_2 - M_1$$



where:

P_1 and P_2 are pressure forces at section 1 and 2.

W = weight of water flowing in the open channel.

F_f = frictional forces.

M_1 and M_2 are rate of change of momentum at section 1 and 2.

Chapter 2: Specific Energy-Depth Relationship

2.1 Specific Energy Curve

It is given as:

$$E = y + \frac{v^2}{2g}$$

But $Q = vA$:

$$\Rightarrow E = y + \frac{Q^2}{2gA^2}$$

Now, consider a rectangular channel with Area, $A = By$.

Then,

$$E = y + \frac{Q^2}{2gB^2y^2}$$

Based on the above equation, if a curve is drawn between *E* and *y*, then a cubic parabola curve is obtained as shown in the figure.

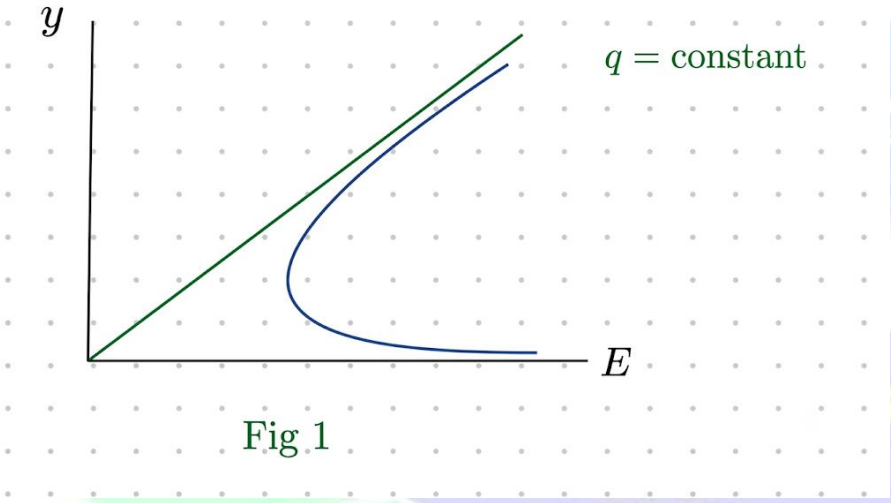
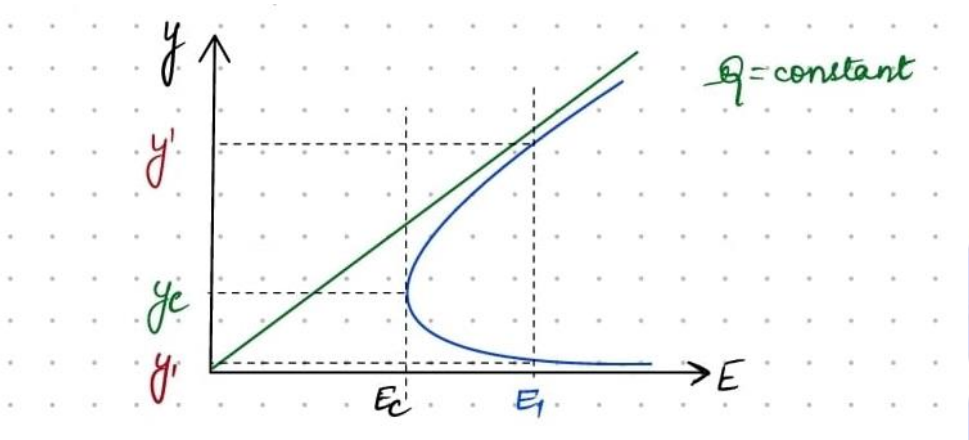


Fig 1

The above curve is known as the specific energy curve.

2.2 Alternate Depths



Alternate depths are two different depths having the same specific energy.

So, $E_1 = y_1 + \frac{Q^2}{2gBy_1^2} = y_2 + \frac{Q^2}{2gBy_2^2}$.

2.3 Critical Energy, E_c

This is the minimum specific energy required to allow a certain discharge to flow.

