Open Channel Hydraulics

CENG 3601

References

- **Chow, V. T. (1959):** Open Channel Hydraulics , McGraw-Hill, New York
- **Subarmanya, K. (2009):** Flow in Open Channels 3rd edition, Tata McGraw Hill Education Private Limited, New Delhi
- **Chanson, H.(2004):** The Hydraulics of Open Channel Flow: An Introduction, 2nd edition Elsevier Butterworth-Heinemann Linacre House, Jordan Hill, Oxford OX2 8DP 200 Wheeler Road, Burlington
- **Sturm, T.W. (2001):** Open Channel Hydraulics, International edition, McGraw-Hill Higher Education
- All other related books and materials

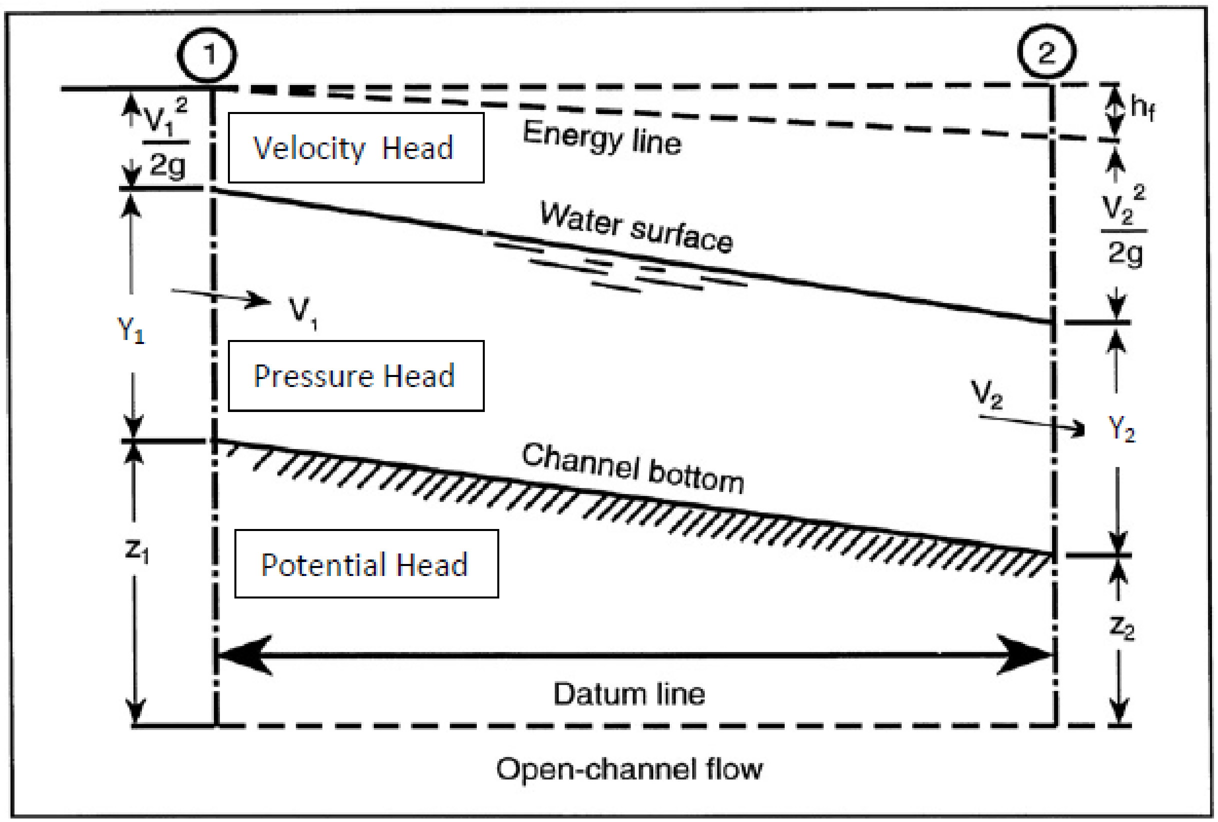
Chapter One : Introduction

- Definition
- Difference between open channel and pipe flow
- Kinds and Types
- Geometric Properties of Open Channels
- Velocity Distribution in Open Channel
- Fundamental Equations
- Energy-Depth Relationships

