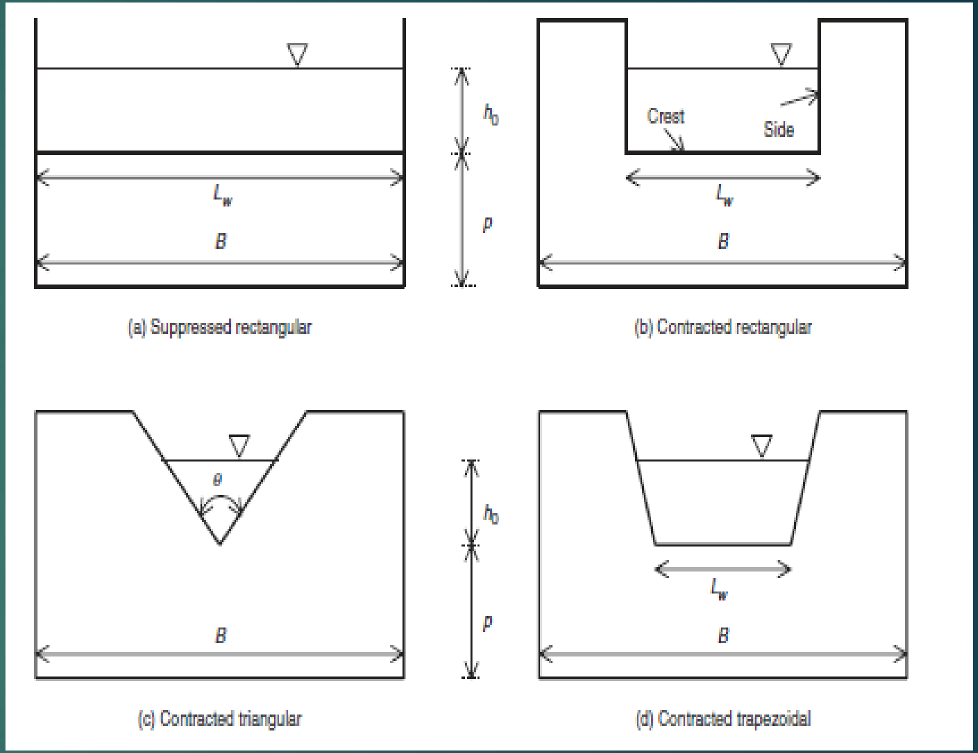
Open Channel Flow

CHAPTER 5

Hydraulic Structures

Hydraulic Structures

- Hydraulic structures are used to control and manage the flow of water in natural and built systems.
- They include flow measurement structures such as weirs, conveyance structures such as culverts, and flood control structures such as dams.
- Measurement of flow in open channels is essential for better management of limited supplies of water.



(a) Suppressed rectangular

(b) Contracted rectangular

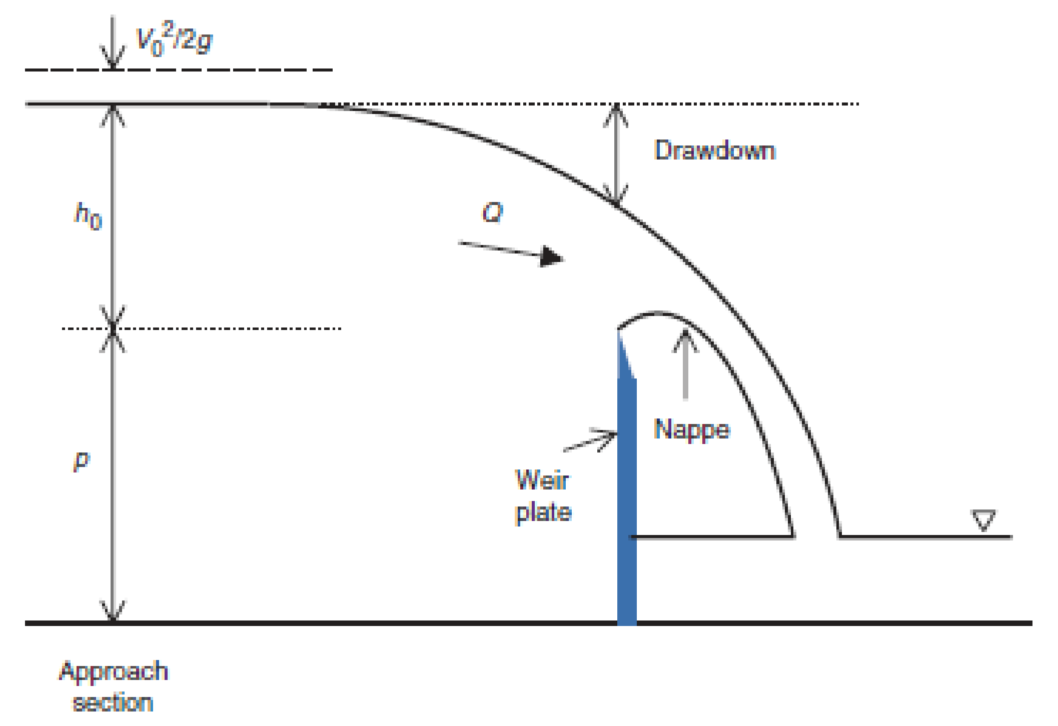
(c) Contracted triangular

(d) Contracted trapezoidal

Hydraulic Structures

- Accurate measurement practices help provide equitable distribution of water between competing demands, and conserve the water supplies by minimizing waste due to excess delivery.

- Most flow measurement structures are emplaced in a channel. They are used to determine the discharge indirectly from measurements of the flow depth.

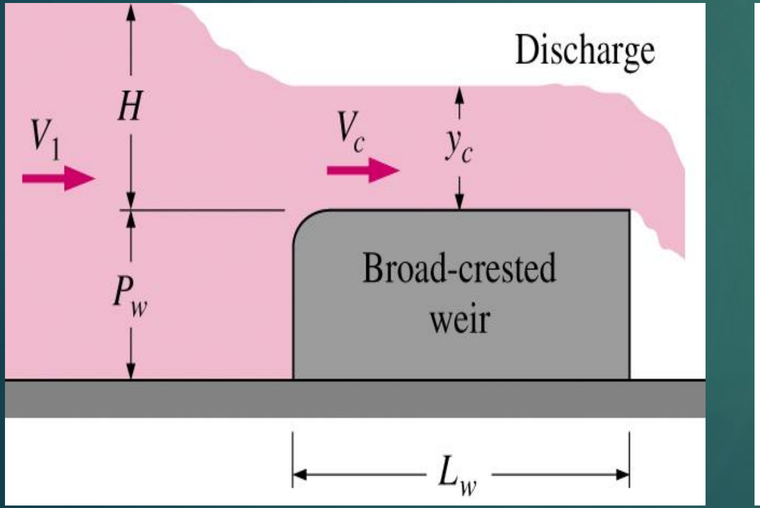


Hydraulic Structures

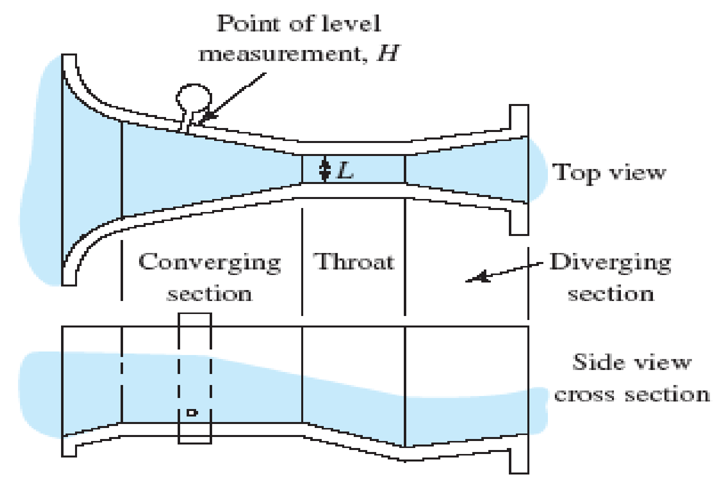
- In open channel flows, flow rate is controlled by partially blocking the channel.

- The way this works is, blocking the channel to change the shape and velocity of the flow (e.g., critical flow).

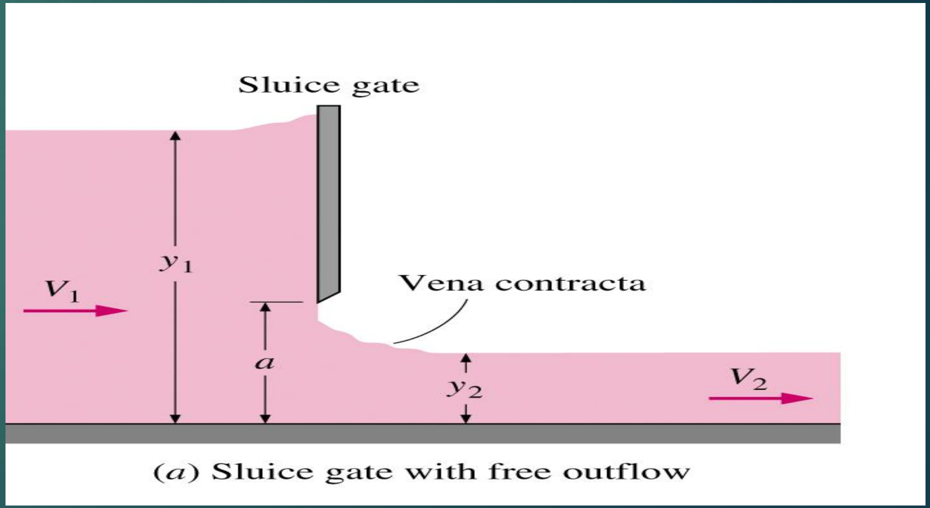
Weir : Flows over a device



Flume: Flows through a device



Underflow gate : Flows under a device



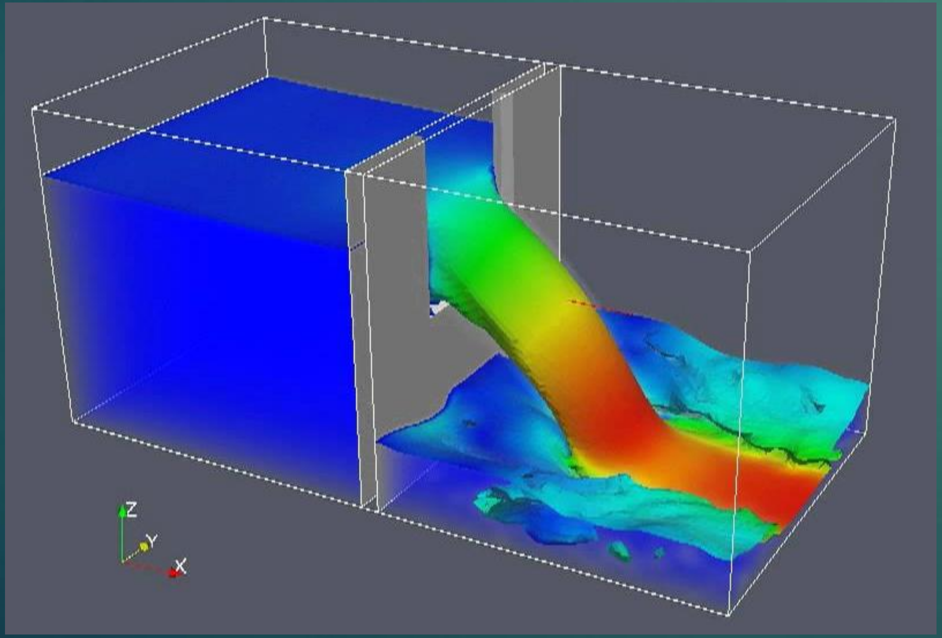
(*a*) Sluice gate with free outflow

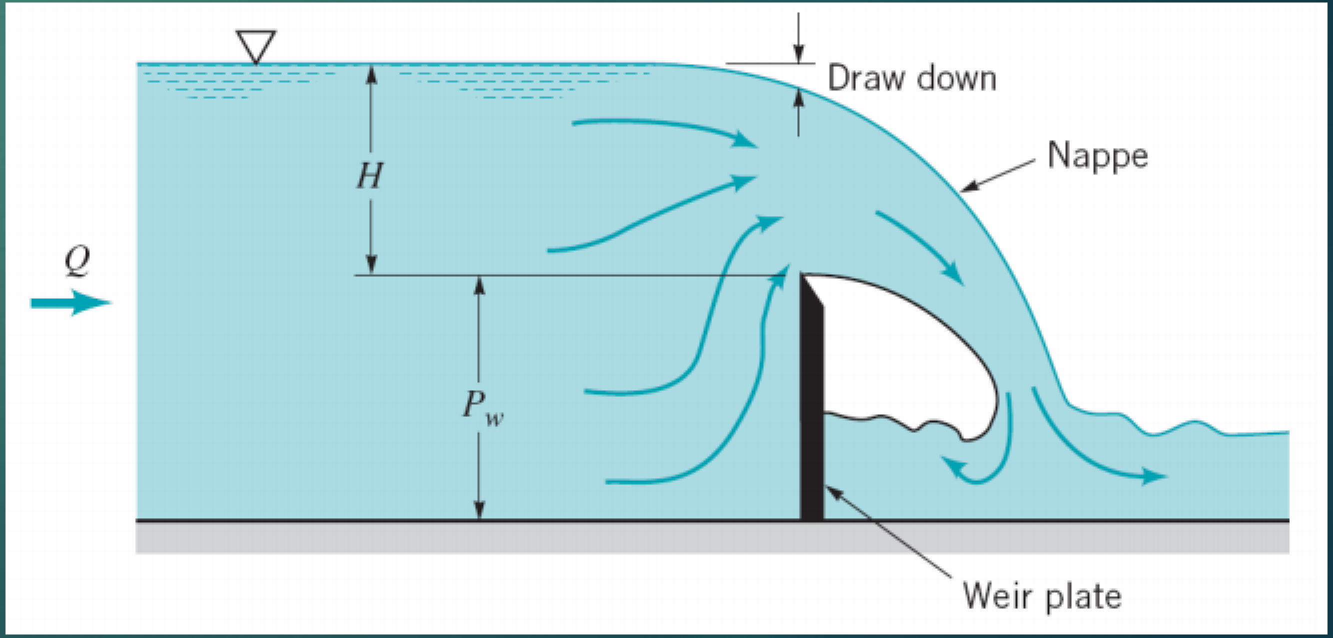
Flow Control and Measurement (weirs)

Weir provides a convenient method of determining the flowrate in an open channel in terms of a single depth measurement.

Flow Control and Measurement

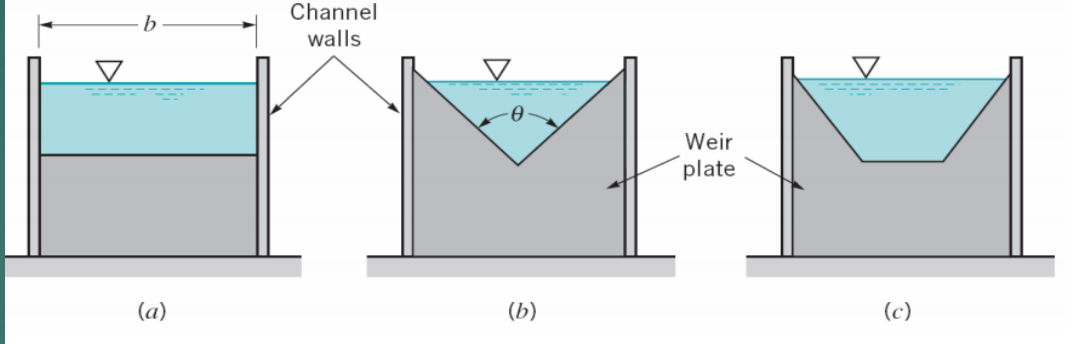
- A sharp-Crested weir is essentially a vertical-edged flat plate placed across the channel.
- The fluid must flow across the sharp edge and drop into the pool downstream of the weir plate.





Flow Control and Measurement

- Sharp-crested weir plate geometry: (a) rectangular, (b) triangular, (c) trapezoidal.

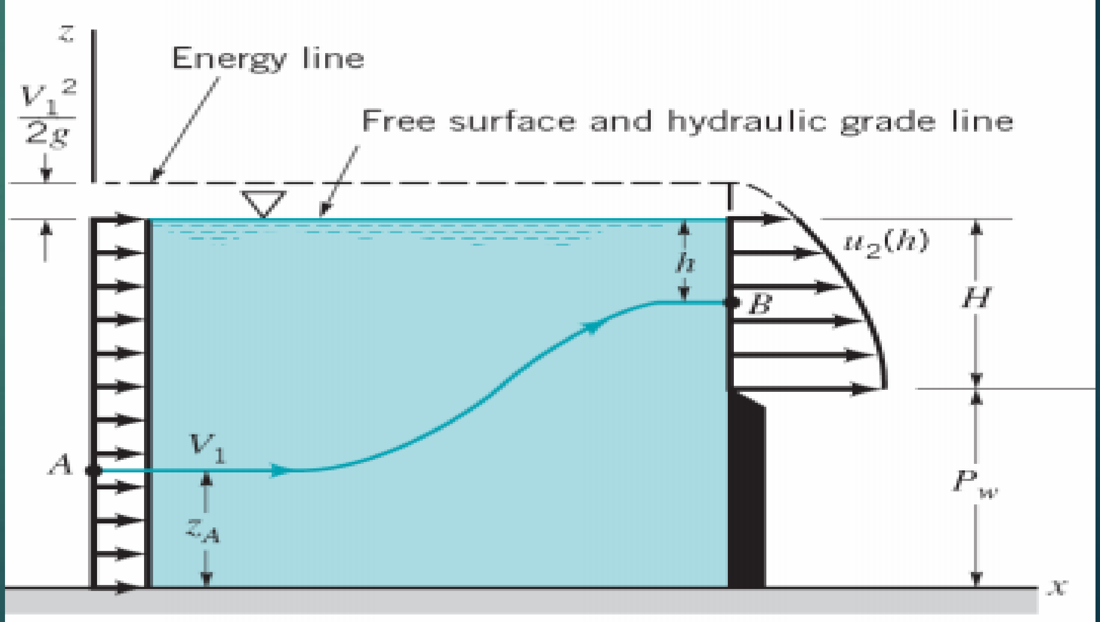


Rectangular sharp crested weir

$$Q = C_{wr}\frac{2}{3}\sqrt{2g}\,bH^{3/2}$$

$$C_{wr} = 0.611 + 0.075\left(\frac{H}{P_W}\right)$$

C_{wr} is the rectangular weir coefficient.

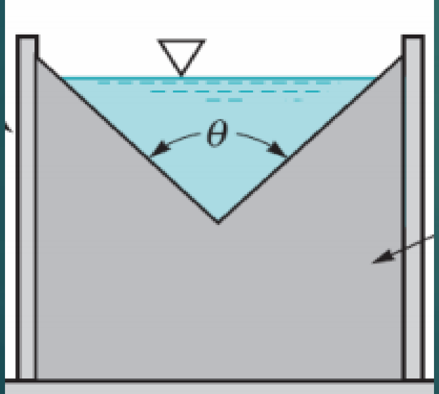


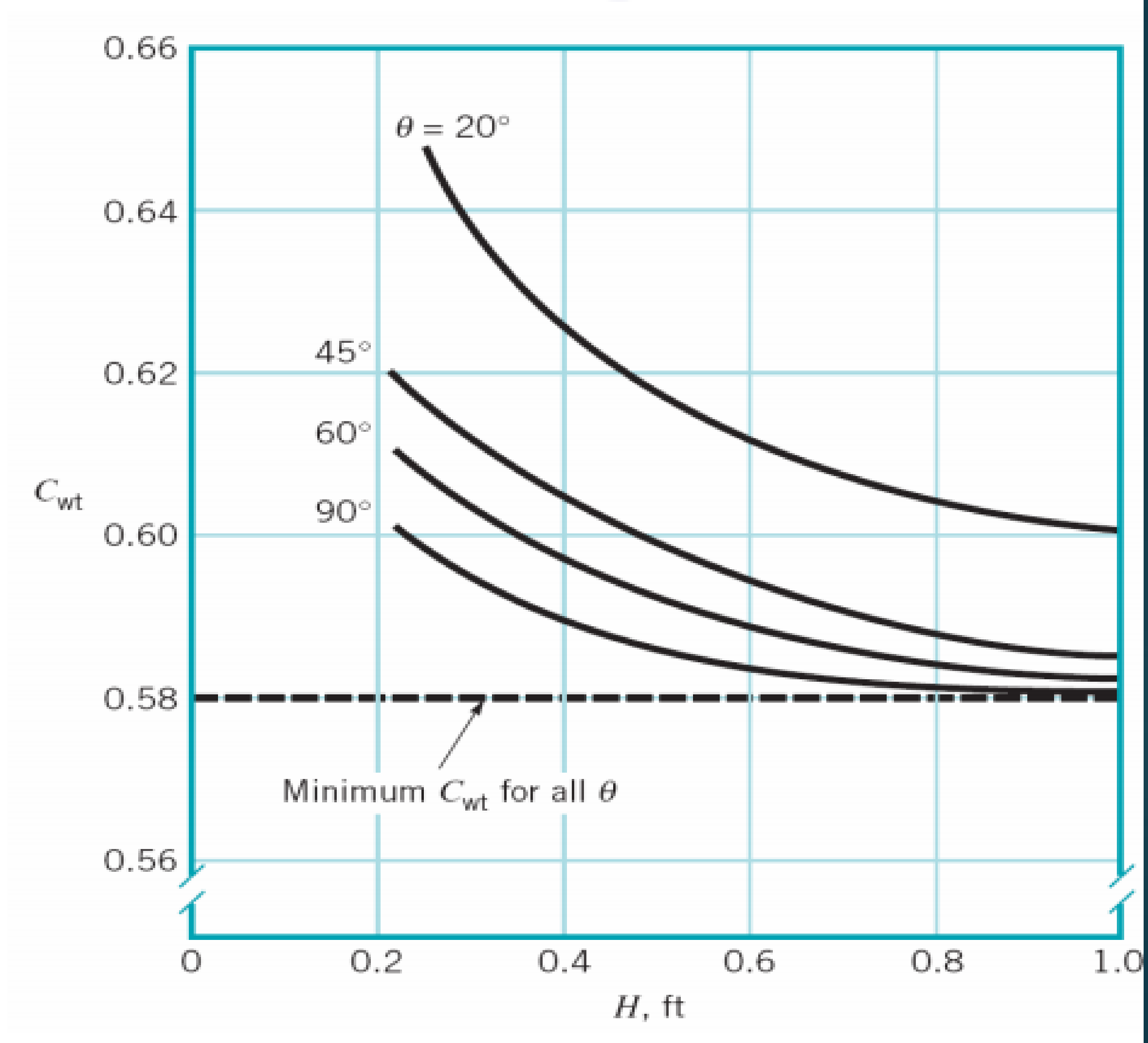
Flow Control and Measurement

Triangle sharp crested weir

$$Q = C_{wt}\frac{8}{15}Tan(\frac{\theta}{2})\sqrt{2g}bH^{5/2}$$

C_{wt} is the triangle weir coefficient.



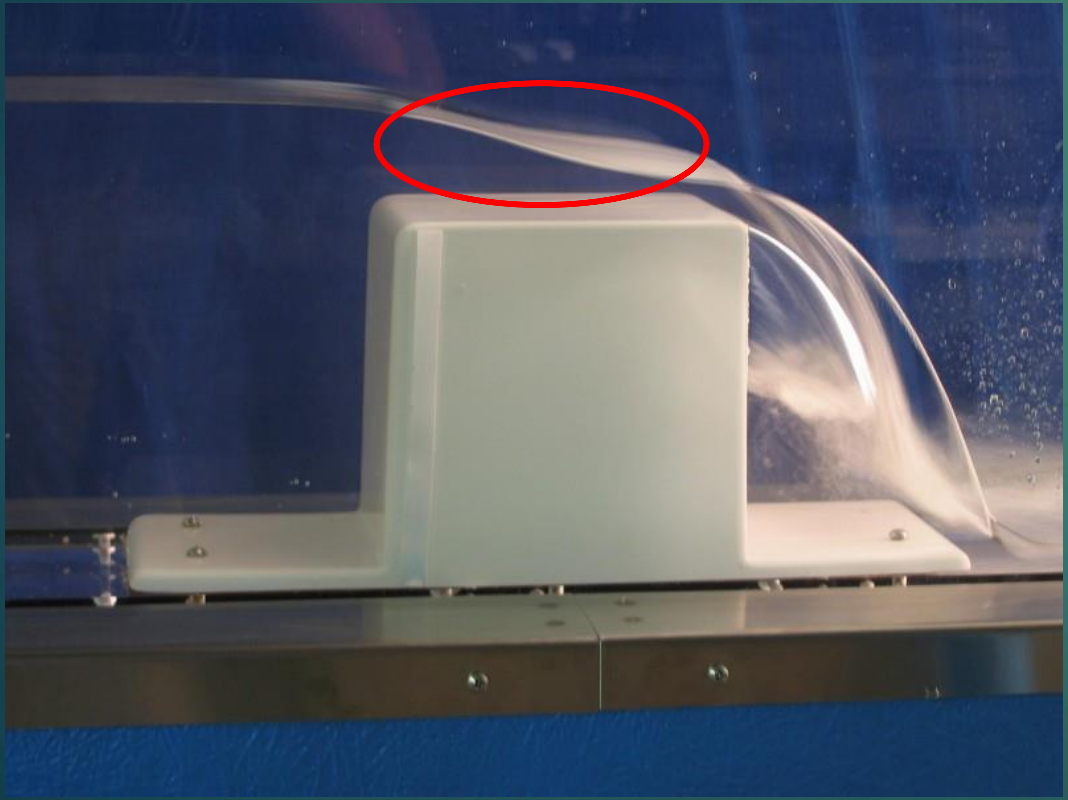


Flow Control and Measurement (Broad Crested weir)

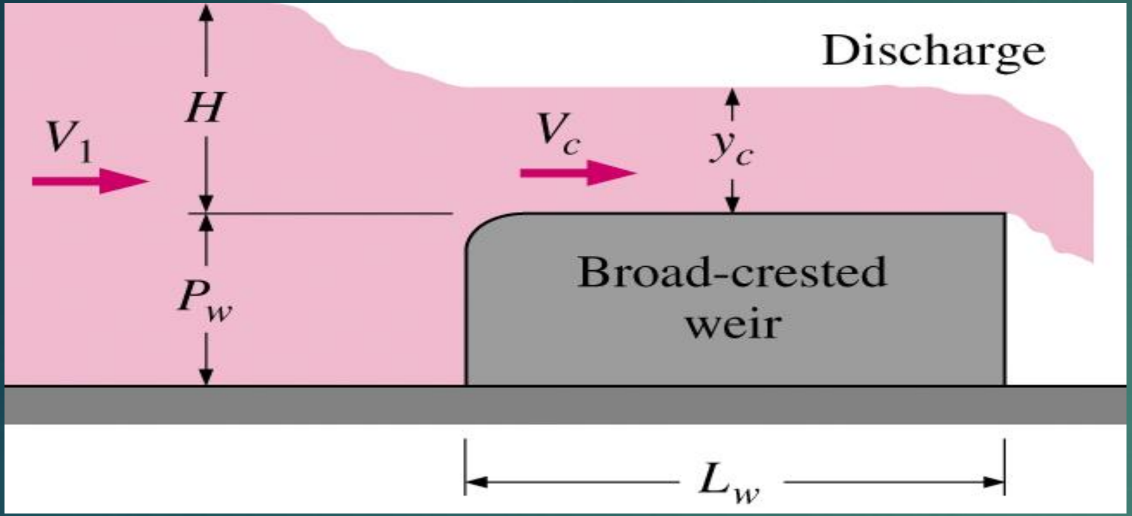
- This is the simplest device for flow measurement.
- The width of the weir is taken as the <u>width of the waterway</u>.

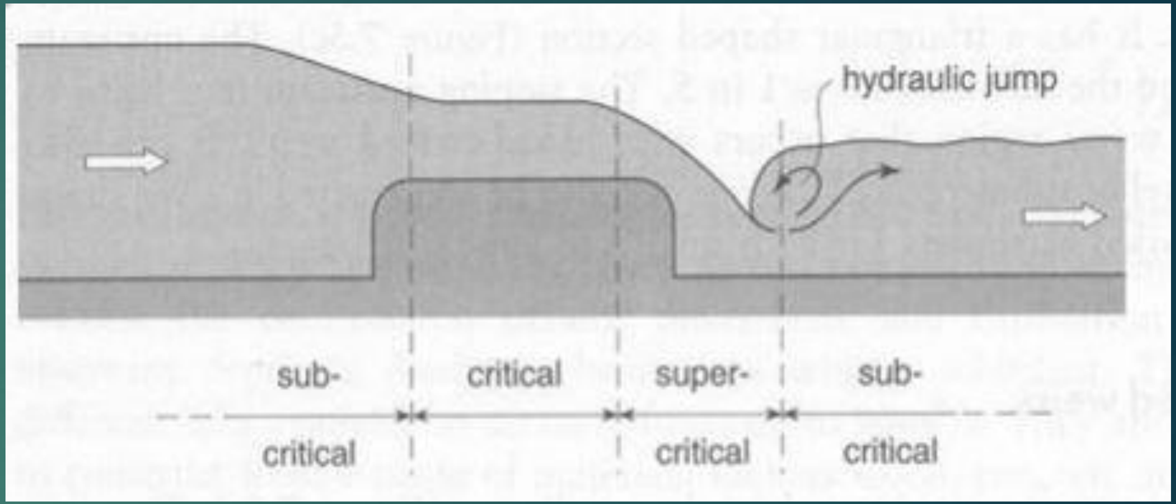
Flow Control and Measurement (Broad Crested weir)

- A key feature of a properly operating broad crested weir is critical flow over the weir crest.