So, if $E < E_c$, then no flow will occur.

2.4 Critical Depth, y_c

This is the depth of flow when a discharge flows with a minimum specific energy i.e. when flow occurs critically.

Remember: $y_1 < y_c < y_1{}'$

2.5 Critical Flow Condition

- This is a flow condition when flow occurs with a minimum specific energy.
- During critical flow, the flow parameters are associated as shown:

$$\frac{Q^2}{g} = \frac{A_c^3}{T_c}$$

2.6 Relationship Between E_c and y_c

During critical flow, $\frac{Q^2}{g} = \frac{A_c^3}{T_c}$.

But $E = y + \frac{Q^2}{2gA^2}$.

Now, during critical flow, $E = E_c = y_c + \frac{Q^2}{2gA_c^3}$.

But $\frac{Q^2}{g} = \frac{A_c^3}{T_c}$.

$\Rightarrow E_c = y_c + \frac{A_c}{2T_c}$.

2.7 Relation Between E_c and y_c for Different Sections

- **Rectangular**: $E_c = \frac{3}{2} y_c$.
- **Triangular**: $E_c = \frac{5}{4} y_c$.

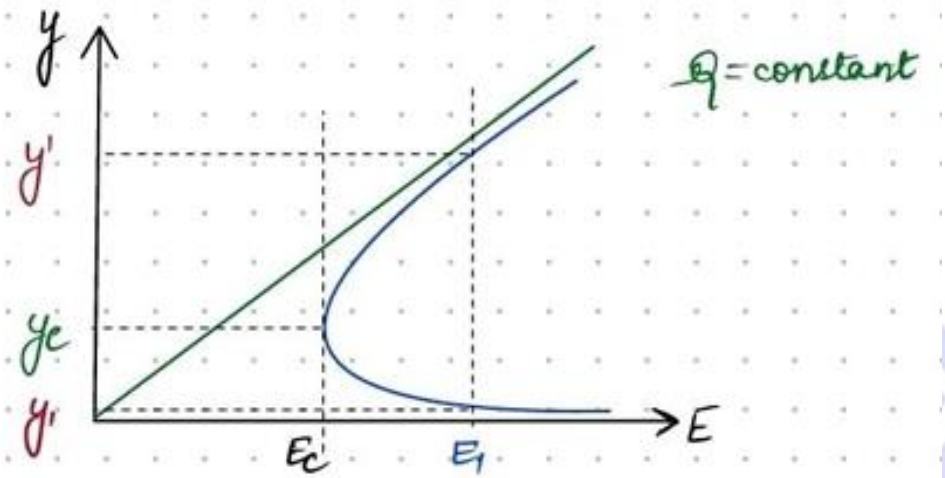
2.8 Froude Number

- Froude Number is a dimensionless number which is used to analyses the open channels and is given as.
- Froude Number $= \sqrt{\frac{\text{Inertia Forces}}{\text{Gravity Forces}}}$.
- $\Rightarrow F = \frac{v}{\sqrt{g\frac{A}{T}}}$.

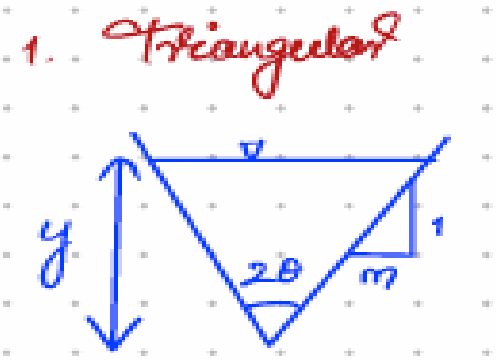
2.9 Types of flow Based on Froude Number