Definitions and Schematic understanding

Open Channel flow

- is a flow of liquid in a conduit with free space
- particularly applied to understand the flow of a liquid in artificial and natural channels



Open channel and pipe flow

Open Channel Flow

- have a free space
- Subject to atmospheric pressure also
- Flow driven by gravity (potential Energy)
- Unknown cross section (due to unknown depth)
- Flow depth computed using continuity and momentum equations
- Atmospheric Pressure as boundary condition

Pipe Flow

- No free space
- Hydraulic pressure only
- Flow driven by pressure
- Known and fixed flow cross section
- Velocity deduced from continuity equation
- No boundary condition

Kinds

Kinds Open Channels

– **Artificial channels**
  - are channels made by man
  - include **irrigation canals, navigation canals, spillways, sewers, culverts and drainage ditches**
  - usually constructed in a regular cross-section shape throughout $\Rightarrow$ **Prismatic channels**
  - have well defined surface roughness's

– **Natural channels**
  - are channels that naturally exist or crated with natural system
  - are neither **regular nor prismatic**
  - surface roughness will often change with **time distance and even elevation**
  - more difficult to accurately analyze and obtain satisfactory results
  - They include **streams, rivers, floodplains**

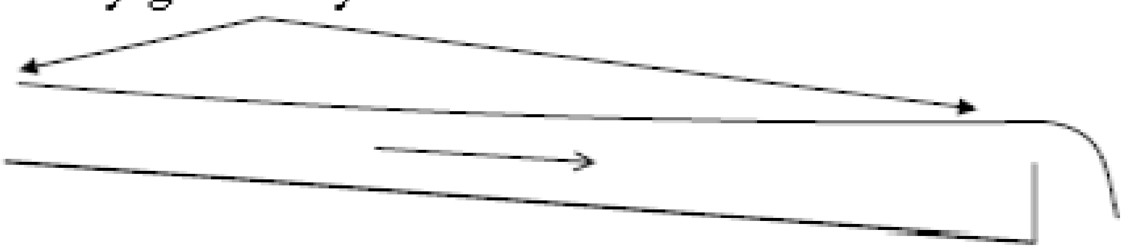
Types of Open Channels

Classifications based on the change in flow depth with respect to time and Space

- **Time as criterion** $\Rightarrow$ Steady and unsteady flow
- **Space as criterion** $\Rightarrow$ Uniform and non uniform flow
- **using combined criteria**
  - **Uniform flow (UF)** $\Rightarrow$ steady and uniform by its nature
  - **Gradually Varied flow (GVF)** $\Rightarrow$ depth various with distance gradually but not with time
  - **Rapidly Varied flow (RVF)** $\Rightarrow$ depth various with distance rapidly but not with time
  - **Unsteady flow** $\Rightarrow$ depth various with both time and distance

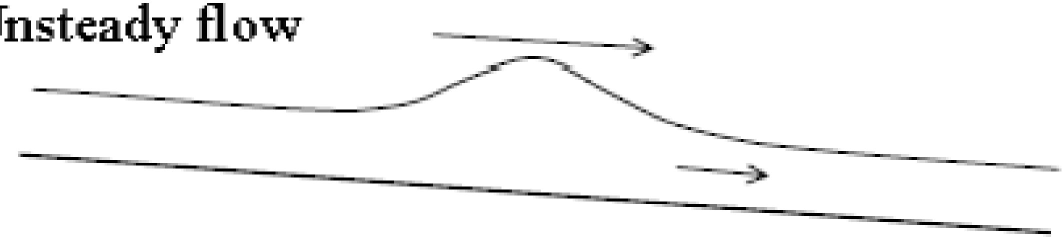
(a) Steady uniform flow

(b) Steady gradually-varied flow



(c) Steady rapidly-varied flow

(d) Unsteady flow



Types of Open Channels
Classification based on the effect of Viscosity

- **The state or behavior of open channel flow is governed by the effects of viscosity relative to inertia**
- **Thus the open channel classified as**
  - **Laminar**
  - **Turbulent**
  - **Transitional**

