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Highway Hydraulics - Fundamental Concepts

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Module 3: Fundamental Hydraulic Concepts

Learning Objectives

By the end of this section, you will be able to:

- **Identify** the appropriate fundamental equation (continuity, energy, or momentum) for various drainage design scenarios.
- **Calculate** average velocity, headloss, and discharge for both open-channel and closed-conduit systems.
- **Evaluate** flow classifications and dimensionless numbers to distinguish between subcritical and supercritical flow regimes.

Executive Summary: The design and analysis of highway drainage structures rely on the conservation of mass, energy, and momentum. These principles govern both pressure flow in full pipes and open-channel flow in channels or partially full conduits. Mastery of these equations, alongside weir and orifice discharge calculations, is essential for predicting hydraulic performance and structural loading in highway infrastructure.

Design Fundamentals

The engineering of drainage structures requires a precise application of three fundamental equations:

1. **Continuity Equation**
2. **Energy Equation**
3. **Momentum Equation**

These equations are utilized differently depending on whether the system is an **open-channel** or a **closed conduit** flowing full. Note that a closed conduit flowing partially full is hydraulically treated as open-channel flow because it possesses a free surface at atmospheric pressure.

Flow Classification

Flow is categorized by its behavior over time, distance, and fluid layers:

- **Uniform vs. Nonuniform:** In uniform flow, depth, discharge, and velocity are constant with respect to distance.
- **Steady vs. Unsteady:** In steady flow, conditions do not change with respect to time at a specific point.
- **Laminar vs. Turbulent:** Laminar flow is characterized by distinct fluid layers, while turbulent flow involves random fluid motion. These are distinguished by the **Reynolds Number**.
- **Subcritical vs. Supercritical:** Distinguished by the **Froude Number (Fr)**.
 - **Fr < 1:** Subcritical (tranquil) flow.
 - **Fr > 1:** Supercritical (rapid) flow.
 - **Fr = 1:** Critical flow.

Basic Principles

Conservation Laws

The three basic flow equations are derived from fundamental physical laws:

- **Conservation of Mass:** Matter is neither created nor destroyed (Continuity).
- **First Law of Thermodynamics:** Energy must be conserved at all times (Energy).
- **Newton's Second Law:** A mass accelerates in proportion to and in the direction of the applied forces (Momentum).

💡 **Design Tip:** While analysis is simplified by assuming **one-dimensional flow** (negligible acceleration in other directions), assuming zero acceleration when it is actually significant can lead to highly inaccurate results.

Continuity Equation

The continuity equation is used for steady flow of incompressible fluids where density is constant.

Equation 3.1:

$$V_1 A_1 = V_2 A_2 = Q = VA$$

Where:

- **V** = Average velocity in the cross section perpendicular to the area, m/s (ft/s)
- **A** = Area perpendicular to the velocity, m² (ft²)
- **Q** = Volume flow rate or discharge, m³/s (ft³/s)

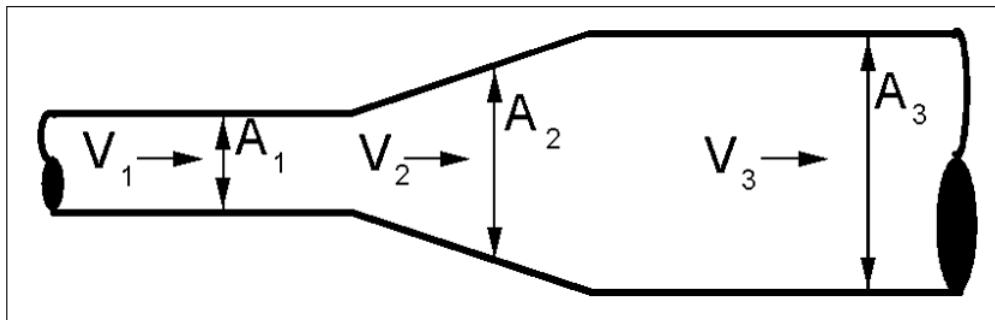

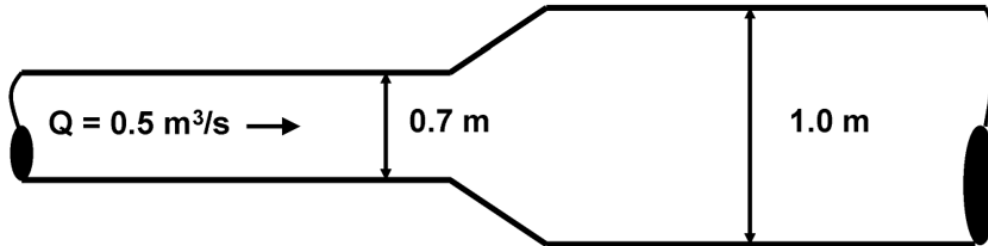


Figure 3.1. Sketch of continuity concept.