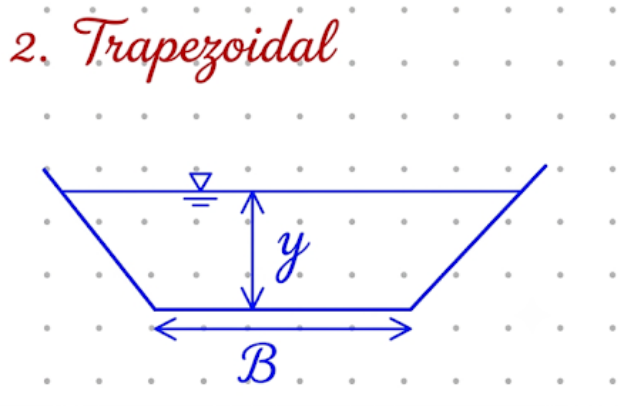
Type of flow	F	y	v
Subcritical	< 1	$> y_c$	$< V_c$
Critical	$= 1$	$= y_c$	$= V_c$
Supercritical	> 1	$< y_c$	$> V_c$

- Where V_c is known as critical velocity and is the velocity during critical flow.



2.10 Different Types of Channel





- **Triangular**:
  - $A = my^2$
  - $P = 2y\sqrt{1+m^2}$
  - $T = 2my$
  - Where m = side slope
  - $\tan\theta = m$
  - Where 2θ is known as the Apex angle
- **Trapezoidal**:
  - $A = By + my^2$
  - $P = B + 2y\sqrt{1+m^2}$
  - $T = B + 2my$

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2.11 Section Factor, Z

- It is given as $Z = \sqrt{\frac{A^3}{T}}$
- $\Rightarrow Z^2 = \frac{A^3}{T}$

2.12 First Hydraulic Exponent, M

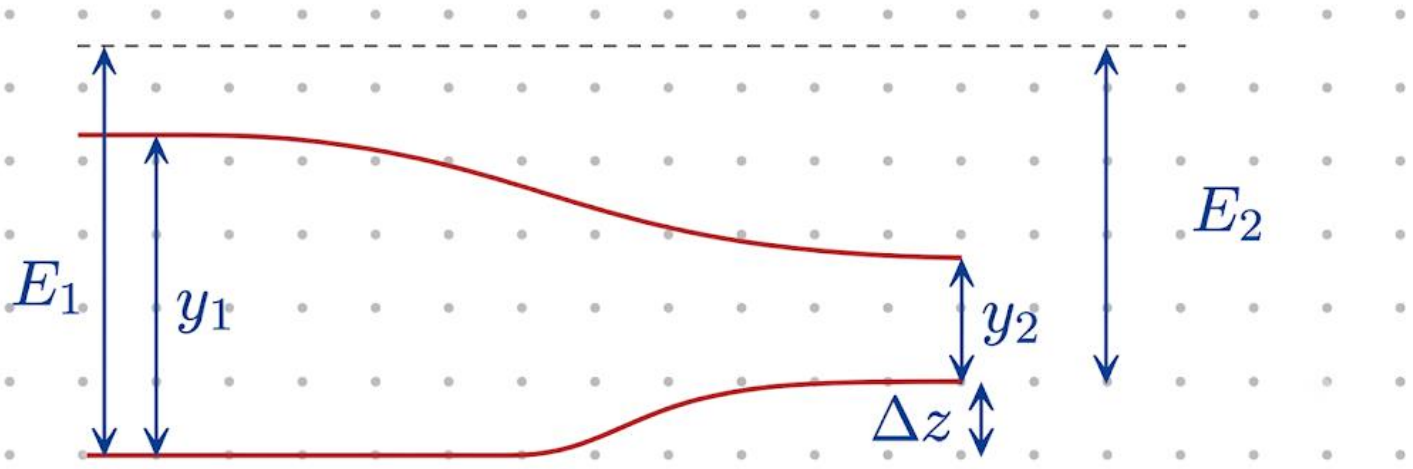
- It is given as $Z^2 = cy^M$
- Where M = First Hydraulic Exponent

2.13 Transition Flow

In such flow, the change in the geometry of the channel occurs when we move along the length of it. Following two cases are studied in such flow:

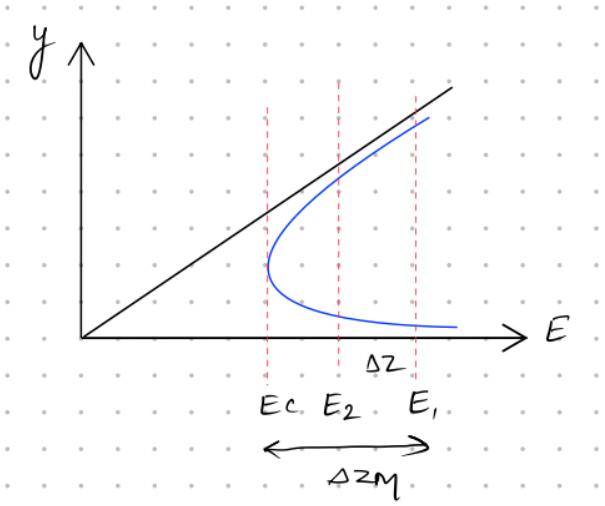
1. **Flow over a hump**
    - In such case, the depth of the channel varies due to the presence of the elevated platform.
2. **Flow over width constriction**
    - In this case the width of the channel changes along its length.

2.13.1 Flow over a hump



- Δz = Height of hump
- E_1 = Specific energy at the upstream

- E_2 = Specific energy at the downstream
- y_1 = Depth of flow at upstream
- y_2 = Depth of flow at downstream



Remember

- $\Delta z = E_1 - E_2$
- Δz_M = Maximum Hump Height $= E_1 - E_c$

Point To be Noted

- For a rectangular, frictionless channel with a subcritical flow, the depth of flow decreases.
- Whereas for a supercritical flow, the depth of flow increases as we move from upstream to downstream.

2.13.2Flow Due To Width Constriction

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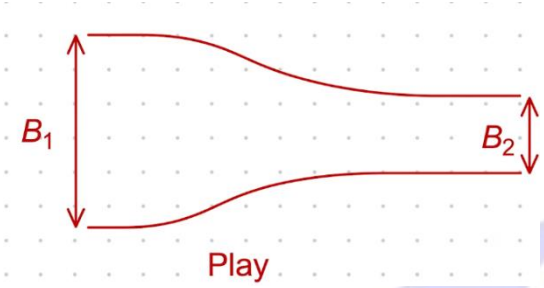
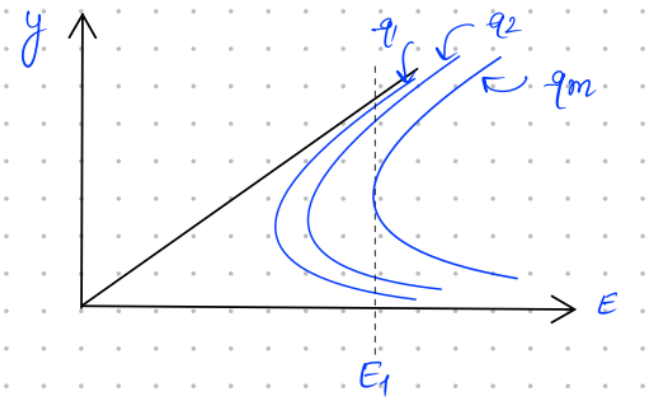


- In this case, the width of the channel (B_1 to B_2) varies as we move along the channel.



- **Discharge Intensity (q):**
  Defined as the discharge per unit width ($q = \frac{Q}{B} = \frac{\text{Discharge}}{\text{width}}$).
- **q_m:** Represents the maximum discharge intensity required to maintain the same specific energy.
- **B_{min}:** The minimum width of the section at the downstream required to maintain the same critical energy.
  - This is calculated as: $B_{min} = \sqrt{\frac{Q^2}{gy_c^3}}$.