$$\mathrm{Re}_{Pipe} = \frac{\rho U D}{\mu}$$

Re > 4000 Turbulent
Re< 2000 laminar
2000 < Re < 4000 Transitional

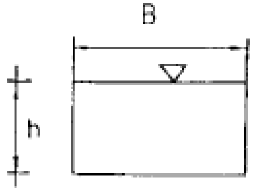
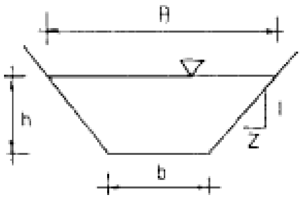
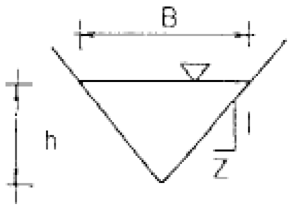
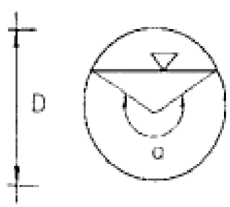
$$\mathrm{Re}_{Channel} = \frac{\rho U D}{4\mu} = \frac{\mathrm{Re}_{Pipe}}{4}$$

Re > 1000 Turbulent
Re< 500 laminar
500 < Re < 1000 Transitionnel

Geometric Properties of Open Channels

- **Depth (y)** the vertical distance from the lowest point of the channel section to the free surface.
- **Stage (z)** - the vertical distance from the free surface to an arbitrary datum
- **Area (A) -** the cross-sectional area of flow, normal to the direction of flow
- **Wetted perimeter (P)** - the length of the wetted surface measured normal to the direction of flow.
- **Surface width (B) -** width of the channel section at the free surface
- **Hydraulic radius (R)** - the ratio of area to wetted perimeter (A/P)
- **Hydraulic mean depth (D)** - the ratio of area to surface width (A/B)

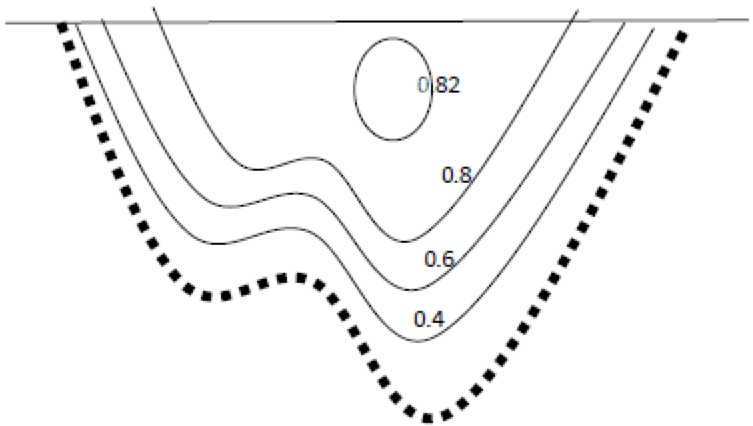
Geometric Properties

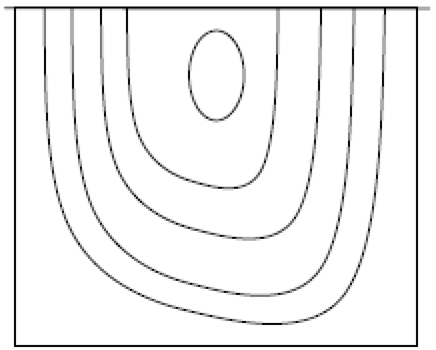
Section	Area A	Wetted perimeter P_w	Hydraulic radius $R = \frac{A}{P_w}$
	$B \times h$	$B + 2h$	$\frac{Bh}{B + 2h}$
	$(b + zh)h$	$b + 2h\sqrt{(1+z^2)}$	$\frac{(b + zh)\, h}{b + 2h\sqrt{1+z^2}}$
	zh^2	$2h\sqrt{1 + z^2}$	$\frac{zh}{2\sqrt{1 + z^2}}$
	$\frac{(\alpha - \sin\alpha)D^2}{8}$	$0.5\alpha D$	$0.25\left[\frac{1-\sin\alpha}{\alpha}\right]D$

