OPEN CHANNEL FLOW

An Introduction

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OUTLINE

- General characteristics
- Surface Waves & Froude Number Effects
- Types of Channel flows
- The Hydraulic Jump
- Conclusion

General characteristics

- Definition:
  - An open channel flow is the flow of a liquid in a channel or a conduit that is not completely filled.
  - A free surface exists between the flowing fluid and the fluid above it
  - The main driving force is the fluid weight. Gravity forces the fluid to flow downhill

General characteristics

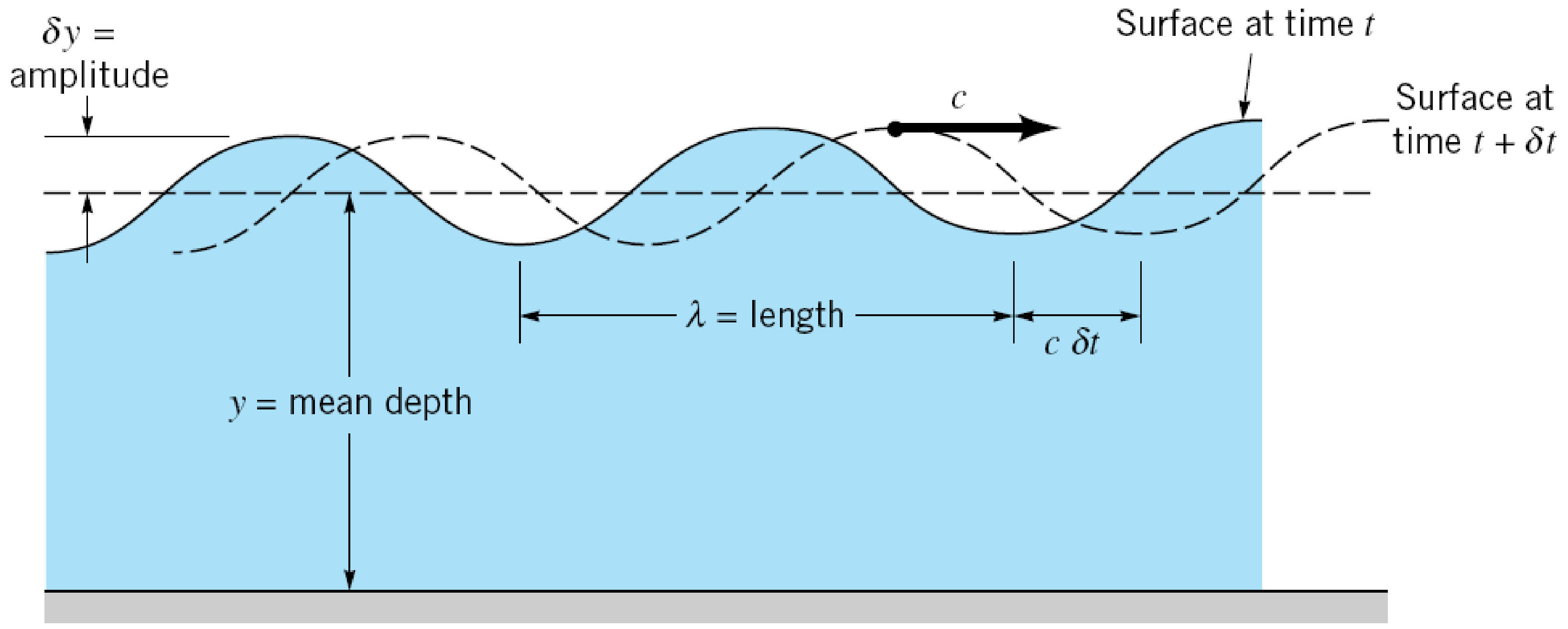
- Characteristics:
  - There can be no pressure force driving the fluid through the channel or conduit
  - The pressure distribution is merely hydrostatic (for the case of uniform steady flow)
  - The free surface allows more phenomena to take place
  - Waves cause the free surface to deform

General characteristics

- Characteristics:
  - Waves move across the surface at speeds depending on their size and the properties of the channel
  - The character of a given channel flow depends on the relative speeds of the waves and the flow field

Surface Waves & Fr Effects

- Surface waves:



Surface Waves & Fr Effects

- Speed
  - From an advanced analysis, the wave speed is given by:

$$c = \left[\frac{g\lambda}{2\pi} \tanh\left(\frac{2\pi}{\lambda} \right) \right]^{1/2}$$

$$\lambda = \text{Wave Length}$$

$$\text{g} = \text{Acceleration of Gravity}$$

Surface Waves & Fr Effects

- Speed
  - There are many occasions for which this relation simplifies:
    - When the water depth is much larger than the wave length then:

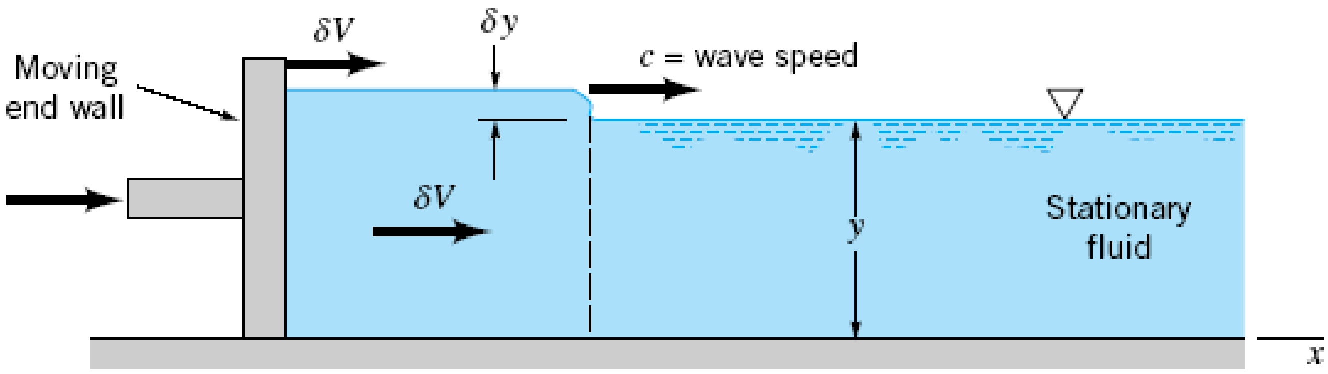
$$c = \sqrt{\frac{g\lambda}{2\pi}}$$

    - When the water depth is much smaller than the wave length, then:

$$c = \sqrt{gy}$$

Surface Waves & Fr Effects

- The Froude Number



Surface Waves & Fr Effects

- The Froude Number
  - Consider a wave moving with speed c with respect to the fluid. Three cases arise:
    - The fluid is stationary so that $V=0$
      Then the wave spreads equally in all directions
    - The fluid is moving with speed $V < c$
      Then the wave moves upstream & upstream locations are said to be in hydraulic communication w/t downstream locations
    - The fluid is moving with speed $V > c$
      Then the wave will be washed away & there is no upstream communication w/t downstream locations

Surface Waves & Fr Effects

- The Froude Number
  - All these effects can be defined by the use of the Froude number:

$$Fr = \frac{V}{\sqrt{gy}} = \frac{V}{c}$$

    - If Fr < 1 → Subcritical flow
    - If Fr >1 → Supercritical flow
    - If Fr ~ 1 → critical flow