Chapter 3: Uniform Flow

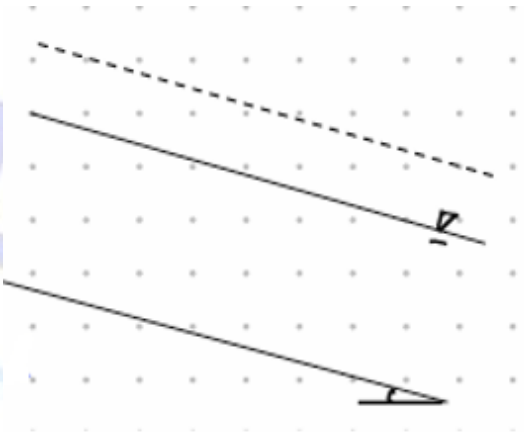
3.1 Uniform Flow

- In such flow, the depth of flow remains constant along the length of the channel.
- **In uniform flow:** $S_0 = S_w = S_f$.

  Where, S_0 = Slope of the channel bed.

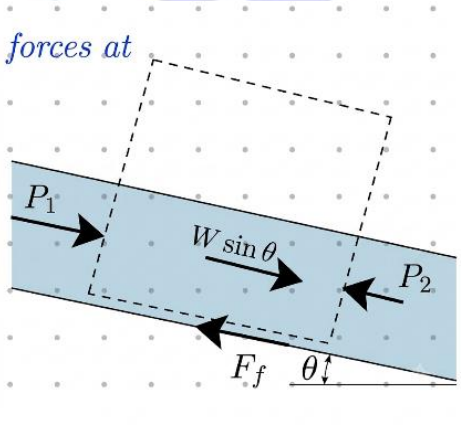
  S_w = Slope of the water surface.

  S_f = Slope of the energy line.



3.2 Governing Equation of GVF

- Applying Momentum Equation in uniform flow, we have: $P_1 - P_2 + W \sin\theta - F_f = M_2 - M_1$.
- But in uniform flow, $P_1 = P_2$ and $M_2 = M_1$.
- So, $W \sin\theta = F_f$.
- For a flow to occur uniformly, gravity forces should be equal to frictional forces.



3.3 Analysis of a Uniform Flow

Following two equations are used to analyses uniform flow:

1. **Chezy's Equation**: $V = C\sqrt{RS_0}$
2. **Manning's Equation**: $V = \frac{1}{n}R^{2/3}\sqrt{S_0}$

Where, V = Average velocity in the channel

C = Chezy's constant

n = Manning's Roughness Coefficient

R = Hydraulic Radius

S_0 = Slope of the channel bed

Remember: $C = \frac{1}{n} R^{1/6}$

3.4 Efficient Sections

- In order to allow maximum discharge through a given channel, its wetted perimeter should be kept minimum.
- Such channels are called Efficient Sections.

Remember: In Efficient Sections, $Q \propto \frac{1}{P}$.

3.5 Geometrical Parameters of an Efficient Section

In efficient sections, geometrical parameters are related to each other in a certain way as shown.

3.5.1 Efficient Rectangular Section

If y_e is the depth of flow when a rectangular section is efficient, then:

1. $A_e = 2y_e^2$
2. $B_e = 2y_e$
3. $P_e = 4y_e$
4. $R_e = \frac{y_e}{2}$

Remember: For a rectangular section to be efficient, keep its width twice its depth of flow.

3.5.2 Efficient Triangular Section

For an efficient triangular section:

1. $A_e = y_e^2$
2. $P_e = 2\sqrt{2}y_e$
3. $m = 1$
4. $R_e = \frac{y_e}{2\sqrt{2}}$

Remember: A right-angled triangular section is an efficient section.

3.5.3 Efficient Trapezoidal Channel

The geometrical parameters for an efficient trapezoidal channel are:

$$A_e = \left(2\sqrt{1+m^2} - m\right) y_e^2$$

$$P_e = \left(4\sqrt{1+m^2} - 2m\right) y_e$$

$$B_e = \left(2\sqrt{1+m^2} - 2m\right) y_e$$

$$R_e = \frac{y_e}{2}$$

Remember: In the case of the most efficient trapezoidal channel, put $m = \frac{1}{\sqrt{3}}$.

