ARTIFICIAL CHANNEL CONTROLS

Fitsume T.

Artificial channel controls

- Weir
- Spillway
- Gate
- Venturi flume

Weir

A weir is a structure that built across a channel to raise the level of water with the water flowing over it.

Classification

- Shape of the opening (rectangular, triangular, trapezoidal, …)
- Shape of the edge (sharp crested ,broad crested)
- Discharge conditions (free or submerged)
- End conditions (contracted or suppressed)

Weir; The Sharp-Crested Weir

- The sharp-crested weir also known as **a notch or a thin plate** weir
- The sharp-crested weirs are extensively used for precise **flow measuring device** in laboratories, industries, and irrigation fields.
- The sharp-crested weir is not only a measuring device for open-channel flow but also the use as **simplest form of overflow spillway.**
- The characteristics of flow over a weir is recognized as the basis of design
- The profile of the spillway was determined in conformity with the shape **of the lower surface of the flow over a sharp-crested weir**

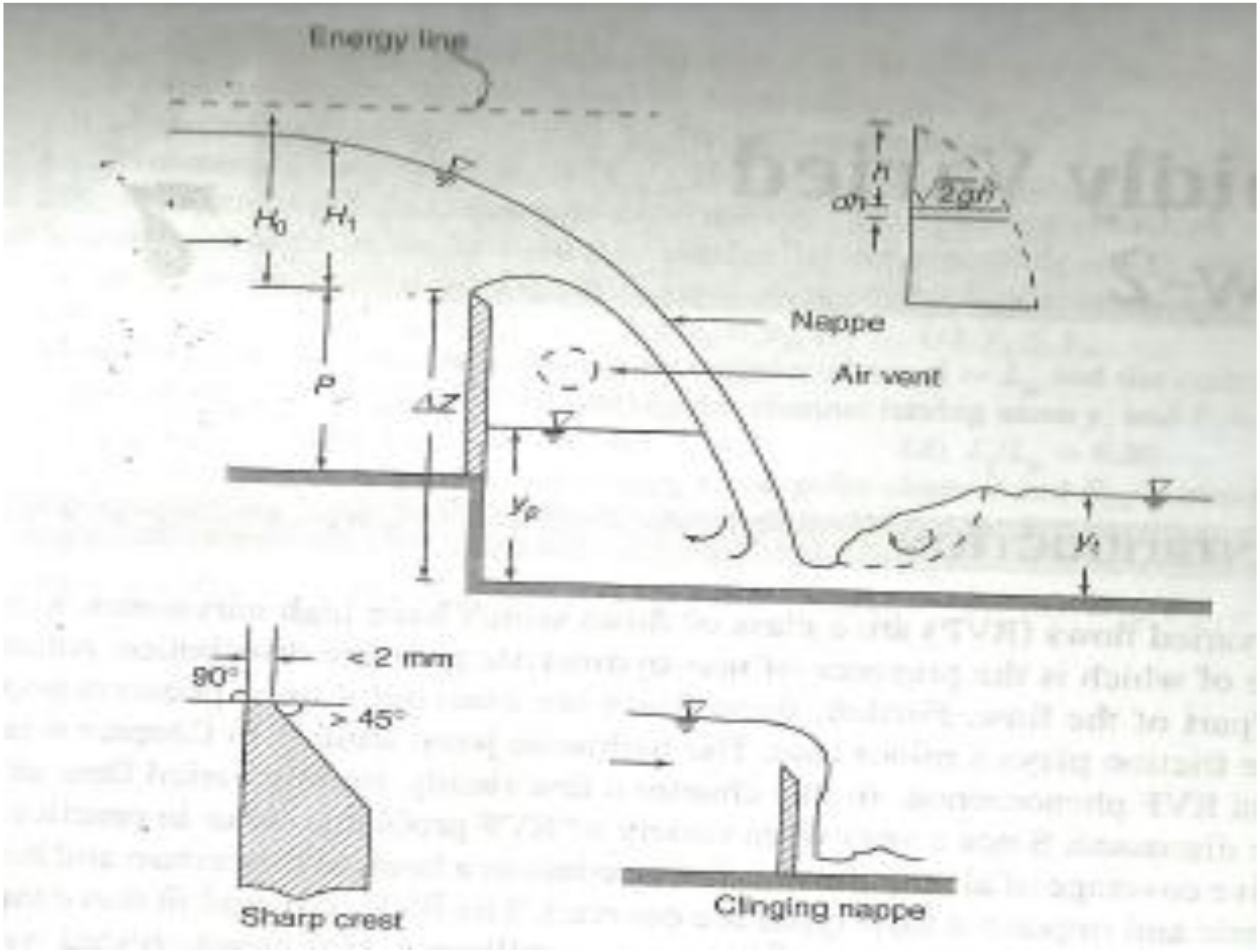
Note

Derivation of discharge relation is based on

- *Uniform approach velocity distribution*
- *Pressure under the nappe is atmospheric*
- *Stream lines over the crest are horizontal (so pressure with in the nappe is zero)*
- *The effect of Viscosity is negligible*

To account for these simplifications C_d (coefficient of discharge is introduced)

Rectangular Sharp-Crested Weir



Rectangular Sharp-Crested Weir

- **Discharge Equation**
  - Consider an ideal un-deflected jet and then apply a coefficient of contraction to account for the deflection due to the action of gravity.
  - For rectangular weir of length L spanning the full width B of the rectangular channel (i.e., L=B),

$$dQ_i = L\sqrt{2gh}dh \qquad Q_i = L\sqrt{2g}\int_{\frac{V_0^2}{2g}}^{H_1+\frac{V_0^2}{2g}} \sqrt{h}dh$$

  - And taking the C_c as the coefficient of contraction and the actual discharge $Q = C_c Q_i$

$$Q = \frac{2}{3}C_c\sqrt{2g}L\left[\left(H_1 + \frac{V_0^2}{2g}\right)^{3/2} - \left(\frac{V_0^2}{2g}\right)^{3/2}\right]$$

