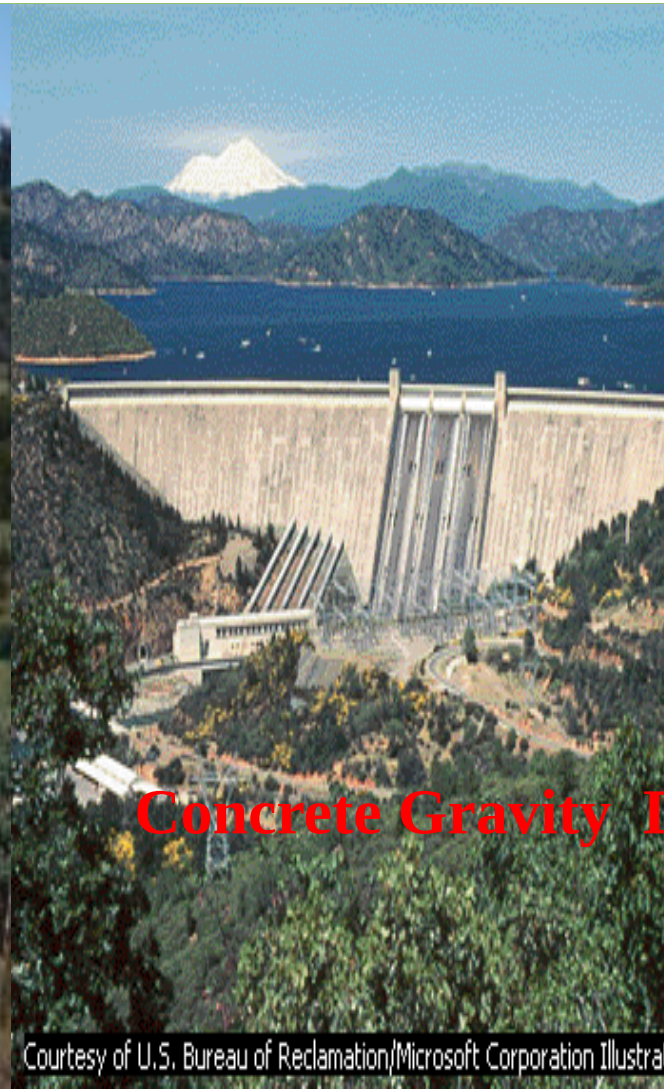


Chapter-Two

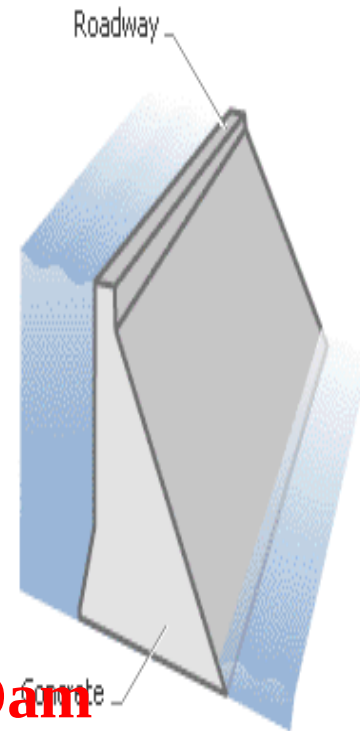
Theory and Principles of Dam Design



Embankment dam



Concrete Gravity Dam



Concrete gravity dam

Last class we were Discuss about:

- *The definition of hydraulic structures/water works structures*
- *Kinds of hydraulic structure(water extracting, conveying, treating and end use structures)*
- *Storage structures(Dams) and different parts and terminologies of dams*
- *Classification of dams*
- *Factor governing the selection of a particular types of dam*
- *Dam site assessment and investigation*

Today We Will Discuss about:

- *Definition of embankment dam*
- *Classification of embankment dam*
- *Merits and demerits*
- *Elements of embankment dam*
- *Cause of failures*
- *Structural components*

2.1. Embankment dam

Introduction

Are constructed from fragmented natural materials;

- ❑ excavated or obtained close to the dam site,
- ❑ placed without the addition of any binding agent, and
- ❑ compacted using high capacity mechanical plant.

Strength and stability derived from:

- ❑ their weight
- ❑ internal friction, and
- ❑ mutual attraction of particles.

Relative to concrete dams,

- ❑ embankment dams offer more flexibility; and
- ❑ can deform slightly to conform to deflection of the foundation without failure.

Classification based on construction material

1. Earth fill Embankment dams:

- ✓ When compacted soils, i.e. clays/silts & sands, account for over 50% of the placed volume of material.
- ✓ Built to any height
- ✓ Has separate spillway
- ✓ Designed as non overflow dam

2. Rock fill Embankment dams:

If compacted rock particles larger than a man can easily lift, i.e. coarse grained frictional material, accounts for over 50% of the placed volume of materials.

- ✓ Requires stronger foundation as compared with earth dam

Classification Cont...

Earth fill Embankment dams:

❖ based on construction method earth dams are divided into:

1. Rolled fill dam(filling the void space through compaction or rolling)

which could further be divided into;

1. Homogeneous type dams

2. Zoned type dams

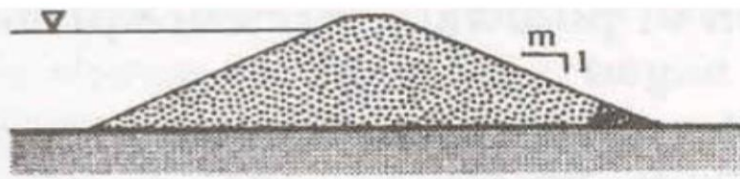
3. Diaphragm type dams

2. Hydraulic fill dam(filling the void space hydraulically)

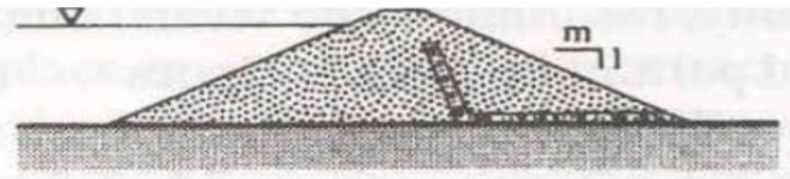
3. Semi-hydraulic fill dam

Homogeneous Earth dam

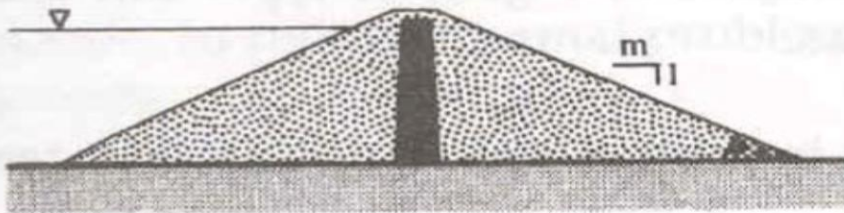
- ❑ It is composed of **only one kind of material**
- ❑ The material must be **sufficiently impervious** to provide an adequate water barrier
- ❑ The **upstream face should be flat** to guard against sloughing due to **rapid drawdown**
- ❑ The **downstream slope should be flat** so that it resists sloughing when **saturated to high level**
- ❑ Regardless of d/s slope and permeability, seeping water will come out in d/s face
 - ✓ **Drainage filters are provided in the d/s**
- ❑ These types of dams are recommended in localities
 - ✓ The available soil shows little variation in permeability
 - ✓ Soils of contrasting permeability are available in small quantities / high cost
- ❑ These types of dams are not recommended
 - ✓ Dispersive and erodible soils such as dispersive clay soils



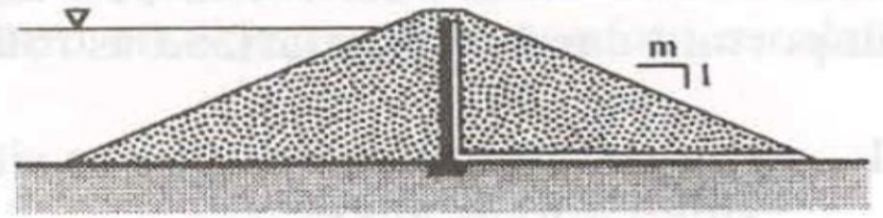
(a) Homogenous with toedrain:
small secondary dams
 $m = 2.0-2.5$



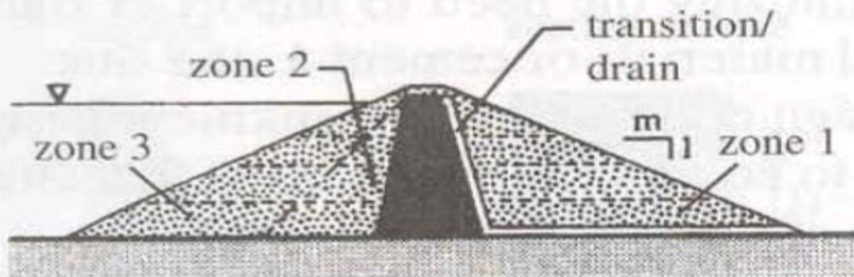
(b) Modern homogeneous with internal chimney drain
 $m = 2.5-3.5$



(c) Slender central clay core:
19th-century 'Pennines' type –
obsolete post 1950
 $m = 2.5-3.5$



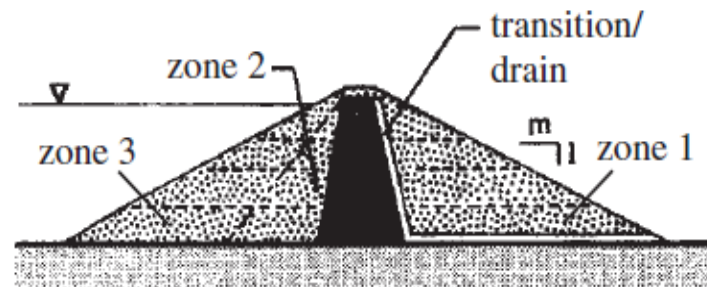
(d) Central concrete core:
smaller dams – obsolescent
 $m = 2.5-3.5$



(e) Wide rolled clay core: zoned with
transitions and drains: note base drain
 $m = 2.5-3.5$

Zoned Earth Dam

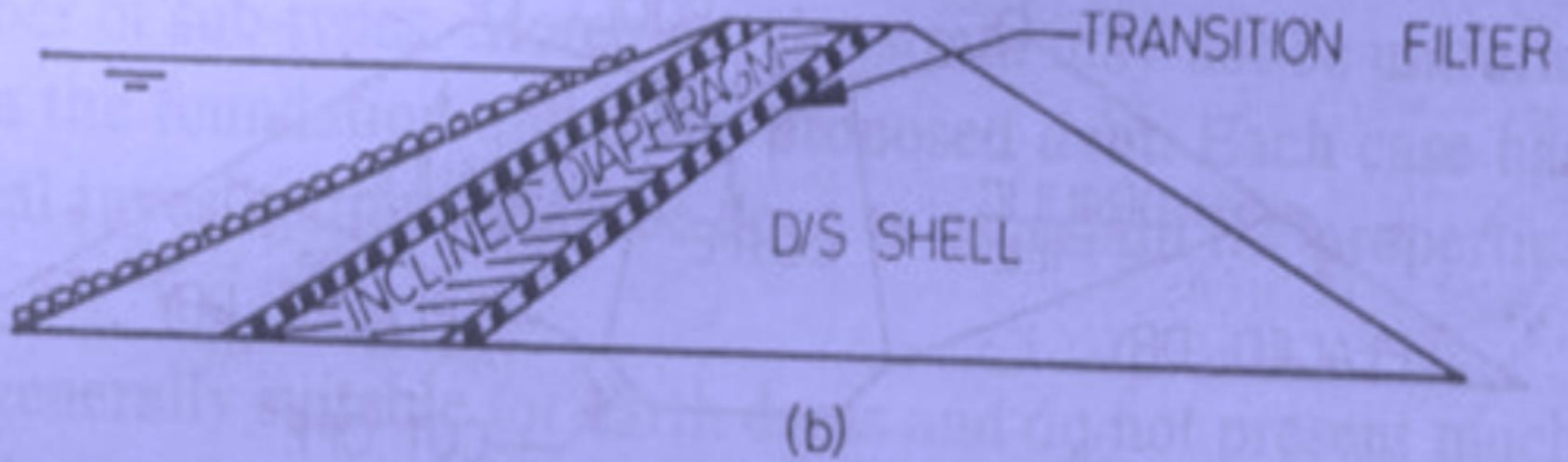
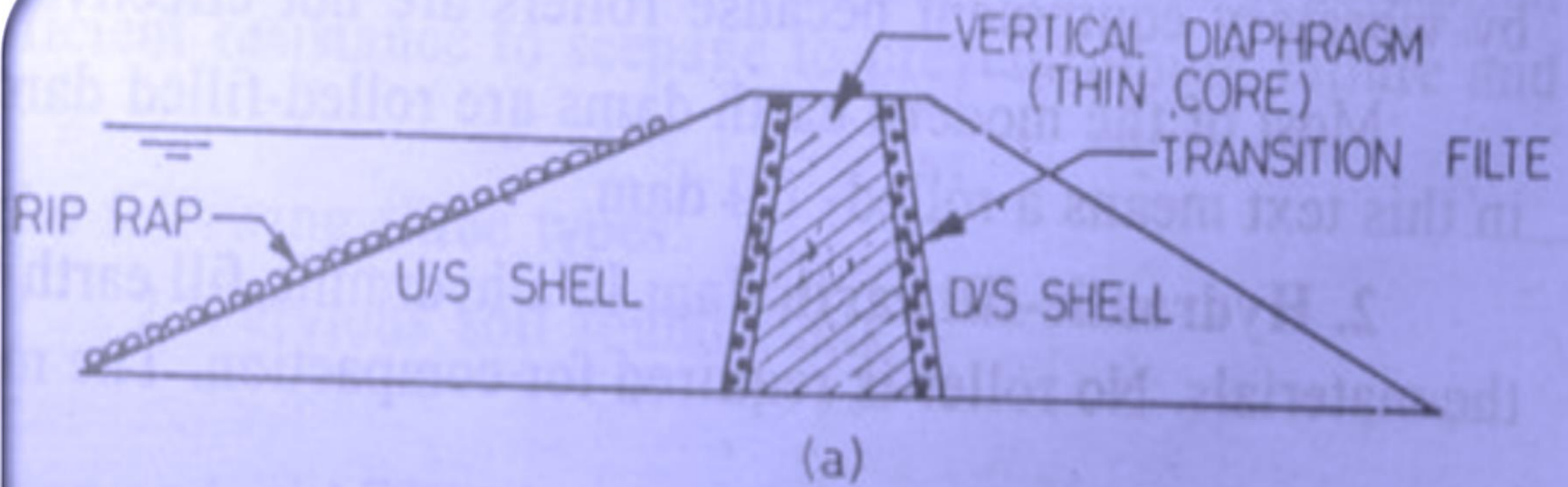
- ❑ It is the most commonly constructed type
- ❑ Three zones. An **impervious core** flanked/supported by **pervious shells**
 - ✓ **Impervious core** controls seepage
 - ✓ The **pervious shell** provides structural support and protects the core
 - ✓ The upstream shell provides stability against rapid drawdowns
 - ✓ The downstream shell acts as a drain to control seepage and lower the phreatic surface
 - ✓ **Transition filter (drains and drainage layers)** control washing out of the core



(e) Wide rolled clay core: zoned with transitions and drains: note base drain
 $m = 2.5-3.5$

Diaphragm Type

- ❖ In this type of section the bulk of embankment is constructed of pervious materials (Sand, gravel, or rock) and a thin diaphragm of impermeable material is provided to form the water barrier.
- ❖ If the core thickness at any elevation is less than 3m or less than the embankment height above the corresponding section then the dam embankment is considered to be the diaphragm type.



Merits & Demerits of Embankment Dams

Merits of Embankment Dams

- ✓ Suitability to different site conditions such as wide valleys, steep sided gorges, etc.
- ✓ Adaptability to a broad range of foundation condition such as rock and pervious soil formation,
- ✓ use of natural materials,
- ✓ Extreme flexibility to accommodate different fill materials,
- ✓ Highly mechanized and effectively continuous construction process,
- ✓ Appreciable accommodation of settlement-deformation without risk of serious cracking and possible failure.