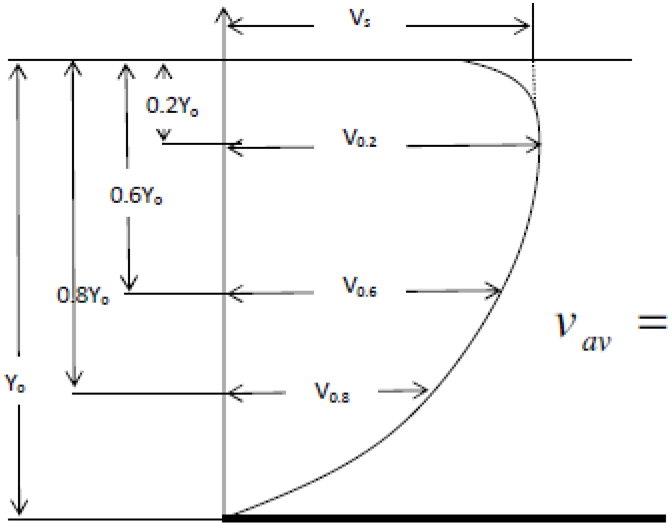
Velocity distribution in open channels

- Naturally three types of velocity are occurred in open channel flow,
  - **Longitudinal:-** the one along the flow direction, (V)
  - **Lateral:-** at the bedside of the channel
  - **Normal :-** perpendicular to the flow direction.
- However, the two velocities **(lateral and normal)** are insignificance as compared to the longitudinal velocity
- Due to the presence of free surface and friction along the channel wall, the longitudinal velocity in a channel are not uniformly distributed.
- The velocity is zero at the solid boundaries and gradually increase with distance from the boundary and reach to its maximum at the center a certain distance below the free surface

Velocity distribution in open channels







$$v_{av} = v_{0.6} = \frac{v_{0.2} + v_{0.8}}{2}$$

Velocity distribution in open channels

- The property of the velocity distribution is used to determine the discharge of stream gauging station using Area-Velocity method
- The surface velocity V_s is related to the average velocity V_{av} as

$$V_{av} = kV_s$$

Where k = a coefficient with a value between 0.8 – 0.95

- The proper value of K depends on the Channel section and has to be determined by field calibrations.
- Important features when analyzing the velocity
  - a single elevation represents the water surface perpendicular to the flow
  - Only the longitudinal velocity is considered so the discharge pass through the section can be expressed as $$Q = AV_{av} = \int v dA$$
  - Mean velocity (Vav) for the entire cross-section is defined on the basis of the longitudinal component of the velocity (v) $$V_{av} = \frac{1}{A}\int v dA$$

Velocity distribution in open channels

- The difference of the two velocities is handle with velocity correction factor (α)
- Consider the Kinetic Energy
  - For an elemental area (dA) the flux of kinetic Energy expressed as

$$KE = (\rho v dA)\frac{v^2}{2}$$

  - For the total area (A) the kinetic Energy flux is

$$KE = \int \frac{\rho}{2} v^3 dA = \alpha \frac{\rho}{2} V_{av}^3 A$$

  - Thus $$\alpha = \frac{\int v^3 dA}{V_{av}^3 A}$$ for discrete values $$\alpha = \frac{\sum v^3 \Delta A}{V_{av}^3 A}$$

Similarly if we consider the momentum, we can get a relation called momentum correction factor (β)

$$\beta = \frac{\int v^2 dA}{V_{av}^2} \text{ or } \frac{\sum v^2 \Delta A}{V_{av}^2 A}$$