  - If we expressed the discharge equation in terms of H_1, the depth of flow upstream of the weir measured above the weir crest as

$$Q = \frac{2}{3}Cd\sqrt{2g}LH_1^{3/2} \qquad C_d = C_c\left[\left(1+\frac{V_0^2}{2gH_1}\right)^{3/2} - \left(\frac{V_0^2}{2gH_1}\right)^{3/2}\right]$$

  - Where Cd = coefficient of discharge which takes into account the velocity of approach V_0 and given by $C_d = 0.611 + 0.08\frac{H_1}{P}$ valid for $H_1/P \le 5.0$

Rectangular Sharp-Crested Weir

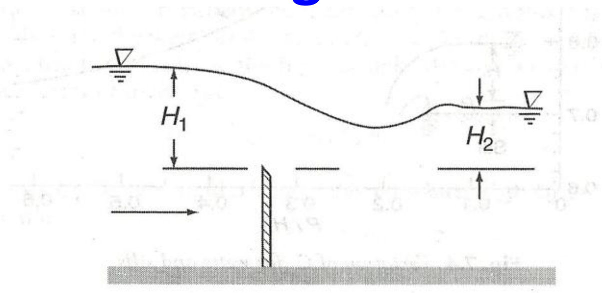
- **Sills**
  - For very small values of P relative to H_1, i.e., for $H_1/p > 20$, the weir acts as a sill, in which the critical depth occurs and termed as sill.

$$Q = B\sqrt{g}\left(H_1 + P\right)^{3/2} = \frac{2}{3}C_d\sqrt{2g}LH_1^{3/2} \text{\_\_\_\_\_\_}, L = B$$

$$H_1 + P = y_c = \left(\frac{Q^2}{gB^2}\right)^{1/3}$$

$$C_d = 1.06\left(1 + \frac{P}{H_1}\right)^{3/2}$$

- **Submergence**



$$Q_s = Q_1\left[1 - \left(\frac{H_2}{H_1}\right)^n\right]^{0.385}$$

- Where Q_1 = free-flow discharge under H_1
- n = exponent of head in the head-discharge relationship $Q= KH^n$.
- For rectangular weir n= 1.5

- **Aeration Need of Rectangular Weir**

$$\frac{Q_a}{Q} = \frac{0.1}{\left(y_p / H_1\right)^{3/2}}$$

$$y_p = \Delta Z\left[\frac{Q_2}{L^2 g\left(\Delta Z\right)^3}\right]^{0.22}$$

Rectangular Sharp-Crested Weir

- **Contracted Weir**
  - When the length of the weir (L) is smaller than the Width the channel
    - The effective weir width reduced
    - the discharge from the contracted weir can be obtained by using effective length (Le)

$$L_e = L - 0.1nH_1$$

n = number of contractions

$$Q = \frac{2}{3} C_d \sqrt{2g} L_e H_{1e}^{3/2}$$

$H_{1e} = H_1 + K_H$

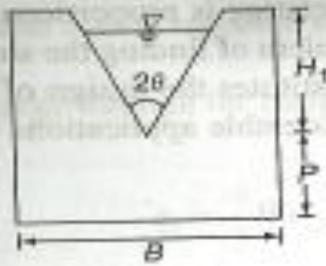
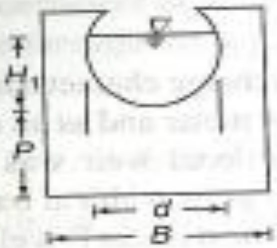
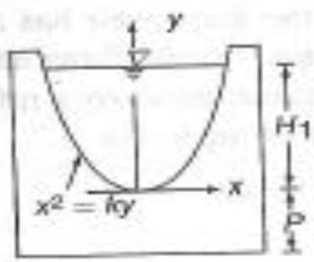
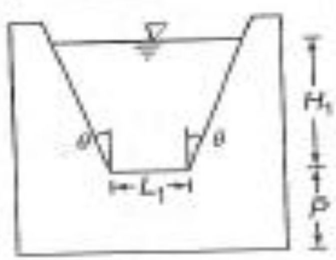
Kh is introduced to account for viscosity and surface tension


2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
50
0

Example 1:

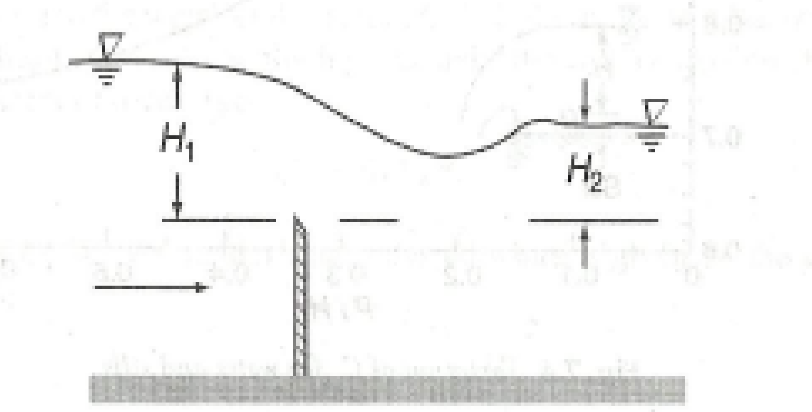
A 2.5m wide rectangular channel has a rectangular weir spanning the full width of the channel. The weir height is 0.75m measured from the bottom of the channel. What discharge is indicated when this weir is working under submerged mode with depths of flow, measured above the bed channel of 1.75m and 1.25m on the upstream and downstream of the weir respectively

Non-Rectangular Sharp-Crested Weir

Shape		Discharge
Triangular		$Q = \frac{8}{15} C_d \sqrt{2g}\ \tan\theta\, H_1^{5/2}$ $C_d = fn(\theta)$ For $2\theta = 90^\circ, C_d = 0.58$
Circular		$Q = C_d\, \phi\, d^{2.5},\ \phi = f(H_1/d),\ C_d = f(H_1/d)$
Parabolic		$Q = \frac{1}{4} \pi C_d \sqrt{k} \sqrt{2g}\, H_1^2$
Trapezoidal		$Q = \frac{2}{3} C_d \sqrt{2g}\, H_1^{3/2} \left(L_1 + \frac{4}{5} H_1 \tan\theta\right)$