Demerits of Embankment Dams

- ✓ Inherently susceptible to damage or destruction by overtopping,
- ✓ Necessity of separate spillway structure,
- ✓ Vulnerability to concealed leakage and internal erosion in dam or foundation

Elements/Components of Embankment Dam

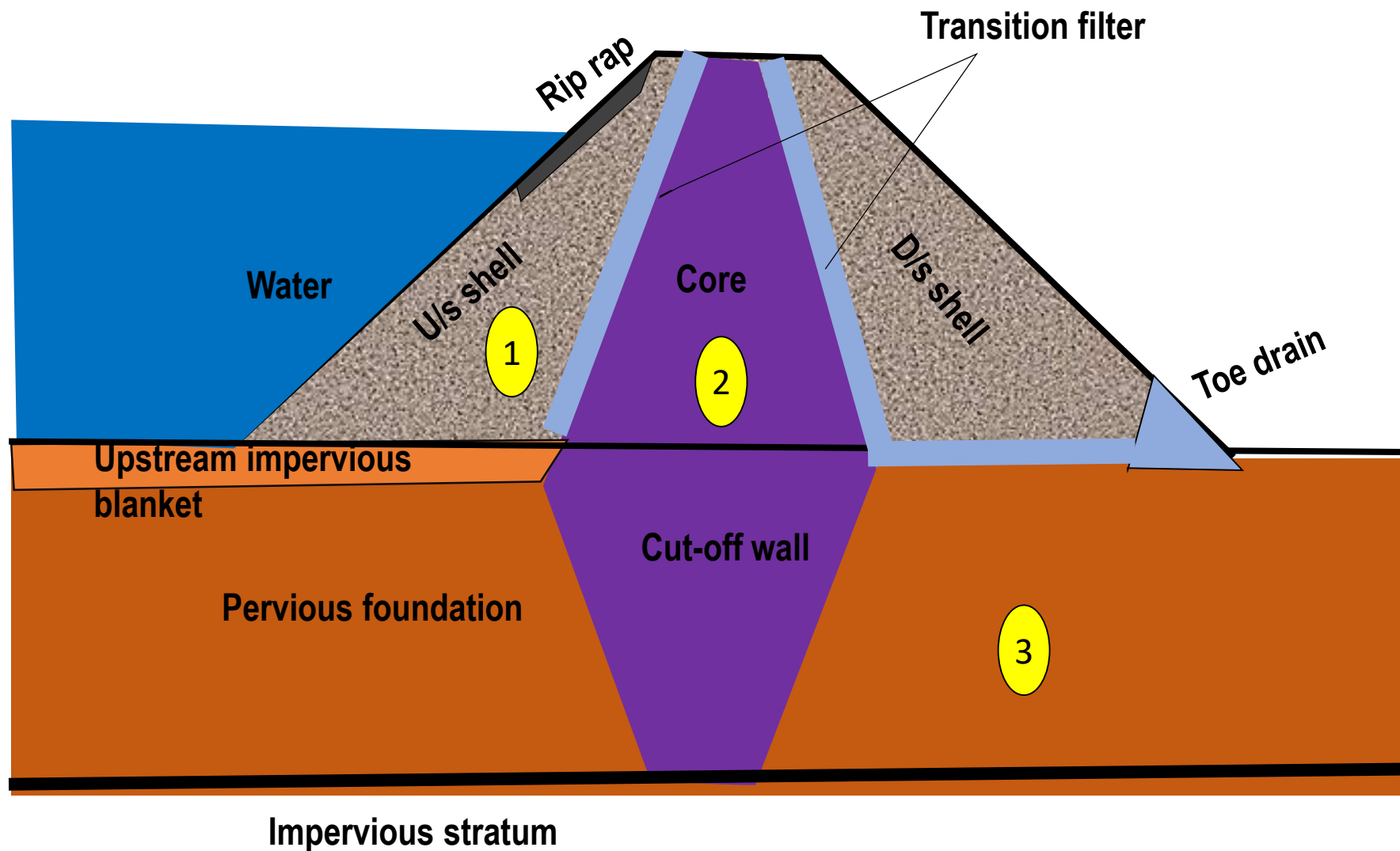
Every embankment dam consists of

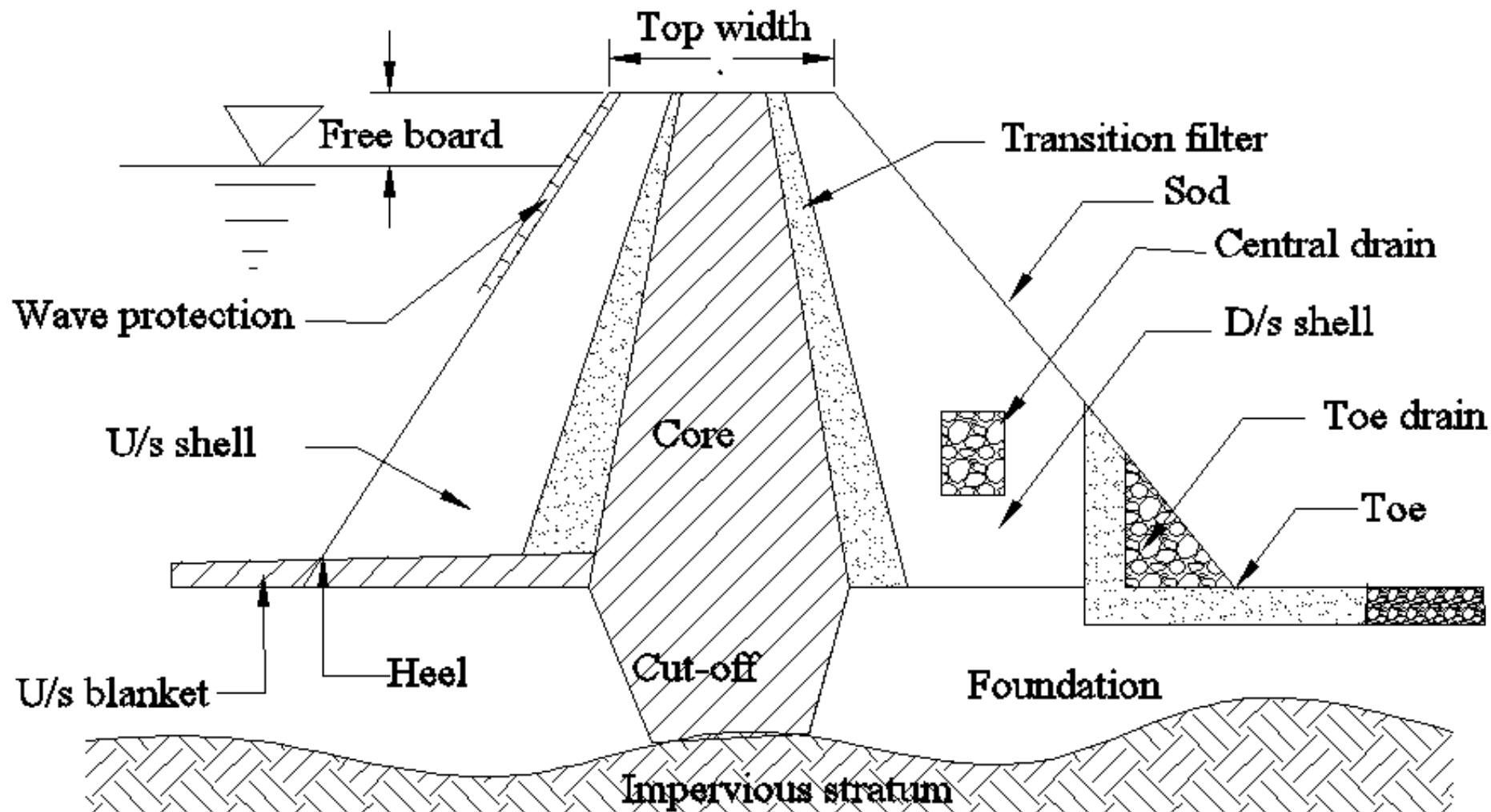
Three basic components

- Foundation,
- Core, and
- Shell.

And a number of appurtenances such as;

- Transition filter,
- Toe drain,
- Riprap,
- Internal drain,
- Sod, etc. which enable the basic components to function efficiently





U.S. Army Corps Of Engineers
Huntington District

Date Of Photography
July 06, 2001

Outlet works

Spillway

Earth Embankment

Gate Control House

An aerial photograph of Fishtrap Lake and Dam. The lake is a large body of water in the foreground, with a marina on the left side. The dam is a long, curved structure made of earth and concrete, separating the lake from the forested area behind it. The spillway is the section of the dam where water can overflow. The gate control house is a small building on the dam. The outlet works are the structures that control the flow of water out of the lake. The earth embankment is the large area of land behind the dam. The surrounding area is heavily forested.

Fishtrap Lake, KY
Fishtrap Lake and Dam, Upstream View

❑ Foundation

- ✓ Provides support both to vertical and horizontal load
- ✓ Resist seepage underneath the embankment

❑ Core

- The core or membrane is used to hold back free water.
- Depending on the structural requirements of the dam, the core may be placed at the center or upstream from the center, or on the upstream face (in the case of certain rock fill dams)
- The core may be extended down into the foundation to impervious layer, if the foundation is incapable of resisting under seepage(pervious)
- The core can be made from Earth, concrete or masonry, steel sheeting, etc.
- Lack of flexibility of concrete and masonry make them undesirable.
- An earth core (when suitable material is available) is usually cheaper and more water tight than any other type.

Design parameters

- Permeability / water tightness of core material
- Compaction extent of core material
- Water content to obtain maximum compaction
- Thickness of the core

Permeability (cm/s)	
Gravel	1 to 100
Sand	1 to 10 ⁻³
Silt	10 ⁻³ to 10 ⁻⁵
Clay	< 10 ⁻⁶

Shell

- ❖ Provides **structural support** for the core
- ❖ **distributes the loads** over the foundation.
- ❖ acts as foundation for most of the appurtenances.
- ❖ Sometimes constructed of same material as the core.
- ❖ Availability and strength are the requirements for selection.

Strength: - the strength for the upstream side should be that at the inundated/immersed condition. The same strength should be used for the downstream face which is below the maximum phreatic line.

Permeability: - **high permeability** is desirable from the standpoint of pressure buildup during construction and stability during sudden drawdown.

Typical compaction requirements:

- 95 – 100% of standard proctor maximum;
- 92 – 97% of modified proctor maximum

Shell cont....

Slopes: -

shell slopes are based on stability analysis.

When the stability is insufficient, improvements are possible by adopting

- Flatter slopes;
- Increasing strength through high density;
- Treatment for weak foundation;
- Drainage of the foundation and embankment

Causes of failure of Emb. Dams

Failure could be comes from

- ✓ Improper design
- ✓ faulty construction
- ✓ Lack of maintenance, etc.

The most common Causes of failure for embankment dams are

- ✓ Hydraulic failure (overtopping , erosion of u/s &d/s face, erosion of d/s toe)
- ✓ Seepage Failure(piping trough dam body and foundation, sloughing of d/s side of dam)
- ✓ Structural Failure(steep slope ,using soft soil, etc)

During construction

- Unstable slope
- Heavy rainfall that washes the d/s face
- Weak foundation

After construction

- Failure of u/s face due to sudden drawdown
- Failure of d/s when the reservoir is full
- Overtopping

❑ Measures for over topping

- ❖ Appropriate design flood and adequate spillway capacity
- ❖ Provide adequate freeboard

For Erosion of upstream face by wave action

Protect the u/s face by **rock riprap**

For Erosion of Downstream face by gully formation

- ❖ Proper maintenance
- ❖ Filling the gullies periodically
- ❖ Grassing the slopes
- ❖ Constructing berms

2.1.2. Structural Components of Emb. Dams

1) Crest of Dam: 3m for low and medium dams and 6m for high dams is recommended to keep the seepage line within the dam.

If road is introduced the width of the dam is determined according to the class of road and determined by road code

Recommended formula's to compute the crest width

a) For very low dam (<10m)

$$B = H/5 + 3$$

b) for dams lower than 30m

$$B = 0.55(H)^{0.5} + H/5$$

c) For dams higher than 30m

$$B = 1.65(H + 1.5)^{1/3}$$

2) side Slope Of Dam: depends on the type of material and dam height for low dam u/s slope = d/s slope for high dam the u/s slope < d/s slope to satisfy static stability

3) Berms (raised banks): constructed at both u/s and d/s side of the dam for the purpose of observing the condition of protections at the slopes.

4)Free board: it is the vertical distance between the normal pool level and the crest of the dam

Fixed to carry the excess water above the maximum flood level.

The minimum height of freeboard is taken as $1.5h_w$

$$h_w = 0.032(V.F)^{1/2} + 0.763 - 0.27(F)^{1/4} \text{ FOR } F < 32 \text{ KM}$$

$$h_w = 0.032(V.F)^{1/2} \text{ for } F > 32 \text{ KM}$$

where h_w = wave height

v = wind velocity (km/hr)

F = fetch length in km (the length measured from n.r.l to the dam)

Also d/t FB are recommended with spillway type and dam height by USBR from table

5) u/s and d/s slope protection: stone pitching (60cm depth) at the u/s side and planting green grass at the d/s slope

6) Drainage structure : lower the seepage curve Prevent seepage water from flowing into the d/s slope Conveying seepage water through the body of the to the d/s part Has two parts intake structure(drainage trench) and conveyance structure

Last class we were discuss about:

- *Definition of embankment dam and Classification of embankment dam*
- *Merits and demerits, Elements of embankment dam, Cause of failures, Structural components*

Today we will discuss about:

- *Criteria for Safe Design of Embankment Dams*
- *Preliminary section of an embankment dam*
- *Seepage analysis*

2.1.3 Criteria for Safe Design of Embankment Dams

❑ An embankment dam must be **stable and safe during all phases of construction and operation of the reservoir**. The practical criteria for the design of embankment dams may be stated briefly as follows.

A. No Hydraulic failure

❑ To prevent hydraulic failures the dam must be **so designed that erosion of the embankment** is prevented.

❑ This implies that the following conditions are satisfied.

- ✓ Selection of appropriate **design flood for the design of the spillway**,
- ✓ Provision of adequate **spillway capacity**: Spillway capacity is sufficient to pass the peak flood without overtopping.
- ✓ Provision of sufficient **freeboard**: Overtopping by wave action at maximum water level is prevented.
- ✓ Erosion of the embankment due to wave action and surface run-off does not occur.
- ✓ The crest should be wide enough to withstand wave action.

B. No Seepage failure

❑ To prevent the seepage failures,

✓ **Quantity of seepage water** through the dam section and foundation should be at minimum level.

✓ **No piping:** Seepage water through the dam body or foundation should not remove any particle or in other words cause piping.

The driving force depends upon the pressure gradient while the resisting force depends upon the strength characteristics of the boundary material.

✓ **The seepage line should be well within the downstream face** of the dam to prevent sloughing.

✓ **No leakage along conduits:** There should not be any leakage of water from the upstream to downstream face. Such leakage may occur through conduits, at joints between earth and concrete sections or through holes made by aquatic animals.

C. No Structural Failure

❑ To prevent structural failures, the embankment and its foundation must be stable under all conditions. This implies that

❑ **The upstream and downstream slopes of the embankment should be stable under all loading conditions** to which they may be subjected including earthquake.

