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Hydraulic Structure I – CENG 3161

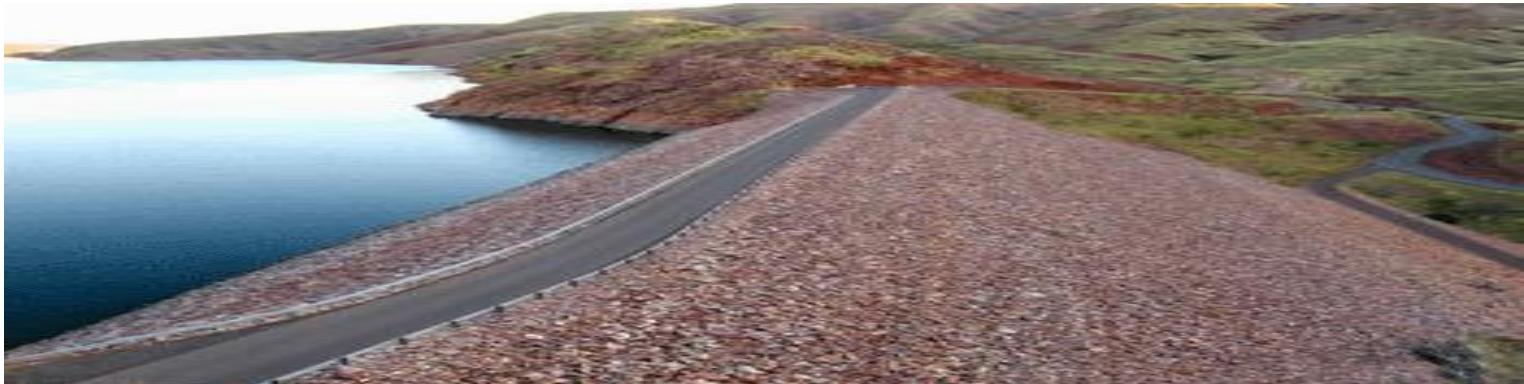
Chapter 2. Design Principle of Dams

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2.2 Embankment Dam

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- Embankment dams are built of soil or rock fill or both.
- Are classified as **non-rigid type** of dam.
- An embankment dam is a dam which resists all the external forces by mainly shear strength of material.
- Strength and stability of embankment dam comes from it's shear strength of material.



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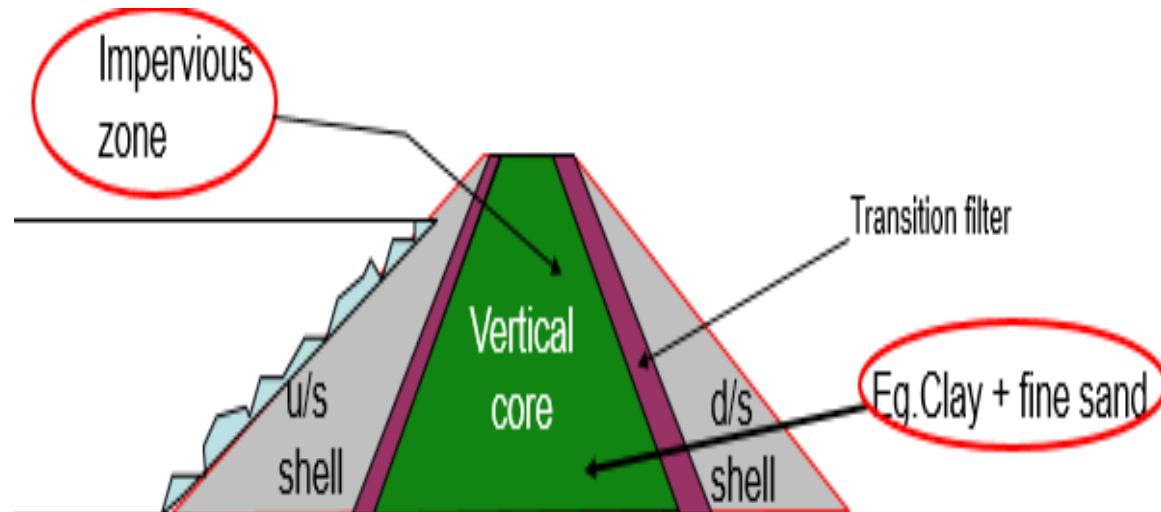


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Elements of Embankment Dam

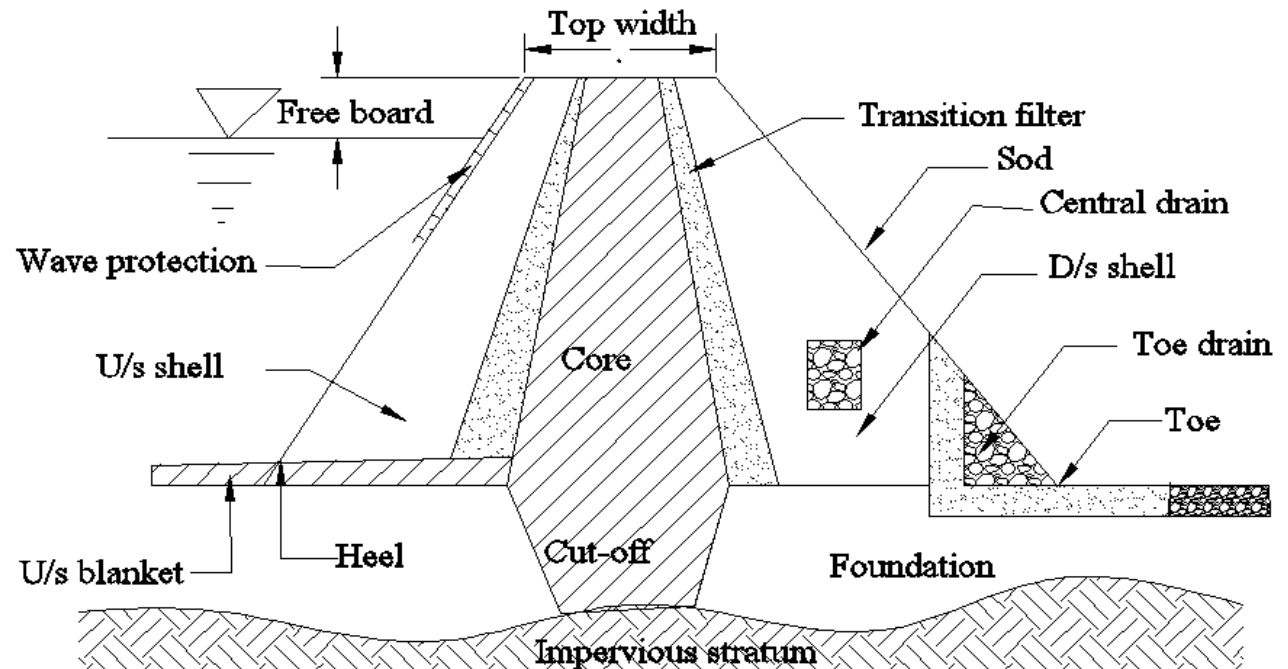
- embankment dam consists of three basic components
 - Foundation,
 - Core, and
 - Shell.



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- And other appurtenances such as;
 - Transition filter,
 - Toe drain,
 - u/s slope protection (Riprap) and d/s slope protection,
 - Internal drain,
 - cutoff



Cont....

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- **Foundation**
 - Provide support to horizontal and vertical load
 - Resist seepage underneath embankment
- **Core**
 - Control seepage water through embankment
 - prevents piping through cracks which may develop in the core
 - Extended in to impervious stratum

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- **Shell**

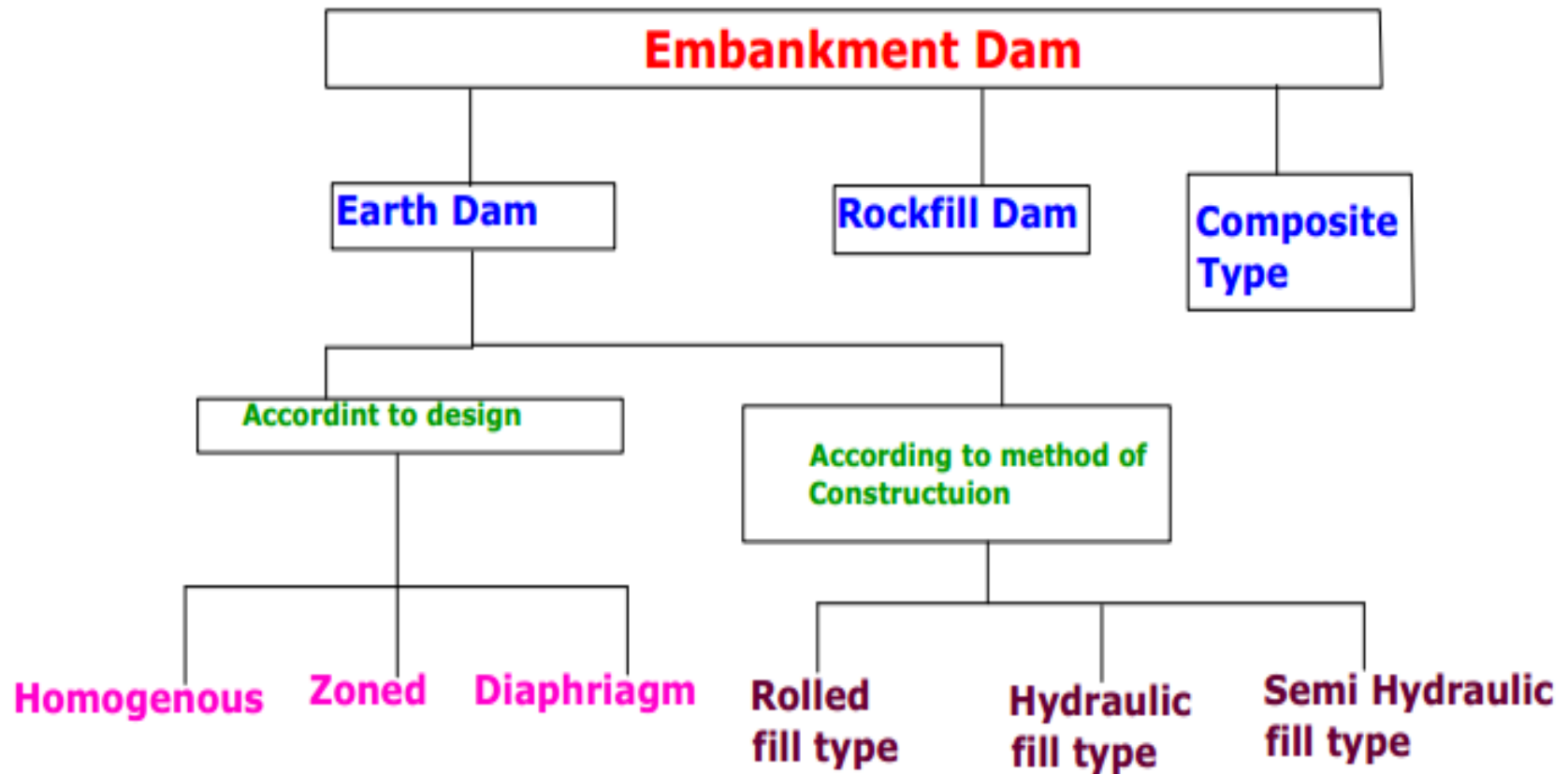
- Provides structural support and protects the core and distribute the load to foundation.
 - ✓ The upstream shell provides stability and free drainage against rapid drawdowns.
 - ✓ The downstream shell acts as a drain to control and lower the phreatic surface.

- **Transition filter**

- Provided b/n core and shell to control migration (washing out) of the core material to the pores of shell.
- Provided if the size of material and permeability's in body of the dam (shell, core and foundation) vary.

2.2.1 Classification of Embankment Dams

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Cont....

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- Based on material of construction
 1. Earth fill embankment dam
 - ✓ If **compacted soils**, i.e. clays/silts & sands, account for **over 50% of the placed volume of material**.
 2. Rock fill embankment dam
 - ✓ If **compacted rock particles**, i.e. coarse grained frictional material, **accounts for over 50% of the placed volume of materials**.
 3. Composite dam
 - Dams constructed from both earth and rock fill.

Cont....

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- Earth dams may be classified on the basis of methods of construction.
 - a) Rolled-fill earth dam
 - b) Hydraulic-fill earth dam
 - c) Semi-hydraulic fill earth dams

Rolled fill Dam

- ✓ In rolled-fill earth dams the embankment **is constructed in successive mechanically compacted layers**.
- ✓ The material **(sand, clay, gravel etc.) is transported from the borrow pits to the dam site** by truckers or scrapers.
- ✓ the soil materials are placed in layers of 15 to 45 cm and then compacted by heavy roller at optimum moisture content (OMC).

Cont....

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Hydraulic fill dam

- the materials are transported from borrow pits to dam site placed through the agency of water.
- In this case, the materials are mixed with water at borrow site to form slush and transported to dam site through flumes or pipes and deposited near the faces of the dam.

Cont....

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Semi-hydraulic dam

- ✓ the coarse material is dumped from trucks as in case of rolled fill dam to dam site without use of water.
- ✓ jet of water are directed on dumped fill, causing finer material to move towards the center thus forming an impervious central core while the coarser material stays near the face of dam.
- ✓ Out of these three types, the rolled-fill earth dams are the most common.

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- ❖ Rolled Fill dams are of three types
 - Homogenous type
 - Zoned type
 - Diaphragm type

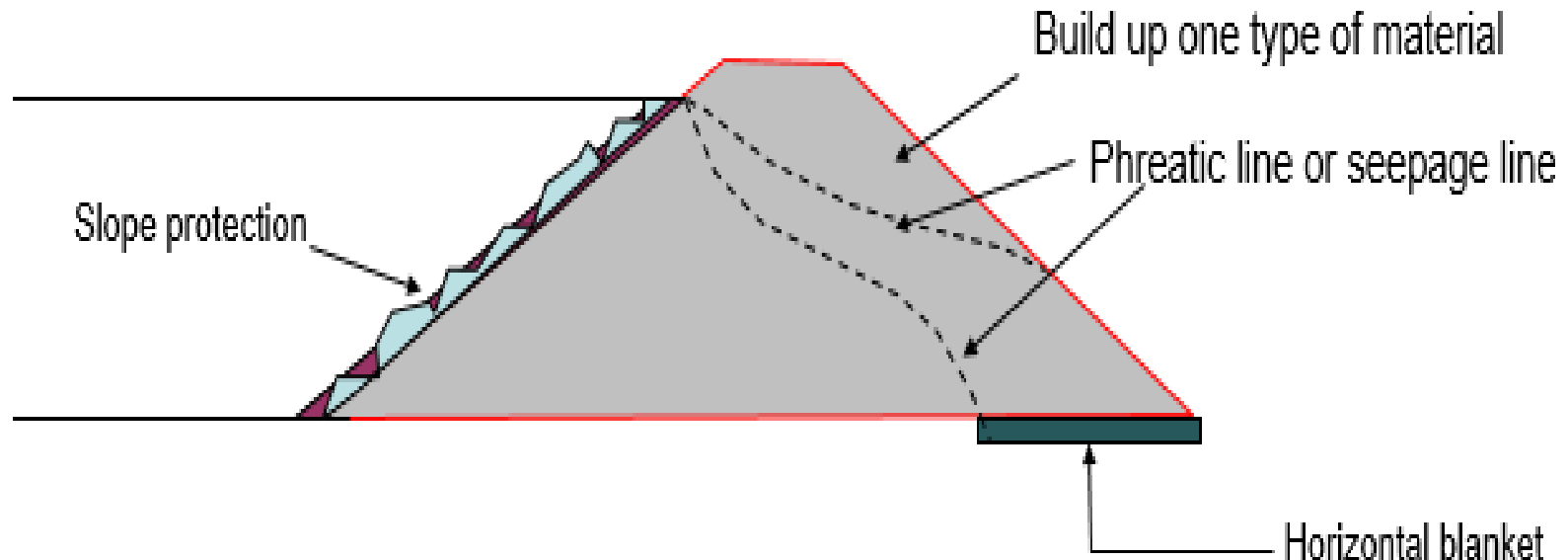
A. Homogeneous Earth Dams:-

- ✓ are constructed entirely of single/one type of earth material except the slope protection.
- ✓ It is used when only a single type of material is economically and locally available and applicable for low and moderate dam.

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- Regardless of d/s slope (flatness) and permeability, seeping water will come out in d/s face unless **drainage filters are provided in the d/s.**



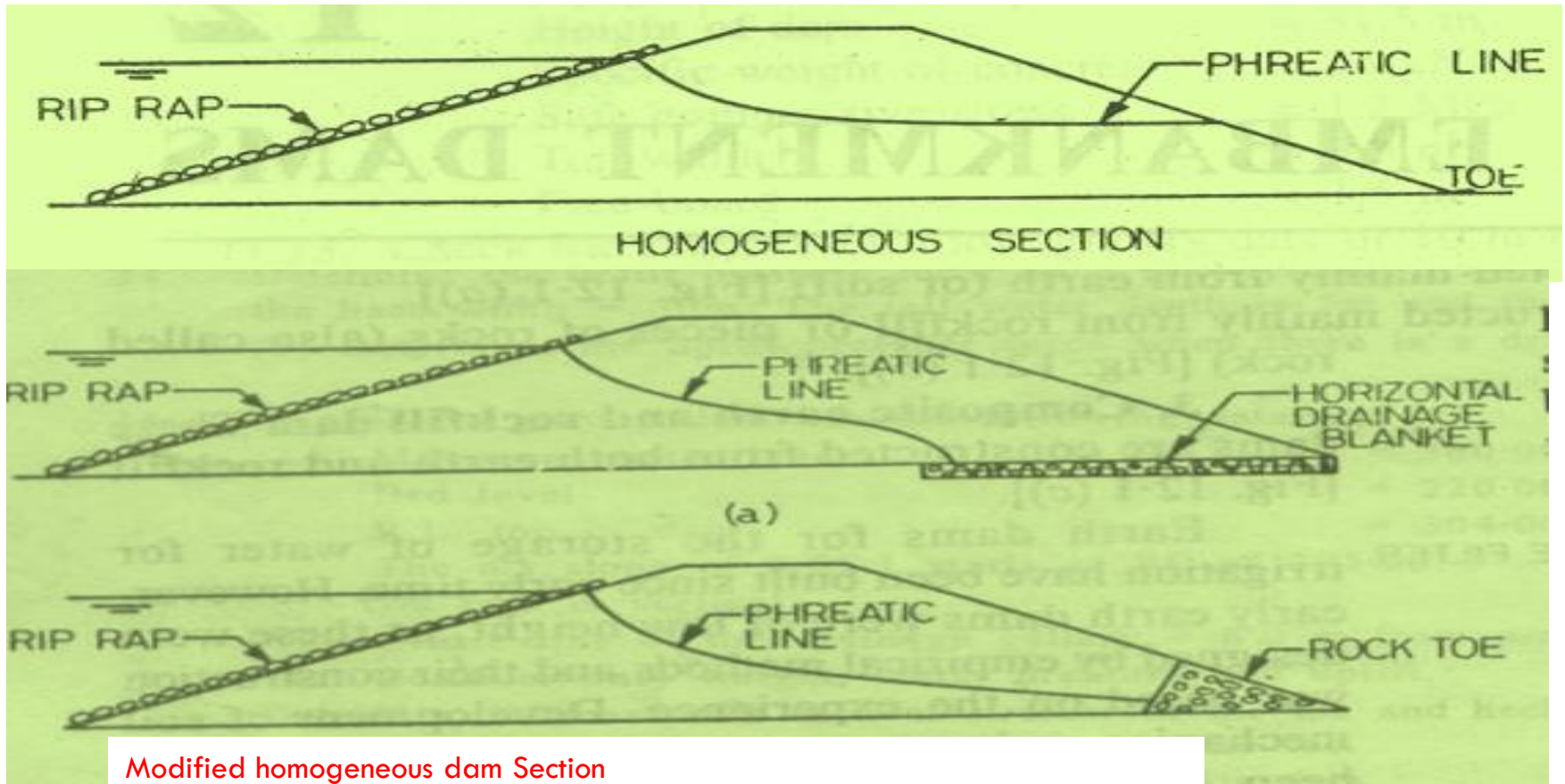
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- The pure homogenous section has been replaced by a modified homogeneous section in which small amounts of carefully placed pervious materials control the action of seepage so as **to permit much steeper slopes**.
- The modified homogeneous section is the one provided with **internal drainage filter system** in the form of horizontal drainage blanket or rock toe or both.