Types of channel flows

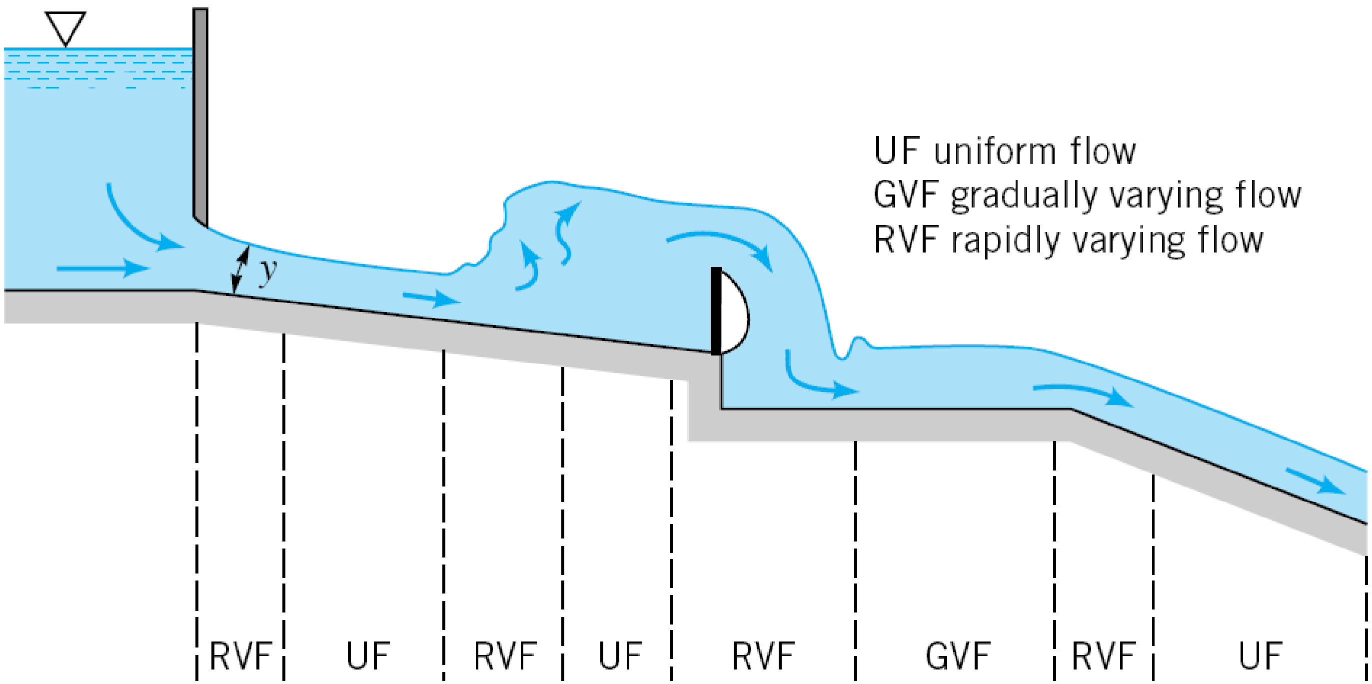
- The most widely used classification of channel flows is as follows:
  - Uniform Flow
  - Gradually varying flow
  - Rapidly varying flow

Types of channel flows

UF: dy/dx = 0

GVF: dy/dx << 1

RVF: dy/dx ~ 1



Types of channel flows

- Unifrom Flow:
  - Unifrom flow is achieved through a balance between the potential energy lost by the fluid as it flows downhill and the energy that is dissipated through viscous effects
  - Examples include:
    - Irrigation canals
    - Natural channels
    - Drainage systems
  - Movie 1
  - Movie 2

Types of channel flows

- Gradually Varying Flow:
  - Gradually varying channel flows occur for many reasons:
    - The bottom slope is not constant
    - The X-section shape varies
    - The X-section area varies
    - Some obstacle along the channel