✓ safe u/s and d/s slopes during construction

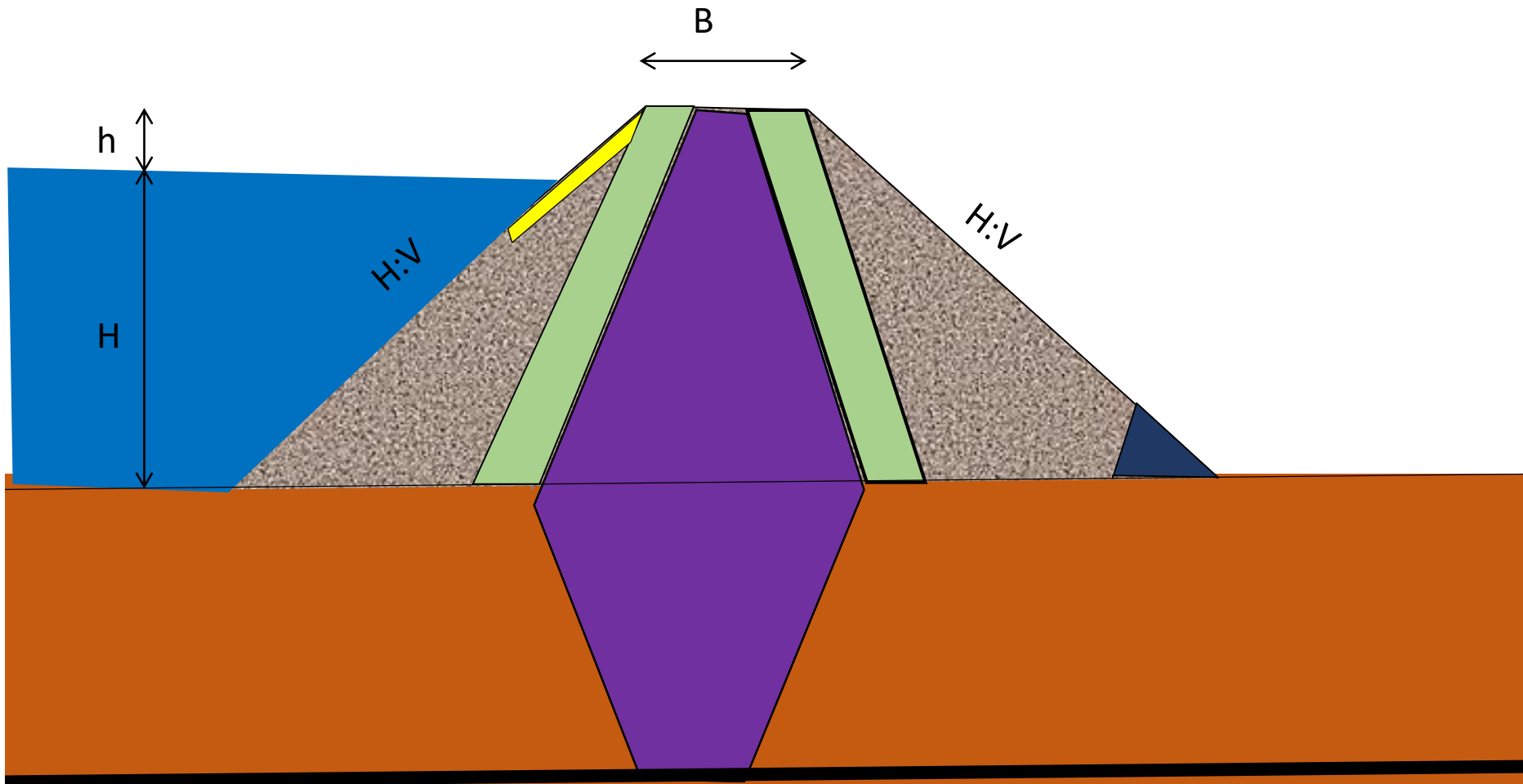
✓ safe u/s face during sudden drawdown

✓ safe d/s slope during steady seepage under reservoir full condition

❑ **The foundation shear stresses should be within the permissible limits of shear strength of the material.**

2.1.4 Preliminary section of an embankment dam

□ The preliminary design of an embankment dam is done on the basis of past experiences and on the basis of the dams built so far.



Dam Height

❑ It is governed by functional requirement(based on the supply and demand).

Top Width

❑ It depends on

- ✓ **Width of the highway** on top of the dam
- ✓ Practicability of construction
- ✓ Height of the structure
- ✓ Wide enough to keep the seepage line well with in the dam when the reservoir is full

$$b = \frac{H}{5} + 3$$

For very low dam ($H < 10\text{m}$)

$$b = 0.55H^{1/2} + 0.2H$$

For medium dam ($10\text{m} < H < 30\text{m}$)

$$b = 1.65(H + 1.5)^{1/3}$$

For large dam ($H > 10\text{m}$)

Free Board

❑ It is the vertical **distance between the crest of the dam and the reservoir level**. It is composed of **allowances for waves and settlement of the dam**

Allowance for Wave

❑ Various empirical formulae depending on wind velocity and reservoir fetch have been suggested for computing wave heights. The Molitor Stevenson formulas are normally used which

$$h_w = 0.032 \sqrt{FV} + 0.763 - 0.271 \sqrt[4]{F}$$

where $F < 32$ km.

$$h_w = 0.032 \sqrt{FV}, \text{ where } F > 32 \text{ km.}$$

❑ On a sloping surface the **wave rides along the slope up to a vertical height of 1.5 times** the wave height above the reservoir level hence $1.5 h_w$ is provided as freeboard.

❑ According to U.S.B.R. criteria distinction is to be made between the normal and minimum freeboards.

❑ **Normal Free Board**: crest level to full reservoir level

❑ **Minimum Free Board**: crest level to maximum water level

Recommended Values of Freeboards

Fetch in km		Normal freeboard in meter	Minimum freeboard in meter
Less than	1.5	1.25	1.00
	1.5	1.50	1.25
	4.0	1.80	1.50
	8.0	2.50	1.80
	15.0	3.00	2.20

It is also recommended that freeboard shown in the above Table be increased by 50 percent if a smooth pavement is provided as protection on the upstream slope.

Allowance for Settlement

❑ Settlement of an embankment will be caused by consolidation in the foundation and in the fill. A settlement allowance of **2%** is considered adequate and is generally provided. However, in case of dams of more than 30m height, an extra 1% allowance is provided to account for the settlement due to earthquake.

Upstream and downstream slopes

❑ The upstream and downstream slopes depends on

- ✓ Height of dam
- ✓ Type of embankment material
- ✓ Type of Foundation material

❑ Terzaghiz side slopes for earth dams

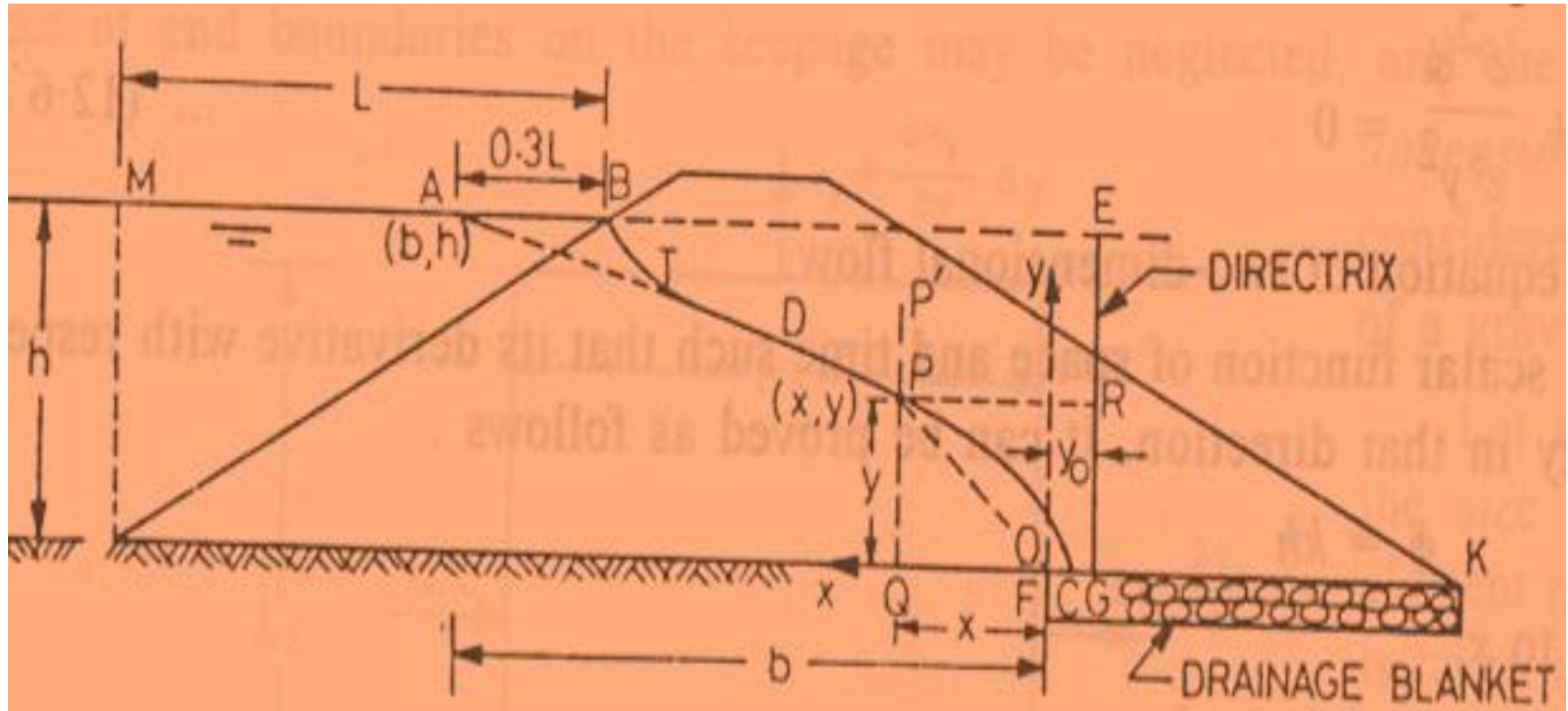
Type of material	Upstream slope	Downstream slope
Homogeneous well graded material	2:1	2:1
Homogeneous coarse silt	3:1	2.5:1
Homogeneous silty clay or clay		
H less than 15 m	2.5:1	2:1
H more than 15 m	3:1	2.5:1
Sand or sand and gravel with clay core	3:1	2.5:1
Sand or sand and gravel with R.C core wall	2.5:1	2:1

2.1.5 Seepage Analysis

For seepage analysis the dimension below free board is used

Seepage water in an embankment dam depends on **stored water head** and **material of the dam body and foundation**.

Phreatic line is the boundary line between the saturated and unsaturated zone.



STEPS

- 1) Compute the location of **A** w.r.t point **B**, where **B** is location of the water surface contact with the u/s dam body. i.e. **0.3** of **L**(the horizontal projection of wetted inclined surface)
- 2) The location of point **B** is theoretically starting point of the base parabola which is expected to represent the phreatic line
- 3) To construct the parabola the location of directrix has to be fixed
 - ❖ Extend the line tangent to the water surface to d/s
 - ❖ Estimate the focus of the parabola depending on the dam drainage location
 - ❖ Taking the center at point **A** ,construct to cross the extended line **AE** with radius **AF**
 - ❖ Draw perpendicular line from the location of arc crossing **AE**
- 4) Let us take the origin (**O**) at the focus with X- positive u/s & Y-positive upward.

5) From the basic property of parabola: distance PF = distance PR

$$\sqrt{x^2 + y^2} = x + y_o$$

Squaring both sides & rearranging

$$y = \sqrt{2xy_o + y_o^2}$$

$$\text{or } x = (y - y_o)^2 / 2y_o$$

Where y_o is the distance from the focus to the directrix, also called focal distance (f) Thus $FG = Y_o$. The value of Y_o can be obtained from the known coordinates or boundary conditions ($X = b$, $Y = h$) of the starting point A.

Substituting the values in equation (i) we have

$$y_o = \sqrt{b^2 + y^2} - b$$

- For different values of X the corresponding values of Y can be computed using the parabola equation $y = \sqrt{2xy_o + y^2_o}$.
- Discharge through dam can also be quantified using analytical approach for this particular situation.

From Darcy's Law: $v = ki$

k = Coefficient of permeability

i = the hydraulic gradient

The seepage discharge per unit length can be given by:

$$q = vA = kiA = k \left(\frac{dy}{dx} \right) * Ly = kyoL$$

Where A is area of flow per unit length

q is required to know at what rate the water flowing from u/s to d/s for filter design.

Worked example

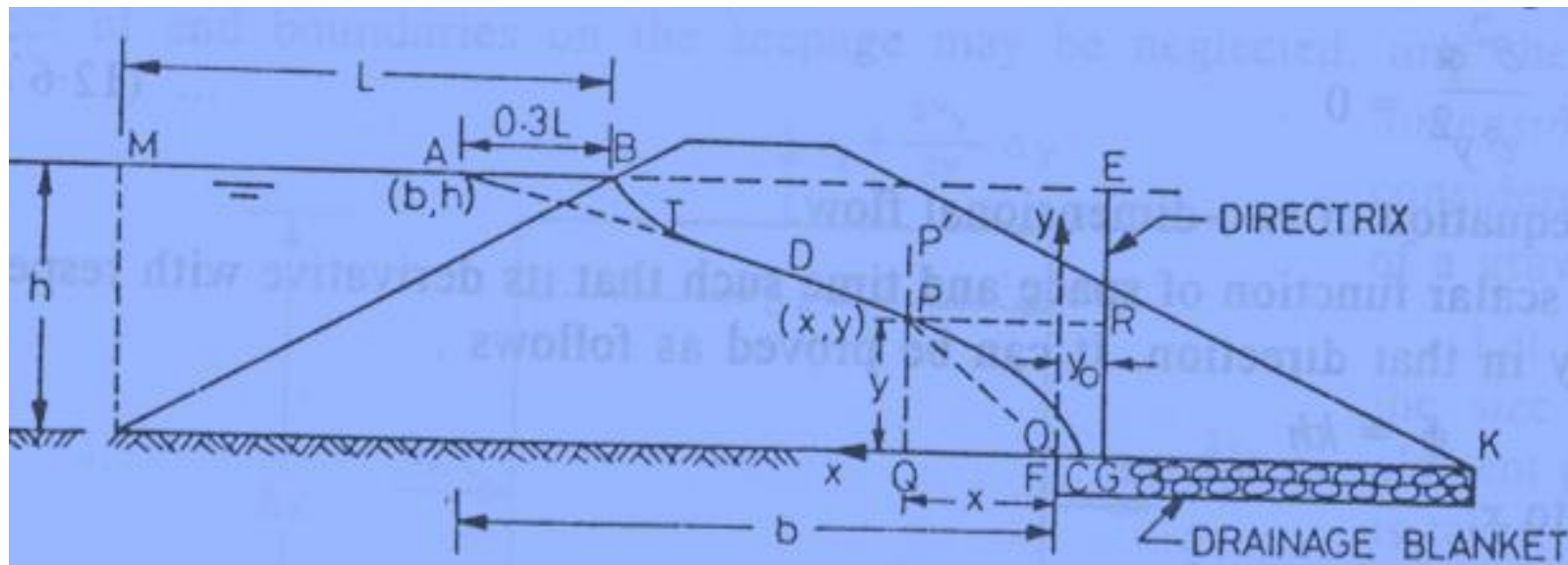
A homogeneous earth fill dam has a top width of 30m and a height of 100m with a freeboard of 10m. The side slopes are 1V: 2.5H. It has a horizontal drainage blanket at the base that extends from the downstream toe to a distance of 100m. The embankment has a permeability of 1.5×10^{-5} m/sec. Determine the seepage through the dam.

