

HYDRAULIC ENGINEERING (2PC510CE)

COMPREHENSIVE STUDY MATERIAL

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UNIT I: OPEN CHANNEL FLOW

1. Introduction to Open Channel Flow

- Definition: Open channel flow is the fluid flow with a free surface exposed to atmospheric pressure, driven primarily by the components of gravity along the channel slope rather than external pressure.
- Pipe Flow vs. Open Channel: Pipes not flowing full (e.g., sewers, culverts) fall under open channel flow because they possess a free surface and are under atmospheric pressure.

2. Types of Channels

- Natural Channels: Irregular in shape, constructed by nature. Examples include rivers, streams, hillsides, rivulets, and tidal estuaries.
- Artificial Channels: Regular geometric shapes (rectangular, trapezoidal, triangular, circular), built by human engineering. Examples include roadside drains, culverts, sewer lines, and tunnels.

3. Types of Flows in Open Channels

- Steady and Unsteady Flow:
 - Steady Flow: Fluid properties (velocity, discharge, depth) at any point do not change with time.
 - Unsteady Flow: Depth or other parameters change with respect to time.
- Uniform and Non-Uniform Flow:
 - Uniform Flow: For a given length of channel, velocity, depth, slope, and cross-section remain constant.
 - Non-Uniform (Varied) Flow: Flow parameters change along the channel length. It is sub-classified into:
 - * Gradually Varied Flow (GVF): Depth changes gradually over a long reach.

* Rapidly Varied Flow (RVF): Depth changes abruptly over a short length (e.g., Hydraulic Jump).

- Laminar and Turbulent Flow: Categorized by Reynolds Number ($Re = \rho VR / \mu$ where $R =$ Hydraulic Radius = Area/Wetted Perimeter):

- Laminar Flow: $Re < 500$

- Transitional Flow: $500 \leq Re \leq 1000$

- Turbulent Flow: $Re > 1000$

- Critical, Sub-Critical, and Super-Critical Flow: Based on Froude Number ($Fe = V / \sqrt{gD}$ where $D =$ Hydraulic Depth = A / T):

- Sub-Critical Flow (Tranquil/Streaming): $Fe < 1.0$; stable flow with deeper depth.

- Critical Flow: $Fe = 1.0$; state of minimum specific energy.

- Super-Critical Flow (Shooting/Rapid/Torrential): $Fe > 1.0$; unstable flow with high velocity and shallow depth.

4. Velocity & Shear Stress Distribution

- Velocity varies across the channel cross-section due to friction along the boundaries.

- The maximum velocity is usually found just below the free surface (0.05 to 0.25 of depth) due to surface resistance.

5. Discharge Formulas through Open Channels

- Chezy's Formula: $V = C \sqrt{mi}$, where $m =$ hydraulic mean depth (A/P), $i =$ bed slope, $C =$ Chezy's constant. Discharge $Q = A \times C \sqrt{mi}$.

- Manning's Formula: $C = (1/n) \times R^{(1/6)}$ or $V = (1/n) \times m^{(2/3)} \times i^{(1/2)}$, where n is Manning's roughness coefficient.

- Bazin's Formula: $C = 157.6 / (1.81 + k/\sqrt{m})$, where k is Bazin's constant.

- Kutter's Formula: Expresses C as a complex function of bed slope (i), roughness (N), and hydraulic radius (m).

6. Most Economical Sections

A section is most economical when it passes maximum discharge for a given area, which requires the wetted perimeter (P) to be a minimum.

- Rectangular Section: Best condition occurs when width is double the depth ($b = 2d$) or hydraulic radius $m = d/2$.

- Trapezoidal Section: Best condition occurs when half of top width equals side slope length ($(b+2nd)/2 = d\sqrt{(n^2+1)}$), or $m = d/2$. Best side slope angle is $\theta = 60^\circ$.

- Circular Section: Maximum velocity occurs when depth $d = 0.81D$ ($\theta = 128^\circ 45'$). Maximum discharge occurs when $d = 0.95D$ ($\theta = 154^\circ$).

7. Specific Energy & Specific Energy Curve

- Specific Energy (E_s): Total energy per unit weight of fluid calculated with the channel bottom taken as the datum: $E_s = h + V^2/(2g) = h + q^2 / (2g h^3)$.

- Critical Depth (h_c): The depth at which specific energy is a minimum for a given discharge. For rectangular channels: $h_c = [q^2/g]^{1/3}$.

- Minimum Specific Energy: $E_{min} = 1.5 \times h_c$.

8. Hydraulic Jump (Rapidly Varied Flow)

- Definition: An abrupt rise in water level occurring when flow transitions from an unstable supercritical state ($Fr > 1$) to a stable subcritical state ($Fr < 1$).

- Applications: Below control structures like weirs/sluice gates, at the toe of a spillway dam to dissipate kinetic energy.