Flow Control and Measurement (Broad Crested weir)





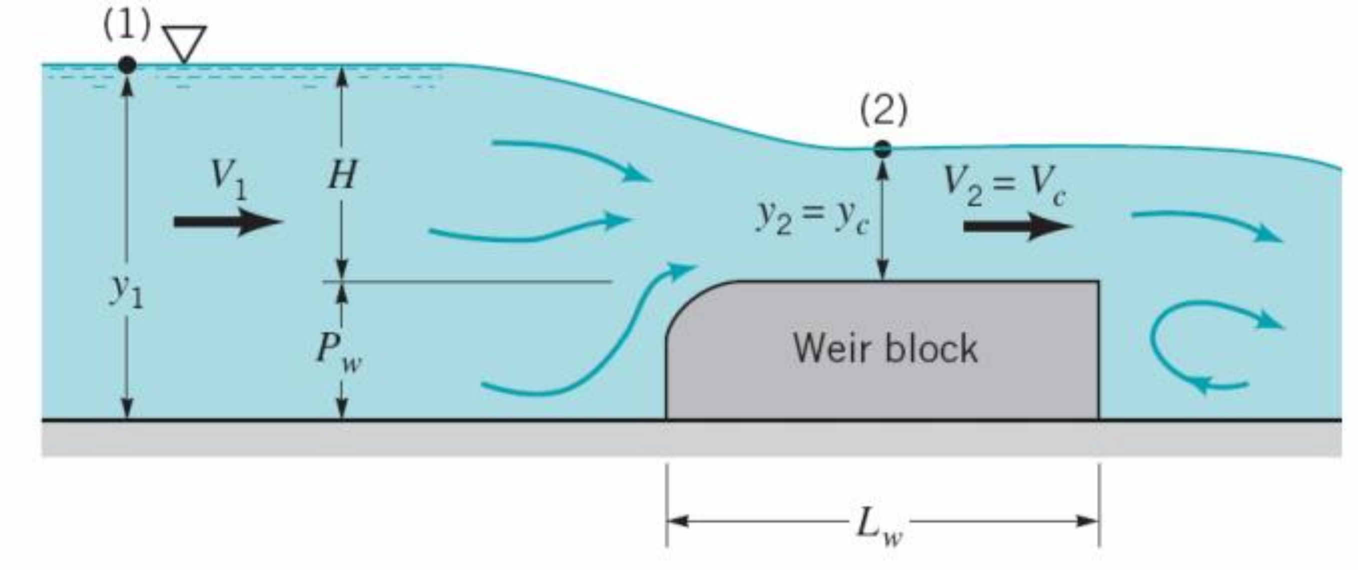
Advantages:

- Cost effective installation due to ease of design and construction.
- Relatively small head loss across the structure
- Capable of measuring discharge in small to medium channels

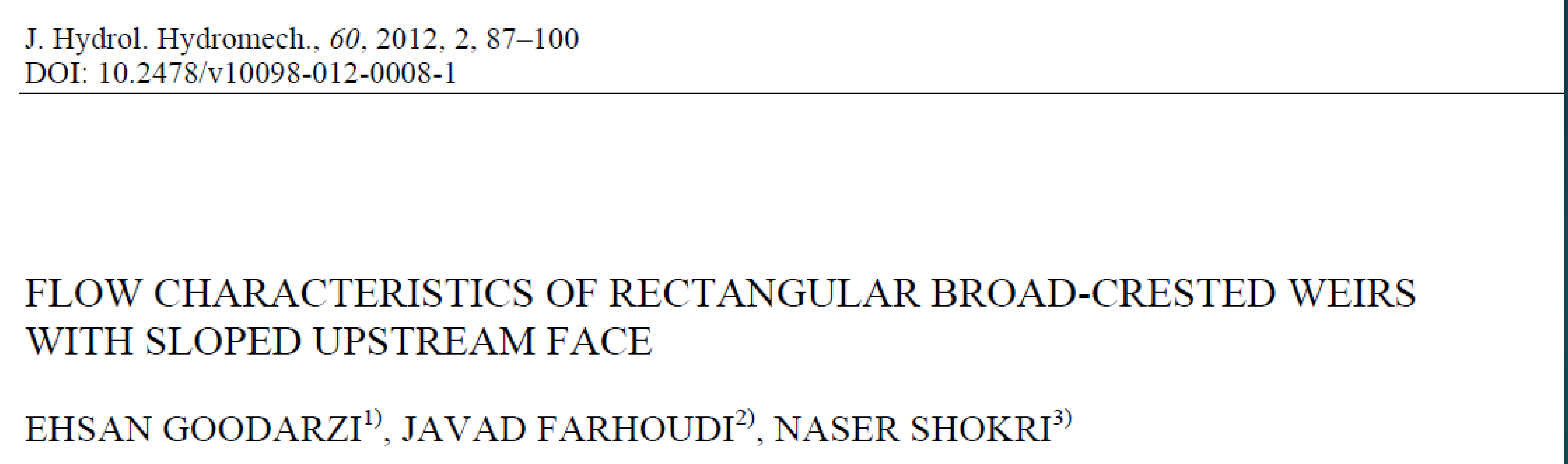
Flow Control and Measurement (Rectangular weir)

$$Q = C_{wb}\sqrt{2g}\,b\left(\frac{2}{3}\right)^{3/2} H^{3/2}$$

$$C_{wb} = \frac{0.65}{\left[1+\frac{H}{P_w}\right]^{1/2}}$$



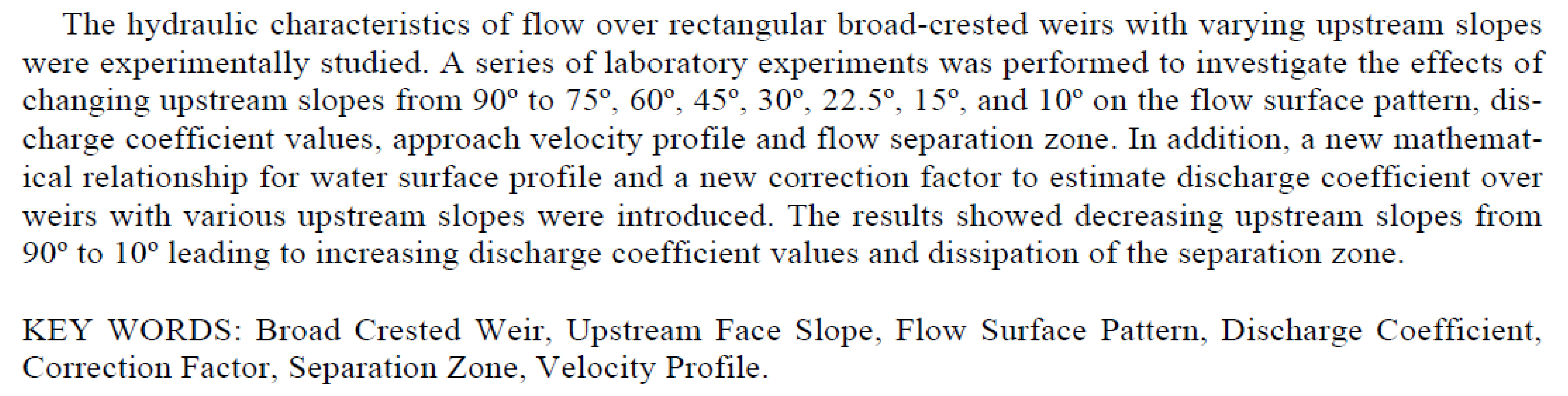
Research Review: Broad-Crested Weir



J. Hydrol. Hydromech., *60*, 2012, 2, 87–100
DOI: 10.2478/v10098-012-0008-1

FLOW CHARACTERISTICS OF RECTANGULAR BROAD-CRESTED WEIRS WITH SLOPED UPSTREAM FACE

EHSAN GOODARZI[1], JAVAD FARHOUDI[2], NASER SHOKRI[3]

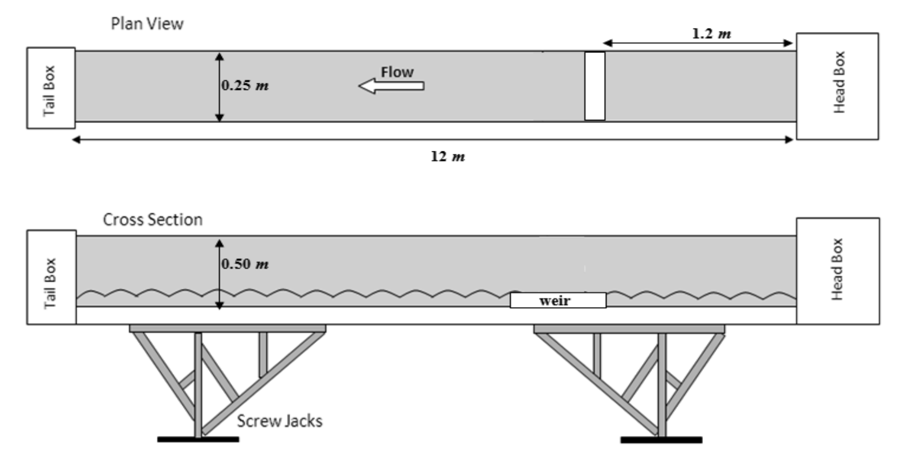


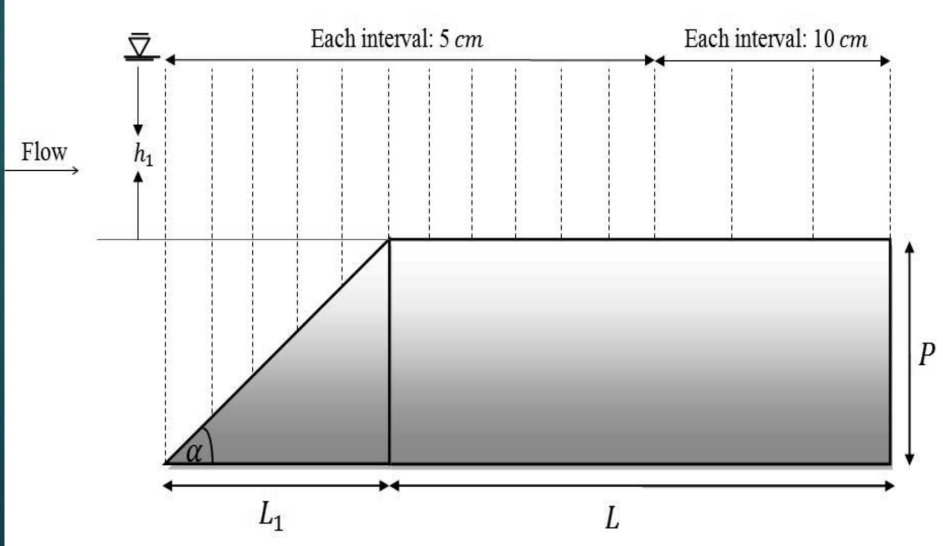
The hydraulic characteristics of flow over rectangular broad-crested weirs with varying upstream slopes were experimentally studied. A series of laboratory experiments was performed to investigate the effects of changing upstream slopes from 90° to 75°, 60°, 45°, 30°, 22.5°, 15°, and 10° on the flow surface pattern, discharge coefficient values, approach velocity profile and flow separation zone. In addition, a new mathematical relationship for water surface profile and a new correction factor to estimate discharge coefficient over weirs with various upstream slopes were introduced. The results showed decreasing upstream slopes from 90° to 10° leading to increasing discharge coefficient values and dissipation of the separation zone.

KEY WORDS: Broad Crested Weir, Upstream Face Slope, Flow Surface Pattern, Discharge Coefficient, Correction Factor, Separation Zone, Velocity Profile.

Research Review: Broad-Crested Weir

A new idea developed to increase the efficiency of hydraulic structures with a modern level of operation and reduce future maintenance costs by changing the character of the flow.





Here, there was a focus on the flow characteristics of rectangular broad-crested weirs with sloped upstream face.

Research Review: Broad-Crested Weir

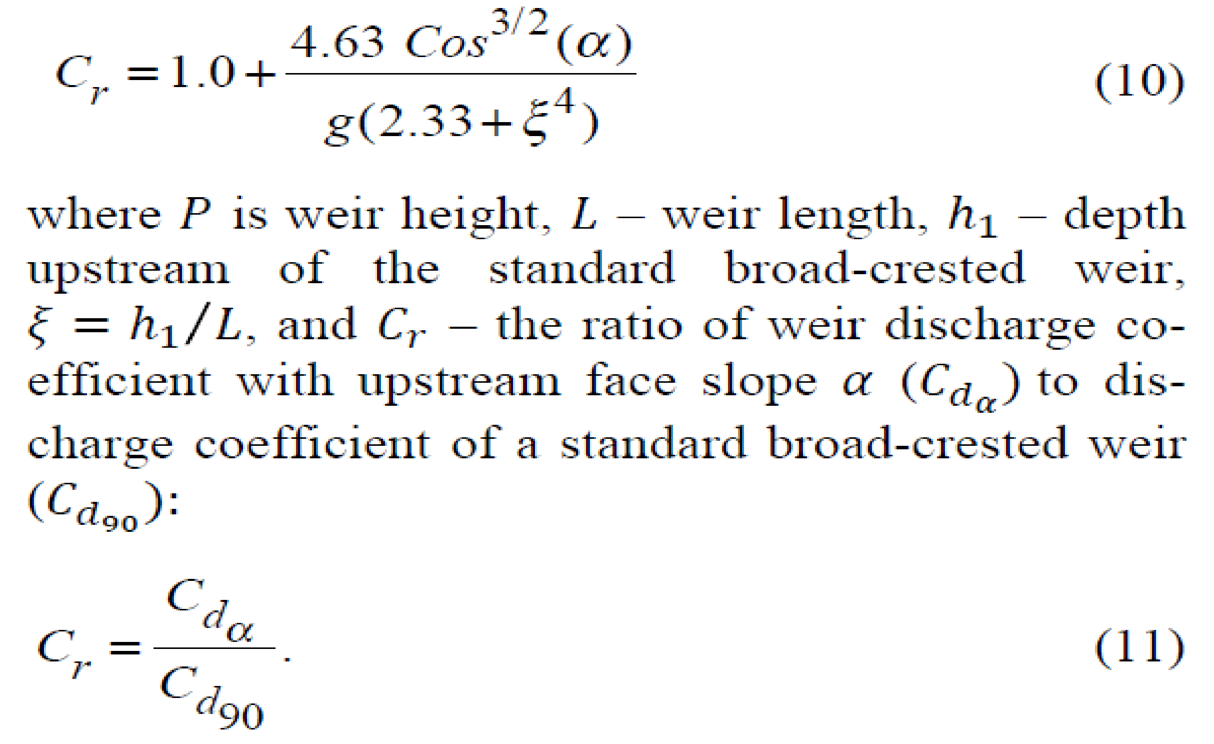
The hydraulic characteristics of flow over various weirs with varying upstream slopes is investigated:

- Flow surface pattern,
- Discharge coefficient,
- Approach velocity profile, and
- flow separation zone.

Decreasing upstream slopes from 90º to 10º increased discharge coefficient about 22%.

Research Review: Broad-Crested Weir

- A new correction factor **Cr** was presented to estimate the discharge coefficient of weir with different upstream face slopes (*Fritz* and *Hager*’s correction factor is modified).



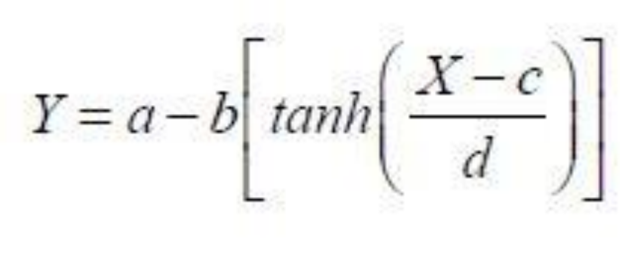
$$C_r = 1.0 + \frac{4.63\ Cos^{3/2}(\alpha)}{g(2.33+\xi^4)} \qquad (10)$$

where P is weir height, L – weir length, h_1 – depth upstream of the standard broad-crested weir, $\xi = h_1/L$, and C_r – the ratio of weir discharge coefficient with upstream face slope α (C_{d_α}) to discharge coefficient of a standard broad-crested weir ($C_{d_{90}}$):

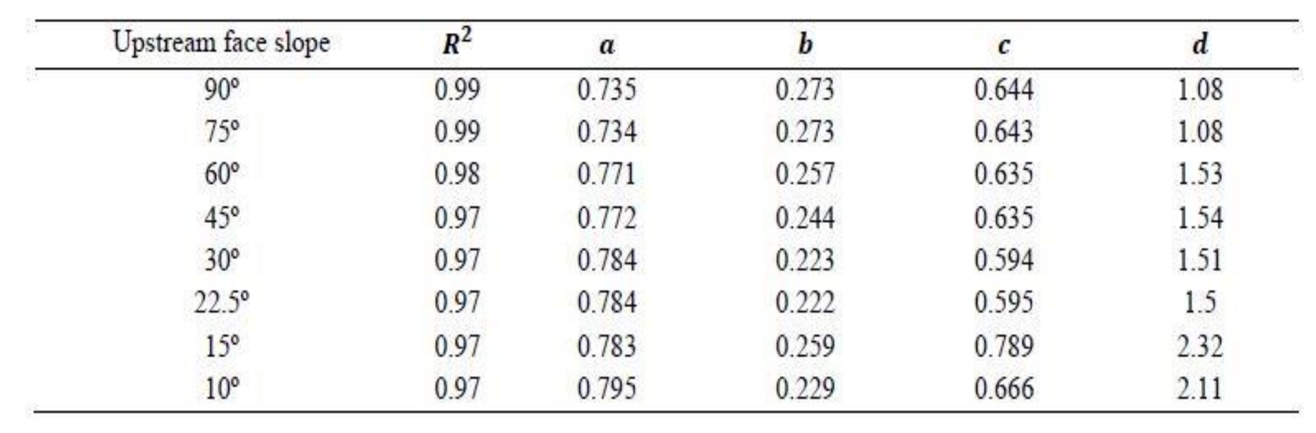
$$C_r = \frac{C_{d_\alpha}}{C_{d_{90}}}. \qquad (11)$$

Research Review: Broad-Crested Weir

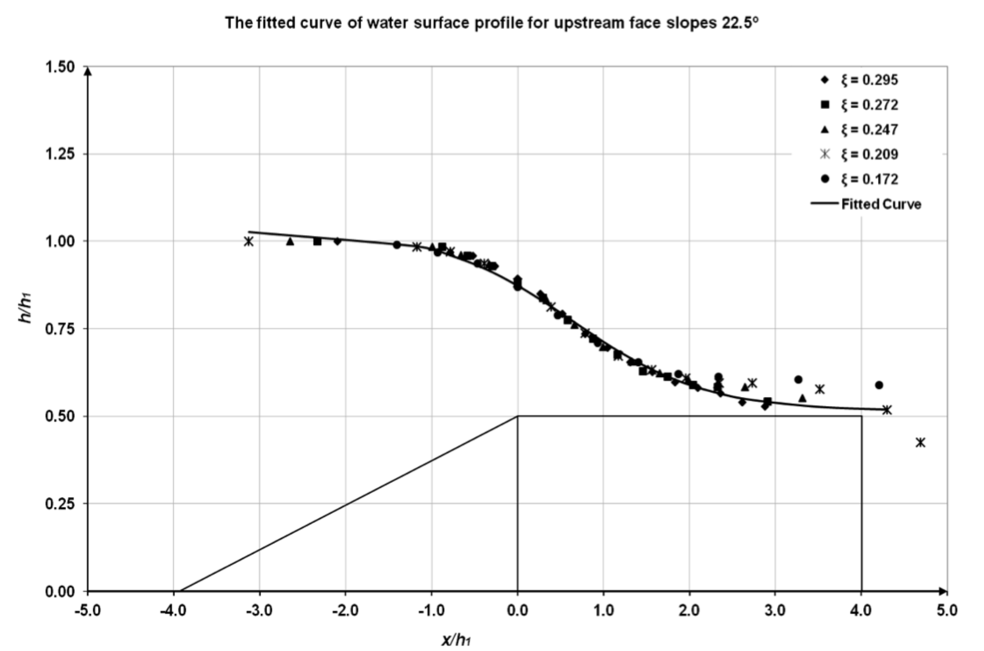
A hyperbolic equation is determined for the flow profiles with different coefficients and constant values for each weir.



$$Y = a - b\left[tanh\left(\frac{X-c}{d} \right) \right]$$



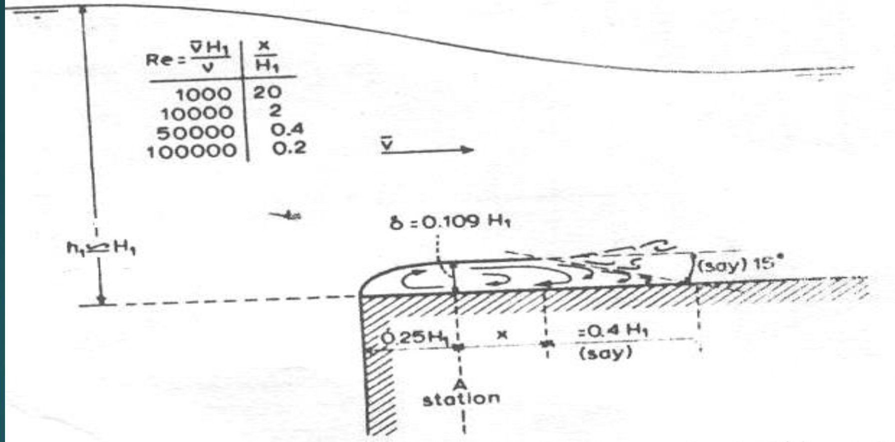
Upstream face slope	R^2	a	b	c	d
90°	0.99	0.735	0.273	0.644	1.08
75°	0.99	0.734	0.273	0.643	1.08
60°	0.98	0.771	0.257	0.635	1.53
45°	0.97	0.772	0.244	0.635	1.54
30°	0.97	0.784	0.223	0.594	1.51
22.5°	0.97	0.784	0.222	0.595	1.5
15°	0.97	0.783	0.259	0.789	2.32
10°	0.97	0.795	0.229	0.666	2.11

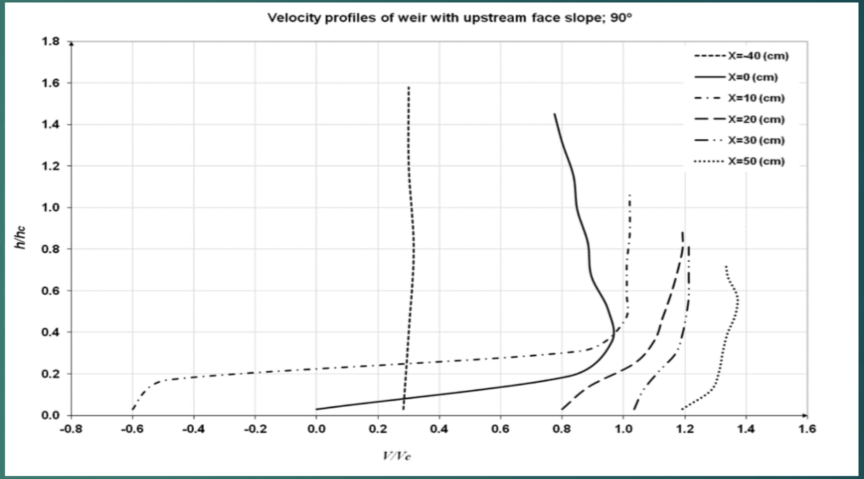


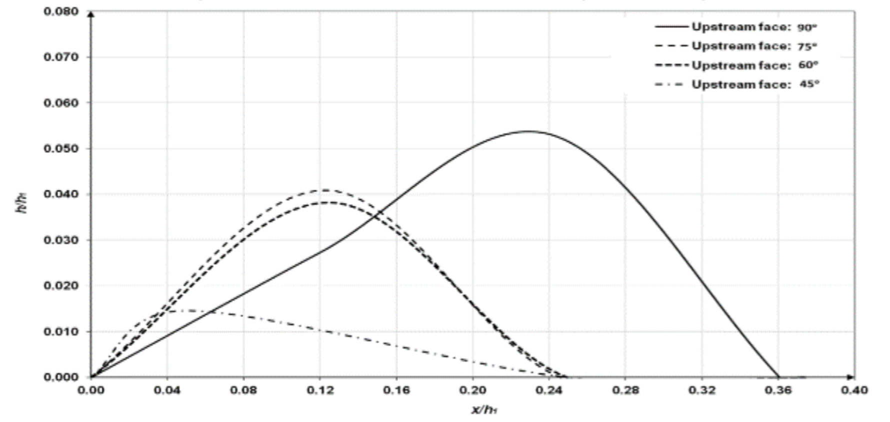
The fitted curve of water surface profile for upstream face slopes 22.5°

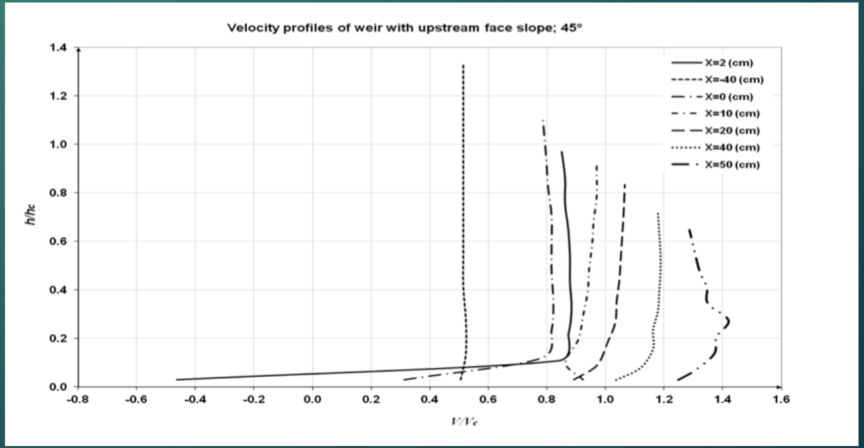
Research Review: Broad-Crested Weir

Decreasing upstream face slope reduces the separation zone and remove negative velocity when upstream slopes are less than 45°.

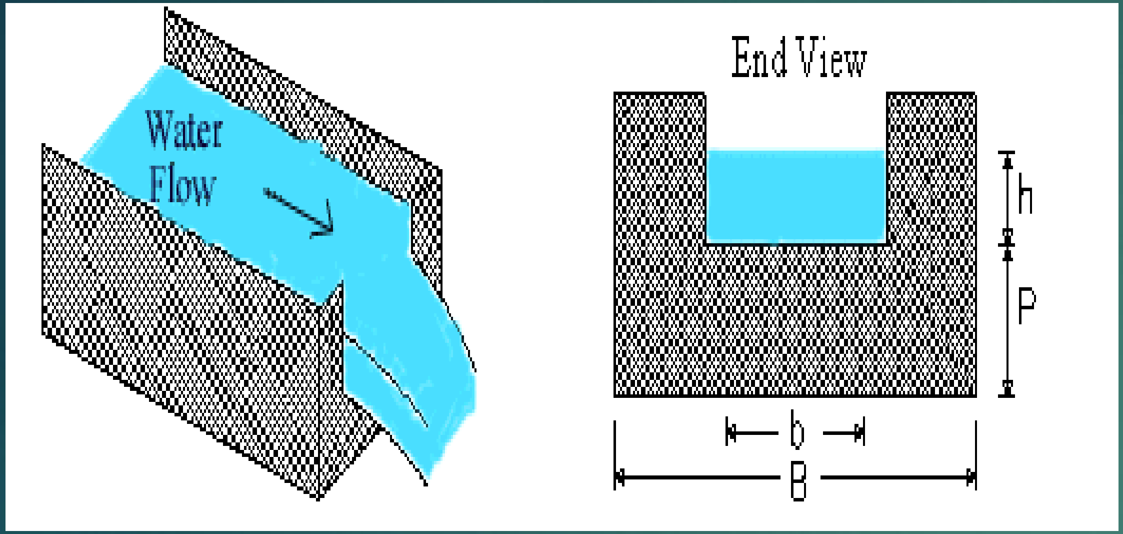


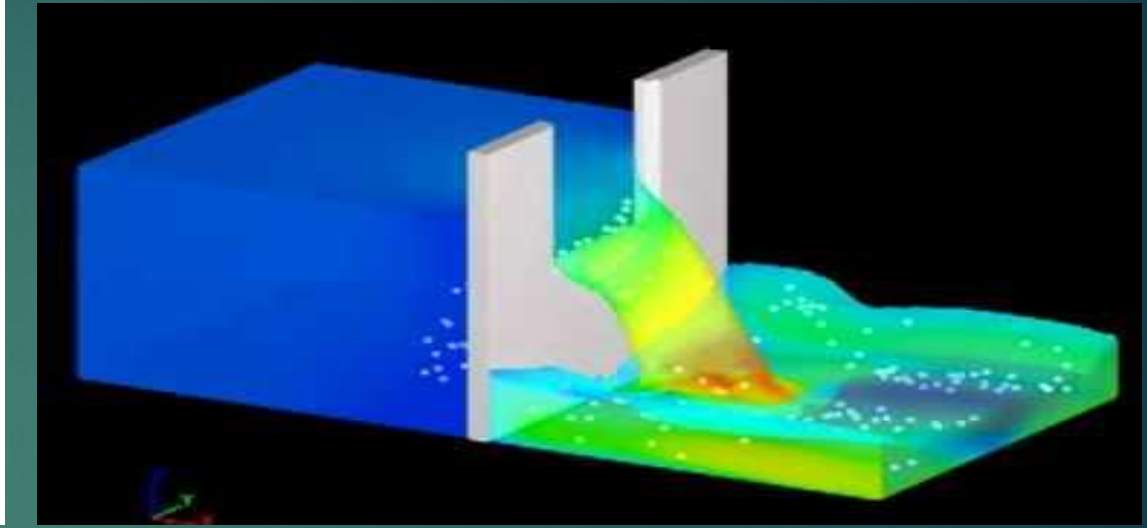

Velocity profiles of weir with upstream face slope; 90°


Separation zones over the crest of weirs with different upstream face slopes

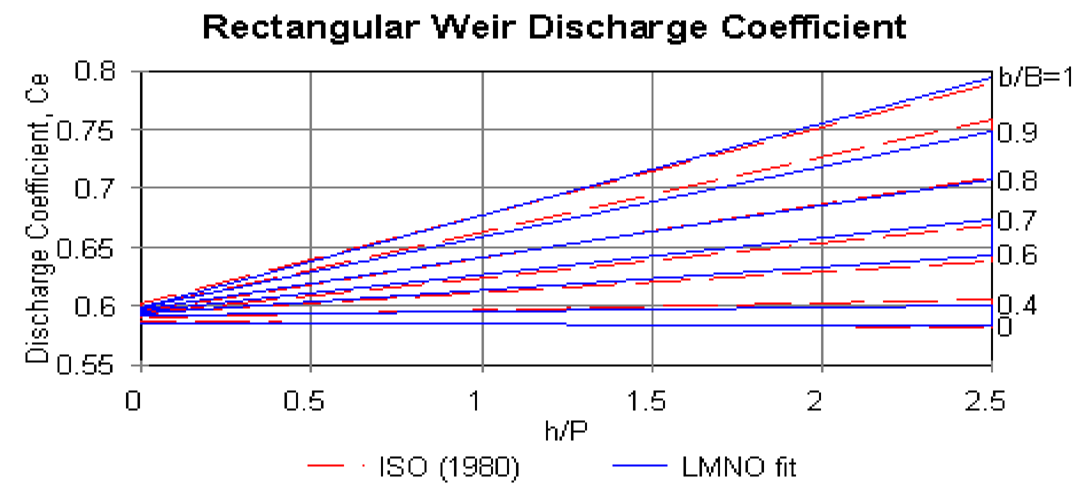

Velocity profiles of weir with upstream face slope; 45°

Flow Control and Measurement (Rectangular weir)

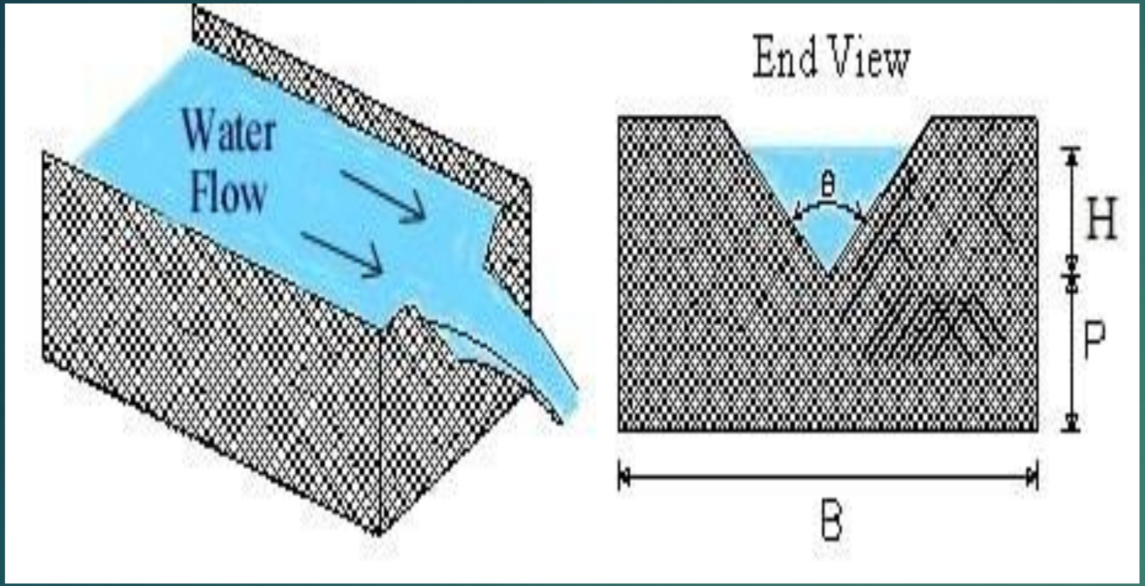


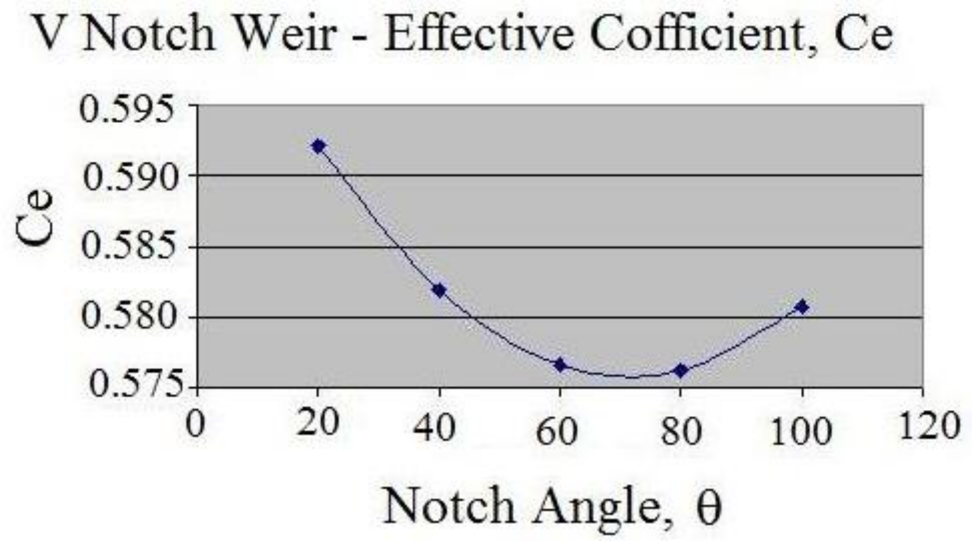


$$Q = \frac{2}{3} C_e \times b \times \sqrt{2g}\, h^{3/2}$$



Flow Control and Measurement (Triangular or V-notch weirs)





$$Q = \frac{8}{15} C_e \times Tan\frac{\theta}{2} \times \sqrt{2g} \times H^{5/2}$$

- One of the best for relatively small flows
- Ce is a function of θ

Flow Control and Measurement (Broad Crested weir)

Example 5-1

Water flows in a rectangular channel with the width of 2 m with H=0.5 m. This flow rate is to be measured by using a:

a. Rectangular sharp-crested weir

b. Triangular sharp-crested weir with $\theta = 90^{\circ}$

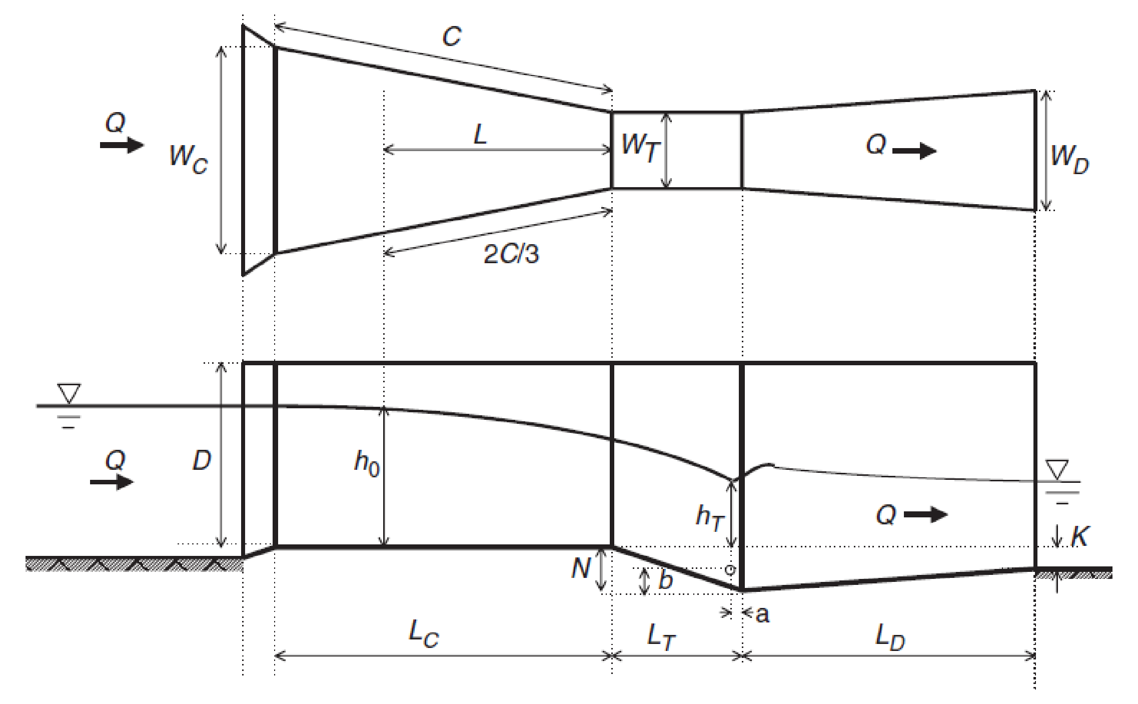
c. Broad crested-weir

If the weir height is 1 m, calculate the flow rate.