Fundamental equations

- The equations which describe the flow of fluid are derived from three fundamental laws of physics:
  - Conservation of matter (or mass)
  - Conservation of energy
  - Conservation of momentum

Fundamental Equations

$$Mass flow entering = mass flow leaving$$

$$Q_{entering} = Q_{leaving}$$

$$V_1A_1 = V_2A_2 = Q$$

$$Total Enegy = Work done + KE + PE$$

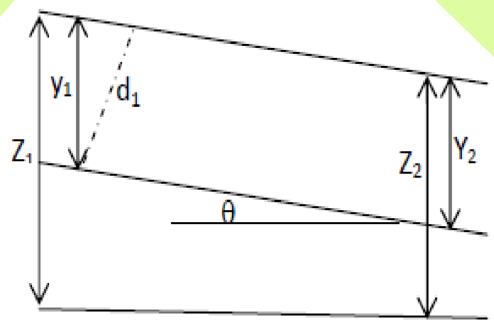
$$T_{energy\ 1} = P_1A_1L + \frac{1}{2}\rho_1 L V_1^2 + \rho_1 A_1 L g z_1$$

$$TEnergy per unit weight = \frac{P_1}{\rho_1 g} + \frac{v_1^2}{2g} + z_1,$$

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + z_2 = H = constant$$

The Continuity Equation (conservation of mass)

Energy equation (conservation of energy)



The momentum equation (momentum principle)

$$Momentum Entering = \rho \delta Q_1 \delta t V_1$$

$$Momentum Leaving = \rho \delta Q_2 \delta t V_2$$

By continuity equation $\delta Q_1 = \delta Q_2 = \delta Q$

By the Newton's second law, $\delta F = \rho \delta Q (V_{2x} - V_{1x})$

$$F_x = \rho Q (V_{2x} - V_{1x})$$

Example 1.1

The velocity distribution in a rectangular channel of width B and depth of flow Y_0 was approximated as

$$V = K_1\sqrt{y}$$

in which K1 is a constant

Calculate

a). The average velocity for the cross section

b). Correction coefficients α and β

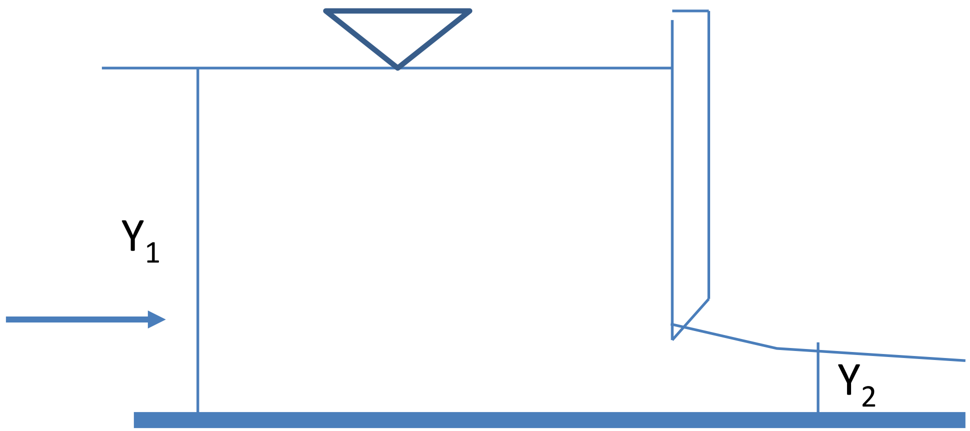
Example 1.2

A sluice gate in a 2.0m wide horizontal rectangular channel is discharging freely as shown in the figure below. If the depths at small up stream (y_1) and downstream(y_2) are 2.5 and 0.2m respectively.

