Open-Channel Hydraulics

An Online Continuing Education Course for Engineers

Course Number: C-4035

Credit: 4 Hours / 4 PDH / 4 CPD

Open-Channel Hydraulics

Robert Duane Nickols, P.E., R.L.S.

Introduction

We can see water flowing in open channels all the time in rivers, streams or man-made ditches along the side of the road. When water flows in an open channel, there is a free surface on the top. In pipe flow, there isn't a free surface. If there is a free surface, then it is open channel flow even in a pipe. Some of the principal factors at work are inertia, gravity and viscosity. Flow will vary with different viscosities so for this course, we will only consider water as the fluid. We will use foot-pound-second units. Water has a unit weight of about 62.4 pounds per cubic foot (pcf). It does not vary significantly at normal temperatures. The acceleration due to gravity on earth is about 32.2 feet per second squared (ft/s^2). Variations in gravity are usually neglected. The modulus of compressibility of water is about 300,000 pounds per square inch (psi), so we usually consider water to be incompressible.

Hydraulic elements of channels

Area (A) is the cross sectional area of flow, normal to the direction of flow. *Depth* (y) is the vertical distance from the bottom of the channel to the free surface. *Wetted perimeter* (P) is the length of the wetted surface measured normal to the direction of flow. *Hydraulic radius* (R) is the ratio of the area to the wetted perimeter, (A/P). (T) is the top width of the free surface. *Hydraulic depth* (D) is the ratio of the area to the top width (A/T). The fluid velocity (V), is in feet per second (fps). (Q) is the flow rate or discharge in cubic feet per second (cfs) and is the product of the area times the velocity (Q = AV).

Let's say we have a rectangular channel that is 3 feet wide and the depth of water (y) is 3 feet.

$A = 3\ ft \times 3\ ft = 9\ ft^2$

$P = 3\ ft + 3\ ft + 3\ ft = 9\ ft$

$R = A/P = 9\ ft^2 / 9\ ft = 1\ ft$

$T = 3\ ft$

$D = A/T = 9\ ft^2 / 3\ ft = 3\ ft$

If V = 2.27 fps

Then $Q = AV = 9\ ft^2 \times 2.27\ ft/s = 20.43$ cfs

Let's say we have a pipe that is 4 feet diameter (d) and it is half full of water. The velocity is 3.22 fps.

$A = \pi d^2/4/2 = \pi \times (4\ ft)^2 / 4 / 2 = 6.28\ ft^2$

$P = \pi d/2 = \pi \times 4\ ft / 2 = 6.28\ ft$

$R = A/P = 12.57\ ft^2 / 6.28\ ft = 1.0\ ft$

$T = d = 4\ ft$

$D = A/T = 6.28\ ft^2 / 4\ ft = 1.57\ ft$

$Q = AV = 6.28\ ft^2 \times 3.22\ ft/s = 20.22$ cfs

Types of Flow

Steady flow is when the depth does not change at a point with respect to time.

Unsteady flow is when the depth does change at a point with respect to time. This could be a traveling wave.

Uniform flow is when the depth and velocity are the same at every section of the channel.

Steady uniform flow is when the depth and velocity are constant with respect to distance and time. This is the type of flow that occurs most often in open channels. The slope of the channel, the hydraulic grade line (water surface) and the energy grade line are all the same.

Steady non-uniform flow is when the depth varies with distance but not with time. This type of flow may be when the depth is *gradually varied* or *rapidly varied.*

Laminar flow is characterized by smooth, parallel and predictable streamlines (the paths a single particle takes). It occurs at relatively low velocity.

Turbulent flow is when the streamlines are erratic and unpredictable. This is the type of flow that occurs most often.

We usually have *steady uniform turbulent flow* in hydraulics.

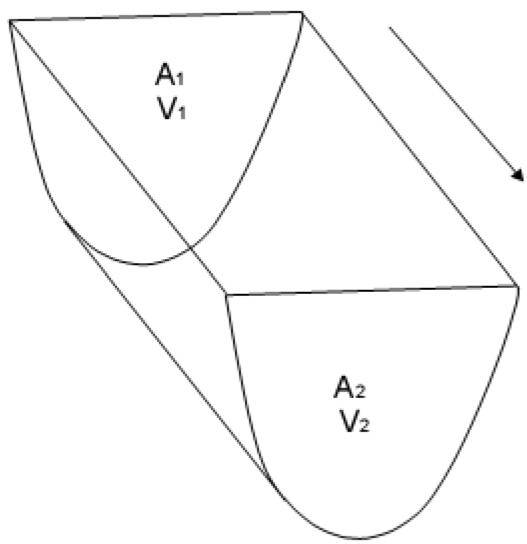
Fundamental Equations

Continuity equation (conservation of mass)

Mass flow $_{entering}$ = Mass flow $_{leaving}$

$$\rho Q_{entering} = \rho Q_{leaving}$$

$$\rho = fluid\ density$$
$$Q = flow\ (cfs)$$
$$Q = AV$$
$$Q = A_1V_1 = A_2V_2 \quad continuity\ equation$$



This applies to steady flow of an incompressible fluid.