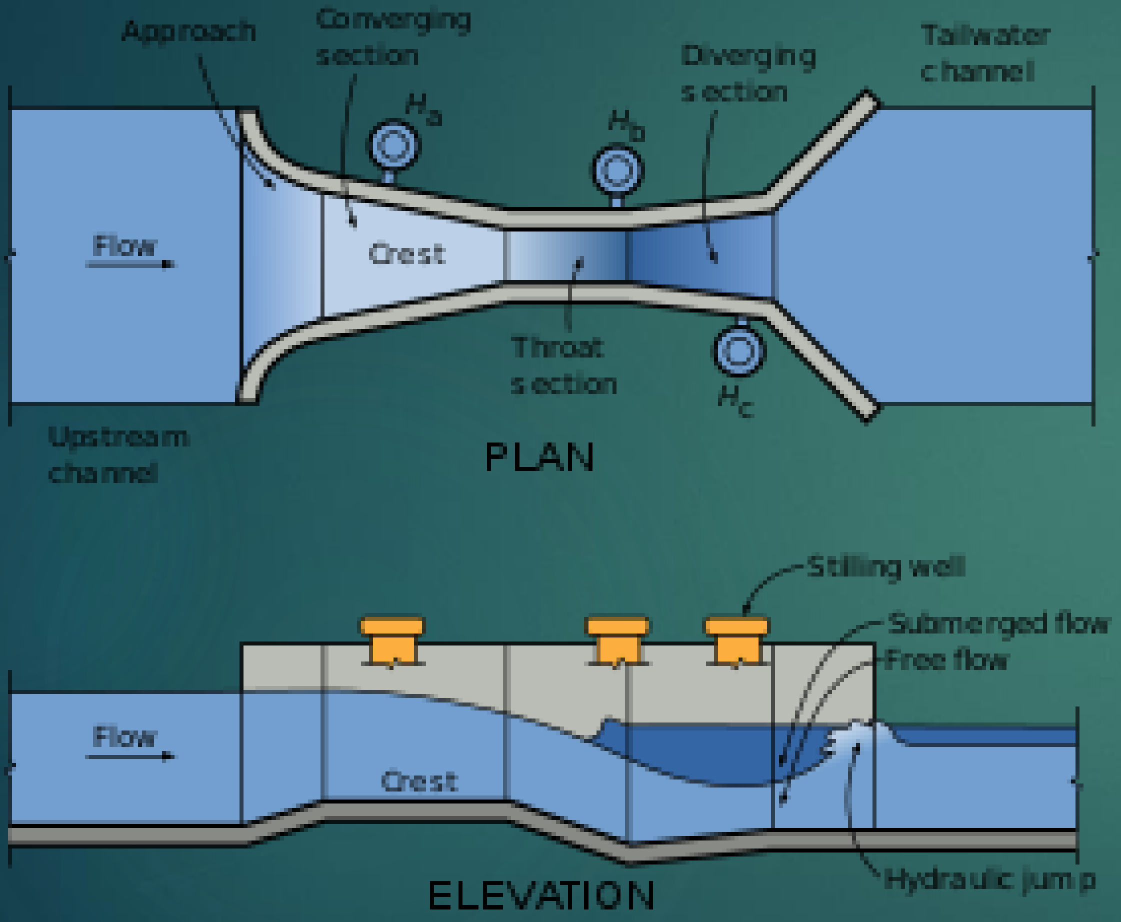
Flow Control and Measurement (Flume)

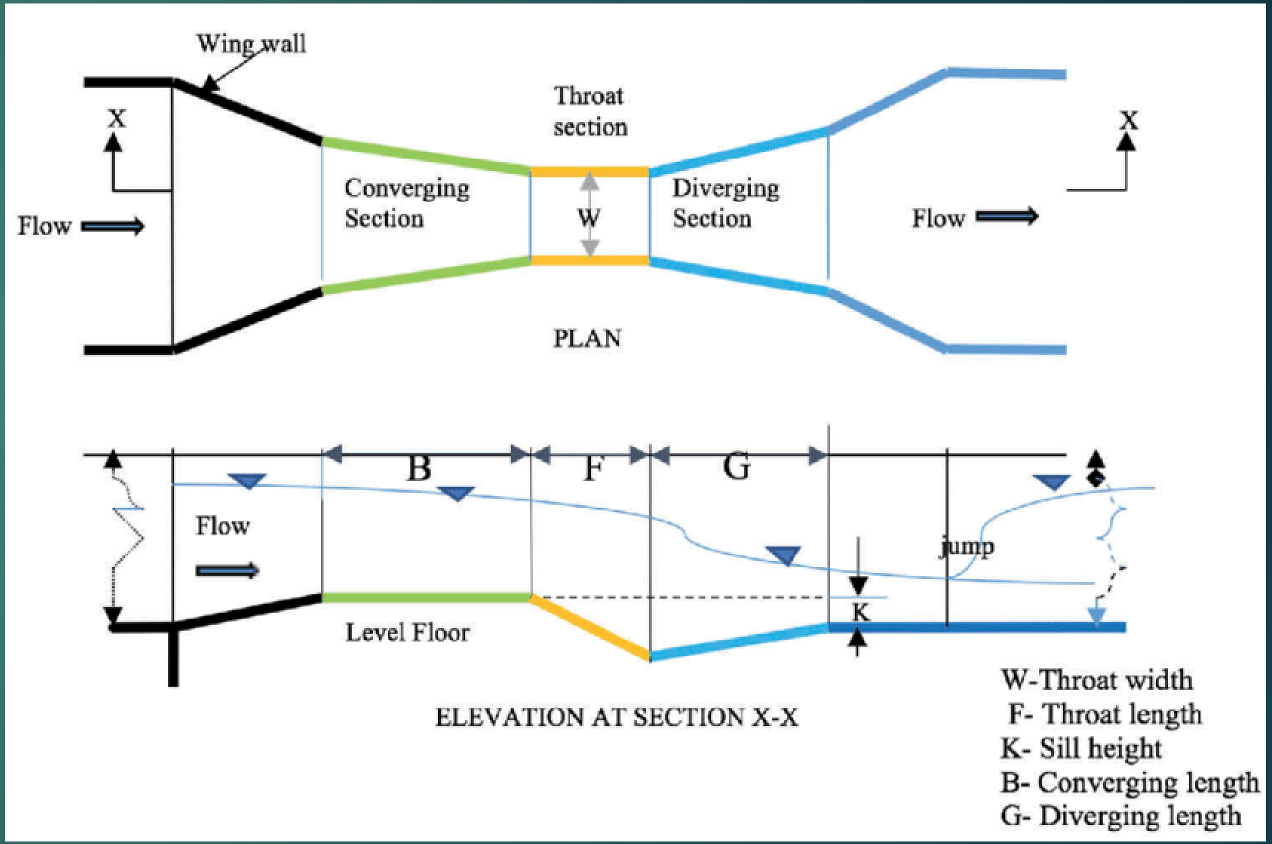
Flumes are open-channel flow segments built with contracted sidewalls and/or raised bottoms.

Among the various types of flumes available as flow measuring devices summarized by US Bureau of Reclamation (2001), the Parshall flume is employed most widely.



Flow Control and Measurement (Flume)

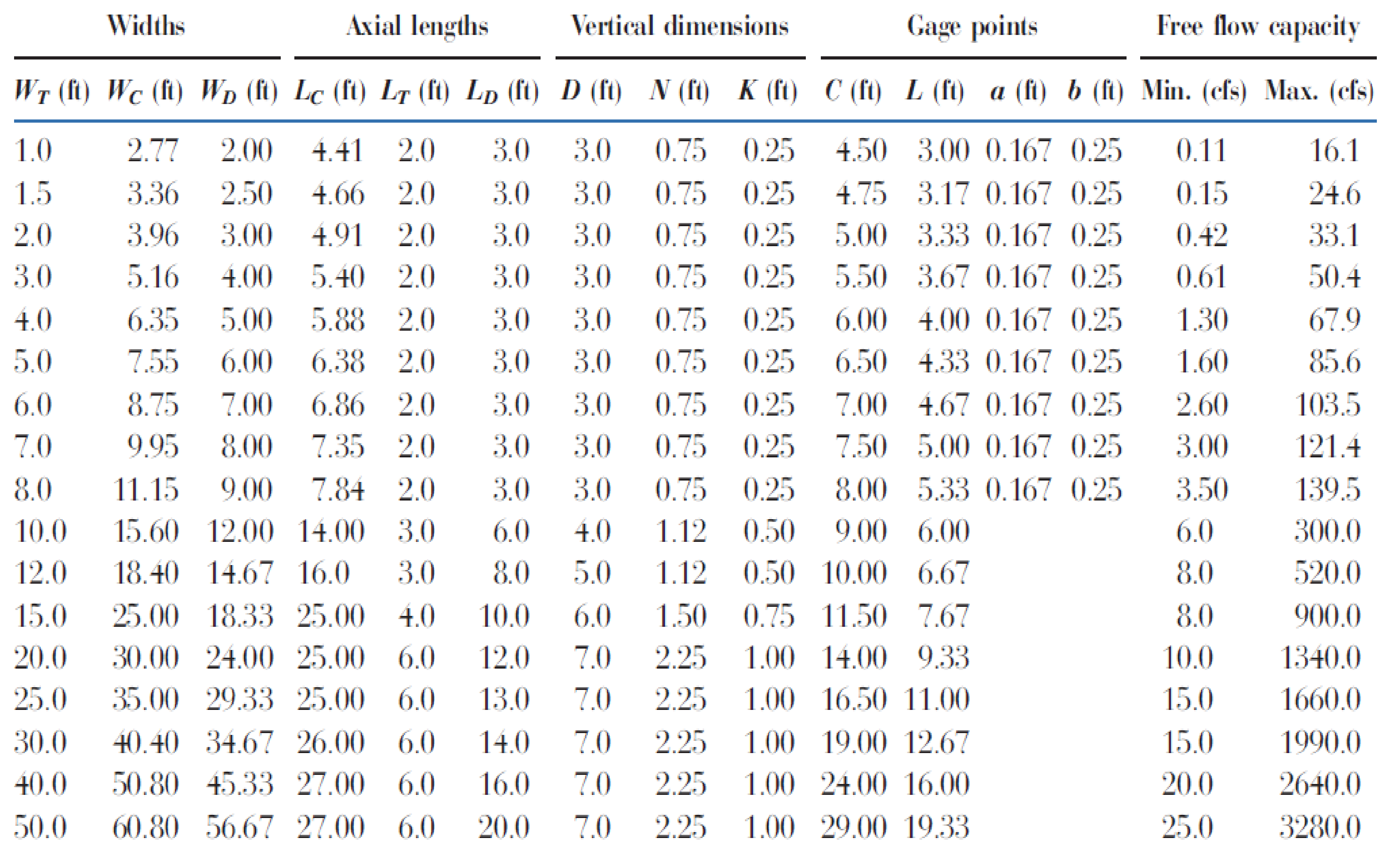




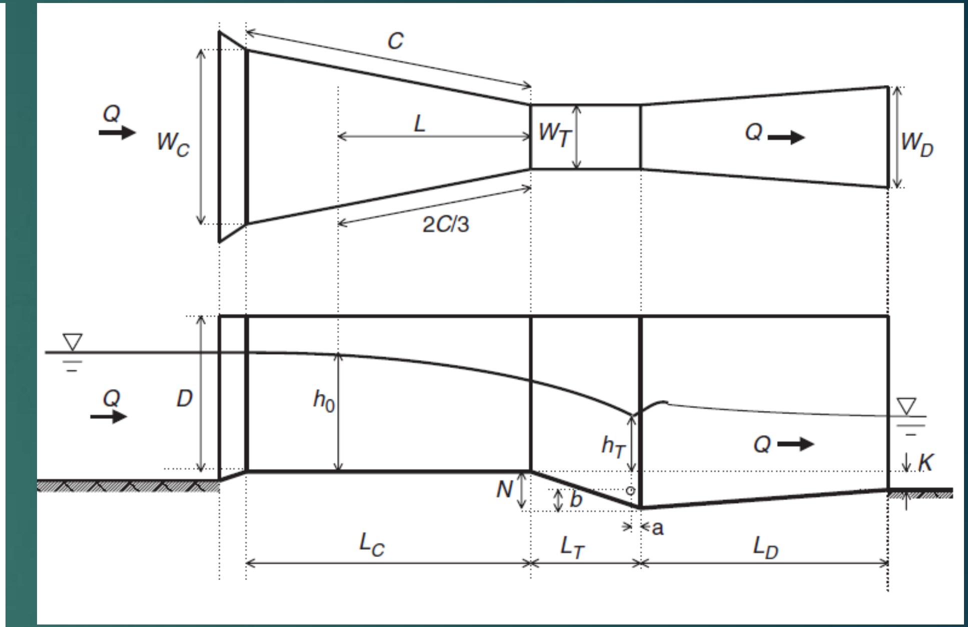
Flow Control and Measurement (Flume)

Flow Control and Measurement (Flume)

A dimension of Parshall flume with the dimensions given in Table for various sizes.



Widths			Axial lengths			Vertical dimensions			Gage points				Free flow capacity	
W_T (ft)	W_C (ft)	W_D (ft)	L_C (ft)	L_T (ft)	L_D (ft)	D (ft)	N (ft)	K (ft)	C (ft)	L (ft)	a (ft)	b (ft)	Min. (cfs)	Max. (cfs)
1.0	2.77	2.00	4.41	2.0	3.0	3.0	0.75	0.25	4.50	3.00	0.167	0.25	0.11	16.1
1.5	3.36	2.50	4.66	2.0	3.0	3.0	0.75	0.25	4.75	3.17	0.167	0.25	0.15	24.6
2.0	3.96	3.00	4.91	2.0	3.0	3.0	0.75	0.25	5.00	3.33	0.167	0.25	0.42	33.1
3.0	5.16	4.00	5.40	2.0	3.0	3.0	0.75	0.25	5.50	3.67	0.167	0.25	0.61	50.4
4.0	6.35	5.00	5.88	2.0	3.0	3.0	0.75	0.25	6.00	4.00	0.167	0.25	1.30	67.9
5.0	7.55	6.00	6.38	2.0	3.0	3.0	0.75	0.25	6.50	4.33	0.167	0.25	1.60	85.6
6.0	8.75	7.00	6.86	2.0	3.0	3.0	0.75	0.25	7.00	4.67	0.167	0.25	2.60	103.5
7.0	9.95	8.00	7.35	2.0	3.0	3.0	0.75	0.25	7.50	5.00	0.167	0.25	3.00	121.4
8.0	11.15	9.00	7.84	2.0	3.0	3.0	0.75	0.25	8.00	5.33	0.167	0.25	3.50	139.5
10.0	15.60	12.00	14.00	3.0	6.0	4.0	1.12	0.50	9.00	6.00			6.0	300.0
12.0	18.40	14.67	16.0	3.0	8.0	5.0	1.12	0.50	10.00	6.67			8.0	520.0
15.0	25.00	18.33	25.00	4.0	10.0	6.0	1.50	0.75	11.50	7.67			8.0	900.0
20.0	30.00	24.00	25.00	6.0	12.0	7.0	2.25	1.00	14.00	9.33			10.0	1340.0
25.0	35.00	29.33	25.00	6.0	13.0	7.0	2.25	1.00	16.50	11.00			15.0	1660.0
30.0	40.40	34.67	26.00	6.0	14.0	7.0	2.25	1.00	19.00	12.67			15.0	1990.0
40.0	50.80	45.33	27.00	6.0	16.0	7.0	2.25	1.00	24.00	16.00			20.0	2640.0
50.0	60.80	56.67	27.00	6.0	20.0	7.0	2.25	1.00	29.00	19.33			25.0	3280.0



Flow Control and Measurement (Flume)

The flow passes through the critical depth at the throat section when the downstream depth is shallow. This condition is known as free flow.

A unique water surface profile develops within the flume for each discharge under the free flow conditions, and it is adequate to take one depth measurement, h_0, to determine the **discharge**.

However, high downstream depths cause submerged flow conditions. In such a case a second depth measurement, h_T, is needed to determine the **discharge**.

Flow Control and Measurement (Flume)

- The percentage of submergence for Parshall flumes is defined as:

$$100(h_T/h_0)$$

- For flumes having a throat width of 1–8 ft, the submergence should exceed 70% to affect the discharge measurement in the flume.
- For flumes with larger throat widths, the threshold submergence is 80% (Kilpatrick and Schneider, 1983).
- The head–discharge relationship under the free flow conditions can be approximately expressed as (Davis, 1963):

$$Y_0 + \frac{Q_0^2}{2Y_0^2(1+0.4X_0)^2} = 1.35Q_0^{0.645}$$

$$\begin{cases} Y_0 = \dfrac{h_0}{W_T} \\ X_0 = \dfrac{L}{W_T} \\ Q_0 = \dfrac{Q_f}{W_T^{5/2} g^{1/2}} \end{cases}$$

free flow discharge

Flow Control and Measurement (Flume)

The solution of this equation requires a trial-and error method.

For flumes with throat widths not exceeding 6 ft, we can replace this Equation with a simpler expression (Dodge, 1963):

$$Q_0 = \frac{Y_0^{1.5504}}{1.3096 X_0^{0.0766}}$$

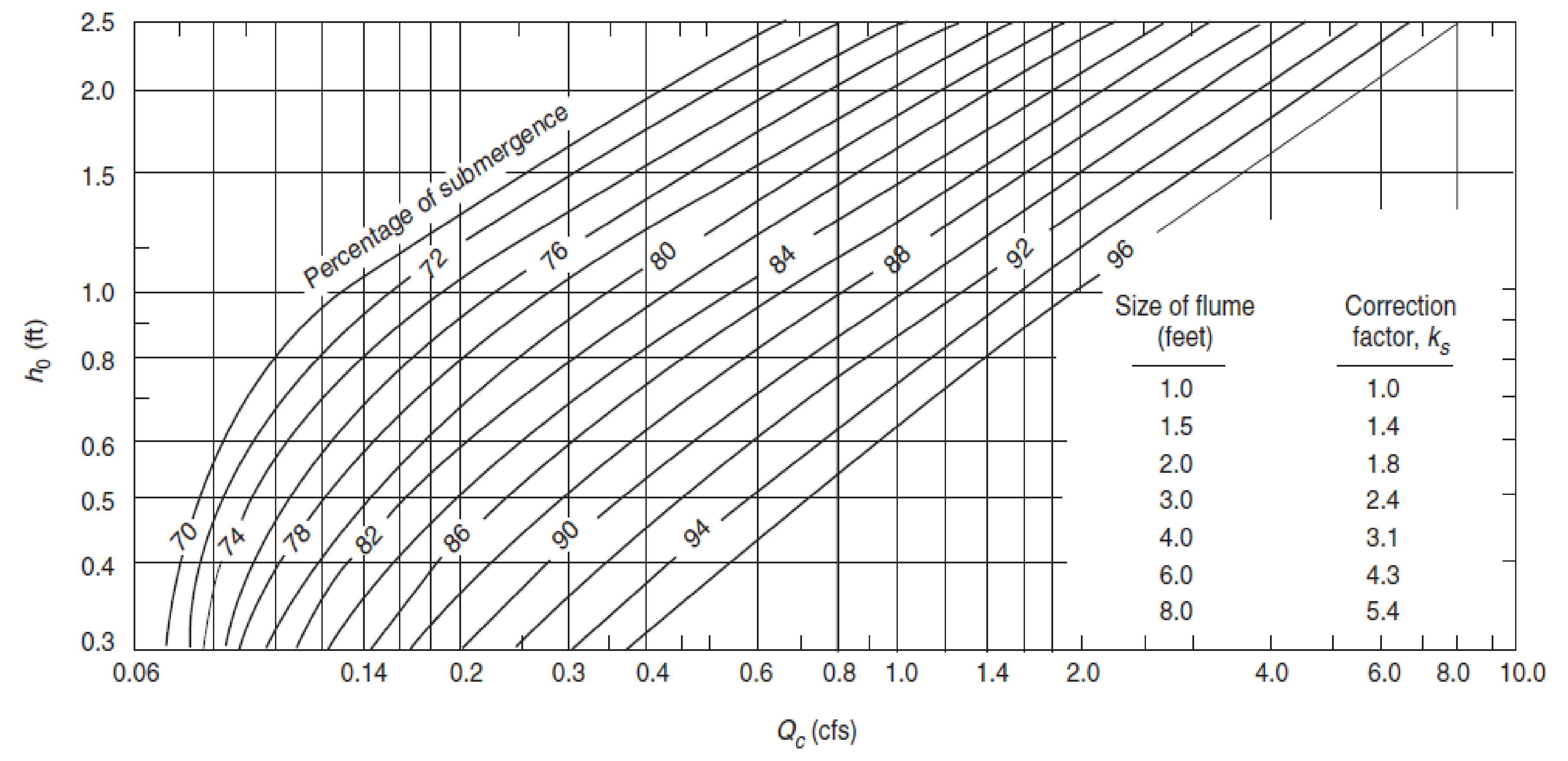
For submerged conditions, the discharge is calculated by using:

$$Q_S = Q_f - K_s Q_C$$

where $Qs =$ submerged flow discharge, $ks =$ discharge correction factor, and $Qc =$ discharge correction unadjusted to flume size (Kilpatrick and Schneider,1983).

Flow Control and Measurement (Flume)

Following Figures can be used to determine ks and Qc, depending on the throat size. In these figures, the percentage of submergence is $100\ h_T/h_0$.

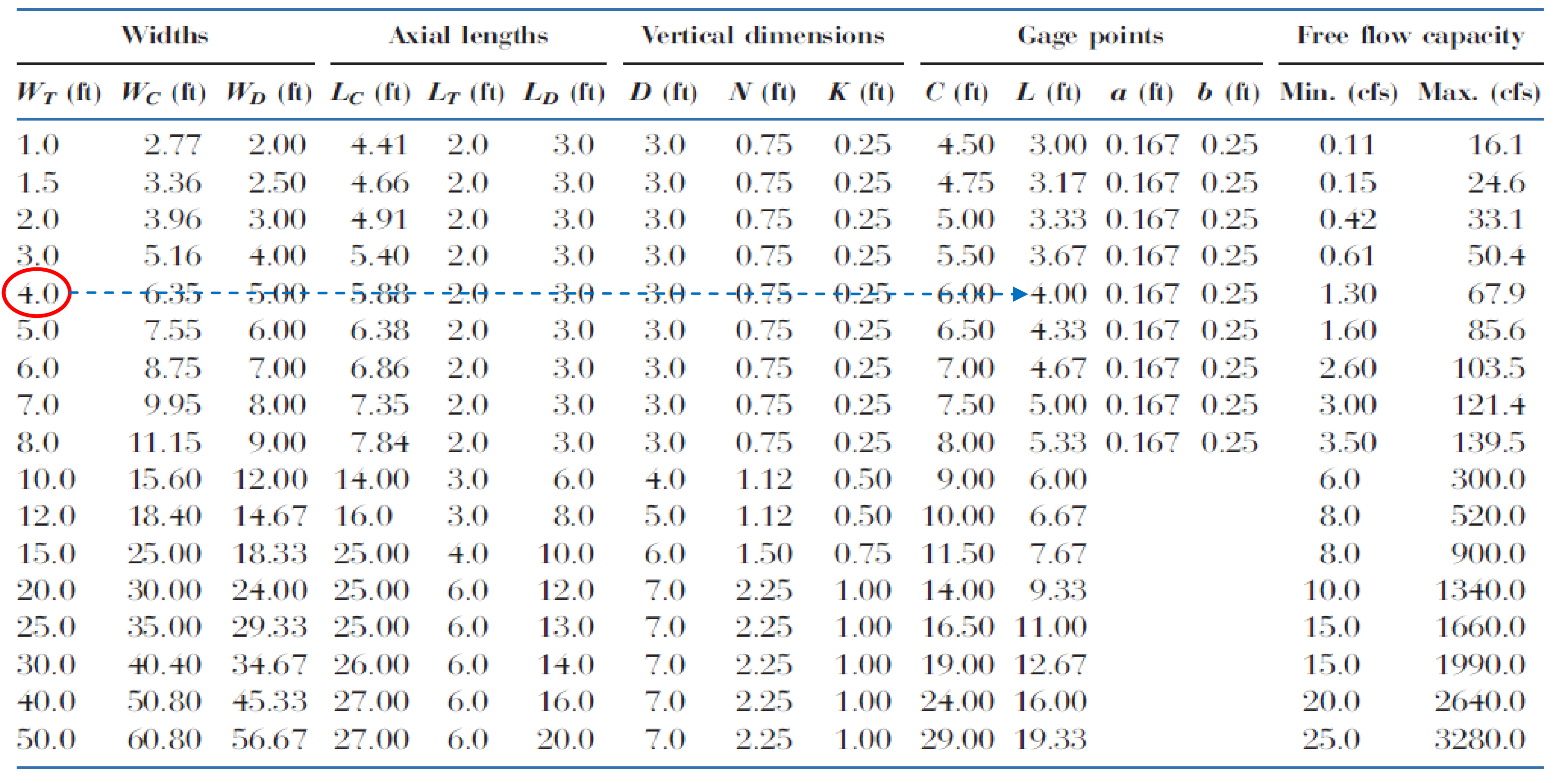


Size of flume (feet)	Correction factor, k_s
1.0	1.0
1.5	1.4
2.0	1.8
3.0	2.4
4.0	3.1
6.0	4.3
8.0	5.4

Flow Control and Measurement (Flume)

Example 5-2

A standard Parshall flume has a throat width of $W_T = 4.0\ ft$. Determine the free flow discharge corresponding to $h_0 = 2.4\ ft$.

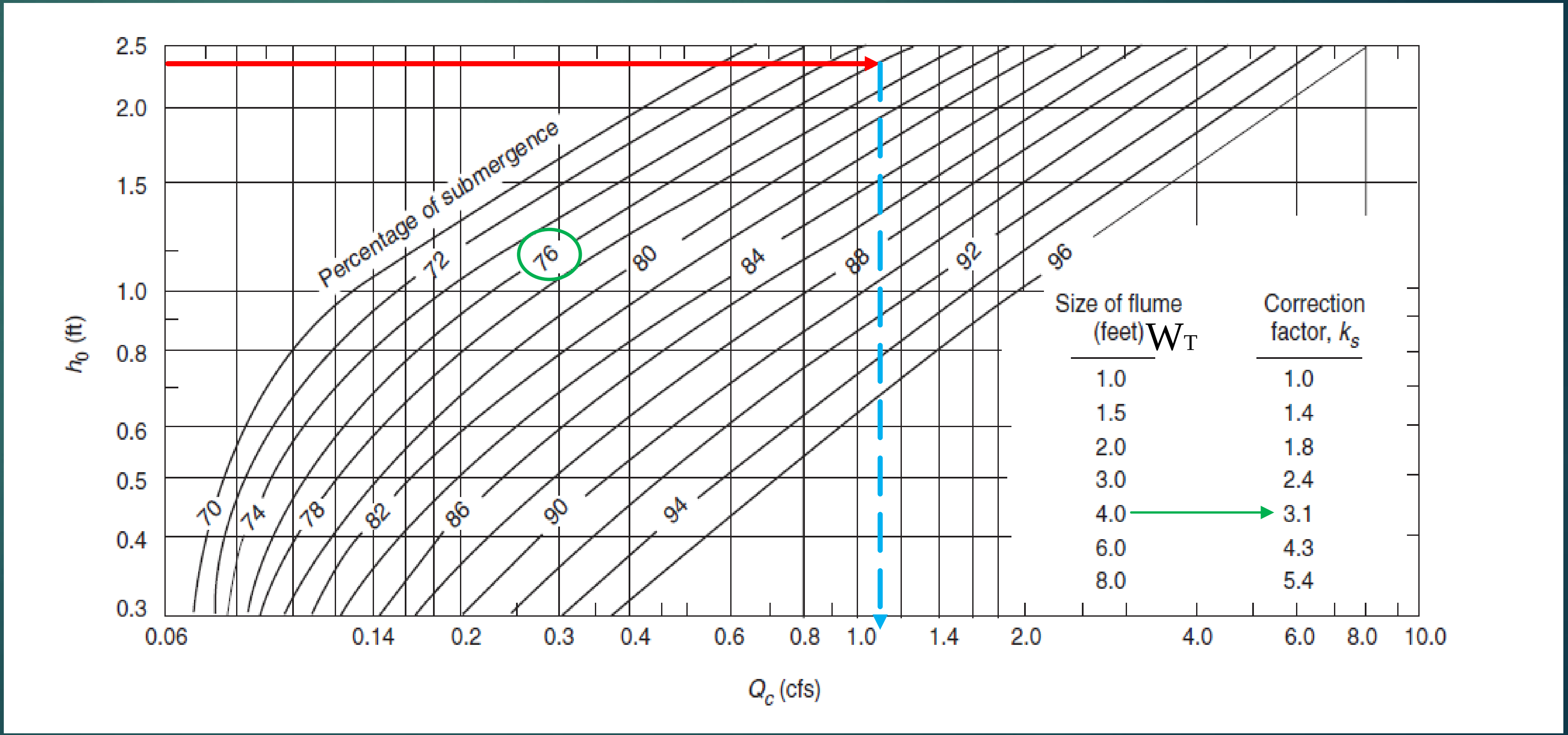


Widths			Axial lengths			Vertical dimensions			Gage points				Free flow capacity	
W_T (ft)	W_C (ft)	W_D (ft)	L_C (ft)	L_T (ft)	L_D (ft)	D (ft)	N (ft)	K (ft)	C (ft)	L (ft)	a (ft)	b (ft)	Min. (cfs)	Max. (cfs)
1.0	2.77	2.00	4.41	2.0	3.0	3.0	0.75	0.25	4.50	3.00	0.167	0.25	0.11	16.1
1.5	3.36	2.50	4.66	2.0	3.0	3.0	0.75	0.25	4.75	3.17	0.167	0.25	0.15	24.6
2.0	3.96	3.00	4.91	2.0	3.0	3.0	0.75	0.25	5.00	3.33	0.167	0.25	0.42	33.1
3.0	5.16	4.00	5.40	2.0	3.0	3.0	0.75	0.25	5.50	3.67	0.167	0.25	0.61	50.4
4.0	6.35	5.00	5.88	2.0	3.0	3.0	0.75	0.25	6.00	4.00	0.167	0.25	1.30	67.9
5.0	7.55	6.00	6.38	2.0	3.0	3.0	0.75	0.25	6.50	4.33	0.167	0.25	1.60	85.6
6.0	8.75	7.00	6.86	2.0	3.0	3.0	0.75	0.25	7.00	4.67	0.167	0.25	2.60	103.5
7.0	9.95	8.00	7.35	2.0	3.0	3.0	0.75	0.25	7.50	5.00	0.167	0.25	3.00	121.4
8.0	11.15	9.00	7.84	2.0	3.0	3.0	0.75	0.25	8.00	5.33	0.167	0.25	3.50	139.5
10.0	15.60	12.00	14.00	3.0	6.0	4.0	1.12	0.50	9.00	6.00			6.0	300.0
12.0	18.40	14.67	16.0	3.0	8.0	5.0	1.12	0.50	10.00	6.67			8.0	520.0
15.0	25.00	18.33	25.00	4.0	10.0	6.0	1.50	0.75	11.50	7.67			8.0	900.0
20.0	30.00	24.00	25.00	6.0	12.0	7.0	2.25	1.00	14.00	9.33			10.0	1340.0
25.0	35.00	29.33	25.00	6.0	13.0	7.0	2.25	1.00	16.50	11.00			15.0	1660.0
30.0	40.40	34.67	26.00	6.0	14.0	7.0	2.25	1.00	19.00	12.67			15.0	1990.0
40.0	50.80	45.33	27.00	6.0	16.0	7.0	2.25	1.00	24.00	16.00			20.0	2640.0
50.0	60.80	56.67	27.00	6.0	20.0	7.0	2.25	1.00	29.00	19.33			25.0	3280.0

Flow Control and Measurement (Flume)

Example 5-3

Suppose the downstream depth is $h_T = 1.82\ ft$ in the Parshall flume considered in Example 5.2. Determine the discharge.