Estimate the discharge in the channel

a). By neglecting Energy losses at gate

b). By assuming the Energy loss at gate to be 10% of the upstream depth y_1



Energy-Depth Relationships

Specific Energy

- The concept of specific energy is first introduced by Bakhmeteft (1932) and has been proven to be very useful in analysis of open channel flow.
- The total energy of a channel flow referred to datum is given by,

$$H = Z + YCos\theta + \alpha V\frac{\alpha V^2}{2g}$$

- If the datum coincides with the channel bed at the cross-section, the resulting expression is known ***as specific energy** and is denoted **by E**.*
- *Thus, specific energy is the energy at a cross-section of an* open channel flow with respect **to the channel bed**.

$$E = YCos\theta + \alpha V\frac{\alpha V^2}{2g}$$

When cosθ =1 and α =1, the equation of specific energy further simplify as:

$$E = Y + V\frac{\alpha V^2}{2g}$$

Energy-Depth …..

we defined Specific Energy as

- Specific energy is the energy at a cross-section of an open channel flow with respect to the channel bed.

Or

- Specific energy is the height of the energy grade line above the channel bottom
- In other respect, since V=Q/A, the equation of specific energy may be written as:

$$E = Y + V\frac{\alpha V^2}{2g} = Y + \frac{Q^2}{2gA^2}$$

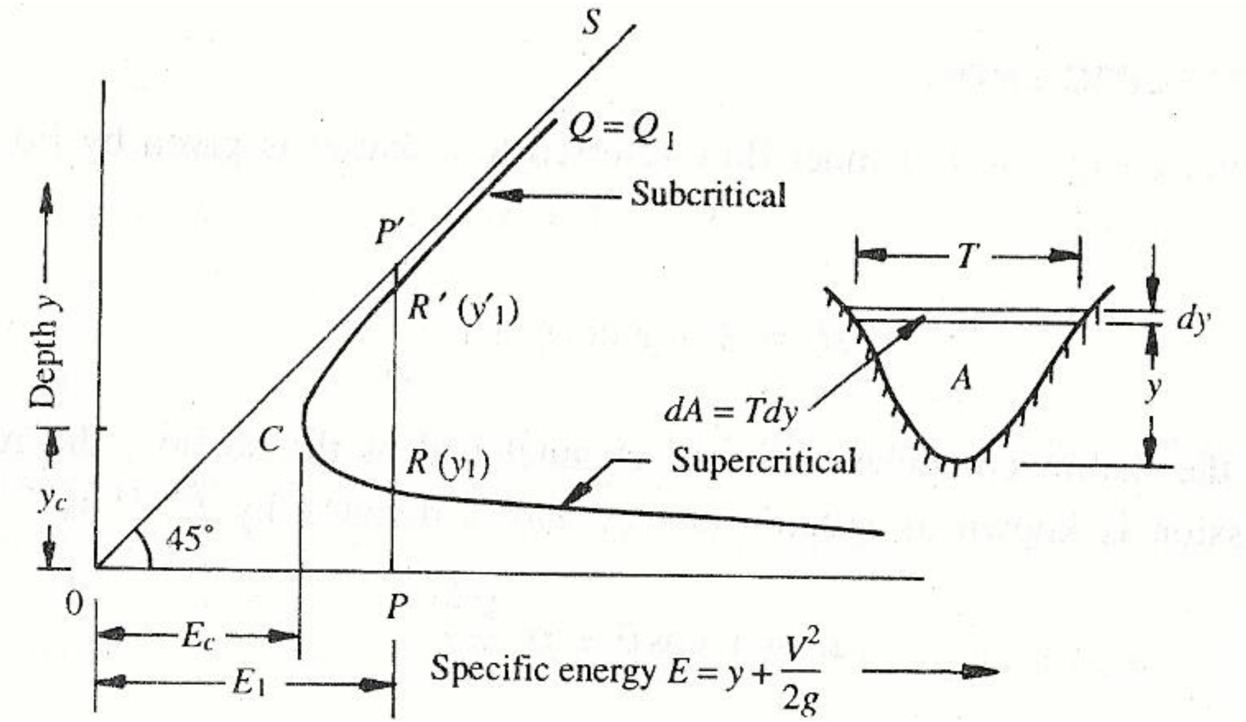
- Here, cross-sectional area A depends on water depth y and can be defined as, A = f(y). and also there is a functional relation between the three variables as,

$$f\,(=E\,,\,y\,,\,Q\,)=0$$

- This functional relationship examine on the plane, with two cases as
  - **Constant Discharge**
  - **Variable Discharge**

Energy-Depth …..