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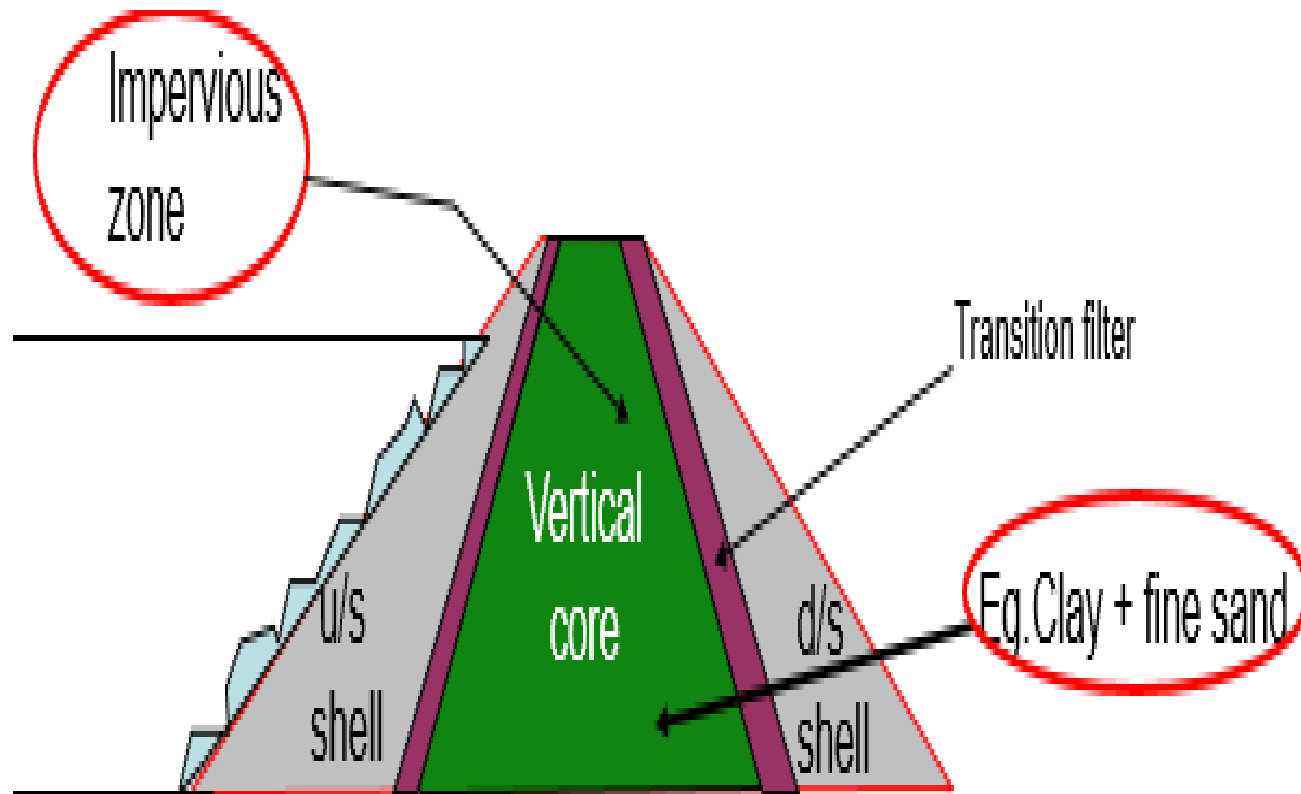
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B. Zoned earth dam

- Is **constructed from two or more types of soil.**
- They are provided with a central impervious core, covered by a relatively pervious transition filter which is finally surrounded by a more pervious outer zones or shells.
- Most common for high dams.
- The **pervious shells** are constructed from course sands and gravels.
- Core is a mixture of clay, silt and fine sand.
- Pure clay is not used as core b/c it swells and cracks.

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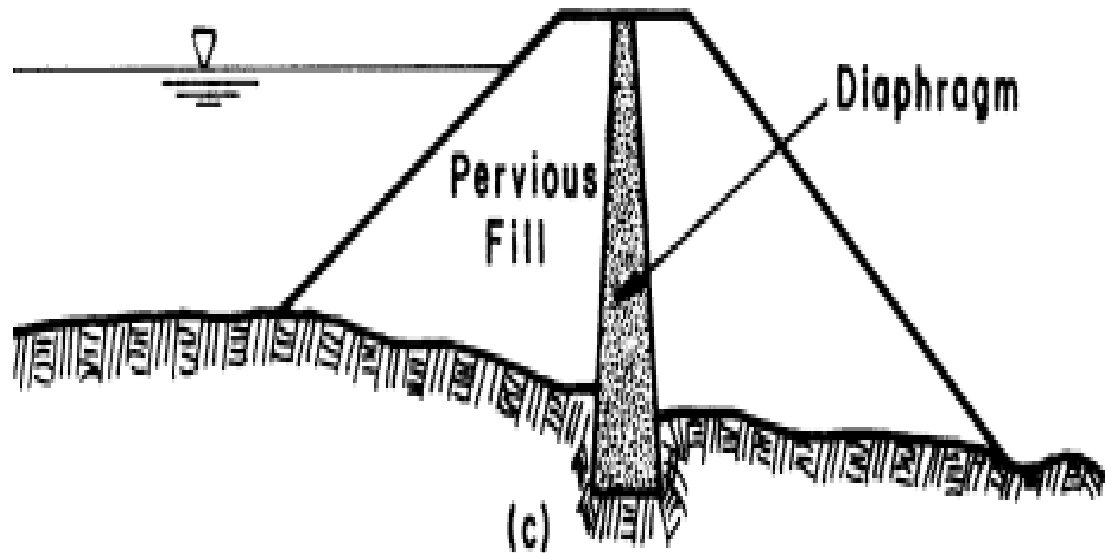
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C. Diaphragm Earth fill Dam

- 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.**
- The same as that of Zone dam but the **main difference is it has thins thickness of core.**
- The dam is a diaphragm type if;
 - ✓ **The thickness of the impervious core is $< 3\text{m}$**
 - ✓ **At any elevation the thickness is less than the height above the elevation**
 - ✓ **If the base width of the core is less than the height of the embankment**

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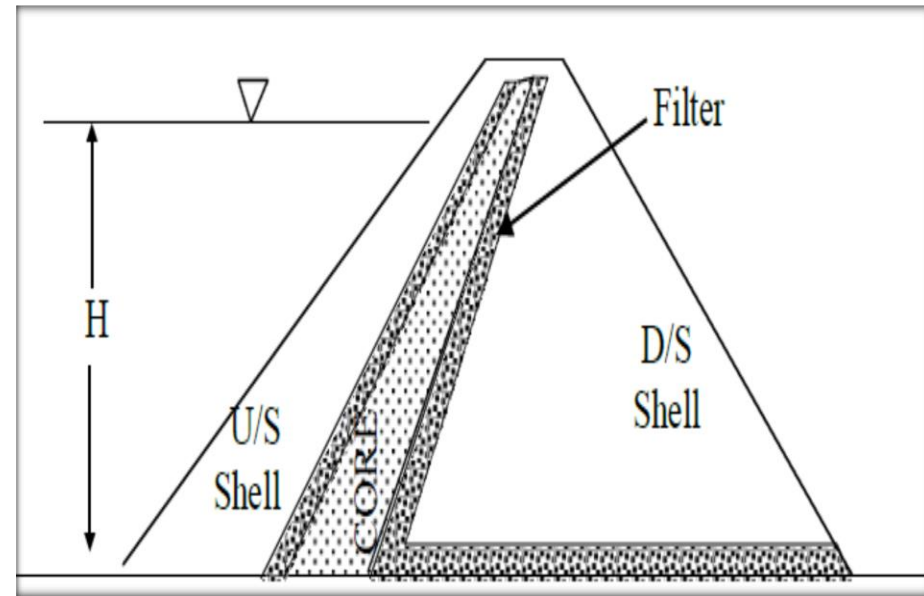
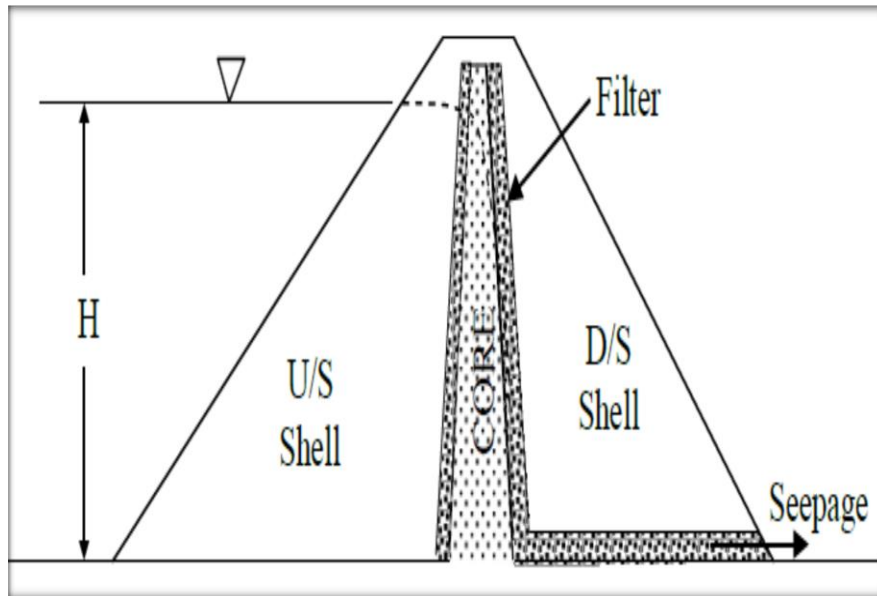
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- ❖ In a given dam site, **if a variety of soil types are available**, zoned embankment is preferable as it will tend to be economical.



Cont....

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Foundation Requirements

- The essential requirements of a foundation for an earth dam are:
 - i. Providing support for the embankment under all conditions of saturation and loading
 - ii. providing sufficient resistance to seepage to prevent excessive loss of water.
- Foundations are grouped in to three main classes according to their predominant characteristics as;

Cont....

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1. Rock foundation
 - ✓ Suitable for earth dams, no problems of bearing capacity
 - ✓ If there is joints, fissures, seals; seepage is problem, so it needs grouting.
2. Pervious foundation → foundation of coarse-grained material
 - ✓ Medium bearing capacity,
 - ✓ Serious percolation / seepage problem thus require special precaution with cut offs
3. Impervious foundation → foundations of fine silt and clay
 - ✓ Low bearing capacity, Low foundation shearing strength, Excessive settlements and pore water pressure

Cont....

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Merits of Embankment Dams

- ✓ Suitability to different site conditions such as wide valleys, steep sided gorges, weak foundation etc.
- ✓ Adaptability to a broad range of foundation condition such as rock and pervious soil formation.
- ✓ Flexibility to accommodate different fill materials,
- ✓ are usually cheaper than gravity dams if suitable earth for construction is available near the site.

Cont....

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- ✓ Can be constructed in a relatively short period.
- ✓ Skilled labour is not required in construction of an earth dam
- ✓ Are more earthquake-resistant than gravity dams.

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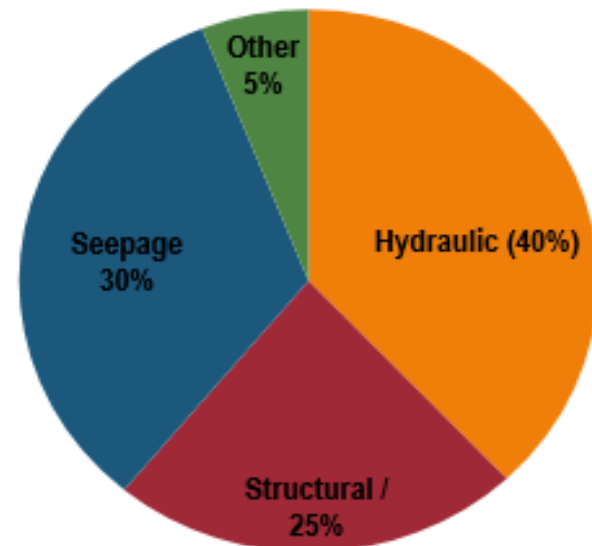
Demerits of Embankment Dams

- Disposed to damage or destruction by overtopping
- Necessity of separate spillway structure,
- Vulnerability to concealed leakage and internal erosion in dam or foundation.
- Cannot be constructed in regions with heavy rainfall, as the slopes might be washed away
- Maintenance cost of an earth dam is quite high. It requires constant supervision.
- Fails suddenly with out any sign of imminent failure.
- limited height

2.2.2 Causes of failures of earth dams

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- Earth dam failures are mainly caused by; improper design, lack of comprehensive investigations, and inadequate care in construction and poor maintenance.
- The various causes of failures can be grouped into three categories as,
 - Hydraulic failures
 - Seepage failures, and
 - Structural failures



Cont....

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1. Hydraulic failure:

- is failure of the dam due to one or more of the following causes:
 - ✓ overtopping,
 - ✓ erosion of upstream face,
 - ✓ erosion of downstream face and
 - ✓ erosion of toe of the dam

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Overtopping of the Dam

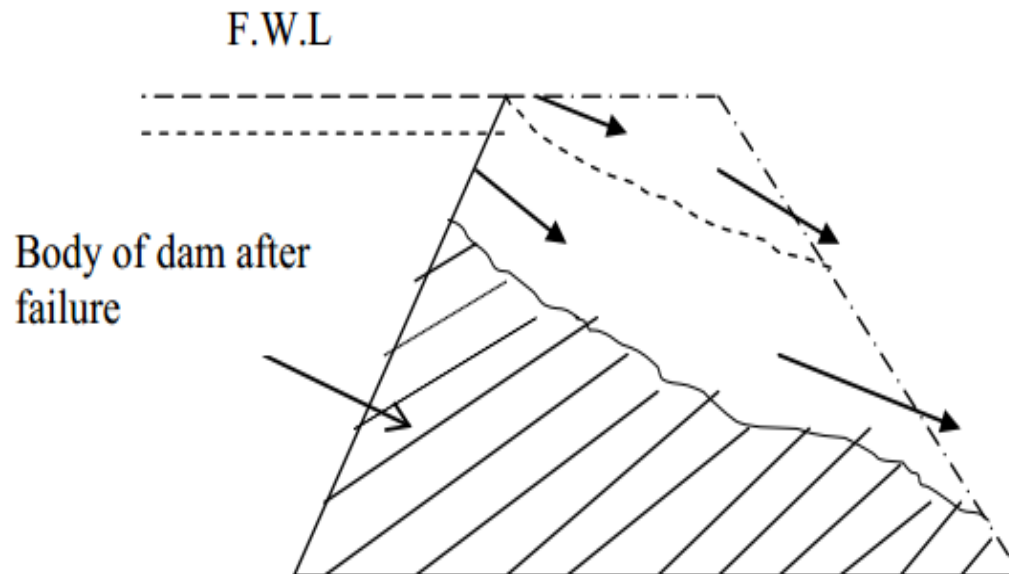
- Overtopping is defined as **uncontrolled flow of water over the crest of the dam or embankment**. Since the **non-overflow (other than spillway) portions of a dam are not usually designed for erosional effect of flowing water**, overtopping may lead to failure of the dam due to excessive erosion or saturation of the downstream slope.
- Main causes of overtopping
 - ✓ **Underestimation of the design flood** and inadequate spillway capacity
 - ✓ large and rapid landslides in the reservoir
 - ✓ Insufficient free board
 - ✓ Malfunction of spillway gates

Cont....

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➤ Measures

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



Cont....

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B. Erosion of upstream face by wave action

➤ Cause

- ✓ When waves due to wind blowing over the impounded water crash on the upstream face of the dam, the **wave dislodges the embankment soils from the face.**

➤ Measure

- ✓ Protect the u/s face by rock riprap



Cont....