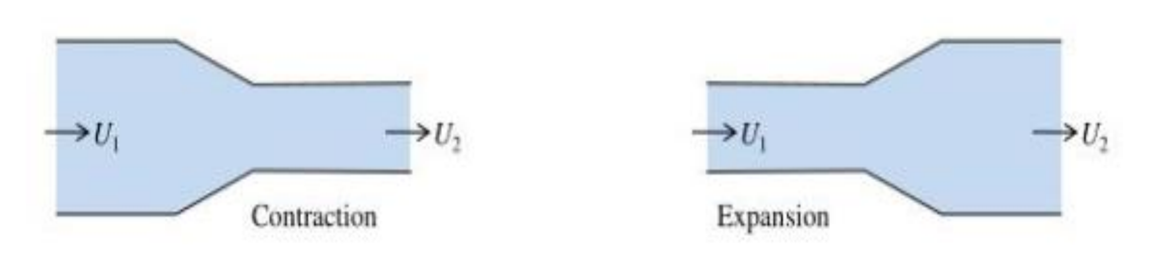
Size of flume (feet) W_T	Correction factor, k_s
1.0	1.0
1.5	1.4
2.0	1.8
3.0	2.4
4.0	3.1
6.0	4.3
8.0	5.4

Channel Transition

- A structure designed to convey water smoothly from a conduit of one shape to one of different shape is called transition.
- A common transition for open channel flow is used between a canal of *trapezoidal* cross section and a flume of *rectangular* cross section.

Channel Transition

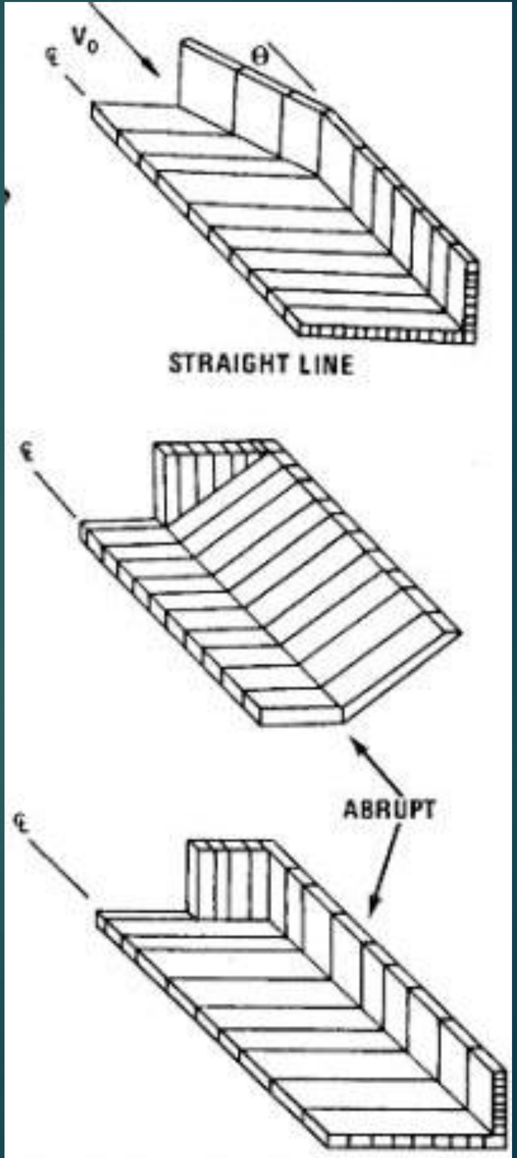
- If the transition is from a conduit of large cross section to one of smaller cross section, it is an inlet transition or a contraction.
- If the transition is from an smaller one to a larger one, it is an expansion.



Channel Transition

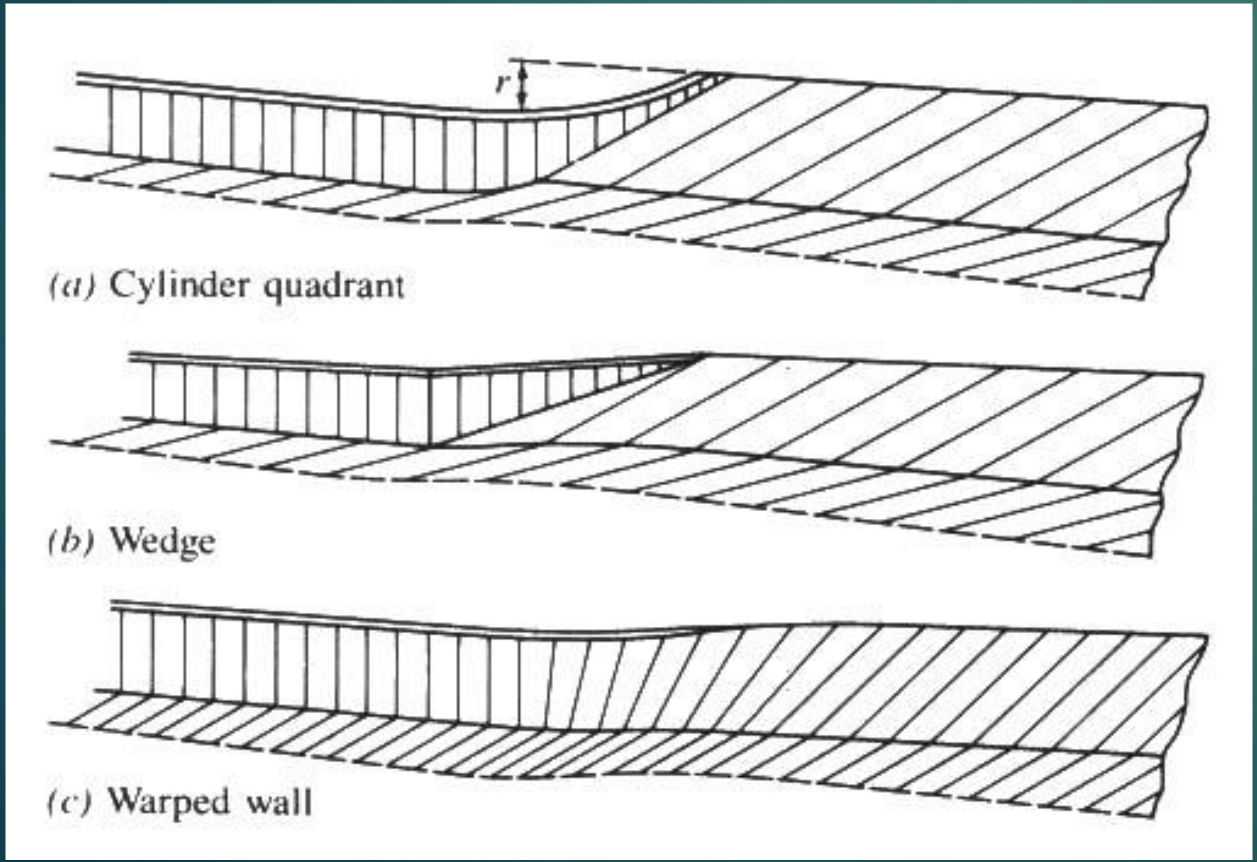
- The simplest type of transition is a straight wall constructed normal to the flow direction.

- This type of transition can work, but it will produce excessive head loss because of the abrupt change in cross section and ensuing separation that would occur.
- To prevent excessive head loss and to reduce the possibility of erosion in the case of an expansion to an erodible channel, a more gradual type of transition is usually used.



Channel Transition

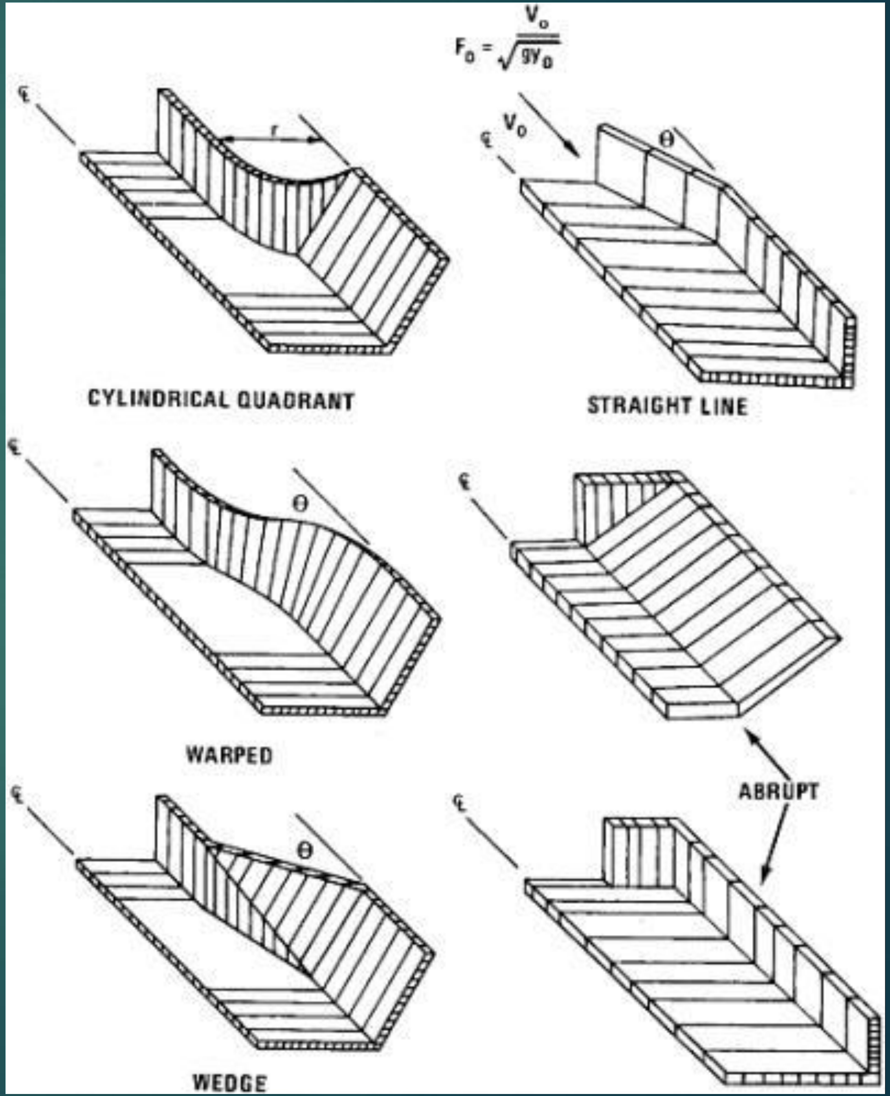
- Three common types of gradual transitions are the Cylinder-quadrant, the Wedge (often called Broken-Back), and the Warped-Wall



(a) Cylinder quadrant

(b) Wedge

(c) Warped wall



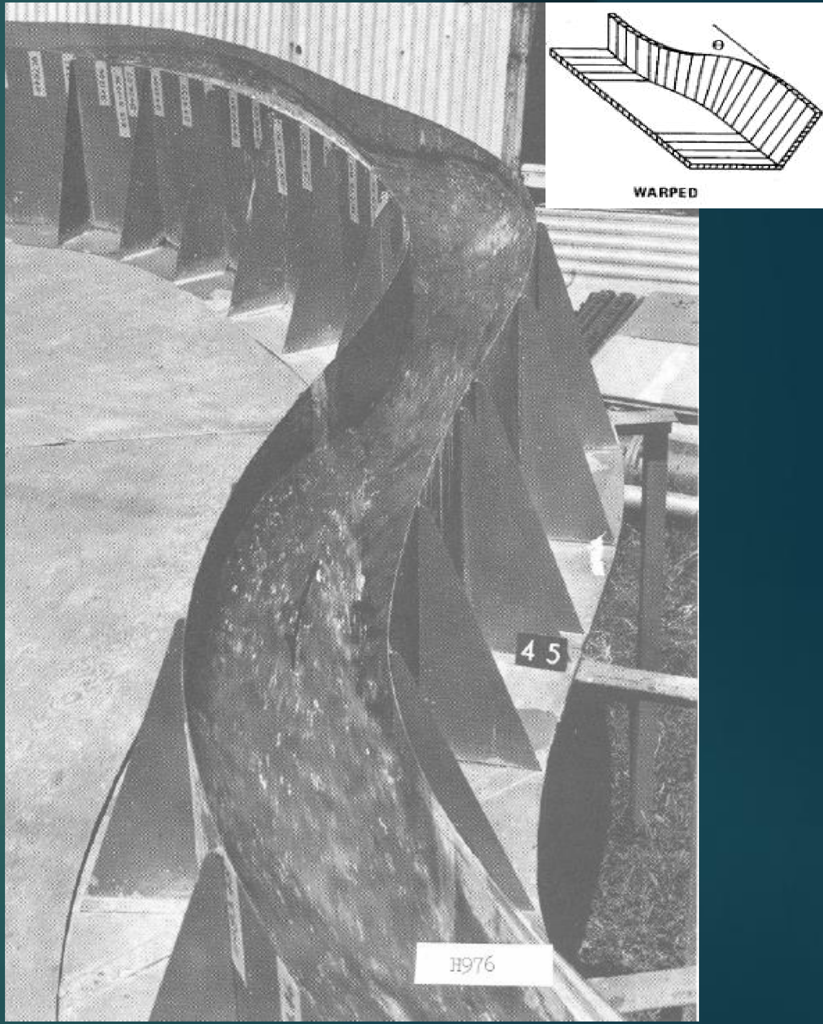
Channel Transition

- All three of these can be successfully used for inlet transitions, but because they are more gradual expansions the Wedge and Warped wall are best suited for expansion if head-loss or erosion is significant.

- The Warped wall is more expensive to build than the others because of the complicated from work required.

- In the case of Wedge transition, the recommended angle is 27.5° and 22.5° respectively, for inlet and expansions.

- For the Warped-Wall transition, the recommended angle is 12.5° for both the inlet and expansion.



Design Channel Transition

- Before the transition itself is designed, the following variables must be given:
  1. Depth in both flume and channel
  2. Velocity in both flume and channel
  3. Water surface elevation in upstream of channel for the case of inlet, and downstream water surface elevation for expansion.

STEPS

1. Choose the type of transition to be used (Cylinder-quadrant, Wedge, or Warped wall)
2. Apply the **energy equation** between the upstream and downstream ends of transition to calculate the water surface elevation:

   2.1. At the downstream end of transition for an inlet transition.

   2.2. At the upstream for an expansion.

Design Channel Transition

- The energy equation will include a head-loss term for the transition.
- For an inlet transition the head-loss is given as:

$$\frac{K_L V^2}{2g}$$

The velocity in the downstream conduit.

The head-loss coefficient for the transition.

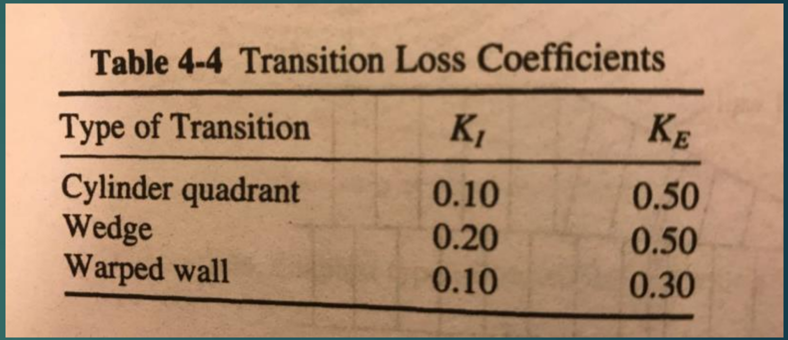


Table 4-4 Transition Loss Coefficients

Type of Transition	K_I	K_E
Cylinder quadrant	0.10	0.50
Wedge	0.20	0.50
Warped wall	0.10	0.30

- For an expansion the head-loss is given as:

$$\frac{K_E(V_1^2 - V_2^2)}{2g}$$

The expansion loss coefficient.

The velocity at the downstream end.

The velocity at the upstream end of expansion.

Design Channel Transition

3.1. For an inlet transition, calculate the downstream invert elevation.

3.2. For an expansion, calculate the upstream invert elevation.

The invert elevation is simply the water surface elevation at that section minus the depth of water in the flume.

4. Establish invert elevations along the transition by making a straight-line elevation change between the upstream and downstream ends of the transition.

Design Channel Transition

5. Establish water surface elevations through the transition.

- As first approximation, assume a straight line change in water surface elevation between the upstream and downstream ends.
- Then using velocities based on the assumed water surface elevations, apply the energy equation from the upstream end of the transition to the other sections to solve for more accurate water surface elevation elevations at prescribed sections.
- For these calculations, a head-loss in proportion to distance along the transition is usually used (for example, the head-loss halfway down the transition would be assumed to be one half of that for the entire section).

Design Channel Transition

Example 5-4

A transition is needed between a trapezoidal channel carrying water (depth is 3.0 ft and velocity is 2.30 ft/s) and a flume of rectangular cross section.

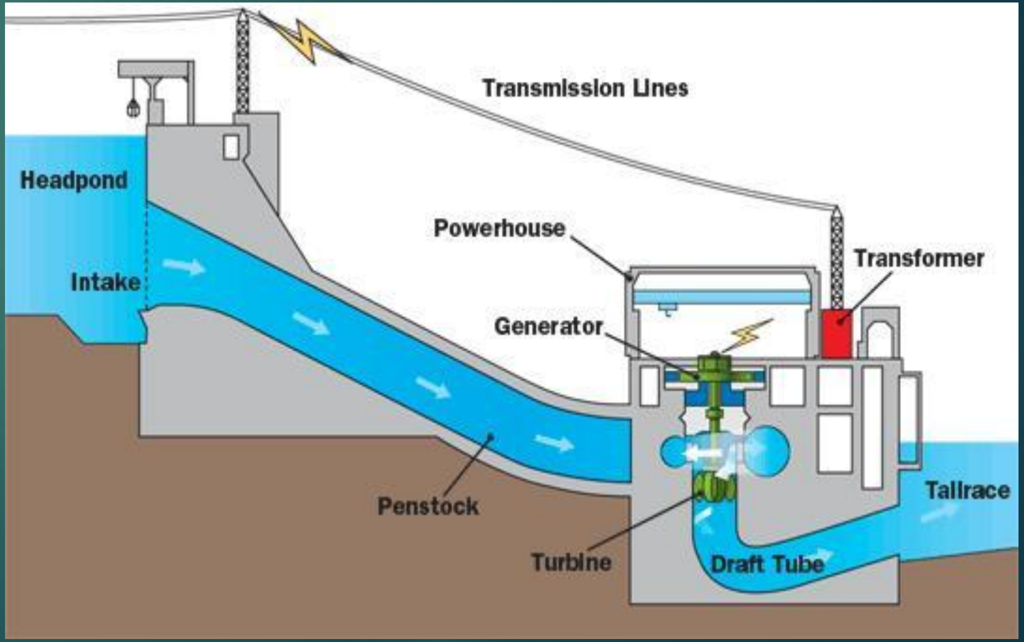
The flume will convey the water around a steep hill. The channel has a bottom width of 10 ft and side slopes of 1 vertical 2 horizontal. The invert elevation of the channel at its downstream end (upstream end of transition) is 1000 ft.

The flume velocity is to be 5.90 ft/s. Determine the proportions for the flume (width and wall height) to keep the Froude number below 0.5, and design a transition to join the channel and flume.

Spillways

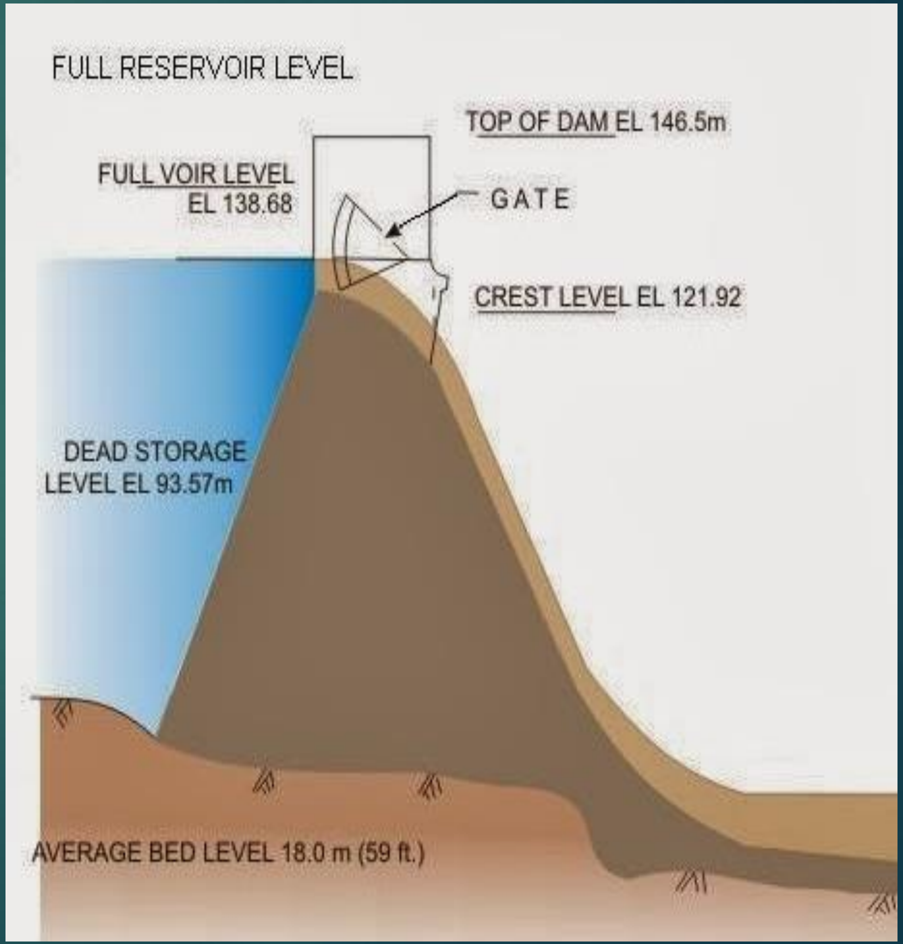
- A Spillway is nearly always required to pass flow by a dam.
- In the case hydropower dams, where large flows pass through hydraulic turbines, spillway maybe used infrequently to pass flood.

- The safe operation of spillways is the main objective in design, because the failure to perform its design function can lead to failure of a dam.
- As dams raise water level, spillways must be designed for high velocity flow.

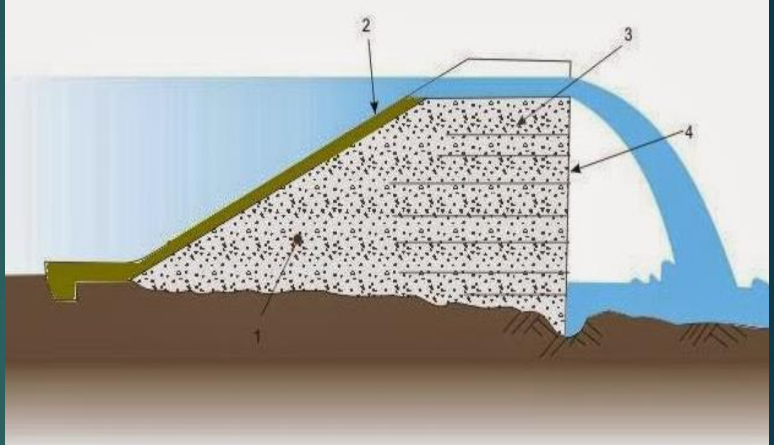


Spillways

Controlled Spillways: It has mechanical structure or gates to regulate the rate of flow of water from the reservoir.



Spillways



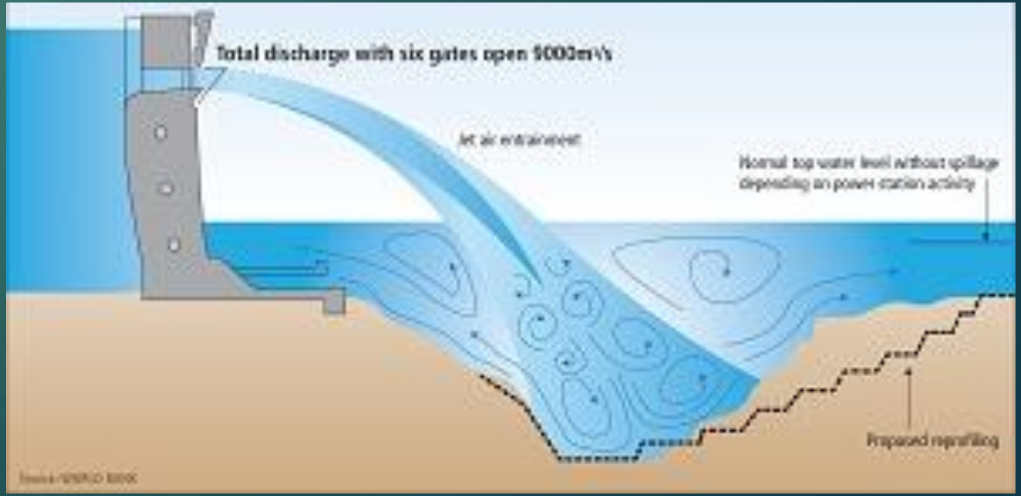
Uncontrolled Spillways: This doesn’t have a gate and when the water raises above the crest of the spillway, start releasing from reservoir.

Spillways

Types of Spillway

Type # 1: Free Over-Fall Spillway

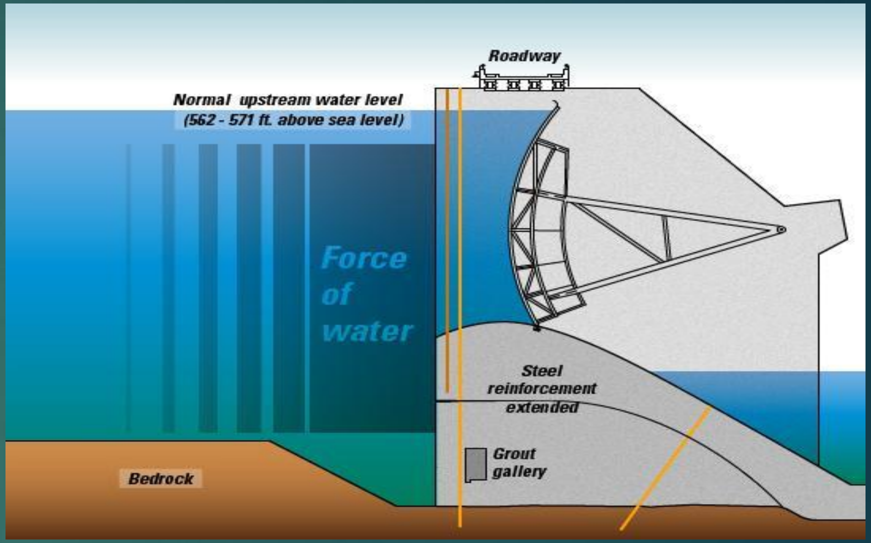
- As the name of the spillway indicates, the flow drops freely from the crest of a free over-fall spillway.
- Such a spillway is better suited for a thin arch dam whose downstream face is nearly vertical.
- In order to protect the stream bed from erosion, an artificial concrete pool is usually constructed which is called Plunge pool.



Spillways

Type # 2: Ogee Spillway

- The ogee or overflow spillway is the most common type of spillway.
- The structure divides naturally into three zones: the crest, the slope, and the toe.
- The nappe-shaped profile is an ideal profile because at the design head, the water flowing over the crest of the spillway always remains in contact with the surface of the spillway as it glides over it.

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Spillways

Type # 2: Ogee Spillway

- The discharge over an ungated spillway is controlled by the head on the crest and the discharge equation is given as:

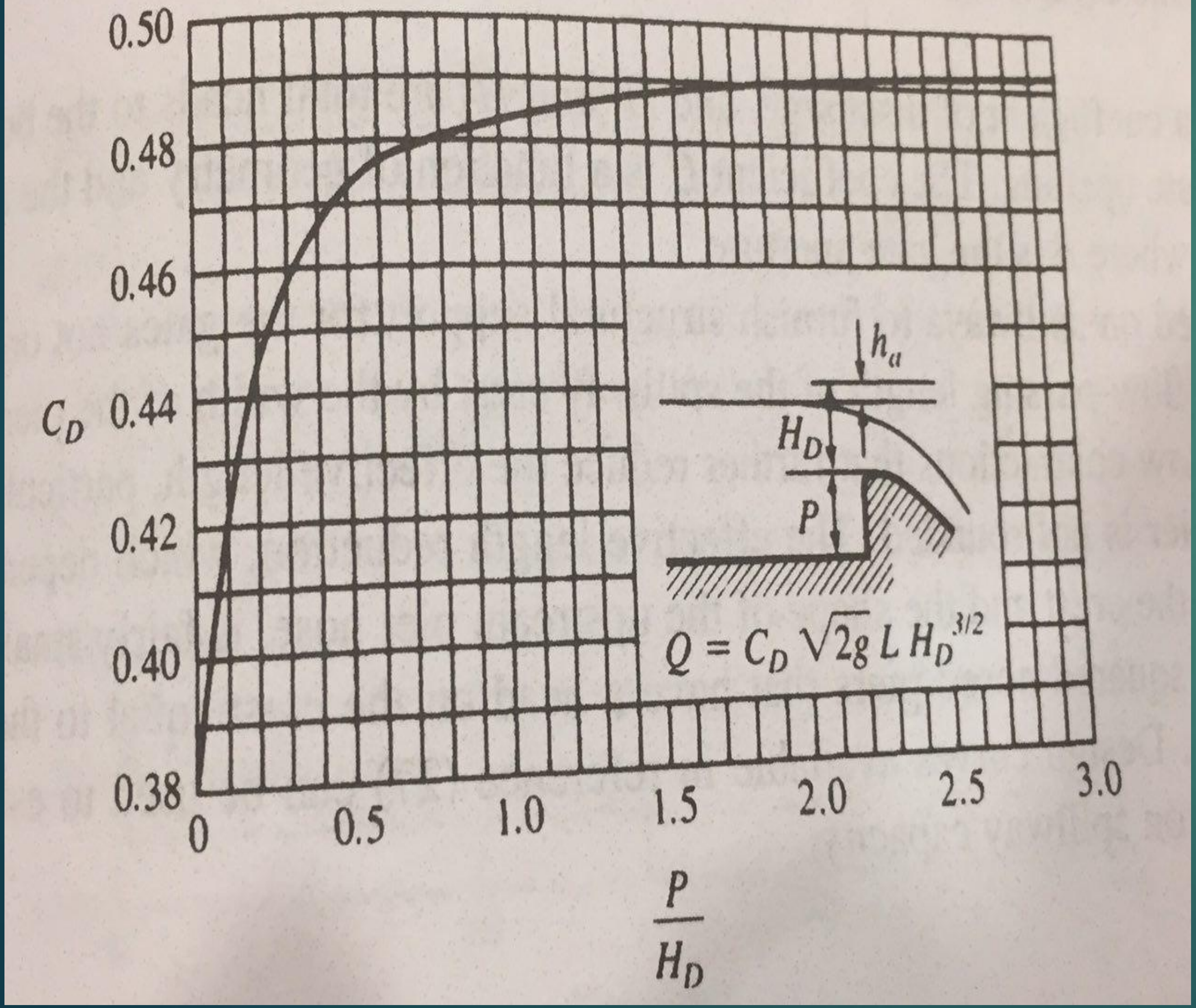
$$Q = C\sqrt{2g}LH^{3/2}$$

  - Where, Q is flow rate, C is dimensionless coefficient of discharge, L is the crest length (or crest width), and H is the total head.