Solution

$$b = \text{base length} - \text{blanket length} - \text{MA}$$

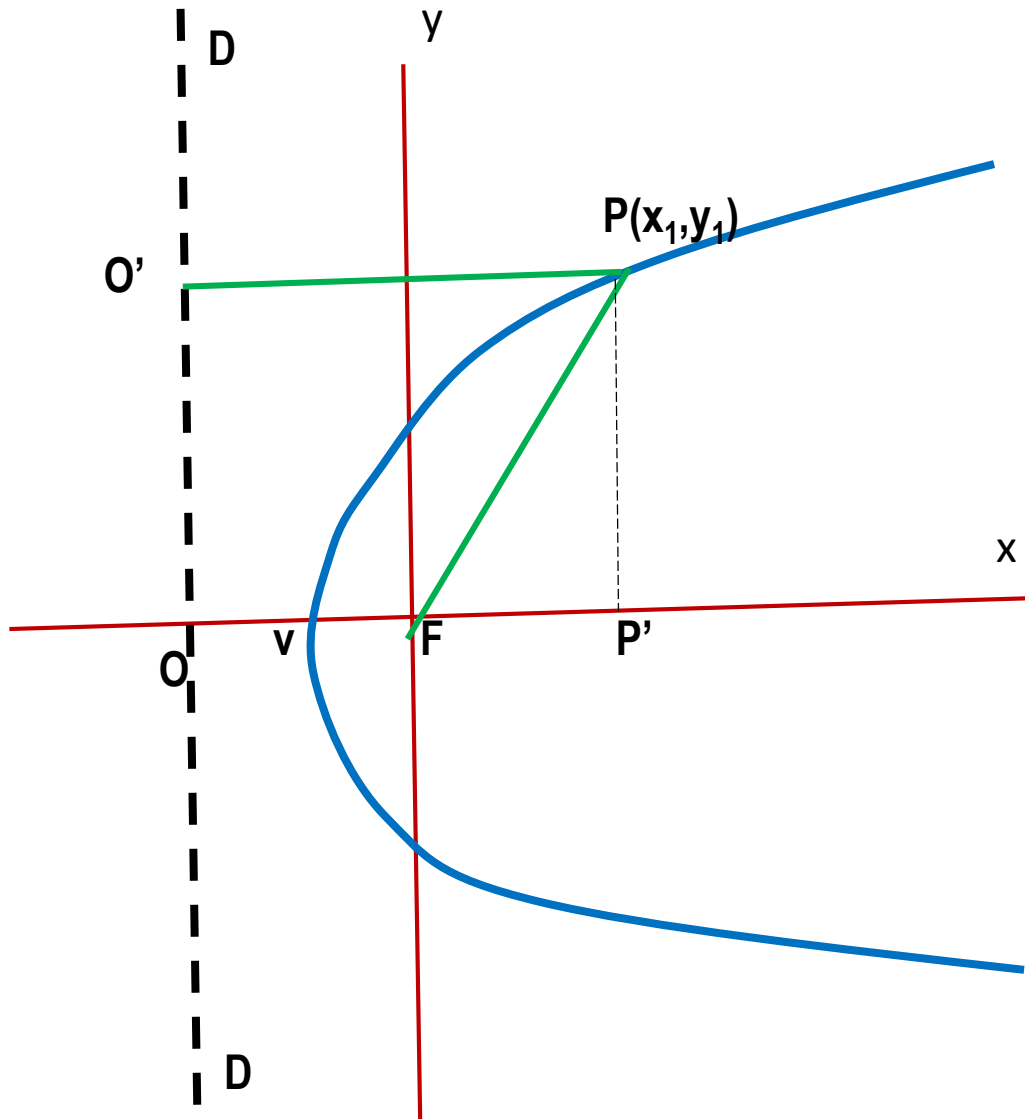
$$= 530 - 100 - 157.5 = 272.5 \text{ m.}$$

$$y_o = \sqrt{b^2 + y^2} - b = [(90)^2 + (272.5)^2]^{1/2} - 272.5 = 14.5 \text{ m}$$

$$q = K (1) (y_0) = (1.5 \times 10^{-5})(14.5) (1) = 2.18 \times 10^{-4} \text{m}^3/\text{sec} \text{ or } 18.8 \text{m}^3/\text{day per meter dam.}$$


Reading assignment: seepage analysis with out drainage blanket

□ Basic property of a parabola



F – Focus

V – Vertex

Line DD – Directrix

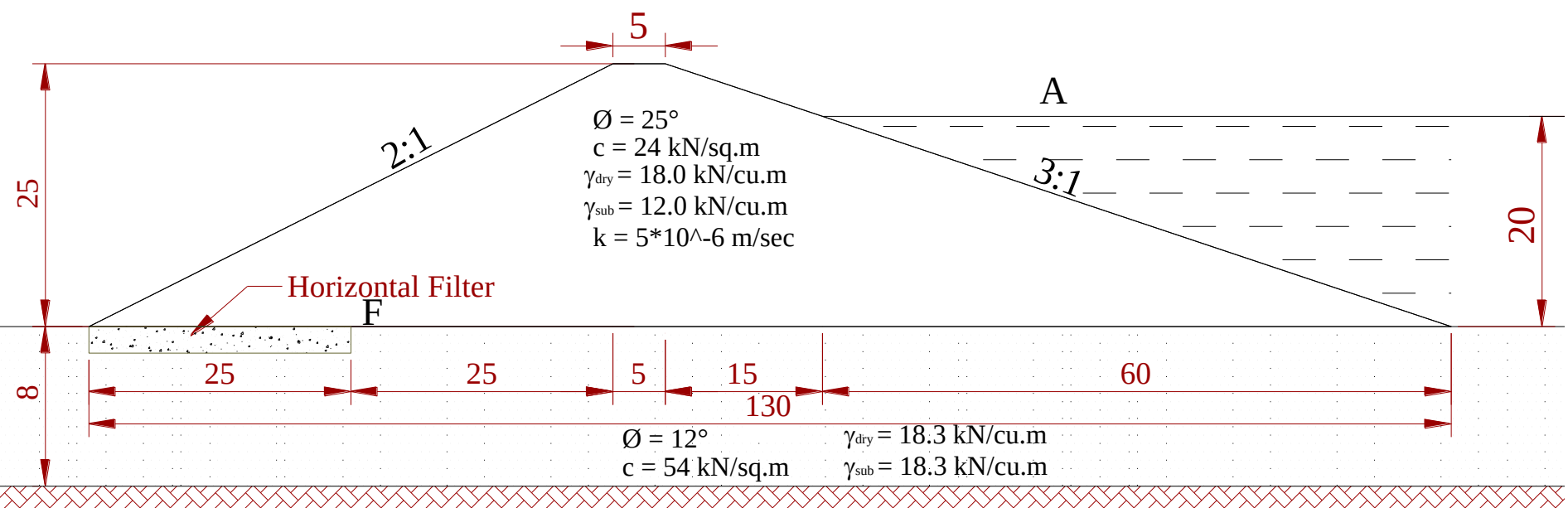
For any point P(x,y)

$$\overline{FP} = \overline{OP'}$$

$$\sqrt{x_1^2 + y_1^2} = \overline{OF} + x_1$$

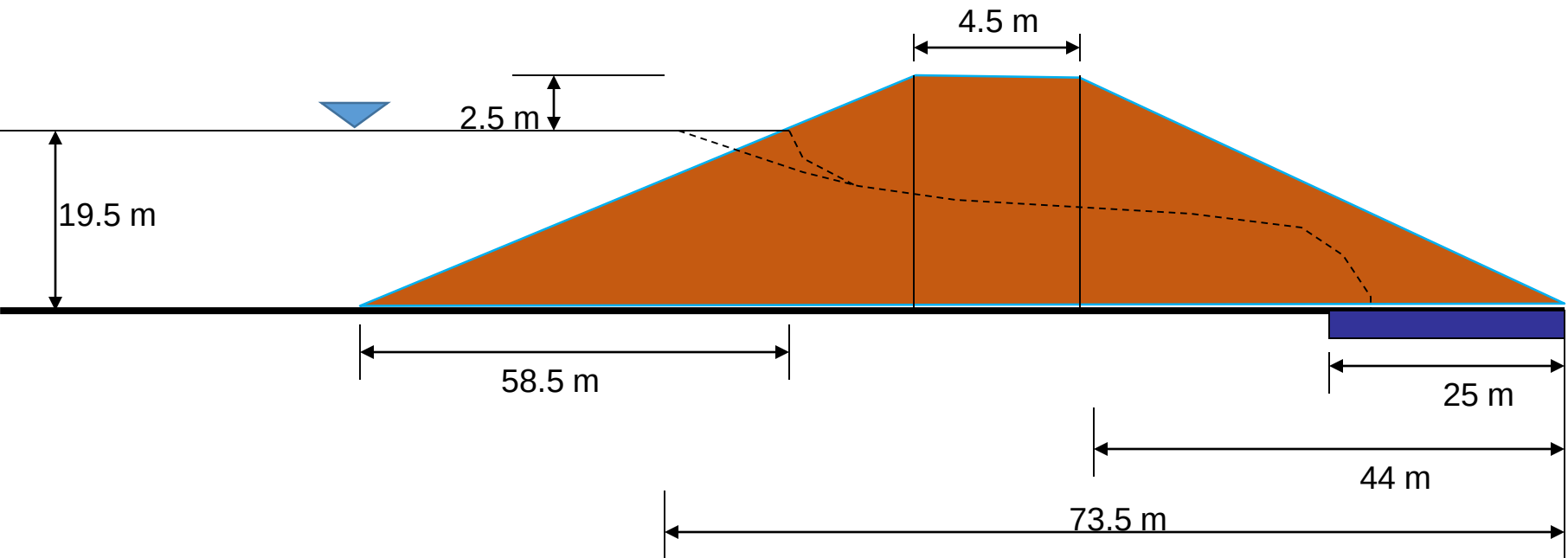
Exercise 1

An earth dam made of a homogeneous material has a horizontal filter and other parameters as shown in the figure. Determine the **phreatic line** and the **seepage quantity** through the body of the dam.



Exercise 2

For the following cross sectional view of earthen dam draw the **seepage line** and determine the **amount of discharge** that passes through the body of the dam; Assume the coefficient of permeability (K) as 5×10^{-6} m/sec



**Thank You for Your
Attention!!!**

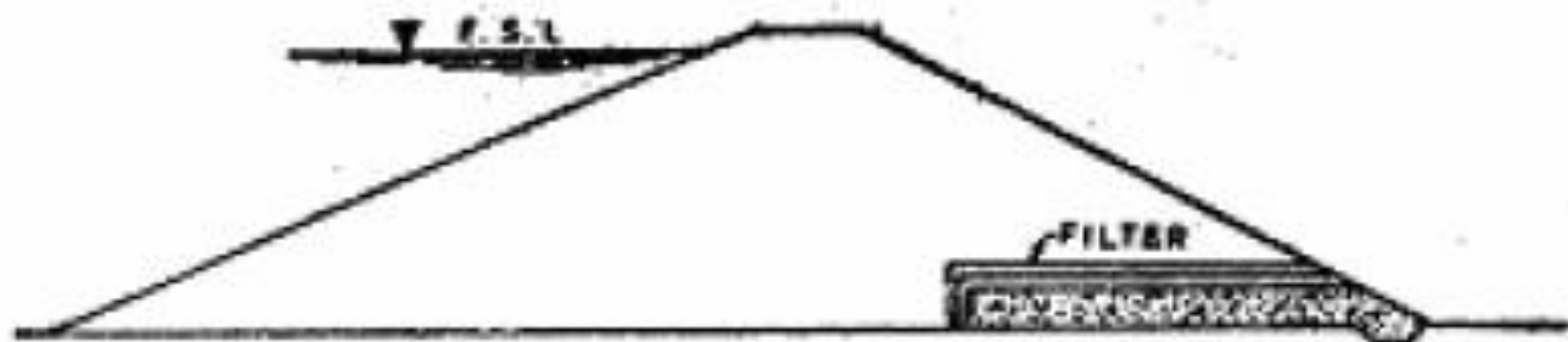
2.1.6 Embankment dam drainage system & filter design criteria

Horizontal drainage blanket

The horizontal blanket is provided over that portion of the foundation downstream from the impervious zone of the dam where high upward seepage forces exist. The blanket must be pervious to drain off effectively and its design should fulfill the usual filter criteria, in order to prevent the movement of particles of the foundation or embankment by seepage discharge.

Chimney Drains

The main disadvantage of the horizontal drainage blankets is to make the earth dam embankment stratified and consequently more pervious in the horizontal direction. The inclined or vertical chimney drains are thus provided in many homogeneous dams to intercept seepage water before it reaches the downstream slope.



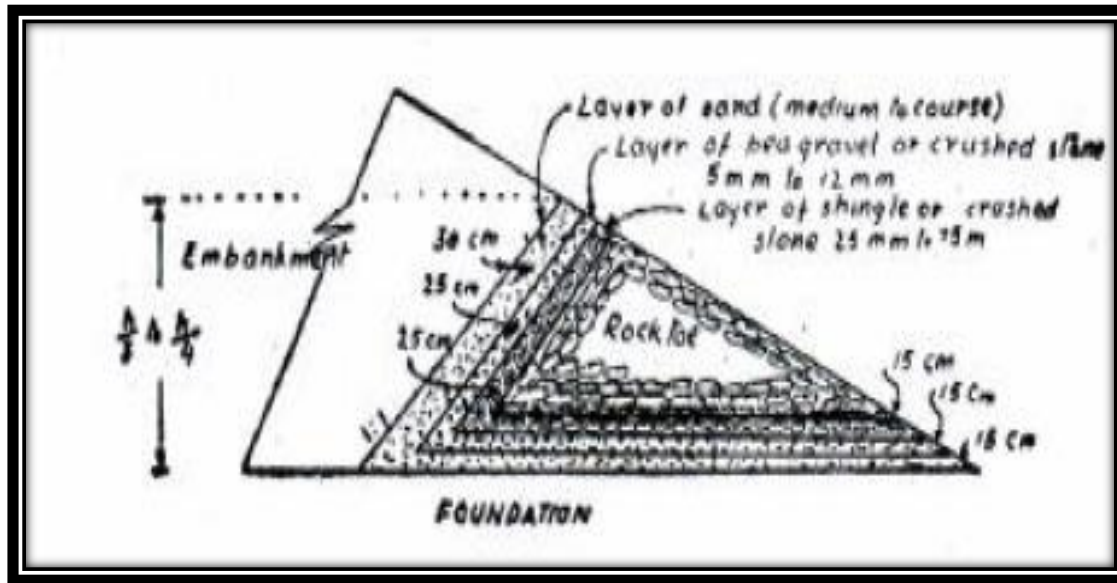
(a) HORIZONTAL DRAINAGE BLANKET WITH ROCK TOE



(b) CHIMNEY BLANKET

Rock Toe

The rock toe consists of sizes usually varying from 15 cm to 20 cm



Transition filter is required to be provided between the homogeneous fill and the rock toe to make the seepage water flow smooth.

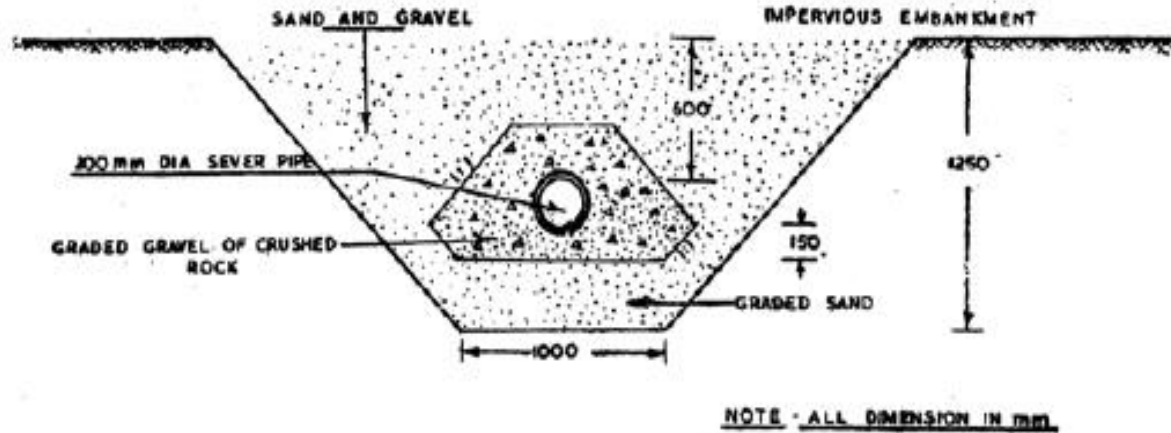
- ✓ 30 cm thick layer of fine sand (15% size = 0.09 mm)
- ✓ 45 cm thick layer of coarse sand (15% size 0.81 mm)
- ✓ 60 cm thick layer of gravel (15% size = 7.3 mm).

The height of rock toe is generally kept between $\frac{1}{3}$ to $\frac{1}{4}$ the height of the dam. The top of rock toe must be sufficiently higher than the tail water level to prevent any wave splashes on the downstream face.

- Generally the discharge face (inward face) of rock toe is kept at slope of 1:1 and the outer face is a continuation of the downstream slope.

Toe Drains and Drainage Trenches

The purpose of these drains is to collect the seepage from the horizontal blanket which discharges into the spillway stilling basin or into the river channel below the dam. Toe drains are also used on impervious foundations to ensure that any seepage that may come through the foundation or the embankment is collected and the ground water is kept below the surface to avoid the creation of boggy areas below the dam.