Broad-Crested Weir

- Weirs with a finite crest width in the direction of flow are called broad-crested weirs
- They have extensive applications as control structures and flow measuring devices
- Practically impossible to generalize their behavior because of a wide variety of crest cross-sectional shapes of the weirs
- Take the example of a free flow over a horizontal broad-crested weir in a rectangular channel



Broad-Crested Weir

- This weir has a sharp upstream corner which causes the flow to separate and then reattach enclosing a separation bubble
- If we keep the sufficiently long width (B_w), the curvature of the stream lines will be small and keep hydrostatic pressure distribution
- The weir serves as inlet of subcritical flow at the upstream of the weir and supercritical flow over it.
- A critical depth control section will occur at the upstream end, in most probably at a location where the bubble thickness is maximum
- Assuming no loss of energy between section 1 and section 2 and also the depth of flow at section 2 to be critical

$$H = y_c + \frac{V_c^2}{2g} = \frac{3}{2} y_c$$

$$V_c = \sqrt{g y_c} \quad \text{and} \quad y_c = \frac{2}{3} H$$

$$q_t = V_c y_c = \frac{2}{3} \sqrt{\left(\frac{2}{3} g\right)} \; H^{3/2} = 1.705 \; H^{3/2}$$

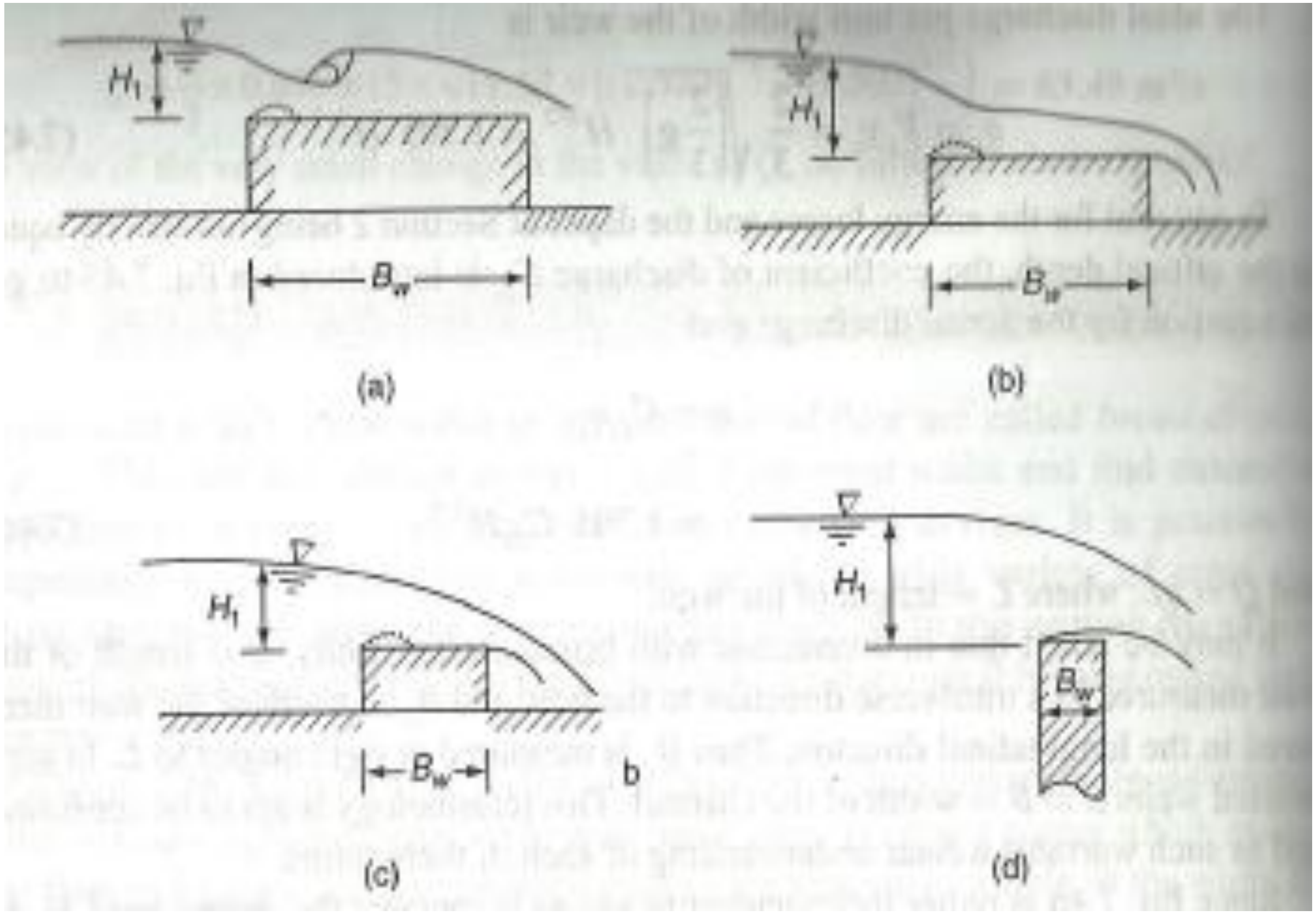
$q = C_{d1} q_t = 1.705 C_{d1} H^{3/2}$

and Q= qL, where L = length of the weir

Classification of Weir

- **Long-crested weir ($H_1/B_w \leq 0.1$)**
  - The critical flow control section is at downstream end of the weir and
  - the resistance of the weir surface plays as important role in determining the value of C_d **$C_d = 0.561(H_1/B_w)^{0.222}$**
- **Broad-Crested weir ($0.1 \leq H_1/B_w \leq 0.35$)**
  - The critical depth control occurs near the upstream end of the weir and the discharge coefficient varies slowly with H_1/B_w. **$C_d = 0.028(H_1/B_w)+0.521$**
- **Narrow-Crested Weir ($0.35 \leq H_1/B_w \leq 1.5$)**
  - The water surface profile will be curvilinear all over the weir. The control section will be at the upstream end. The upper limit of this range depends upon the value of H1/P **$C_d = 0.12(H_1/B_w)+ 0.492$**
- **Sharp-Crested weir ($H_1/B_w \geq 1.5$)**
  - The flow separates at the upstream corner and jumps clear across the weir crest. The flow surface is highly curved.

