



1

Hydraulic Structure I – CENG 3161

Chapter 2. Design Principle of Dams

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2.1 Concrete Dam

2

Gravity dam

- A gravity dam is a solid structure, made of concrete or masonry, constructed across a river to create a reservoir on its upstream.
- Is the structure which is designed in a such a way that its own weight resist the external forces.
- Gravity dam are triangular in shape with little modification at the top and bottom and straight in plan.

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3

- Are usually consists of two sections; namely non-overflow and overflow(spillway) sections.
- Suitable in gorges with U-shaped valley with strong foundation and where material of construction for earth dam is unavailable.
- It requires a sound bedrock foundation.

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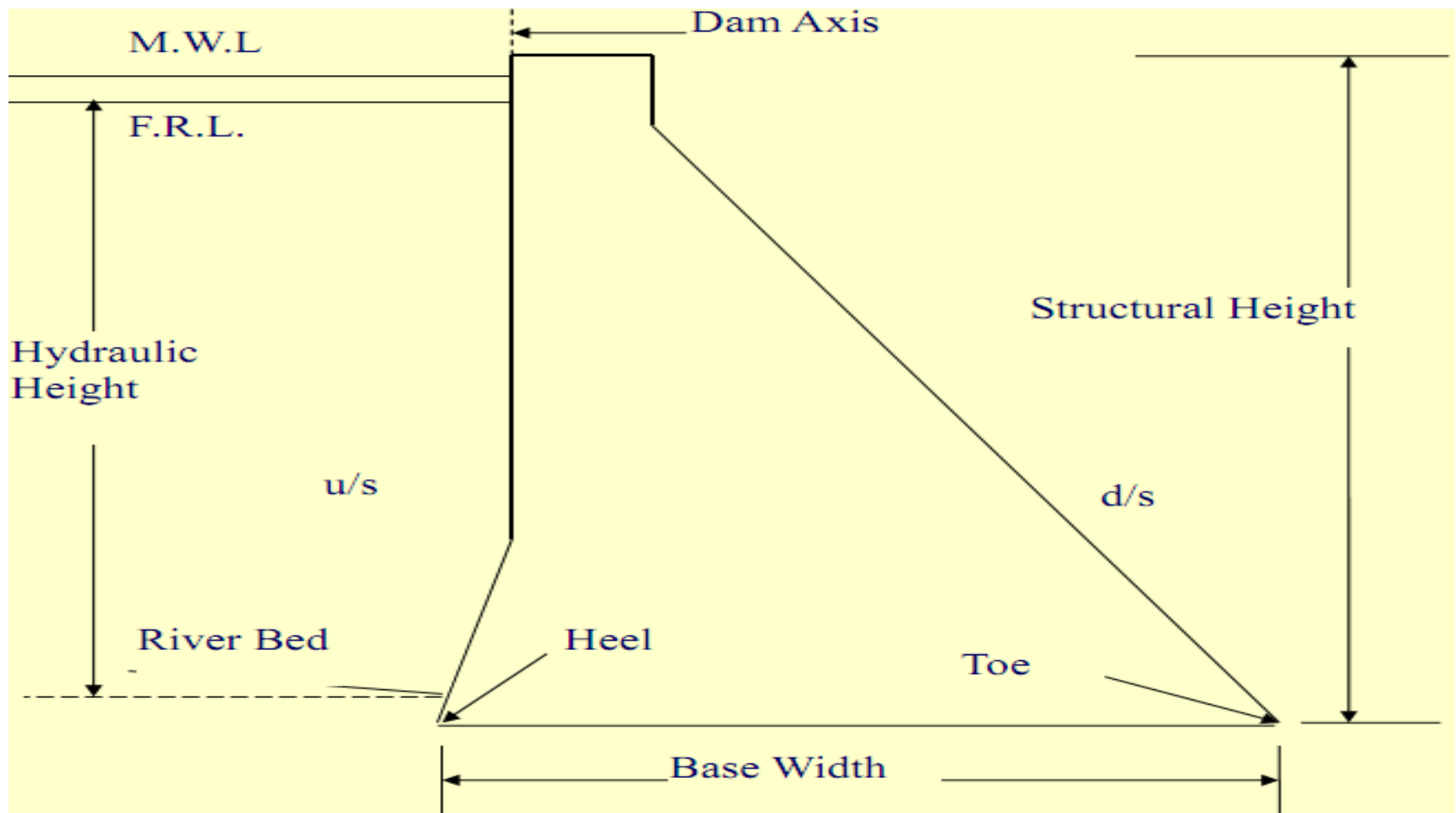
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Basic definitions

1. Axis of the dam:

- is the line of the upstream edge of the top (or crown) of the dam.
- The axis of the dam in plan is also called the base line of the dam.

2. Length of the dam:

- Is the distance from one abutment to the other, measured along the axis of the dam at the level of the top of the dam.

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8

3. Structural height of the dam:

- Is the difference in elevations of the top of the dam and the lowest point in the excavated foundation.
- In general, the height of the dam means its structural height.

4. Toe and Heel:

- The toe of the dam is the downstream edge of the base, and the heel is the upstream edge of the base.

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9

5. Maximum base width of the dam:

- is the maximum horizontal distance between the heel and the toe of the maximum section of the dam in the middle of the valley.

6. Hydraulic height of the dam:

- is equal to the difference in elevations of the highest controlled water surface on the upstream of the dam (i. e. FRL) and the lowest point in the river bed.

2.1.1 Forces acting on gravity dam

10

- The first consideration in designing a dam is the determination of the forces acting on the structure.
- These forces may be categorized in to three force condition depending on relative importance:

1. PRIMARY FORCES:

- These are of major importance to all dams, irrespective of type (we can't neglect this force at any cost or time). They are:
 - a. Water pressure(head water and tail water pressures)
 - b. Self weight of dam
 - c. Uplift(seepage) pressure

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11

2. Secondary forces

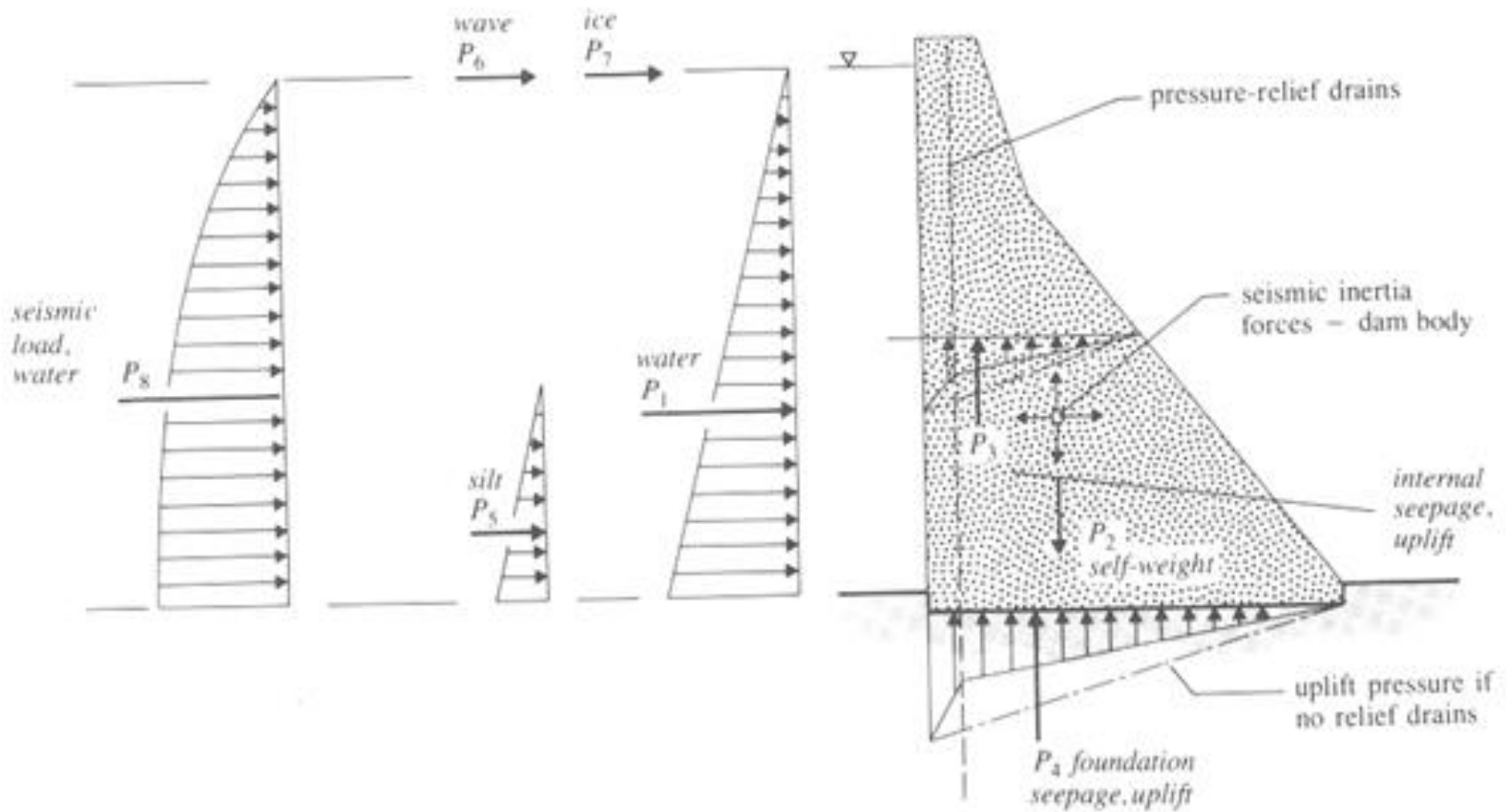
- ✓ are universally applicable although of lesser magnitude (importance only to certain types of dams).
- ✓ E.g. silt load, wave load, wind load. ice loads...etc.

3. Exceptional forces

- ✓ Limited applicability and low probability of occurrence.
- ✓ E.g. Earthquake force

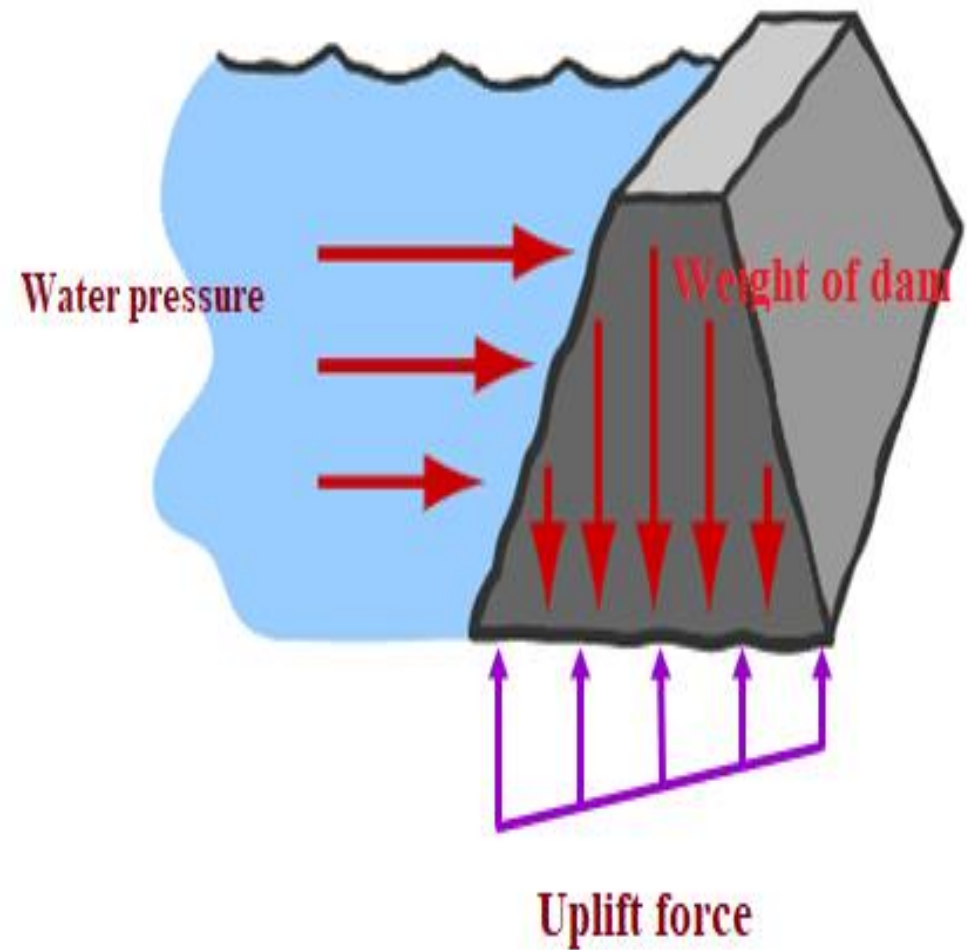
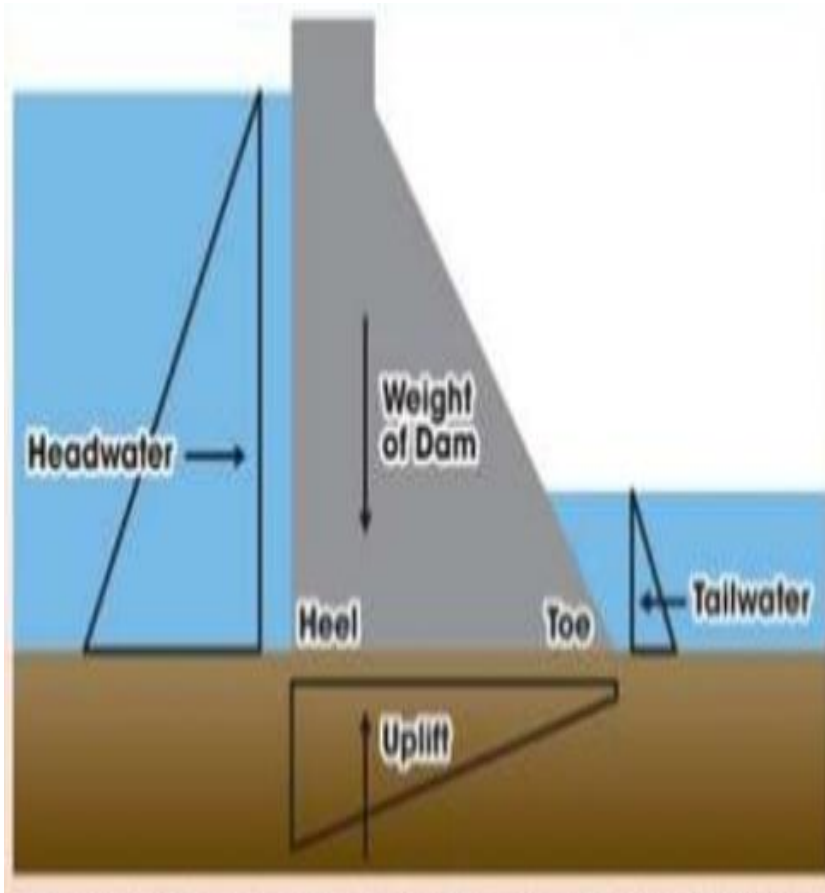
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- The forces that give stability to the dam includes:
 1. Weight of the dam
 2. Thrust of the tail water
- ❖ Forces, such as **weight of the dam** and **water pressure** can be directly calculated from the unit weight of materials and properties of fluid pressure.

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15

I. Primary loads

1. Water pressure(Head water and tail water)

- Water pressure is the major external force acting on gravity dam.
- It is the force exerted by the water stored in the reservoir on the upstream and the water depth at the tail of the dam at d/s.
- The water pressure always acts normal to the face of dam and determined from rule of hydrostatics pressure distribution which is triangular in shape.

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16

- Water pressure (P) varies linearly with depth of water from water surface to the bottom and expressed as $P = \gamma_w h$.
- The computation of water pressure depends up on the **nature of the upstream faces of the dam.**

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17

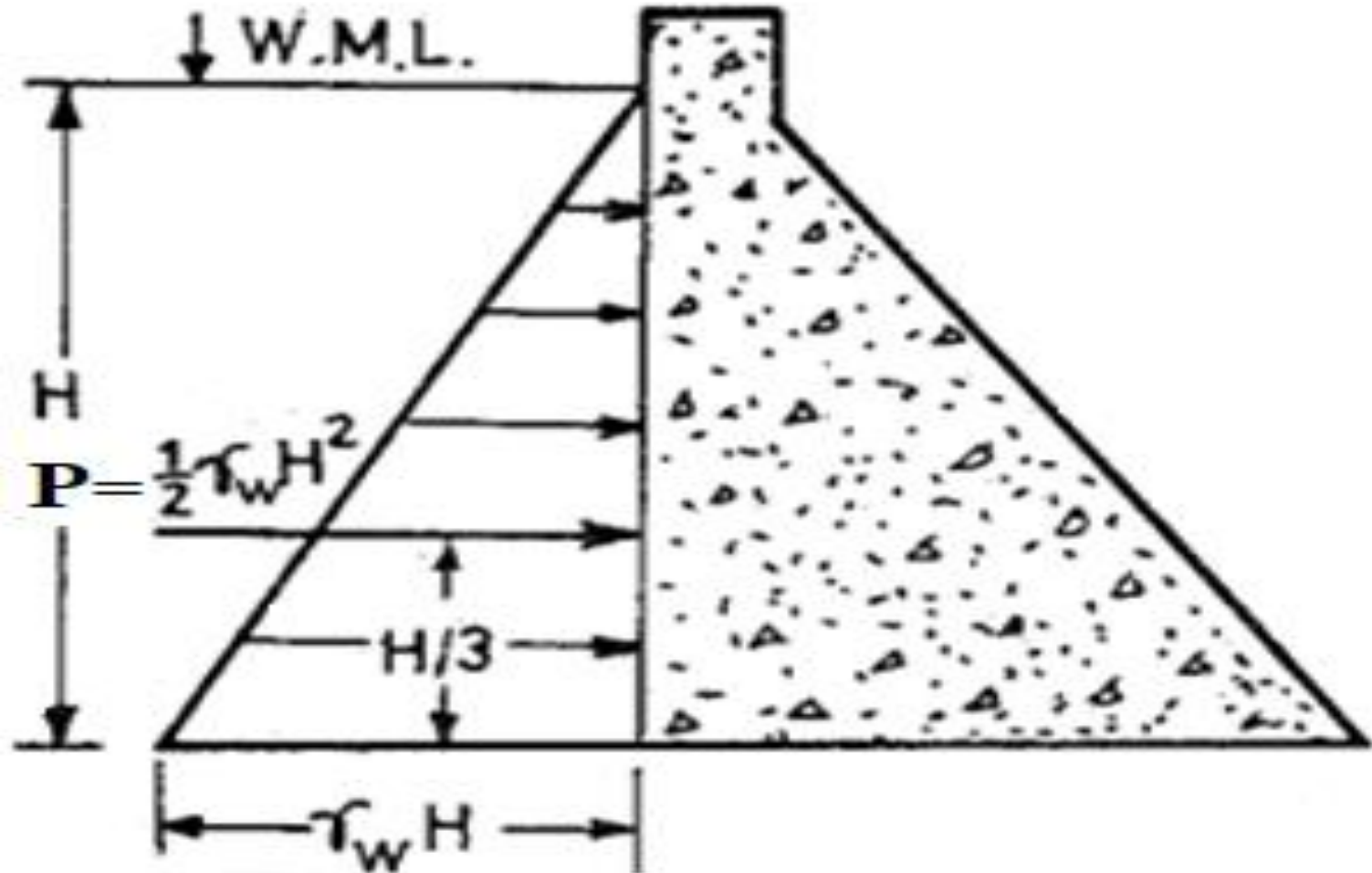
Case -1: Non –over flow section

U/s face vertical:

- When the upstream face of the dam is vertical, the water pressure diagram is triangular in shape with a pressure intensity zero at the water surface and equal to $\gamma_w h$ at the base, where h is the depth of water.
- The resultant force due to water pressure per unit length is horizontal and is given by $P_H = \frac{1}{2} \gamma_w H^2$.
- It acts horizontally at a height of $h/3$ above the base of the dam.