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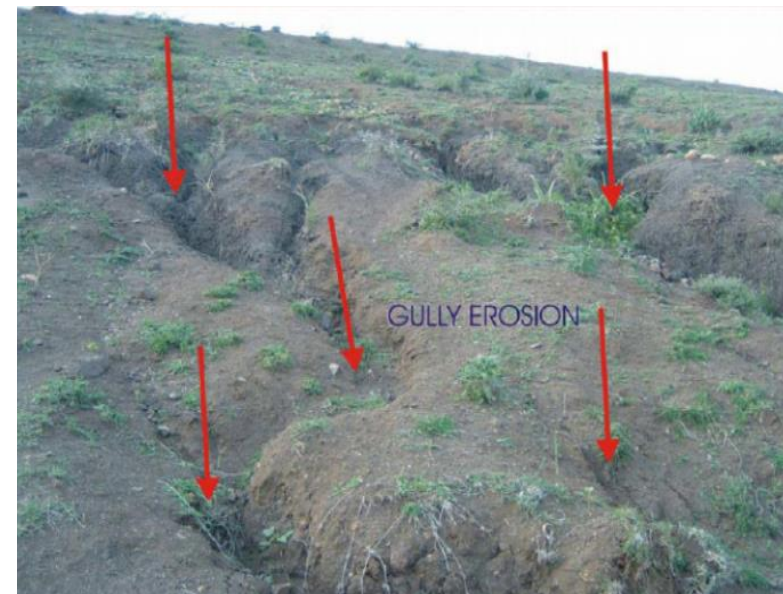
C. Erosion of Downstream face by gully formation

➤ Causes

- ❖ Heavy rains falling directly over the d/s face may lead to the formation of a moving water that may erode the d/s face leading to the formation of gullies

➤ Measures

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



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D. Erosion of the Downstream Toe

- Two reasons for erosion of the d/s toe
 - ✓ Due to the tail water
 - ✓ Cross currents from spillway buckets

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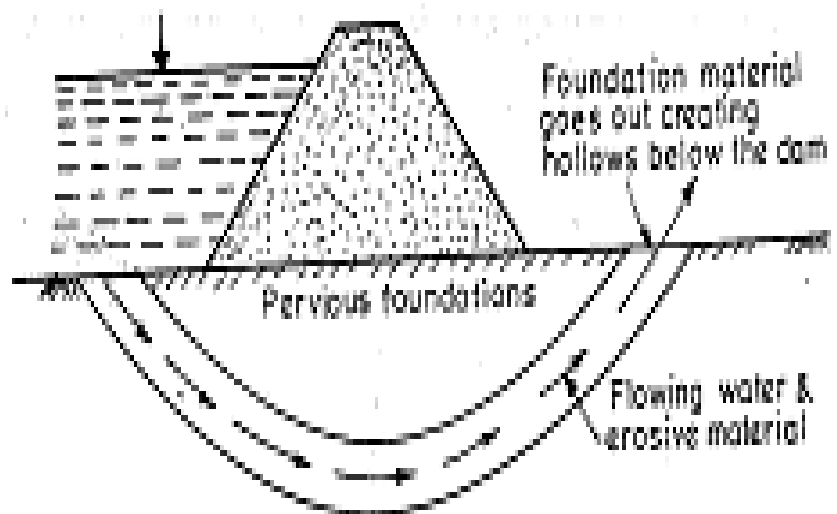
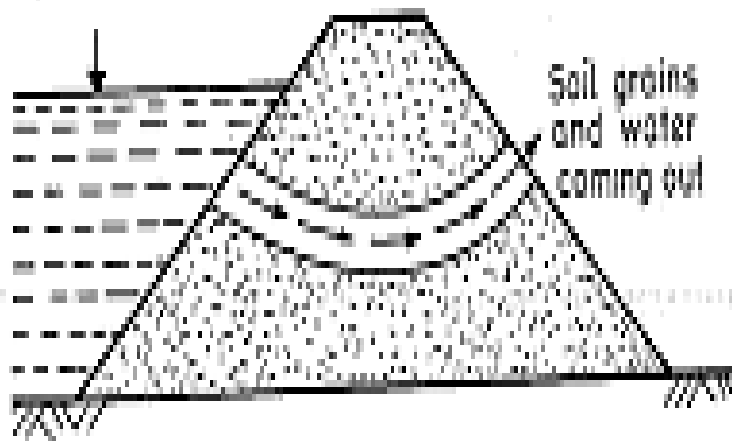
2. Seepage Failure

- Embankment **body and foundation are pervious**. They act as pathways for water seepage. If such **seepage is uncontrolled in terms of volume and velocity**, it may lead to
 - ✓ Piping (internal erosion) through the dam and foundation
 - ✓ Uplift
 - ✓ Sloughing and subsequent failure of the dam
 - ✓ Conduit leakage
- Piping is the **progressive erosion and subsequent removal of the soil grains** from within **the body of the dam or the foundation of the dam**.

Cont....

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- Sloughing is the progressive removal of soil from the wet downstream face below phreatic line.
- Cause of piping : -
 - Faulty construction - cracks in embankment due to settlement
 - Insufficient compaction - burrowing animals



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3. Structural failure

- In earth dams are generally shear failures leading to sliding of the embankments or the foundations.
- Structural failures in earth dams are of the following types:
 - (a) Slides in embankments
 - (b) Foundation slides
 - (c) Liquefaction slides
 - (d) Failures due to earthquakes
 - (e) Failure due to holes caused by burrowing animals
 - (f) Failure due to holes caused by leaching of water-soluble salts.

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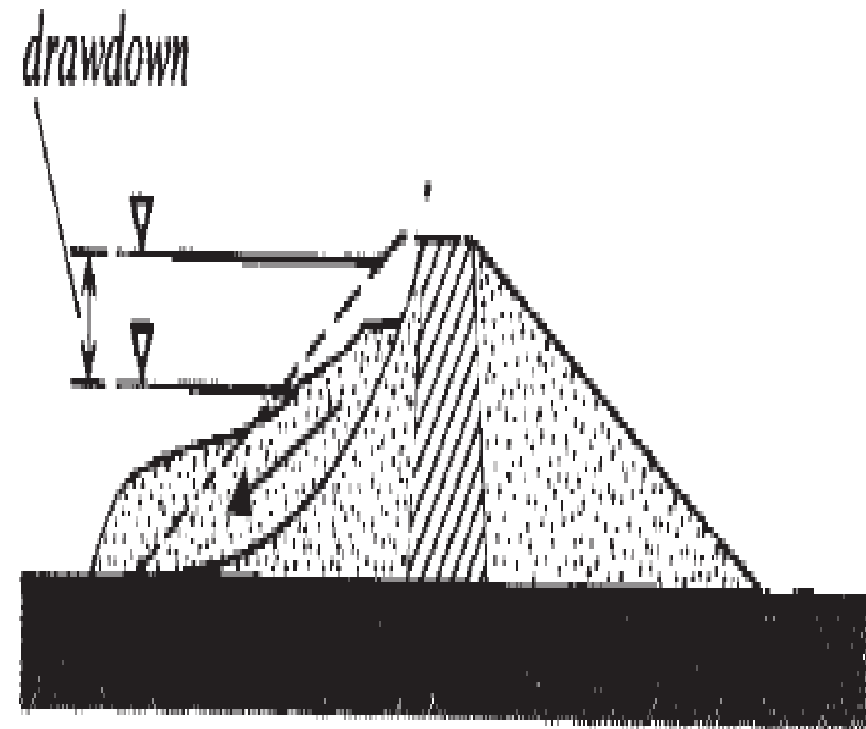
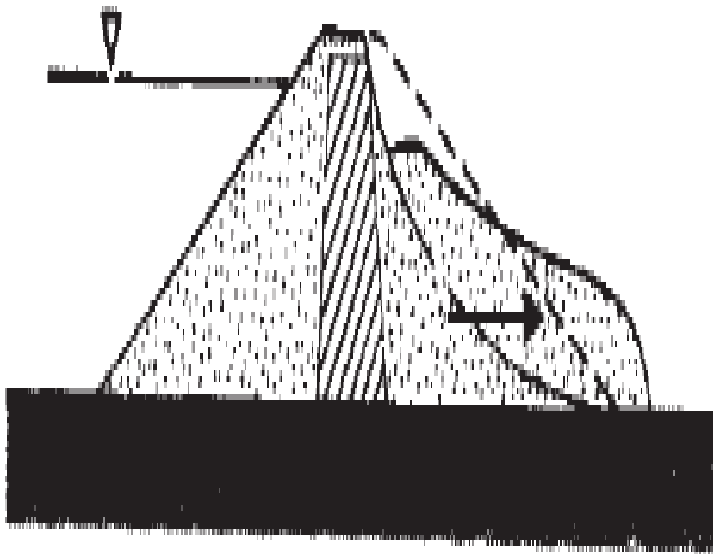
A. Embankment Slope Failures

- Occurs when the shear force causing sliding on any potential sliding surface exceed the resisting forces.
(when embankment slope are too steep)
- The most critical condition of slide
 - ✓ for the d/s slope, it is when the reservoir is full.
 - ✓ for the u/s slope, sudden drawdown of the reservoir.

Which is Pore water pressure decreases shear strength of soil.

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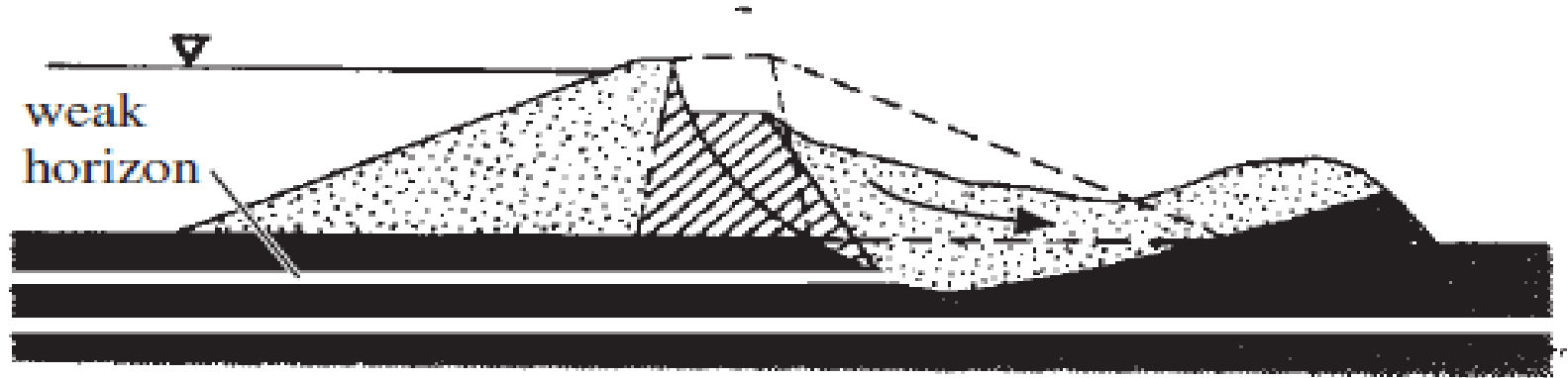


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B. Foundation Slide

- When the foundation materials are made of silt, soft clay etc. **The entire dam may slide over the foundation.** Fissured rocks, shales etc may exist under the dam and this may cause the dam to slide.



2.2.3 Design Principle

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Design Criteria for earth dams

1. **No overtopping:** the water must not be allowed to overtop; thus:
 - ✓ Design flood should not be under estimated
 - ✓ Adequate free board should be given
 - ✓ Suitable allowance should be provided on height of dam for settlement.
2. **No seepage failure:**
 - ✓ The phreatic surface should be within the body of the dam
 - ✓ Seepage should be controlled
 - ✓ The dam and foundation should be safe against piping failure

Cont....

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3. **Proper slope protection:** Stone pitching for u/s slope and berm for d/s slope

- ✓ U/s slope should be protected against erosion by waves,
- ✓ D/s slope and the crest should be protected against erosion due to rain and wind

4. **No structural failure**

- ✓ U/s slope should be stable during sudden drawdown
- ✓ D/s slope should be safe and stable during steady seepage (placing a layer of rock, cobbles, or sod (grass) - to collect and dispose the rain runoff).

Cont....

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- ✓ Stresses at the foundation must be within the permissible limit
- ✓ Safe during earth quake

5. Proper drainage:

- ✓ To take care of the seepage through the dam and foundation

6. Economic section

- ✓ As far as possible, the materials available near the dam site should be used to reduce the cost.

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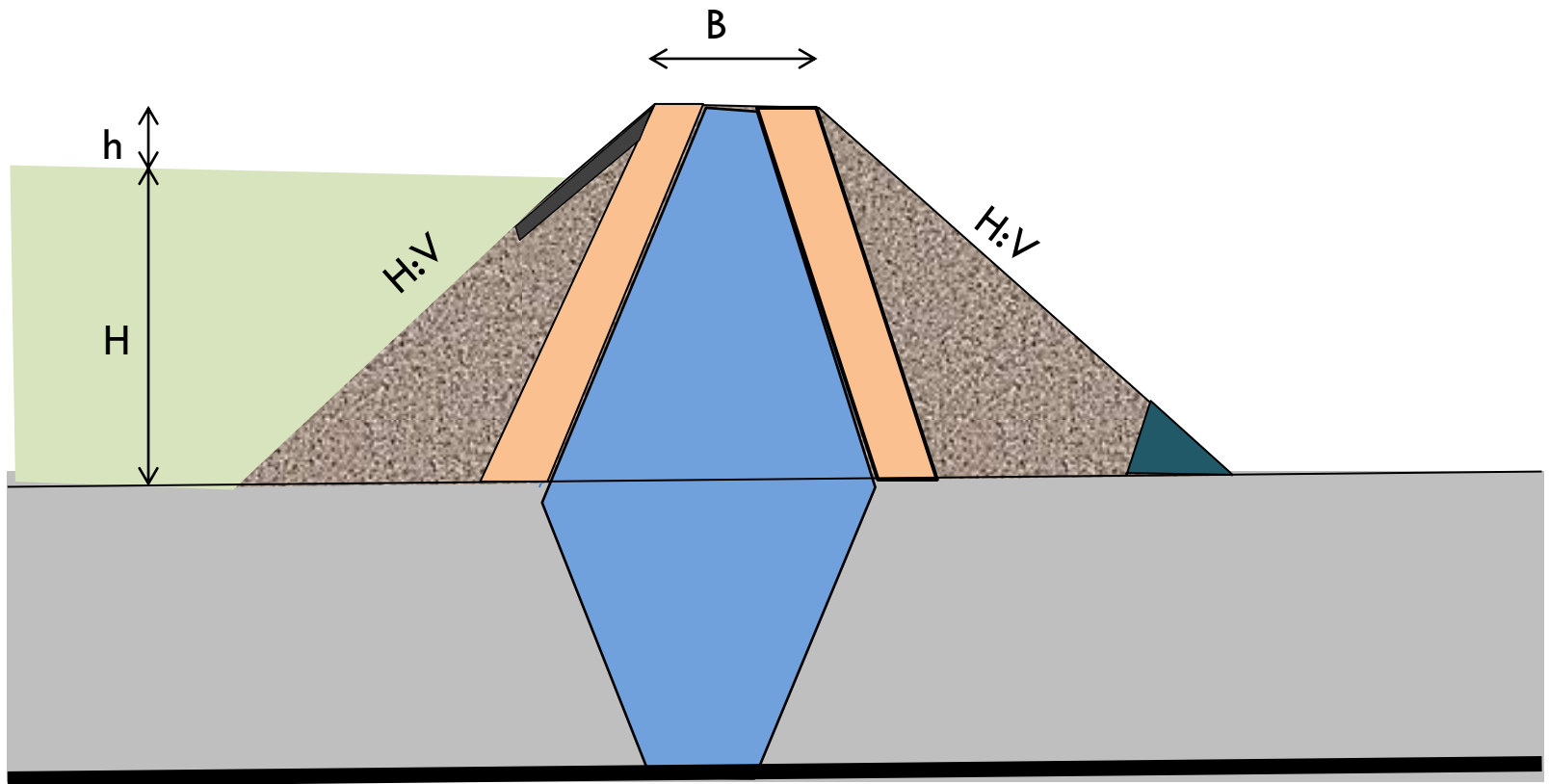
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Embankment Design

- There are two aspects of the design of an earth dam
 - ✓ To determine the X-section of the dam and
 - ✓ To analyses the stability of the proposed x-section which will fulfill its required function with adequate safety.

Cont....

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Cont....

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preliminary section of an Earth Dams

- 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.
- We shall discuss here the preliminary selection of the following terms:

1. Crest of dam/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.

Cont....

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

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 ($H > 10\text{m}$)

2. Free Board

- It is the vertical **distance between the crest of the dam and the reservoir level.**
- Provided on the basis of overtopping.
- Freeboard = $1.5 h_w$ + additional safety provision
- It is composed of **allowances for waves and settlement of the dam.**

Cont....

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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;

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

where $F < 32$ km.

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

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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

Cont....

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3. Upstream and downstream slopes

- The upstream and downstream slopes depends on
 - ✓ Height of dam
 - ✓ Type of embankment material for construction
 - ✓ 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

Cont....

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4. Slope protection:

- For upstream slope- riprap and concrete pavement is provided
- For downstream slope- planting grass and berm

Cont....

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Checking the stability of an earth dam

- To analysis the stability the following check are usually carried out
 - 1.The flow net is drawn to determine the seepage discharge and the pore water pressure.
 2. The D/S slope is checked for the stability during steady seepage condition.
 3. The U/S slope is checked for the stability during sudden drawdown conditions.

Cont....

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- 4 both the u/s and d/s slopes are checked for the stability during construction period.
5. If the foundation consists of weak soil, such as plastic clay, it is checked against foundation shear.

Cont....

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Seepage analysis

- The main purposes of seepage analysis are
 - a. To determine the **quantity of water** that pass through the **dam body and foundation (Q)**;
 - b. To determine the distribution of **pore water pressure** for **stability analysis**
 - c. To determine the **exit hydraulic gradients** and **uplift pressures** to assess the safety of the dam and foundation
 - d. For construction of flow nets as it represents one flow boundary.

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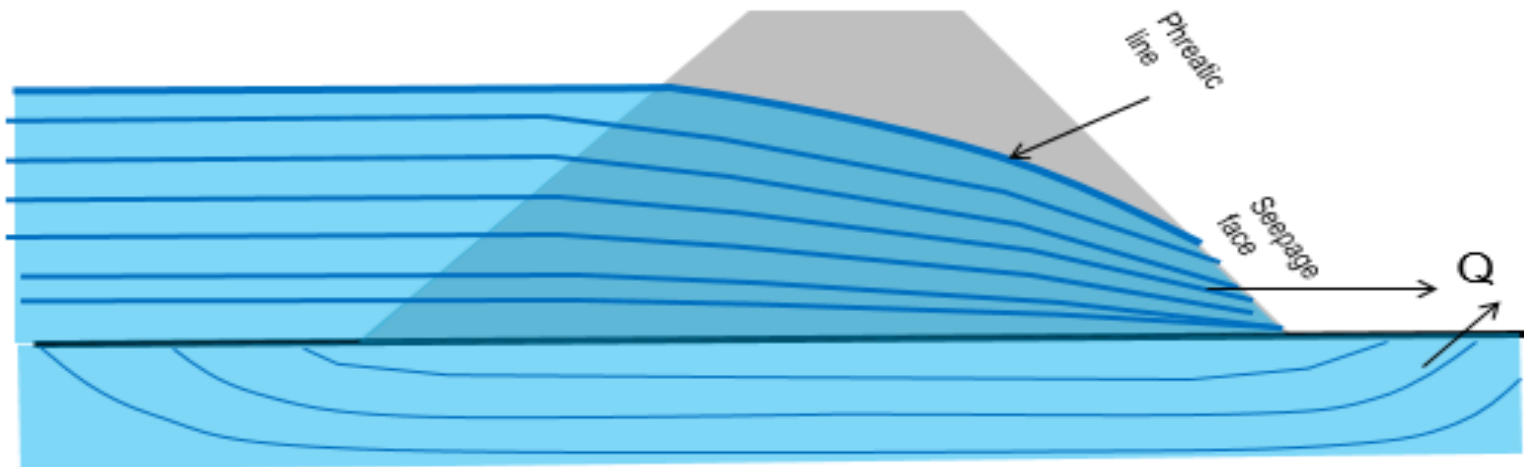
- The following assumptions are usually made in the seepage analysis.
 1. The soil in the embankment and foundation is incompressible and isotropic.
 2. Water is incompressible.
 3. Darcy's law is valid.
 4. The flow is steady.
 5. The soil is fully saturated.
 6. The hydraulic boundary conditions at the entry and at the exit of the seepage flow are known.