Classification of Weir



$$C_d = \frac{Q}{\frac{2}{3}\sqrt{2g}\, L H_1^{3/2}} \text{ and } C_{d1} = \frac{Q}{1.705\, L H^{3/2}}$$

Flow over Spillway

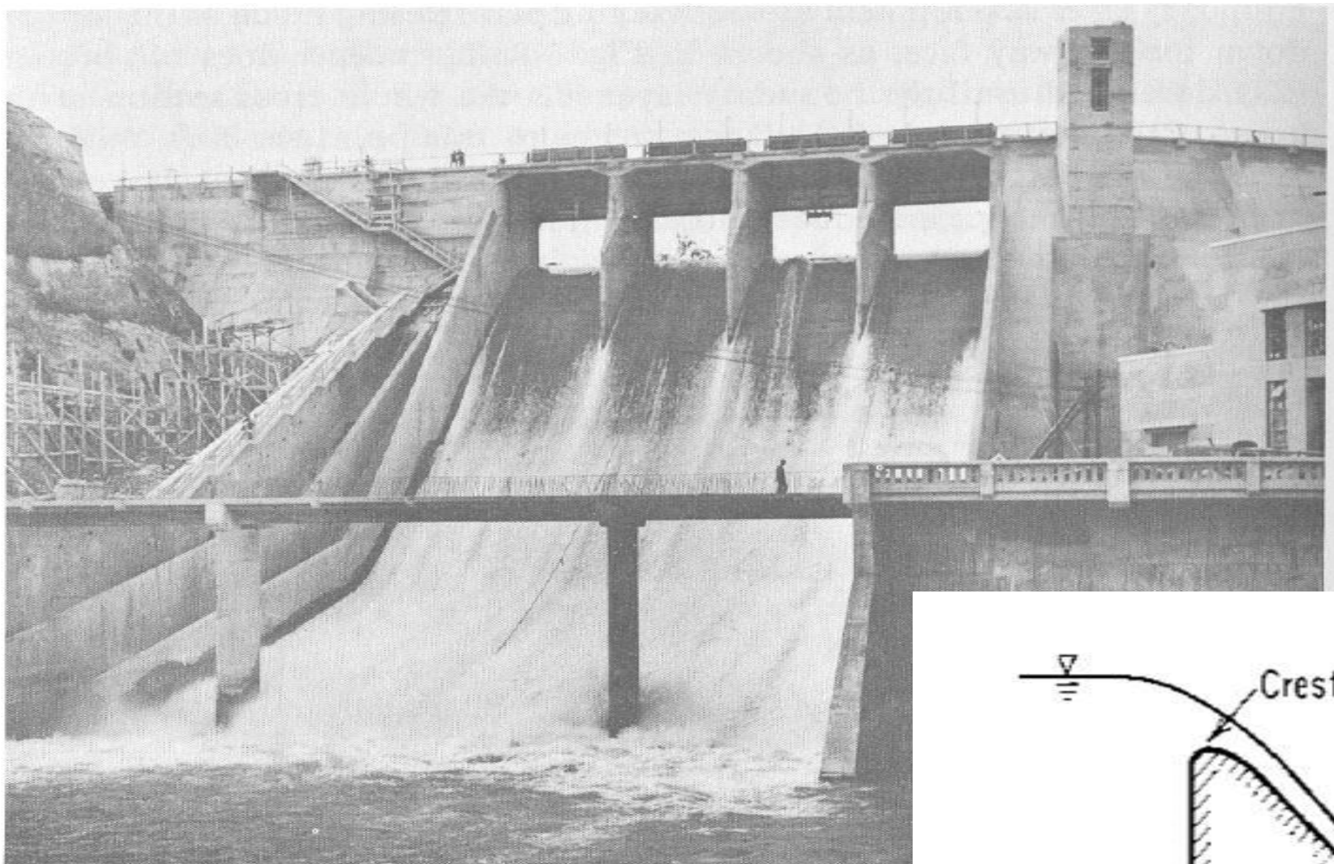
- **Spillways:**
  - Is a structure constructing for safe disposal of excess water from a dam or a weir
  - It can be constructed on the dam or one end of the dam or total away from the dam structure
  - It should be designed as structural and hydraulically adequate
  - The discharge capacity should be estimate effectively otherwise
    - If it underestimates, lead for the overtopping of the dam and structural lose
    - If it overestimated, raise the cost of the construction

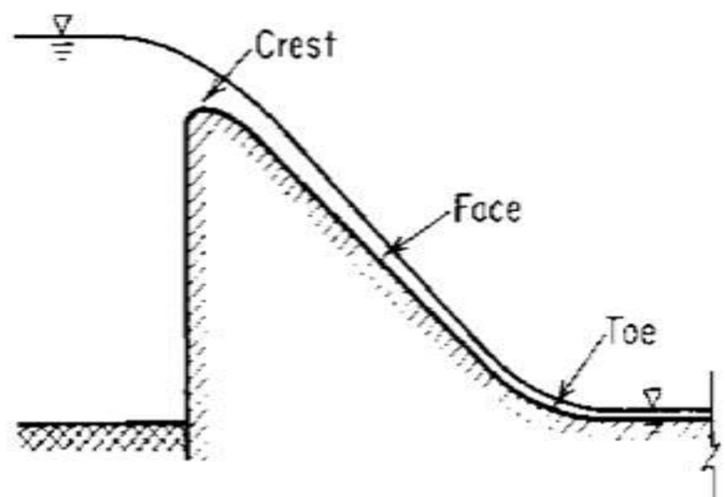
Flow over Spillway

Types of Spillways

- Based on the structure
  - Straight Drop spillway
  - **Overflow (ogee) spillway**
  - Chute spillway (Through or open channel spillway)
  - Side channel spillway
  - Shaft spillway
  - Siphon spillway
- Based on the availability of gate
  - Controlled spillway
  - Uncontrolled spillway