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18

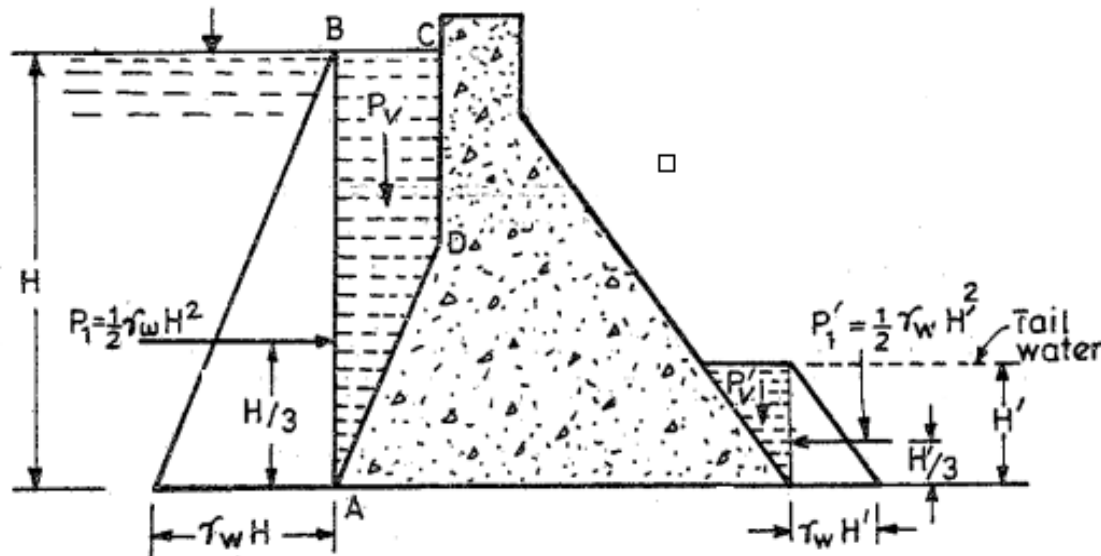


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19

U/s face inclined:

- When the upstream face is **either inclined or partly vertical and partly inclined**, the force due to water pressure can be resolved in to horizontal component (P_H) and the vertical component (P_V).



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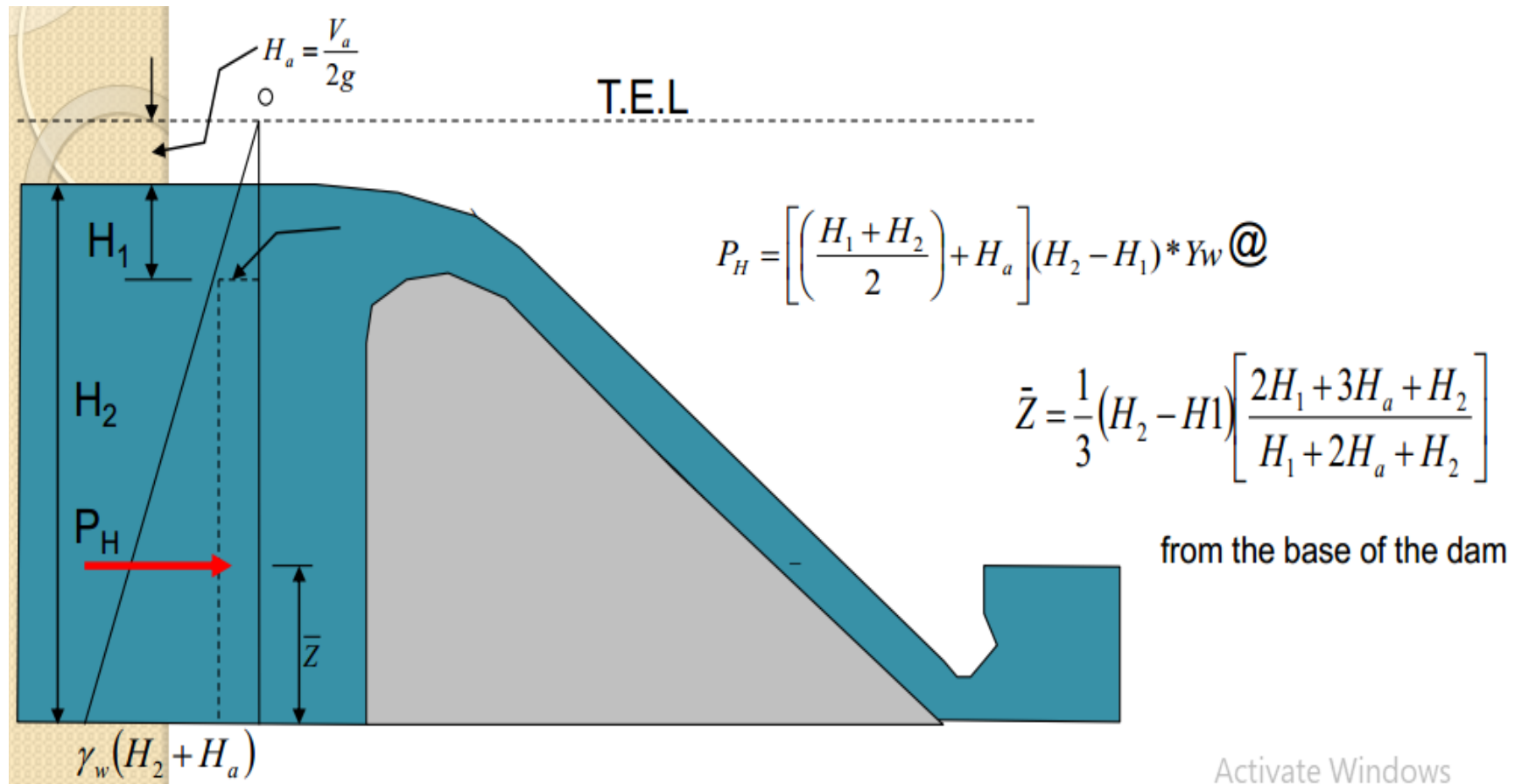
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- The horizontal component, $P_H = \frac{1}{2} \gamma_w H^2$ acts at $H/3$ from the base.
- The vertical component, P_V is equal to weight of fluid mass vertically above the upstream face acting through the center of gravity of the mass.
- $P_V = \text{Weight of water in ABCDA} = \gamma_w V_{\text{ABCDA}}$
- Similarly if there is tail water on d/s it will have horizontal and vertical components.
- $F_H' = \frac{1}{2} \gamma_w H'^2 (\text{kN/m})$
- $F_V' = \gamma_w V (\text{kN/m})$

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21

Case -2: Over flow section



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22

2. UPLIFT (OR SEEPAGE) FORCE

- It is the force exerted by water as it seeps through body of the dam, between dam and foundation and in the foundation.
- It acts vertically upwards at any horizontal section of the dam as well as its foundation and causes a reduction in the effective weight hence acts against dam stability.
- The computation of uplift pressure involves the consideration of two factors, viz.
 - (i) area factor/ η /- describes the percentage of area over which the up lift pressure acts
 - (ii) intensity factor (Φ) – describes the intensity of the uplift pressure at various points

$$U = \eta \Phi \gamma_w H$$

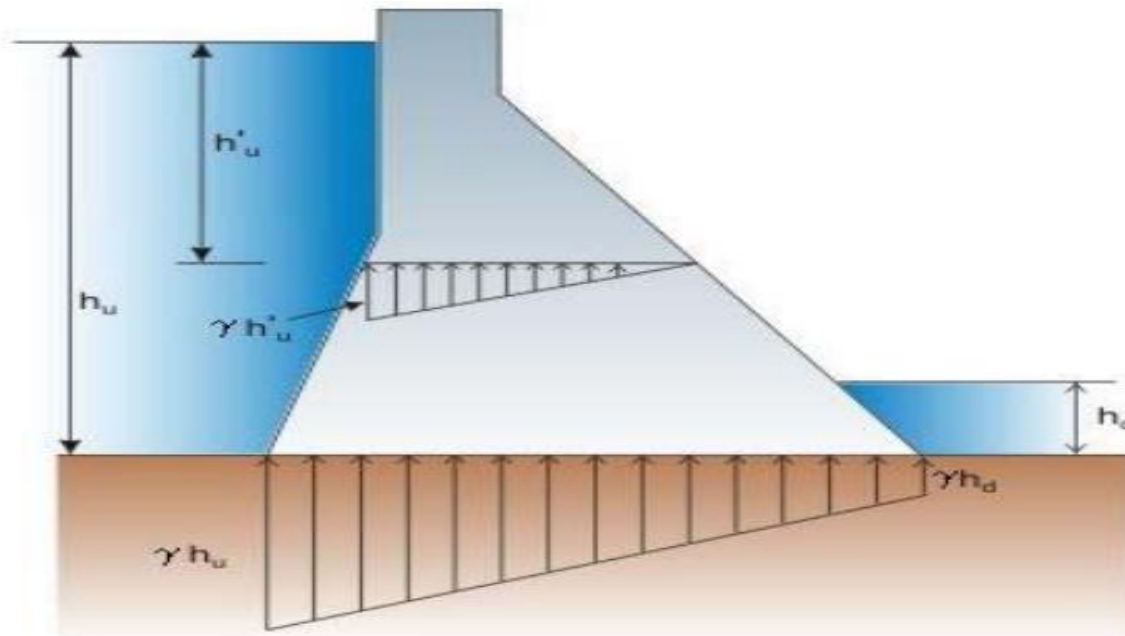
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23

- pressure generally does not occur on the entire horizontal area, because in some portions, there are no pores in which water can enter.
- After different investigation Terzagh and other scholars found area factor for both rock and concrete is nearly unity(1).
- The intensity of uplift pressure at the upstream is equal to the hydrostatic pressure corresponding to full reservoir level where as at the down stream it is equal to the hydrostatic pressure to the tail water level.

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24

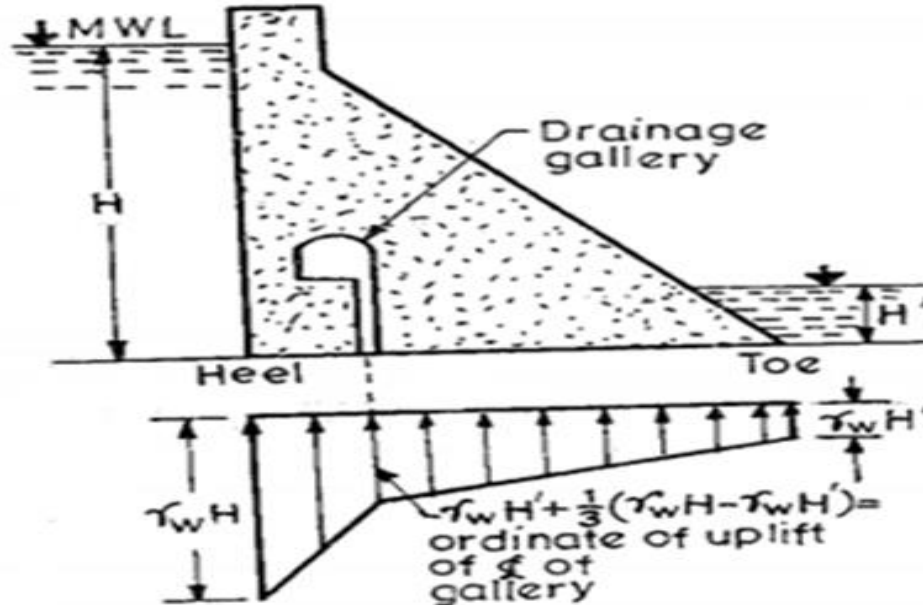


- Total uplift force on the base of the dam w/o drain,
$$U = \gamma_w (H_u + H_d) / 2 * (1 * B)$$

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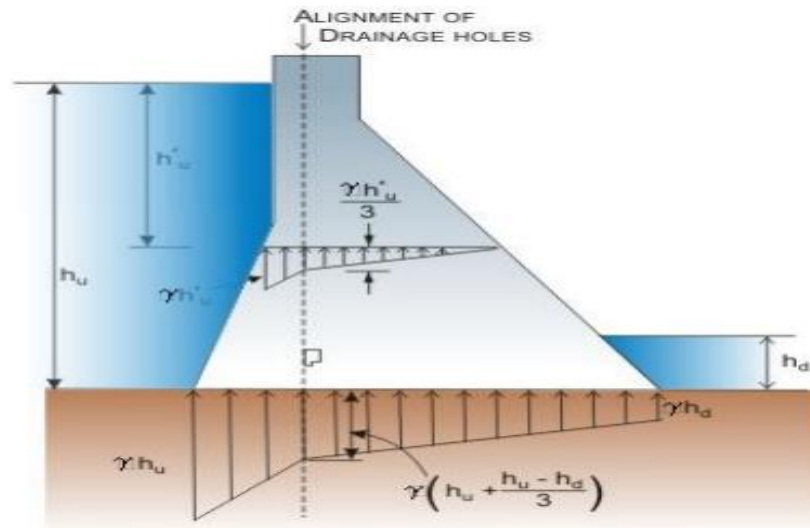
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- Uplift pressure can be reduced by providing drains through the concrete of the dam/drainage galleries/ and by drilling drainage holes in to the foundation rock /relief wells/.



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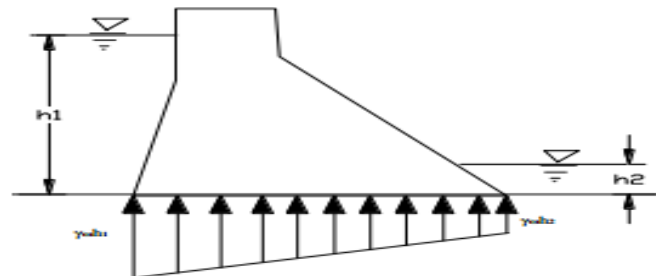


- The uplift pressure on the line of the dam drainage galleries, is equal to hydrostatic pressure at d/s face(toe) plus 1/3 of the difference of pressures at the u/s and d/s faces, or
- $$U = \gamma_w \left(H' + \frac{1}{3}(H - H') \right)$$

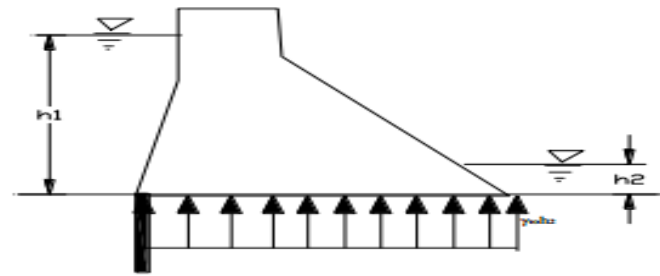
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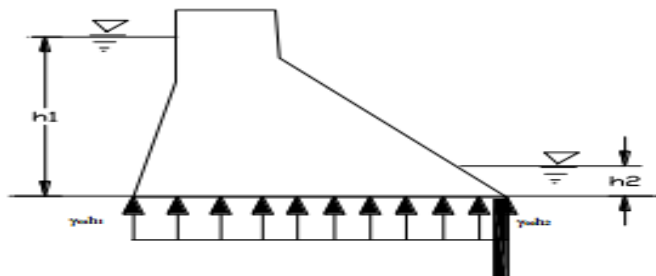
- The uplift pressure at the contact of the dam with the foundation may also be reduced by constructing a cut off wall or grout curtain close to the u/s face of the dam and extending it for considerable depth in the foundation.



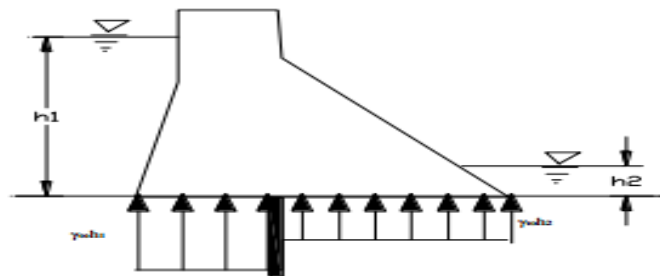
When flow from u/s to d/s face is allowed



With u/s effective cutoff



With d/s effective cutoff



With an intermediate cutoff

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28

3. Self weight of dam

- It is main **stabilizing force** in a gravity dam.

Weight of ancillary structures may be included.

- In 2-D analysis, Weight of the dam per unit length is considered and it is equal to the product of the area of cross-section of the dam and the specific weight (or unit weight) of the material.

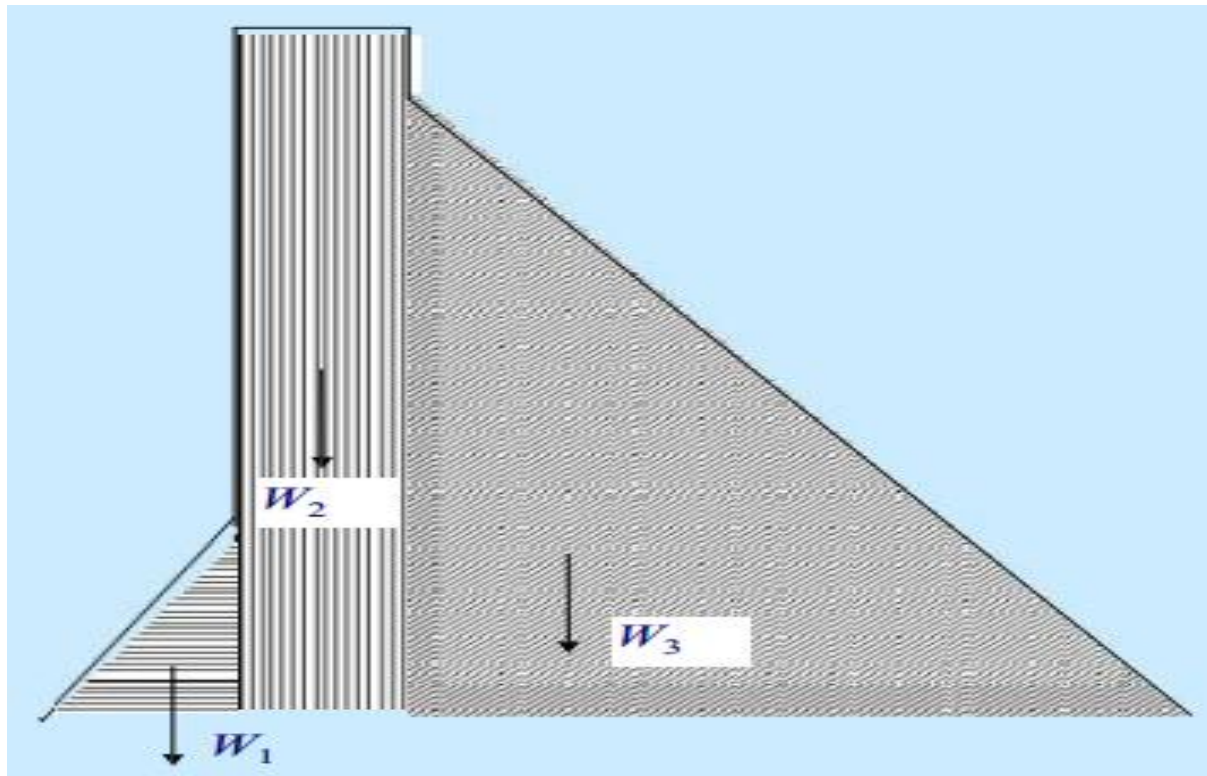
$$W = \gamma_C * A, \text{ unit weight of concrete} \\ (24\text{KN/M}^3)$$

$$W_{\text{Total}} = W_1 + W_2 + W_3$$

W_{Total} passes through c.g of section.

