Fluid Mechanics

Topic 8

Open Channel Flow

OPEN-CHANNEL FLOW

What is Open-Channel flow?

- Rivers, streams, gutters, sewer pipe
- driven by gravity, open to atmosphere on one side?

Features of open channel flow (OCF)

- Flow is most often turbulent
- the channel slope and cross section can vary along its length

	Pipe flow	OCF
Driving force		
Flow area		
Boundary conditions		

Classification of OCF

Steady flow

- the flow speed and depth do not vary with time
- Conservation of mass in a steady-state OCF:

Classification of OCF

Uniform flow

- the depth of flow doesn’t vary along the channel length
- Conservation of momentum on uniform OCF:

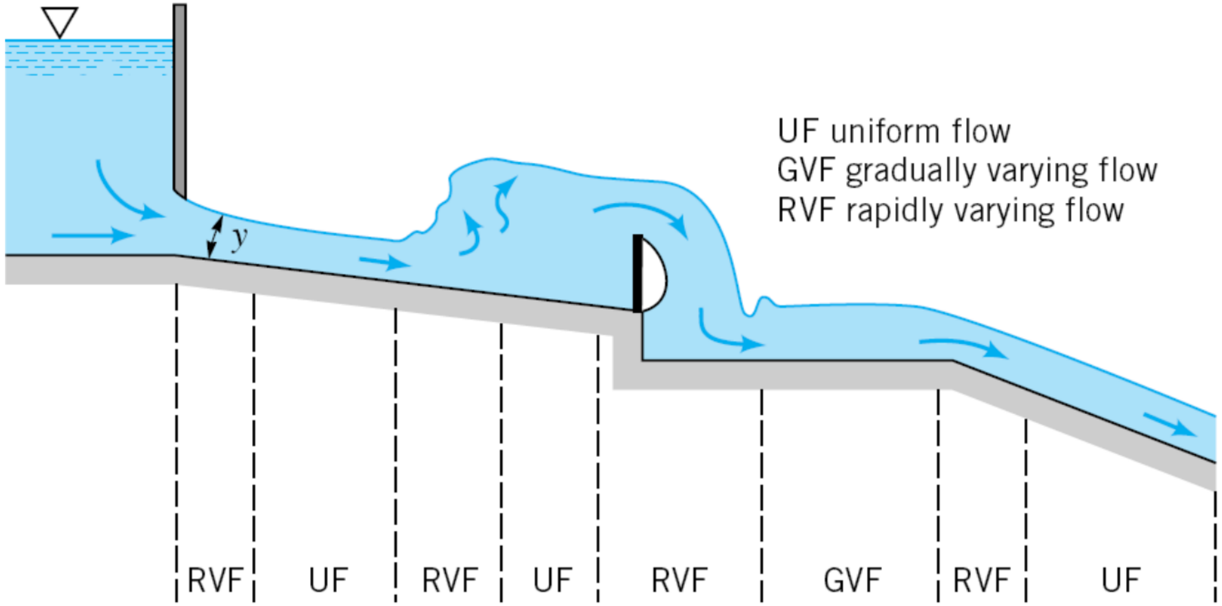
Classification of OCF

Gradually varied flow (GVF)

- depth of flow does vary along channel, but the height only changes gradually, with $\frac{dh}{dx} \ll 1$

Rapidly varied flow (RVF)

- depth of flow does vary along the channel, but does so rapidly with $\frac{dh}{dx} \sim O(1)$



Uniform open channel flow

Can we predict the depth of uniform flow if we know what the flowrate is, and vice-versa?

Engineers have typically used empirical, rather than analytical, formulas to make predictions. Why is this the case?

A useful empirical approach is Manning's equation:

$$\boxed{V = \frac{1}{n} R_h^{2/3} S^{1/2}}$$

We will now examine these terms.

Uniform open channel flow

Hydraulic radius (R_h)
How do we describe the friction exerted by a complex, irregularly shaped channel?

We define the hydraulic radius as $R_h = A/P$, which we use as a representation of channel dimensions for irregular channels.

Hydraulic Radius

1. Rectangular

2. Unfilled circular channel

Slope

In Gradually varied OCF, the slope is small enough ($\theta \ll 1°$) that we can make the approximation that $\theta \approx \sin(\theta) \approx \tan(\theta)$. In this case, these all represent the channel slope, S.

Notes on Manning's equation:

1. Mannings equation is not dimensionally consistent. Requires input in SI

2. Inherent uncertainty in estimates using this equation, +/- 20%

3. Only works for earth! Empirically determined in earth's gravity.

Slope

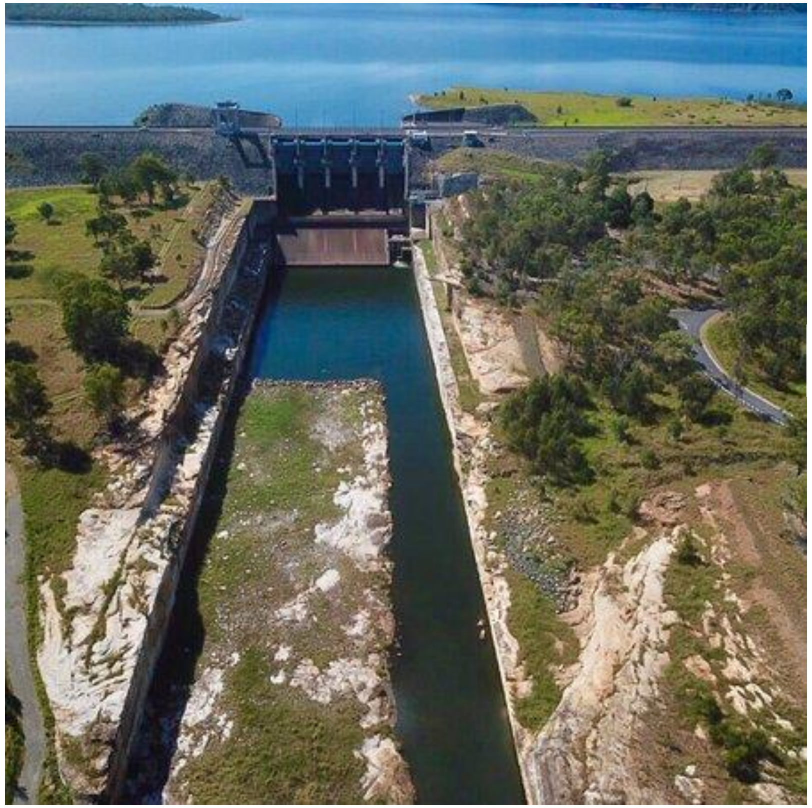
Complex channels can be treated as compound channels along their cross section. Compound channels can occur, for example, in flooded rivers, where the cross section includes a deep main channel (low n) and shallow flood plains (high n)

Example Problem 8.1

Consider a triangular irrigation channel with a bottom angle of 90° and a slope of 1:2000. If the channel is required to carry flow rates of up to 4 m^3/s, and requires a concrete lining thickness of 50 mm, how much concrete will be required to line a 500m long channel?

Example Problem 8.2

When water levels rose at the Wivenhoe Dam outside Brisbane due to a heavy rainfall in January 2011, water had to be released from the dam. This created the flooding shown in the second image below. Use these figures to estimate the discharge from the dam.



before

after

According to Manning's equation, which of the following will have the greater flow depth?

$$V = \frac{1}{n} R_h^{2/3} S^{1/2}$$

low n

high n

low S

high S

low R_h

high R_h

Rapidly varied flow

We will examine examples of OCF where the flow depth changes rapidly.

- Flow over obstacles
- Hydraulic Jumps

The Froude number is important for rapidly varied OCF

$$\mathrm{Fr} = \frac{U}{\sqrt{gh}} = \frac{\text{flow velocity}}{\text{wave speed}}$$

$\boldsymbol{Fr < 1}$**: subcritical flow**
waves can propagate upstream and downstream
$\boldsymbol{Fr > 1}$**: supercritical flow**
waves cannot propagate upstream, only downstream
$\boldsymbol{Fr = 1}$**: critical flow**
wave speed exactly matches flow velocity. waves cannot propagate upstream, only downstream

Specific Energy

We want to able to predict the depth of the flow to find out the flow rate. To do this, we will look at the specific energy (E) of the flow and how this varies with depth.

Specific energy = velocity head + elevation head

Specific Energy

We define specific energy (E) as:

Since $U = Q/bh$, this becomes:

This equation tells us how the energy in a flow varies with changing depth.

<u>Note: Q is conserved along a channel but E is not necessarily conserved</u>

- May lose E to turbulence or change in the bed height

Specific Energy Diagram

This is a graphical representation of equation 2, relating *h* to *E* in RVF

Notes on Specific Energy

Note 1: There are two limiting behaviors of specific energy:

- as depth → ∞, elevation head dominates
- as depth → 0, velocity head dominates
- There is a given depth for any flow rate that minimises the specific energy
    - This depth is called the 'critical depth'

Notes on Specific Energy

Note 2: For any given amount of specific energy, there are two possible flow depths that can be either subcritical or supercritical. It is possible for OCF to transfer from one to the other without a change in energy.

RVF Example 1: Frictionless flow over an obstacle

- Which option will the free surface take at point 2?

RVF Example 1. Real Energy vs. Specific Energy

RVF Example 1. Real Energy vs. Specific Energy

Rise in bed height requires decrease in specific energy to keep real energy constant

<u>subcritical flow: loss in elevation head</u>

<u>supercritical flow: loss in velocity head</u>

Example Problem 8.3: Flow over an obstacle

A stream approaches a 0.05 m bump at 1.2 m/s and with a depth of 0.5 m. Estimate the change in the free surface height over the bump.

In the previous example, the type of flow (supercritical or subcritical) did not change at the obstacle.
If the obstacle is large enough, however, it will trigger a spontaneous transition from subcritical to supercritical flow.

How high would the obstacle in 8.3 have to be to trigger this transition?

RVF Example 2: Hydraulic jump

A hydraulic jump is a mechanism for OCF to transition rapidly from supercritical to subcritical flow. This transition is not spontaneous, and is a response to a downstream depth requirement. Criteria for Hydraulic Jump:

1)

2)

Cause of upstream supercritical flow	Downstream depth requirement
(a) Large obstacles	(i) Flow over a weir

Cause of upstream supercritical flow	Downstream depth requirement
(b) Flow under a sluice gate	(ii) Decrease in slope
(c) Increase in slope	(iii) Increased roughness

Question: What is the depth change across a hydraulic jump?

We apply conservation of momentum in the x-direction. Note that in RVF, $L \sim O(h_2 - h_1)$ [L is small], so any forces that scale on L can be neglected

Question: How much energy is dissipated across a hydraulic jump?

How might we lose energy across a hydraulic jump?

Hydraulic jumps are often used to dissipate energy in channels to prevent damage to structures (dam spillways, for example) and excess erosion. They can also be used for chemical mixing.

Example Problem 8.4: Flow under a sluice gate

Water flows along a 25 m wide channel with a flow rate of 20 $m^3/2$ and approaches a sluice gate with a depth of 2.5 m. Determine:

(i) The flow depth to which the water will jump after the gate

(ii) The head loss across the jump