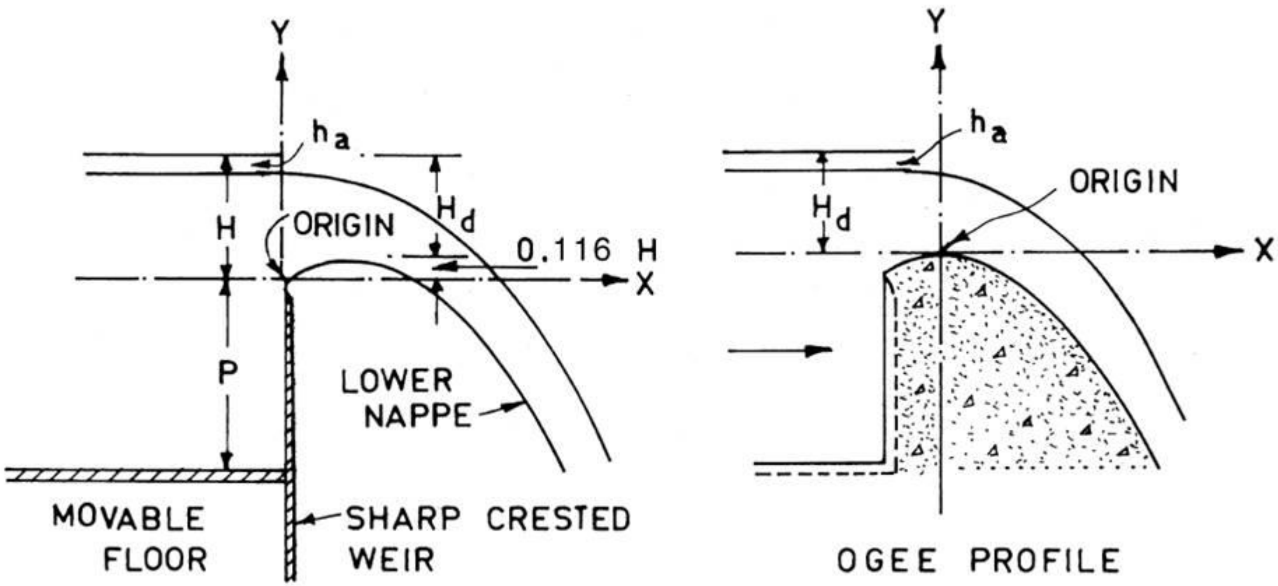
Ogee Spillway





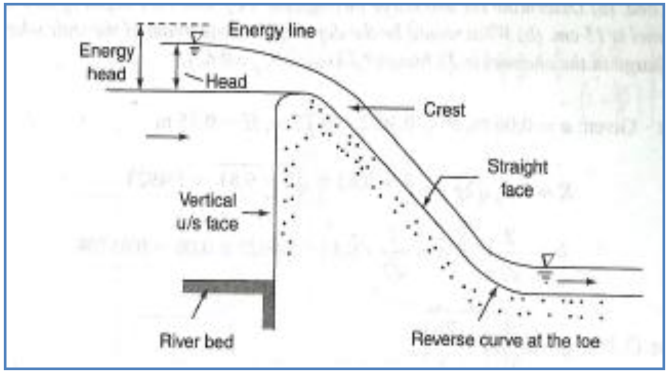
(c) General view

Ogee Vs sharp crested profile



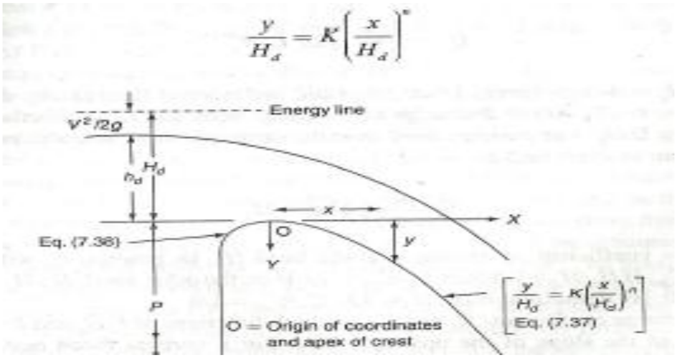
Ogee Spillway

- The ogee spillway is also known as ***Overflow Spillway***
- It is a control weir having an ogee (S-shaped) overflow profile
- It is the most extensively used spillway to safely pass the flood flow out of a reservoir
- The profile assures for the ***design head***, a ***high discharge coefficient***, and at the same time ***atmospheric pressure*** on the weir
- The crest profile of the spillway is so chosen without causing dangerous cavitations condition and vibrations Thus
- The heads smaller than the design head cause small trajectories and hence result in positive pressures and lower discharge coefficients $\Rightarrow$ ***cavitations'***
- For the heads higher than the design head, the lower nappe trajectory tends to pull away from the spillway surface and hence negative pressure and higher discharge coefficient $\Rightarrow$ ***vibrations***



Design of Ogee Spillway

- **Downstream crest**
  - It is extensively studied
  - It need accurate data for the nappe profile and discharge coefficient
  - The profile of the crest downstream of the apex can be expressed as