- Depth Relationship: $d_2 = -d_1/2 + \sqrt{[d_1^2/4 + 2q^2/(gd_1)]} = (d_1/2) * [\sqrt{(1 + 8Fr_1^2)} - 1]$

- Loss of Energy (h_L): $h_L = (d_2 - d_1)^3 / (4 d_1 d_2)$

9. Gradually Varied Flow (GVF) & Flow Profiles

- Governing Equation: $dh/dx = (i_b - i_e) / [1 - Fr^2]$

- Backwater Curve: $dh/dx > 0$ (depth increases in flow direction).

- Dropdown Curve: $dh/dx < 0$ (depth decreases in flow direction).

- Slopes Classification: Steep (S: $So > Sc$), Critical (C: $So = Sc$), Mild (M: $So < Sc$), Horizontal (H: $So = 0$), Adverse (A: So is negative). Profiles include M1, M2, M3, S1, S2, S3, etc.

UNIT II: DIMENSIONAL ANALYSIS & MODEL ANALYSIS

1. Fundamentals of Dimensions & Units

- Fundamental Dimensions: Mass [M], Length [L], and Time [T].

- Secondary/Derived Dimensions: Quantities expressed using combinations of fundamental parameters (e.g., Velocity [LT^{-1}], Force [MLT^{-2}], Density [ML^{-3}], Power [ML^2T^{-3}]).

- Dimensional Homogeneity: An equation is homogenous if the dimensions on both sides of the equation are equal (e.g., $V = \sqrt{2gH}$ where both sides reduce to $[LT^{-1}]$).

2. Methods of Dimensional Analysis

- Rayleigh's Method: Used to form relationships if a variable depends on up to 3 or 4 variables maximum. Expressed as $X = K \cdot (X_1^a \cdot X_2^b \cdot X_3^c)$.
- Buckingham's π -Theorem: Essential when variables exceed 4. If a phenomenon has 'n' variables containing 'm' fundamental dimensions, they can be grouped into $(n - m)$ independent dimensionless parameters called π -terms: $f(\pi_1, \pi_2, \dots, \pi_{n-m}) = 0$.
 - Selection of Repeating Variables: Chosen variables must include geometric, flow, and fluid properties, but must not combine to form a dimensionless group or include the dependent variable itself.

3. Similitude & Model Analysis

- Model vs. Prototype: A model is a miniature or scaled replica used to predict the behavior of the real system (prototype).
- Geometric Similarity: Linear dimension ratios are identical: $L_r = L_m/L_p = B_m/B_p = D_m/D_p$. Area ratio $A_r = L_r^2$; Volume ratio $V_r = L_r^3$.
- Kinematic Similarity: Velocity and acceleration ratios are equal at corresponding points: $V_r = V_m/V_p$; $a_r = a_m/a_p$.
- Dynamic Similarity: Forces acting at corresponding points maintain a constant ratio: $Fr = F_m/F_p$.

4. Dimensionless Numbers & Model Laws

- Reynolds Number ($Re = \rho VL/\mu$): Inertia force / Viscous force. Applied in pipe flows, submarines, and fully immersed structures.
- Froude Number ($Fr = V/\sqrt{Lg}$): $\sqrt{(\text{Inertia force} / \text{Gravity force})}$. Applied in free surface flows like open channels, spillways, and weirs.
- Euler Number ($Eu = V/\sqrt{p/\rho}$): $\sqrt{(\text{Inertia force} / \text{Pressure force})}$. Applied in closed fully turbulent conduits and cavitation studies.
- Weber Number ($We = V/\sqrt{\sigma/\rho L}$): $\sqrt{(\text{Inertia force} / \text{Surface tension force})}$. Applied in ultra-low head weir flows and capillary soil movements.
- Mach Number ($M = V/C$): $\sqrt{(\text{Inertia force} / \text{Elastic force})}$. Applied in supersonic projectile mechanics and water hammer problems.

UNIT III: IMPACT OF FREE JETS

1. Impulse-Momentum Principle

- Derived from Newton's Second Law: Force = Mass $\times$ Acceleration = Rate of change of momentum. $F = (\text{Mass/Time}) \times (\text{Initial Velocity} - \text{Final Velocity}) = \rho aV(V_1 - V_2)$.

2. Force Exerted by a Jet on a Stationary Plate

- Flat Vertical Plate: $F_x = \rho aV^2$
- Flat Inclined Plate: Normal force $F_N = \rho aV^2 \sin \theta$; Component in jet direction $F_x = F_N \sin \theta = \rho aV^2 \sin^2 \theta$.
- Curved Plate (Striking Center): $F_x = \rho aV^2(1 + \cos \theta)$ [if jet is deflected through angle θ].
- Curved Plate (Striking at Tip Unsymmetrically): $F_x = \rho aV^2(\cos \theta + \cos \phi)$.

3. Force Exerted by a Jet on a Moving Plate

- Fluid impacts plate with a relative velocity $(V - u)$, where u is plate velocity.
- Vertical Moving Plate: $F_x = \rho a(V - u)^2$
- Inclined Moving Plate: $F_x = \rho a(V - u)^2 \sin^2 \theta$
- Curved Moving Plate (Center Strike): $F_x = \rho a(V - u)^2(1 + \cos \theta)$
- Vanes on a Wheel (Series of Vanes): Mass flow rate striking the wheel becomes equal to the total nozzle discharge (ρaV) . Hence, Force $F_x = \rho aV(V - u)$ for flat plates and $F_x = \rho aV(V - u)(1 + \cos \theta)$ for curved buckets.