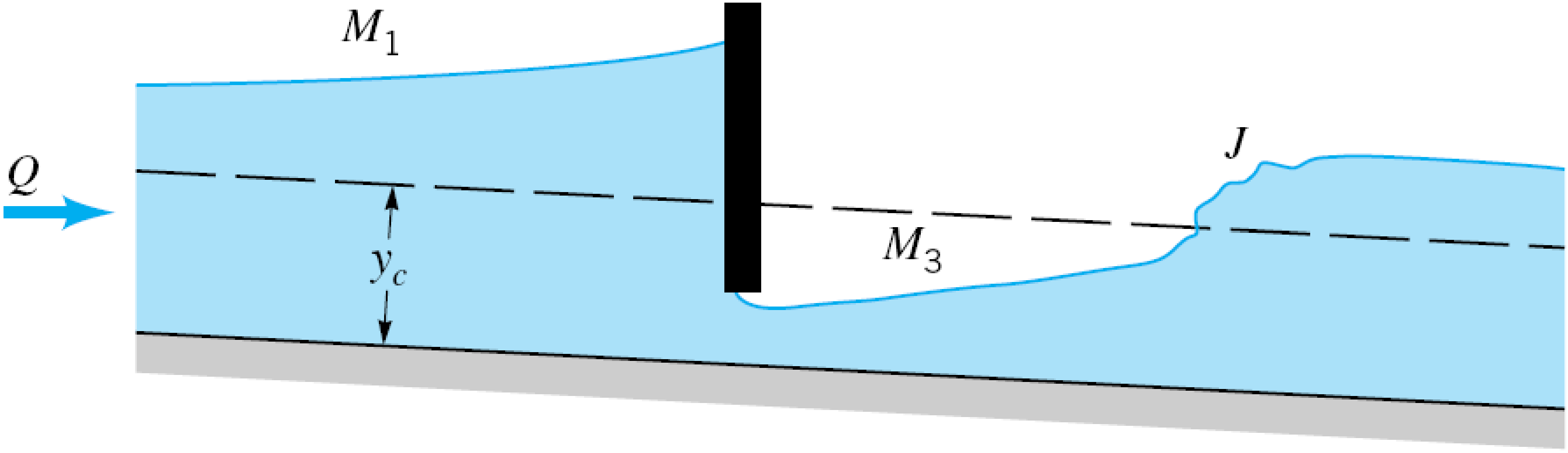
Types of channel flows

- Gradually varied flow is classified according to the value of the channel slope as compared to the slope needed to produce uniform critical flow. Below is such a classification

Slope Type	Slope Notation	Froude No.	Surface Shape Designation
$S_0 < S_{0c}$	Mild (M)	Fr $<$ 1	M-1
		Fr $<$ 1	M-2
		Fr $>$ 1	M-3
$S_0 = S_{0c}$	Critical (C)	Fr $<$ 1	C-1
		Fr $>$ 1	C-3
$S_0 > S_{0c}$	Steep (S)	Fr $<$ 1	S-1
		Fr $>$ 1	S-2
		Fr $>$ 1	S-3
$S_0 = 0$	Horizontal (H)	Fr $<$ 1	H-2
		Fr $>$ 1	H-3
$S_0 < 0$	Adverse (A)	Fr $<$ 1	A-2
		Fr $>$ 1	A-3

Types of channel flows

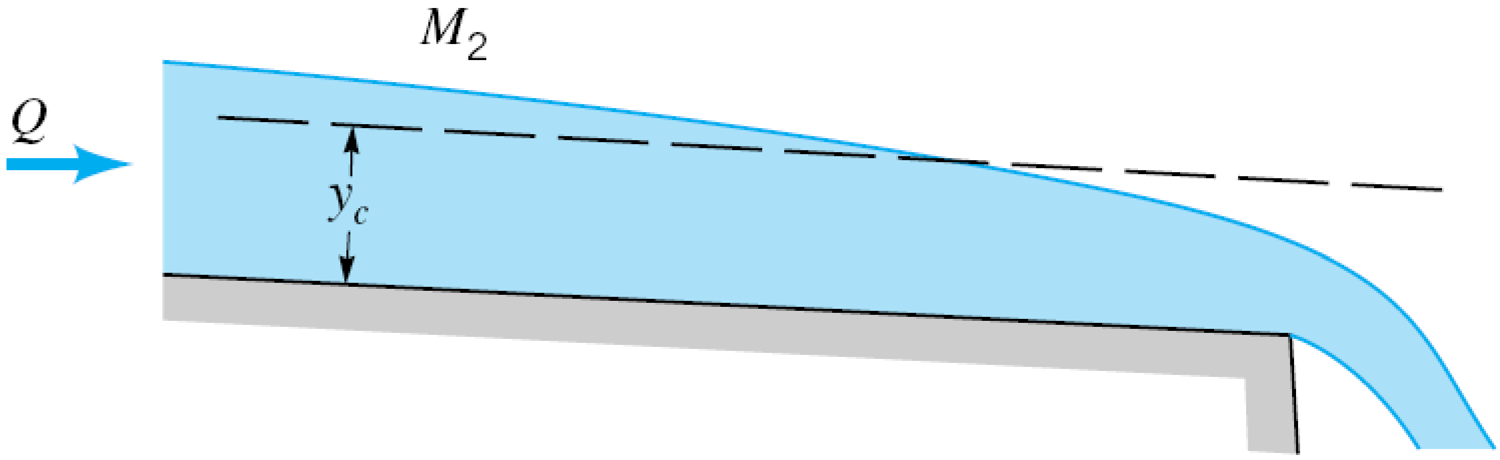
- Gradually Varying Flow:



Mild Slope

Types of channel flows

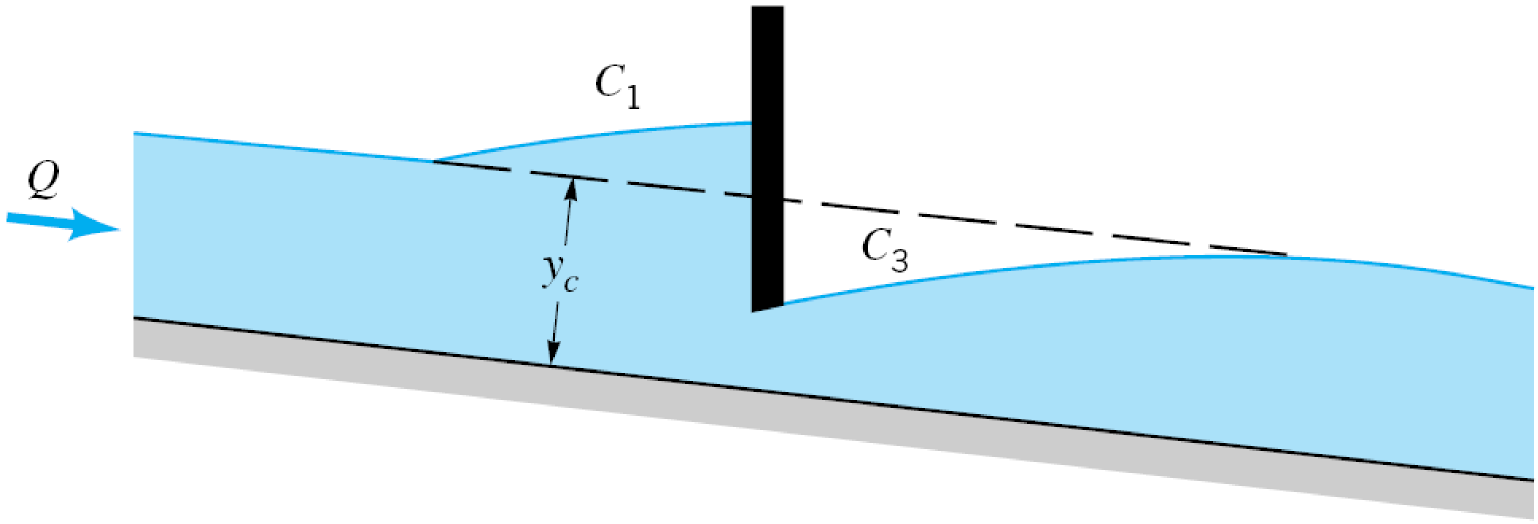
- Gradually Varying Flow:



Mild slope

Types of channel flows

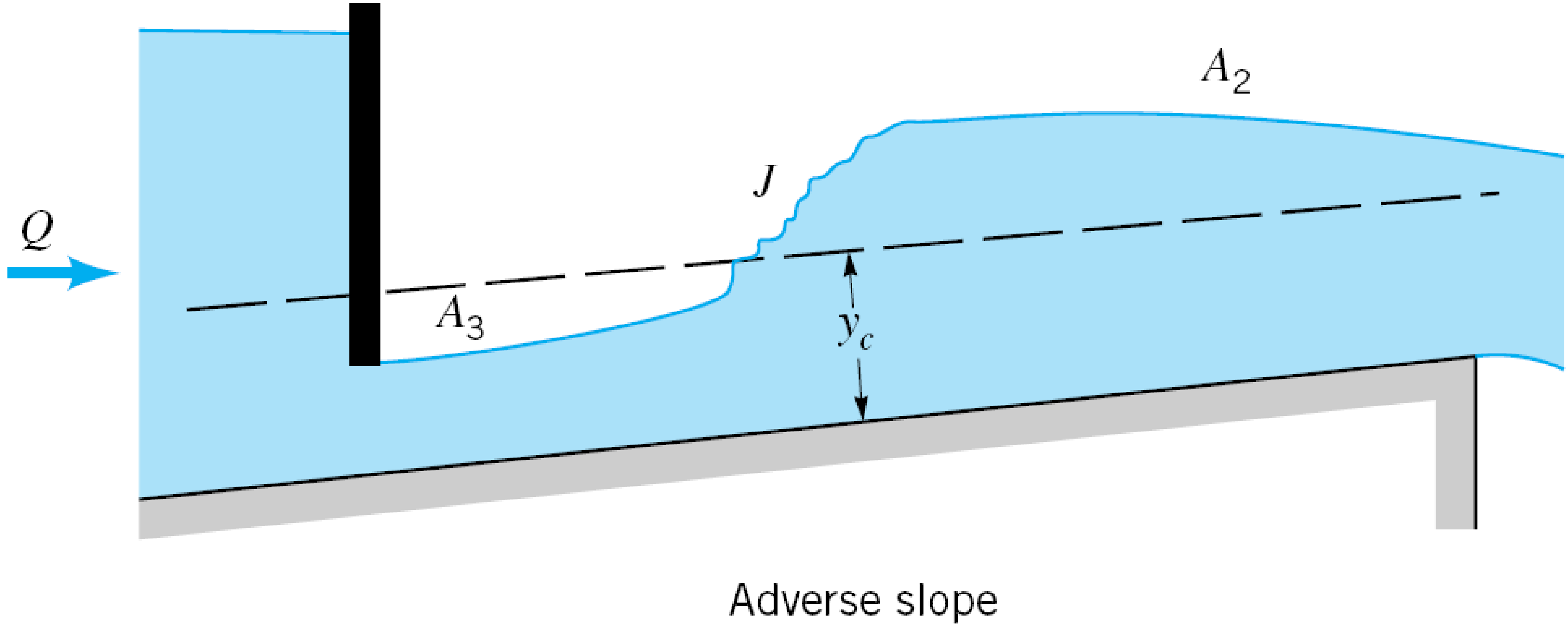
- Gradually Varying Flow:



Critical slope

Types of channel flows

- Gradually Varying Flow:



Types of channel flows

- Rapidly Varied Flow
  - These occur when the change in fluid depth is significant along a very small distance
  - RVF's are very complex to model & occur in many situations:
    - Constant area channel flows (Hydraulic jump)
    - Sudden change in channel geometry (expansion or contraction of cross section)

Types of channel flows

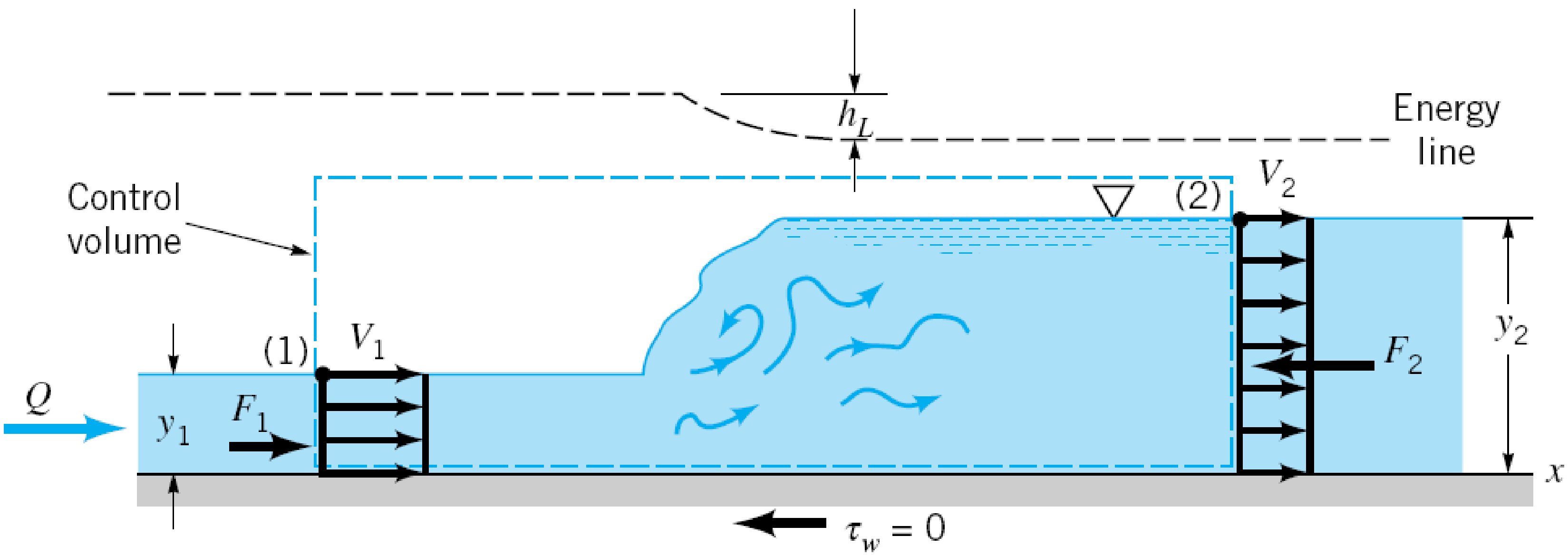
- Rapidly Varied Flow
  - Three dimensional in general
  - Any model must account for the effects of the dimensionality of the flow
  - Erosion of channel bottom