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29



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30

II. Secondary forces

1. Sediment/silt pressure or load (F_s)

- Sediment/silt deposition in the reservoir results in a horizontal force on upstream face of the dam.
- F_s is a function of
 - sediment depth, (h_s)
 - Submerged unit weight of sediment, (γ_{sub})
 - active pressure coefficient, (K_a)

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31

- The magnitude of this force is determined according to Rankine's formula.

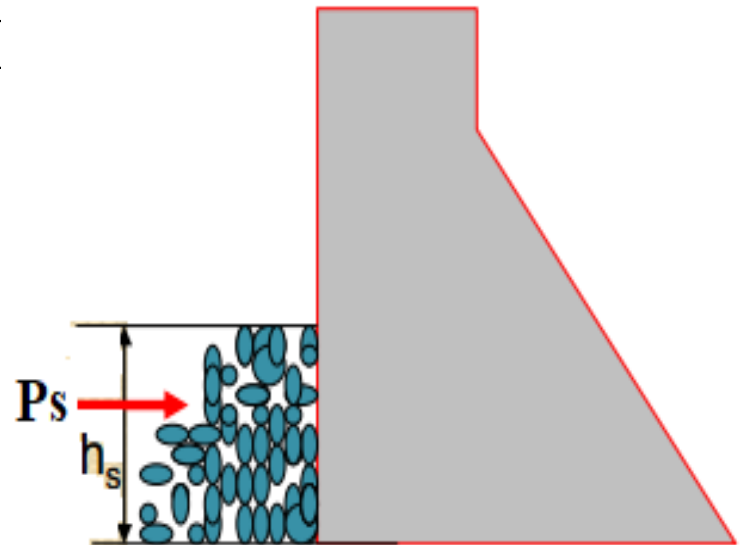
$$F_s = \frac{1}{2} K_a \gamma_{\text{sub}} h_s^2 \dots\dots\dots \text{acts at } h_s/3 \text{ from the base}$$

$$\text{Where , } K_a = (1 - \sin\phi) / (1 + \sin\phi)$$

ϕ = angle of internal friction of material.

$$\gamma_{\text{sub}} = 18-20 \text{ KN/M}$$

$$\phi = 30^\circ$$



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32

2. Wave Pressure, P_w

- Waves are generated on the surface of reservoir by the blowing winds, which exerts a pressure on the upstream side of the dam.
- This pressure force, P_w depends on fetch (extent of the water surface on which the water blows) and wind velocity.
- Wave pressure (P_w) is determined from wave height (h_w) as follows.

$$h_w = 0.032\sqrt{V_w F} + 0.763 - 0.271(F)^{1/4} \quad \text{for } F < 32 \text{ km}$$

$$h_w = 0.032\sqrt{V_w F} \quad \text{for } F > 32 \text{ km}$$

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33

Where: h_w – wave height or height of water surface from top of crest to bottom of trough, m

V_w – wind velocity, in km/hr and

F – Fetch or straight length of water surface in km

➤ Maximum pressure intensity due to wave action is given by,

Max. $P_w = 2.4 \gamma_w h_w$ and acts at $h_w/8$ above still water surface.

➤ Wave Pressure distribution is assumed to be triangular of height $5h_w/3$.

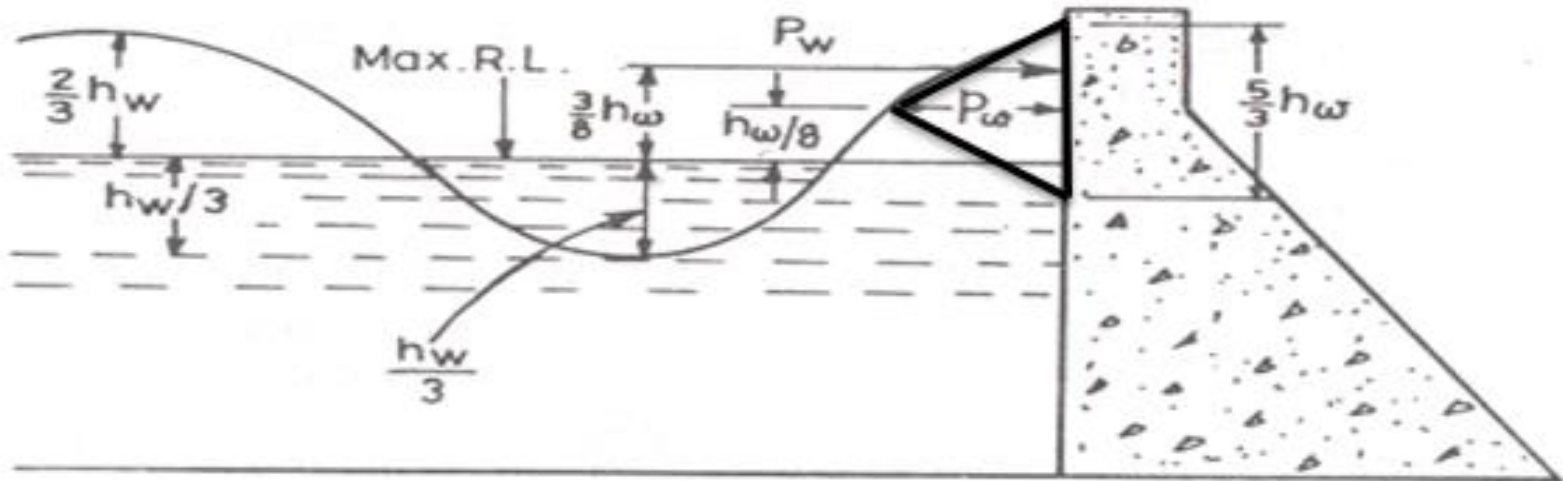
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34

- Total force due to wave action $\mathbf{P}_w$ is given by,

$$\mathbf{P}_w = \frac{1}{2}(2.4 \gamma_w h w) * \frac{5}{3} h w = 2 \gamma_w h w^2 = 19.62 h w^2$$
 acts
at $\frac{3}{8} h w = 0.375 h w$ above stilled water surface.

Max. $\mathbf{P}_w = 2.4 \gamma_w h w$



Cont....

35

3. Ice pressure

- It can be significant where ice sheets form appreciable thickness & persist for lengthy periods.
- $P_{ice} = 145 \text{ KN/m}^2$ for ice $> 0.6\text{m}$ thick, other wise neglected (USBR, 1976).

4. Wind pressure

- Since dam is constructed in sheltered location wind pressure is seldom a factor on the design of dams.
- When the dam is full, wind acts only on the d/s side thus contribute to stability.
- When empty the wind can act on the u/s face but insignificant compared to hydrostatic load.

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36

III. Exceptional load

Earthquake forces

- Earthquake force is considered if dam is to be constructed in seismic area.
- An earthquake produces waves which are capable of shaking the earth upon which the dam is resting, in every possible direction.
- An earthquake wave may move in any direction, but for design purposes the earthquake acceleration is resolved into horizontal and vertical acceleration α_h and α_v .

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37

1. Effect of vertical acceleration

➤ It may act upward or downward.

❖ When vertical acc/n. act in upward d/n:-

➤ Foundation of the dam lifted upward and becomes closer to the body of the dam

➤ Effective weight of the dam will increase.

❖ When vertical acc/n. act in downward d/n:-

➤ Foundation moves away from the dam body.

➤ Reduce effective weight and stability of the dam, hence this is worst case for design.

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38

2. Effect of horizontal acceleration

- Can occur in either u/s or d/s directions.
- Horizontal acc/n may cause the following two forces.
This are Inertia forces in the body of the dam and hydrodynamic forces of water.

i. Inertia forces

- It is the force due to the load of the dam under earthquake incidences.
- It acts in direction opposite to earthquake force.
- It is product of mass of the dam and acc/n i.e.
 $\text{Inertia} = \text{mass} * \text{acc/n}.$

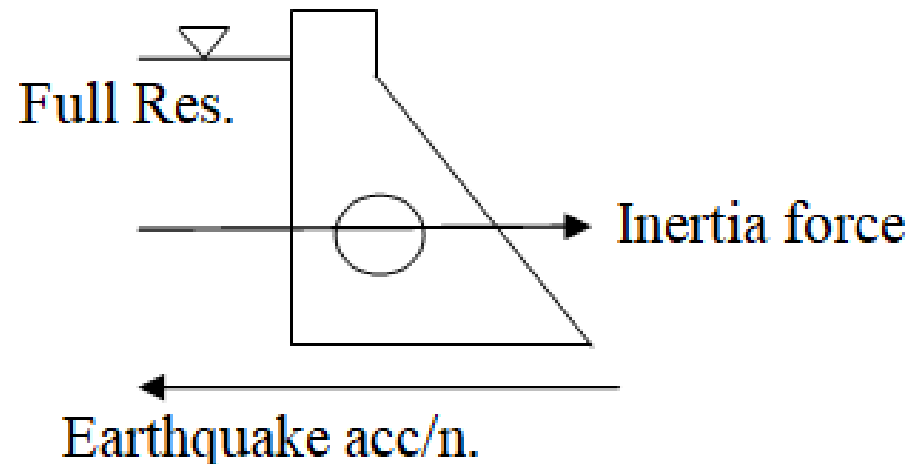
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39

➤ Dam design can be done taking in to account the conditions for which worst incidences occurs:-

a. Reservoir full condition:

- the worst case occurs when the earthquake acceleration moves from d/s to u/s and inertia force is acts from u/s to d/s.

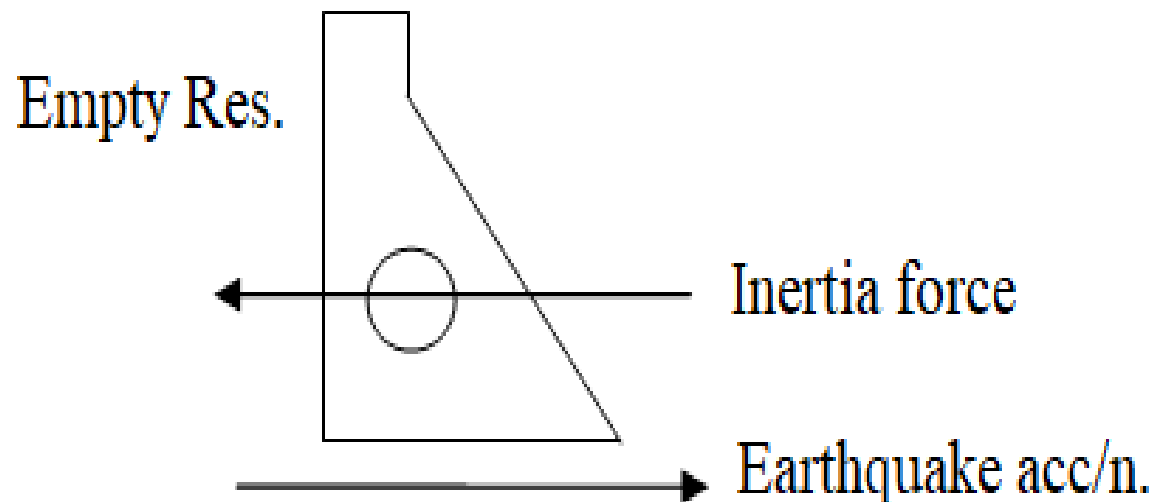


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b. Reservoir empty condition:

- the worst case occurs when the earthquake acceleration moves from u/s to d/s and inertia force acts from d/s to u/s direction.



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41

ii. Hydrodynamic pressure

- Due to horizontal acceleration of the foundation and dam there is an instantaneous hydrodynamic pressure (or suction) exerted against the dam in addition to hydrostatic forces.
- Direction of hydrodynamic force is opposite to d/n of earthquake forces.

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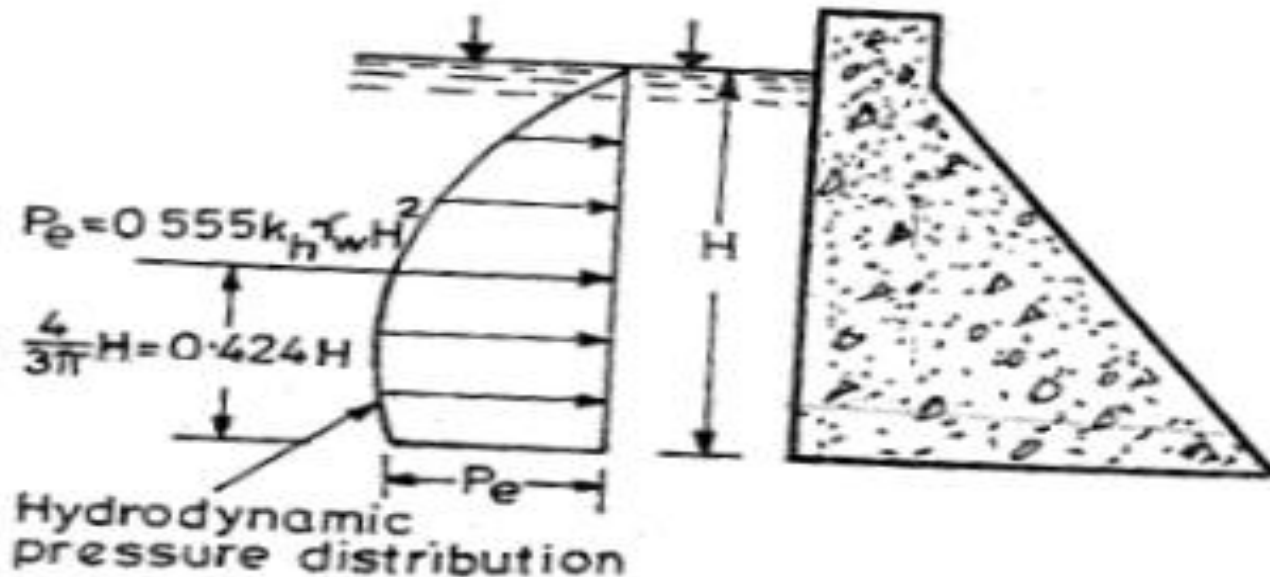
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- Magnitude of hydrodynamic force is calculated by;
 - a. **Van Korman's methods:** suggested that the hydrodynamic pressure has **parabolic variation** and the pressure force
- $F_e = 0.555 * K_h * \gamma_w * H^2$...acts at $4H/3\pi$ above the base.
- Where, K_h = is fraction of gravity adopted for horizontal acceleration such as 0.1, 0.2.. etc. e.g. 0.1g, 0.2g
- Moment of this force about the base,

$$= M_e = P_e \left(\frac{4H}{3\pi} \right) = 0.424 P_e \cdot H$$

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43



- Similar pressure will be developed by tail water on d/s if direction of earthquake is reversed.

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44

b. Zanger's methods:

- The intensity of the hydrodynamic pressure at a depth y below the water surface in the reservoir with the total depth of water H is given by

$P_e = C * \alpha_h * \gamma_w * H$, C is dimensionless coefficient and given by

$$C = \frac{C_m}{2} \left[\frac{y}{H} \left(2 - \frac{y}{H} \right) + \sqrt{\left(\frac{y}{H} \left(2 - \frac{y}{H} \right) \right)} \right] \text{ and } C_m = 0.735 \left(1 - \frac{\phi}{90} \right)$$

- Where, Φ is angle in degree the upstream face of the dam makes with the vertical
- Y is depth below water surface

2.1.2 Design and Analysis of Gravity Dams

45

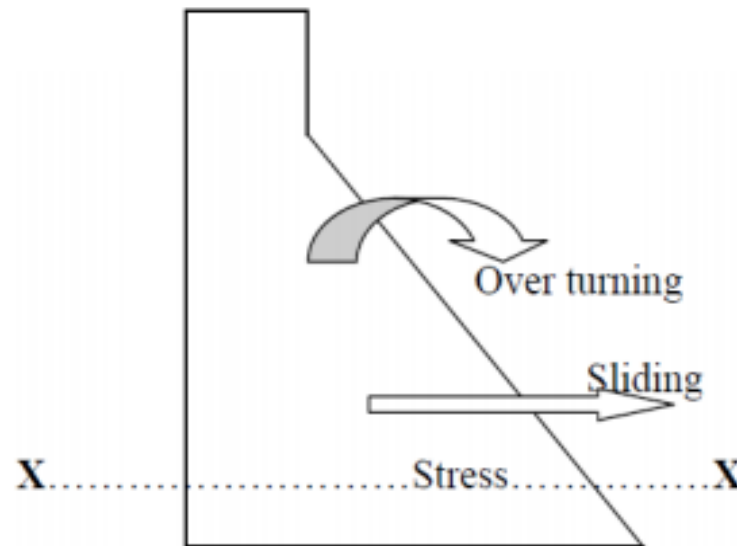
Stability requirement for gravity dam

- Gravity dam must be designed in a such safe way against all possible modes of failure, with adequate factor of safety.
- Gravity dam may fail in the following way:-
 1. Overturning/rotation/ about toe
 2. Sliding/shear
 3. Compression or Crushing
 4. Tension.

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46

- The failure may occur at the foundation plane (i.e. at the base of the dam) or at any other plane at higher plane.



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47

1. Overturning failure

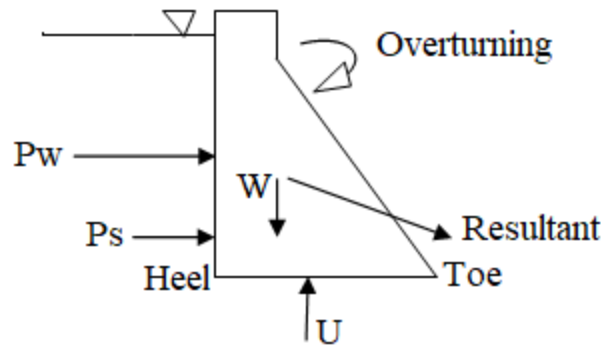
- If tension is ignored, overturning of the dam section occurs when the resultant force (R) at any section cuts near the downstream toe of the dam i.e. when R passes outside the base.
- In this case the resultant moment at the toe becomes clockwise(or -Ve).
- For stability requirements, the dam must be safe against overturning.