UNIT IV: HYDRAULIC TURBINES

1. Classification of Turbines

- Energy at Inlet: Impulse (only kinetic energy available, e.g., Pelton Wheel) vs. Reaction (both kinetic and pressure energy present, e.g., Francis, Kaplan).
- Direction of Flow: Tangential (Pelton), Radial (Francis), Axial (Kaplan), Mixed (Modern Francis).
- Head Requirements: High Head ($>250\text{m}$: Pelton), Medium Head (45m – 250m : Francis), Low Head ($<45\text{m}$: Kaplan).
- Specific Speed (N_s): Low Specific Speed (Pelton: 10 – 35), Medium (Francis: 60 – 300), High (Kaplan: 300 – 1000).

2. Design & Analysis of Turbines

- Pelton Wheel: High-head tangential impulse turbine. Speed ratio $u/V \approx 0.45$ to 0.48 . Jet ratio $m = D/d$. No. of buckets $= (0.5 \times m) + 15$.
- Francis Turbine: Medium-head inward mixed-flow reaction turbine. Fluid enters radially and exits axially. Work done $= \rho Q(V_{w1} u_1 \pm V_{w2} u_2)$.
- Kaplan Turbine: Low-head axial-flow reaction turbine with adjustable runner blades. Flow rate depends on outer diameter (D_o) and hub/boss diameter (D_b): $Q = \pi/4 \times (D_o^2 - D_b^2) \times V_{f1}$.

3. Ancillary Systems

- Draft Tube: A divergent conduit connecting reaction turbine outlet to the tailrace. It converts exit kinetic energy into pressure head, allowing the turbine to be set above tailrace without losing head.
- Surge Tank: An open standpipe/chamber placed along long penstocks to absorb water hammer pressure transients during sudden valve closure and supply immediate fluid during valve openings.
- Governing: Mechanism to regulate turbine speed automatically by altering water discharge via a spear/deflector (Impulse) or guide vanes (Reaction) under varying load demands.

4. Performance Parameters

- Unit Quantities: Performance parameters computed under a simulated 1m net head: Unit Speed $N_u = N/\sqrt{H}$; Unit Discharge $Q_u = Q/\sqrt{H}$; Unit Power $P_u = P/H^{1.5}$.
- Cavitation: Boiling of fluid at ambient operating temperatures due to localized pressure dropping below vapor pressure. Occurs at reaction runner outlet or draft tube inlet. Avoided by ensuring Net Positive Suction Head Available (NPSHA) $>$ Required (NPSHR).

UNIT V: CENTRIFUGAL PUMPS

1. Principles of Centrifugal Pumps

- Operating Principle: Works on the reverse principle of a radial reaction turbine. Mechanical energy from an external source (electric motor) is converted into hydraulic pressure energy via centrifugal force developed by a rotating impeller equipped with backward-curved vanes.

2. Classification and Configurations

- Single-stage (one impeller for normal heads) vs. Multi-stage (multiple impellers connected in series for ultra-high heads, or in parallel for high discharge capacity).
- Shaft Alignment: Horizontal or Vertical type configurations.

3. Component Infrastructure

- Strainer and Foot Valve: Located at suction pipe inlet; prevents debris and maintains prime via a one-way check valve.
- Suction Pipe: Connects pump eye to sump fluid source.
- Impeller & Casing: Rotates fluid inside volute, vortex, or diffuser casing layouts to minimize eddy losses.
- Delivery Line: Transports pressurized fluid via delivery valves to destination tanks.

4. Heads & Efficiencies

- Static Head (H_s): Vertical height difference between suction sump level and delivery water surface ($H_s = h_s + h_d$).
- Manometric Head (H_m): Total head that the pump must generate to overcome static lift, frictional losses in suction/delivery pipes, and the final delivery kinetic energy head: $H_m = h_s + h_d + h_{fs} + h_{fd} + V_d^2/(2g)$.
- Manometric Efficiency (η_{man}): Ratio of manometric head to the total energy head imparted by the impeller to the unit weight of fluid: $\eta_{man} = g H_m / (V_w u_2)$.

5. Operation Criteria & Constraints

- Minimum Starting Speed: The pump will not lift water unless the centrifugal pressure head generated by the impeller exceeds the manometric head: $N_{min} = (120 * \eta_{man} * V_w * D_2) / (\pi * (D_2^2 - D_1^2))$ roughly derived from $u_2^2 - u_1^2 \geq 2gH_m$.
- Specific Speed of Pump (N_s): $N_s = N\sqrt{Q} / H^{0.75}$.
- Cavitation in Pumps: Occurs near the impeller eye or inlet where pressure drops below vapor thresholds. Results in bubble collapse, pit damage to metal surfaces, vibrations, drop in efficiency, and acoustic noise.