Perforated Pipe

The following criteria are applicable for preventing infiltration of filter material into perforated pipe, screens, etc.):

$$\frac{\text{minimum 50 percent size of filter material}}{\text{hole diameter or slot width}} \geq 1.0$$

Principles of Filter design

The objective of filters and drains used as seepage control measures for embankments is to efficiently control the movement of water within and about the embankment

Design requirements of filter/drain

- **stability requirement,**
- **permeability requirement, and**
- **Retention function**

stability requirement

Filter material must be more open and have a **larger grain size** than the protected soil.

Seepage from the finer soil to the filter can cause movement of the finer soil particles from the protected soil into and through the filter which will endanger the embankment.

Destruction of the protected soil structure may occur due to the loss of material. Also, clogging of the filter may occur causing loss of the filter's ability to remove water from the protected soil.

Table B-1
Categories of Base Soil Materials

Category	Percent finer than the No. 200 (0.075 mm) sieve
1	85
2	40-85
3	15-39
4	15

e. Determine the maximum D_{15} size for the filter in accordance with Table B-2. Note that the maximum D_{15} is not required to be smaller than 0.20 mm.

Table B-2
Criteria for Filters

Base soil category	Base soil description, and percent finer than No. 200 (0.075 mm) sieve ¹	Filter criteria in terms of maximum D_{15} size ²	Note
1	Fine silts and clays; more than 85% finer	$D_{15} \leq 9 \times d_{85}$	(1)
2	Sands, silts, clays, and silty and clayey sands; 40 to 85% finer.	$D_{15} \leq 0.7 \text{ mm}$	
3	Silty and clayey sands and gravels; 15 to 39% finer	$D_{15} \leq \frac{40-A}{40-15}$ $\{(4 \times d_{85}) - 0.7 \text{ mm}\} + 0.7 \text{ mm}$	(2),(3)
4	Sands and gravels; less than 15% finer.	$D_{15} \leq 4 \text{ to } 5 \times d_{85}$	(4)

“d” is used to represent the grain size for the protected (or base) material and the upper case “D” the grain size for the filter material

Permeability

- The requirement that seepage move more quickly through the filter than through the protected soil (called the permeability criterion) is again met by a grain-size relationship criterion based on experience:
- Permeability of a granular soil is roughly proportional to the square of the 10 to 15 percent size material. Thus, the permeability criterion ensures that filter materials have approximately 9 to 25 or more times the permeability of the protected soil.
- Generally, a permeability ratio of at least 5 is preferred; however, in the case of a wide band of uniform base material gradations, a permeability ratio as low as 3 may be used with respect to the maximum 15 percent size of the base material. There may be situations, particularly where the filter is not part of a drain, where the permeability of the filter is not important. In those situations, this criterion may be ignored.

Retention Criteria

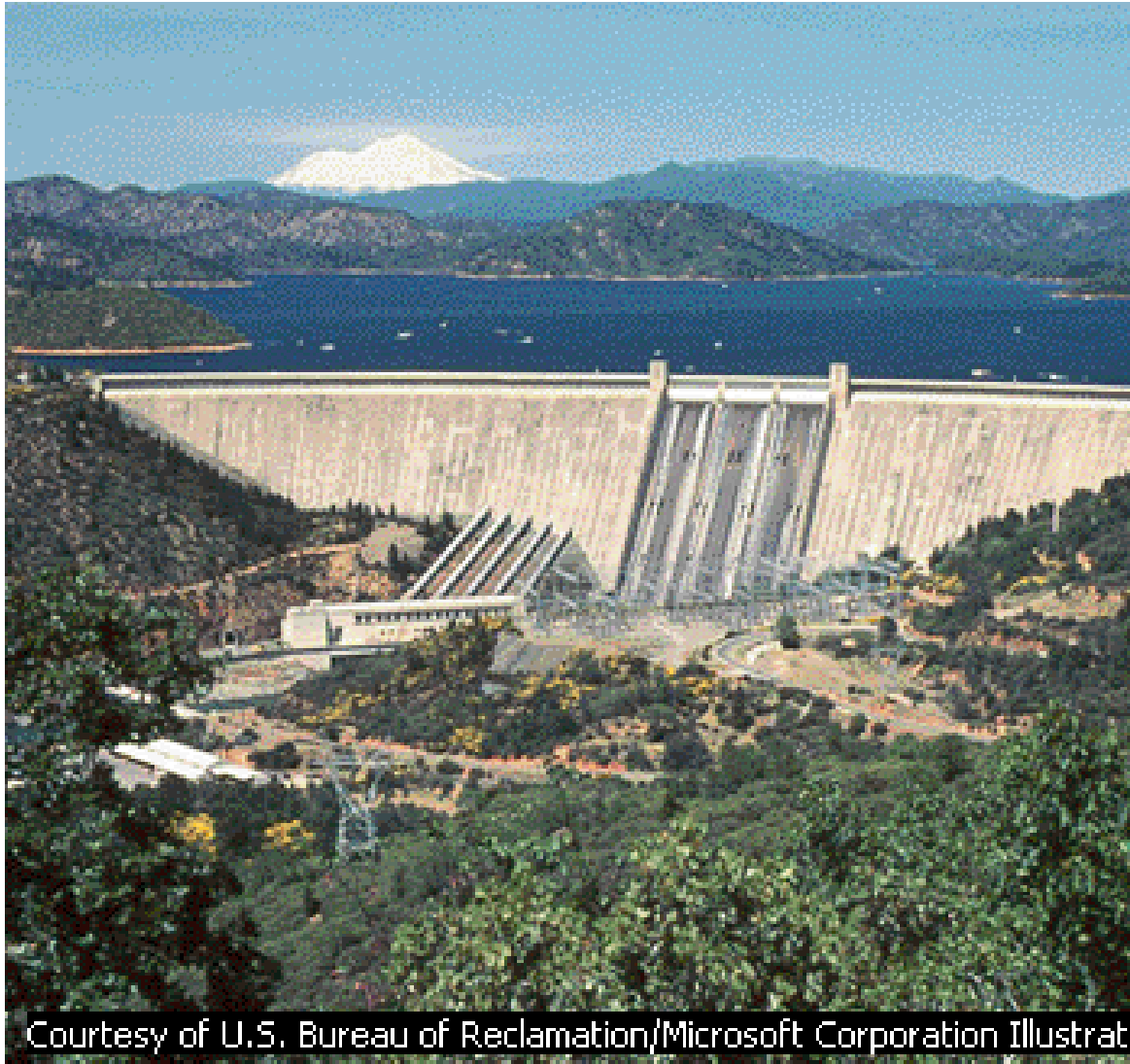
The filter must prevent migration of soil particles from adjacent foundation or fill materials. Thus, a fine filter must prevent migration of finer grained impervious fill or foundation material; a coarse filter or drain must prevent any tendency for movement of the fine filter

$$\text{Terzaghi criterion } D_{15}/d_{85} < 4$$

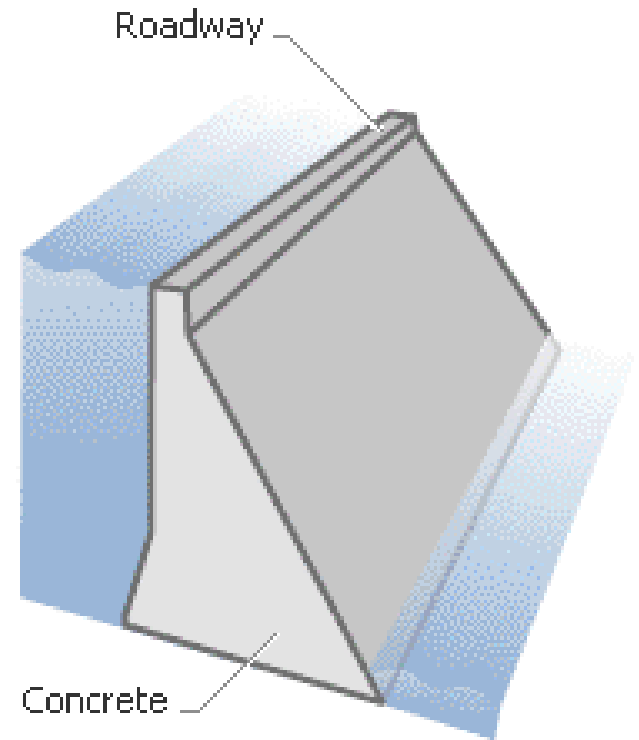
2.1. Concrete Gravity Dam

- ❖ Rigid structure
- ❖ Maintain stability from
 - ❖ Geometric shape - Triangular
 - ❖ Weight(Mass) of concrete
 - ❖ Strength of concrete
- ❖ Could be overflow and/or non-overflow
- ❖ Usually straight along the dam axis/Sometimes curved.

Typical Concrete gravity dam

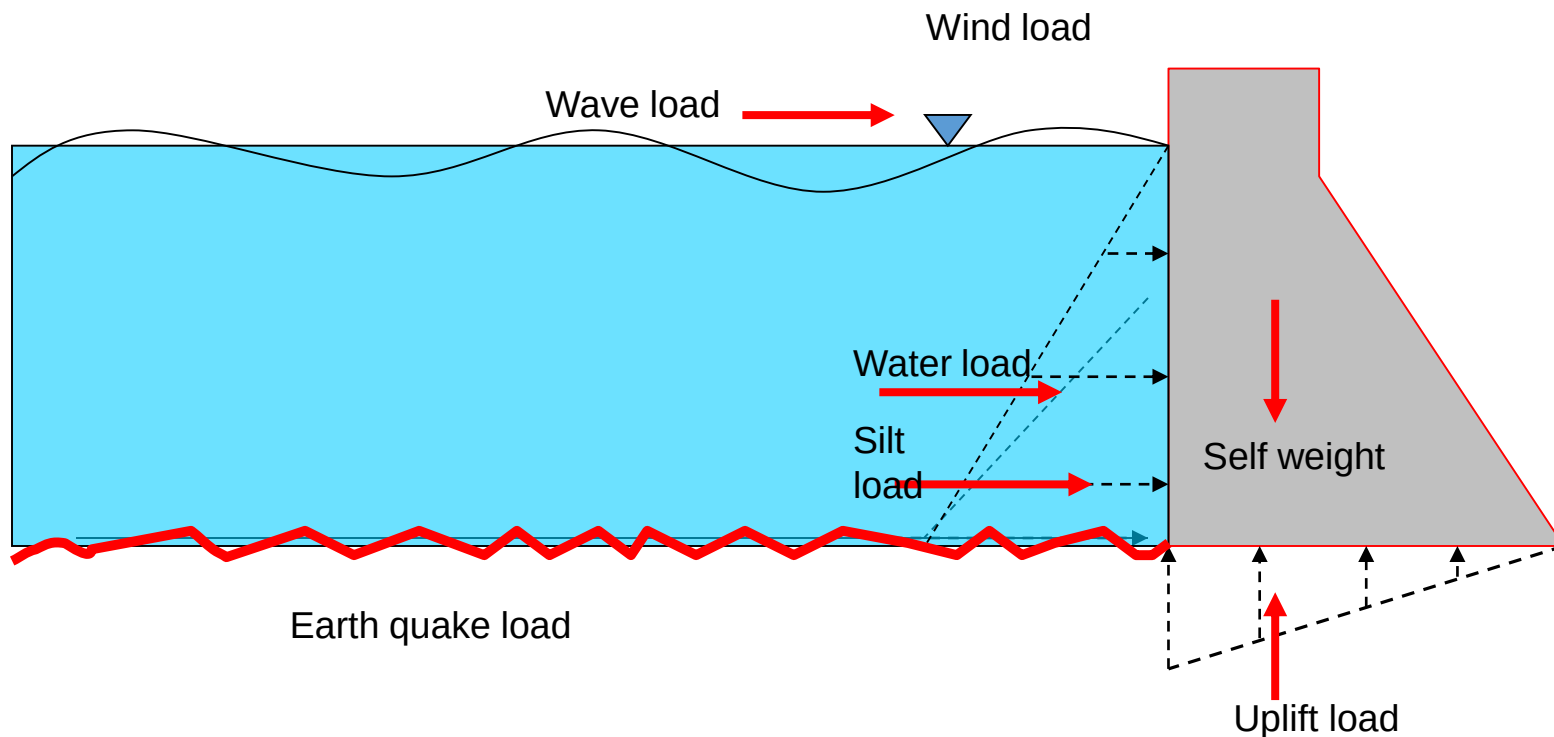


Courtesy of U.S. Bureau of Reclamation/Microsoft Corporation Illustration



Concrete gravity dam

- The structural integrity of any dam must be maintained under different loading circumstances.
- The gravity dam is mainly subjected to the following main forces:



➤ As per the degree of relative importance loads on the dam can be classified as ;

✓ **Primary loads:-** Major important loads irrespective of the dam type;

E.g. Self weight load, water load and seepage & uplift load

✓ **Secondary loads:-** Universally applicable loads , even though there magnitude is less;

E.g. Silt load, hydrodynamic load or wave load, wind Load, ice load, thermal & dam/foundation interaction effect

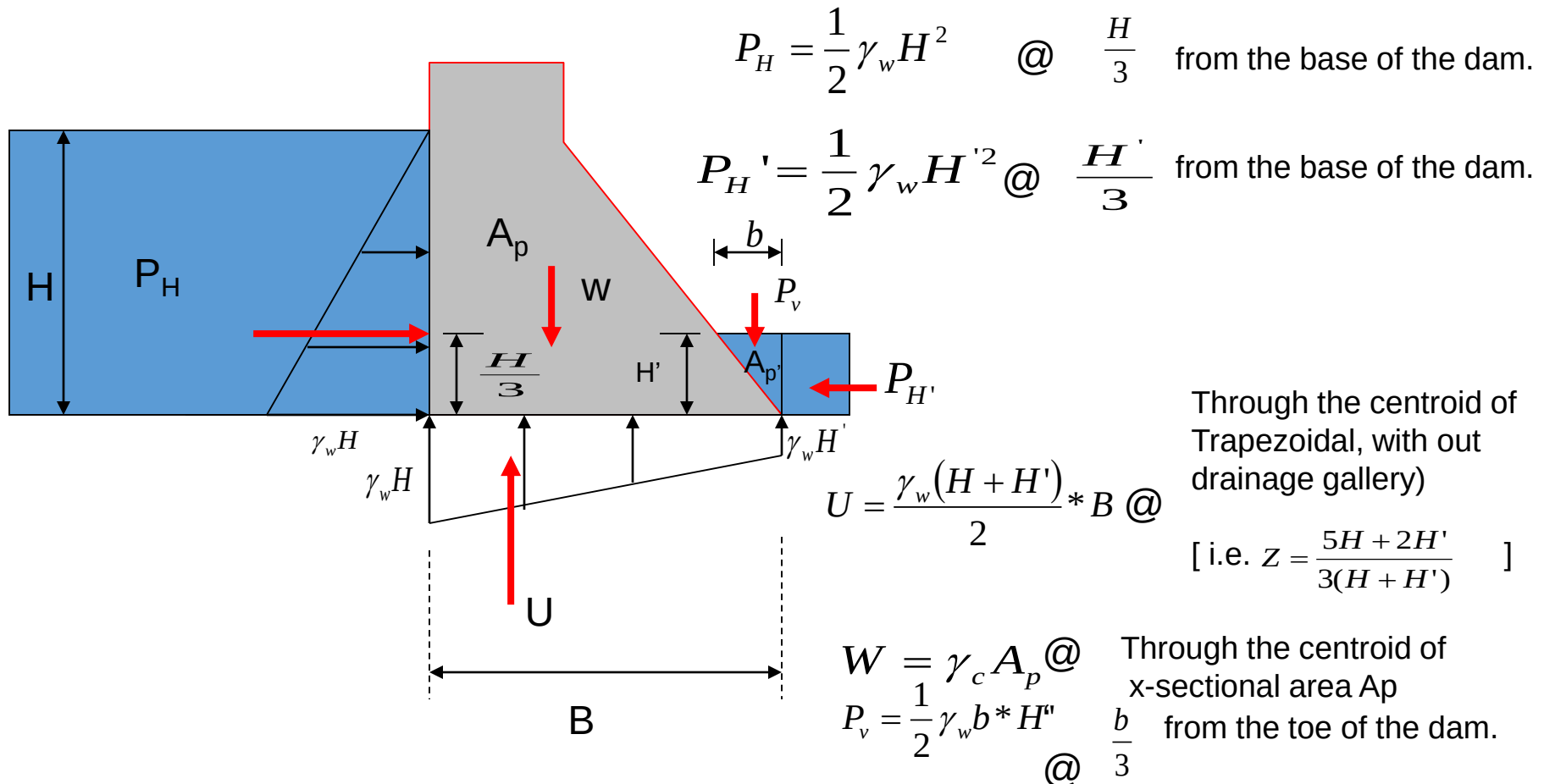
✓ **Exceptional loads:-** loads which has limited applicability;