So, B_{em} = width for most efficient trapezoidal channel $= \frac{2}{\sqrt{3}} y_{em}$

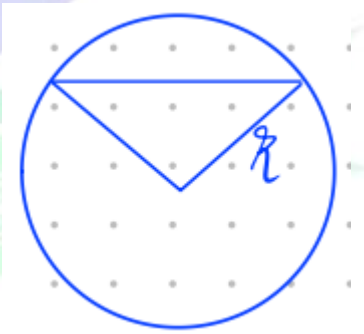
$$A_{em} = \frac{3}{\sqrt{3}} y_{em}$$

$$P_{em} = \frac{6}{\sqrt{3}} y_{em}$$

$$R_{em} = \frac{y_{em}}{2}$$

3.5.4 Efficient Circular Channel

- For the most efficient circular channel, the following parameters are observed.
- If R is the radius of the circle, then it is for maximum discharge.



Efficient Circular Channel Parameters:

$y = 0.95D$, where D is the diameter of the channel.

Central Angle = $150°11'$.

$$\frac{\text{Maximum Discharge}}{\text{Discharge when running full}} = \frac{Q_m}{Q_f} = 1.07.$$

Remember: At a depth of $0.81D$, the maximum velocity is obtained.

3.6 Conveyance of the Channel

Manning's equation is given as $Q = \frac{1}{n} AR^{2/3}\sqrt{S_0}$.

Conveyance of the channel is given as $K = \frac{1}{n} AR^{2/3}$.

Where $K =$ Conveyance of the channel.

So, $Q = K\sqrt{S_0}$.

3.7 Second Hydraulic Exponent, N

If K is the conveyance of the channel, then

$K^2 = C_2 y^N$.

Where $N =$ Second Hydraulic Exponent.

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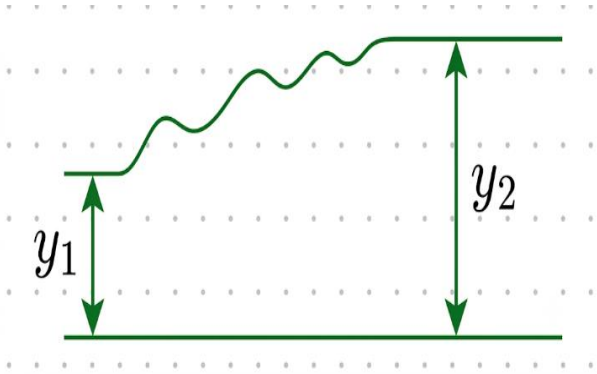
Chapter 4: Rapidly Varied Flow

4.1 Rapidly Varied Flow (RVF):
In RVF, the depth of flow changes rapidly over a short distance of the channel. RVF belongs to the steady, non-uniform category. A hydraulic jump is an example of RVF.



4.2 Hydraulic Jump: This is a phenomenon in which the dissipation of energy takes place with an increase in depth of flow over a short length of the channel.

Remember: A hydraulic jump occurs when a supercritical flow meets a subcritical flow.

4.3 Governing Equation of RVF:
Applying the momentum equation, we have
$P_1 - P_2 + W \sin\theta - F_f = M_2 - M_1$.
If the channel is horizontal and frictionless, then

- **Governing Equation**: For a horizontal and frictionless channel, the governing equation is $P_1 - P_2 = M_2 - M_1$, which implies $P + M =$ constant. Solving further results in $A\bar{y} + \frac{Q^2}{gA} =$ Specific Force.

4.4 Specific Force: It is given as Specific force $= A\bar{y} + \frac{Q^2}{gA}$.

4.5 Sequent Depths: These are the depths of flow before and after the jump.
Remember

- Sequent depths are two different depths having the same specific force.
- Sequent depths are also known as conjugate depths.

4.6 Height and Length of Jump

- Height of Jump = $y_2 - y_1$.
- Length of Jump = 5 to 7 times the height of jump.