Cont....

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Line of seepage or phreatic line in earth dams

- Seepage is considered to be all movement of water from the reservoir through the embankment, abutments, and foundation
- Phreatic line /seepage line/ Saturation line is the line at the upper surface of the seepage flow at which the pressure is atmospheric.



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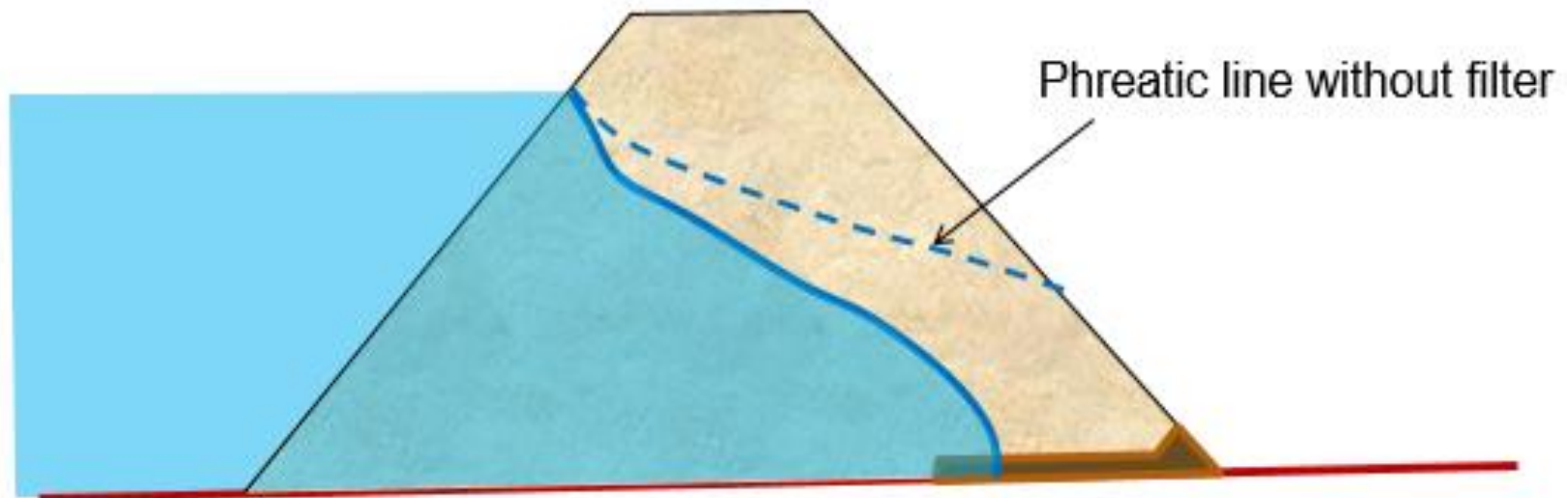
- It is absolutely essential to determine the position of the phreatic line, as its position will enable to determine the following:
 - i. The divide line between the dry (or moist) and submerged soil.
 - ii. The top stream line and hence, helps us in drawing the flow net.
 - iii. To ensure that the phreatic line doesn't cut the downstream face of the dam, which is extremely necessary for preventing softening of the dam.

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phreatic line for a homogenous earth dam with a horizontal drainage blanket

- It has been found that the seepage line is pushed down by the filter and it is very nearly parabolic except near its junction with u/s face.

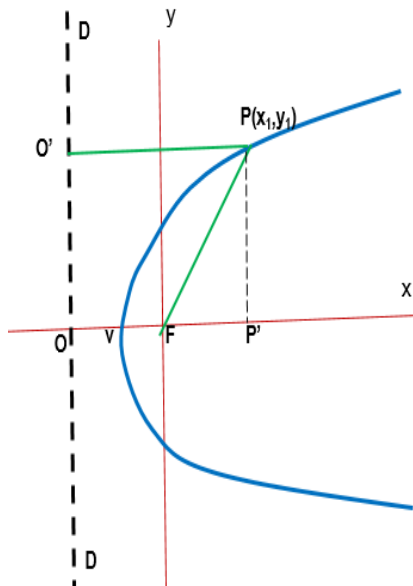


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- The basic property of parabola which is utilized to draw the base parabola is that the distance of any point P from the focus is equal to the distance of the same point from the directrix.

□ Basic property of a parabola

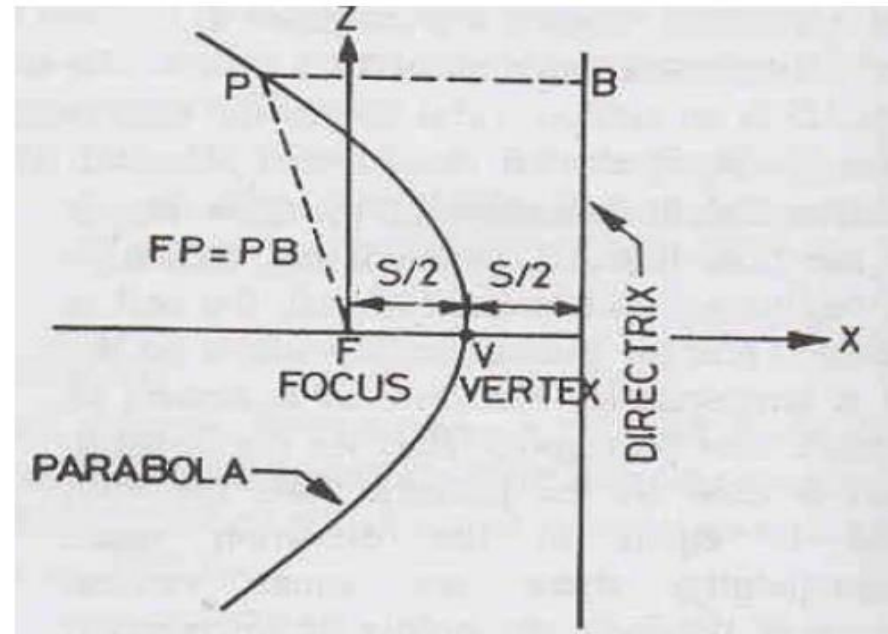


F - Focus
V - Vertex
Line DD - Directrix

For any point P(x, y)

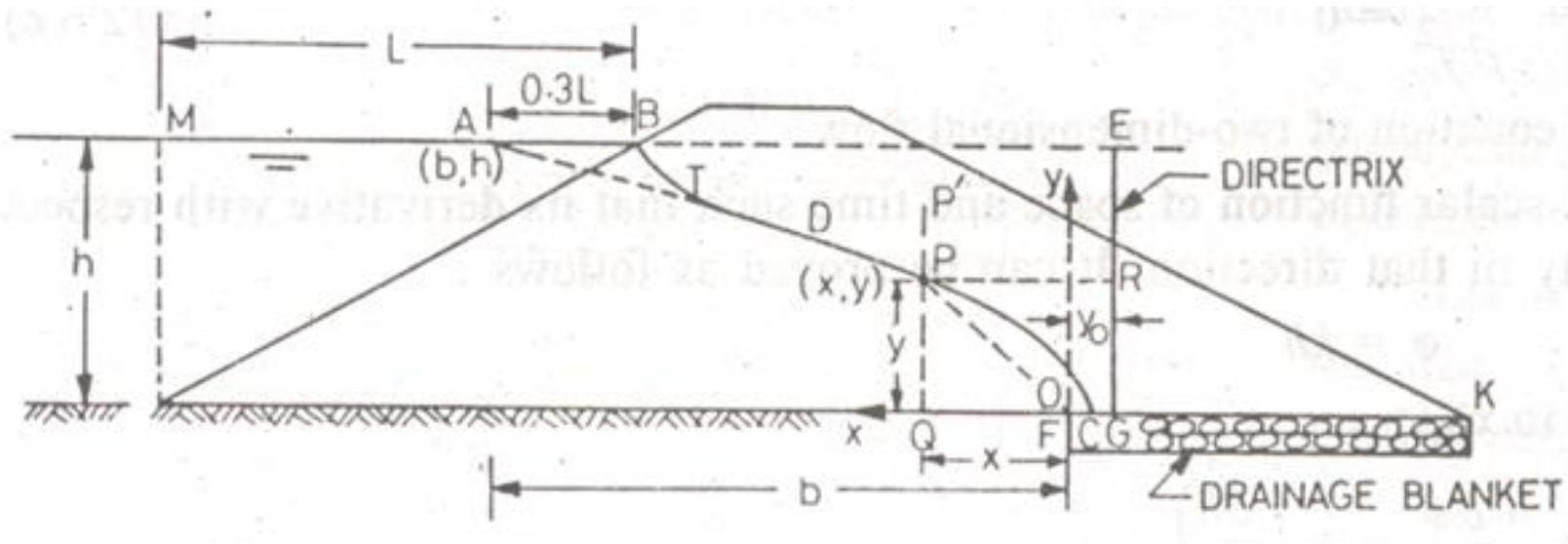
$$\overline{FP} = \overline{OP'}$$

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



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1. The **base parabola** has its focus at the inside edge of the drainage filter at F.
2. The base parabola intersects the u/s water at A, & $AB = 0.3L$:
3. EG is the directrix of the parabola, the vertex (C) is found at $y_0/2$ from F.

Cont....

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4. From the property of a parabola, for any point P(x,y)

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

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

- The equation for the parabola is; $y = \sqrt{2xy_o + y_o^2}$
- At point A; $x = b$ & $y = h$, $y_o = \sqrt{b^2 + h^2} - b$
- Plot the parabola for different x
- As actual phreatic line starts from point B make **corrections at entrance.**

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- Discharge through the body of the dam
 - ✓ Consider any section through the dam body
 - ✓ The cross-sectional area is given by
 - ❖ $A = y * 1$, A is area of flow per unit length
- Let the hydraulic gradient to be approximated by the slope of the parabola

$$i = \frac{dy}{dx}$$

- From the Darcy's Equation, $v = ki$ k = Coefficient of permeability

$$Q = VA = kiA$$

i = the hydraulic gradient

$$Q = VA = kiA = k \frac{dy}{dx} y$$

Cont....

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➤ From the equation of a parabola, $y = \sqrt{2xy_o + y_o^2}$

$$\frac{dy}{dx} = \frac{y_o}{\sqrt{y_o^2 + 2xy_o}}$$

$$Q = k \frac{dy}{dx} y = k * \frac{y_o}{\sqrt{y_o^2 + 2xy_o}} * \sqrt{2xy_o + y_o^2}$$

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

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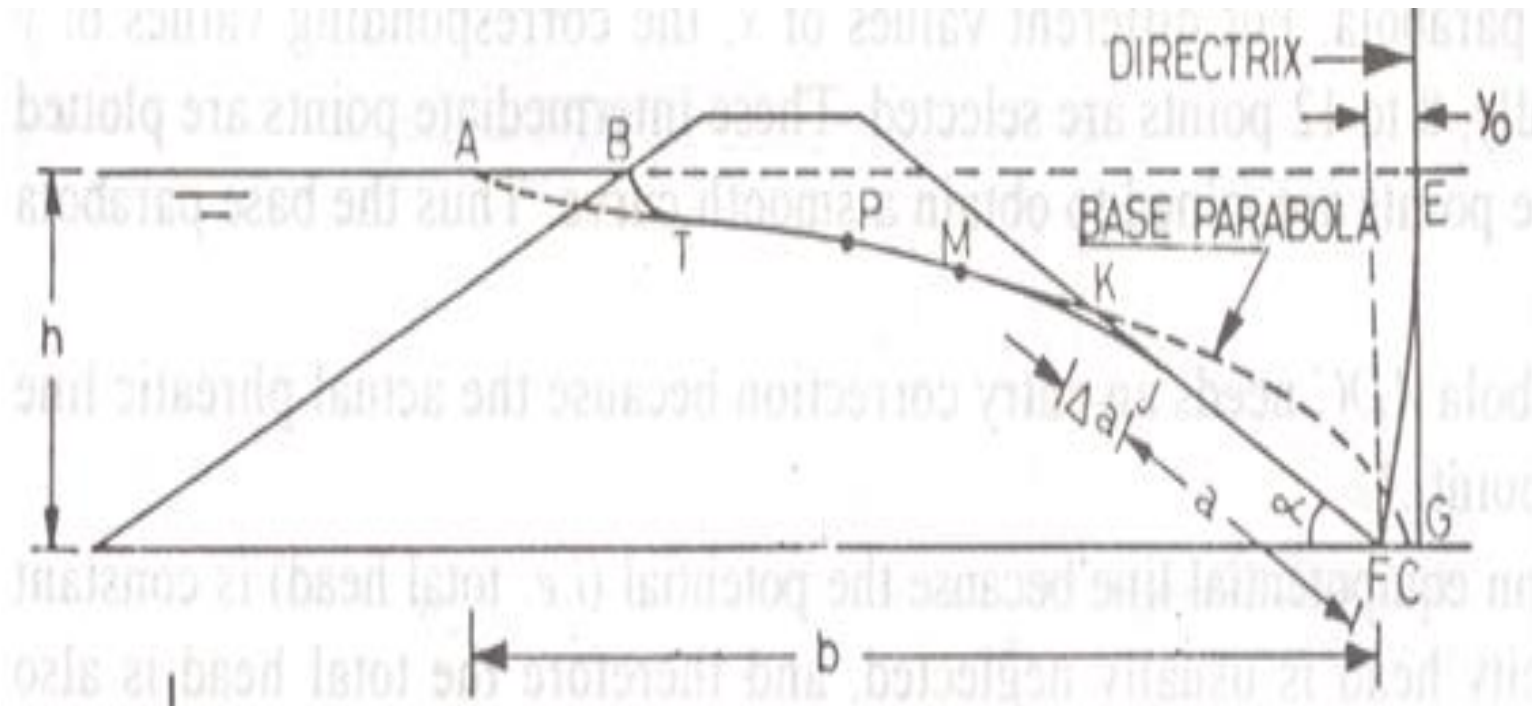
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Phreatic line for a dam with no filter

- In this case the phreatic line cuts the d/s faces at point J above the toe.
- In this case both Entry and exit correction is required.
- The focus (F) of the base parabola is located at the d/s toe of the dam & its starting point A is located at a distance of $0.3L$ from B.
- The base parabola cut the d/s face at pt. K above the toe and extends beyond the limit of the dam, as show by the dotted line.
- The portion JF is called discharge face and always remains saturated.

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- The correction JK (Δa) by which the parabola is to be shifted downward can be determined as follows.

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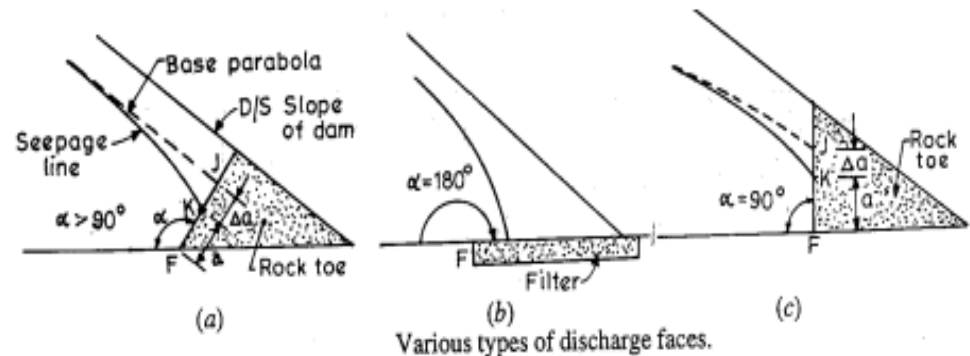
Graphical general solution

- ✓ Casagrande has shown that the exit correction Δa depends up on the slope angle α of the discharge face and he has given the values $\Delta a/a + \Delta a$ for different values of angle α as follows.

α in degrees	$\frac{\Delta a}{a + \Delta a}$
30°	0.36
60°	0.32
90°	0.26
120°	0.18
135°	0.14
150°	0.10
180°	0.0

→ a and Δa can be related as

$$\Delta a = (a + \Delta a) \left[\frac{180^\circ - \alpha}{400^\circ} \right]$$



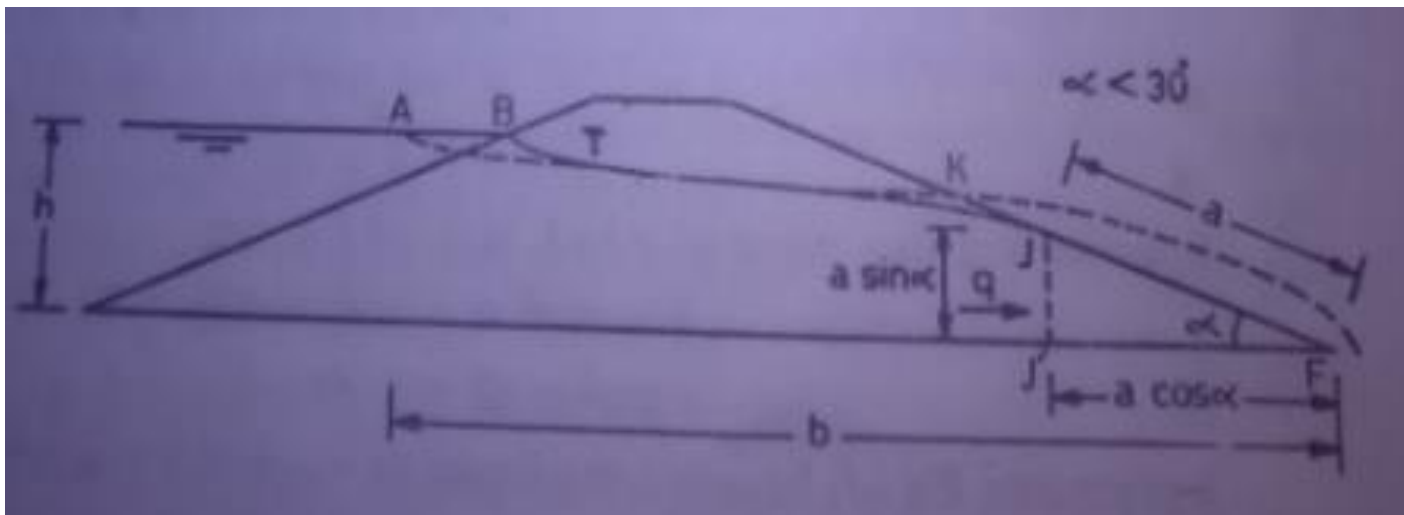
Cont....