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48

- The factor of safety against overturning is defined as the ratio of the restoring moment (+ ve M_R)/forces to the overturning moments (- ve M_O)/forces about the toe.

$$Fs = \frac{\sum \text{Restoring moments/forces}}{\sum \text{Overturning moments/forces}} = \frac{\sum M_R}{\sum M_O} = \frac{\sum F_R}{\sum F_O}$$



- ❖ F.S. should not be less than 1.5 (i.e. F.S. > 1.5 is desirable.)

Cont....

49

- Over turning may occur due to the following conditions:
 1. If there are tension cracks at the U/s edge (heel).
 - ✓ Water under high pressure will enter the cracks and the over turning moment will further increase due to reduced bed width and increased uplift pressure, and it may eventually failure by over turning.
 2. If the toe is crashed due to excessive compressive stresses.
 - ✓ The crashed area becomes ineffective and therefore there is a reduction in effective width. The resultant may pass outside the reduced effective width of the section.

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50

2. Sliding failure

- A dam will fail in sliding at its base, or any other level, if the horizontal force causing sliding are more than the resistance available to it at that level.
- The resistance against sliding may be due to friction alone, or due to friction and shear strength of the joint.
- If the shear strength is not taken in to account, the factor of safety is known as factor of safety against sliding which will be applicable for small dams.

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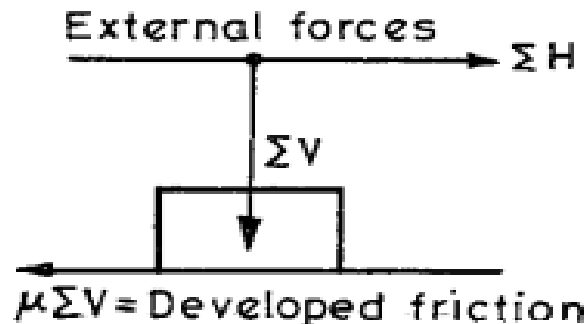
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- The factor of safety against sliding is given by:

$$F_s = \frac{\sum \text{Horizontal forces resisting sliding}}{\sum \text{Horizontal forces causing sliding}} = \frac{\mu \sum V}{\sum H}$$

μ = coefficient of static friction of material above and below joint.

$$F_s > 1.$$



- In low gravity dams, safety against sliding should be checked only for friction, but in high dams shear strength of the joints should also be considered for an economical design.

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52

- Factor of safety considering shear stress of joint known as Shear Friction Factor (S.F.F.) and is defined by the equation.

$$\text{F.S.S.} = \frac{\mu \sum V + bq}{\sum H}$$

b = width of the dam at the joint

q = average shearing strength of the joint which varies from 1400KN/m² (for poor rock) to 4000KN/m² (good rock)

μ = varies from 0.65-0.75

❖ minimum **S.F.F should be greater than 5** during the most sever conditions of reservoir load combined with maximum horizontal and vertical earthquake accelerations.

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53

3. Failure due to overstressing/crushing/

- Occurs when the compressive stress in the dam or foundation exceeds safe limit/ allowable working stresses/.
- The max compressive stress in the dam or its foundation is usually determined by applying in the theory of bending combined with thrust(or eccentrically loaded short columns)
- The stress at any point at the base of the dam or within the dam body can be calculated from equation...

$$\sigma_{max/min} = \frac{\Sigma F_V}{B} \left(1 \pm \frac{6e}{B} \right), \sigma_{max} = \frac{\Sigma F_V}{B} \left(1 + \frac{6e}{B} \right), \sigma_{min} = \frac{\Sigma F_V}{B} \left(1 - \frac{6e}{B} \right)$$

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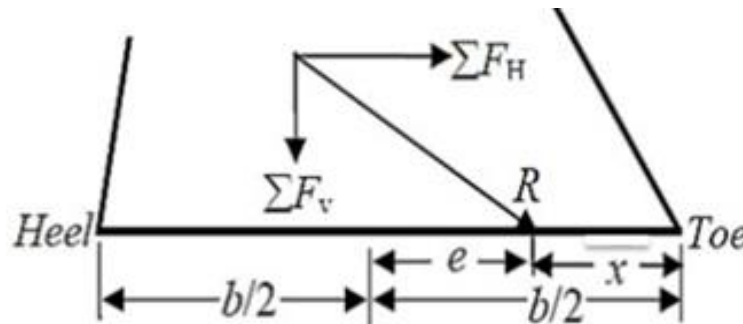
$\sigma_{max/min}$ = maximum/minimum stress

e = eccentricity (the distance from centre of the section to points of application of force).

ΣF_V = sum of vertical forces

B = base width

➤ For safety, $\sigma_{max} = \frac{\Sigma F_V}{B} \left(1 + \frac{6e}{B} \right) \leq \sigma_{allowable}$



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55

- ✓ If $\sigma_{max} \geq \sigma_{allowable}$ overstressing/crushing failure/
- ✓ If $\sigma_{min} \leq 0$ negative pressure/cracking failure/
- ✓ $\sigma_{allowable}$ for concrete = $30\text{KN}/\text{cm}^2 = 3000\text{KN}/\text{m}^2$
- For reservoir full condition, resultant is near the toe, so compressive stress produced at toe.
- For reservoir empty condition, resultant is near the heel, so compressive stress produced at heel.

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56

a. For reservoir full condition

i. max stress at toe(d/s edge)

$$\sigma_{max} = \frac{\sum F_V}{B} \left(1 + \frac{6e}{B} \right)$$

ii. Min stress at heel(u/s edge)

$$\sigma_{min} = \frac{\sum F_V}{B} \left(1 - \frac{6e}{B} \right)$$

b. For reservoir empty condition

i. max stress at the heel(u/s edge)

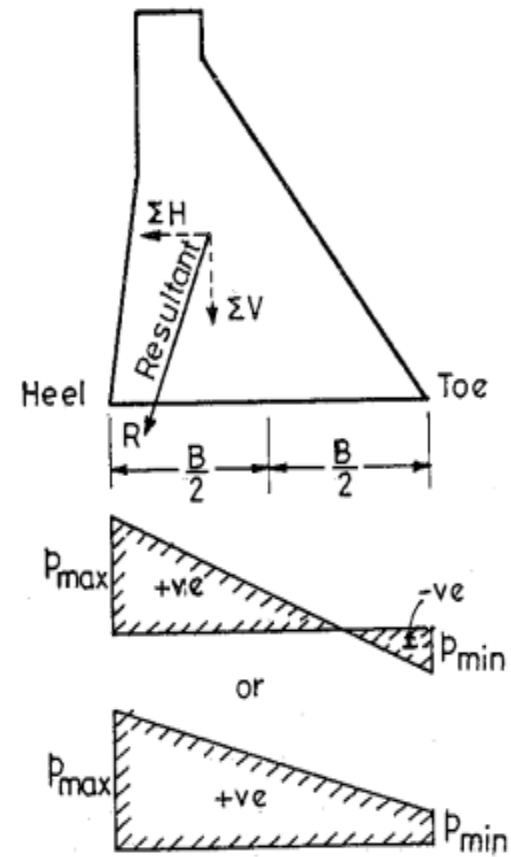
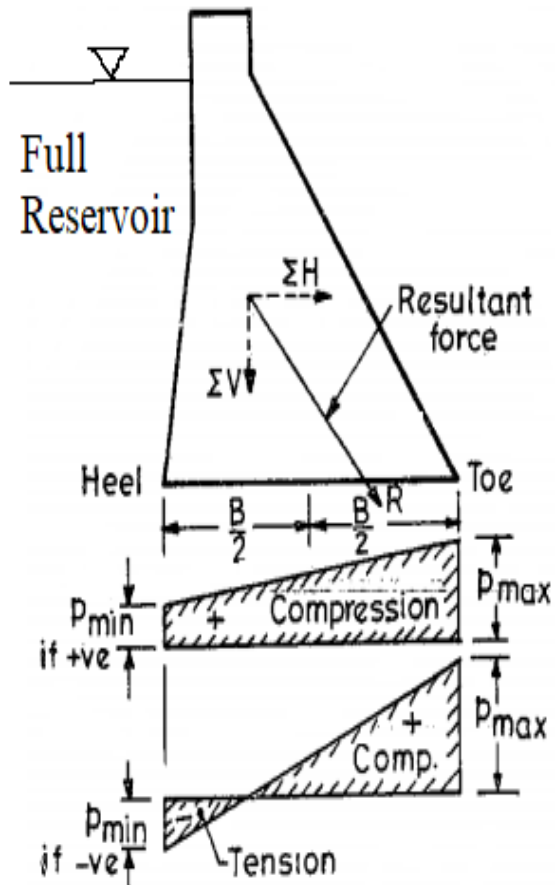
$$\sigma_{max} = \frac{\sum F_V}{B} \left(1 + \frac{6e}{B} \right)$$

ii. Min stress at the toe (d/s edge)

$$\sigma_{min} = \frac{\sum F_V}{B} \left(1 - \frac{6e}{B} \right)$$

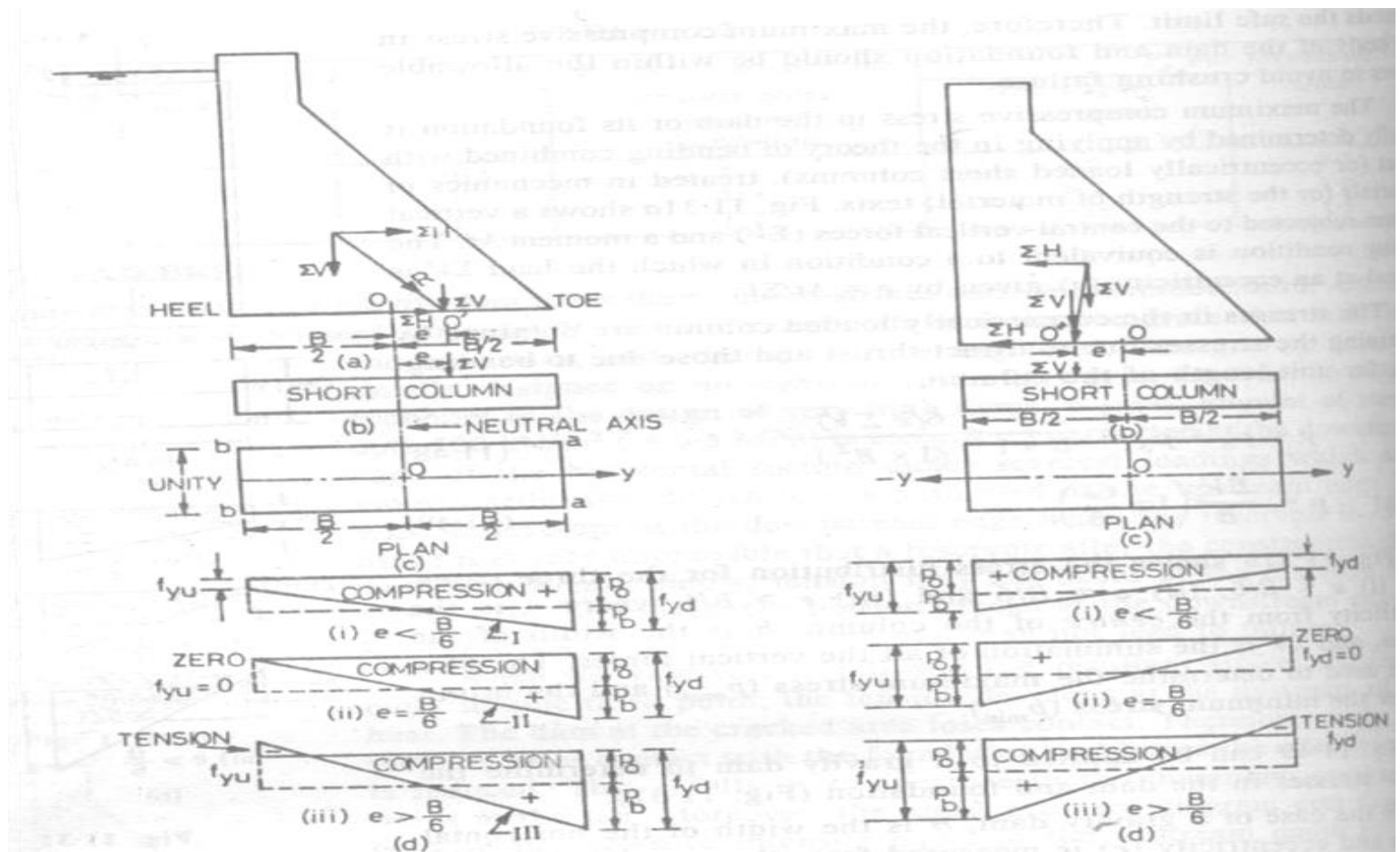
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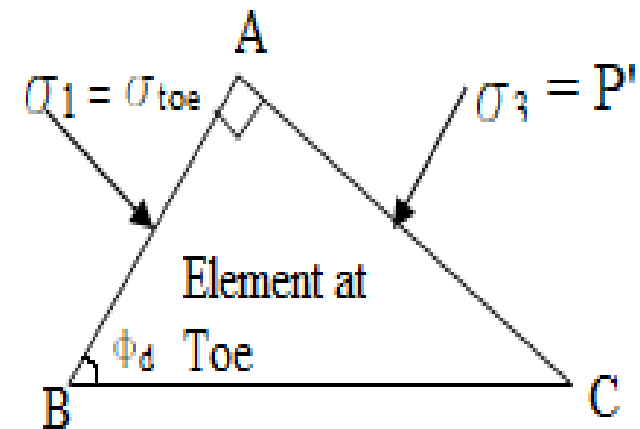
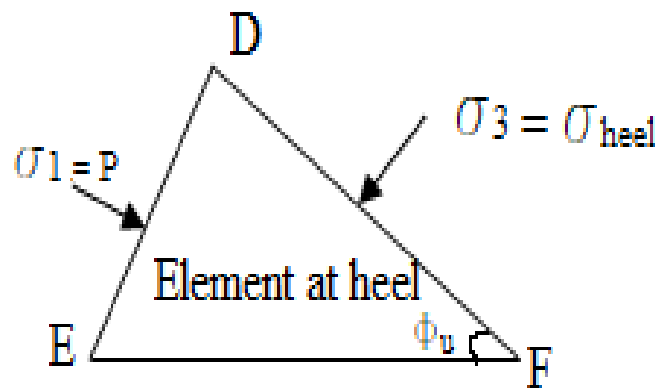
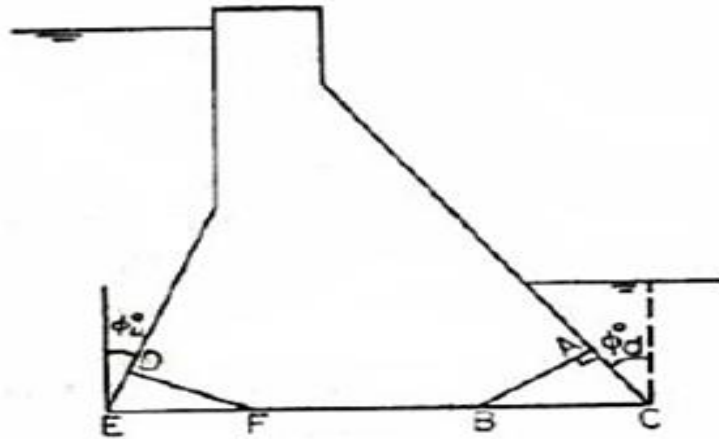
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Principal stresses and shear stresses

- The vertical stress intensity, σ_{max} or σ_{min} determined above is not the maximum direct stress produced anywhere in the dam.
- The maximum normal stress will be, in fact, the major principal stresses that will be generated on the major principal plane.

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60



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61

➤ The principal stresses at the toe is given by

$$(\sigma_1)_{\text{toe}} = \sigma_{\text{toe}} \sec^2 \Phi_d - (P' - P_e) \tan^2 \Phi_d, \quad \sigma_{\text{toe}} = \sigma_{\text{max}}$$

P' = Tail water pressure, P_e = Hydrodynamic pressure due to TW

- For d/s side, the **worst condition occurs** when tail water ($P'=0$), so maximum principal stress is

$$(\sigma_1)_{\text{toe}} = \sigma_{\text{toe}} \sec^2 \Phi_d$$

- Since $\sec^2 \Phi_d = 1 + \tan^2 \Phi_d > 1$, $\sigma_1 > \sigma_{\text{toe}}$ therefore in design we consider (σ_1) than σ_{toe} . So $(\sigma_1) <$ allowable stress.

Cont....

62

➤ The principal stresses at the heel is given by

$$\begin{aligned} (\sigma_1)_{\text{heel}} &= \sigma_{\text{heel}} \sec^2 \Phi_u - (P_w + P_e) \tan^2 \Phi_u, \\ \sigma_{\text{heel}} &= \sigma_{\text{min}} \end{aligned}$$

P_w = water pressure u/s, P_e = Hydrodynamic pressure due to u/s water

- At heel, water pressure(P_w) is $> \sigma_1$, hence $P = \gamma_w h$ is major principal stress and σ_1 is minor principal stress.
- For reservoir empty condition, P_w & $P_e = 0$,
$$(\sigma_1)_{\text{heel}} = \sigma_{\text{heel}} \sec^2 \Phi_u$$

Cont....

63

➤ The shear stress at d/s(toe) is given by

$$\tau_{toe} = (\sigma_{toe} - (P' - P_e)) \tan \phi_d$$

- If there is no tail water, $P' = 0$ and $P_e = 0$,

$$\tau_{toe} = \sigma_{toe} \tan \phi_d$$

- The D/n of the shear stress is towards the up stream.

➤ The shear stress at u/s(heel) is given by

$$\tau_{heel} = -(\sigma_{heel} - (P + P_e)) \tan \phi_u$$

- If reservoir is empty, $P = P_e = 0$

$$\tau_{heel} = -\sigma_{heel} \tan \phi_u$$

- The D/n of the shear stress is towards the down stream

Cont....