4.7 Expressions for Rectangular Sections

- The following expressions are used for horizontal, frictionless, and rectangular sections.

4.7.1 Relation Between Sequent Depths and Froude Number

- $\frac{y_2}{y_1} = \frac{1}{2}\left[-1 + \sqrt{1 + 8F_1^2}\right]$. or
- $\frac{y_1}{y_2} = \frac{1}{2}\left[-1 + \sqrt{1 + 8F_2^2}\right]$.

4.7.2 Relationship Between Sequent Depths and Critical Depth

- $y_1 y_2 (y_1 + y_2) = 2y_c^3 = \frac{2Q^2}{gB^2}$.

4.7.3 Energy Loss

- $E_L = E_2 - E_1$.
- $E_L = \frac{(y_2 - y_1)^3}{4y_1 y_2}$.

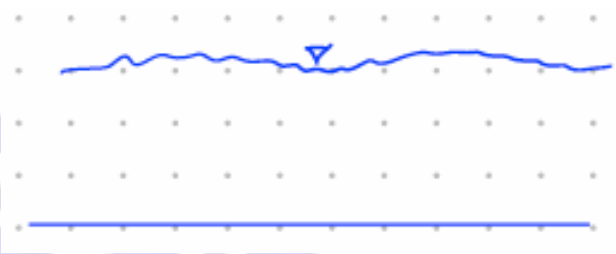
4.8 Classification of Jumps:

Based on the provided notes, hydraulic jumps are classified into 5 categories based on the Froude number (F_1):

Type of Jump	F1	EL/E1
Undular	1-1.7	0
Weak	1.7-2.5	18%
Oscillating	2.5-4.5	45%
Steady	4.5-9	70%
Strong	>9	>70%

Chapter 5: Gradually Varied Flow

5.1 Gradually Varied Flow (GVF)



- In GVF, the depth of flow varies gradually over a long distance of the channel.
- GVF belongs to steady non-uniform flow.

5.2 Governing Equation of GVF

- The slope of the water surface is given as: $\frac{dy}{dx} = \frac{S_0 - S_f}{1 - \frac{Q^2 T}{gA^3}}$.

5.3 Critical Slope

- It is the slope where a given discharge flows uniformly as well as with minimum energy.
- Thus, at critical slope, flow is uniform as well as critical.

5.4 Steep and Mild Slope

- A slope greater than critical slope is known as steep slope.
- Flow is supercritical in steep slope.

- **Steep and Mild Slopes**:
  - For a steep slope, the slope is greater than the critical slope.
  - A slope is said to be mild if it is less than the critical slope.
  - For a mild slope, the slope is less than the critical slope.
  - Flow is subcritical in a mild slope.

5.5 GVF Profiles:

There is a total of 12 GVF profiles.

- **For a steep slope**:
  - $y > y_c > y_0$ is the S_1 profile.

- $y_c > y > y_0$ is the S_2 profile.
- $y_c > y_0 > y$ is the S_3 profile.

- **For a mild slope**:
  - $y > y_0 > y_c$ is the M_1 profile.
  - $y_0 > y > y_c$ is the M_2 profile.
  - $y_0 > y_c > y$ is the M_3 profile.
- **For Critical Slope**:
  - $y > y_0 = y_c$ is the C_1 profile.
  - $y_0 = y_c > y$ is the C_3 profile.
- **For Horizontal channel**:
  - $y > y_c$ is the H_2 profile.
  - $y_c > y$ is the H_3 profile.
- **For Adverse slope**:
  - $y > y_c$ *is the* A_2 *profile.*
  - $y_c > y$ *is the* A_3 *profile.*

Remember: A hydraulic jump occurs when a steep slope (supercritical) meets a mild slope (subcritical).

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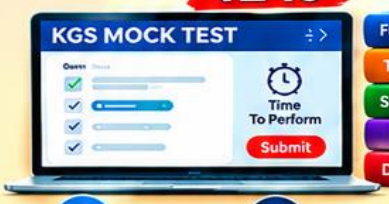

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