66

- The value of $a + \Delta a$ can be determined from polar equation of parabola as follows; $a + \Delta a = \frac{y_o}{1 + \cos \alpha}$ or by measuring $\overline{FK}$

Discharge through the earth dam

Schaffernak and Iterson's Solution for $\alpha < 30^\circ$



Cont....

67

$$i = \frac{dy}{dx}$$

$$Q = K \frac{dy}{dx} A = K \frac{dy}{dx} y$$

Integrating

$$Qx = K \frac{y^2}{2} + C$$

At pt A At $x = b, y = H$

$$C = Qb - K \frac{H^2}{2}$$

$$Qx = K \frac{y^2}{2} + Qb - K \frac{H^2}{2}$$

$$Q = \frac{K}{2(x-b)} (y^2 - H^2)$$

1

At pt J $y = a \sin \alpha$

$$\frac{dy}{dx} = \tan \alpha$$

$$Q = K a \sin \alpha \tan \alpha \quad 2$$

Equating 1 & 2

$$K a \sin \alpha \tan \alpha = \frac{K}{2(x-b)} (y^2 - H^2)$$

At J $y = a \sin \alpha$ & $x = a \cos \alpha$

Solving for a

$$a = \frac{b}{\cos \alpha} - \sqrt{\frac{b^2}{\cos^2 \alpha} - \frac{h^2}{\sin^2 \alpha}} \quad 3$$

Once **a** is known from **3**, discharge per unit length at JJ' is found by 2, **Q = k * a * sinα * tanα**.

Cont....

68

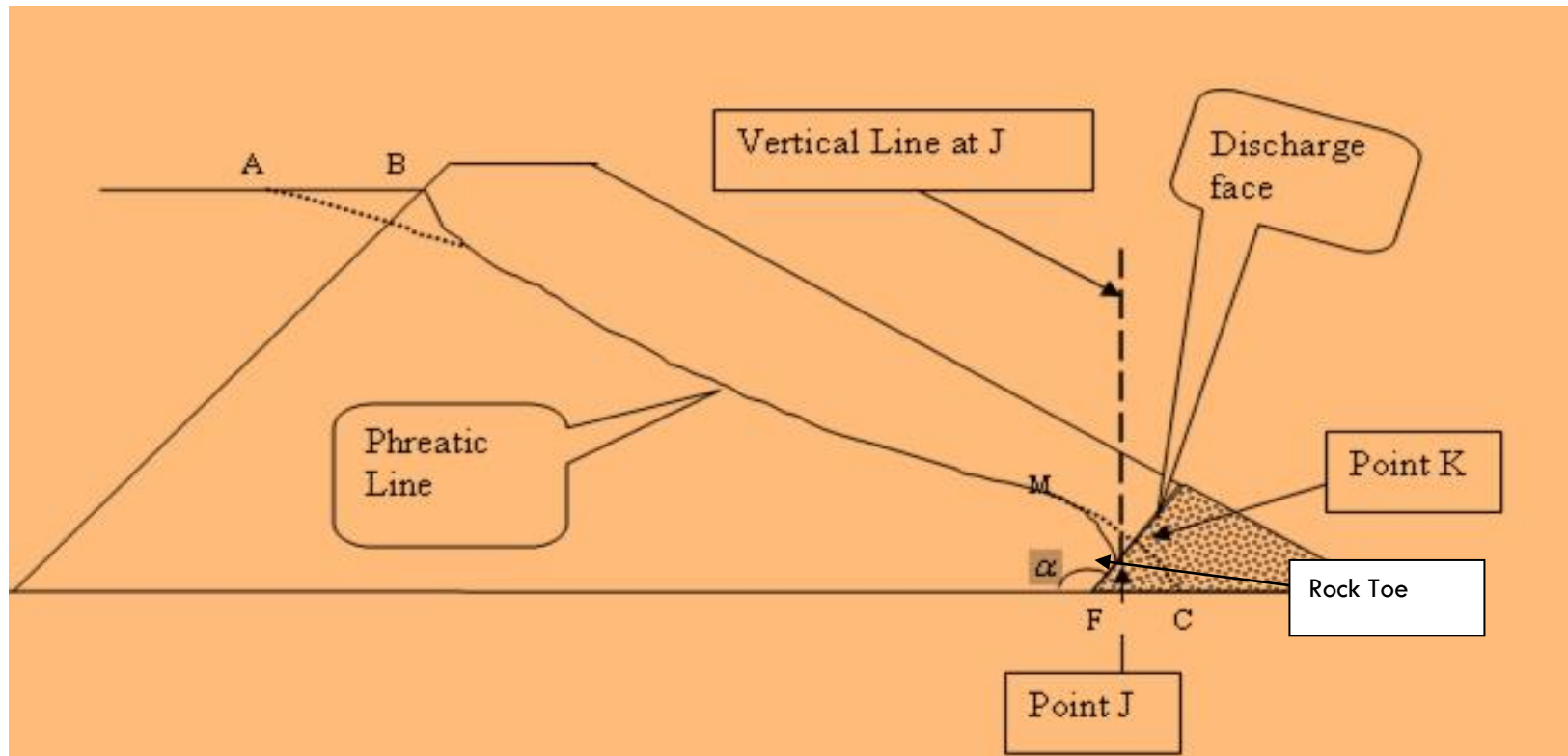
Phreatic line for homogeneous earth dam with rock toe

- The u/s face of the rock toe is usually inclined ($\alpha > 90^\circ$) or vertical ($\alpha = 90^\circ$) sometimes, also it acts as a discharge face.
- The focus **F** of the base parabola lies at u/s end of rock toe.
- The base parabola cuts the discharge face at point K and the value of $a + \Delta a$ may be obtained by measuring the distance FK or from equation $a + \Delta a = \frac{y_o}{1 + \cos \alpha}$.

Cont....

69

- Entry and exit correction is required.



Cont....

70

- For known value of α , the value of $(\Delta a/a + \Delta a)$ is obtained from table below and exit correction is done.

α in degrees	$\frac{\Delta a}{a + \Delta a}$
30°	0.36
60°	0.32
90°	0.26
120°	0.18
135°	0.14
150°	0.10
180°	0.0

Cont....

71

- The point J is then marked on the u/s face of the rock toe at a distance of Δa from K.
- The phreatic line is drawn by making a transition curve by eye judgment from the point J to the point M on the base parabola.

Cont....

72

Flow net

- Once the phreatic line in an earth dam has been drawn, the flow net can be obtained.
- The phreatic line represents the top hydraulic boundary of the seepage flow.
- Generally the graphical method of flow construction is used. The electrical-analogy method is also sometimes used.

Cont....

73

Graphical method

- The graphical methods makes use of the properties of the flow net. The flow net is drawn by trial and error.
- First a rough flow net is drawn and then it is modified successively till a good flow net is obtained.

Properties of the flow net

1. The flow lines and equipotential lines meet at right angles to each other.
2. Because the phreatic line is also a flow line, the equipotential lines intersect it at right angles.
3. Since the pressure at the phreatic line is zero, the successive equipotential lines make equal vertical intercepts on the phreatic line.

Cont....

74

4. The flow fields obtained by the intersections of the equipotential lines and the flow lines are approximately squares in shape.
5. The discharge between any two adjacent flow lines is constant.
6. The potential drop between any two adjacent equipotential lines also constant.
7. The smaller the dimensions of the flow field, the greater is the hydraulic gradient and the velocity of flow through it.
8. In a homogeneous soil, every transition in the flow lines and equipotential lines is smooth and gradual.

Cont....

75

Uses of flow nets

The flow nets can be used for the following purposes

1. Determination of discharge through the dam.
2. Determination of pore water pressure.
3. Determination of hydraulic gradient.

Cont....

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Estimating Seepage Quantity from Flow Net

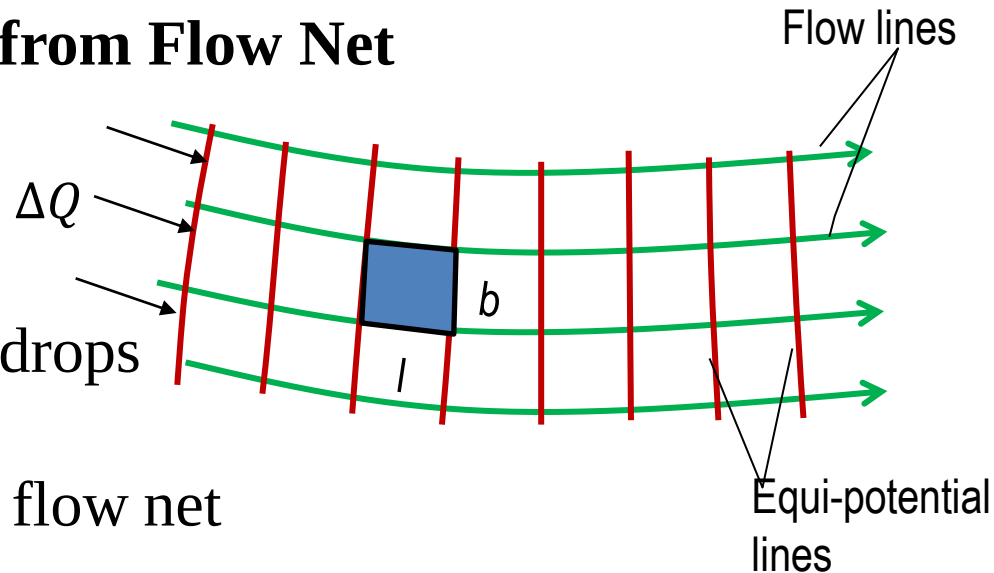
- ❑ Let
- ❑ N_f – number of flow channels
- ❑ N_d – number of equi-potential drops
- N_f / N_d – shape factor
- ❑ Consider a flow element in a flow net
- ❑ Let

b – width; l – length; note $b=l$

Δh – head drop between two equi-potential lines

h – total head drop

Δq – discharge passing through the flow element / channel



Cont....

77

- From Darcy's law
 - Discharge through the element (one flow channel)

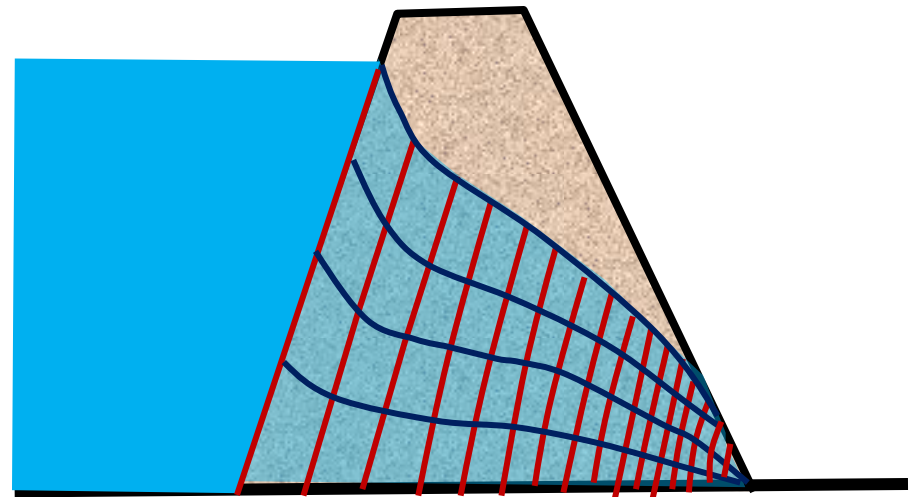
$$\Delta Q = K \frac{\Delta h}{l} (b \cdot 1) = K \Delta h$$

$$\Delta Q = K \frac{h}{N_d}$$

- The total discharge through all flow channels

$$Q = \sum \Delta Q$$

$$Q = N_f \Delta Q = N_f K \frac{h}{N_d}$$



Cont....

78

Control of Seepage through earth dam and its foundation

The effects of seepage are:

- Loss of water
- Piping failure
- Reduce slope stability and result in dam failure
- Causes local sloughing- if phreatic line cuts d/s face
- Pore water pressure- it developed below phreatic line reducing shear strength as well as stability of dam.

Cont....

79

- Seepage control measures are divided in to two main categories
 - ✓ Measures to reduce quantity of Seepage – lessen loss of water
 - ✓ Measures for Safe drainage of seeping water – No piping

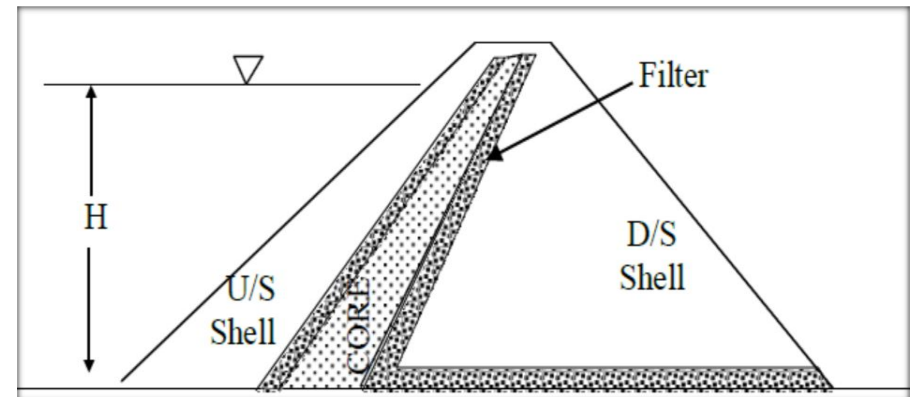
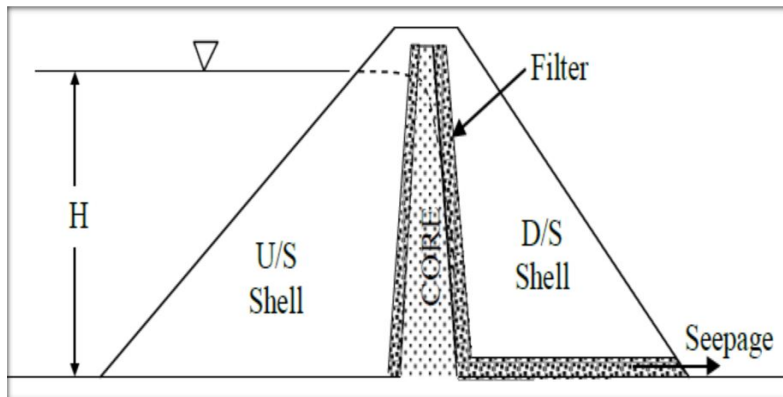
Cont....

80

Measures to reduce quantity of Seepage

I. IN DAM:

- ✓ The only measure is provision of impervious core within the body of the dam called embankment zonation.
- ✓ **Embankment zonation** : -for reducing seepage through the body of the dam, a core of impervious material such as silt clay or clayey silt is generally provided.



Cont....

81

- Vertical core provides a high pressure at the contact plane b/n core and foundation, hence it is effective in reducing seepage.
- However, inclined core has advantage that d/s portion of the dam can be constructed first and core can be placed next.

II. IN FOUNDATION:

- If the foundation consists of alluvial deposits of pervious sand and gravel with impervious stratum at a great depth measures to be adopted are;
 - ✓ cut-off,
 - ✓ u/s impervious blanket
 - ✓ Grouting

Cont....

82

Cutoff trenches:

- Is made of concrete or sheet pile and provided in foundation to reduce seepage.
- Divided in to; positive cutoff trench, partial cutoff trench.

Positive cutoff trenches

- ✓ Extends from bottom of dam to the impervious stratum.

Partial cutoff trenches

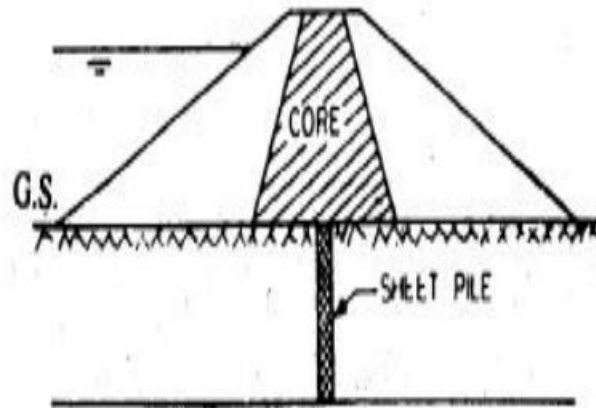
- ✓ Extend down into an intermediate stratum of lower permeability.

Sheet piling cut offs: -

- A steel sheet pile cut off consists of interconnected sheet piles to form a continuous impervious barrier.

Cont....

83



Grouting:-

- The stability and impermeability of pervious overburden foundation can be improved by injection a substance which will act as a binder & fill the voids.

Cont....

84

Upstream blankets: -

- Connected to the **impervious zone of the dam and extends to u/s.**
- provided to increase the path of percolation.
- u/s blankets are used **when cutoff to the bed rock not practicable due to excessive depth.**
- The length of the blanket will be governed by the desired reduction in the amount of under seepage and its thickness usually varies from 1.5 to 3.0 m.
- The length of the u/s blanket can be obtained from the following formula.

$$l = \frac{khd - pqb}{pq}$$

Cont....