Upstream face	K	n
Vertical	0.500	1.850
1H:1/3V	0.517	1.836
1H:1V	0.534	1.776

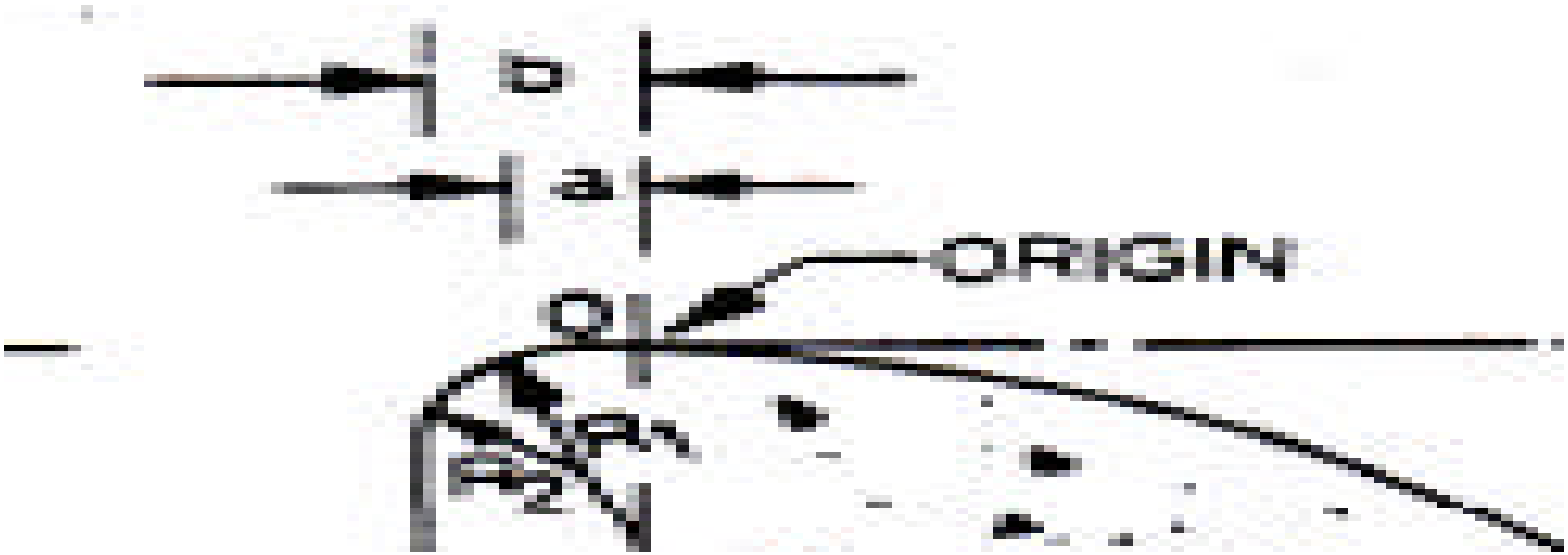
  - The above Equation is applicable only for the positive values of x and y,

- **Crest Profile**
  - Usually given a series of compound curves
  - Cassidy reported the equation for the upstream portion of a vertical faced spillway as

$$\frac{Y}{H_d} = 0.724\left(\frac{X}{H_d} + 0.270\right)^{1.85} - 0.432\left(\frac{X}{H_d} + 0.270\right)^{0.625} + 0.126$$

For the region $-0.270 \leq \frac{x}{H_d} \leq 0.126$

U/s face



U/s Slope	a/Hd	b/Hd	R1/Hd	R2/Hd
Vertical	0.175	0.282	0.5	0.20
1:3 (H:V)	0.139	0.237	0.68	0.21
2:3 (H:V)	0.115	0.214	0.48	0.27
3:3 (H:V)	0	0.199	0.45	

Design of Ogee Spillway

- Discharge

$$Q_d = \frac{2}{3} C_{d0} \sqrt{2g} L_e H_d^{3/2}$$

In which H_d = design-energy head (i.e., head inclusive of the velocity of approach head), C_{d0} = coefficient of discharge at the design head and Le = effective length of the spillway.

If h > 1.33 H_d then C_{do} = 2.2

If H_0 = any energy head over the ogee spillway, the corresponding discharge Q can be expressed as

$$Q = \frac{2}{3} C_0 \sqrt{2g} L_e H_0^{3/2}$$

Where C_0 = coefficient of discharge at the head H_0.

In general, C_0 will be different from C_{d0}. If $H_0/H_d > 1$ then $C_0/C_{d0} > 1.0$

Coefficient of Discharge Co

- Ogee spillway has a relatively high value of the coefficient of discharge (Co) because of its shape. The maximum value of Co is about 2.20, if no negative pressure occurs on the crest. However, **the value of Co is not constant**. It depends upon the shape of the ogee profile, and also upon the following factors:

    i. Depth of approach/ Height of spillway crest above the stream bed

    ii. Ratio of actual total head to the design total head.

    iii. Slope of the upstream face of spillway

    iv. Extent of the downstream submergence of crest

Design of Ogee Spillway

Effective Length (Le) of Ogee Spillway

$$L_e = L - 2\left[K_p * N + K_a\right]H_e$$

Where L = the net clear length of the spillway crest

Kp = pier construction coefficient

Ka = Abutment contraction Coefficient

N= number of piers

He = Total head

Kp and Ka mainly depend on the shape of the piers and abutments

Square piers K_p =0.1

Round nose piers k_p =0.01

Pointed nose pire k_p = 0

Square abutment, ka = 0.2

Rounded abutment, ka = 0.1

Example

- Design an ogee spillway with the following data
- Height of spillway crest above river bed=100m
- Number of spans =6
- Clear distance b/n piers =15m
- Thickness of square nosed pier=3m
- Square nosed abutments
- Slope of downstream face of over flow section=0.8H:1V
- Vertical u/s face
- Discharge coefficient

$$C_d = 0.745$$

$$C = \frac{2}{3} C_d \sqrt{2g} = 2.2$$

Critical depth flumes

- A free flowing critical depth or standing wave flume is essentially a streamlined constriction built in an open channel where a sufficient fall is available so that critical flow occurs in the throat of the flume.
- The channel constriction by both side and/or bottom contractions.

$$Q = C_0 h^n$$

Critical depth flumes

- where 'C_0' is a coefficient depending on the breadth (b) of the throat, on the velocity head $V^2/2g$ *at the head measurement section, and on those factors which influence* the discharge coefficient;
- 'h' is the piezometric level over the flume crest at a specified point in the converging approach channel and
- n is a factor usually varies between 1.5 and 2.5 depending on the geometry of the control section.