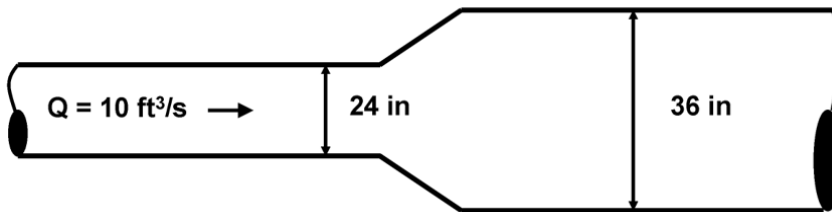
 **Calculation Note:** For circular pipes flowing full, always calculate the area as $A = (\pi * D^2) / 4$.

- **Example Problem 3.1 (SI Units)**



- **Given:** Storm drain (full flow) transitioning from 0.7 m to 1.0 m diameter; $Q = 0.5 \text{ m}^3/\text{s}$.
- **Velocity at 0.7 m Section:** $V = 0.5 / [(\pi * 0.7^2) / 4] = 1.30 \text{ m/s}$.
- **Velocity at 1.0 m Section:** $V = 0.5 / [(\pi * 1.0^2) / 4] = 0.64 \text{ m/s}$.

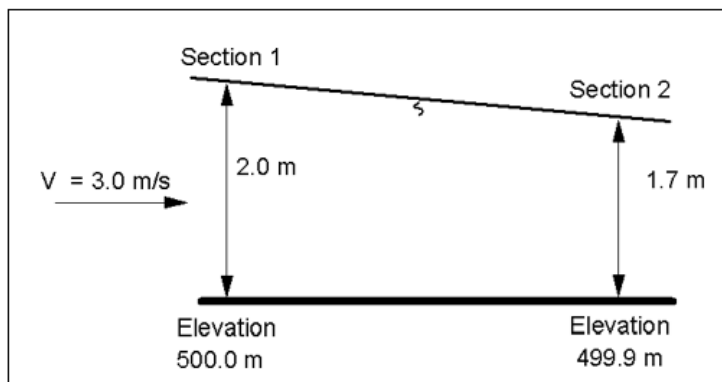
- **Example Problem 3.1 (English Units)**



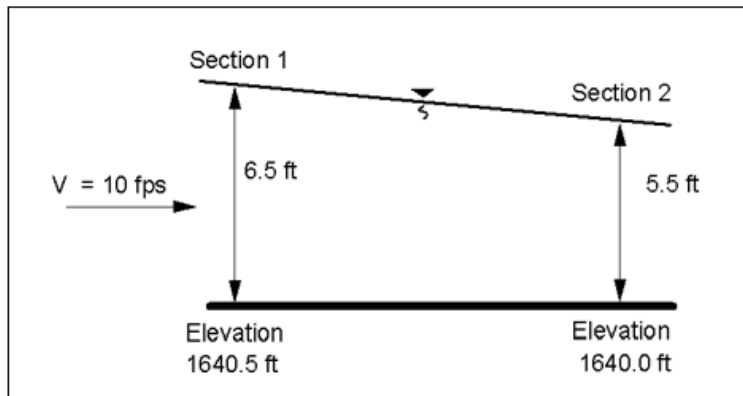
Energy Equation

The energy equation is a scalar equation used to track the total energy head across sections.