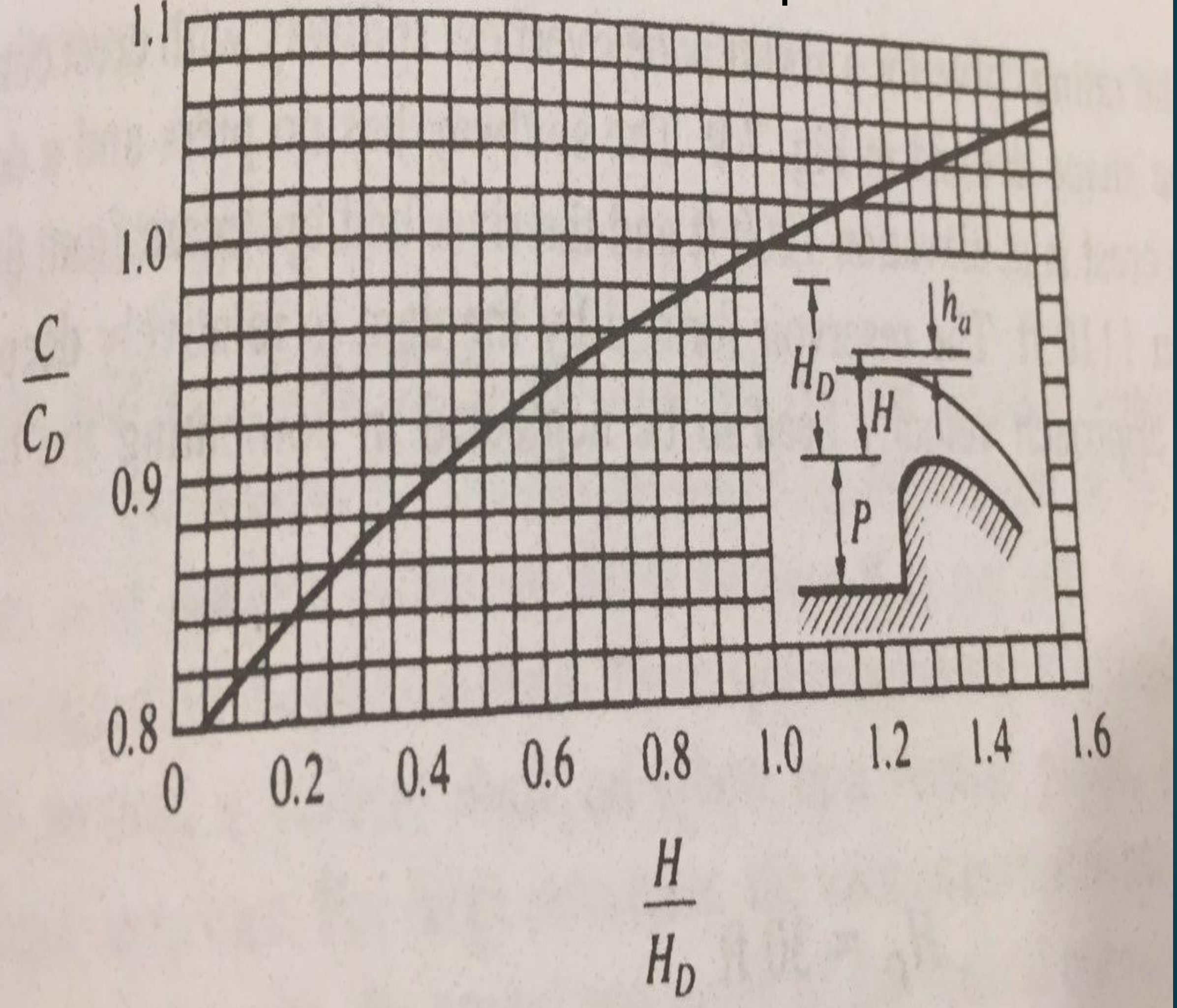
  - The coefficient C depends on the approach depth, shape of the crest, and the upstream face slope.

Spillways

HD is the design head, **P** is the height of the spillway crest



CD is the value of C when H equals **HD**



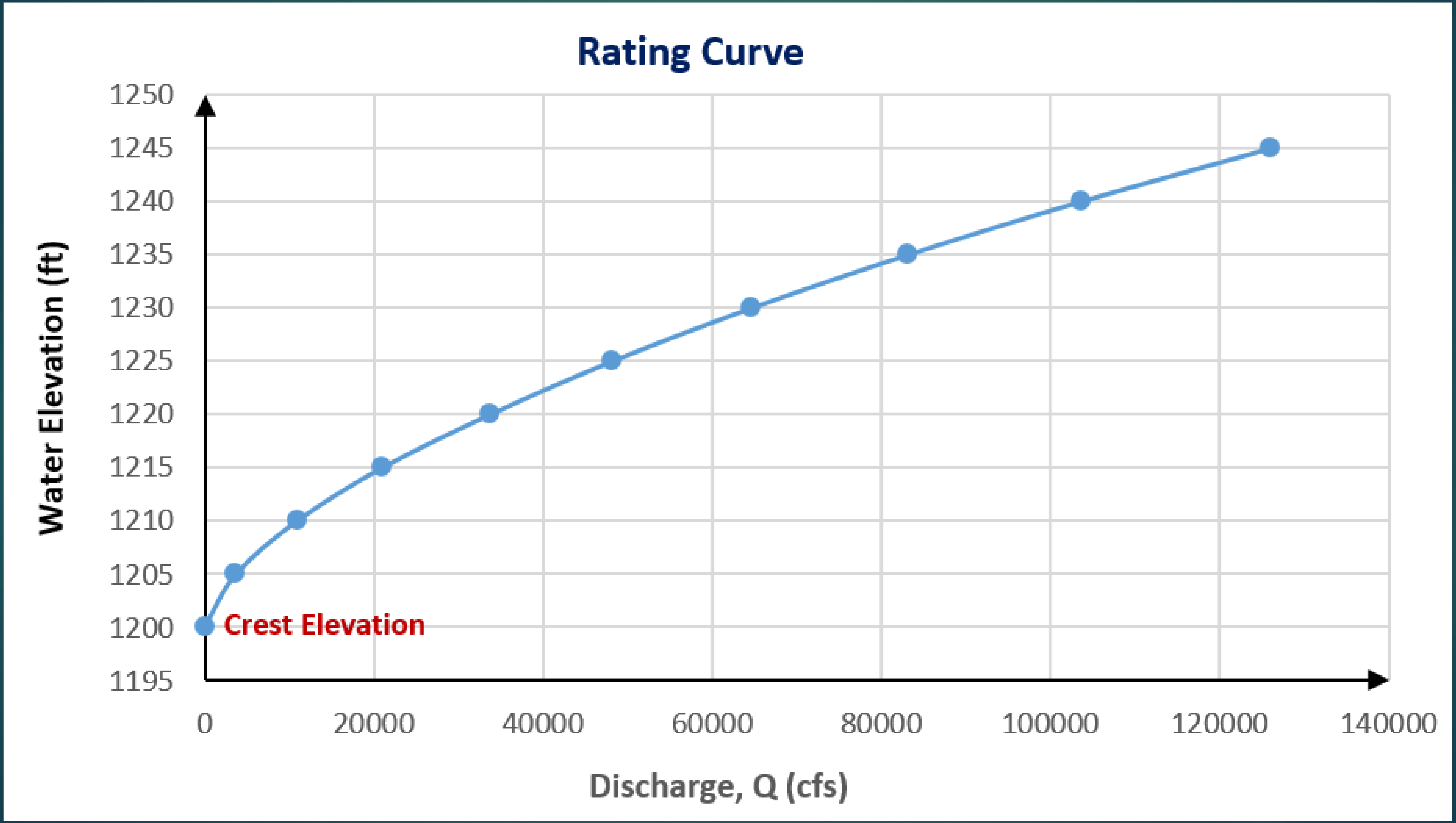
Spillways

Example 5-5

Determine the rating curve for a 100-ft wide overflow spillway with a design head of 30 ft. The crest is at elevation 1200 ft and the river bed upstream from the spillway is at elevation 1110 ft.

Rating Curve is a curve that shows the variation of water elevation flow rate.

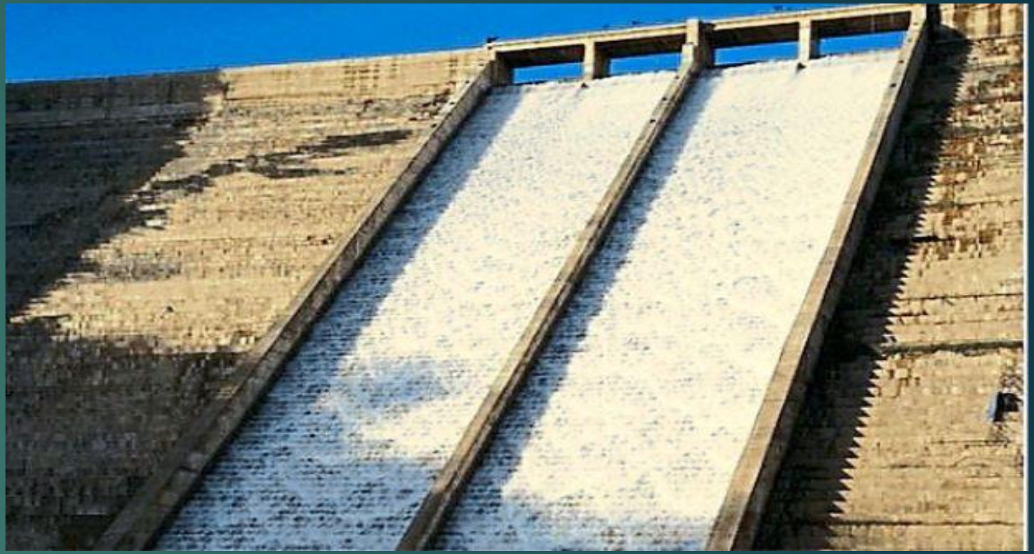
Spillways


Rating Curve
1250
1245
1240
1235
1230
1225
1220
1215
1210
1205
1200
1195
Water Elevation (ft)
Crest Elevation
0
20000
40000
60000
80000
100000
120000
140000
Discharge, Q (cfs)

Spillways

Type # 3: Chute Spillway

- Chute spillways are common and basic in design.
- The spillway's slope and it's sides are lined with concrete.



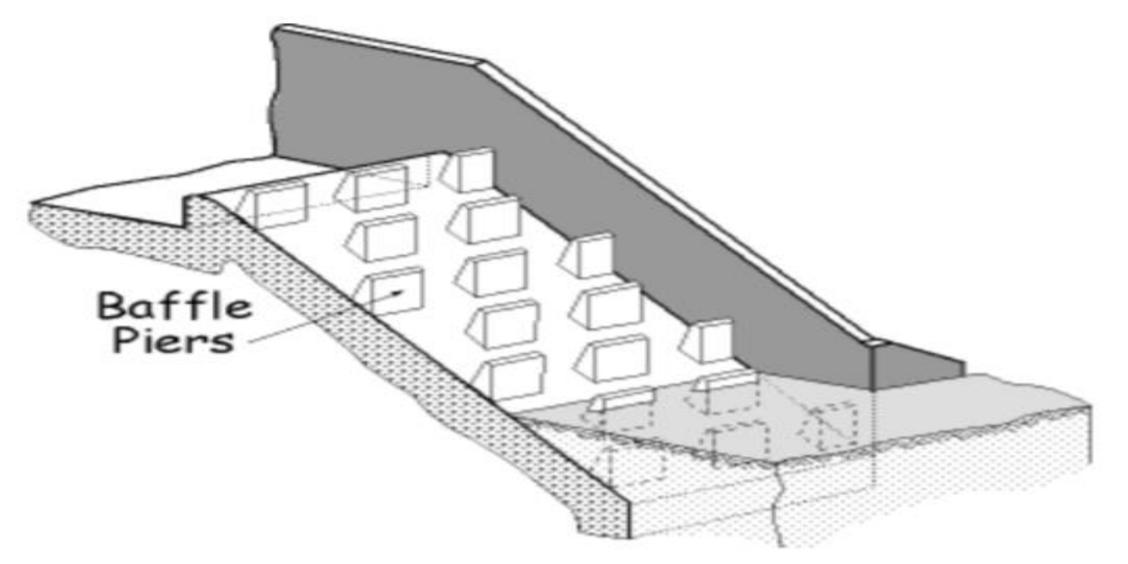
Advantages:

- The simplicity of their design and construction,
- Their adaptability to all types of foundation ranging from solid rock to soft clay.

Spillways

Baffled Chute Spillway

- A baffled chute spillway is composed of a chute that the surface is covered by a number of densely spaced baffle blocks.
- The baffle blocks dissipate the kinetic energy of the flowing water effectively.
- Special design is needed to maintain sufficiently small velocities at the entrance of a chute.

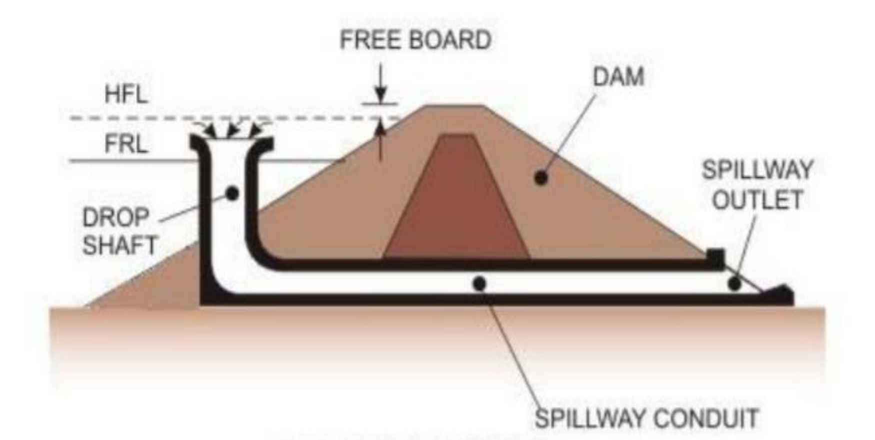


Spillways

Spillways

Type # 4: Shaft Spillway

- In a shaft spillway, water enters a horizontal crest, drops through a vertical or sloping shaft and then flows through a horizontal (or nearly horizontal) tunnel.
- The horizontal or the conduit may be taken either through the body of dam or through the underground.
- This spillway is not suitable for large capacity and deep reservoirs because of stability problems.
- Repair and maintenance of shaft spillways are difficult.



Spillways

Shaft Spillway (uncontrolled)

©Youtube.com/Alphavideochannel

Spillways

Shaft Spillway (controlled)

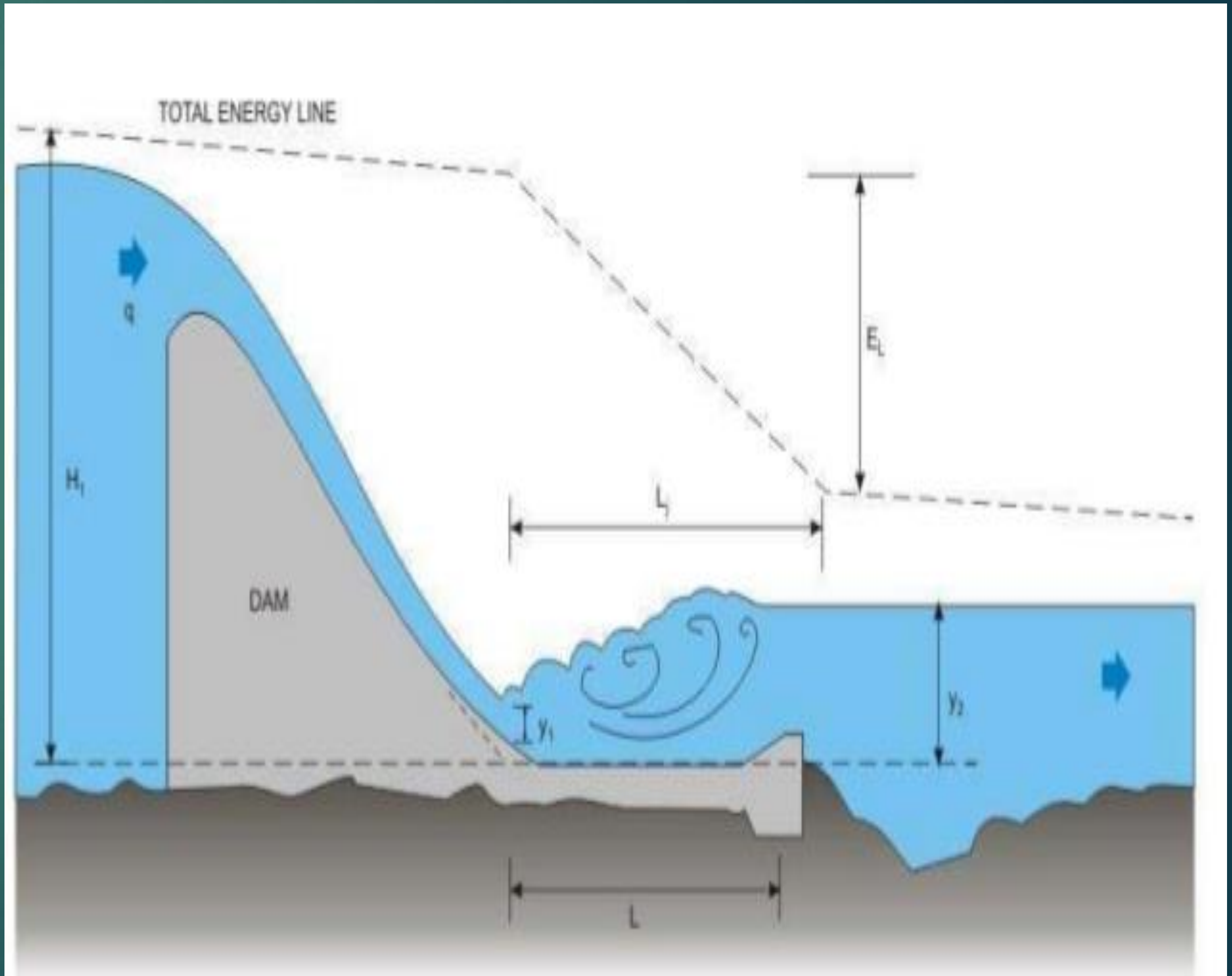
Terminal Structures

- As the water flows over the spillway crest and down the spillway body, it gains very high velocities as the potential energy is converted to kinetic energy.
- At the toe of the spillway the flow is supercritical, and it has high enough energy to cause erosion in the streambeds and banks downstream.
- Stilling basins are used for the flow to dissipate part of this energy before it is conveyed to the downstream river channel.

Terminal Structures

Position of Hydraulic Jump

- The energy dissipation occurs through a hydraulic jump in the stilling basin.
- But where and how this energy dissipated is of utmost importance in controlling erosion.
- The floor elevation, length, and width of a stilling basin should be designed to ensure a stable jump that is contained within the basin.

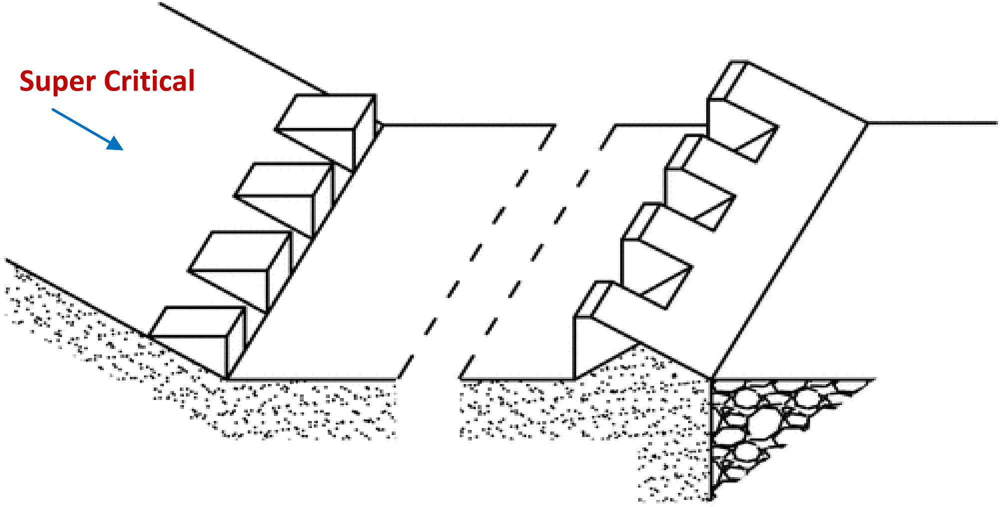


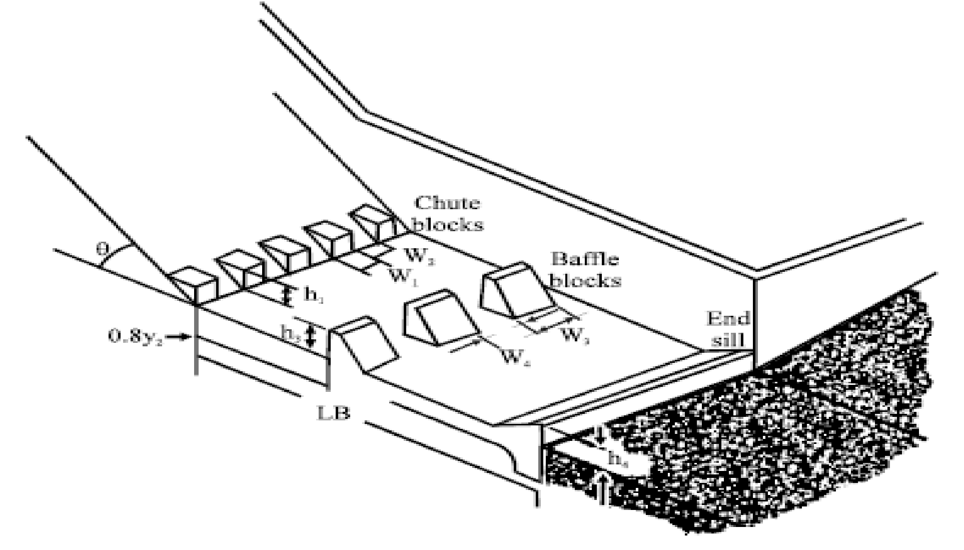
Terminal Structures

- As the flow in spillway is supercritical, we need a subcritical flow at downstream to generate a hydraulic jump.
- The stilling basin is a structure in which a hydraulic jump is generated.

$$\frac{y_2}{y_1} = \frac{1}{2}\sqrt{1 + 8Fr_1^2} - 1$$

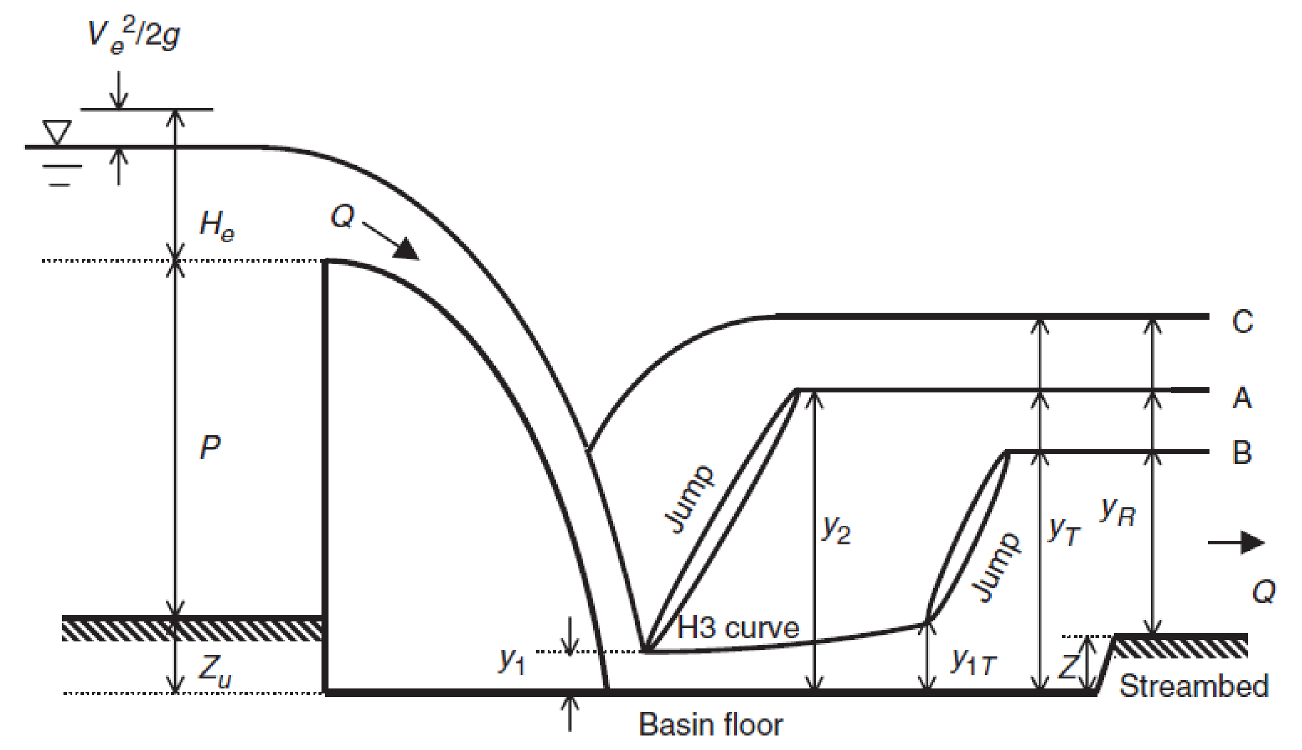
- The positioning of a hydraulic jump on the horizontal surface of the basin is very sensitive the depth y_2 from the hydraulic jump equation.





Terminal Structures

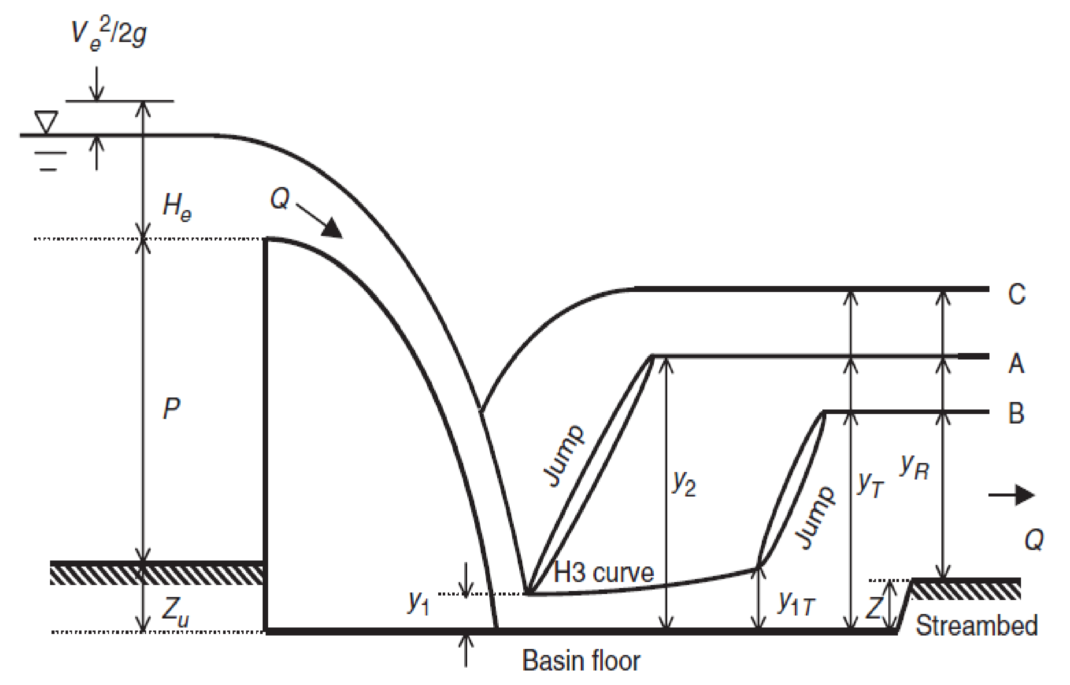
- The position of a hydraulic jump below a spillway depends on the spillway head and height, the discharge, the tailwater depth, and the width of the stilling basin.



- In case A the hydraulic jump occurs at the spillway toe,
- In case B it occurs some distance downstream.
- In case C represents a drowned jump.

Terminal Structures

- We can determine the flow depth, y_1, at the toe of the spillway by writing the energy equation between this section and a section just upstream of the spillway crest.
- Neglecting the energy loss between the two sections, we can write



$$Z_u + P + H_e = y_1 + \frac{V_1^2}{2g}$$

- Most stilling basins are rectangular in cross-section with a constant width, B.

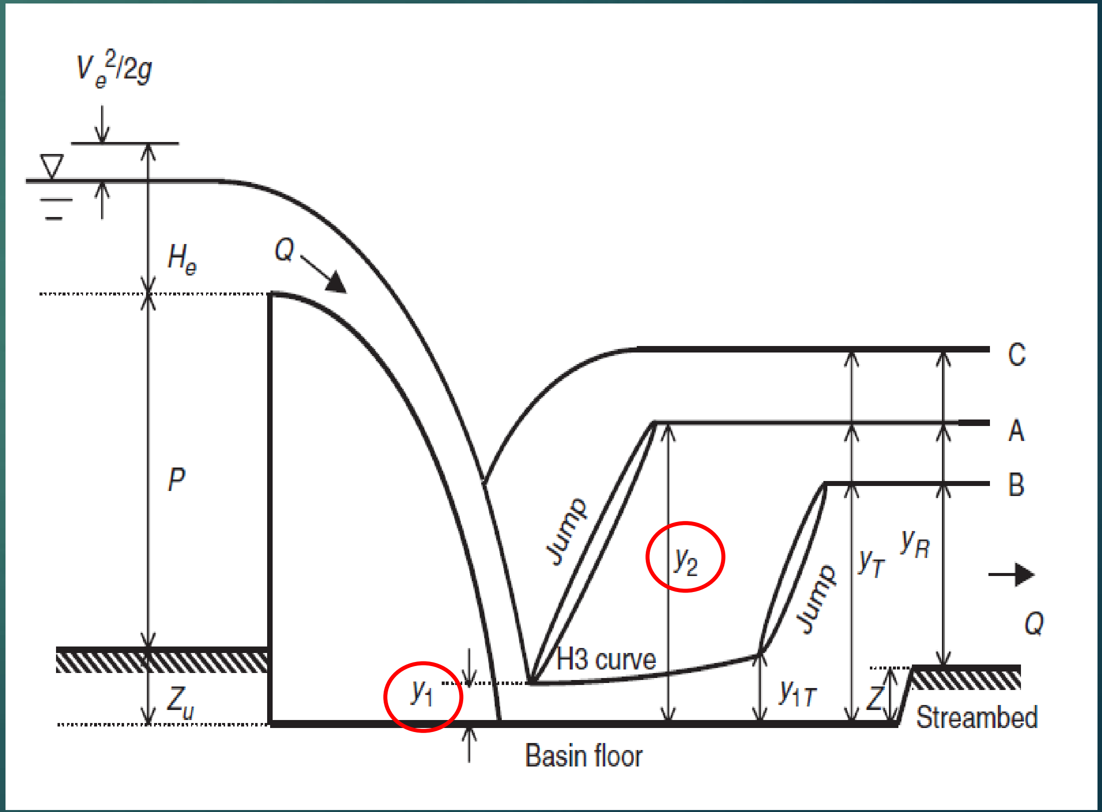
$$Z_u + P + H_e = y_1 + \frac{Q^2}{2gy_1^2B^2}$$

Terminal Structures

$$Z_u + P + H_e = y_1 + \frac{Q^2}{2gy_1^2B^2}$$

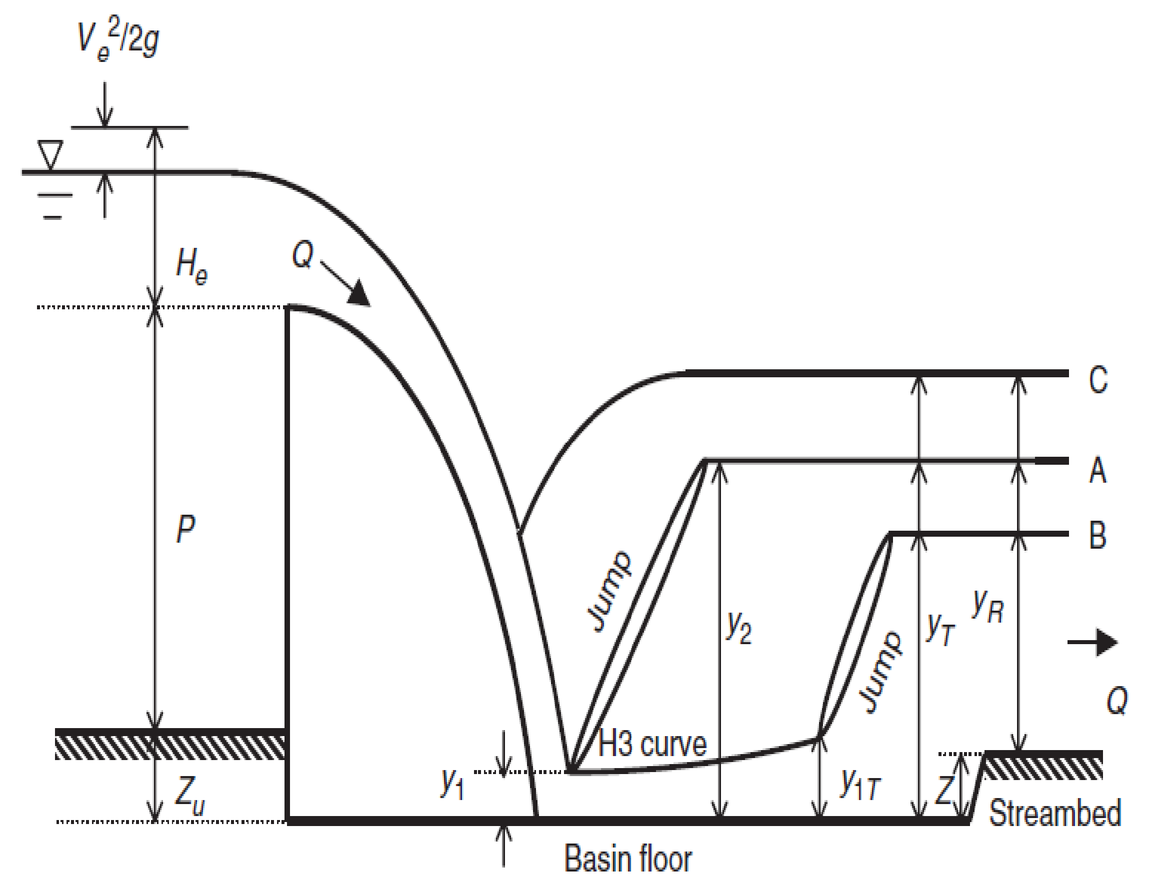
- We can solve this equation for y_1 by trial and error to find positive values of y_1 which one of them is subcritical and the other one supercritical.
- We are interested here in the supercritical depth.
- if a hydraulic jump occurred right at the toe of the spillway, the flow depth after the jump would be y_2 and can be calculated as follow:

$$\frac{y_2}{y_1} = \frac{1}{2}\sqrt{1 + 8Fr_1^2 - 1}$$



Terminal Structures

- In Figure, y_R represents the flow depth in the downstream river channel.
- From the continuity principle, the discharge Q in the river must be the same as the discharge over the spillway.
- However, the flow depth y_R depends on the cross-sectional properties of the channel, the Manning roughness factor, and the longitudinal slope.
- If $y_2 = y_T = y_R + Z$, then a hydraulic jump will occur right at the toe of the spillway as in profile A.