Examples **Critical depth flumes**

1. The critical depth flumes are

(i) Long throated flumes.

(ii) Throatless flumes with rounded.

(iii) Throatless flumes with broken phase transition.

(iv) Parshall flume.

(v) H flumes

(vi) Venturi flume with sub critical constriction.

Culvert Hydraulics

- **Key Hydraulic Principles**

(Manning's, continuity and energy equations)

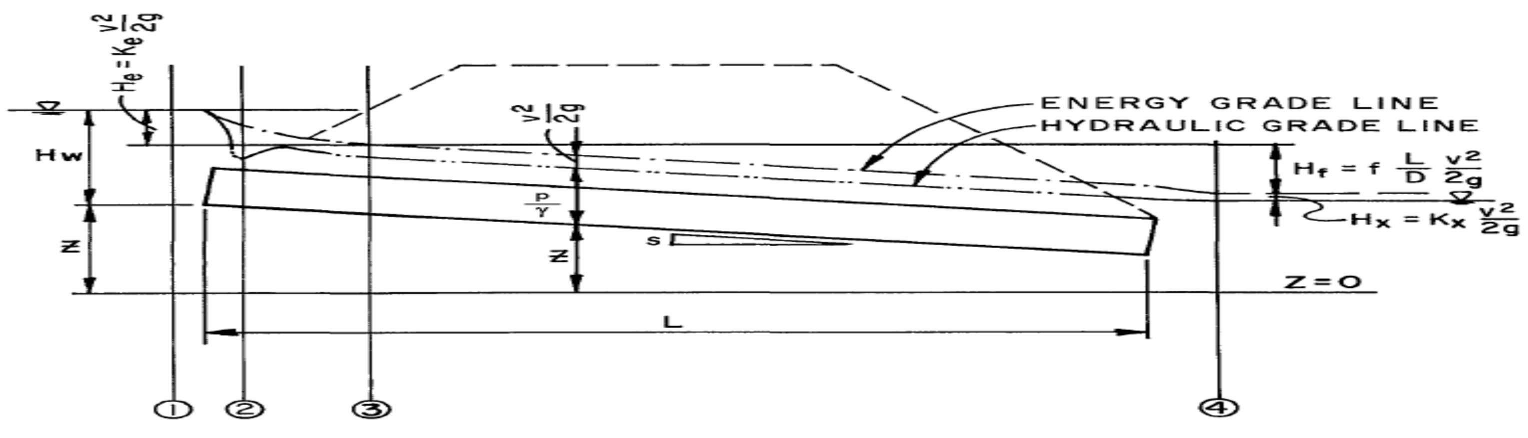
$$Q = \frac{1.49}{n} A R^{2/3} S^{1/2}$$

$$Q = v_1 A_1 = v_2 A_2$$

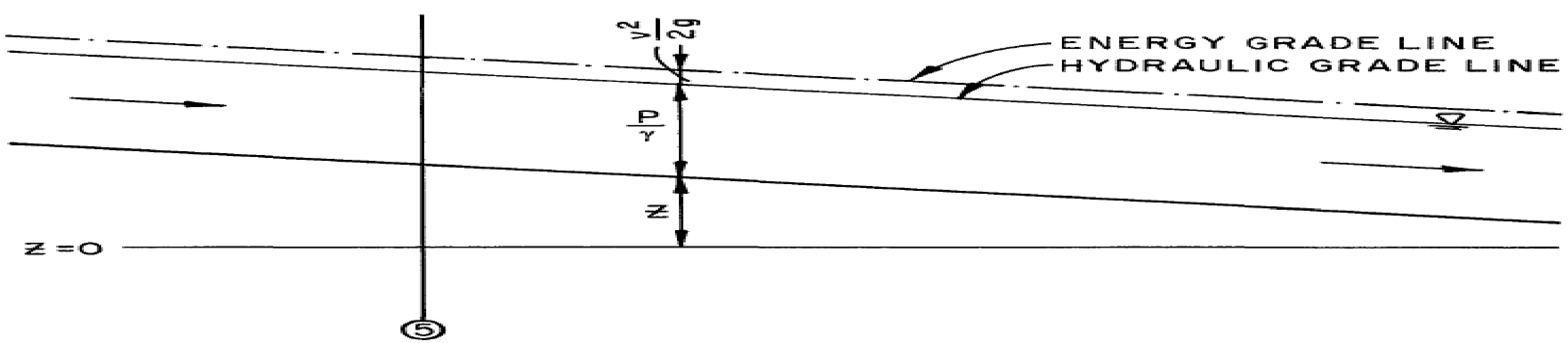
$$\frac{v^2}{2g} + \frac{p}{\gamma} + z + \text{losses} = \text{constant}$$