- **Example Problem 3.2 (SI Units)**



- **Example Problem 3.2 (English Units)**



Equation 3.2:

$$\alpha_1 \frac{V_1^2}{2g} + \frac{p_1}{\gamma} + Z_1 = \alpha_2 \frac{V_2^2}{2g} + \frac{p_2}{\gamma} + Z_2 + h_L$$

Where:


- α = Kinetic energy correction factor
- V = Average velocity, m/s (ft/s)
- g = Acceleration of gravity, 9.81 m/s² (32.2 ft/s²)
- p = Pressure, N/m² or Pa (lbs/ft²)
- γ = Unit weight of water, 9,800 N/m³ (62.4 lbs/ft³)
- Z = Elevation above a horizontal datum, m (ft)
- h_L = Headloss due to friction and form losses, m (ft)

Equation 3.3 (Kinetic Energy Correction):

$$\alpha = \frac{1}{V^3 A} \int v^3 dA$$

Where:

- α = Kinetic energy correction factor
- V = Average velocity in the cross section, m/s (ft/s)
- A = Area perpendicular to the velocity, m² (ft²)
- v = Velocity at a point or average in a vertical, m/s (ft/s)

 **Design Tip:** Even with nonuniform velocity distributions, the kinetic energy correction is typically small (within 10%). For standard highway drainage design, α is normally assumed to be **1.0**.

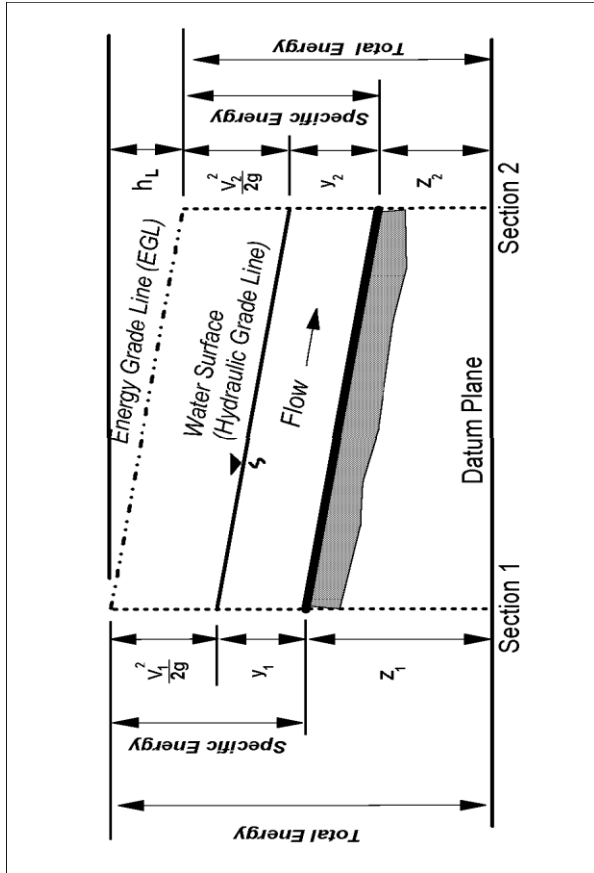


Figure 3.2. Sketch of energy concept for open-channel flow.

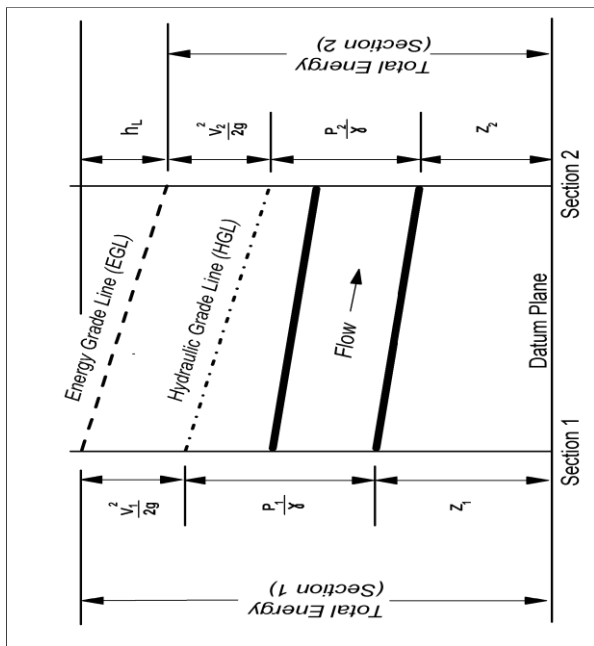


Figure 3.3. Sketch of energy concept for pressure flow in a pipe.



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