E.g. Tectonic load earthquake

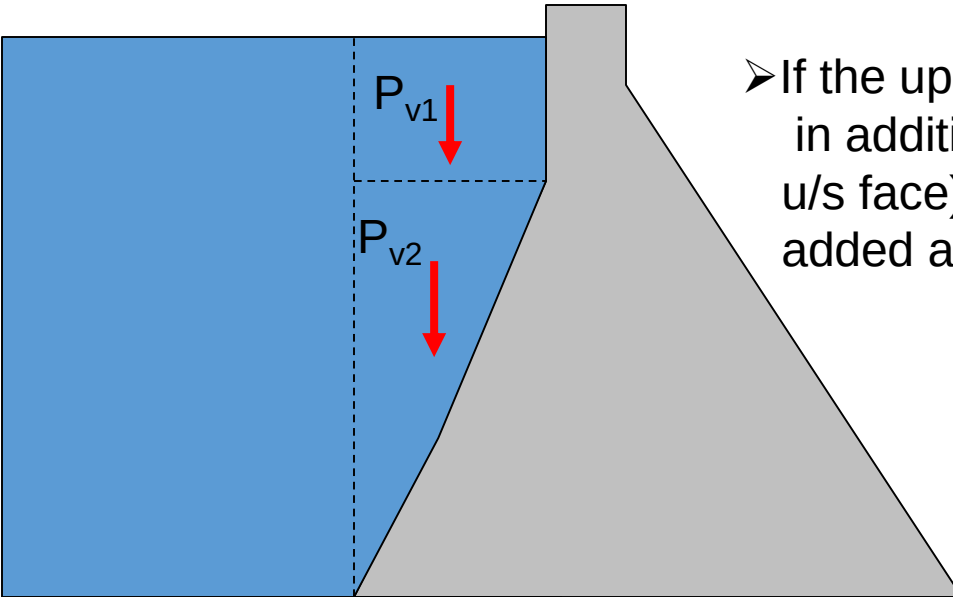
Loads and their centeroidal location in gravity dams

Case 1: Non-over flow section

(i) Up stream vertical face



(ii) Up stream face inclined



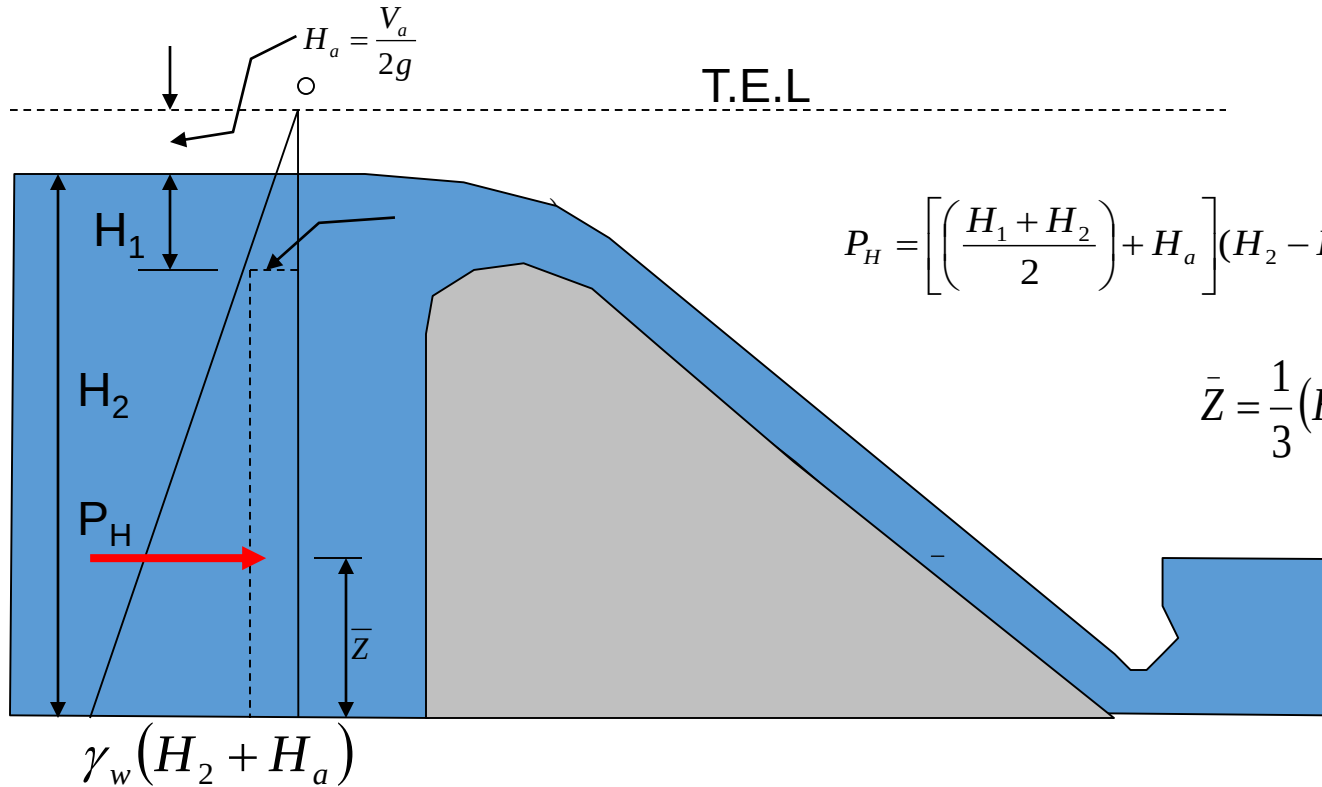
- If the upstream face of the gravity dam is inclined in addition to the previous loads (loads in vertical u/s face) , only vertical loads of water i.e. P_v will be added at its centroidal point from the toe of the dam.

where

$$P_v = P_{v1} + P_{v2}$$

Conti...

Case 2: Over flow section



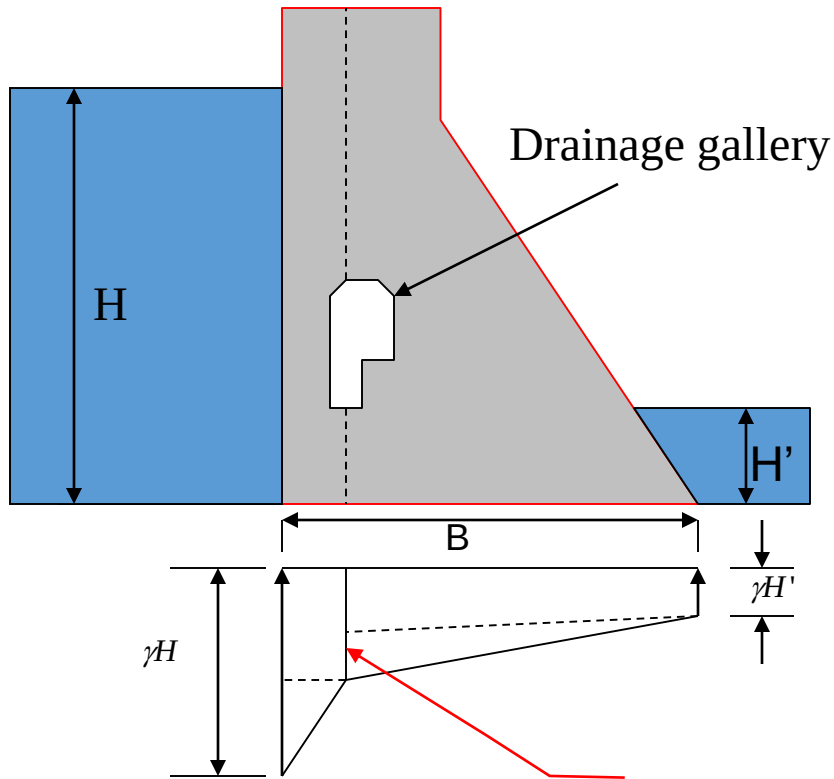
$$P_H = \left[\left(\frac{H_1 + H_2}{2} \right) + H_a \right] (H_2 - H_1) * Y_w @$$

$$\bar{Z} = \frac{1}{3} (H_2 - H_1) \left[\frac{2H_1 + 3H_a + H_2}{H_1 + 2H_a + H_2} \right]$$

from the base of the dam

Uplift pressure with drainage gallery

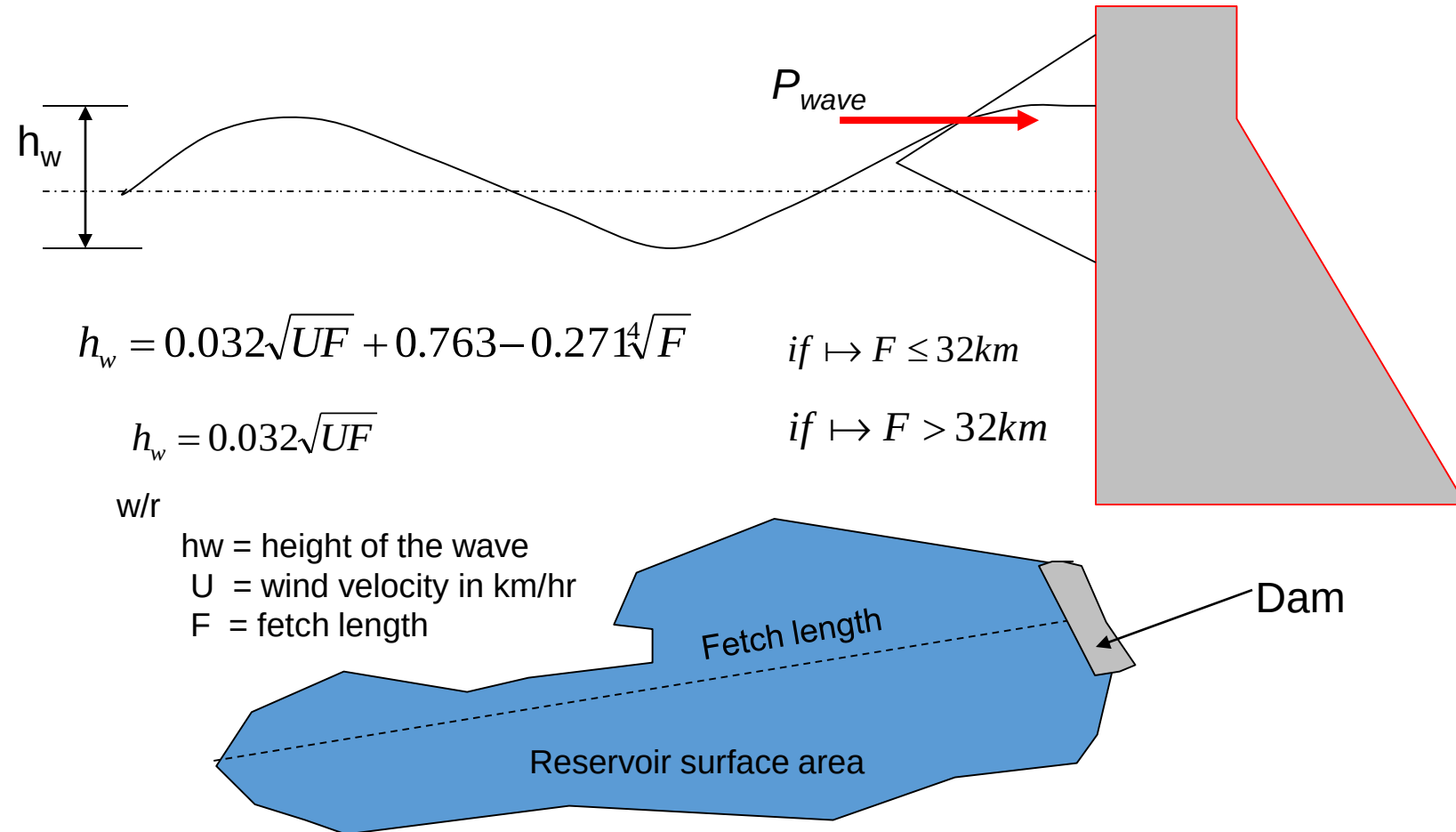
- To reduce the uplift pressure, drains are formed through the body of the dam, this makes the intensity of the uplift pressure to be different from the full concrete dam.



$$\gamma \left[H' + \frac{1}{3}(H - H') \right]$$

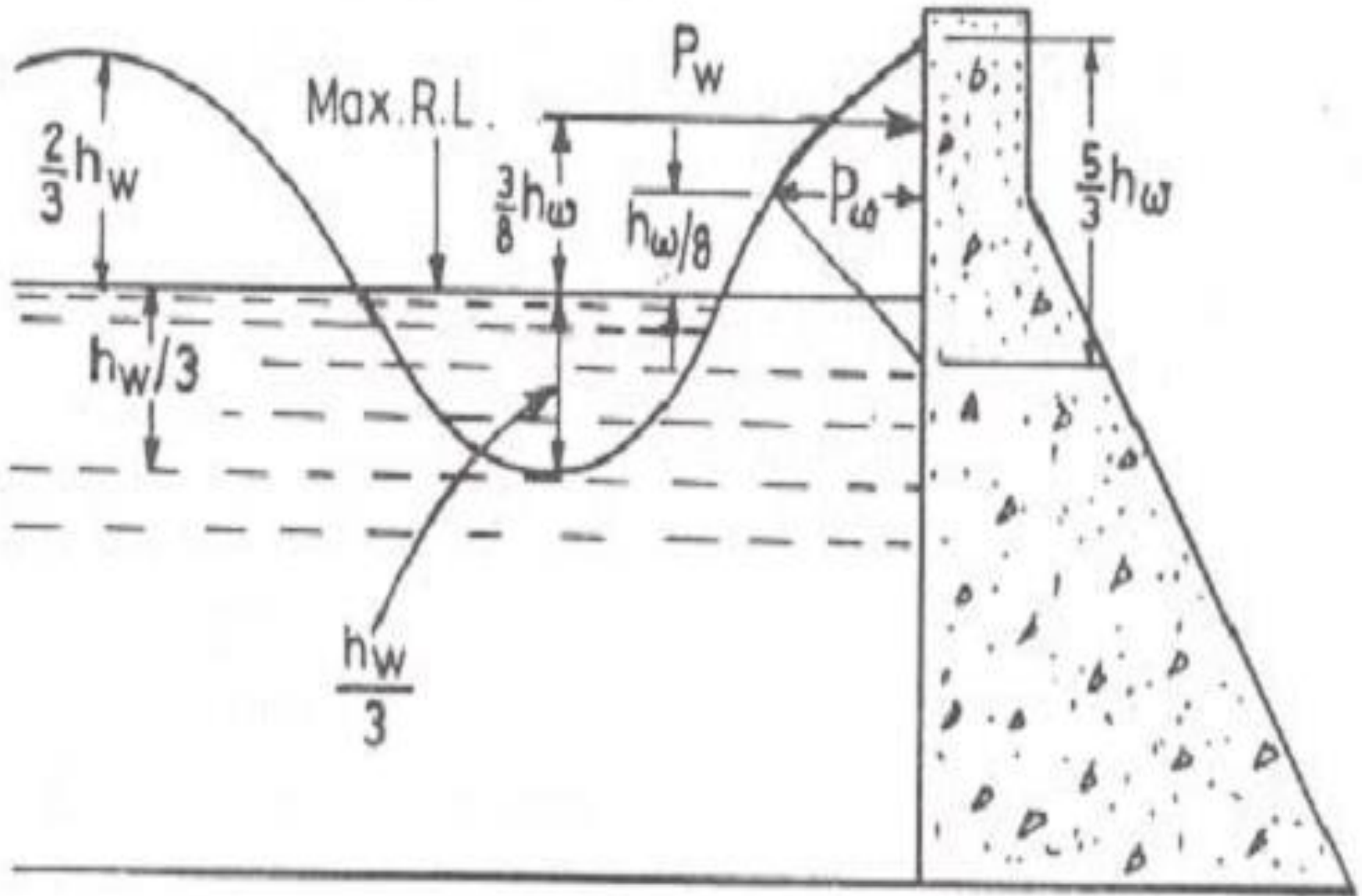
Wave Pressure (hydrodynamic wave load)

- Waves are generated on the reservoir by the blowing winds.