64

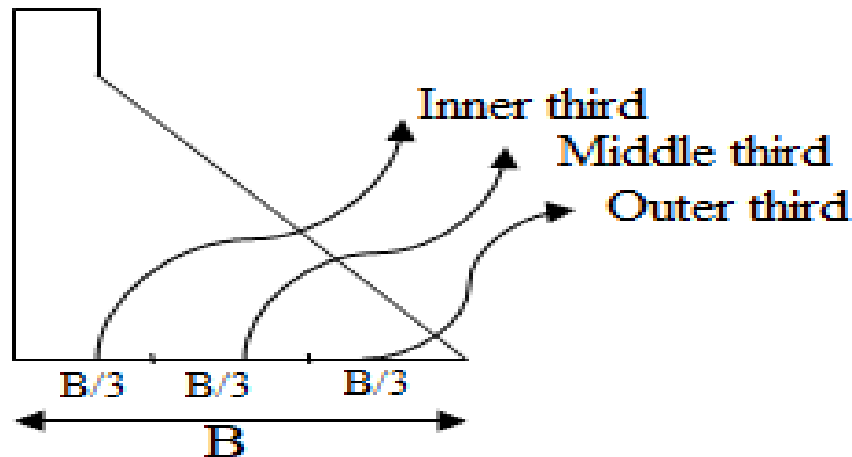
4. Tension failure

- Tension failure may occur in a gravity dam when the resultant strikes outside the middle third.
- Concrete gravity dams are usually designed in such a way that **no tension is developed anywhere**; since concrete cannot withstand sustained tensile stresses.
- To ensure no tension is developed, $\sigma_{min} = 0$.
- $\sigma_{min} = \frac{\Sigma F_V}{B} \left(1 - \frac{6e}{B} \right) = 0 \rightarrow \left(1 - \frac{6e}{B} \right) = 0 \rightarrow e = B/6$
- Maximum value of eccentricity permitted on either side of the centre is equal to $B/6$; which leads to a famous middle third rule; ***“the resultant must lie within the middle third”***.

Cont....

65

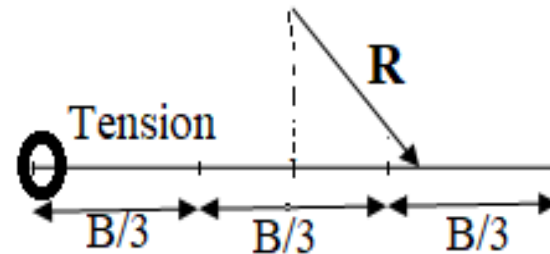
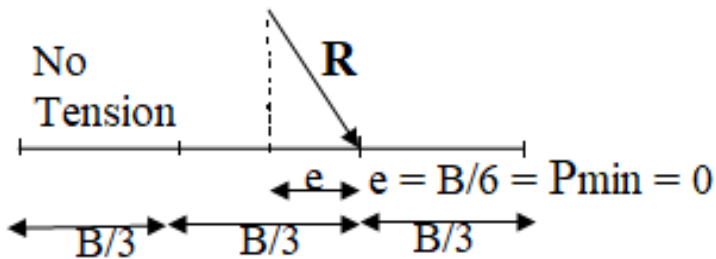
- If tension crack develops at the heel of the dam → crack width losses contact with foundation → effective width reduces → results in increase σ_{max} at the toe → also **uplift pressure increase** and net downward force or **stabilizing force decreases**.



Cont....

66

- If **R** lies in middle third, no tension formed and if **R** lies in rather than middle third tension is formed.
- If $e \leq B/6$ $\longrightarrow$ No tension
- If $e > B/6$ $\longrightarrow$ Tension will be developed.



Cont....

67

Flow chart for the stability analysis of gravity dam

1. Consider unit length of a dam
2. Calculate the vertical forces and their lever arm at the toe
 - Weight of dam
 - Weight of water acting on inclined faces
 - Uplift forces
 - Vertical earthquake forces

➤ Find sum of these vertical forces ($\sum F_V$)
3. Calculate the horizontal forces and their lever arm at the toe
 - Horizontal water pressure
 - Horizontal earthquake forces

➤ Find out the sum of horizontal forces ($\sum F_H$)

Cont....

68

4. Calculate the moments of all forces at the toe
 - Disturbing moments taken as $-Ve$, $\sum M_D$
 - Restoring moments taken as $+Ve$, $\sum M_R$
- Find the algebraic sum of all the moments, i.e.

$$\sum M = (\sum M_R - \sum M_D)$$

5. Find out location of resultant force by determining its distance from the toe, $\bar{x} = \frac{\sum M}{\sum F_V}$

6. Find out the eccentricity (e) of the resultant (R) using,

$$e = \frac{B}{2} - \bar{x}.$$

- $e \leq \frac{B}{6} \rightarrow$ for no tension to develop anywhere in the dam

Cont....

69

7. Determine the maximum stresses at the toe and heel using, $\sigma_{max/min} = \frac{\sum F_V}{B} \left(1 \pm \frac{6e}{B} \right)$

8. Find out the principal stresses at the toe and heel

$$(s_1)_{toe} = \sigma_{toe} \sec^2 F_d - (P' - P_e) \tan^2 F_d$$

$$(s_1)_{heel} = \sigma_{heel} \sec^2 F_u - (P_w + P_e) \tan^2 F_u$$

9. Find the shear stresses at the toe and heel

$$t_{toe} = (\sigma_{toe} - (P' + P_e)) \tan F_d$$

$$t_{heel} = -(\sigma_{heel} - (P + P_e)) \tan F_u$$

Cont....

70

10. Determine the Fs against overturning

$$F_S = \frac{\sum M_R}{\sum M_O} \geq 1.5$$

11. Determine Fs against sliding

$$F_S = \frac{\mu \sum F_V}{\sum F_H} > 1$$

12. Check shear friction factor

$$F.S.S. = \frac{\mu \sum F_V + bq}{\sum F_H} > 5$$

B= width of joint, q= shear strength of joint (14Kg/m³)

Cont....

71

Design of gravity dams

Two of the various methods used in the design of gravity dams are:-

- ✓ Multiple step method (or zone method)
- ✓ Single step method

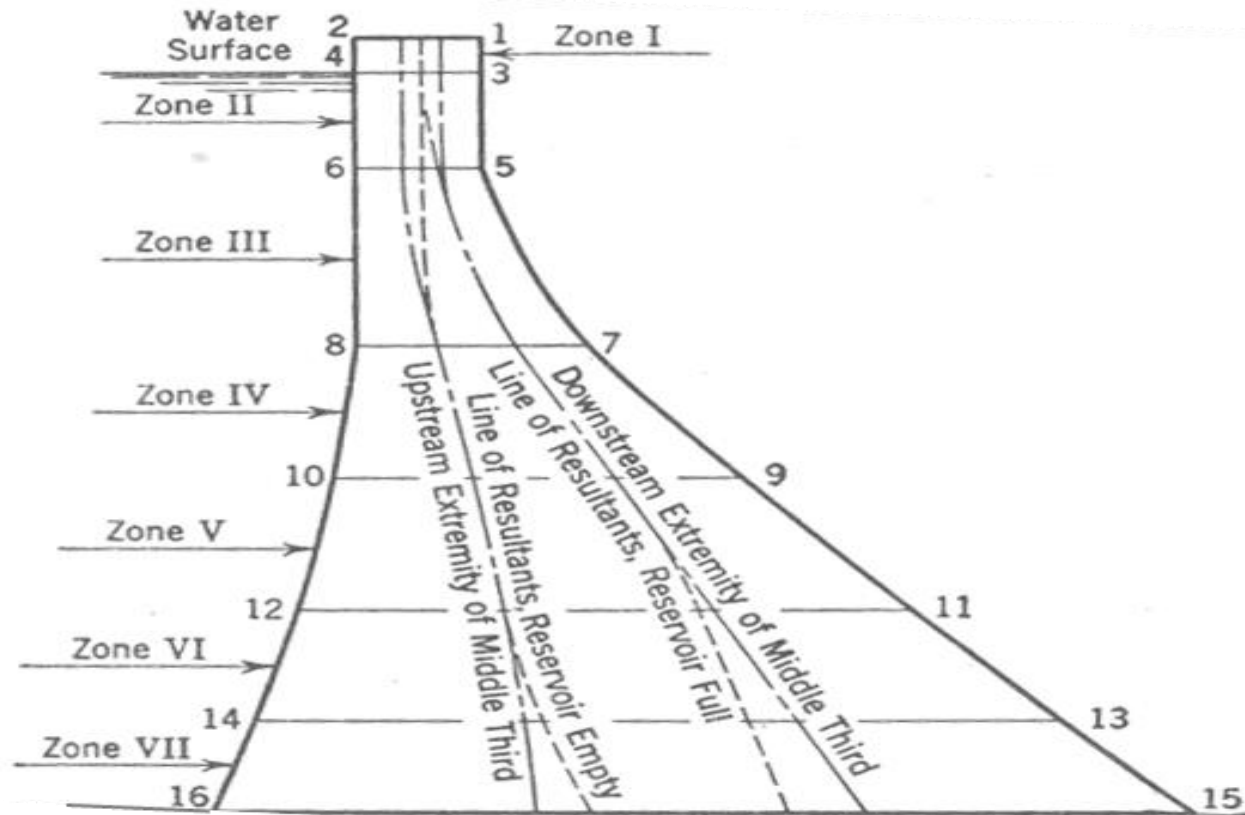
1. Multiple step method (or zone method)

- Section of the dam is divided into a number of zones. (The face slopes are altered at suitable interval).
- Design commences/starts/ from crest level, and descends through profile stages corresponding to predetermined elevations.

Cont....

72

- Each zone is designed in such away that all requirements of stability are satisfied.



Cont....

73

Zone-1

- ✓ This is a rectangular section above the maximum water surface (1-2-3-4) or if there is ice, it is the one above the bottom of the ice sheet.
- ✓ If there **is no ice**, the **height of zone-I** is controlled by free board requirements and **the width is determined by practical consideration** or economy.
- ✓ If there ice sheets the height of zone I is fixed on the consideration of **sliding of the zone due to ice pressure**.
- ✓ The resultant force passes through the mid-point of the base.

Cont....

74

Zone- 2

- ✓ is also a rectangular section and extends from bottom of zone-1 to a depth where the resultant in the reservoir full condition reaches the d/s extremity of middle third point of the base.
- ✓ That portion of the dam b/n the bottom of zone I and the plane 5-6 constitutes zone II.

Zone- 3

- ✓ Below the bottom of zone II, the u/s face continues to be vertical while the d/s face must begin to batter/sloped/ to keep R in middle 3rd.
- ✓ The line of the resultant continues to coincide with the d/s extremity of the middle third when the reservoir is full.

Cont....

75

- ✓ This zone extends to a depth where the resultant in the reservoir empty condition reaches the u/s extremity of middle third point of the base.
- ✓ Therefore, zone III is the portion b/n 5-6 and 7-8.

Zone- 4

- ✓ in this zone both the upstream and downstream faces are inclined so that the resultant of both in the reservoir full and empty conditions lie at the middle third point (section 7-8 to 9-10).
- ✓ This zone extends to a point where principal stress at the toe is equal to allowable stress of concrete for full reservoir condition (i.e. $(\sigma_1)_{\text{toe}} = \sigma_{all}$).
- ✓ Low dams ends at this zone.

Cont....

76

Zone- 5 (section 9-10 to 11-12)

- ✓ It has inclined face u/s and d/s like zone-4, however the slopes are more flatter. D/s slope is flattened so that the principal stress remain well within allowable limit.
- ✓ This zone extends to a depth where the principal stress at the heel of the section reaches the permissible limits in the reservoir empty case (i.e. $(\sigma_1)_{\text{heel}} = \sigma_{\text{all}}$).

Zone- 6 (section 11-12 to 13-14)

- ✓ The slope of both u/s and d/s face are adjusted so that the principal stress at both faces remain well within the allowable limits.
- ✓ This zone extends to a depth where the principal stress at the toe of the section reaches the permissible limits (i.e. $(\sigma_1)_{\text{toe}} = \sigma_{\text{all}}$).

Cont....

77

Zone- 7 (section 13-14 to 15-16)

- ✓ As the height of the dam increases, the slope of both u/s and d/s faces increases (more flattened).
- ✓ Consequently, at some plane the value of $\text{Sec}^2 \phi$ (for d/s face) may become so great that the principal stress at the d/s face may exceed the maximum allowable limit.
- ✓ Thus, the principal stress at d/s edge cannot be kept within limit by further flattening the d/s slope.
- ✓ If one reaches this zone during design, it is better to change u/s and d/s slope in zone 3-5 to eliminate zone-7.

Cont....

78

- ✓ If these changes do not bring the principal stress within limits, it is better to start design again with a reduced height, increased top width and/or better quality concrete.

2. Single step design method

- ✓ For high dams, going beyond zone IV, it is found that the shape of u/s and d/s slopes is sometimes unusual shape.
- ✓ The u/s face has a relatively flat slope while the d/s face has outward convex shape.

Cont....

79

- ✓ Such a shape for the d/s face of the dam is not desirable b/c the outer layer of such a section tends to buckle outward and unless the buckling forces is cancelled by the weight component normal to the face, tension results.
- ✓ To avoid this curvature the dam must be redesigned by single step design method.
- ✓ In the single step method of design the entire section of the dam is assumed as a single zone.
- ✓ In this method, suitable top width and free board are assumed.

Cont....

80

- ✓ The d/s slope is usually assumed between 0.7:1 to 0.8:1.
- ✓ The u/s face is kept vertical for some depth which is determined by trial.
- ✓ The **slope of u/s and d/s face of the dam are adjusted to ensure no tension develops**, and the principal stresses at the u/s face for reservoir empty condition and at the d/s face for the reservoir full condition are **within allowable limits**
- ✓ The dam section is then checked for all stability requirements for reservoir empty and full conditions.

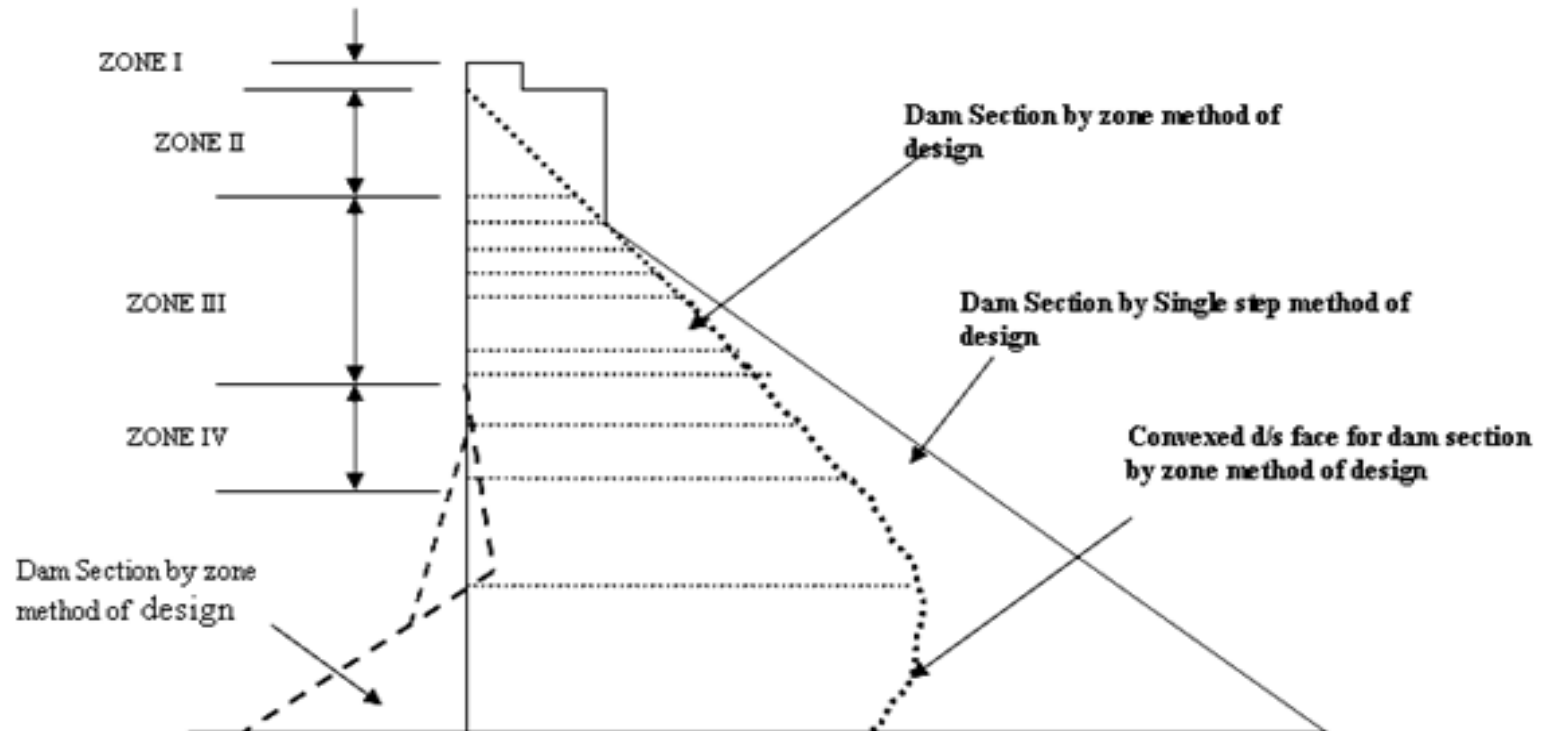
Cont....

81

- Generally the following conclusions are made from gravity design:-
 1. Dams of lesser heights can be designed economically only by multiple-step design method.
 2. If high strength concrete used in construction, even high dam can be designed by multiple step method; thus limiting dam height to zone-4, and eliminating above zone-5.
 3. High dams beyond zone IV are designed by single step method so that convex curvature of d/s face is avoided.

Cont....

82



Cont....

83

Joints in gravity dams (Reading Assignment)

- As gravity dam is a huge concrete, structure it is essential to provide suitable joints at appropriate places.
- Depending upon the location and purpose served, joints provided in dams may be classified as follows:
 - a) Construction joint (or horizontal joints)
 - b) Contraction joints.

Cont....

84

- a) Construction joint (horizontal joints)
 - ✓ Provided for ease in construction of dam (economical and convenient construction).
 - ✓ This joint is necessary since entire work of concreting **the whole dam cannot be completed in one stretch.**
 - ✓ They are the joints introduced b/n successive lifts.
 - ✓ (The lift is the **height by which the dam is raised in one continuous operation by pouring concrete** (or laying masonry)).
 - ✓ For solid gravity dam **lifts of about 1.5m is adopted.**

Cont....

85

- The concrete of the next lift is placed after sufficient time is allowed for the previously placed concrete to cool and attain its initial set and become hard.
- Prior to the placement of concrete of the next lift:-
 - ✓ 12.5mm mortar should be applied to have proper bond between successive lifts,
 - ✓ the surface of the previous placed concrete is thoroughly cleaned by the use of high velocity jet of water and air as well as wet- sand blasting process.

Cont....

86

b) Contraction Joints (vertical joints)

- ✓ are mainly provided to avoid cracks caused by shrinkage of concrete due to temperature changes.
- ✓ Surface cracks may develop due to high daily temperature difference b/n the surface and near the surface areas of the dam.
- ✓ Cracks adversely affect water tightness, durability, appearance and internal stresses of concrete.
- ✓ Contraction joints are of two types:
 - i) Transverse joint
 - ii) Longitudinal joints

Cont....

87

i. Transverse joints

- ✓ They are provided normal to the axis of the dam.
- ✓ Extend vertically from foundation to the top of the dam and are continuous from u/s to d/s face of the dam, thus dividing the dam in to separate blocks.
- ✓ Provided to allow contraction of concrete on the two sides and prevent development of transverse cracks in the dam.

ii. Longitudinal joints

- ✓ They are provided parallel to the axis of the dam.
- ✓ Provided to prevent longitudinal cracks.
- ✓ Run between two adjacent transverse joint and are thus not continuous all along the length of the dam.
- ✓ Subdivide each block formed by transverse joints.
- ✓ Spacing of these joints varies b/n 15 and 30m.