85

Where;

k = mean horizontal permeability coefficient

h = the gross height

p = percentage (stated as decimal) of flow under dam w/o a blanket to which level it is desired to reduce the seepage by means of a blanket

b = length of impervious dam material

$q = k(h/b) \times d \times 1$ seepage flow under the dam (approximate)

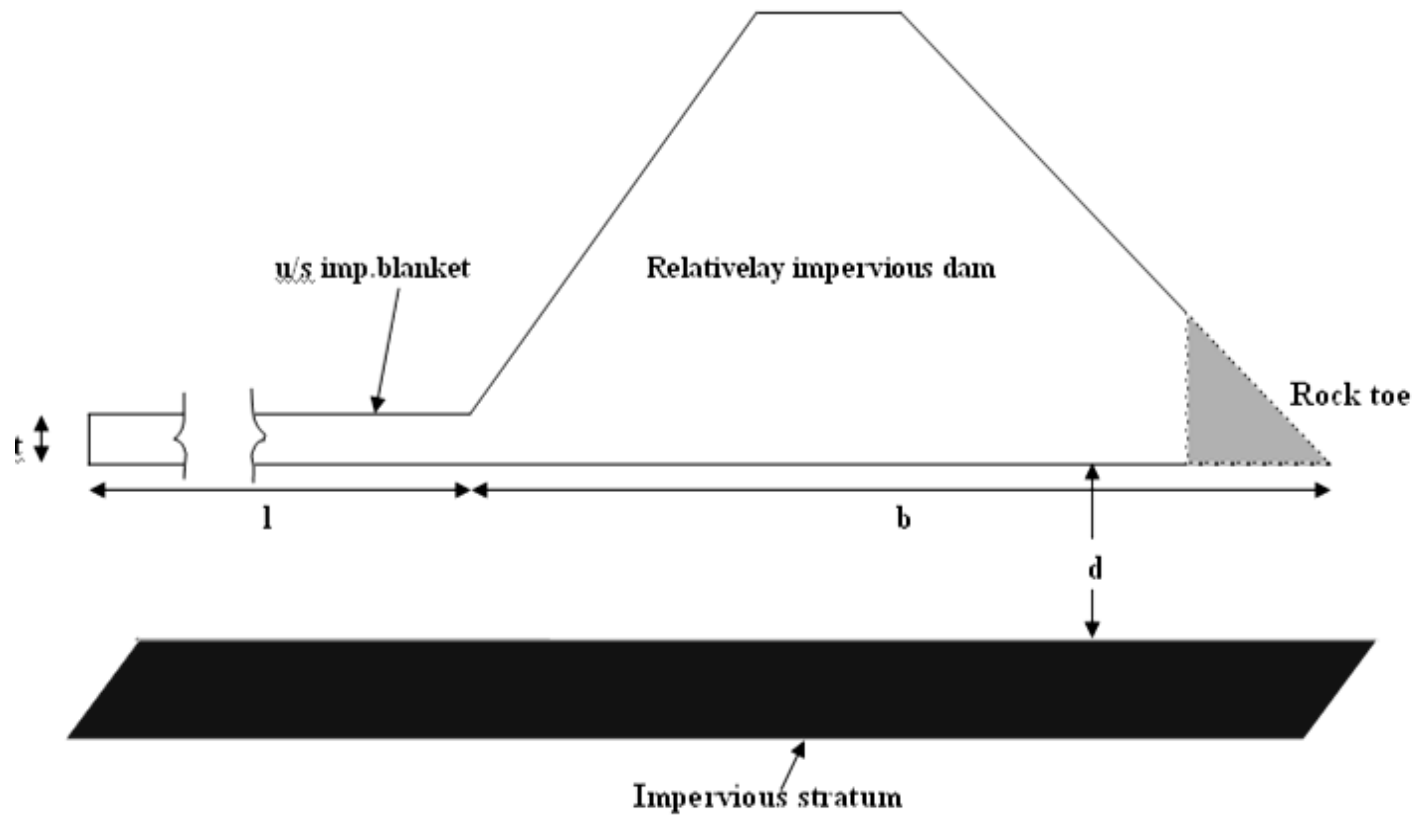
d = depth of pervious foundation

$q' = pq$

Where q' is the seepage quantity after provision of u/s blanket

Cont....

86



Cont....

87

Measures for Safe drainage of seeping water – No piping

- ✓ Some water always seeps through the dam and foundation even after adopting several seepage control.

IN DAM:

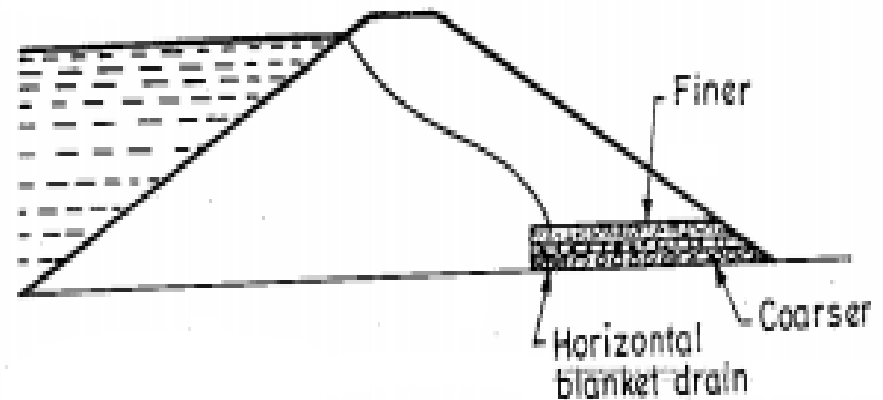
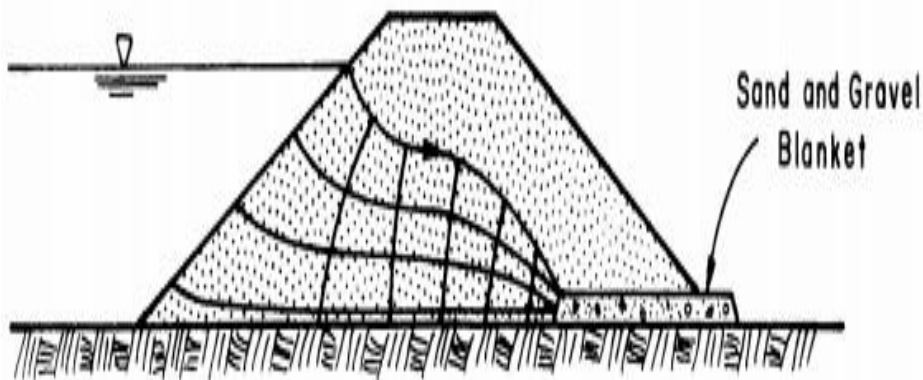
- ✓ Horizontal drainage blanket
- ✓ Rock toe
- ✓ Chimney drain
- ✓ Strip drain

Cont....

88

I. Horizontal drainage blanket

- The blanket extends from the d/s toe for a distance of about three times the height of the dam but not longer than $\frac{2}{3}$ of the base width.
- In the case of zoned section it extends up to the core.
- Used for moderate height dams.

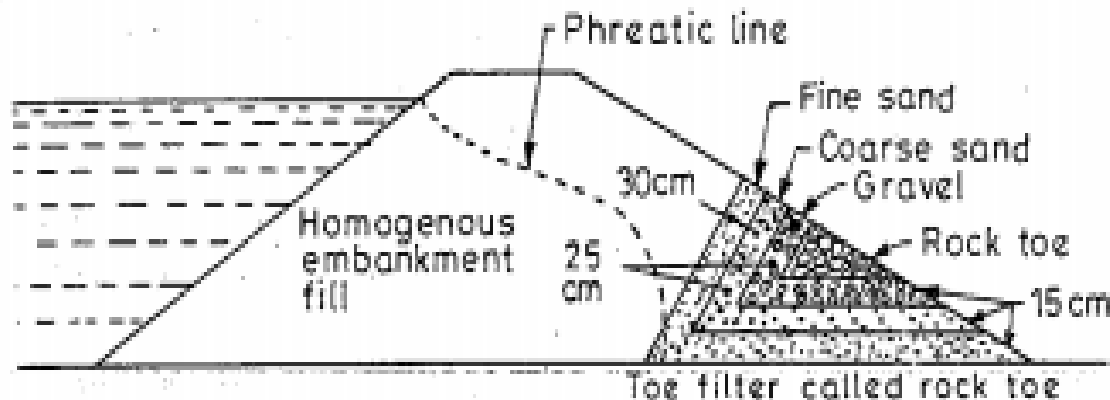


Cont....

89

2. Rock toe:

- The rock toe is provided at the d/s toe of the earth dam and it forms part of the dam.
- It consists of stones of size varying from 15 to 20 cm.
- The u/s face of the rock toe may be vertical or inclined.
- The height of the rock toe is generally b/n $H/3$ to $H/4$, where H is the height of the dam



Cont....

90

3. Chimney drain:

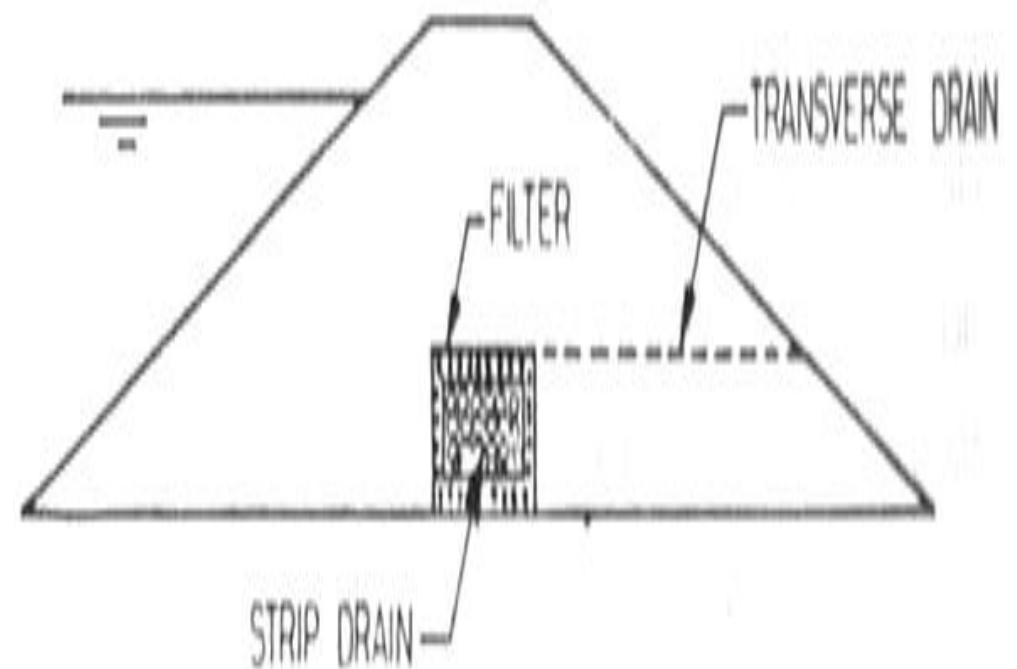
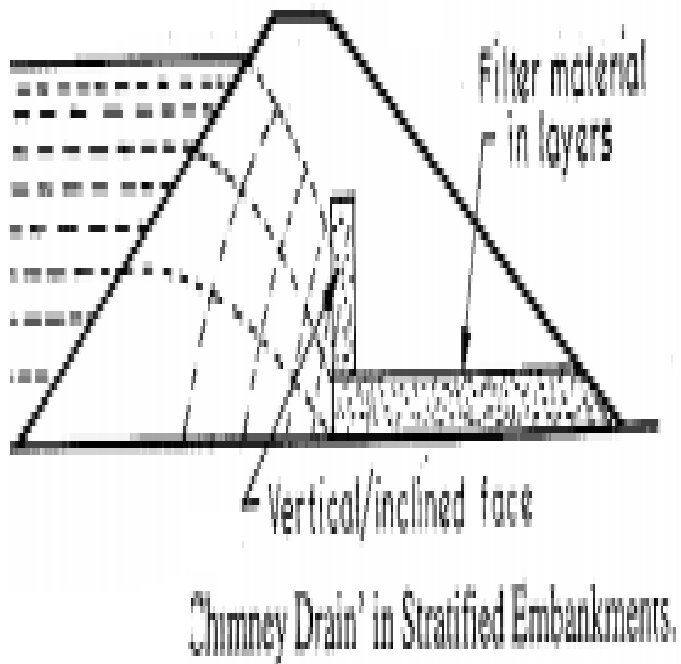
- A chimney drain is a **vertical/nearly vertical drain located inside the dam so that it intercepts all layers of the dam** in the seepage zone.

4. Strip drain:

- A strip drain is **provided instead of a horizontal drainage blanket if there is scarcity of pervious materials in the area**.
- Transverse drains are provided to **carry water from the strip drain to another parallel drain located at the d/s toe of the dam**

Cont....

91



Cont....

92

IN FOUNDATION

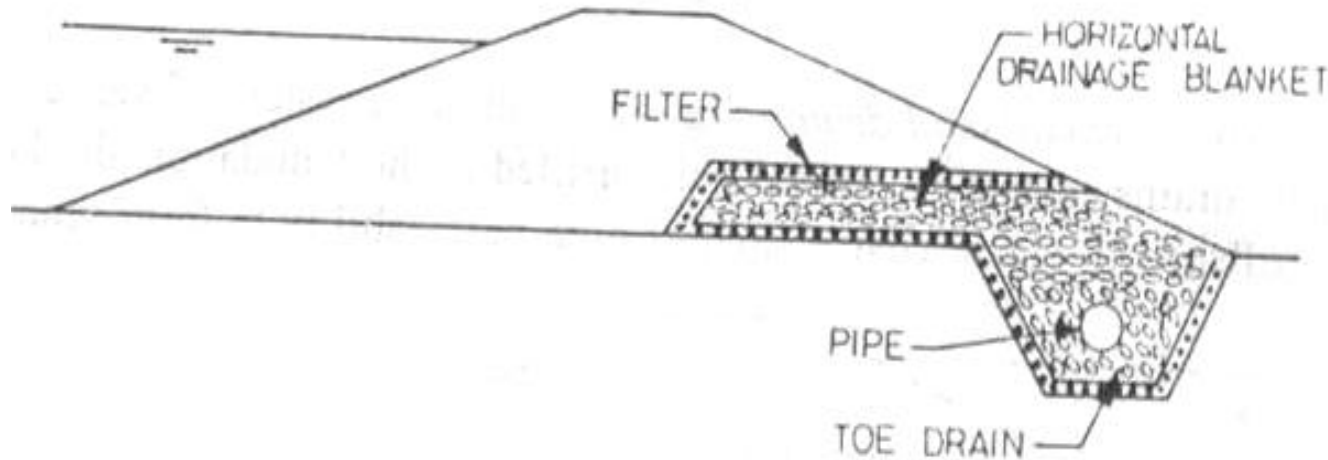
- In general, the drainage systems provided for the dam can also serve for the purpose of drainage of foundation.
- ✓ Toe drains
- ✓ Drainage trenches
- ✓ Relief Wells
- ✓ Vertical Sand Drains

Cont....

93

1. Toe drain and drainage blanket:

- The purpose of toe drains is to collect the seepage water from the horizontal drainage blanket and foundation to carry it to an outfall pipe which then discharges the water in to the river or spillway stilling basin.



Cont....

94

2. Drainage trenches:

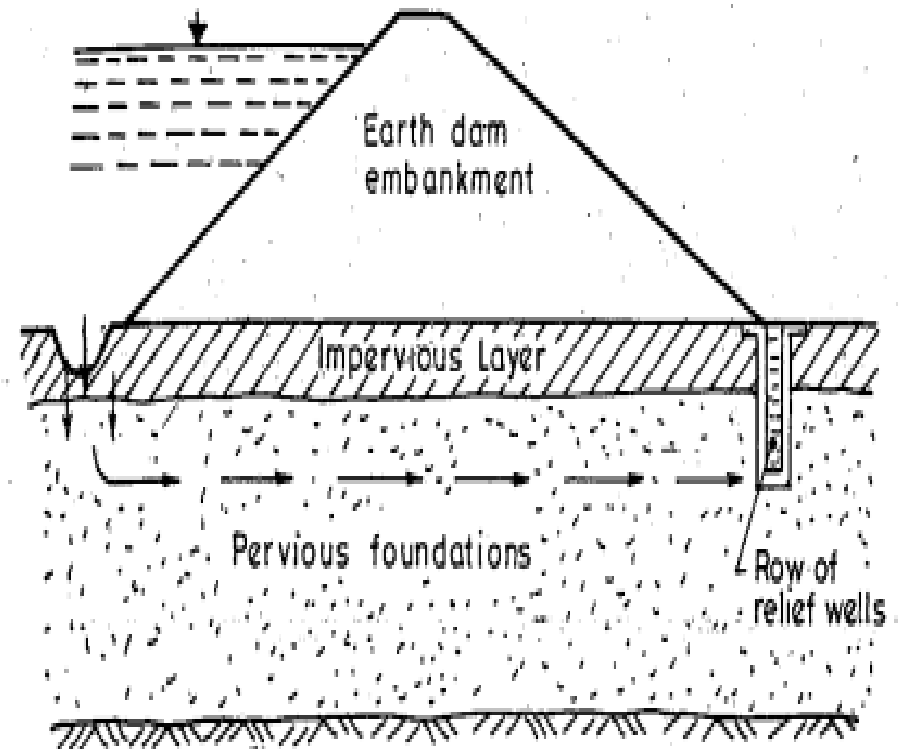
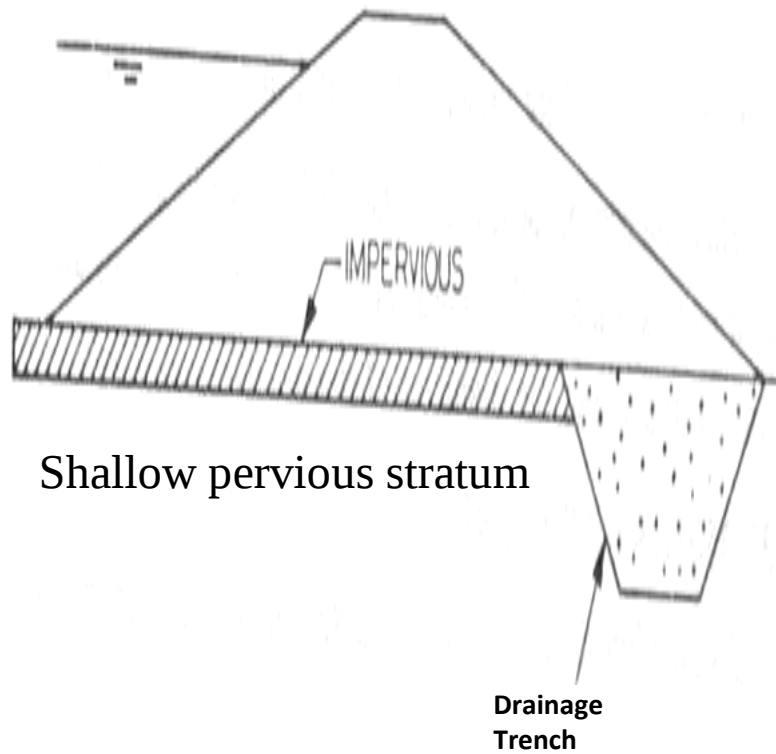
- ✓ Drainage trenches are used when a thin impervious top stratum overlies a shallow pervious stratum of the foundation so that the trench can be built to penetrate the pervious stratum substantially.