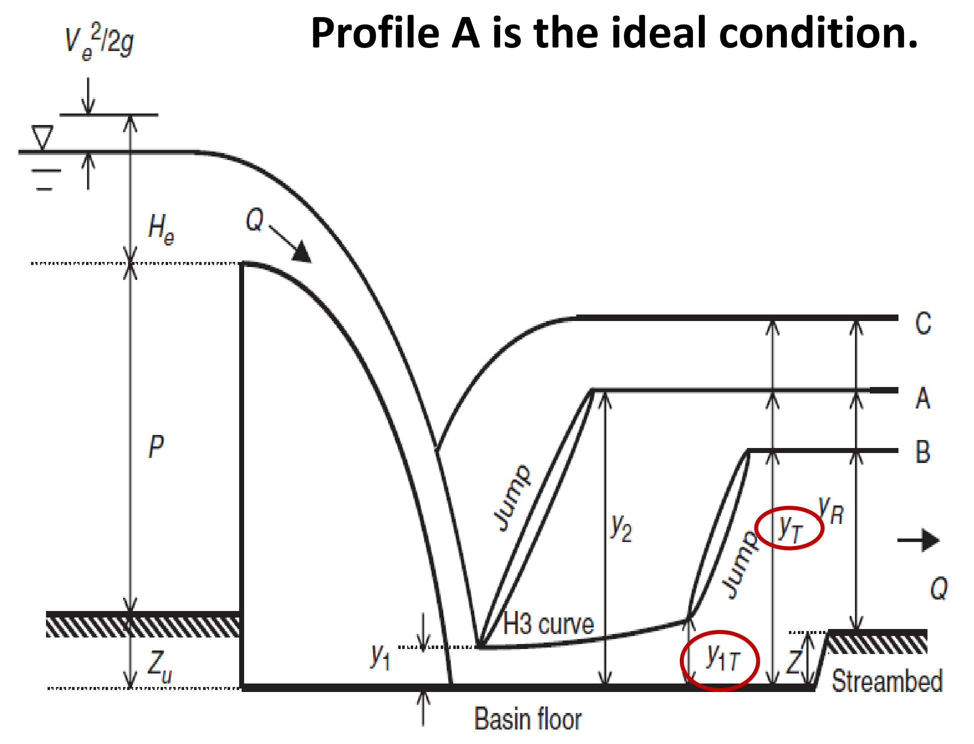


Terminal Structures

- If $y_2 > y_T$, the jump will not occur at the toe.

$$\frac{y_{1T}}{y_T} = \frac{1}{2}\sqrt{1 + 8Fr_T^2} - 1$$

- If $y_2 < y_T$, the jump will be forced upstream and drowned over the spillway body as shown in Figure by profile C.
- A drowned jump does not dissipate a significant amount of energy and is not desired in a stilling basin.
- However, condition B is not desirable either, since it would require a longer and more expensive stilling basin to contain the jump.
- where Fr_T is the Froude number corresponding to the tailwater depth y_T.

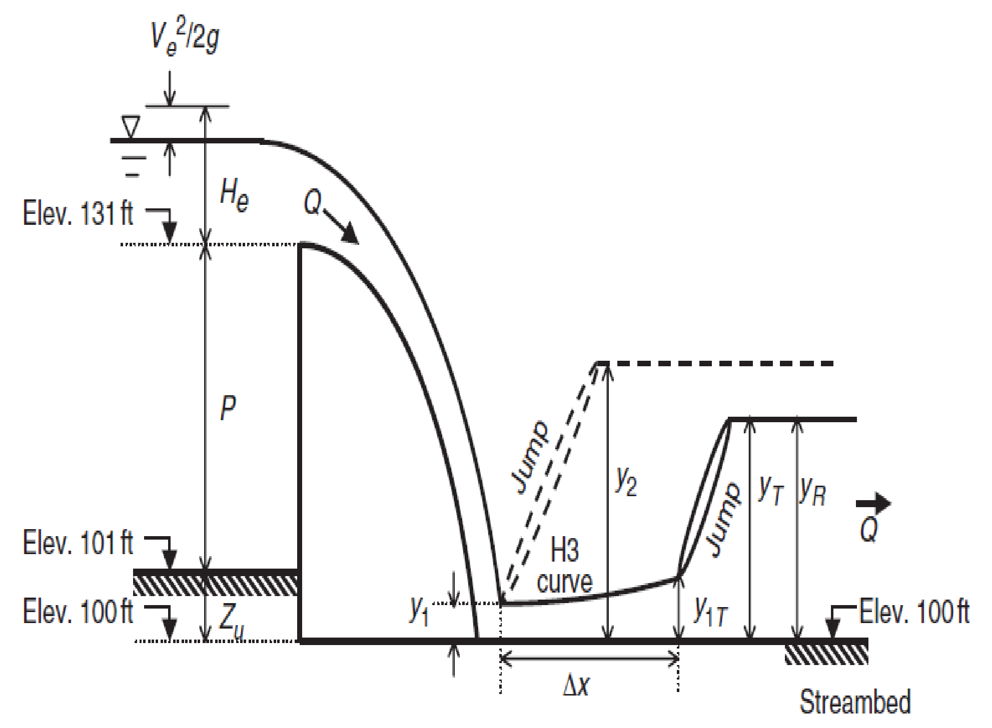

Profile A is the ideal condition.

Terminal Structures

Example 5-5

The crest of the spillway shown in Figure is shaped for a design head of 12 ft with an effective crest length of 20 ft. The crest elevation is 131 ft, and the elevation of the reservoir floor is 101 ft.

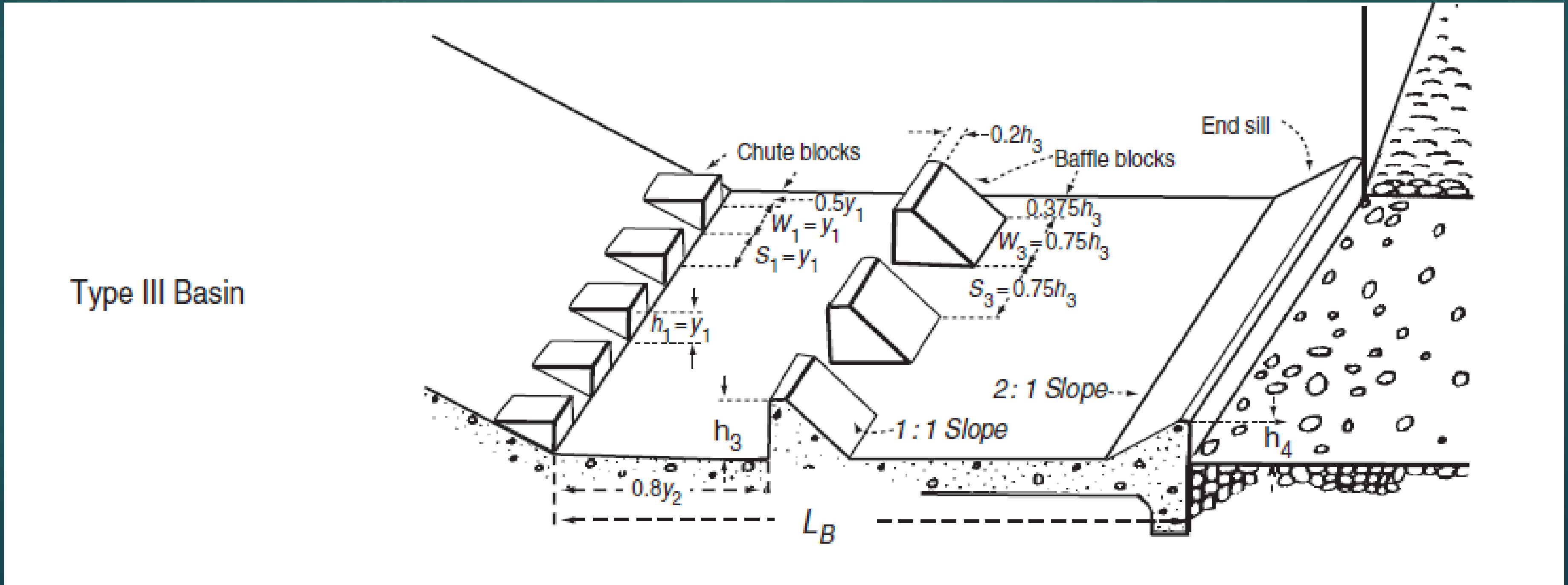
A hydraulic jump forms over a horizontal apron, which is 20 ft wide. The apron elevation is 100 ft. The natural stream can be approximated by a trapezoidal channel that has a bottom width of B=20 ft, side slopes of m=1.5, a Manning roughness factor of n=0.022, and a longitudinal bottom slope of S0=0.0001. Determine the position of the hydraulic jump with respect to the spillway toe for the design head condition.



Terminal Structures

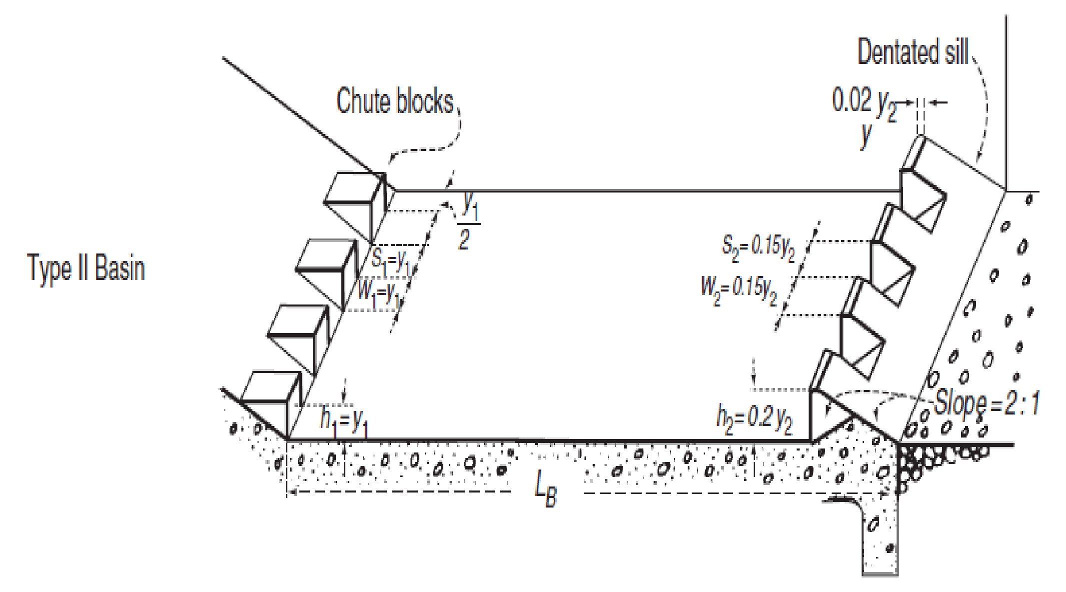
Stilling Basin Sections

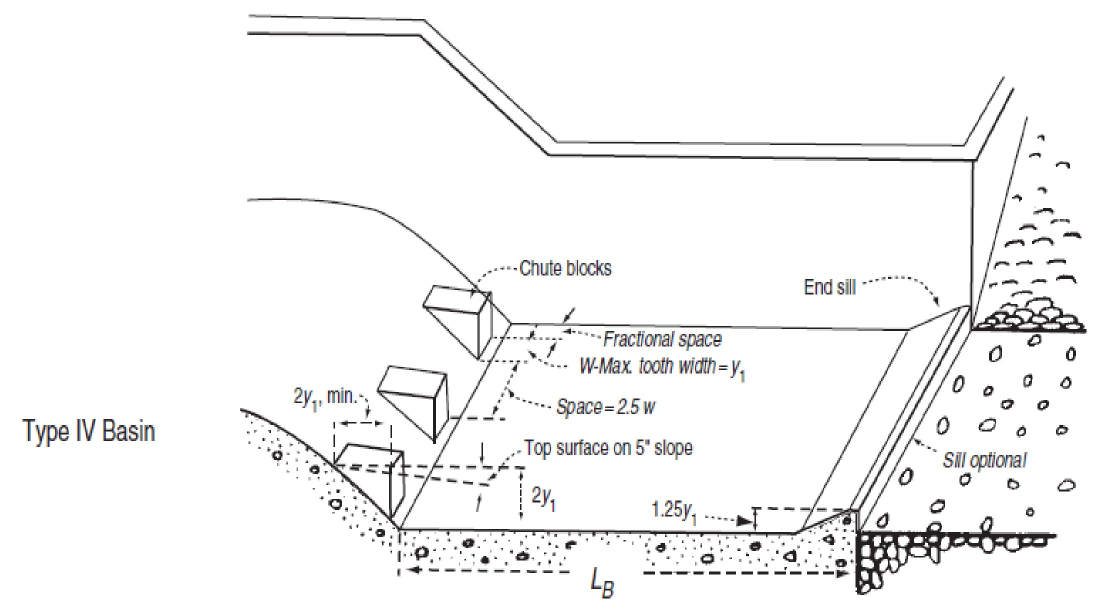
- Stilling basins include chute blocks, baffle blocks, end sills.
- Chute blocks, located at the entrance to the stilling basin and help initially to spread some of the water.



Terminal Structures

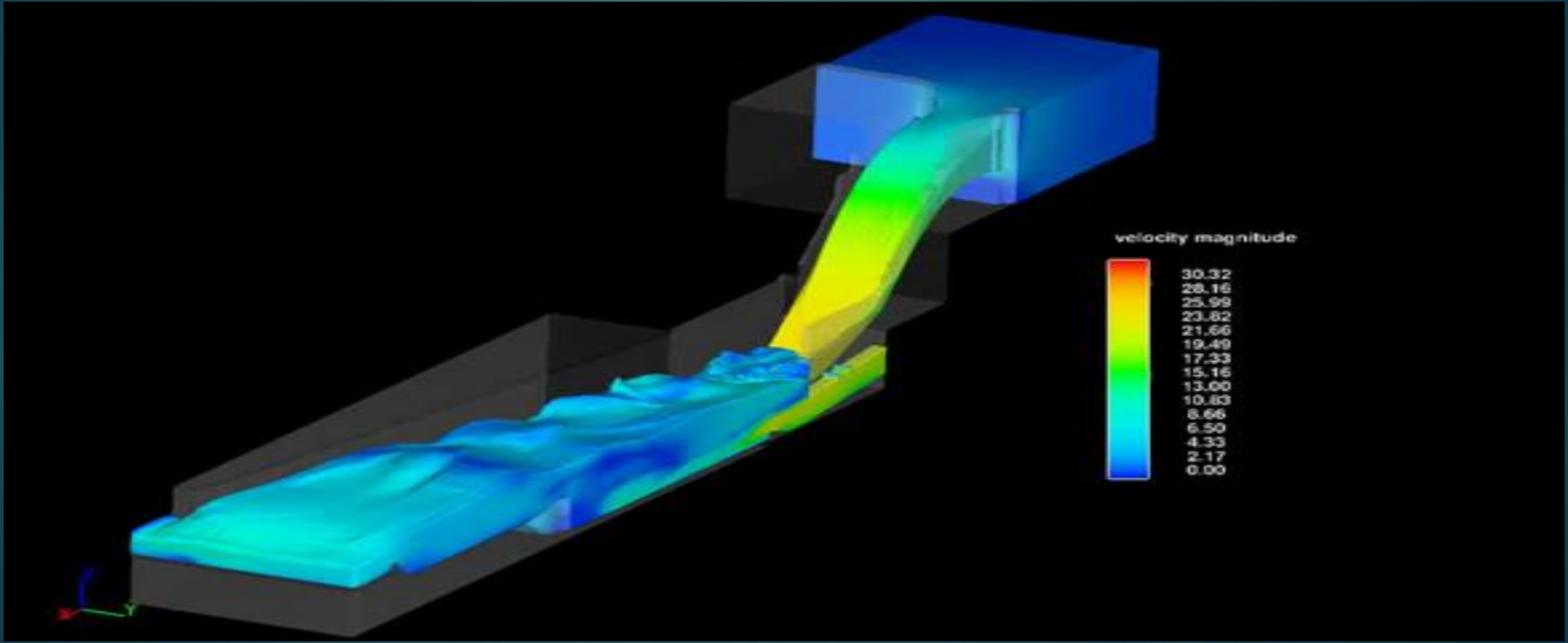
- The resisting force of the baffle blocks on the flow helps to stabilize the jump.
- The sill at the end of basin lifts the flow away from the downstream bed and produces a return current that deposits bed material immediately downstream from the stilling basin.





Terminal Structures

Simulation of Spillway, Stilling Basin and Bottom Outlet



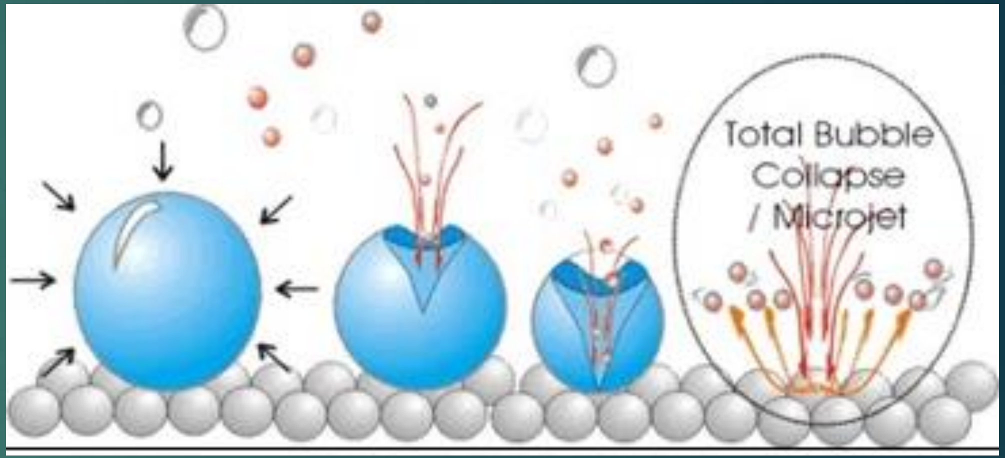
Terminal Structures

Stilling Basin

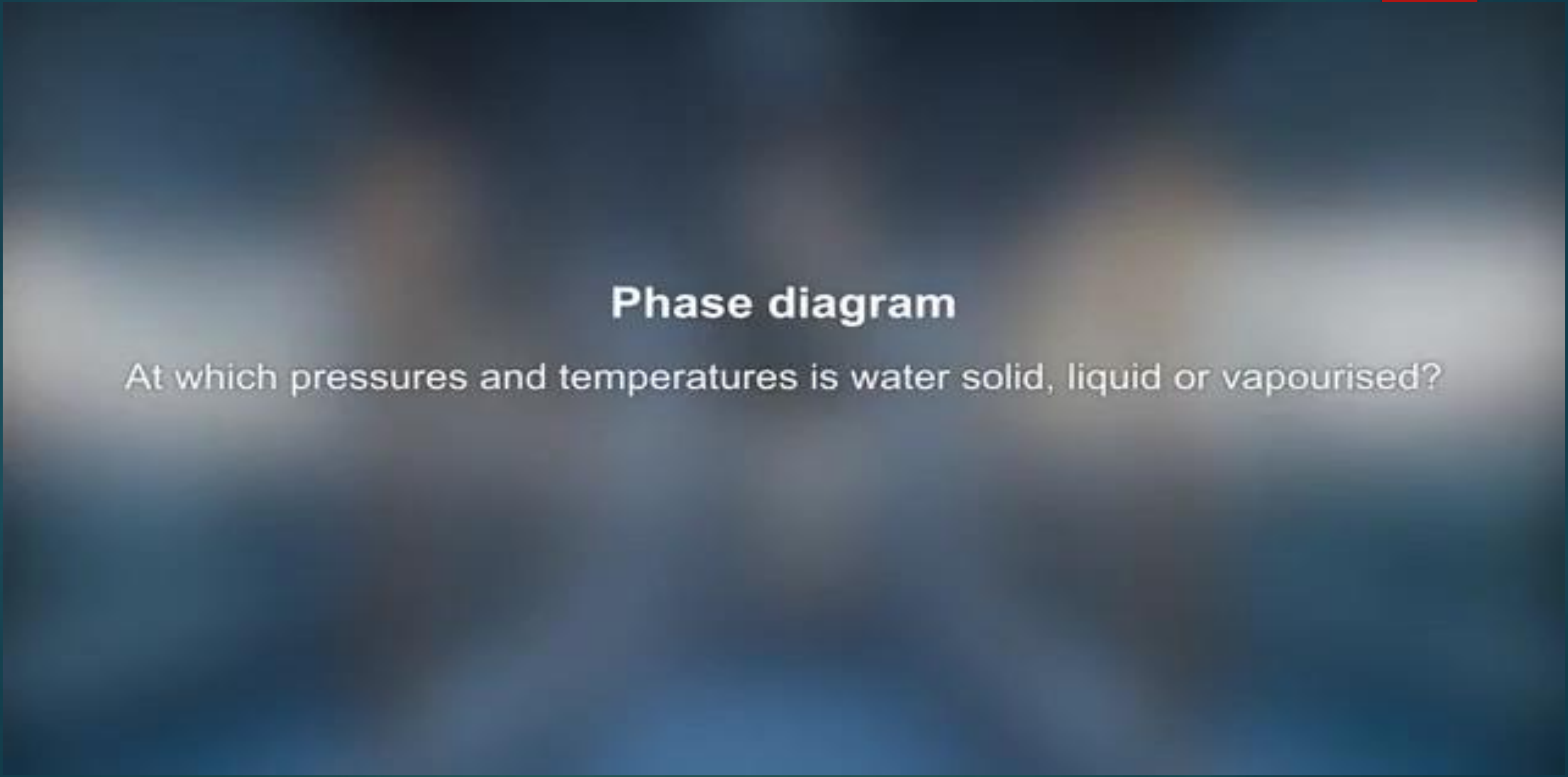
Terminal Structures

Cavitation

- Cavitation is a rapid formation and collapse of vapour bubbles within a liquid.
- It usually occurs when a liquid is subjected to rapid changes of pressure that cause the formation of cavities where the pressure is relatively low.
- When subjected to higher pressure, the voids implode and can generate an intense shock wave and martials will be eroded.
- Cavitation causes reduced performance or potential damage to the flow surface.



Cavitation



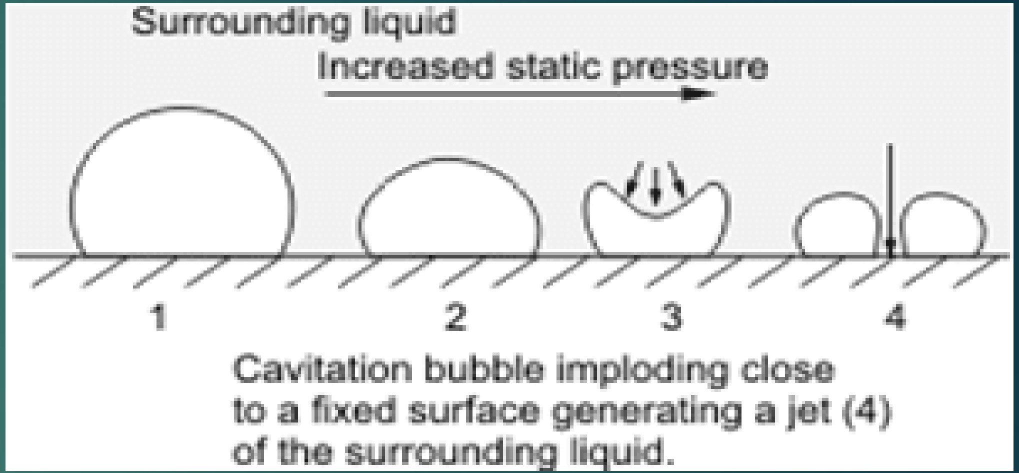
Phase diagram

At which pressures and temperatures is water solid, liquid or vapourised?

Cavitation

Cavitation in Spillways

- Spillways of high dams produce high velocities that combined with the roughness that can be resulted in cavitation.
- Cavitation damage occurs on concrete surface when discontinuity is encountered in the path of high velocity water flow.
- This discontinuity in the flow path cause the water to lift off the flow surface, creating negative pressure zones and resulting bubbles of water vapor.



- These bubbles travel downstream and collapse.

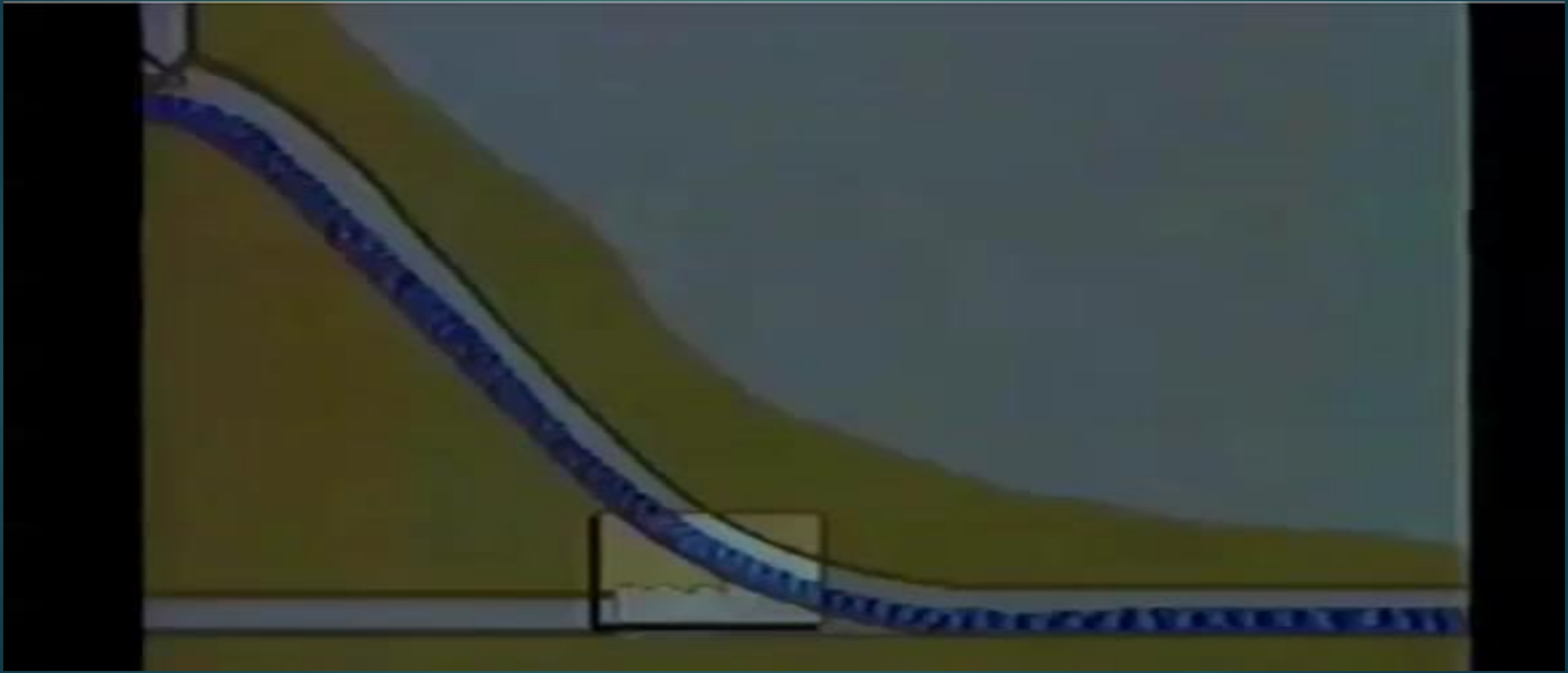
Cavitation

Cavitation in Spillways

- If the bubbles collapse against a concrete surface, it sends a very high pressure impact over an infinitely small area of the surface.
- Such high pressure impacts can remove particles of concrete, forming another discontinuity which then create more extensive cavitation damage.
- To date, no material, including stainless steel and cast iron, has been found capable of withstanding fully developed instances of cavitation.

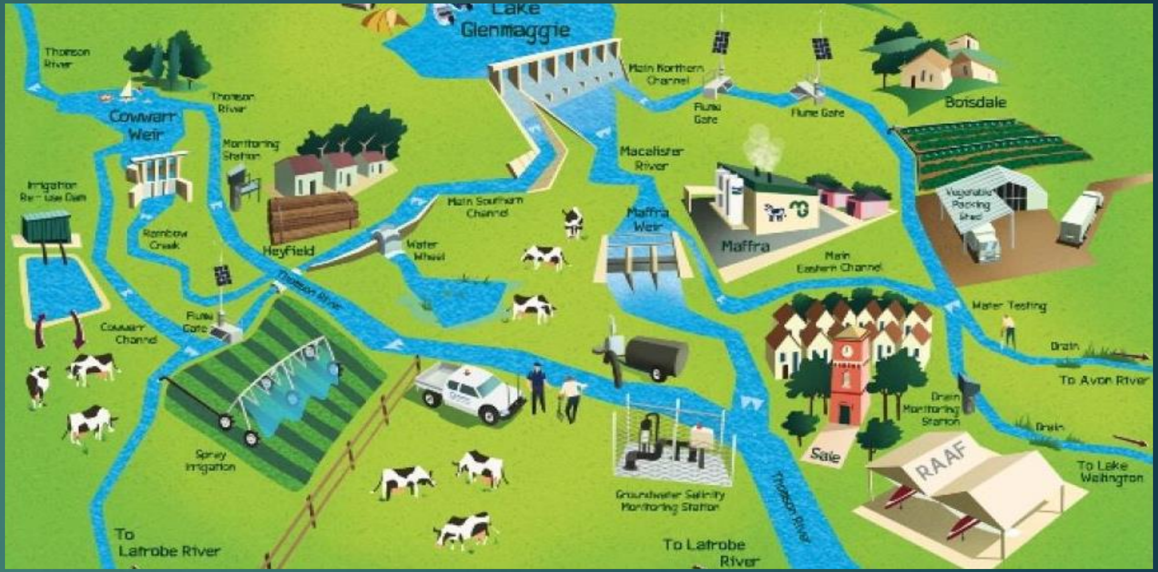
Cavitation

Spillway Cavitation



Dams and Reservoirs | Introduction

- Rivers are sources of water supply for drinking, industrial and agricultural uses and source of energy in the form of hydroelectric power.
- Rivers maybe serve as transportation arteries and sources of recreation.
- Rivers are also often used for sewage disposal.
- However, flooded rivers causing property damage and loss of life.