Cont....

88

Galleries

- A gallery is an **opening provided for obtaining access to the interior of the dam for various purposes.**
- It may run in transverse or longitudinal direction and may run horizontally or on a slope.
- ❖ **Shape: -**
 - ✓ Usually rectangular with its top and bottom either flat or semi-circular.
 - ✓ For flat, top and bottom all corners are rounded to reduce stress concentration.
- ❖ **Size:**
 - ✓ **Large enough to provide working space** and access for equipment for normal maintenance.
 - ✓ Its size in general varies from 1.5m to 1.8m in width and 2.2 to 2.4m in height.

Cont....

89

Purposes of a Gallery

1. To provide drainage of the dam section. Water seeping from u/s face of the dam is drained off through galleries.
2. To provide facilities for drilling and grouting operations for foundation of the dam.
3. To provide space for the piping system and equipment used for grouting of the contraction joints as well as for the post cooling of concrete blocks.
4. To provide access to the interior of the dam for inspection and also for installing various instruments to study structural behavior of the dam after completion.

Cont....

90

5. To provide access to, and room for mechanical and electrical equipment required for the operation of gates for outlet conduits, power penstocks and spillway crest.

6. To provide access routes for visitors; to provide access through the dam for control cables and/or power cables.

➤ Depending upon the purposes served the galleries can be classified as follow:

i)Foundation gallery

ii)Drainage gallery

iii)Grouting gallery

iv)Inspection gallery

Cont....

91

Inspection Galleries



Cont....

92

Control of cracking in concrete

- Cracking of concrete results from temperature change.
- Surface cracks are produced due to daily variation in temperature while interior cracks are produced due to heat of hydration liberated by cement.
- Methods to minimize development of cracks are:-
 1. Pre cooling of concrete
 - ✓ Concrete is pre-cooled before it is placed in dam. This is done by cooling aggregate and sand by refrigerated water and blowing air through them.

Cont....

93

2. Post cooling of concrete
 - ✓ Achieved by circulating refrigerated water through pipes embedded in concrete in each lift.
3. Using low heat cement
 - ✓ Low heat of hydration in concrete
4. Using lower percentage of cement
5. Restricting the height of the lift, sayn1.5m
6. Allowing considerable time b/n laying of two successive vertical lifts, say about 4 days.
7. Water curing

Cont....

94

Foundation treatment

- The foundation must be strong enough to withstand the entire load acting upon it.
- Defects in dam foundations are:-
 - ✓ Bedding planes, unconformity, shale beds, etc.
 - ✓ Faults, joints, seams and cracks, etc.

Cont....

95

Methods of treatment

1. First surface has to be prepared (done by removing all loose overburden of weathered rock, decayed or weak rock till sound bed rock is exposed).
2. Excavation of seams of decayed or weak rock by tunneling and back filling tunnels with concrete.
3. Excavating for and making concrete cutoff walls across leakage channels in the dam foundation where the water channels are too large or too wet for mining and grouting.
4. Grouting the foundation to increase its strength and tender it impervious.

Cont....

96

Types of grouting

1. Foundation Grouting:

- ✓ This consists of injecting under pressure a mixture of cement and water (called grout) in to holes drilled in the foundation rock for the purpose of sealing seams, cracks and fissures or filling voids present in the rock.

2. Consolidation Grouting:

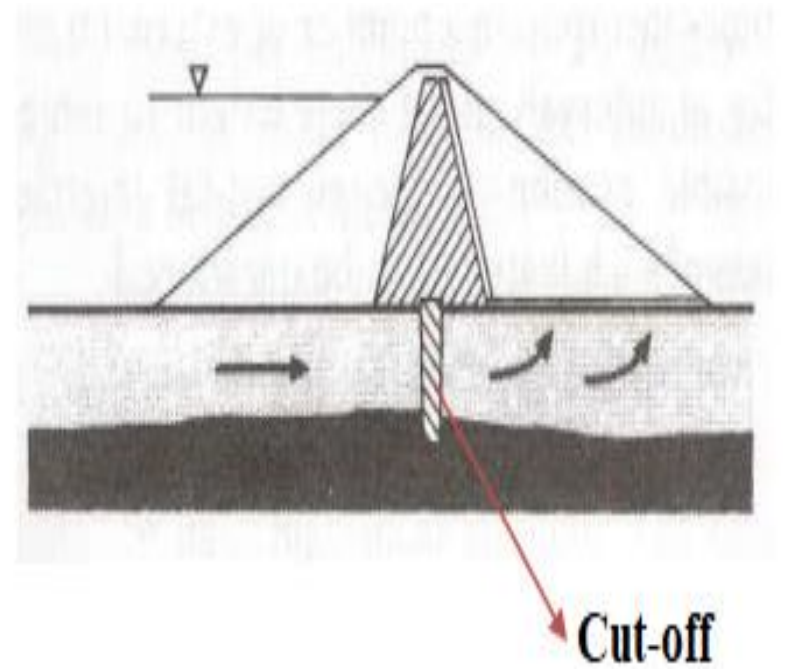
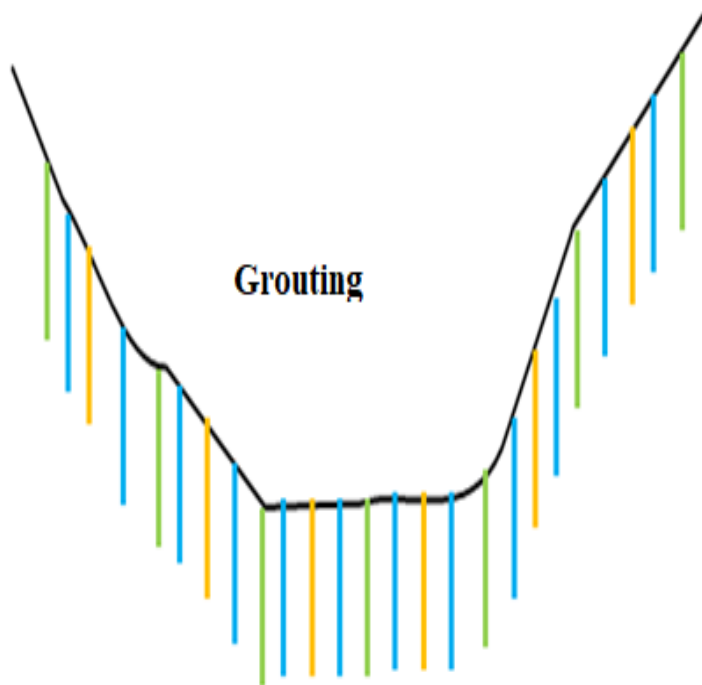
- ✓ Done to consolidate the entire rock foundation and thus to increase its strength.

3. Curtain Grouting:

- ✓ Done to create a deep curtain or a barrier in the foundation rock at the heel of the dam which will prevent leakage from the reservoir and thus reduce the uplift pressure on the dam.

Cont....

97



2.1.3 Design of Concrete Arch & Buttress Dams

98

The arch dams and the buttress dams are concrete dams, like gravity dams.

Arch Dam

An arch dam may be defined as a solid wall curved in plan standing across the entire width of the river, in a single span

- Arch dam obtain it's stability from self weight and to great extent from virtue of arch action.
- Structurally resist the imposed loads by combination of
 - arch action and
 - cantilever action.

Cont....

99

- The arch action depends primarily on amount of curvature of the dam and on the shape of the valley.
- The greater the curvature in plan, the greater will be the load that can be transferred to the abutment.
- Arch dam transmits the major portion of the;-
 - **water load** to the abutments or valley sides hence, large horizontal reactions are required by the abutments
 - The **weight of structure** to the floor of the valley

Cont....

100

- When compared to gravity and buttress dam;
 - Are structurally more efficient,
 - Greatly reduce the volume of concrete required(50-85%)
- Suitable to the site with V-shaped valley with strong abutment and foundation.
- The rock abutments should be strong enough to resist the thrust developed by arch action.

Cont....

101



Cont....

102



Cont....

103

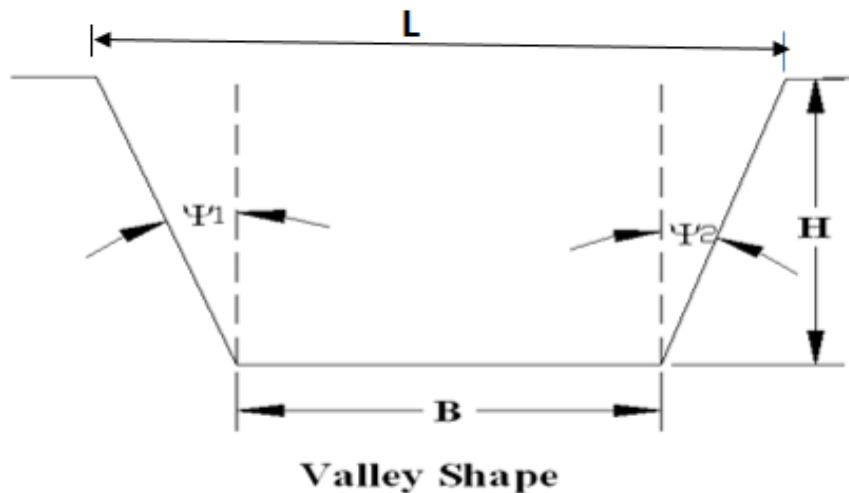
- **Valley suited for arch dams;**
 - **Narrow gorges** provide the most natural solution for an arch dam construction,
 - usually recommended ratio of crest length to dam height being 5 or less. ($\frac{\text{Valley width}}{\text{Dam height}} < 5$)
- Sarkaria has proposed a Canyon Shape Factor (C.S.F.) which would **indicate the suitability of the site for an arch dam**. The Canyon Shape Factor (C.S.F.) is Given By:

$$CSF = \frac{B + H(\sec \psi_1 + \sec \psi_2)}{H}$$

Cont....

104

- If CSF are from 2 to 5 the valley is suitable for arch dam construction.
- The lower value of CSF, the thinner the section



- B = bottom width
- L = crest length
- H = dam height

Cont....

105

- **Classification of valleys by CSF**

Valley type	Bottom width B	ψ_1	ψ_2	CSF
U shaped	$< H$	$< 15^\circ$	$< 15^\circ$	< 3.1
Narrow V shaped	0	$< 35^\circ$	$< 35^\circ$	< 2.4
Wide V-shaped	0	$> 35^\circ$	$> 35^\circ$	> 2.4
Composite U-V shaped	$< 2H$	$> 15^\circ$	$> 15^\circ$	$\cong 4.1$
Wide and flat shapes	$> 2H$	ψ_1	ψ_2	> 4.0
Unclassified	Highly irregular valley shape			

Cont....

106

- Since water pressure is transferred to abutments by arch action, overturning & sliding stability have little relevance in arch dam and **failure can occur only as a result of overstress**.
- The **horizontal component of arch thrust** must be transferred in to the abutment at a safe entry angle β as shown in the figure below.
- Safe entry angle is the one that will not promote abutment yielding or instability.



Cont....

107

Classification of arch dams

1. Massive head arch dam

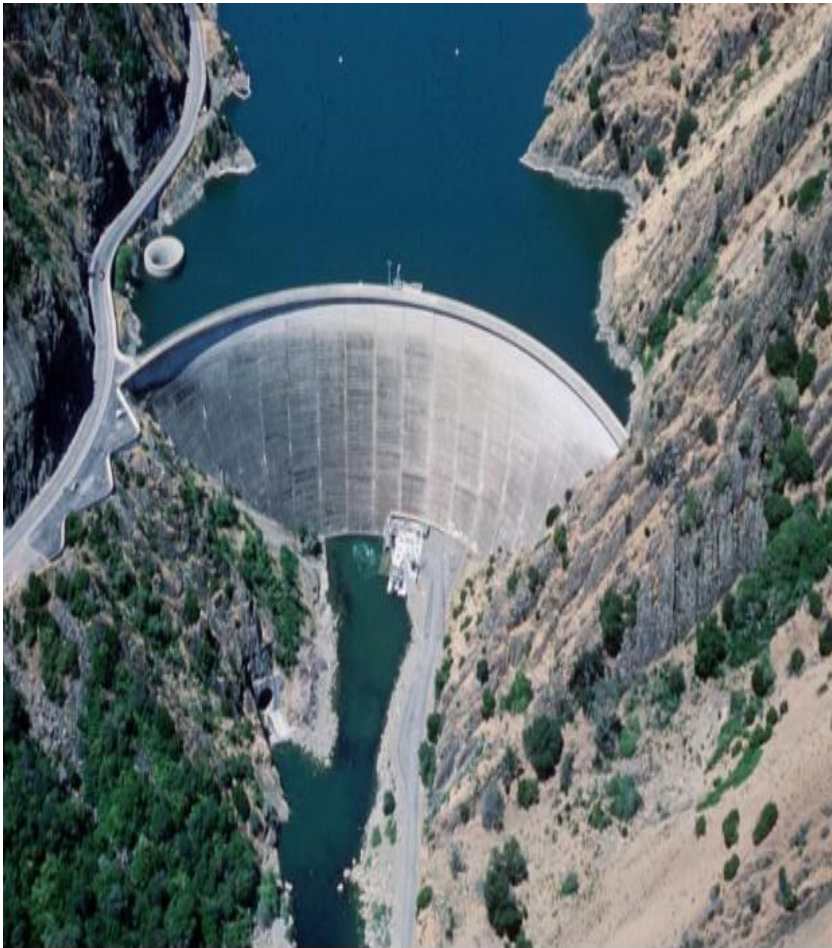
- The whole span of the dam is covered by a single curved wall usually vertical or nearly so.

2. Multiple arch dam

- series of arches cover the whole span of the dam, usually inclined and supported on piers or buttresses.
- Multiple arch dams are usually considered as a type of buttress dam and will be described later.

Cont....

108



Cont....

109

- Massive head arch dam is divided in to the following:
 - ✓ Constant radius arch dams,
 - ✓ Constant angle arch dams,
 - ✓ Variable radius arch dams,

1. Constant radius/constant center arch dams/

- Is the simplest geometry and has vertical u/s face.
- u/s face (extrados radius, r_e) is constant at all elevations from top to bottom.
- But, d/s face (intrados radius, r_i) is varying (decrease from top to bottom).

Cont....

110

- Intrados curves and extrados curves are usually **concentric**. Thus the **thickness of the arch increases with depth** below the top of the dam.
- The central angle is between 100° - 150° .
- It is apparent that **central angle, 2θ , for r_i vary at different elevation**, max. @ Crest level and minimum at the bottom.
- Since **r_e, r_i and middle line of horizontal arch rings passes through common point on vertical line** it is called **constant center arch dam**.

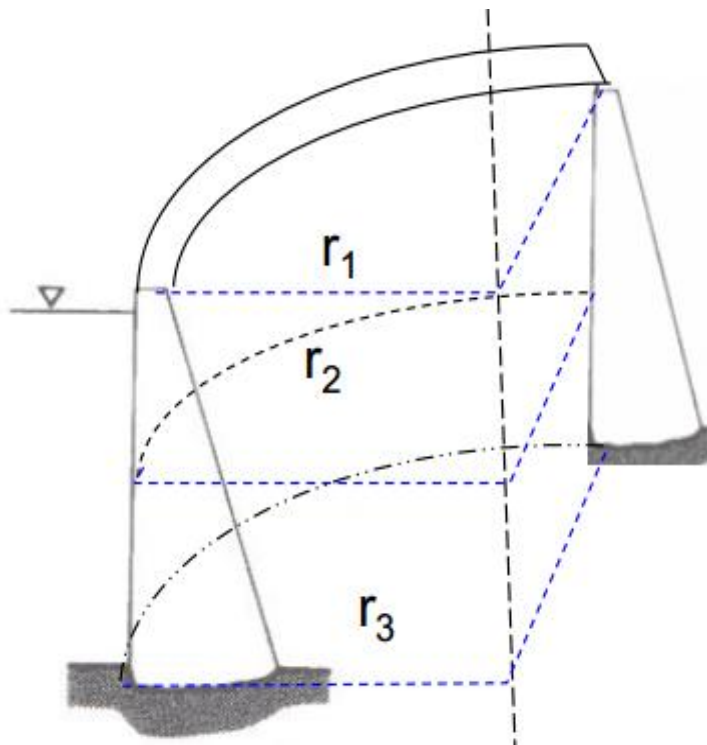
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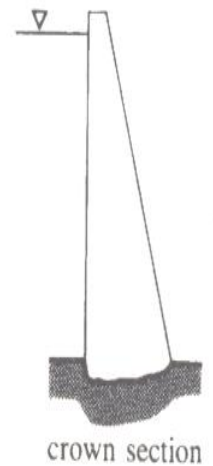
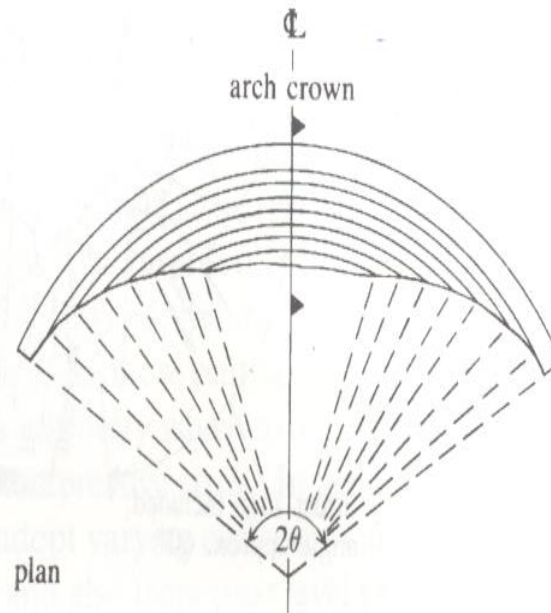
- Central angle (2θ) decreases as the depth below the crest increases, thus **arch action developed at the lower ring (bottom) is smaller than at the higher ring,** hence large proportion of water load at lower is carried by cantilever action making the dam thick and uneconomical at the bottom.
- It's particularly adapted to **U-shaped canyon** where cantilever action carries a relatively large proportion of water load at lower elevations.

Cont....

112



(a) Constant radius arch dam



Cont....