Constant discharge : $Q = Q_1 = Q2 \Rightarrow E = f(y, Q)$.



- The depths of flow can be either PR = y_1 or PR\` = $y_1$\`. These two possible depths having the same specific energy are known as ***alternate depths.***
- The corresponding Froude number of the alternative depths also given as

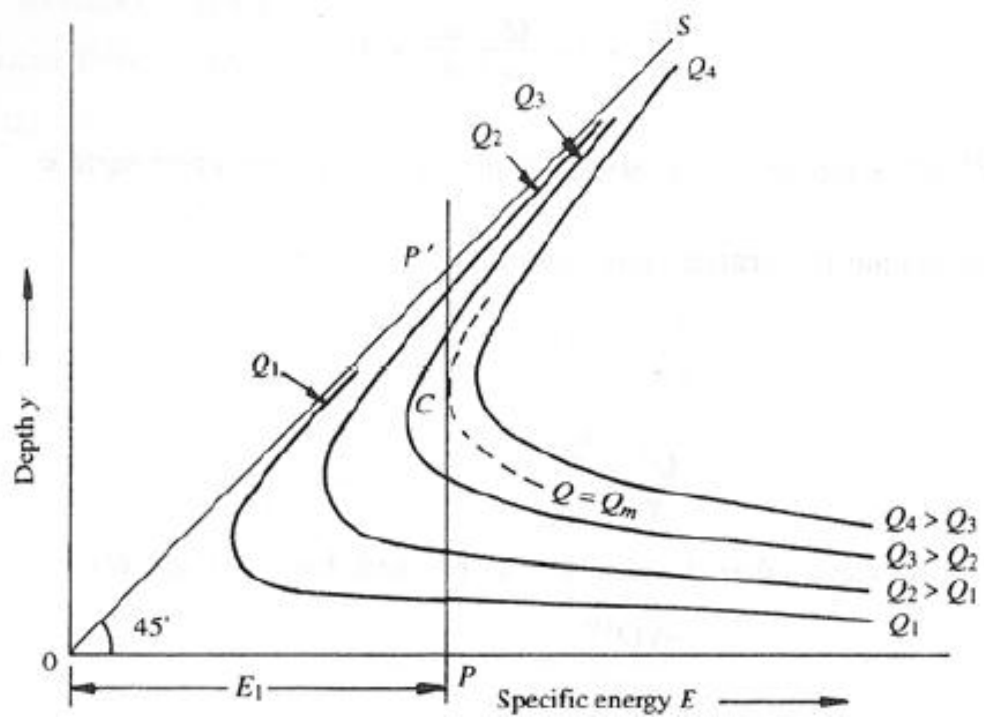
$$F = \frac{V}{\sqrt{g\frac{A}{T}}} = \frac{V}{\sqrt{gY}} \Rightarrow F_1 = \frac{V_1}{\sqrt{gY_1}}$$

Example 1.3

- A rectangular channel 2.50 m wide has a specific energy of 1.50 m when carrying a discharge of 6.48 m^3/sec. Calculate the alternate depths and corresponding Froude numbers.

Energy-Depth ….

Variable Discharge : $Q = Q_1 = Q2 \Rightarrow E = f(y, Q)$.



- In this condition Q1<Q2<Q3< ------ Qn .
- Consider a section PP', the ordinate PP'=E=E_1=constant. Different Q curves give different intercepts. Thus the alternative depths of a given Q can be computed by considering constant specific energy.

Example 1-4

A flow of 5.0 m /sec is passing at a depth of 1.50 through a rectangular channel of width 2.50 m. What is the specific energy of the flow? What is the value of the alternate depth to the existing depth?