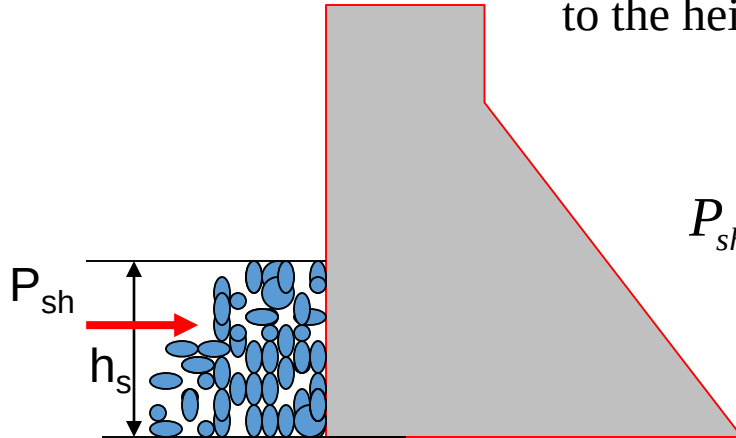
$$P_{wave} = 2\gamma_w h_w^2 \quad @ \quad 0.375h_w \text{ above the stilled water level.}$$

Wave Pressure (hydrodynamic wave load)



Sediment load

N.B: it is usual practice to assume the value of h_s equals to the height of **dead storage**.



$$P_{sh} = K_a \frac{\gamma'_s h_s^2}{2} \quad @ \quad \frac{h_s}{3} \quad \text{above the base of the dam.}$$

The submerged unit weight γ'_s and the active lateral pressure coefficient K_a is given by

$$\gamma'_s = \gamma_s - \gamma_w \quad K_a = \frac{1 - \sin \phi_s}{1 + \sin \phi_s}$$

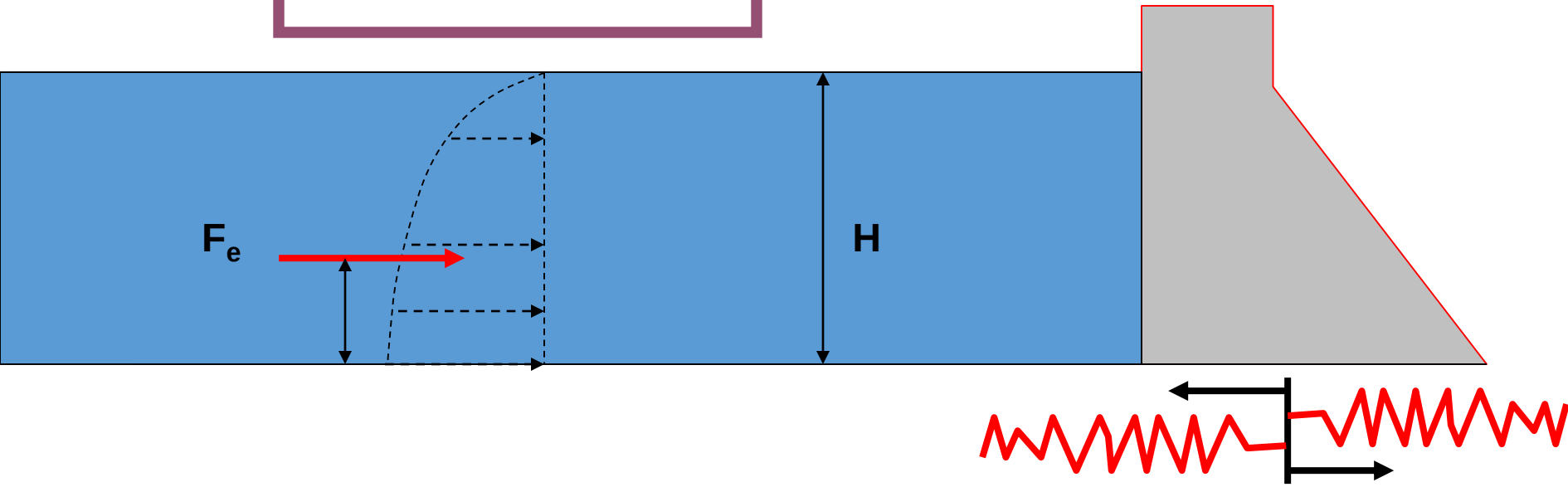
Where: ϕ_s is the angle of shear resistance

γ_s is sediment saturated unit weight

Horizontal acceleration(α_h)

Hydro-dynamic pressure.

Horizontal Inertia force.



$F_e = 0.555\alpha_h\gamma_w H^2$ acts @ $\frac{4H}{3\pi}$ from the base of the dam.

Von – Karman formula

There is also a hydrodynamic formula developed by **Zanger**, but for average ordinary purposes, the **Von-Karman** formula is sufficient.

ICE PRESSURE

- ❖ Ice load can be introduced in circumstances where ice sheets form to appreciable thickness and persist for lengthy periods.
- ❖ An acceptable initial provision for ice load, P_{ice} , where considered necessary is given by $P_{ice} = 145 \text{ kN/m}^2$ for ice thickness in excess of 0.6m (USBR, 1976).

WIND PRESSURE

- ❖ Wind pressure is seldom a factor on the design of dams.
 - ❖ The maximum possible pressures are small when compared to the loads for which the dam is designed, and it acts against the water load.
- The superstructure of dams carrying very large sluice gates may need to be proportioned to resist wind loads of 1 kN/m^2 to 1.5 kN/m^2 .

Design and analysis of gravity dam

In general Gravity dam may fail in the following way

- By over turning rotation about the toe;;
- By shear failure called sliding

1- Over turning stability

To make the structure of the dam stable from rotational or overturning failure the following governing criteria should be satisfied.

F_o (factor of safety against over turning) should be greater than 1.5

$$F_o = \frac{\sum M_{+ve}}{\sum M_{-ve}} > 1.5 \dots \dots \dots (\text{safe against overturning})$$

2-Sliding Stability (Fs)

- Sliding Factor (F_{ss})
- Shear friction Factor (F_{sf})
- Limit equilibrium factor (F_{LE})

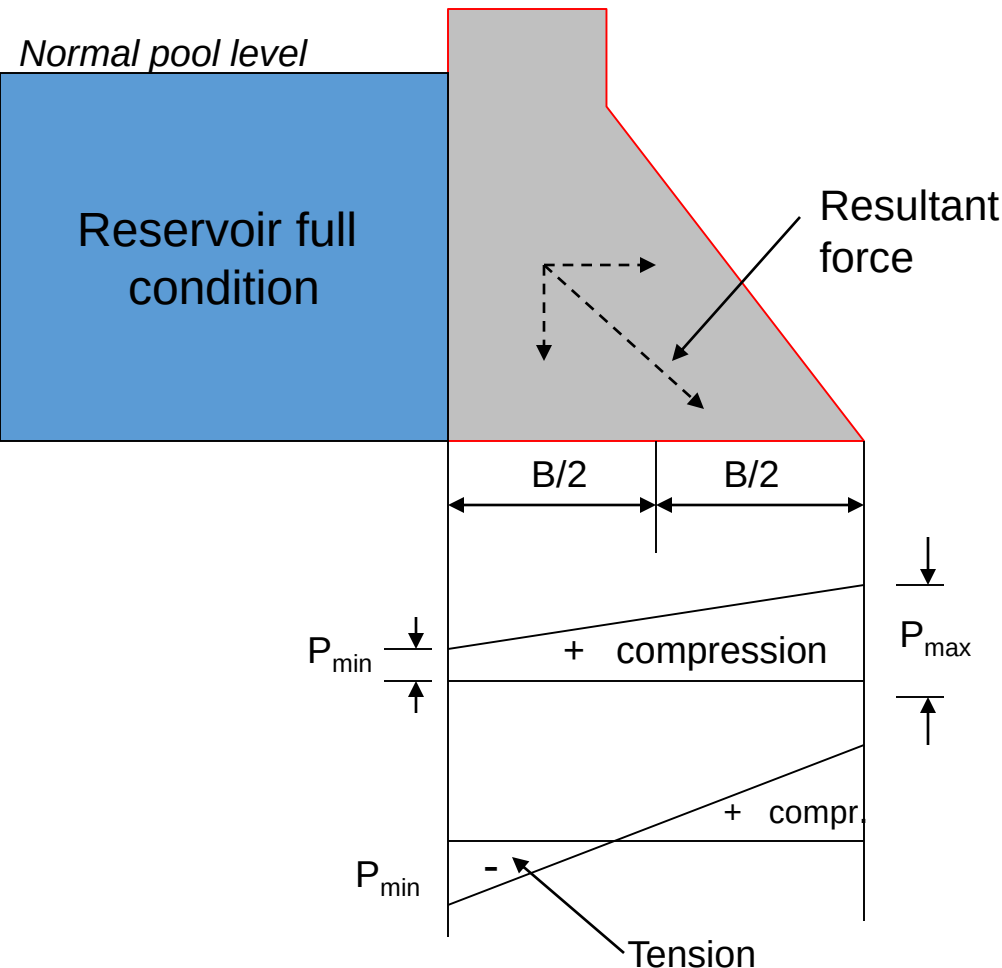
i) Sliding factor can be defined by

$$F_{ss} = \frac{\sum H}{\sum V} \quad , \text{ for horizontal plane}$$

$$F_{ss} = \frac{\frac{\sum H}{\sum V} - \tan \alpha}{1 + \left(\frac{\sum H}{\sum V} \right) \tan \alpha} \quad , \text{ for foundations inclined at a small angle } \alpha$$

Stress analysis (compression or crushing)

- If the compressive stress introduced in the dam is greater than its allowable stress ,the dam may fail.



$$P_{\max} = \frac{\sum V}{B} \left[1 + \frac{6e}{B} \right]$$

$$P_{\min} = \frac{\sum V}{B} \left[1 - \frac{6e}{B} \right]$$

Where;

e = Eccentricity of the resultant force from the center of the base

$\sum V$ = Total vertical force

B = Base width

- Because of the gravity dam materials can not sustain tensile stresses, it should be designed for **certain amount or no tension** should develop anywhere in the body of the dam.
- The maximum permissible tensile stress for high concrete gravity dams, under worst loadings, may be taken as **500 kN/m²** (5kg/cm²).

$$P_{\min} = \frac{\sum V}{B} \left[1 - \frac{6e}{B} \right] = 0$$

$$e = \frac{B}{6}$$

NB: A tension crack by itself does not fail the structure, but it leads to failure of the structure by producing excessive compressive stresses.

- In order to ensure that no tension is developed anywhere, the amount of $P_{\min}$ should at most equal to zero.
- The maximum value of eccentricity, that can be permitted on either side of the center is equal to $B/6$ ----- “***the resultant must lie within the middle third***”.
- The resultant distance from the toe of the dam () is given by

$$\bar{x} = \frac{\sum M}{\sum V}$$

Freeboard Allowance/Determination

- ❖ Freeboard protects dams from overflow caused by wind-induced tides and waves. It is the vertical distance between maximum water level (still water) and dam crest.
- ❖ Provision of a freeboard is required to avoid overtopping (damages, destruction) of dam due to wind set-up and wind generated waves.
- ❖ The freeboard may have several components:
 - ✓ Rise in reservoir level due to flood routing (flood surcharge)
 - ✓ Seethe effects
 - ✓ Wind set-up of the water surface
 - ✓ Wave action
 - ✓ Run-up of waves on the dam

- ❖ Seiche effects, periodic undulation of reservoirs, although in big reservoirs reach up to 0.5 m (Thomas 1976), are usually neglected particularly in medium sized reservoirs.
- ❖ A first step in wave height determinations is a study of available wind records to determine velocities and related durations and directions. Three basic considerations are generally used in establishing freeboard allowance. These are **wave characteristics, wind setup, and wave run-up.**

Wind set-up (wind tide)

❖ When wind blows over a water surface, it exerts a horizontal stress on the water, driving it in the direction of the wind and resulting in the piling up of the water at one end of the reservoir. This effect is called “wind tide” or “wind set-up.” The wind set-up is determined by Zuider Zee formula,

$$S = \frac{U_{\Delta}^2 F}{63200 D} \quad (\text{Metric units})$$

$$S = \frac{U_{\Delta}^2 F}{1400 D} \quad (\text{FPS units})$$

Cont...

Where S is the wind set-up (m or ft), U_A is the wind velocity (km/h or mph), F is the fetch (km or miles) and D is average water depth along fetch line (m or ft). Wind-stress factor U_Δ (adjusted wind speed, in mph)

U –wind speed over water (mph)

$$U_\Delta = 0.589 U^{1.23}$$

Wave run-up

❖ R_s , is the vertical height above the still-water level and is related to the wave height in non-dimensional form as

Where R_s is run up (ft); H_s (ft); Θ = angle of inclination of slope with horizontal; and L_0 is wave length, given by

$$\frac{R_s}{H_s} = \frac{1}{0.4 - \sqrt{\frac{H_s}{L_0} \cot \Theta}}$$

$L_0 = 5.12 T^2$ [in feet] or $L_0 = 1.56 T^2$ [in m] and T is the wave period given by

$$T = 0.46 U_{\Delta}^{0.44} F^{0.28} \text{ (FPS units)} \quad T = 0.32 U_{\Delta}^{0.44} F^{0.28} \text{ (SI units)}$$

Cont...

❖ The probability of an extreme wind coinciding with the maximum flood level in the reservoir is usually very small, and thus it may be deemed unnecessary to superimpose all the extreme conditions for freeboard determination, particularly in the case of concrete dams. Equally, it is a matter of engineering judgment of possible damage from some water passing over the dam and the cost of a large freeboard for a wave run-up which will ultimately determine the adopted freeboard value. Generally,

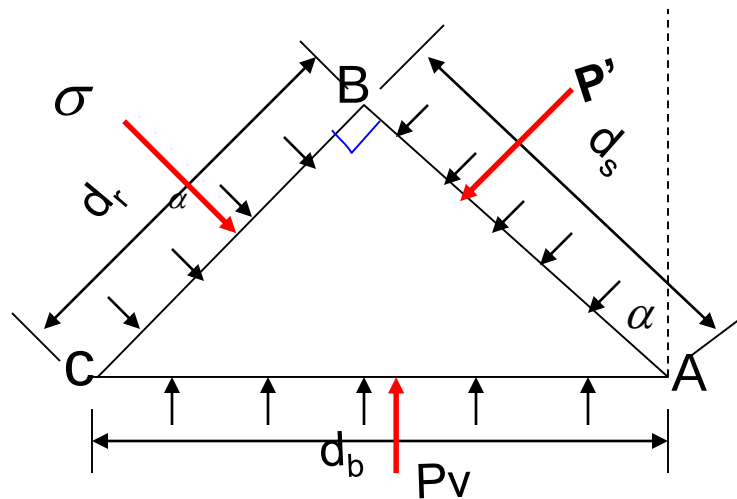
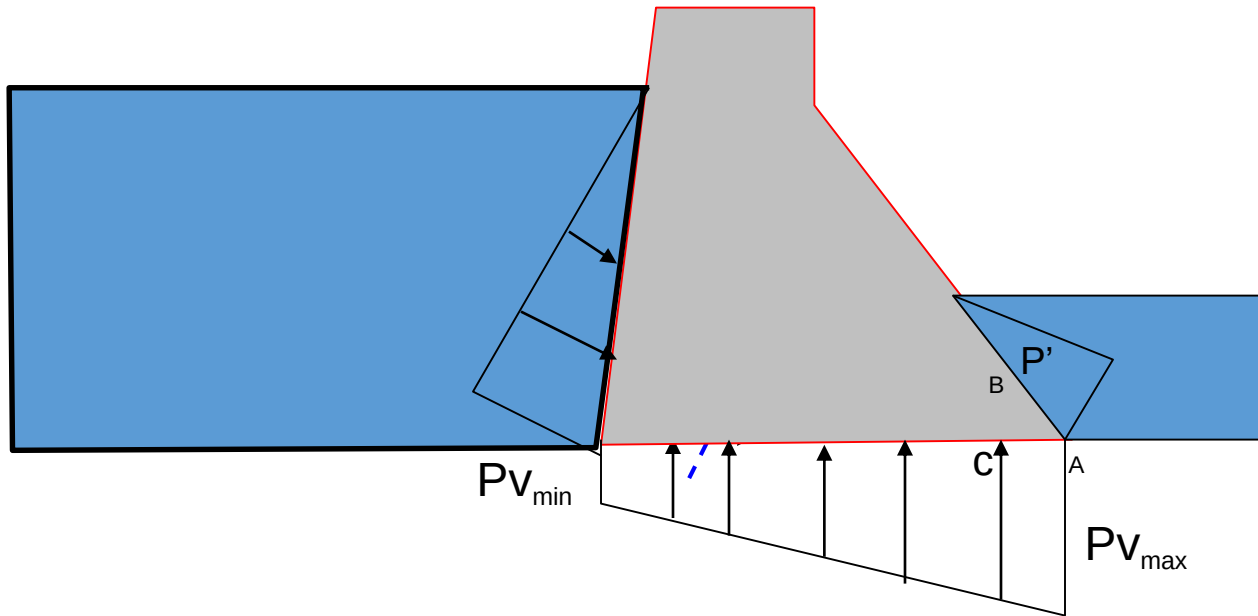
Freeboard = wind set-up (wind tide) + run-up of significant waves + Settlement allowance

Cont...