113

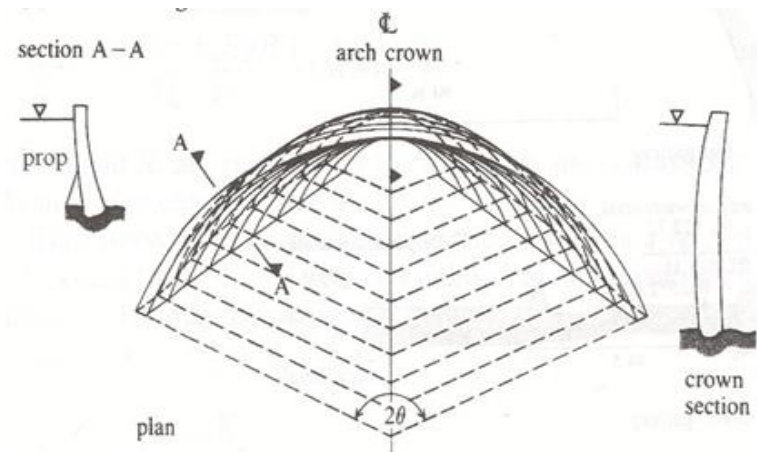
2. Constant angle arch dam:

- Central angle of the arch rings **at various elevations is constant**, but the **radii do vary** (radius decreases as depth below the crest increases).
- It's **design is made by adopting best central angle of $133^{\circ}34'$** .
- It uses about 70% concrete as compared to constant radius arch dam.
- Central angle may range from 100° - 150° .

Cont....

114

- It is best suited to narrow & steep-sided V-shaped valleys.
- Large arch action is developed in the arch ring at all elevation, thus a large proportion of water load is carried by arch action hence it's thickness is smaller than constant radius arch dam.
- It has curved u/s face.



Cont....

115

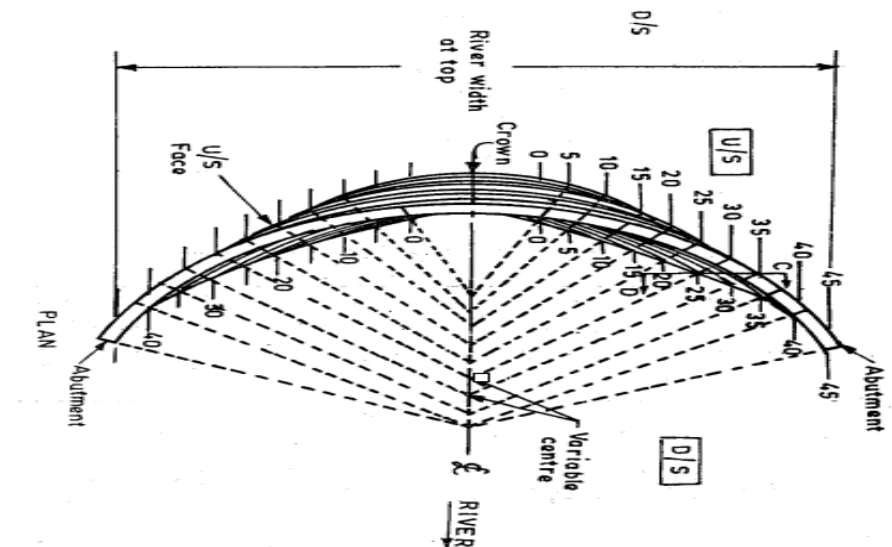
3. Variable radius /center/ arch dam

- Both radius (r_e and r_i) and center angle are not constant at different elevations.
- The radii of the extrados and intrados surfaces vary from the top to bottom, usually maximum at the top and minimum at the base.
- Central angle varies at different elevations usually ranges from 180° to 150° .

Cont....

116

- More economical than constant radius arch dam (saves 18% of concrete) and less economical than constant angle arch dam (requires 17% more concrete).
- Suitable to U and V-shaped valley.



Cont....

117

Forces acting on arch dam

- The loads are the same as that of gravity dams.
- Uplift forces are less important if no cracking occurs. Uplift in cracks results in **d/s deflection** and **increase in σ_{max} in arch and cantilever elements**.
- **Internal stresses** caused by temperature changes, ice pressure and yielding of abutments are very important.
- Ice pressure applicable in a cold countries and cause heavy concentration loading at the top of arch.

Design methods of Arch Dam

118

- Arch dam is designed using the following theories;
 1. Thin cylinder theory
 2. Thick cylinder theory
 3. Elastic theory
 4. Trial load method

1. Thin Cylinder Theory

- The weight of concrete and water in the dam is carried directly to the foundation.
- The horizontal water load is carried entirely by arch action.

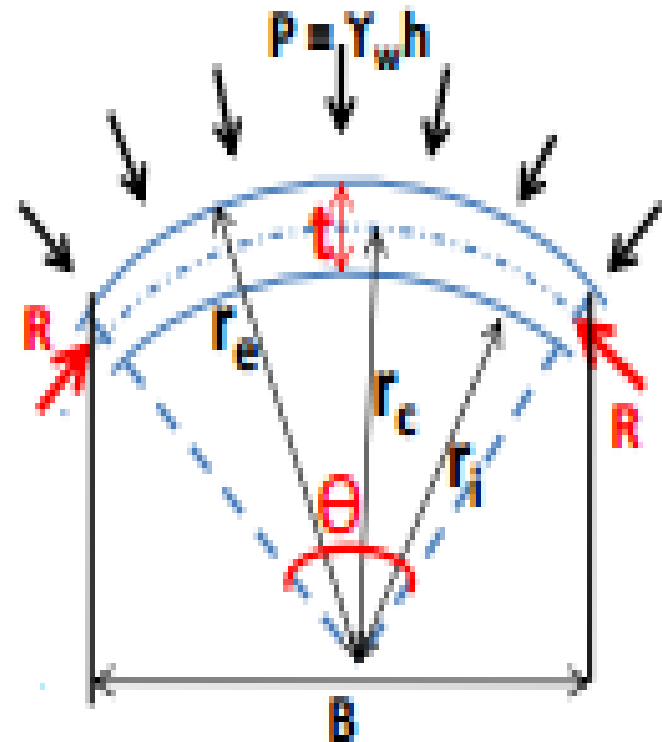
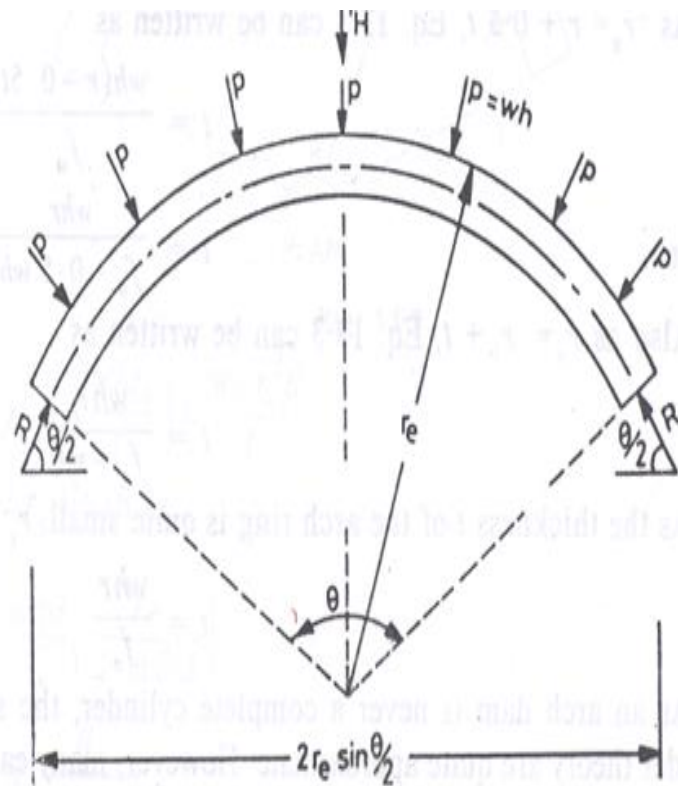
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119

- The theory assumes:
 - ✓ the arch is simply supported at the abutments and
 - ✓ the stresses are approximately the same as in thin cylinder of equal outside radius r_e (i.e. since cylinder is thin the **stress distribution for u/s and d/s are the same**).
- The **pressure on the arch ring equal to the hydrostatic pressure** at the corresponding elevation and the **stress distribution across the arch ring is uniform**.

Cont....

120



Cont....

121

- If the arch ring is at depth 'h' below water surface, then $P = \gamma h$ (hydrostatic pressure acting in radial d/n).
- Total hydrostatic pressure force is given by;

$$P = \gamma h * 2r_e \sin\theta/2 = 2\gamma h r_e \sin\theta/2$$

- If R is abutment reaction it's component in u/s d/n which resists the pressure force P is equal to $R \sin\theta/2$
- Pressure force (P) = total vertical abutment reaction (R)
- $2\gamma h r_e \sin\theta/2 = 2R \sin\theta/2$
→ $R = \gamma h r_e$ (abutment reaction)

Cont....

122

- If σ is compressive stress developed in the arch ring at the abutments for unit height,

$$\rightarrow \sigma = \frac{\gamma h r_e}{A} = \frac{\gamma h r_e}{t \cdot 1}, \dots \quad (\text{Average stress}), \quad \sigma = \frac{R}{A}$$

- If 'f' is allowable compressive stress for arch material then in limiting case,

$$\sigma = f.$$

$$t = \frac{\gamma h r_e}{f}$$

- This equation indicates that;
 - thickness t of arch ring increases linearly with depth below water surface
 - thickness t of arch ring increases linearly with radius of the ring
 - thickness t of arch ring varies inversely with allowable stress, f.

Cont....

123

❖ Thickness (t) in terms of intrados (r_i) and mean radius (r) is described as follows;

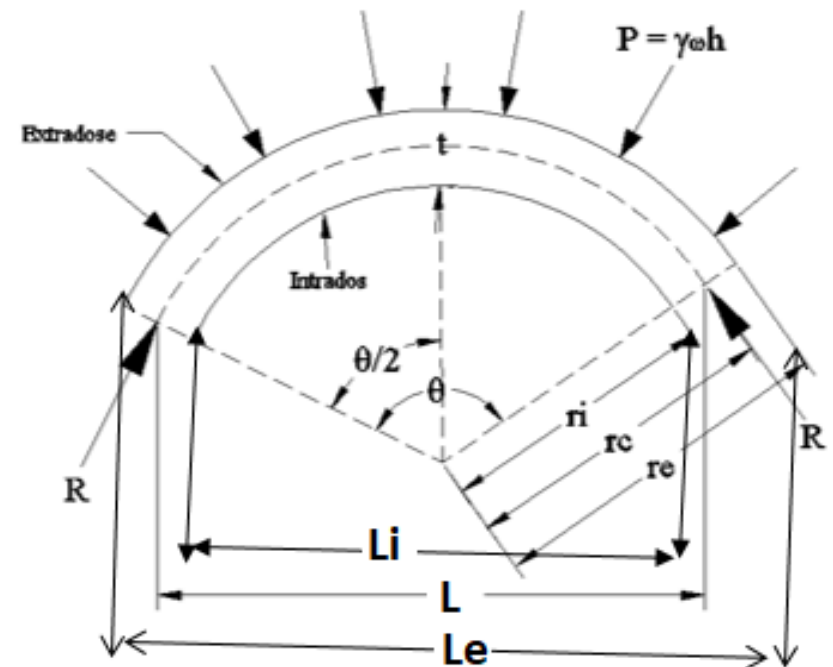
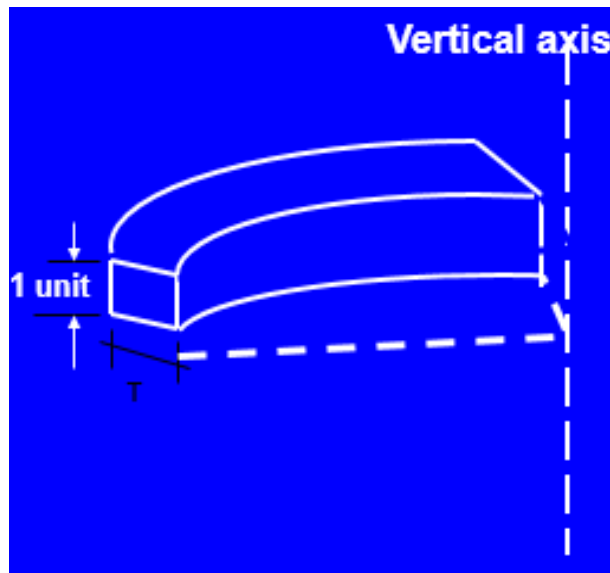
- $r_i = r_e - t \rightarrow r_e = r_i + t \rightarrow t = \frac{\gamma h r_i}{f - \gamma h}$
- $r = r_e - \frac{1}{2}t \rightarrow r_e = r + \frac{1}{2}t \rightarrow t = \frac{\gamma h r}{f - 0.5\gamma h}$

Cont....

124

Most economical central angle of an arch

- Most economical central angle (i.e. angle subtended at the center) of arch dam, is an angle for which the volume of concrete require is minimum



Cont....

125

- Volume of concrete, V , per unit depth of arch ring is given by;
- $V = A * \text{arch length}$
- $V = A * r_e \theta$, θ in radians
- $A = h * t = t * 1 = t$, (cross sectional area of arch ring for unit height) $V = r_e \theta t \rightarrow$ but, $t = \frac{\gamma h r_e}{f}$
- $V = r_e \theta \left(\frac{\gamma h r_e}{f} \right) = \frac{\gamma h r_e^2 \theta}{f}$
- $L_e = 2 r_e \sin \theta / 2$, $L_e =$ exterior span length of arch
- $r_e = \frac{L_e}{2 \sin \theta / 2}$

Cont....

126

- $V = \frac{\gamma h \theta}{f} * \left(\frac{L_e}{2 \sin \theta / 2} \right)^2 = \frac{\gamma h \theta}{f} * \frac{L_e^2}{4 \sin^2 \left(\frac{\theta}{2} \right)}$
- Let $K = \frac{\gamma h L_e^2}{4f}$
- $V = K * \left(\frac{\theta}{\sin^2 \left(\frac{\theta}{2} \right)} \right)$
- For minimum volume of concrete, $\frac{dV}{d\theta} = 0$,
- $\frac{dV}{d\theta} = \frac{d}{d\theta} \left(K * \left(\frac{\theta}{\sin^2 \left(\frac{\theta}{2} \right)} \right) \right) = k \frac{d}{d\theta} \left(\left(\frac{\theta}{\sin^2 \left(\frac{\theta}{2} \right)} \right) \right) = 0$

Cont....

127

- $\sin^2\left(\frac{\theta}{2}\right) - \theta * 2\sin\left(\frac{\theta}{2}\right)\left(\frac{1}{2}\cos\frac{\theta}{2}\right) = 0$
- $\sin^2\left(\frac{\theta}{2}\right) = \theta\sin\left(\frac{\theta}{2}\right)\left(\cos\frac{\theta}{2}\right)$
- $\tan\left(\frac{\theta}{2}\right) = \theta$
- $\theta = 133^0 34'$ or $\theta = 2.331$ radians
- Thus the volume of concrete required for an arch ring will be minimum when central angle is $133^0 34'$.
- For most economical angle, $L_e = 2r_e \sin\left(\frac{\theta}{2}\right) = 2r_e \sin\left(\frac{133^0 34'}{2}\right)$
 $r_e = 0.544 * L_e$
 $r_i = 0.544 * L_i$, L_i = interior span length
 $r = 0.544 * L$

Cont....

128

- The **minimum concrete volume** for the whole dam with constant radius is obtained by increasing top angle but topography does not always permit very large angle at the top of the dam.
- In actual arch dams, the central angle is usually in range of 100° - 140° .

Cont....

129

2. Thick cylinder theory

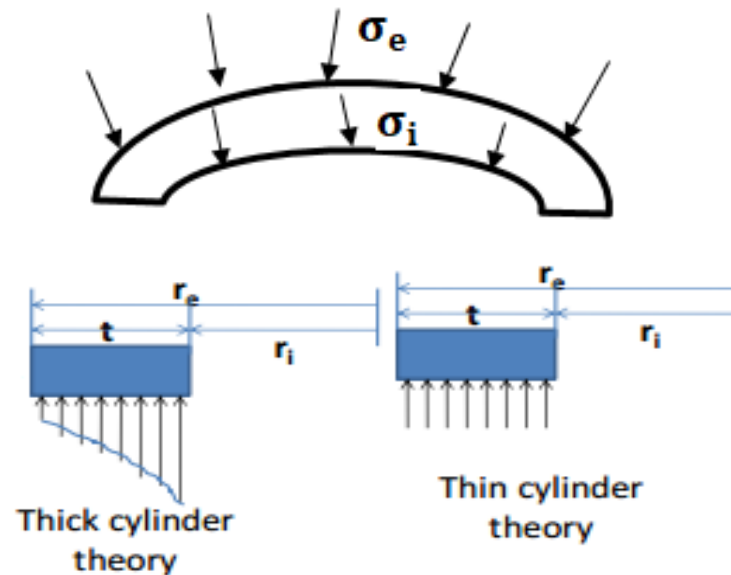
- In thick cylinder theory, the stress developed on u/s and d/s side of arch is not the same, unlike a thin cylinder theory.
- Max. stress occurs at intrados than extrados.
 - $\sigma_e = \sigma_i$ (for thin cylinder theory)
 - $\sigma_e \neq \sigma_i$ (for thick cylinder theory)
 - $\sigma_e = P \left(\frac{r_e^2 + r_i^2}{r_e^2 - r_i^2} \right)$
 - $\sigma_i = \frac{2Pr_e^2}{r_e^2 - r_i^2}$ where $P = \gamma h$

Cont....

130

➤ The thickness, t is given by;

$$t = r_e \left[1 - \sqrt{1 - \frac{2P}{f}} \right]$$



Buttress dam

131

- It is an improvement over hollow concrete gravity dam to reduce volume of concrete by cutting down concrete where it remains unstressed.
- Buttress dams are those dams which have sloping u/s face (membrane) and transmit the water load to a series of buttress at right angle to the axis of the dam.
- It's stability comes from weight of dam and to large extent from weight of water on u/s face.
- Sloping membrane is made of R.C.C deck slab.

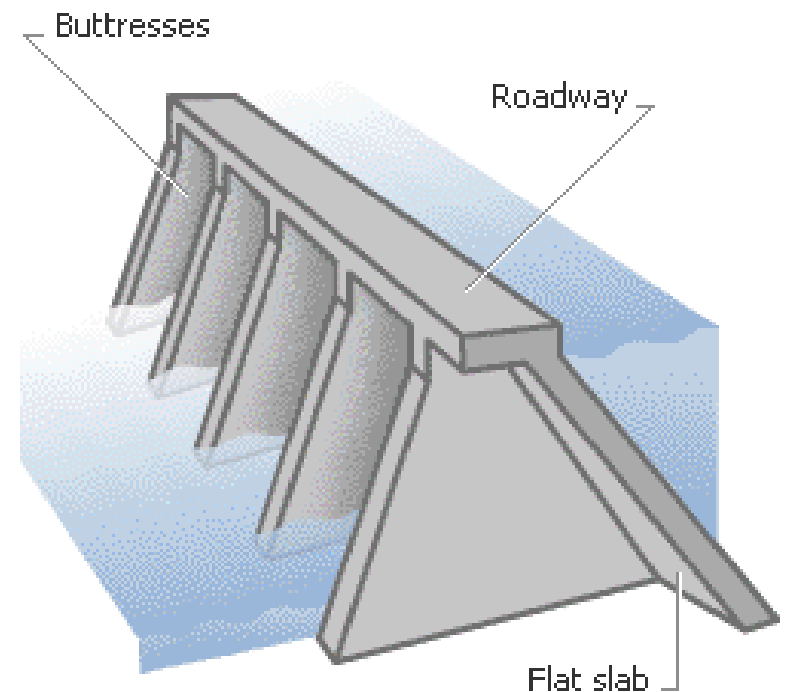
Cont....