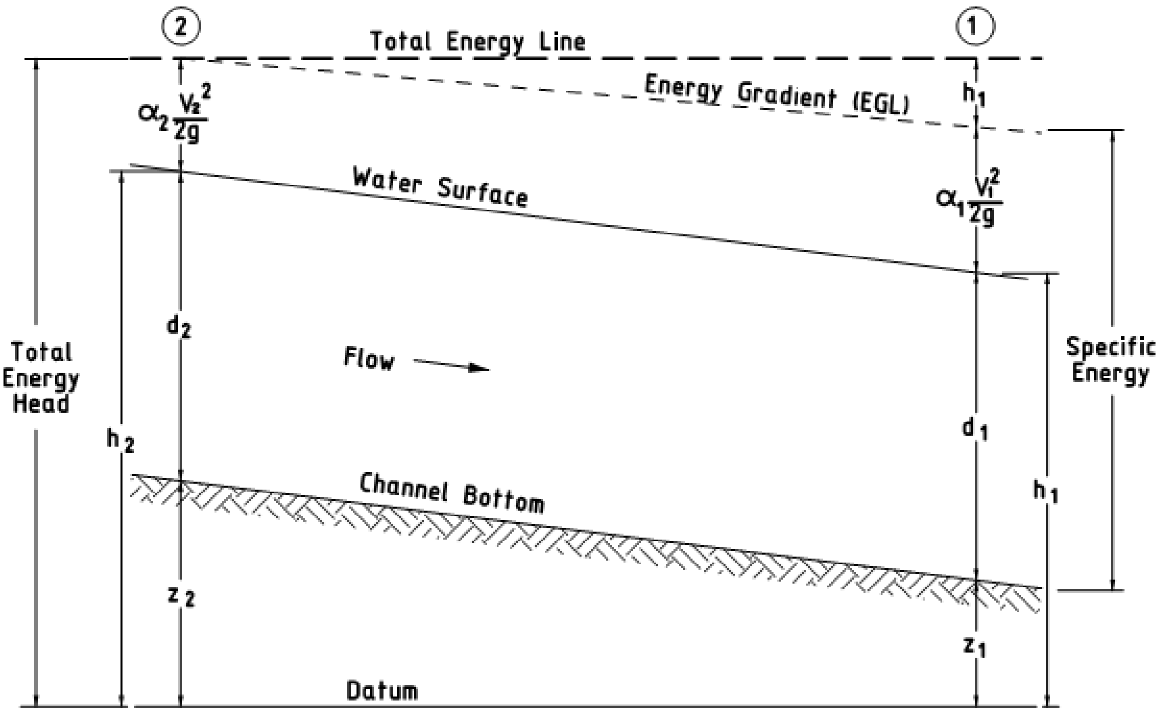
Let's say that A_1 = 4 ft² and V_1 = 3 ft/s and A_2 = 6 ft² then what is V_2?

Q = A_1V_1 = 4 ft^2 x 3 ft/s = 12 cfs

V_2=Q/A_2 = 12 cfs / 6 ft² = 2 ft/s

Energy equation (conservation of energy)

If we assume there is no loss due to friction, then the energy entering must equal the energy leaving.



$$d_2 + \frac{v_2^2}{2g} + z_2 = d_1 + \frac{v_1^2}{2g} + z_1 = H = constant \quad (Bernoulli\ equation)$$