3. Relief Wells:

- ✓ Are generally used for drainage of the foundation if it consists of a deep pervious stratum which is stratified and whose permeability increases with depth.
- ✓ It is provided to collect water seeping through foundation and to reduce the pore pressure in the foundation.
- ✓ Relief well consists of an interior perforated pipe or a well screen with a minimum diameter of 15 cm.

Cont....

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Cont....

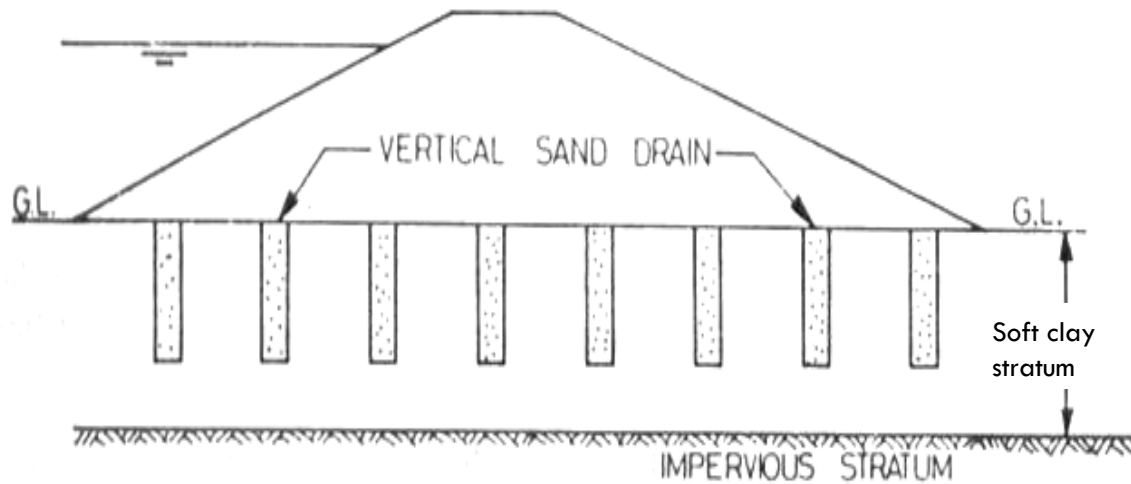
96

4. Vertical Sand drains:

- ✓ These drains consist of vertical holes drilled in the foundation all along the base of the dam.
- ✓ These holes are **filled with clean, coarse sand of high permeability** to form sand columns.
- ✓ Vertical sand drains are quite effective for the drainage of soft clay foundation which can not be easily drained by other methods.
- ✓ Vertical sand drains can also act as relief wells and thus help in reducing the pore pressure and controlling under seepage.

Cont....

97



Cont....

98

Slope Stability Analysis

- Failure of an embankment dam can result from instability of either the upstream or down stream slopes.
- The soil mass in an earth dam because of its slope, is subjected to actuating (or driving) forces which tend to cause movement (or sliding) of the soil mass.
- This movement is resisted by the stabilizing (or resisting) forces, which develop at the potential sliding surface because of the shear strength of the soil.

Cont....

99

- The side slopes of the earth dam will remain stable, if the sum of the resisting forces on every possible surface of failure is greater than the sum of the actuating forces.
- Failure surface may lie within the embankment or may pass through embankment and foundation of soil.

Cont....

100

- Stability analyses are generally needed under the following four critical conditions:
 - ✓ Stability analysis of down stream slope during steady seepage.
 - ✓ Stability of up stream slope during sudden Draw down.
 - ✓ Stability of up stream & down stream slope during and immediately after construction.
 - ✓ Stability of foundation against shear.

Cont....

101

- There are various methods of slope stability analysis among them **Swedish slip -circle** or slices method is the most common.

Swedish slip –circle/ slice method/

- In this method the potential surface is assumed to be cylindrical/ curved slip surface.
- For this failure surface **actuating and resisting forces are determined and FS is found.**

Cont....

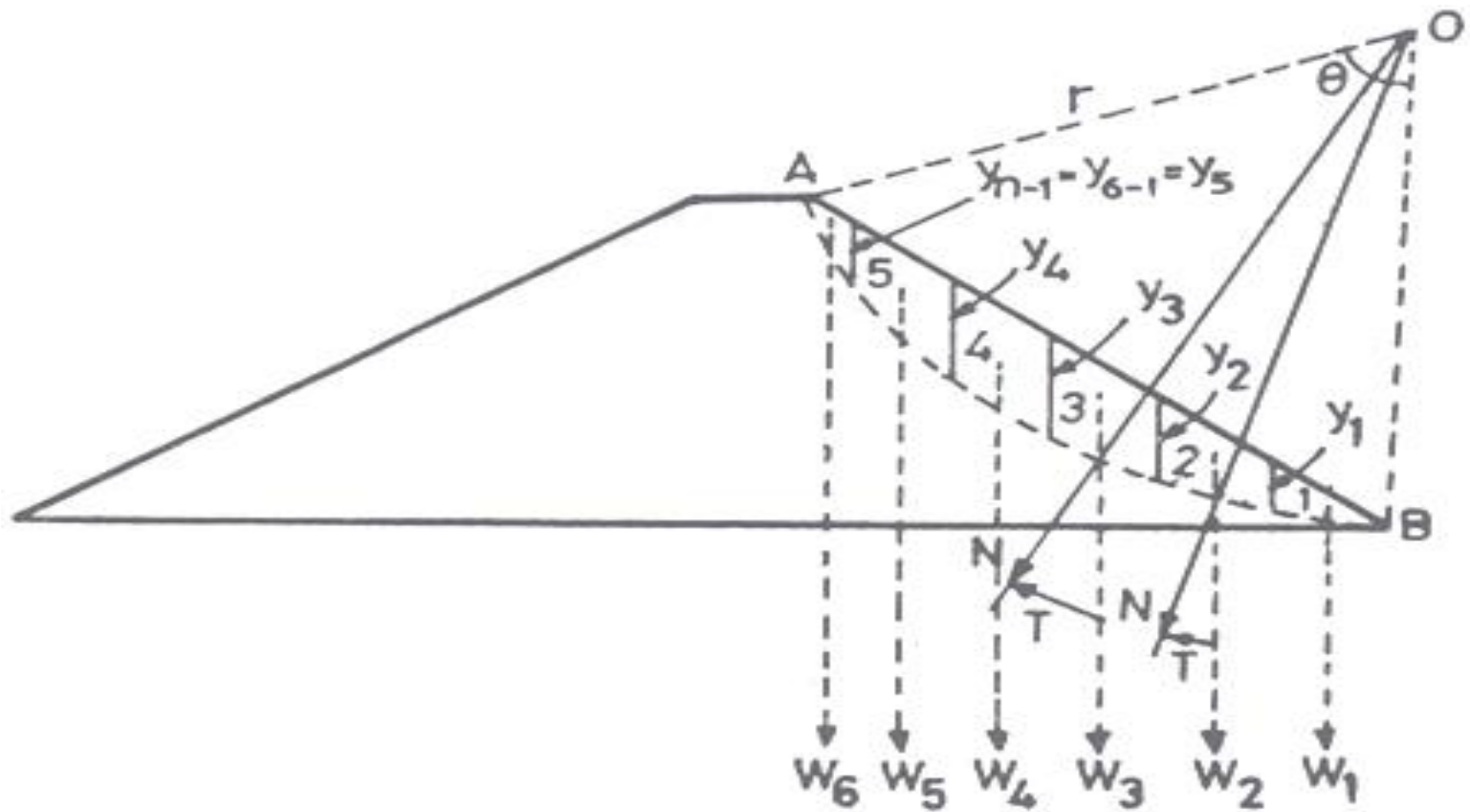
102

- The factor of safety is defined as the ratio of the resisting moments to the actuating moments acting on the assumed failure surface.

$$FS = \frac{\text{Resisting moment}}{\text{Actuating moment}} = \frac{\text{Resisting forces}}{\text{Actuating forces}}$$

Cont....

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Cont....

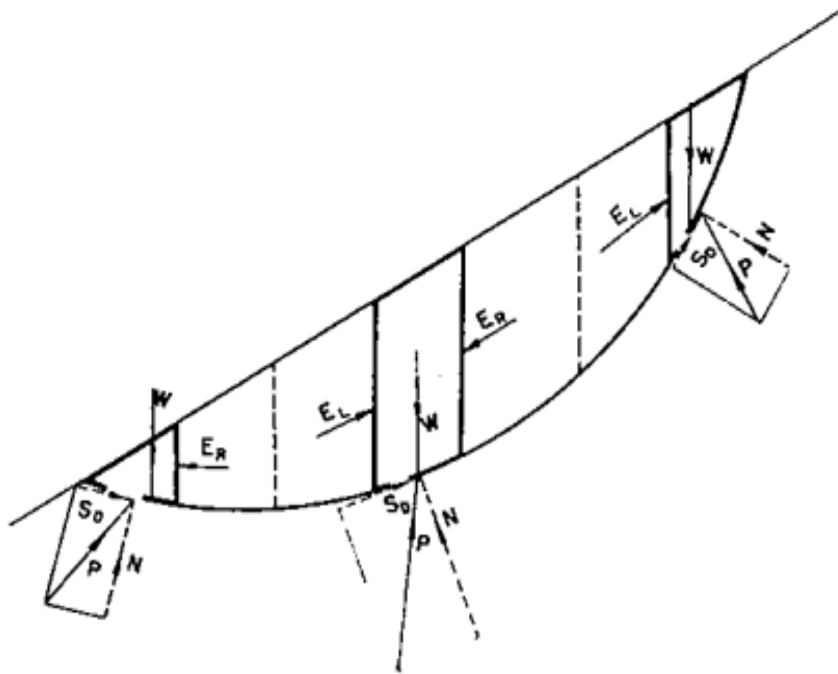
104

- The figure shows a trial slip surface AB which is circular; the radius of the circle, r and its center o .
- The number of slices is usually kept 5 to 15.
- The greater the number the more is accuracy.
- It is convenient to have all the slices of equal width b , but not necessarily.

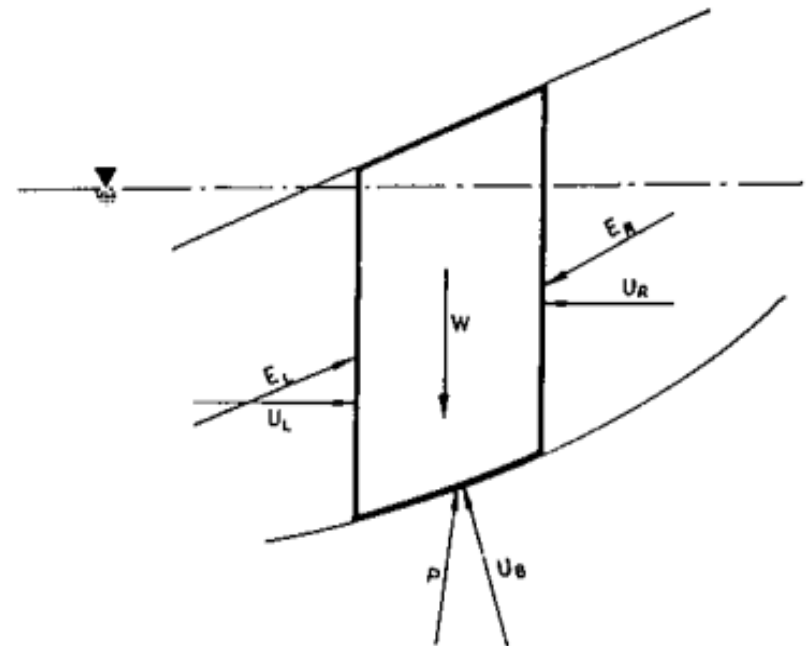
Cont....

105

- Slice method



Method of slices—only earth forces shown.



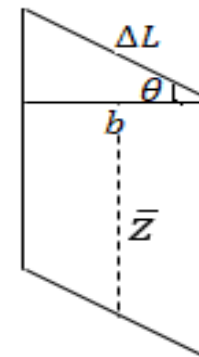
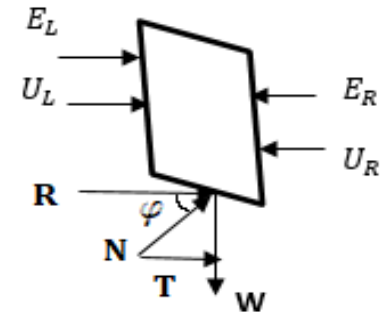
Forces acting on a slice in slices method.

Cont....

106

- **Procedure for Analysis**

- ✓ From the slices take slice 4 as example.
- ✓ Forces acting on this the slip are;
 - Weight, $W \rightarrow$ acts through c.g.
 - Tangential force, T
 - Normal force, N
 - Pore water pressure force, U_B, U_R, U_L .
 - Soil reaction force, $E_R, E_L \rightarrow$ rxn b/n adjacent slices
 - Cohesion force, $C=c\Delta L \rightarrow$ acts along curved surface
 - Reaction R at the base of slice

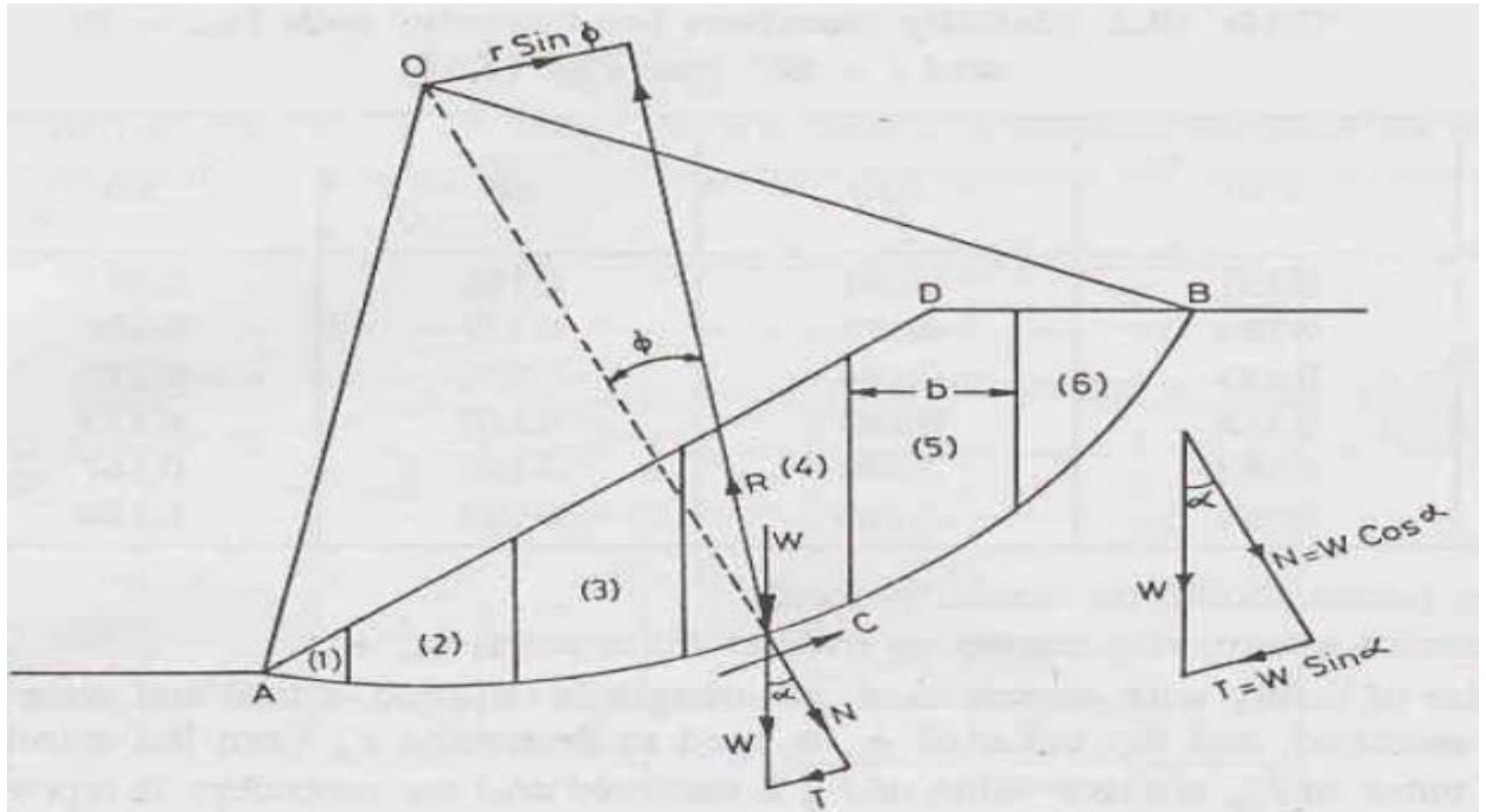


Cont....

107

- The force U_B acts in the normal to arc surface.
- U_R and U_L , E_R and E_L are equal and opposite force so they cancel each other.
- Actuating forces, $\rightarrow T$ and U_B
- Stabilizing forces, $\rightarrow C$ and N
- Resolving vector W into tangential and normal gives;
$$T = W\sin\theta, N = W\cos\theta$$
- θ is the angle which the normal makes with the vertical/weight.
- c is unit cohesion and ΔL is the length of the base of the strip.

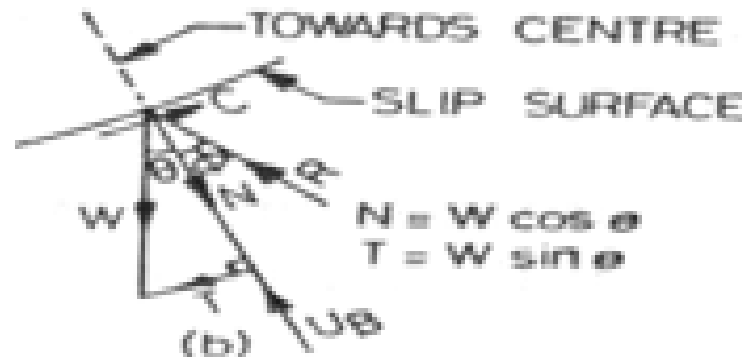
108



Cont....

109

- Thus resolving all the forces in the normal and tangential direction;
- $N - U_B = R \cos \varphi \rightarrow$ In normal (radial) direction
- $T - C = R \sin \varphi \rightarrow$ In tangential direction
- $T - C = (N - U_B) \frac{\sin \varphi}{\cos \varphi} = (N - U_B) \tan \varphi$
- $T = (N - U_B) \tan \varphi + C = (N - U_B) \tan \varphi + c \Delta L$



Cont....