Dams and Reservoirs | Introduction

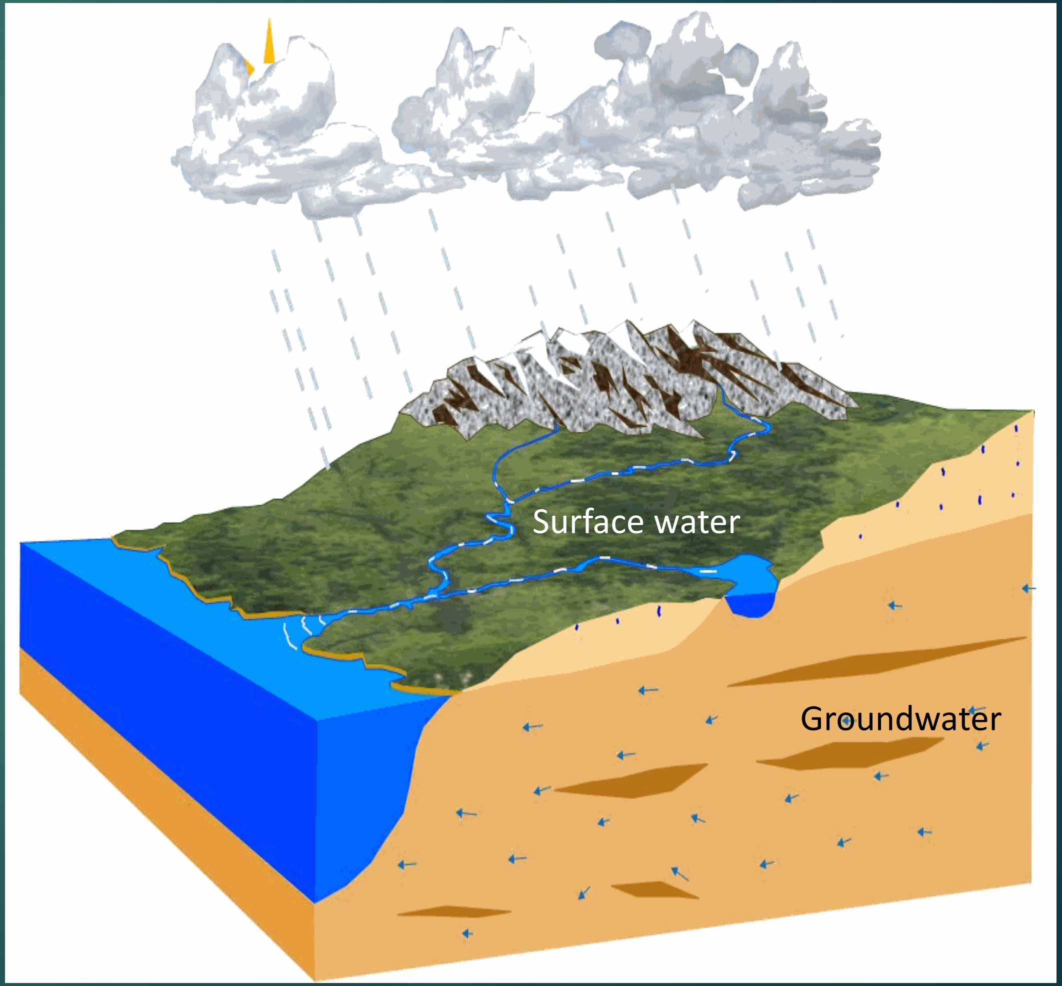
- As rivers have played an important and life-sustaining role in human societies, we need to control them to our advantages.
- Building structures such as dams is a way to control rivers.
- The most important items that must be considered in the planning and design of a *dam* and *reservoir* are:

1. Hydrological Data
2. Geologic Data
3. Reservoir Data
4. Environmental Data

Dams and Reservoirs | Introduction

Hydrological Data

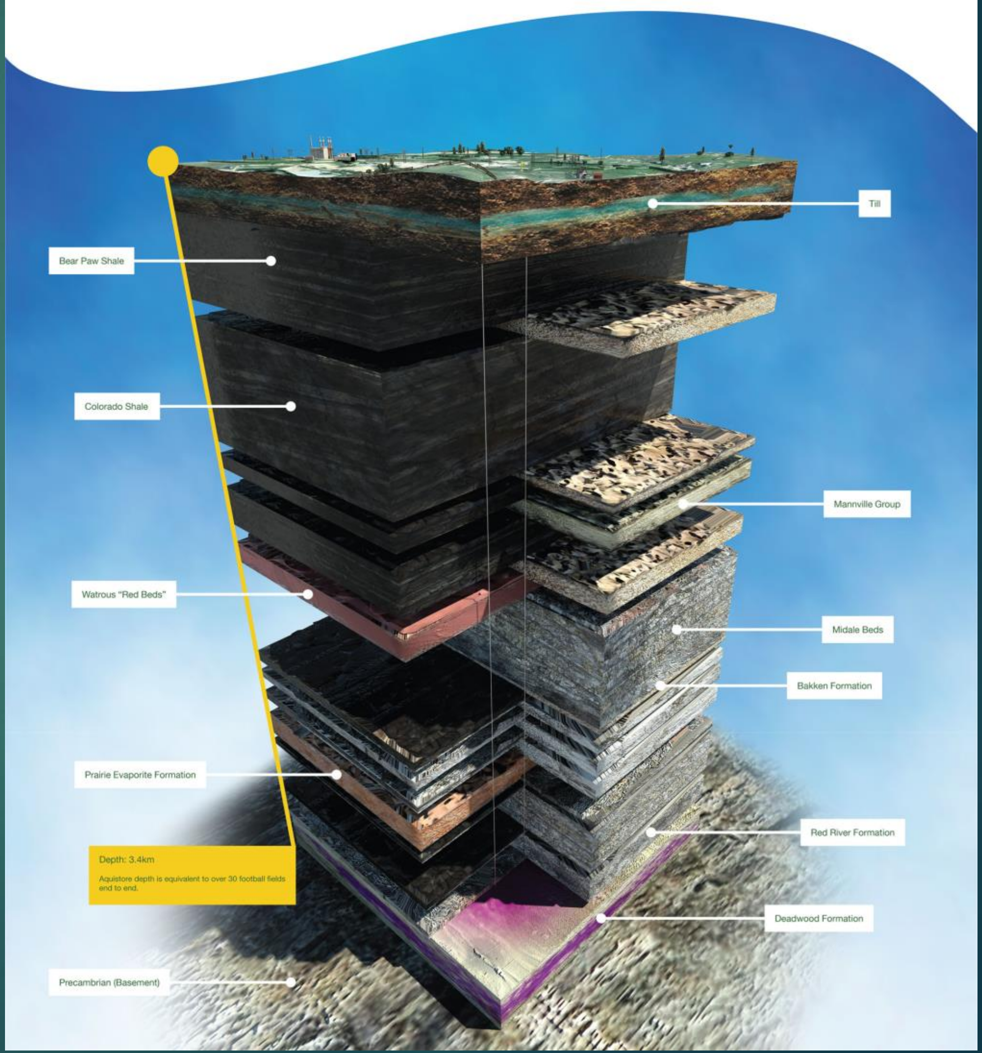
- **Hydrology** is the scientific study of the movement, distribution, and quality of water on Earth and other planets.
- Main Hydrological data are Surface water data, Water quality data, and Groundwater data.
- Data are used to determine the flood and drought conditions as well as obtaining the required capacity of the reservoir.



Dams and Reservoirs | Introduction

Geologic Data

- **Geology** is the study of the Earth, the materials of which it is made, the structure of those materials, and the processes acting upon them.
- Geology data of the area that dam is to be built are used to find the structural ability of the foundation materials.
- Geology data also help engineers to indicate the leakage and erosion problems.



Dams and Reservoirs | Introduction

Reservoir Data

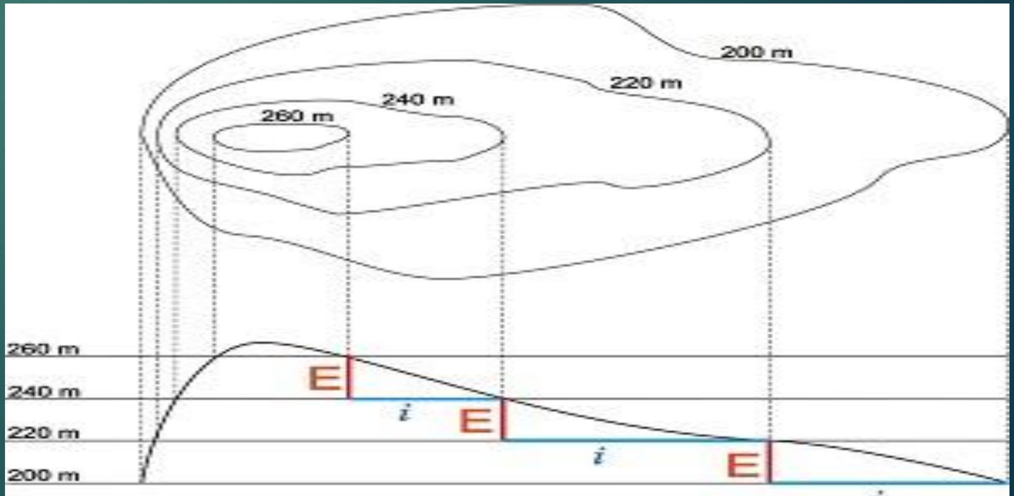
- Topographic maps, land ownerships, land classification, location of roads and public utilities.

Environment Data

- We need Environmental Impact Statement (EIS) or Environmental Impact Report (EIR) to assess the impact that maybe created by the project.

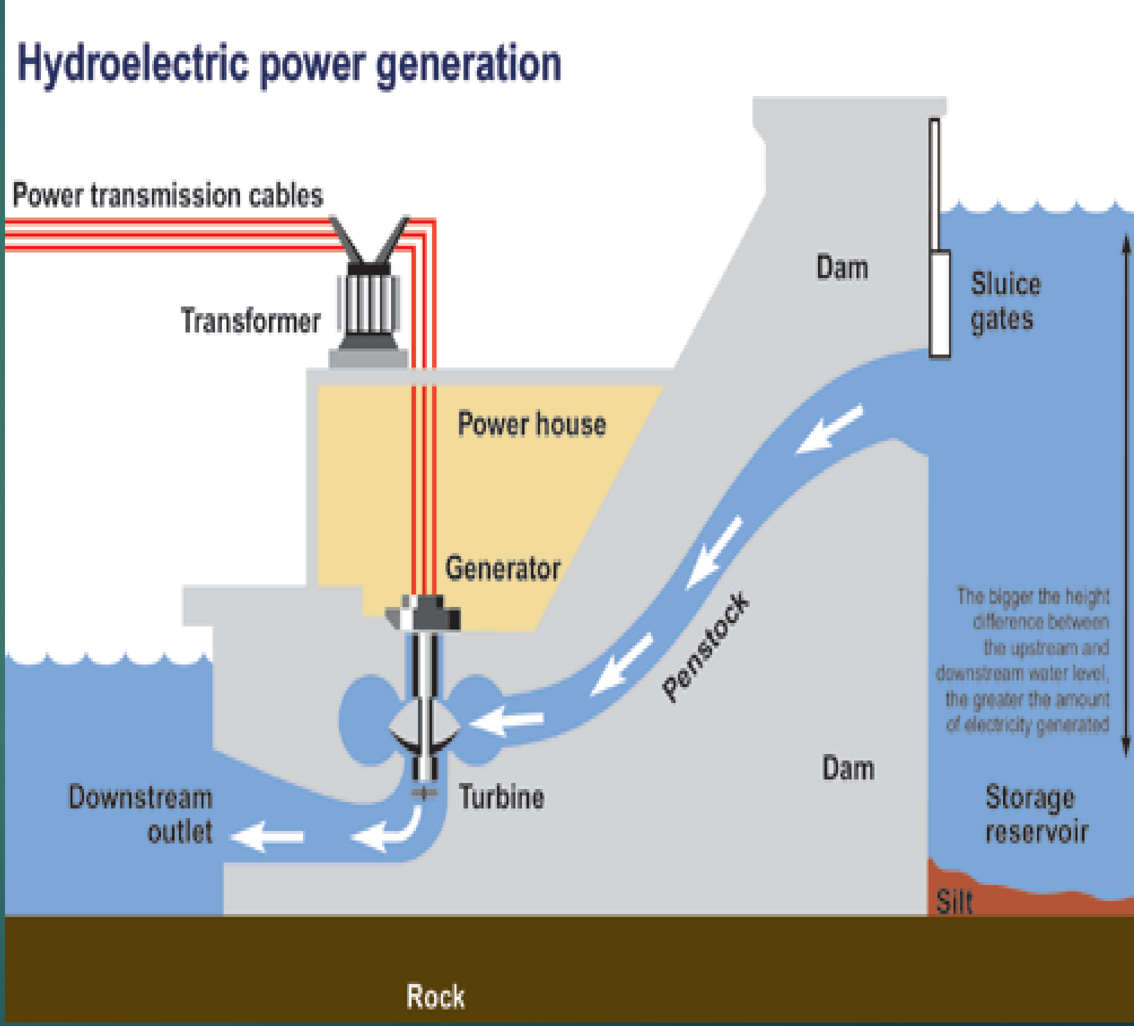
○ A topographic map uses lines to show change in elevation and to determine the heights of features such as mountains and valleys.

○ Topographic maps can show the heights of features a variety of ways, including contour lines, relief, and color.



Dams and Reservoirs | Dams

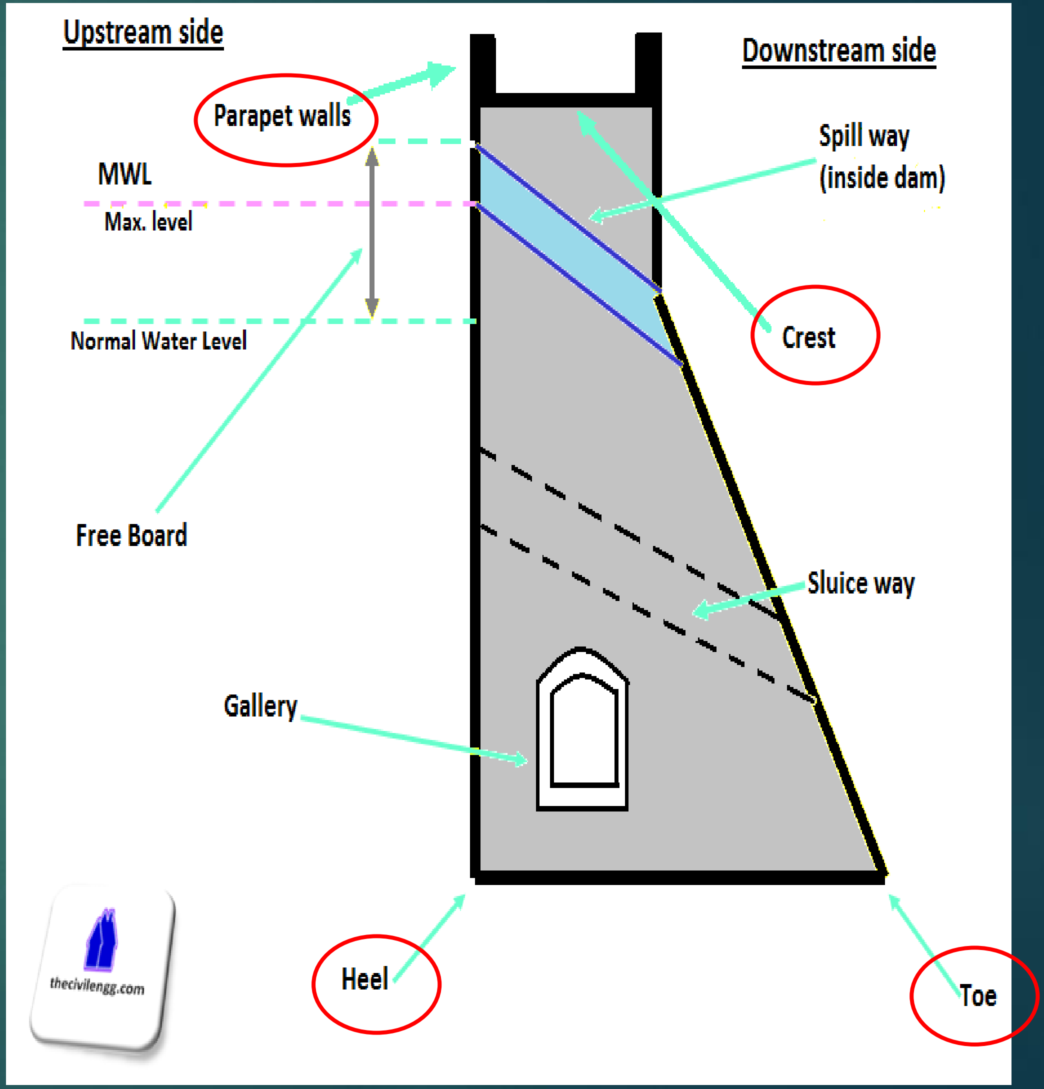
- A dam is a hydraulic structure built across a river to create a reservoir on its upstream side.
- Purposes: Water-supply (drinking, irrigation, industry), Hydropower, Flood Control, Navigation, Fishing and Recreation.
- Dam construction is an efficient way to manage water resources by creating reservoir to storage water and distributes it at the right time into downstream districts.



Dams and Reservoirs | Dams

Different parts and terminologies of Dams:

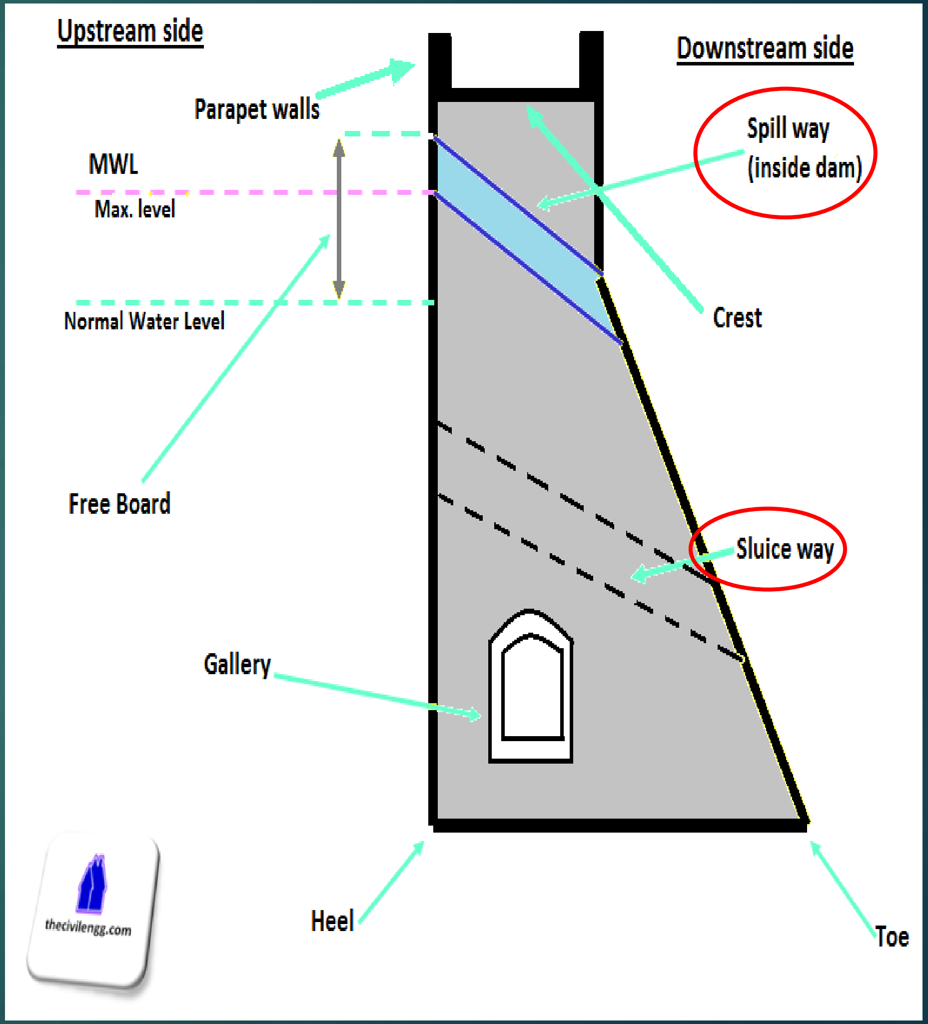
- **Crest**: The top of the Dam. These may in some cases be used for providing a roadway or walkway over the dam.
- **Parapet walls**: Low Protective walls on either side of the roadway or walkway on the crest.
- **Heel**: Portion of Dam in contact with ground or river-bed at upstream side.
- **Toe**: Portion of dam in contact with ground or river-bed at downstream side.



Dams and Reservoirs | Dams

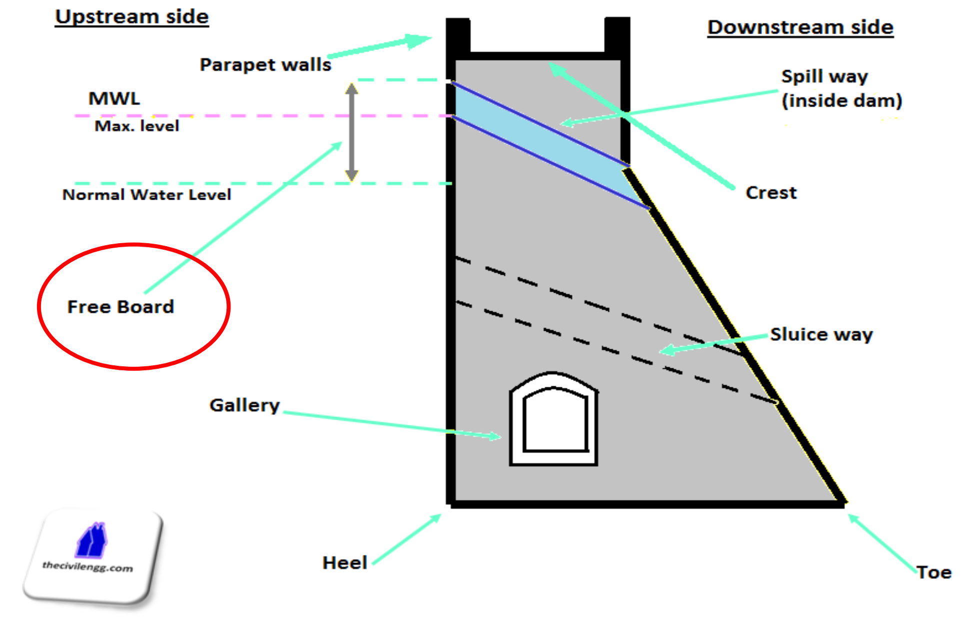
- Spillway: It is a waterway near the top of dam for the passage of excessive water from the reservoir.

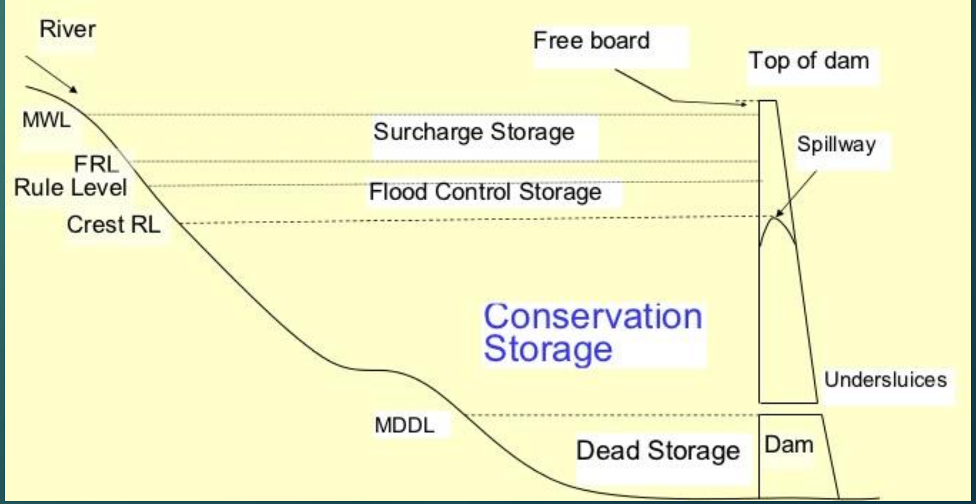
- Sluice way: Opening in the dam near the base, provided to clear the silt accumulation in the reservoir.



Dams and Reservoirs | Dams

- Free board: The **space** between the highest level of water in the reservoir and the top of the dam.
- Dead Storage level: The portion of total storage capacity that is equal to the volume of water below the level of the lowest outlet (the minimum supply level).
- Diversion Tunnel: Tunnel constructed to divert or change the direction of water to bypass the dam construction site.
- The dam is built while the river flows through the diversion tunnel.

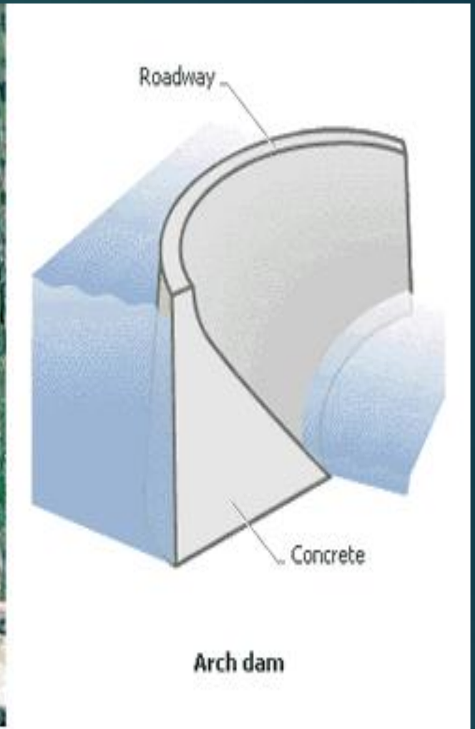




Dams and Reservoirs | Dams

Types of Dams

- **Arch Dams**: An arch dam is curved in plan, with its convexity towards the upstream side.
- They transfers the water pressure and other forces mainly to the abutments by arch action.
- An arch dam is quite suitable for narrow canyons with strong flanks.



Dams and Reservoirs | Dams

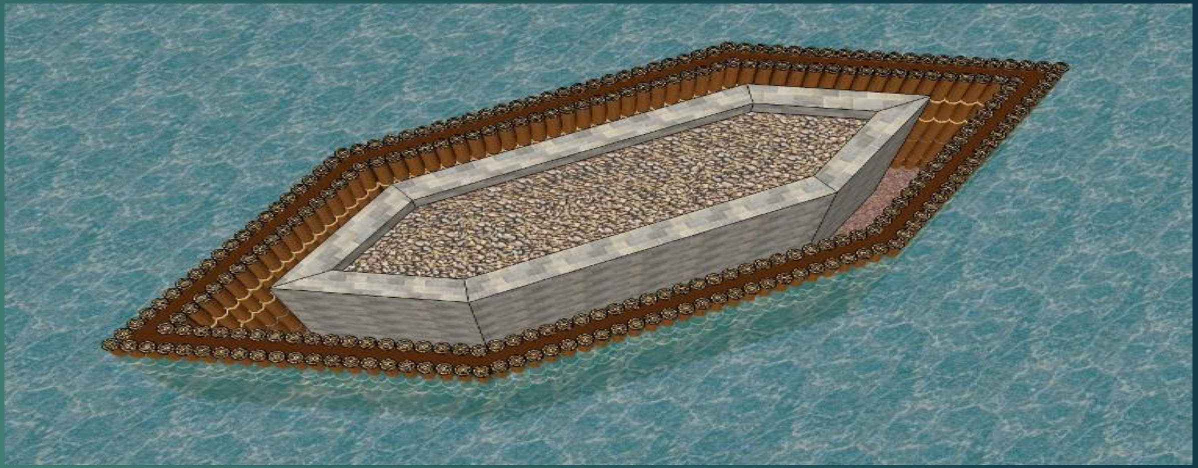
Based Examples of Arch dam: Hoover Dam (USA) and Idukki Dam (India)

Dams and Reservoirs | Dams

- **Diversion dams**: A diversion dam is constructed for the purpose of diverting water of the river into an off-taking canal (or a conduit).
- Such shorter dams are used for irrigation, and for diversion from a stream to a distant storage reservoir.
- It is usually of low height and has a small storage reservoir on its upstream.

Dams and Reservoirs | Dams

- **Coffer Dam:** It is built around the construction site to exclude water.
- It creates a dry work environment for the major work to proceed.
- A coffer dam is thus a temporary dam constructed for facilitating construction.



Dams and Reservoirs | Dams

- **Steel Dam**: A steel dam consists of a steel framework, with a steel skin plate on its upstream face.

Dams and Reservoirs | Dams

- **Timber Dam**: Main load-carrying structural elements of timber dam are made of wood.
- Timber dams are made for small heads (2-4 m or, rarely, 4-8 m) .

Dams and Reservoirs | Dams

- **Gravity Dam**: A gravity dam is a massive sized dam fabricated from concrete or stone masonry.
- By using concrete, the weight of the dam is actually able to resist the horizontal thrust of water pushing against it. This is why it is called a gravity dam.
- Gravity essentially holds the dam down to the ground, stopping water from toppling it over.
- Since gravity dams must rely on their own weight to hold back water, it is necessary that they are built on a solid foundation of bedrock.

Dams and Reservoirs | Dams

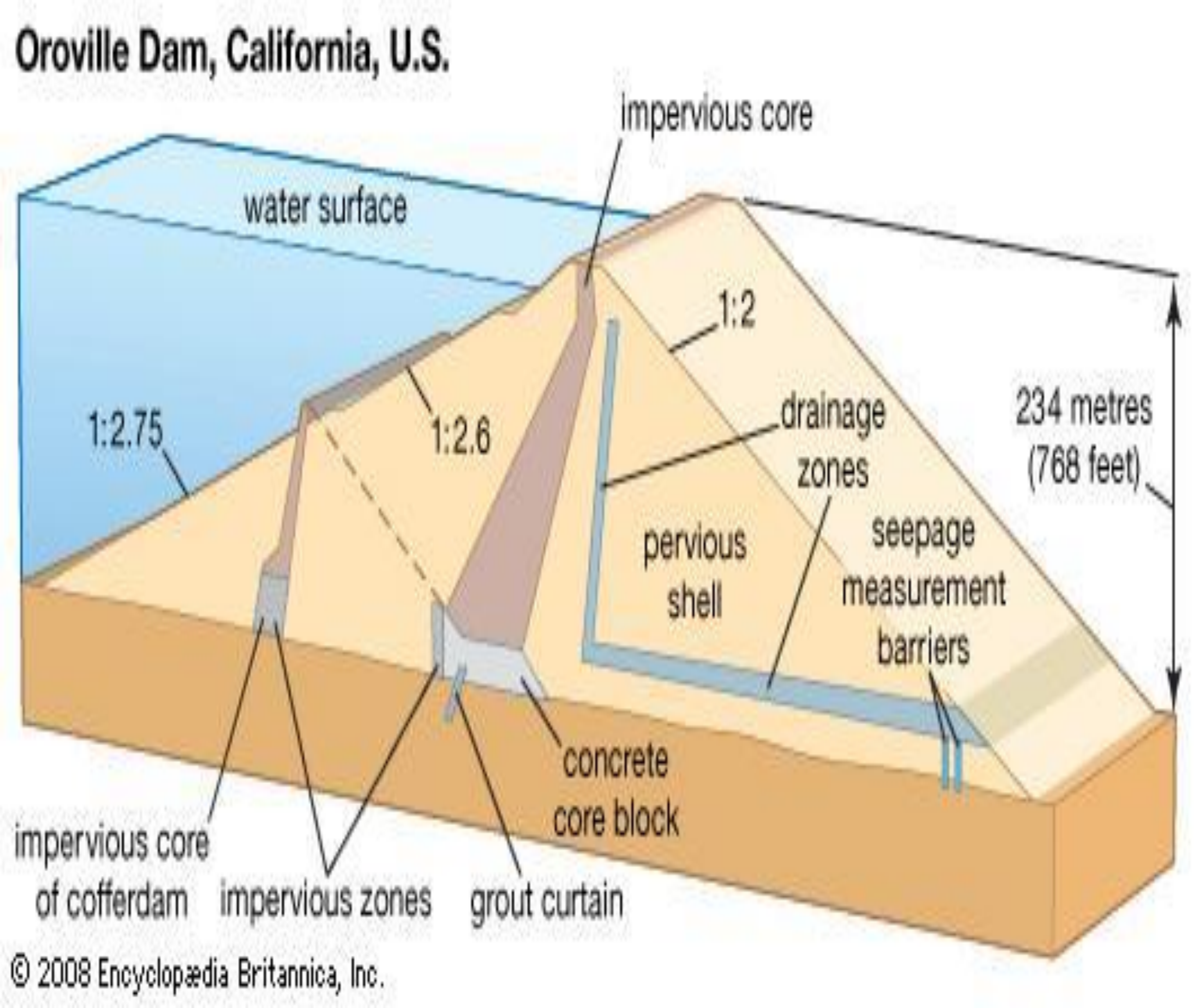
Examples: **Grand Coulee Dam** (USA), and **Itaipu Dam** (Between Brazil and Paraguay).

Dams and Reservoirs | Dams

- **Earth-fill Dams**: An earth dam is made of earth (or soil) built up by compacting successive layers of earth, using the most impervious materials to form a core.

- Earth dam resists the forces exerted upon it mainly due to shear strength of the soil.

- Although the weight of the earth dam also helps in resisting the forces, the structural behavior of an earth dam is entirely different from that of a gravity dam.



Oroville Dam, California, U.S.