$$d = \frac{p}{\gamma} = pressure\ head$$

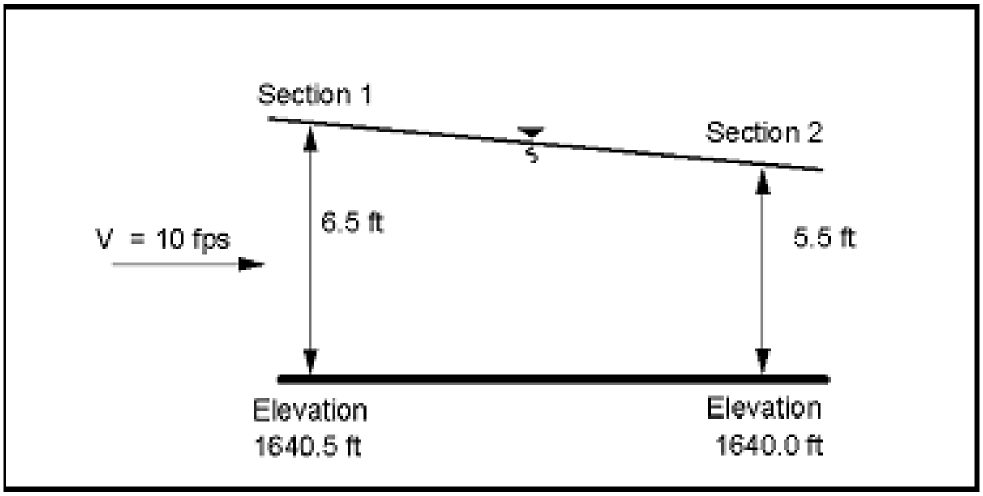
$$\frac{v^2}{2g} = velocity\ head$$

$$z = potential\ head\ (all\ are\ in\ units\ of\ feet)$$

If we consider the loss due to friction, then the equation would look like this:

$$d_2 + \frac{v_2^2}{2g} + z_2 = d_1 + \frac{v_1^2}{2g} + z_1 + h_f = H = constant$$

Given: The velocity upstream in a rectangular channel that is 3 feet wide is 10.0 ft/s and the depth of flow is 6.5 feet. The downstream end is 5.5 feet deep. The elevation of the channel bed at the upstream end is 1640.5 feet and is 1640.0 feet at the downstream end. Determine the head loss due to friction.



Find: Headloss (h_f)

Solution:

$$Q = AV = (10\ ft\ /\ s)(6.5\ ft)(3\ ft) = 195\ cfs$$

$$A_2 = (5.5\ ft)(3\ ft) = 16.5\ ft^2$$

$$V_2 = Q/A_2 = 195\ cfs\ /\ 16.5\ ft^2 = 11.82\ ft/s$$

$$\frac{V_1^2}{2g} + y_1 + z_1 = \frac{V_2^2}{2g} + y_2 + z_2 + h_f$$

$$\frac{(10)^2}{(2)(32.2)} + 6.5 + 1640.5 = \frac{(11.82)^2}{(2)(32.2)} + 5.5 + 1640.0 + h_f$$

$$h_f = (1.55 + 6.5 + 1640.5) - (2.17 + 5.5 + 1640.0) = 0.88\ feet$$

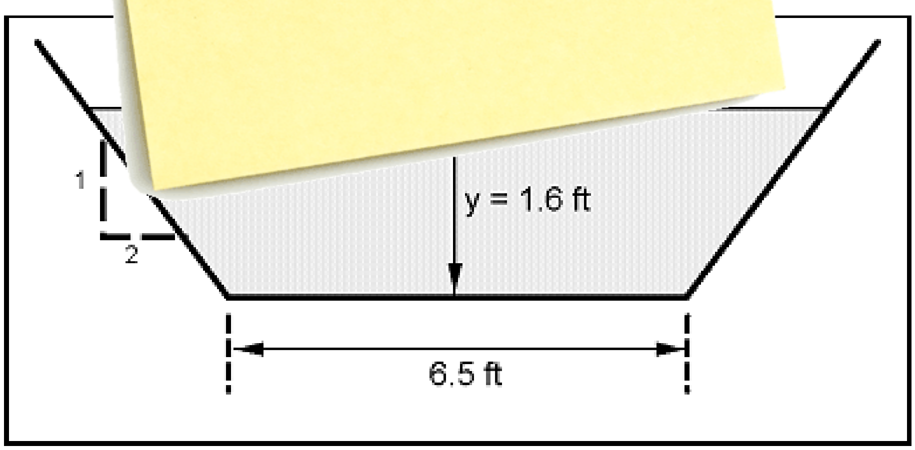
Uniform, Steady Flow

Steady uniform flow is almost achieved in nature. One of the most commonly used equations used in open channel flow is the Manning Equation. It was introduced by an Irish Engineer named Robert Manning in 1889 as an alternative to the Chezy Equation.

Under uniform flow conditions the bottom slope of the channel is the same as the water surface (the hydraulic grade line) and the energy grade line. The energy grade line is $V^2/2g$ above the water surface.

Manning Equation: (about 1889)

Given: A trapezoi… …ith side slope 2:1, the channel slo… …et and n=0.02.



Find: Velocity (V) and flow or discharge (Q)