- **Energy and Hydraulic Grade Lines**

Closed Channel



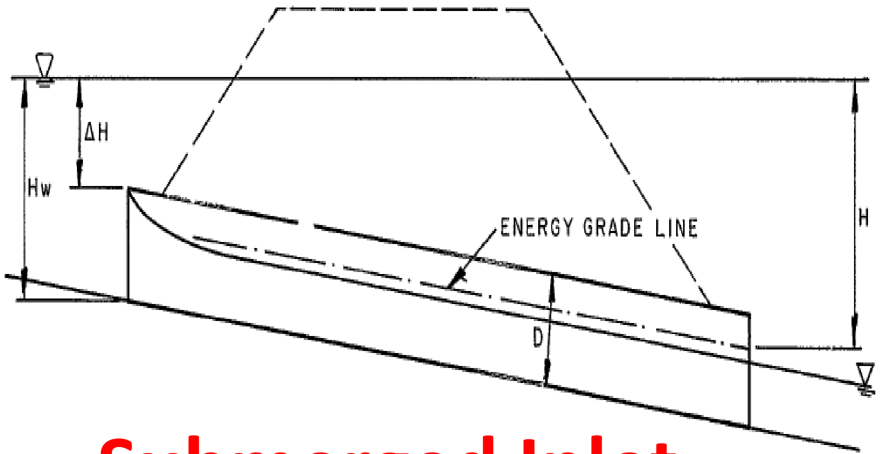
Open Channel



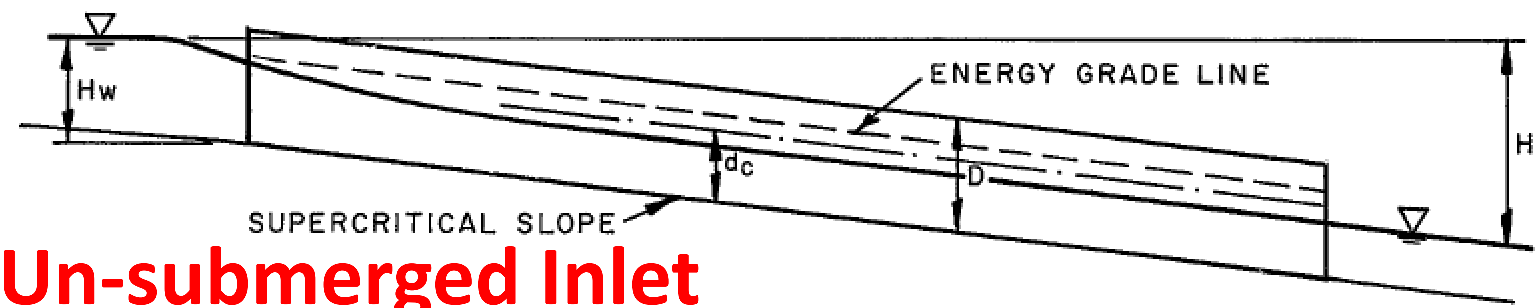
Inlet Control

A culvert operates with inlet control when the flow capacity is controlled at the entrance by these factors:

- Depth of headwater
- Cross-sectional area
- Inlet edge configuration
- Barrel shape



Submerged Inlet



Un-submerged Inlet

Outlet Control

If the headwater is high enough, the culvert slope sufficiently flat, and the culvert sufficiently long, the control will shift to the outlet.

In outlet control, the discharge is a function of the inlet losses, the headwater depth, the culvert roughness, the culvert length, the barrel diameter, the culvert slope, and sometimes the tail water elevation.

In outlet control, culvert hydraulic performance is determined by these factors:

- Depth of headwater
- Cross-sectional area
- Inlet edge configuration
- Culvert shape
- Barrel slope
- Barrel length
- Barrel roughness
- Depth of tail water

Outlet Control

- Outlet control will exist under two conditions. The first and least common is that where the headwater is insufficient to submerge the top of the culvert, and the culvert slope is subcritical.
- The most common condition exists when the culvert is flowing full A culvert flowing under outlet control is defined as a hydraulically long culvert

Partially full conduit

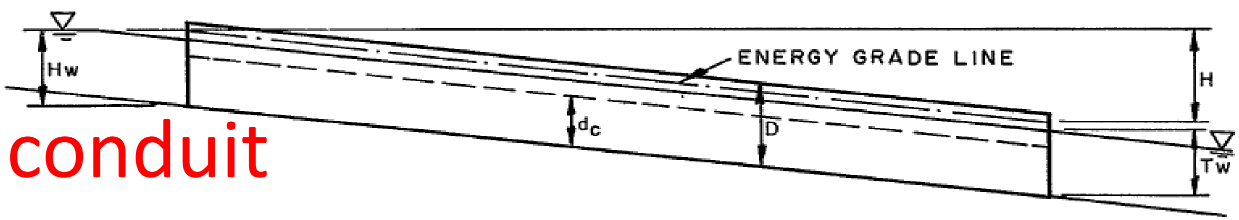
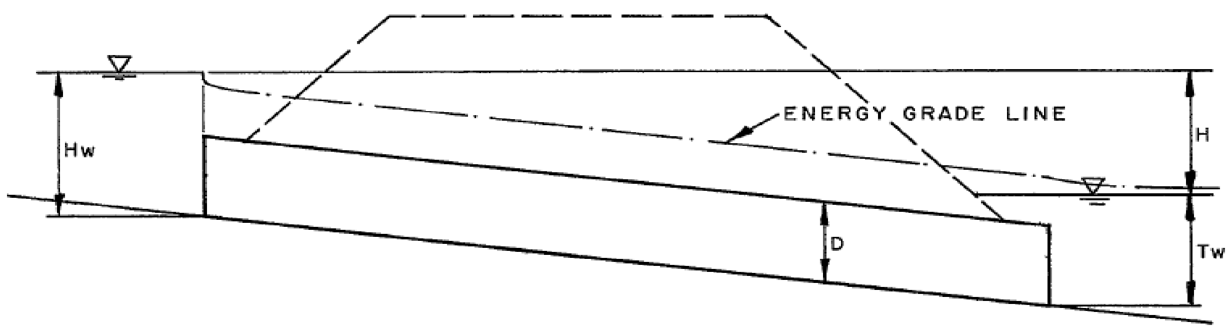


Figure CU-5—Outlet Control—Partially Full Conduit

Full conduit



Energy Losses

In short conduits, such as culverts, the form losses due to the entrance can be as important as the friction losses through the conduit.

The losses that must be evaluated to determine the carrying capacity of the culverts consist of inlet (or entrance) losses, friction losses and outlet (or exit) losses.

Inlet Losses

- For inlet losses, the governing equations are:

$$Q = CA\sqrt{2gH}$$

$$H_e = K_e \frac{v^2}{2g}$$

where:

Q = flow rate or discharge (cfs)

C = contraction coefficient (dimensionless)

A = cross-sectional area (ft^2)

g = acceleration due to gravity, 32.2 (ft/sec^2)

H = total head (ft)

H_e = head loss at entrance (ft)

K_e = entrance loss coefficient

v = average velocity (ft/sec)

Losses ….

Outlet Losses

For outlet losses, the governing equations are related to the difference in velocity head between the pipe flow and that in the downstream channel at the end of the pipe.

Friction Losses

Friction head loss for turbulent flow in pipes flowing full can be determined from the Darcy-Weisbach equation.