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Dams and Reservoirs | Dams

Examples: Rongunsky dam (Russia)

Dams and Reservoirs | Dams

Hydropower Dams

Dams and Reservoirs | Dam Failure

Dams can fail for one or a combination of the following reasons:

- Overtopping caused by floods that exceed the capacity of the dam
- Structural failure of materials used in dam construction
- Movement and/or failure of the foundation supporting the dam
- Settlement and cracking of concrete or embankment dams
- Piping and internal erosion of soil in embankment dams
- Inadequate maintenance and upkeep

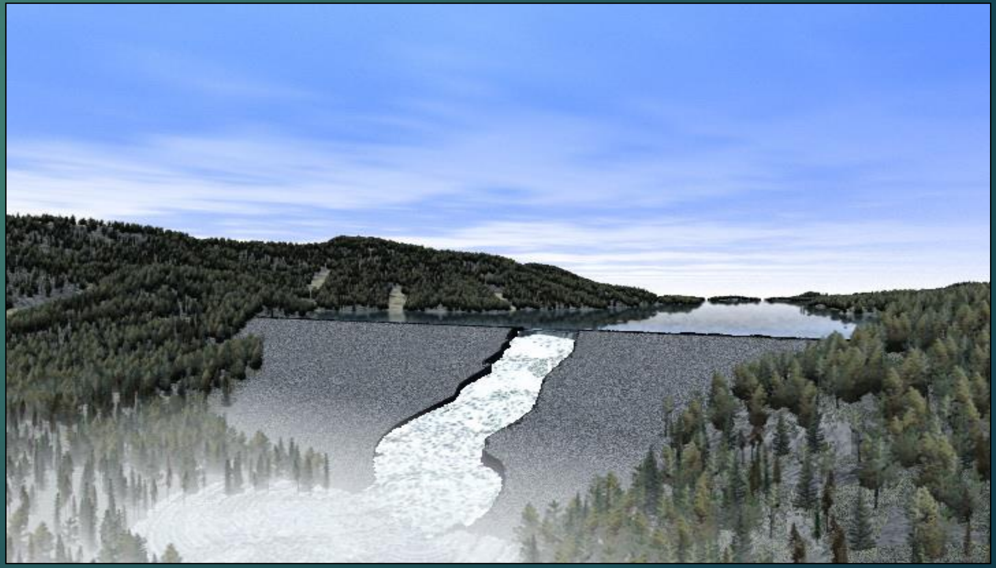
Dams and Reservoirs | Dam Failure

- The proper design of a dam's spillway prevents any undesirable problems such as overtopping.
- A spillway is a structure used to provide the controlled release of flows from a dam into a downstream area.


Dams and Reservoirs | Dam Failure

Overtopping

- If the spillway capacity is not enough to pass the flow, Overtopping or overflow of an embankment dam happens and will cause dam failure.
- Failure of dams due to overtopping is a common failure mode, accounting for 30 percent of the failures in the U.S. over the last 75 years.



Dams and Reservoirs | Dam Failure

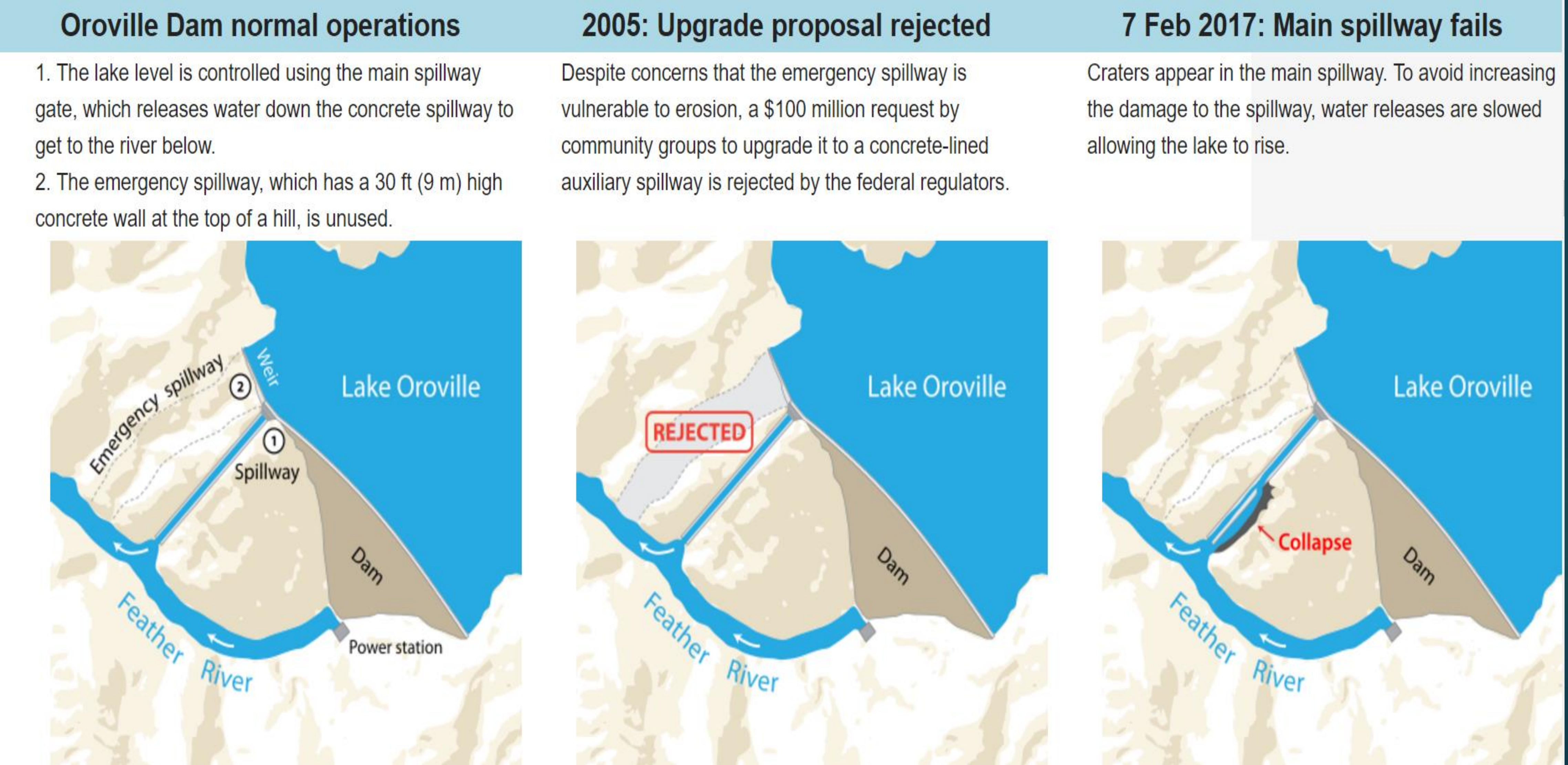
Overtopping

Dams and Reservoirs | Dam Failure

Oroville Dam Overtopping

- It is an earthfill embankment dam.
- Purpose Water supply, flood control, power
- Construction 1961-1968
- Crest elevation: 1328.6 ft
- Height above foundation: 770 ft
- Crest Length: 6920 ft
- Crest Width: 80 ft
- Crest length: 1700 ft
- Discharge Capacity: 250,000 cfs

Dams and Reservoirs | Dam Failure



Oroville Dam normal operations

1. The lake level is controlled using the main spillway gate, which releases water down the concrete spillway to get to the river below.
2. The emergency spillway, which has a 30 ft (9 m) high concrete wall at the top of a hill, is unused.

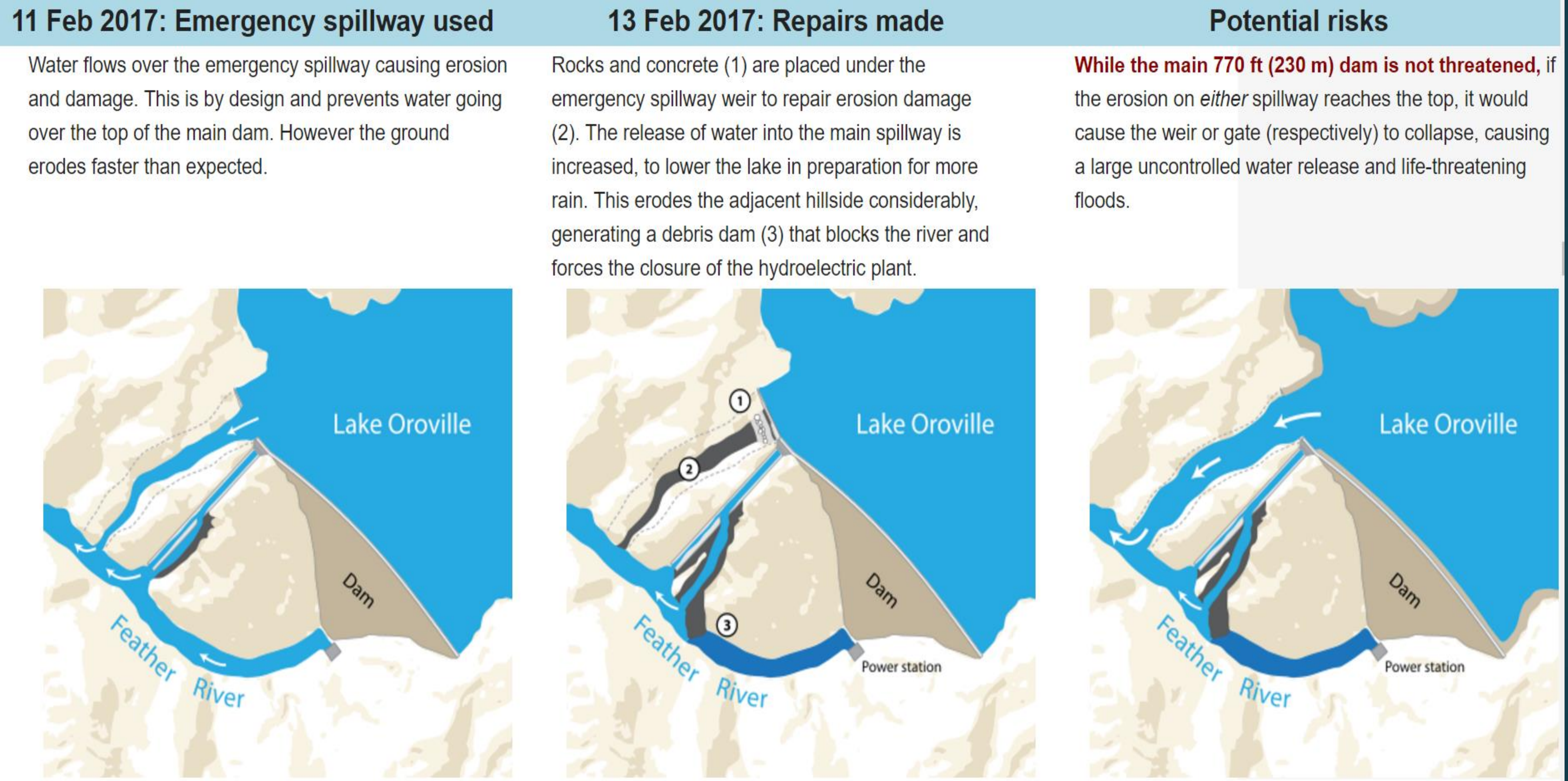
2005: Upgrade proposal rejected

Despite concerns that the emergency spillway is vulnerable to erosion, a $100 million request by community groups to upgrade it to a concrete-lined auxiliary spillway is rejected by the federal regulators.

7 Feb 2017: Main spillway fails

Craters appear in the main spillway. To avoid increasing the damage to the spillway, water releases are slowed allowing the lake to rise.

Dams and Reservoirs | Dam Failure



11 Feb 2017: Emergency spillway used

Water flows over the emergency spillway causing erosion and damage. This is by design and prevents water going over the top of the main dam. However the ground erodes faster than expected.

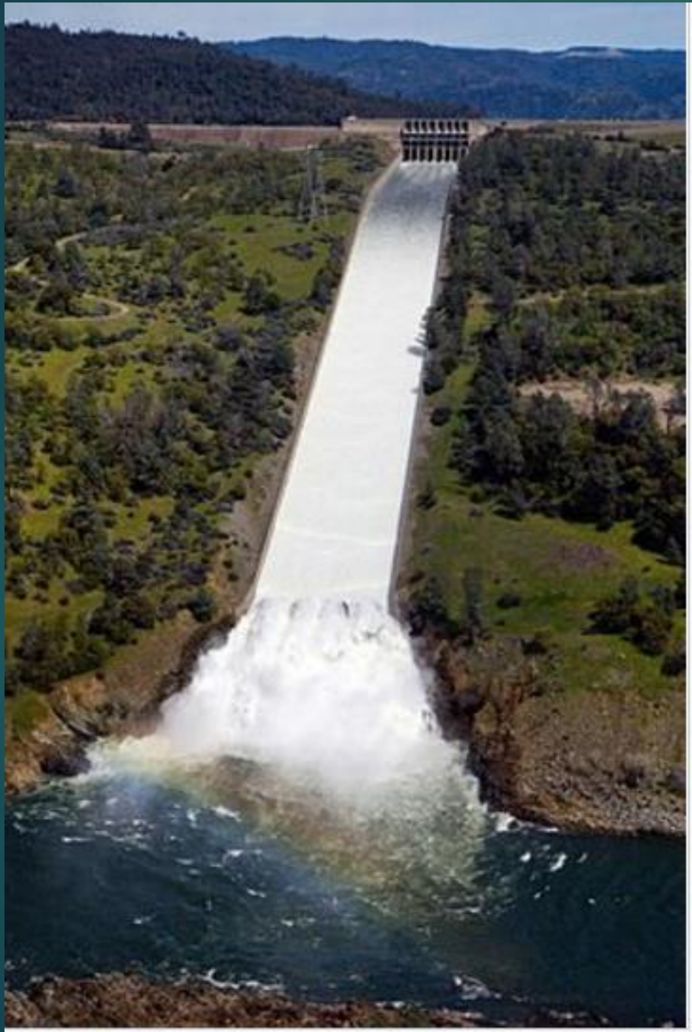
13 Feb 2017: Repairs made

Rocks and concrete (1) are placed under the emergency spillway weir to repair erosion damage (2). The release of water into the main spillway is increased, to lower the lake in preparation for more rain. This erodes the adjacent hillside considerably, generating a debris dam (3) that blocks the river and forces the closure of the hydroelectric plant.

Potential risks

While the main 770 ft (230 m) dam is not threatened, if the erosion on *either* spillway reaches the top, it would cause the weir or gate (respectively) to collapse, causing a large uncontrolled water release and life-threatening floods.

Dams and Reservoirs | Dam Failure



March 2011

February 7, 2017

February 27, 2017

Dams and Reservoirs | Dam Failure

Dams and Reservoirs | Dam Failure

- Oroville Dam repair cost estimated at $4.7 million per day.

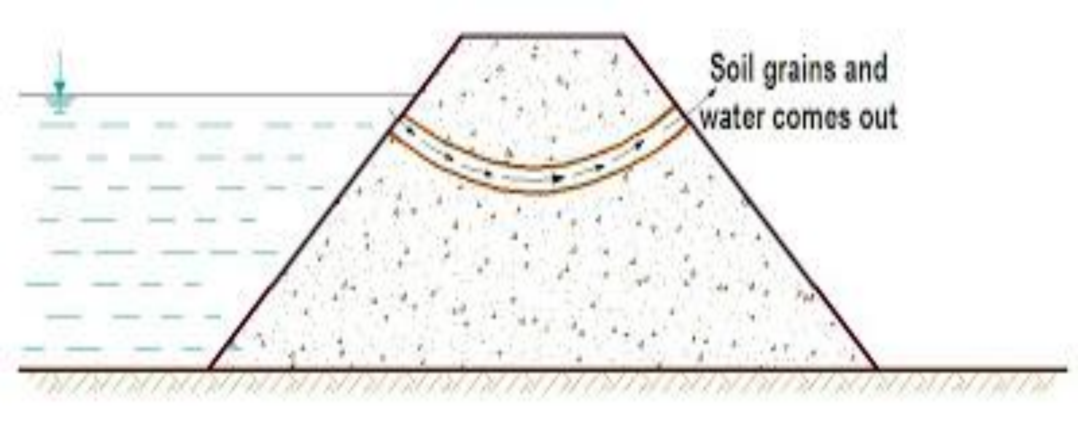
Here's a snapshot of the resources involved in the repair effort:

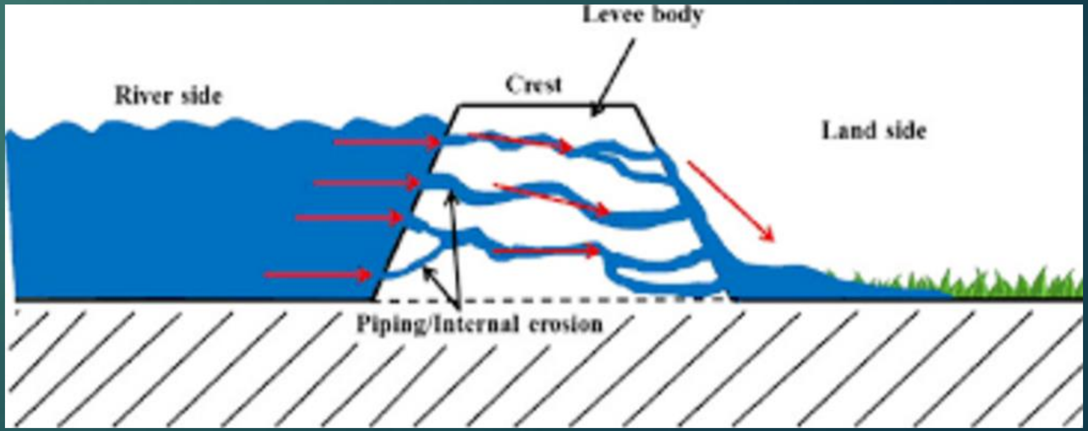
- More than 125 construction crews
- 40 truckloads of aggregate rock
- 1,200 tons of rock deposited in eroded/damaged areas per hour
- Two helicopter drops of rocks, concrete and/or other materials every minute and a half
- A California National Guard Black Hawk helicopter is assisting with drops

Dams and Reservoirs | Dam Failure

Internal Erosion

- The process of moving soil particles throughout the foundation or core of the dam is called internal erosion
- Internal erosion is one of the main causes of dam breaking.
- It is dangerous because there is no external evidence during the episode and a dam may fail only some hours after evidence of internal erosion.





Dams and Reservoirs | Dam Failure

- Fines and soil particles when a water leak (seeps) through the dam body tends to make a pipe in the body of dam.

- Internal erosion of the foundation or embankment caused by seepage is known as piping.

- The piping failure is defined as breaking dam due to water penetrating throughout the embankment (or foundation) of dam and continuously widening the pipe.

- The process of internal erosion divided into four main parts:
  - Beginning of erosion
  - Continuance of erosion
  - Development to form a pipe, and
  - Configuration of a breach

Dams and Reservoirs | Dam Failure

Seepage

Dams and Reservoirs | Dam Failure

Seepage

Dams and Reservoirs | Dam Failure

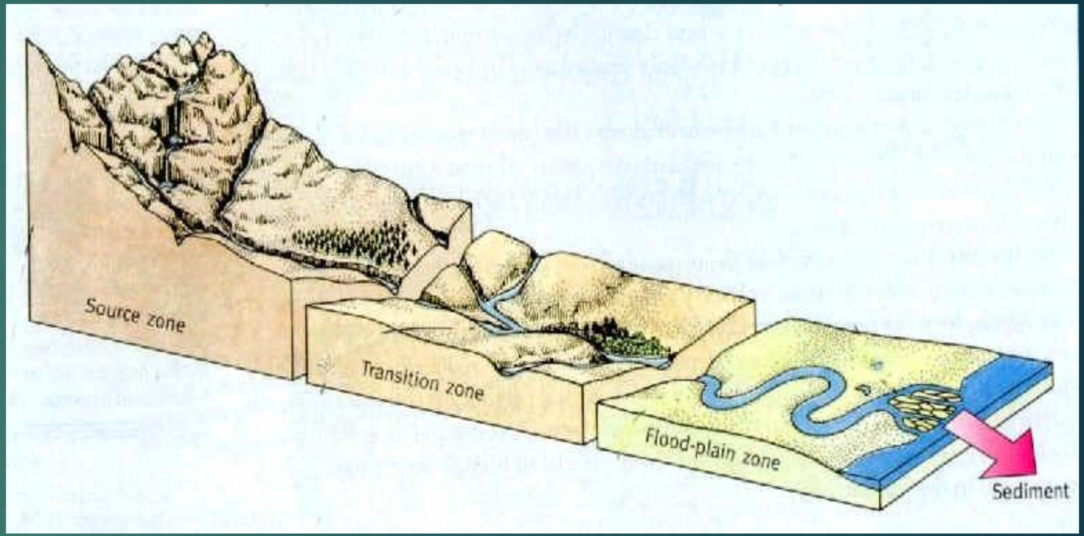
- Failed with small amount of water stored in the reservoir

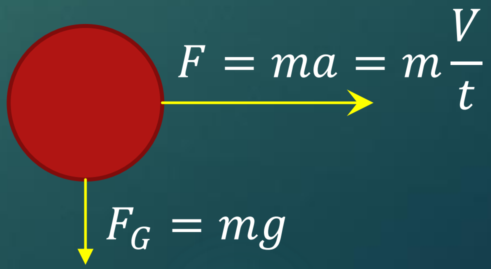
- Started as seepage through cracks in the rock of the right abutment.
- Dam had no filter-drainage zone.

Dams and Reservoirs | Sedimentation

Sedimentation

- The flow of water from the catchment upstream of a reservoir is capable of eroding the catchment area and of depositing material upstream of the reservoir.
- Sedimentation is the process of depositing sediment.
- The nature of the material in the catchment area and the slope of the catchment area are important factors.





$$F = ma = m\frac{V}{t}$$

Newton’s second law

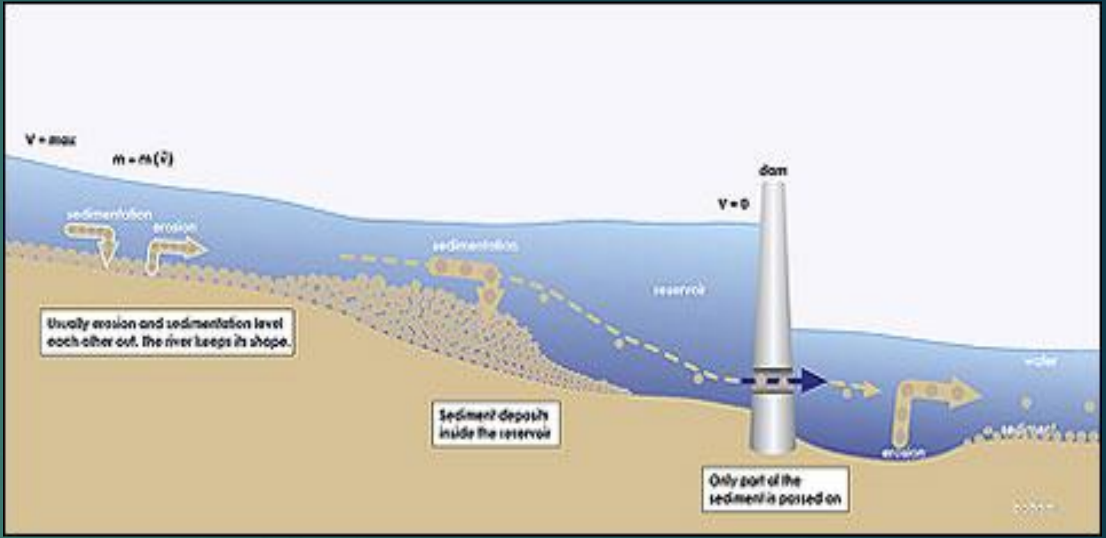
$$F_G = mg$$

Dams and Reservoirs | Sedimentation

- Sediments make the water appear brownish-grey
- Erosion due to intensive industrialized land use, and poor soil management.

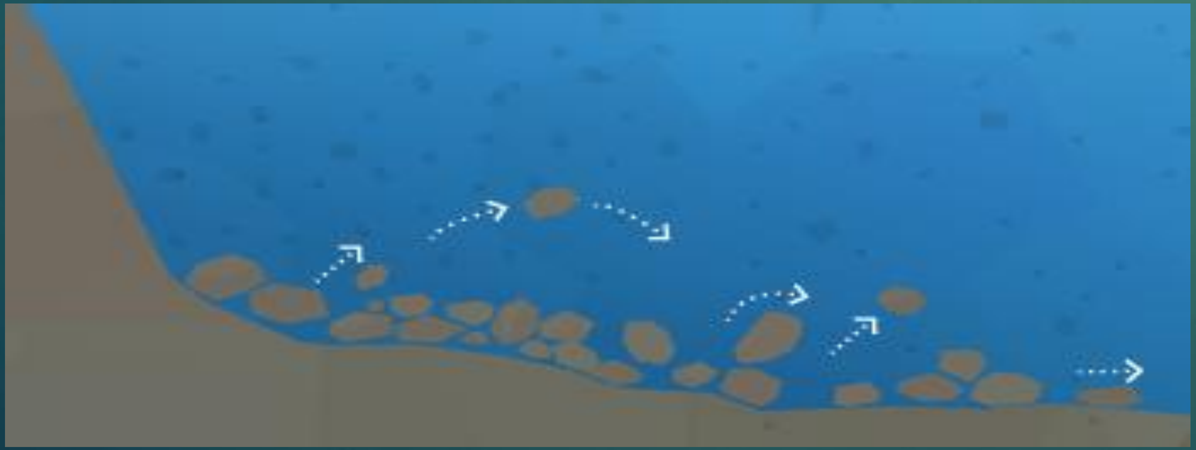
Dams and Reservoirs | Sedimentation

- If a high dam is constructed across the stream, a reservoir is produced.
- The flow velocity in the reservoir will be much smaller than the stream velocity.
- So, all sediment coming into reservoir will settle out and will be trapped.
- <u>Reservoir sedimentation</u> is filling of the reservoir behind a dam with sediment carried into the reservoir by streams.
- Therefore, the reservoir should be designed with enough volume to hold the sediment and still operate as water storage reservoir.



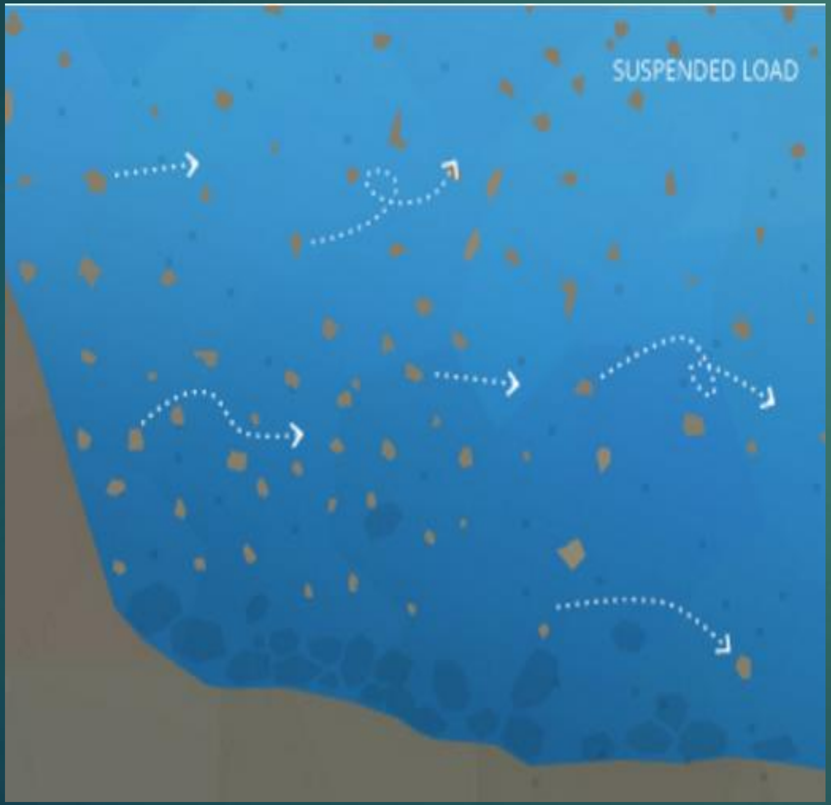
Dams and Reservoirs | Sedimentation

- Sediment transport, is also known as sediment load.
- The total load includes all particles moving as bedload, suspended load, and wash load.
- **Bedload** is the portion of sediment transport that rolls, slides or bounces along the bottom of a waterway.



Dams and Reservoirs | Sedimentation

- The suspended load is the amount of sediment carried downstream by the water flow.

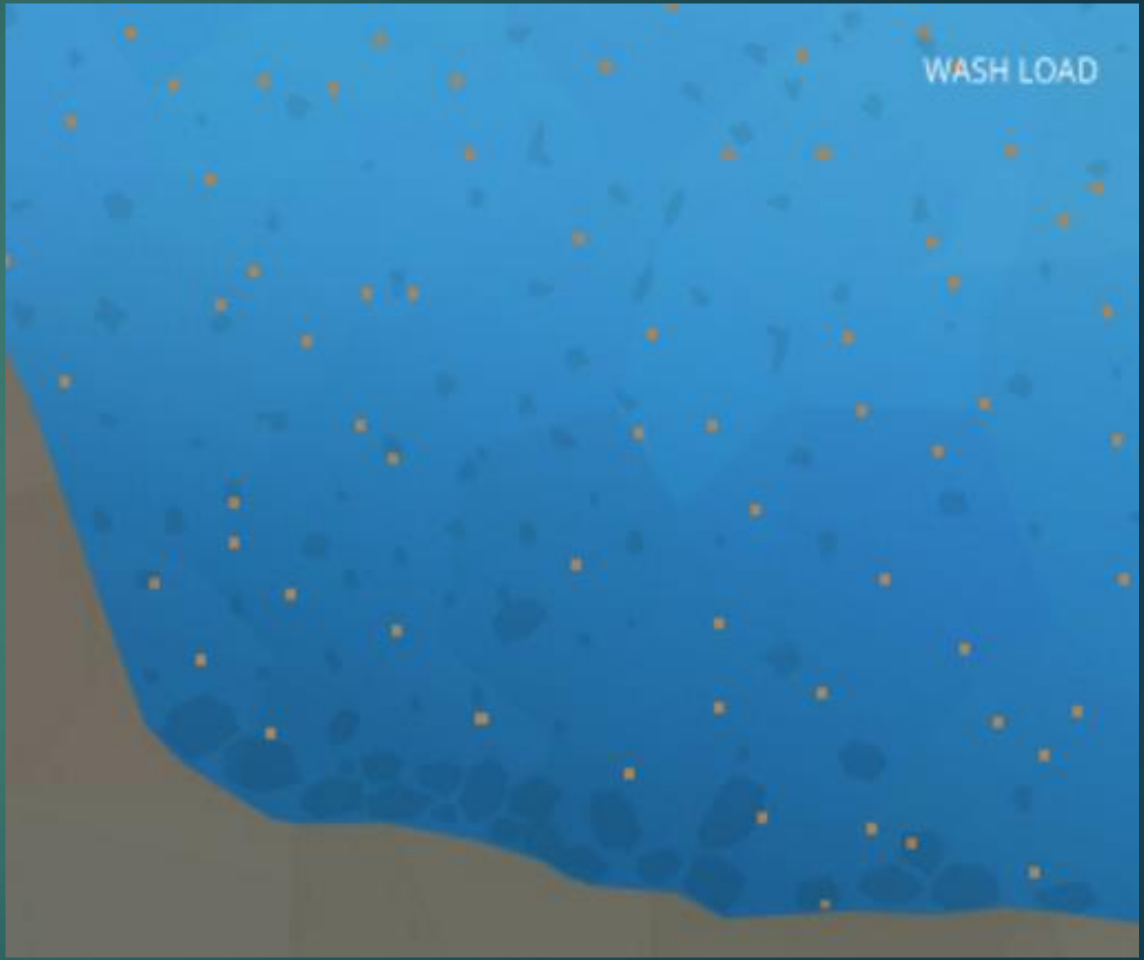


Dams and Reservoirs | Sedimentation

- The wash load is differentiated from the suspended load because it will not settle to the bottom of a waterway during a low or no flow period.

- Instead, these particles remain in permanent suspension as they are small enough to bounce off water molecules and stay a float.

- However, during flow periods, the wash load and suspended load are indistinguishable.



Dams and Reservoirs | Sedimentation

Stokes law

- If the particle is spherical, the settling velocity can be described by Stokes's law under laminar flow condition.

- Settling velocity also known as fall velocity, is the velocity reached by a particle as it falls through a fluid. It is dependent on factors like size and shape of particle.

$$V = \frac{g}{18\vartheta}(\rho_s - \rho)d^2 = \frac{g}{18\vartheta}(SG - 1)d^2$$

V is settling velocity

$\mathrm{SG} = \frac{\rho_s}{\rho}$ is specific gravity

ρ_s is density of particles

ρ is density of water

d is particle dimeter

Dams and Reservoirs | Sedimentation

Example 5-6

Determine the settling velocity of the particle if

Water temp, T = 9.5°C

Particle diameter, $d = 6.56 \times 10^{-4}\ ft\ (0.2\ x10^{-3}m)$

S.G. of the particle = 2.65

Acceleration of gravity, $g = 32.2\ ft/s^2 s2\ (9.81\ m/s^2)$

Example 5-7

How long will take for soil particles with diameters of the following sizes to settle to a depth of 1 m.

Fine sand $d = 5.2 \times 10^{-2}\ mm$

Silt $d = 5.0 \times 10^{-3}\ mm$

Clay $d = 5.0 \times 10^{-4}\ mm$

$$\rho_s = 2650\ \frac{kg}{m^3}$$

$$\vartheta = 1 \times 10^{-3} \frac{kg}{ms}$$