132

- Buttresses are triangular concrete walls which transmit the water pressure from the deck slab to the foundation.
- Are adaptable to an overflow or a non-overflow type.

Cont....

133



Flat slab buttress dam

Courtesy of U.S. Bureau of Reclamation/Microsoft Corporation Illustration

Cont....

134



Cont....

135

When compared to Gravity dam:-

Requires $\frac{1}{2}$ to $\frac{2}{3}$ of the volume of concrete i.e. it saves more than 30%.

- Economical for dams of $h \geq 14\text{m}$.
- Less massive than gravity dam hence suitable on weak foundation.
- formwork needs skilled labor,

Cont....

136

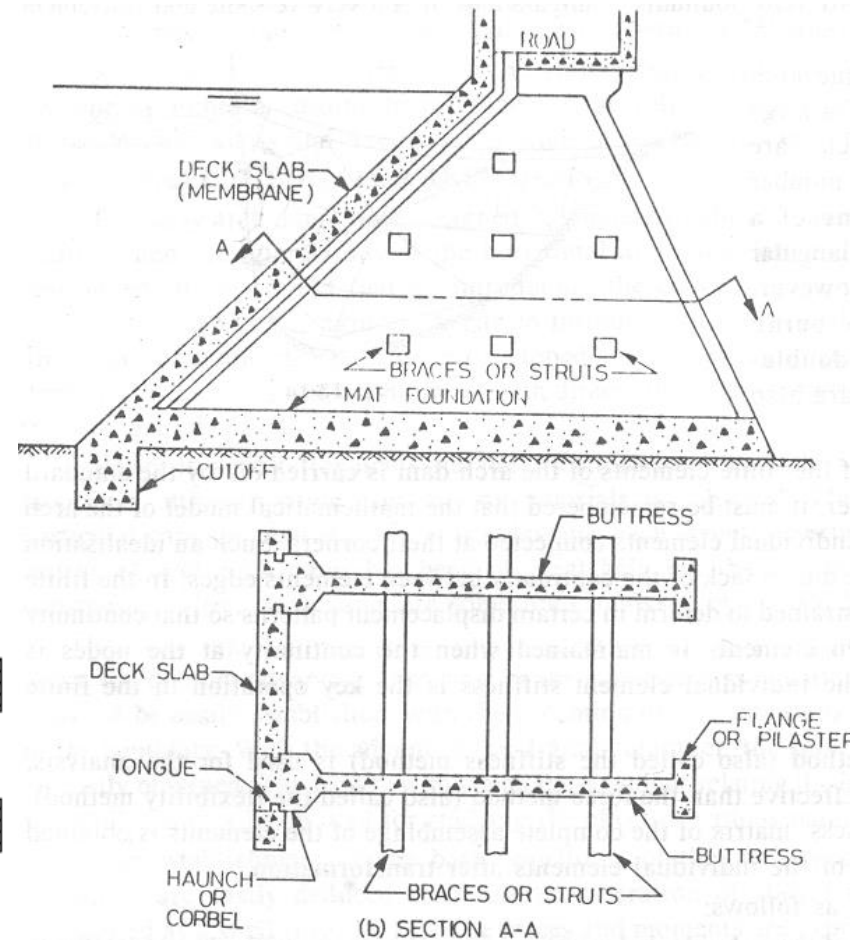
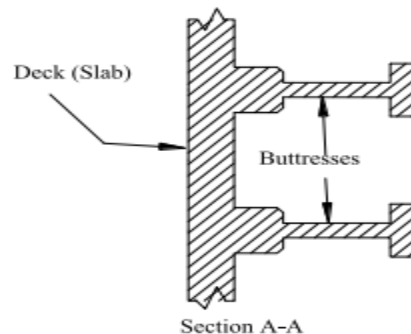
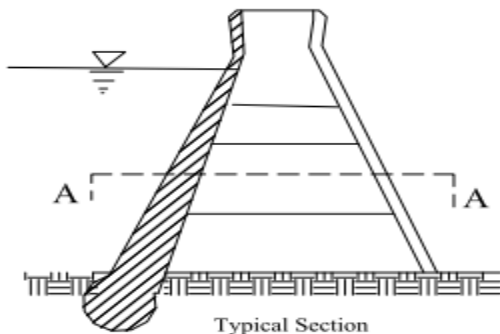
- It needs reinforcement
- More **safety against overturning and sliding** (because of the larger vertical component of hydrostatic force exerted on the inclined dam face).
- **Decreased** uplift pressure

Cont....

137

Component parts of Buttress Dams

- ✓ Sloping membrane
- ✓ Buttresses
- ✓ Footings or mat foundation
- ✓ Lateral Braces (strut)
- ✓ Haunches or Corbels
- ✓ Cutoff (Concrete)



Cont....

138

1. Sloping membrane (u/s deck)
 - It supports water load and transmit to series of buttresses.
2. Buttresses
 - Constructed at right angle to axis of dam at certain intervals
 - They support sloping membrane & transfer the load to foundation.
3. Mat foundation or footings
 - For buttresses it is used to transfer the load to foundation.
 - If **foundation is strong**, spread footing is provided and if **foundation is weak**, mat footing is required.

Cont....

139

4. Lateral braces (strut)

- Provided b/n adjacent buttresses to reduce unsupported length, to provide lateral stiffness and to resist buckling of buttresses.

5. Cutoff concrete-

- provided at u/s to reduce or prevent seepage.

6. Haunch (corbels)

- Is wide top of buttresses, which transmit load from sloping membrane to buttresses.

Cont....

140

Forces on buttress dam

- Are the same as the forces on gravity dam.
- 1. Weight of dam
 - is not main stabilizing force b/c of flat u/s slope and **weight of water on this face is large and helps in the stability** of buttress dam.
- 2. Uplift pressure
 - Not a major force in buttress dam, b/c it is reduced by gaps b/n buttresses
 - If separate spread footing is used **uplift pressure is reduced by gaps b/n buttresses**
 - If mat footing is used uplift pressure is calculated as in gravity dam.

Cont....

141

3. Water pressure

- Computed the same as in gravity dam but **vertical force of water pressure which is equal to weight of water on u/s face is quite large.**

4. Other forces

- Wind load, silt load, earthquake and wave load is calculated as in gravity.

Cont....

142

Classification of Buttress Dams

Two ways of classification

- A. Based on the type of deck(**Sloping Membrane**)
 - 1. Deck/flat slab or Amberson type
 - 2. Multiple-arch type
 - 3. Massive/bulk/ head type
- B. Based on the joint between the deck and buttresses
 - 1. Rigid buttress dams
 - 2. Articulated/flexible/ buttress dams
 - 3. Intermediate or semi-rigid buttress dams

Cont....

143

1. Deck slab/Flat Slab or Amburesn type Buttress Dam

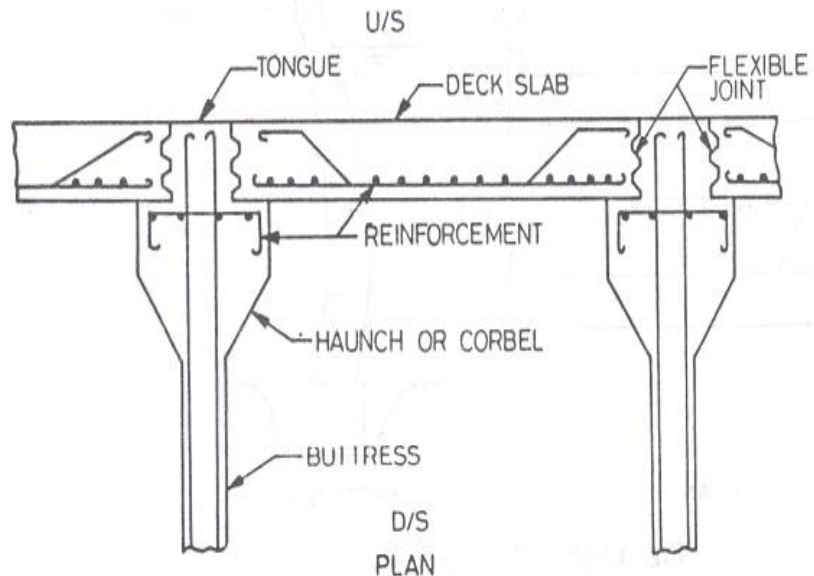
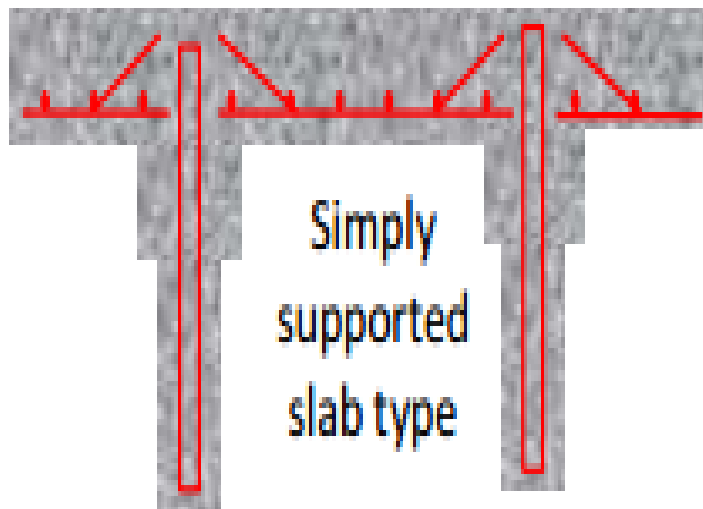
- In this type of buttress dam the u/s sloping deck slab consists of a reinforced concrete slab supported by as series of buttresses.
- The inclination of deck slab usually varies b/n 35'-45' with horizontal.
- Deck slab may Further Sub divided into:-
 - i. Simple deck slab type buttress dams (Simply Supported Slab)
 - ii. Fixed (or continuous) Deck Slab Type Buttress Dams
 - iii. Cantilever Deck slab type Buttress Dams

Cont....

144

i. Simple deck slab type buttress dams (Simply Supported Slab)

- The deck slab is not rigidly connected to the buttresses but it is in the form of simply supported slab.
- Reinforcement are provided only on d/s side.



Cont....

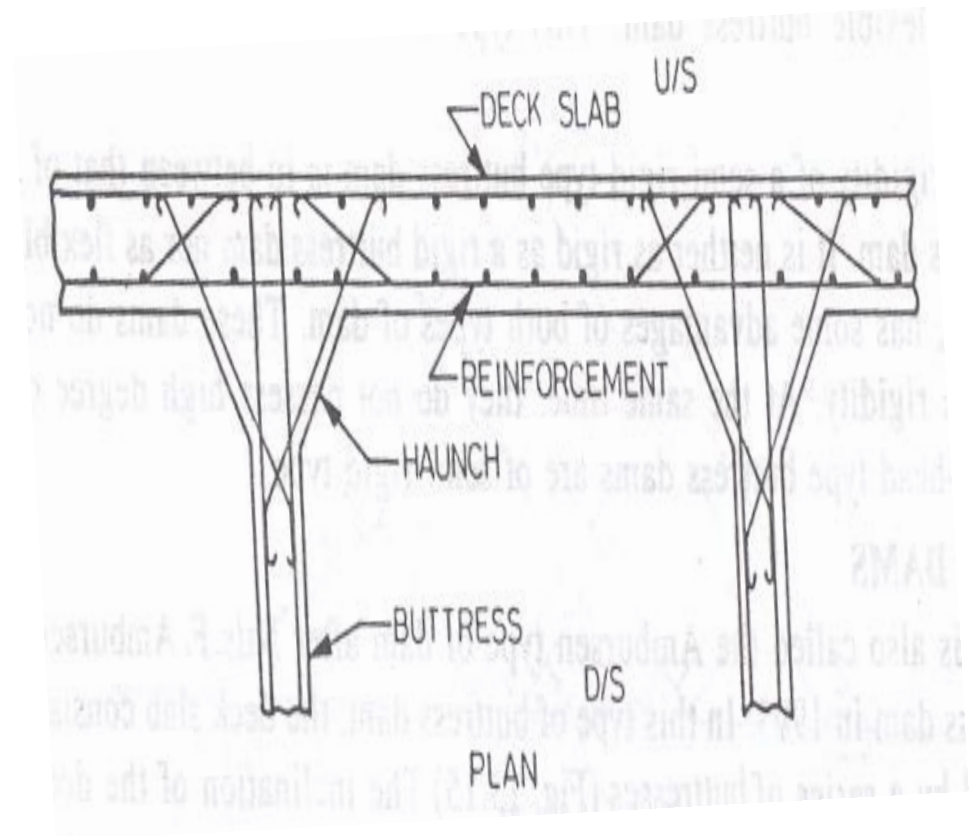
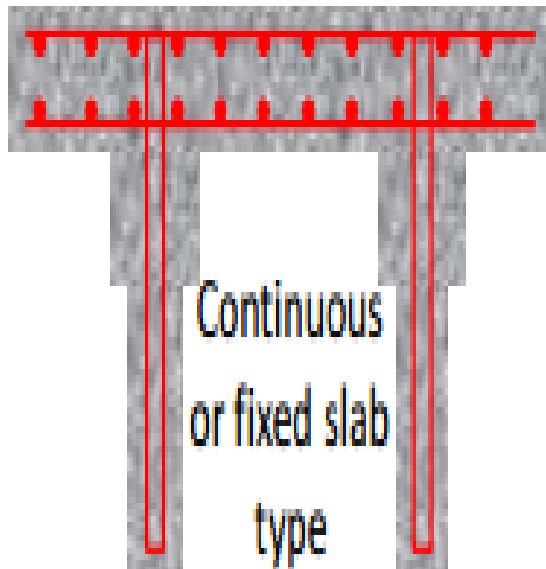
145

ii. Fixed (or continuous) Deck Slab Type Buttress Dams

- ❖ The deck slab is cast monolithic with the buttresses and it acts as a continuous slab.
- ❖ Reinforcement is provided both on upstream & downstream faces of the slab.
- ❖ This type of deck can be used only when the foundation is strong;

Cont....

146

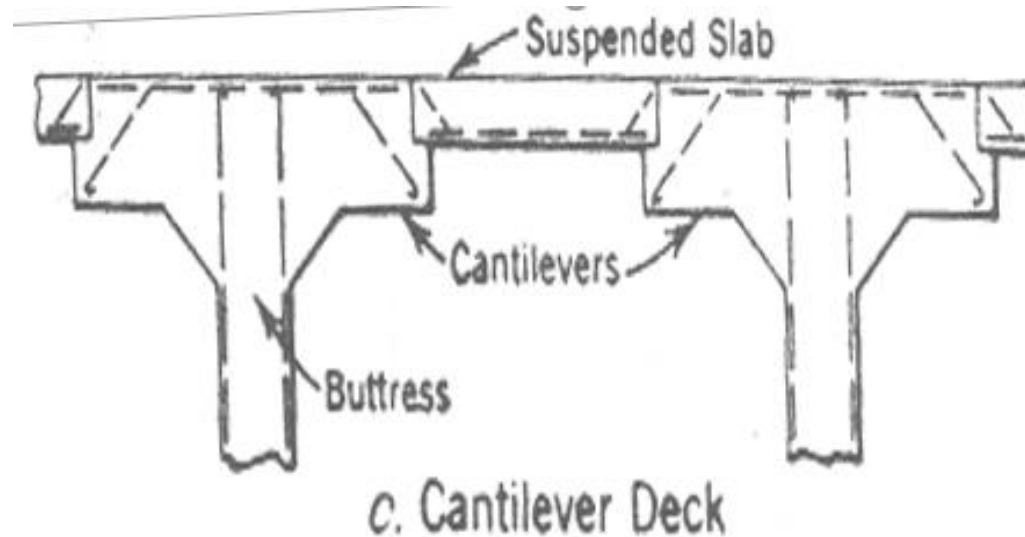


Cont....

147

iii. Cantilever Deck slab type Buttress Dams

- The deck slab is cast monolithically with the buttresses in such a manner that it over hangs on either side of the buttress and acts as cantilever.



Cont....

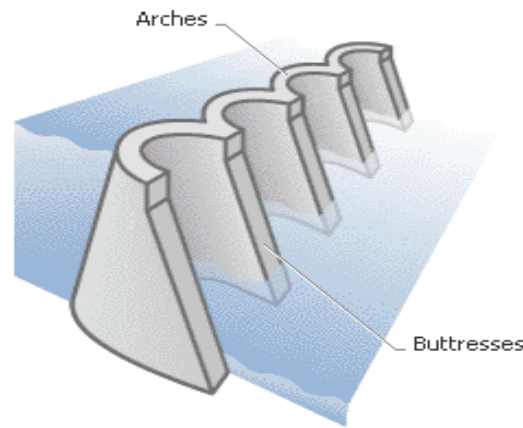
148

2. Multiple Arch Types Buttress Dams

- The sloping membrane or deck consists of a series of R.C arches supported by a number of buttresses. The u/s face of the dam is usually inclined at 45° .



Encarta Encyclopedia, Culver Pictures/PNI/Microsoft Corporation Illustration



Multiple arch dam

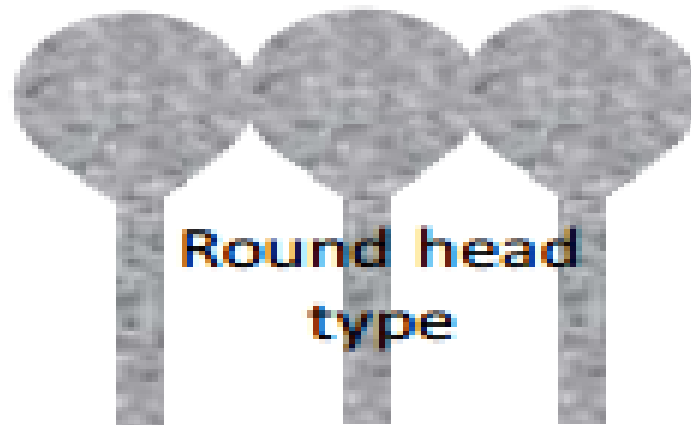


Cont....

149

3. Massive /bulk/ Head Type Buttress Dams:-

- The dam is thus made of a series of buttresses with massive heads placed side by side.



Cont....

150

Classification Based on the joint b/n the sloping membrane Buttresses

➤ Rigid buttress dams: -

- The upstream **deck is cast monolithically with the buttresses** and hence the ends of the deck cannot move.
- E.g. continuous deck slab type, multiple arch type & multiple dome type buttress dams

Cont....

151

➤ Flexible (or articulated) Buttress Dams:

- sloping membrane or deck is not constructed monolithic with the buttresses, as such these dams are flexible. E.g. simple deck slab type.

➤ Semi - rigid buttress Dams: -

- It is neither as rigid as rigid buttress dam nor as flexible as a flexible buttress dam.
- It is therefore in b/n that of rigid buttress dam & a flexible buttress dam. E.g. The massive head type buttress dam

THANK YOU