The Hydraulic Jump

- The change in slope is always upward,never downward
- Movie

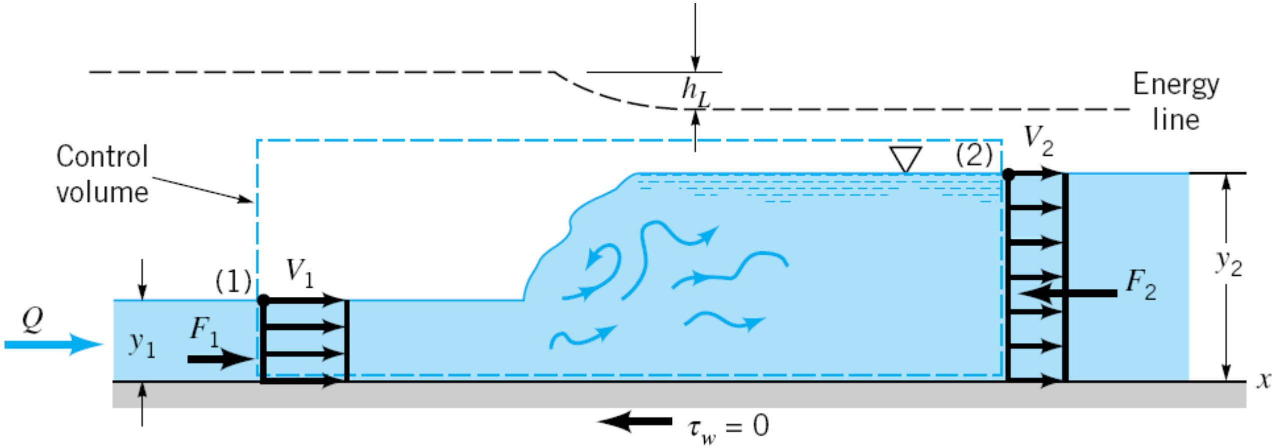
The Hydraulic Jump

- Meaning: When there is a “conflict” between the upstream & downstream influences that control a certain location in the channel
- The simplest HJ occurs in a horizontal rectangular channel



The Hydraulic Jump

- Application of the momentum equation, conservation of mass, and conservation of energy on the previous control volume yields:



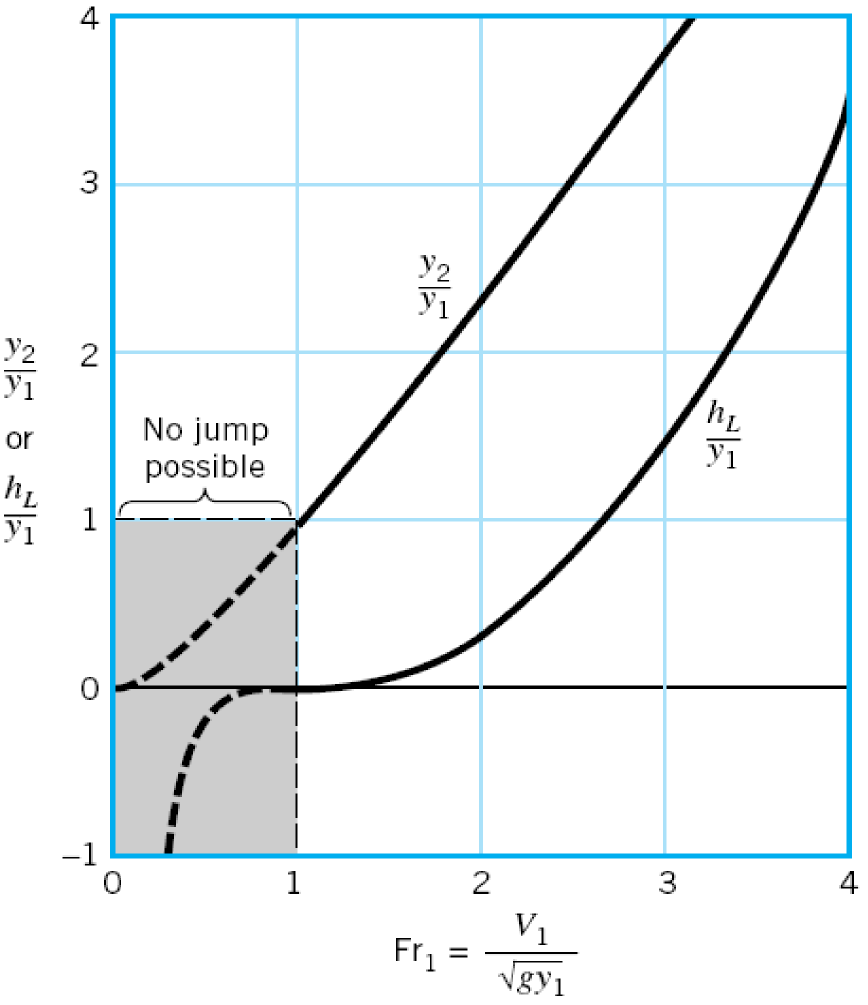
$$\frac{y_1^2}{2} - \frac{y_2^2}{2} = \frac{V_1 y_1}{g}(V_2 - V_1) \qquad y_1 b V_1 = y_2 b V_2 = Q \qquad y_1 + \frac{V_1^2}{2g} = y_2 + \frac{V_2^2}{2g} + h_L$$

The Hydraulic Jump

- The trivial solution is when y1 = y2, V1 = V2 and HL = 0 and thus no hydraulic jump is possible
- However, since the previous equations are nonlinear, we note that these yield various possible solutions. By mathematically manipulating the equations we can reach the following form:

$$\frac{y_2}{y_1} = \frac{1}{2}\left(-1 + \sqrt{1 + 8\mathrm{Fr}_1^2}\right)$$

The Hydraulic Jump

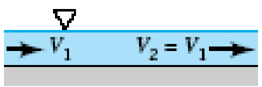
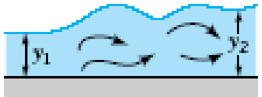
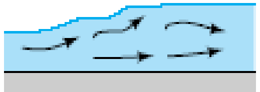
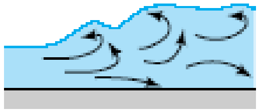
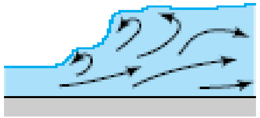
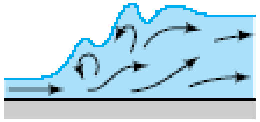


- Depth ratio and dimensionless head loss as a function of Froude number

The Hydraulic Jump

- We cam further classify hydraulic jumps according to the following

Classification of Hydraulic Jumps (Ref. 12)

Fr_1	y_2/y_1	Classification	Sketch
<1	1	Jump impossible	
1 to 1.7	1 to 2.0	Standing wave or undulant jump	
1.7 to 2.5	2.0 to 3.1	Weak jump	
2.5 to 4.5	3.1 to 5.9	Oscillating jump	
4.5 to 9.0	5.9 to 12	Stable, well-balanced steady jump; insensitive to downstream conditions	
>9.0	>12	Rough, somewhat intermittent strong jump	

Conclusion

- The froude number requirement does not always guarantee the creation of a hydraulic jump. The trivial solution can always exist
- Open channel flows are very complex to model
- An open channel flow is usually solved by bisecting the channel into several sections where the flow can be correctly described as being UF, GVF or RVF
- Turbulence effects should also be included in the analysis
- …and so on…