FREE BOARD: Free board is generally provided equal to $\frac{3}{2}h_w$ where h_w is wave height.

However modern practice is to provide a maximum free board equal to 3 to 4% of the height of dam, though free board equal to 5% or more might prove economical.

Principal stress



$$\sigma = p_v \sec^2 \alpha - p' \tan^2 \alpha$$

For σ to be maximum, p' should be zero.

Procedure: Two dimensional analysis can be carried out analytically or graphically.

(a) *Analytical Method.* The stability of the dam can be analysed in the following steps :

- (i) Consider unit length of the dam.
- (ii) Work out the magnitude and directions of all the vertical forces acting on the dam and their algebraic sum, i.e. ΣV .
- (iii) Similarly, work out all the horizontal forces and their algebraic sum, i.e. ΣH .
- (iv) Determine the lever arm of all these forces about the toe.
- (v) Determine the moments of all these forces about the toe and find out the algebraic sum of all those moments, i.e. ΣM .
- (vi) Find out the location of the resultant force by determining its distance from the toe,

$$\bar{x} = \frac{\Sigma M}{\Sigma V}.$$

- (vii) Find out the eccentricity (e) of the resultant (R) using $e = \frac{B}{2} - \bar{x}$. It must be less than $B/6$ in order to ensure that no tension is developed anywhere in the dam.
- (viii) Determine the vertical stresses at the toe and heel using Eq. (19.15), i.e.

$$p_v = \frac{\Sigma V}{B} \left[1 \pm \frac{6e}{B} \right] \quad \text{---(19.15)}$$

Sometimes stresses are found by ignoring uplift.

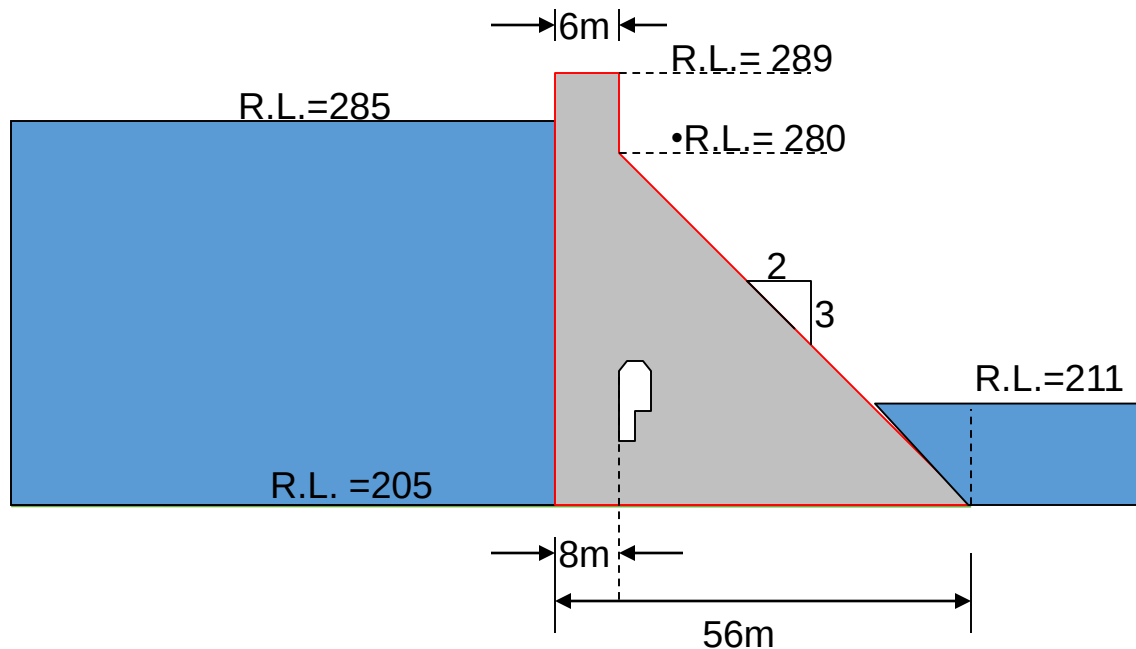
- (ix) Determine the maximum normal stresses, i.e. principal stresses at the toe and the heel using equations (19.18) to (19.20). They should not exceed the maximum allowable values. The crushing strength of concrete varies between 1500 to 3000 kN/m² depending upon its grade M15 to M30.
- (x) Determine the factor of safety against overturning as equal to $\frac{\Sigma \text{Stabilising moment (+)}}{\Sigma \text{Disturbing moment (-)}}$; +ve sign is used for anti-clockwise moments and -ve sign is used for clockwise moments.

- (xi) Determine the factor of safety against sliding, using Sliding factor = $\frac{\mu \Sigma V}{\Sigma H}$.

Example 2.1

For the following situation calculate;

- The maximum vertical stresses at the toe and heel of the dam.
- The major principal stresses at the toe of the dam.
- The intensity of shear stresses at the toe of the dam.



Example 2.2

Given a particular gravity dam profile with the following data.

Height of the dam = 63m	Free board = 3m
U/S slope 0.2H: 1V	Height of U/S inclined face = 20m
Top width = 10m	Total base width = 54m
D/S slope 0.8H: 1V	Tail water depth = 10m
US seismic zone 2	Wind velocity = 80Km/hr
	D/s vertical face = 10m

Expected depth of silt deposit = 10m
Fetch distance of reservoir from dam site = 40km
Location of uplift drainage from the heel of the dam = 9m

Required:

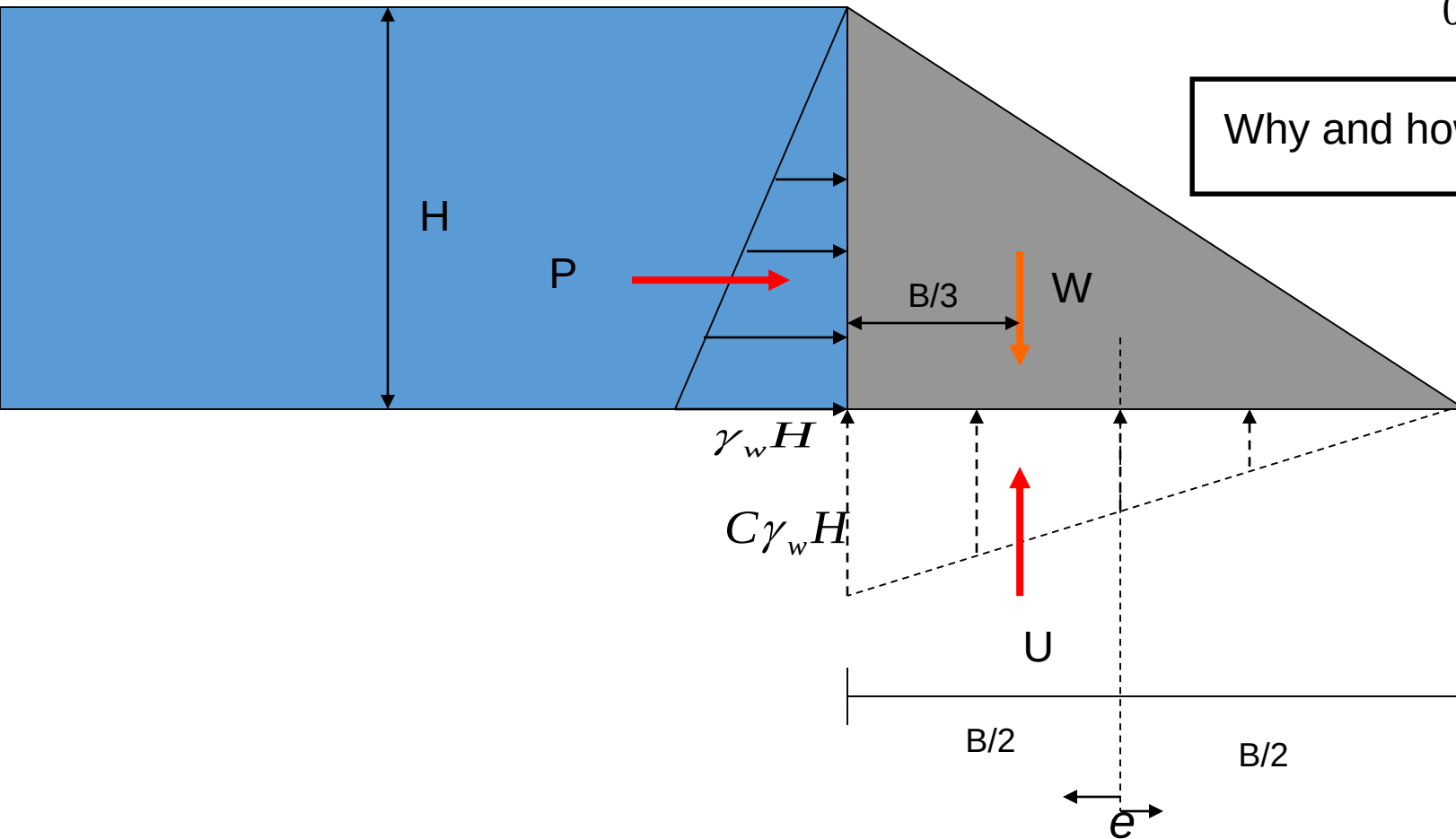
Draw the profile, show the direction and location of all forces and quantify their magnitudes in diagram & tabular form.

Base width design for gravity dam for reservoir full condition

I) In order to no tension to be develop in the body of the dam the following should be satisfied

$$B = \frac{H}{\sqrt{G_c - C}}$$

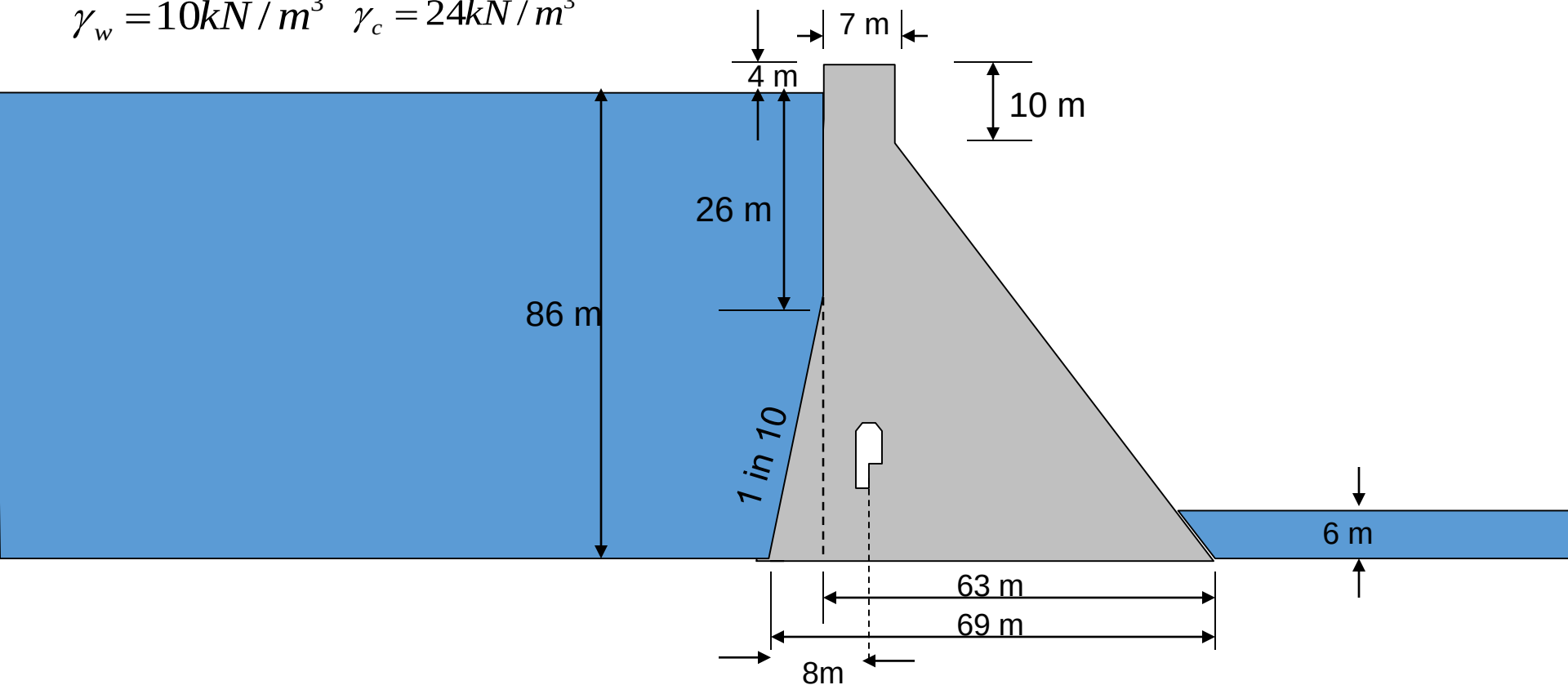
II) In order the dam is to be safe from sliding the following should be satisfied $B \geq \frac{H}{0.75(G_c - C)}$



Exercise 2.3

For the following section of gravity dam examine the stability for reservoir full condition. Take the horizontal and vertical earth-quake force as 0.1 g and 0.05 g respectively. Find also the Principal and shear stress at the toe.

$$\gamma_w = 10 \text{ kN/m}^3 \quad \gamma_c = 24 \text{ kN/m}^3$$



Name of the forces	Designation	Magnitude of forces in kN		Lever arm (m)	Moment about the toe
Down ward wight of dam		Vertical	Horizontal		
	W_1	$(+) 0.5 * 6 * 60 * 24 = 4,320$		65.00	$(+) 280800$
	W_2	$(+) 7 * 90 * 24 = 15120$		59.50	$(+) 899640$
	W_3	$(+) 0.5 * 56 * 80 * 24 = 53760$		37.33	$(+) 2006860.8$
		$\Sigma V_1 = 73,200$			$\Sigma M_1 = (+) 3187300.8$
Horizontal earth quake force	Pw_1		$0.1 W_1 = 0.1 * 4,320 = 432$	20.00	$(+) 8640.00$
	Pw_2		$0.1 W_2 = 0.1 * 15120 = 1512$	45.00	$(+) 68040$
	Pw_3		$0.1 W_3 = 0.1 * 53760 = 5376$	26.67	$(+) 143377.92$
			$\Sigma H = 73,200$		$\Sigma M_2 = 220057.92$
vertical earthquake force					
					$\Sigma M_3 = 0.05 * \Sigma M_1 = 0.05 * 3187300.8$
		$\Sigma V_2 = 0.05 * \Sigma V_1 = 0.05 * 73,200 = 3660$			$= 159365.04$

Reading assignment: Safety and Selection of Dams

Thank you!