110

- Resisting force = $(N - U_B)\tan\phi + c\Delta L$
- Driving force = T
- $FS = \frac{\text{Resisting forces}}{\text{Actuating forces}} = \frac{(N - U_B)\tan\phi + c\Delta L}{T}$
- For total sliding force,
- $FS = \frac{\sum[(N - U_B)\tan\phi + c\Delta L]}{\sum T}$

<i>Location</i>	<i>Driving force</i>	<i>Resisting force</i>
Below phreatic surface	Saturated weight	Submerged weight
Above phreatic surface	Moist weight	Moist weight

Cont....

111

- For a homogeneous section ϕ is constant
- $FS = \frac{\tan\phi \sum(N-U_B) + \sum c\Delta L}{\sum T}$, $\Delta L = b \sec\theta$
- $FS = \frac{\tan\phi \sum(W \cos\theta - U * \Delta L) + \sum c\Delta L}{\sum W \sin\theta} =$
 $\frac{\tan\phi \sum(W \cos\theta - U * b \sec\theta) + \sum c * b \sec\theta}{\sum W \sin\theta}$

Cont....

112

- If soil is dry, pore water pressure is zero.
- $$FS = \frac{\tan\phi \sum(W\cos\theta) + \sum C*b\sec\theta}{\sum W\sin\theta}$$
- $L = \sum \Delta L = \frac{2\pi r\delta}{360^\circ}$, L is the length of the entire arc of the slip circle.
- δ = angle in degrees subtended by the slip surface at the center.

Cont....

113

- Pore water pressure force ($\bar{U}$) = pore water pressure (U) $\times \Delta L$
- U is determined from flow net or other means.
- The slip surface which gives minimum factor of safety is the critical.
- The minimum F_s should be greater than the allowable one (1.5).

Cont....

114

Summary of procedure for earth dam stability analysis

1. Take a trial slip surface and divide the wedge above the slip surface into 5 to 15 vertical slices.
2. Determine the Weight W of each slice and its line of action.

$W = (b * \bar{z})\gamma_{material}$, z = middle ordinate of the slice, b = width of the slice

3. Measure the angle θ which the normal makes with the vertical and compute N and T .

$$T = W\sin\theta, \quad N = W\cos\theta$$

Cont....

115

4. Determine the pore water pressure, u , at the base of the slice and U_B .

$$U_B = U * b \sec \theta$$

5. Determine the cohesive force, $C=c\Delta L$
6. Determine the factor of safety for slip surface from equations given above.

$$FS = \frac{\tan \phi \sum (W \cos \theta - U * b \sec \theta) + \sum c * b \sec \theta}{\sum W \sin \theta}$$

Cont....

116

7. Repeat the procedure for a number of other trail surfaces.
 - ✓ The trail surface which gives the minimum factor of safety is the most critical circle.
 - ✓ The minimum factors of safety should be greater than the specified safe value.

Cont....

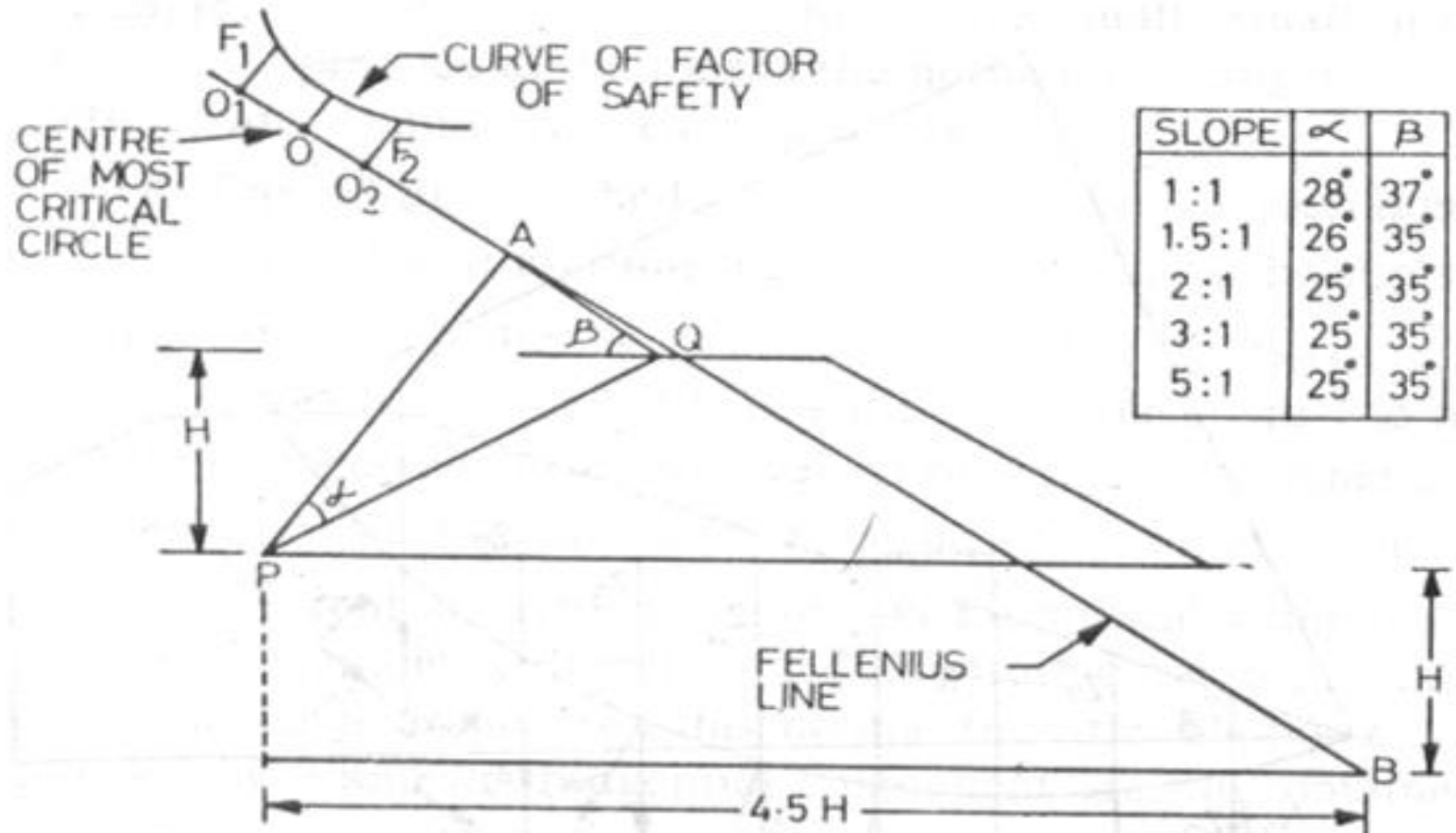
117

Location of the most CRITICAL circle

- ✓ To reduce number of trials, Fellenius suggested a line called Fellenius line (line AB) for a homogeneous slope (see fig below) on which the most critical circle lies.
- **Steps;**
- Locate point B.
- Locate point A by drawing line PA and PQ from slope and angle given on table below.

Cont....

118



Cont....

119

- The center O with minimum factor of safety is the center of the most critical circle.
- For a purely cohesive soil, the point A itself represents the center of the most critical circle.

Cont....

120

Loading cases

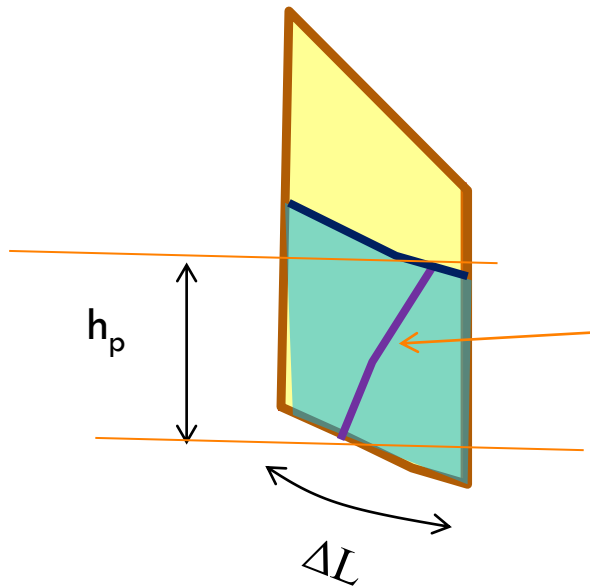
The following loading conditions are usually evaluated for stability analysis of embankment dams: (1) steady-state seepage, (2) sudden drawdown and (3) end of construction.

Case 1: Stability of Downstream Slope during Steady State Seepage

- The most critical condition for the d/s slope is **when the reservoir is full & the steady state seepage** is taking place at full rate
- The soil mass **below the phreatic line** will be subjected to **pore water pressure**. This will reduce the shear strength development.

Cont....

121



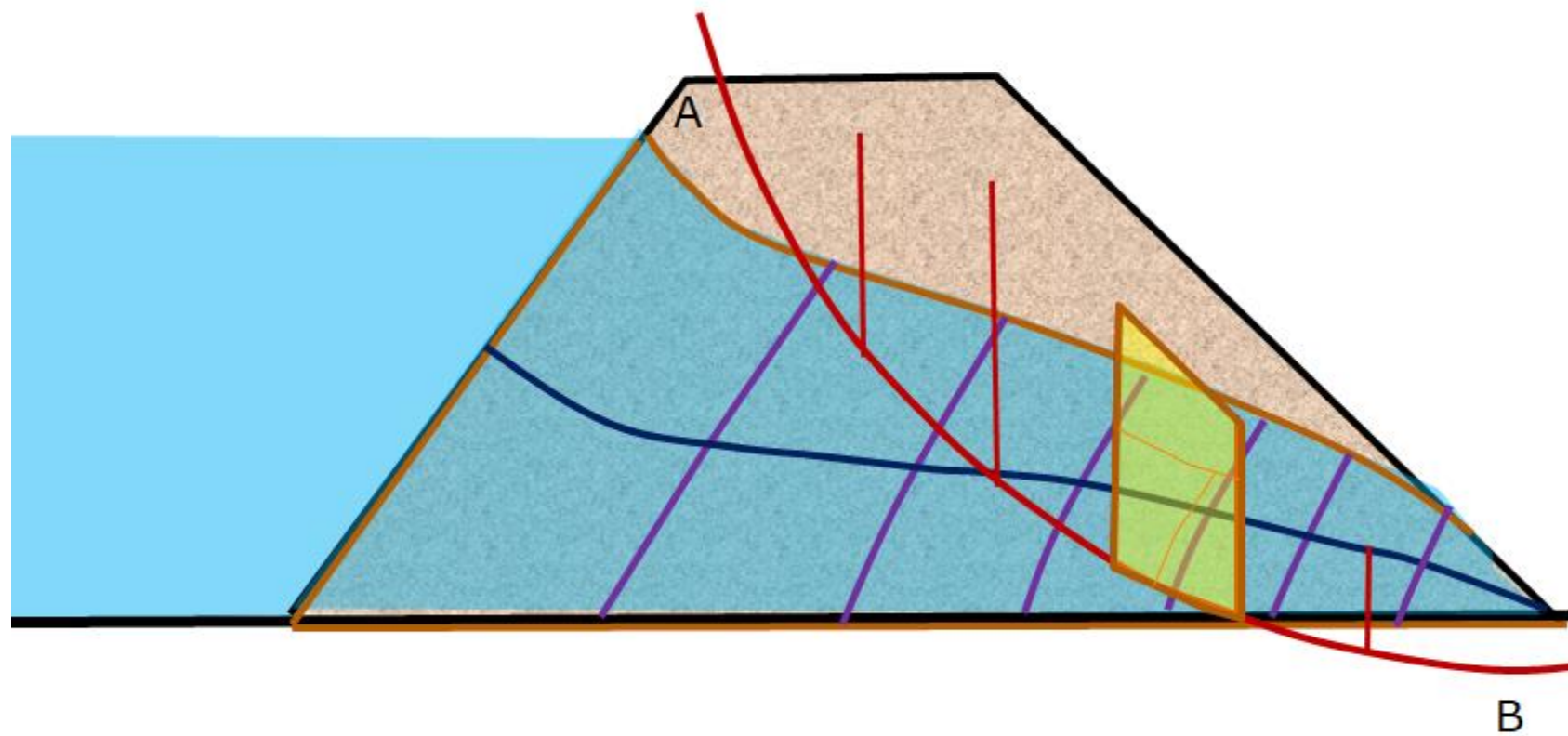
$$U = \text{Pore pressure} = h_p \gamma_w$$

$$\text{Uplift force} = U \Delta L = h_p \gamma_w \Delta L$$

$$FS = \frac{C' \overline{AB} + \tan \phi' \sum_{i=1}^n (N_i - U_i \Delta L_i)}{\sum_{i=1}^n T_i}$$

$$FS = \frac{C' \overline{AB} + \tan \phi' \sum_{i=1}^n W_{sub,i} \cos \alpha_i}{\sum_{i=1}^n W_{sat,i} \sin \alpha_i}$$

$$FS > 1.5$$



Cont....

123

Case 2. Stability of U/s Slope during Sudden Drawdown

- The critical condition for the u/s slope is when the reservoir which is initially at full reservoir level is suddenly emptied.
- Generally, **hypothetical instantaneous drawdown is assumed**. This means there is no time for drainage to occur that relieve the pore water pressure developed in the soil along the sliding surface. In such cases the water level will remain as it is when the soil pore were full of water.

$$FS = \frac{C' \overline{AB} + \tan \phi' \sum_{i=1}^n (N_i - U_i \Delta L_i)}{\sum_{i=1}^n T_i}$$

$$FS = \frac{C' \overline{AB} + \tan \phi' \sum_{i=1}^n W_{sub,i} \cos \alpha_i}{\sum_{i=1}^n W_{sat,i} \sin \alpha_i}$$

$$FS > 1.5$$

Cont....

124

Case 3. Stability of U/s & D/s Slopes at the End of Construction

- End-of-construction loading condition is usually analyzed for new embankments that
 - **include fine-grained soils**, and
 - are constructed on **fine-grained saturated foundations** that may develop excess pore pressures from the loading of the embankment.
- The embankment is constructed in layers with soils at or above their optimum moisture content that undergo internal consolidation because of the weight of the overlying layers. Embankment layers may become saturated during construction as a result of consolidation of the layers or by rainfall.
- Because of the low permeability of fine-grained soils and the relatively short time for construction of the embankment, there is little drainage of the water from the soil during construction: resulting in the development of significant pore pressures.

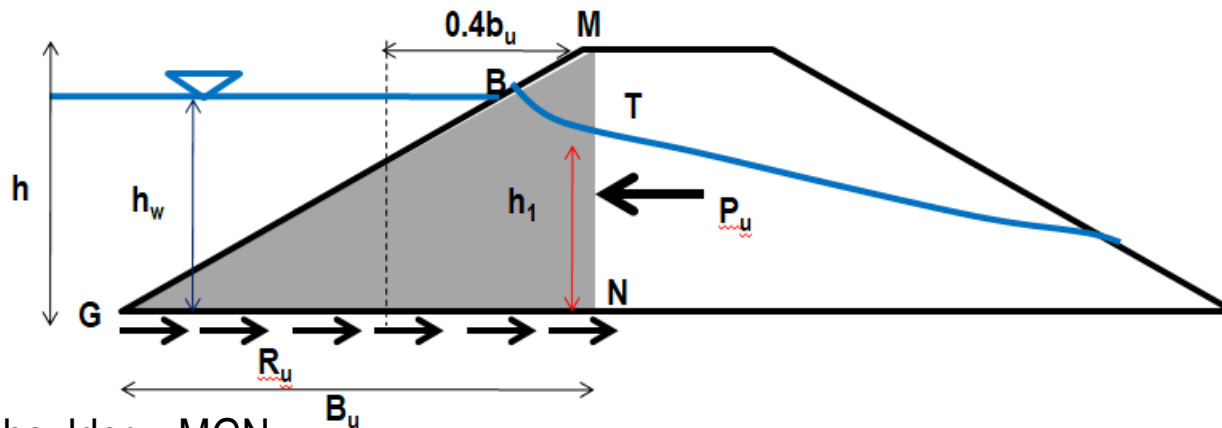
$$FS = \frac{C' \overline{AB} + \tan \phi' \sum_{i=1}^n (N_i - U_i \Delta L_i)}{\sum_{i=1}^n T_i}$$

Cont....

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Sliding Block Method : Approximate Methods

Case 4: Stability of the u/s slope of the dam during sudden drawdown from the consideration of horizontal shear developed at base under the u/s of the dam,



Upstream shoulder – MGN

h – dam height

B_u – width

h_w – u/s water depth

h_1 – saturated height

BGNT – saturated soil

MBT – dry soil

P_u - Horizontal Destabilizing Force

R_u – Resisting shear strength

Cont....

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A) Horizontal Force / Destabilizing Force

A-1. Effective lateral earth pressure force

$$P_e = \frac{\gamma_1 h^2}{2} \tan^2(45 - \frac{\phi}{2})$$

$$\gamma_1 = \frac{\gamma_{\text{sub}} h_1 + \gamma_{\text{dry}} (h - h_1)}{h}$$

A-2. Pore water pressure

$$P_p = \frac{\gamma_w h_1^2}{2}$$

A-3. Total destabilizing force

$$P_u = P_e + P_p = \frac{\gamma_1 h^2}{2} \tan^2(45 - \frac{\phi}{2}) + \frac{\gamma_w h_1^2}{2}$$

A-4. Average shear ~~area~~ stress

$$\tau_{\text{avg}} = \frac{P_u}{B_v \times 1} = \frac{P_u}{B_v}$$

Cont....

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B) Resisting Shear Strength

$$R_u = C + W \tan \phi$$

$$C = \text{cohesive force} \\ = c \times B_u \times 1 = cB$$

W = Weight of the shoulder GMW

$$= \gamma_{\text{sub}} \text{Area}_{\text{GMW}} + \gamma_{\text{dry}} \text{Area}_{\text{BM}} \gamma$$

$$\approx \gamma_{\text{sub}} \text{Area}_{\text{GMW}} = \frac{1}{2} \gamma_{\text{sub}} B_u h$$

C) Safety against sliding

$$F.S = \frac{R_u}{P_u} > 1.5$$

Cont....

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d) Critical shear stress

□ Shear stress is not uniform along GW

□ It is maximum at $0.6 B_v$ from

□ The max shear stress

$$\tau_{\max} = 1.4 \tau_{\text{avg}}$$

e) Shear strength at critical point

$$\tau_{\text{crit}} = c + \gamma_{\text{sub}} 0.6h \tan \phi$$

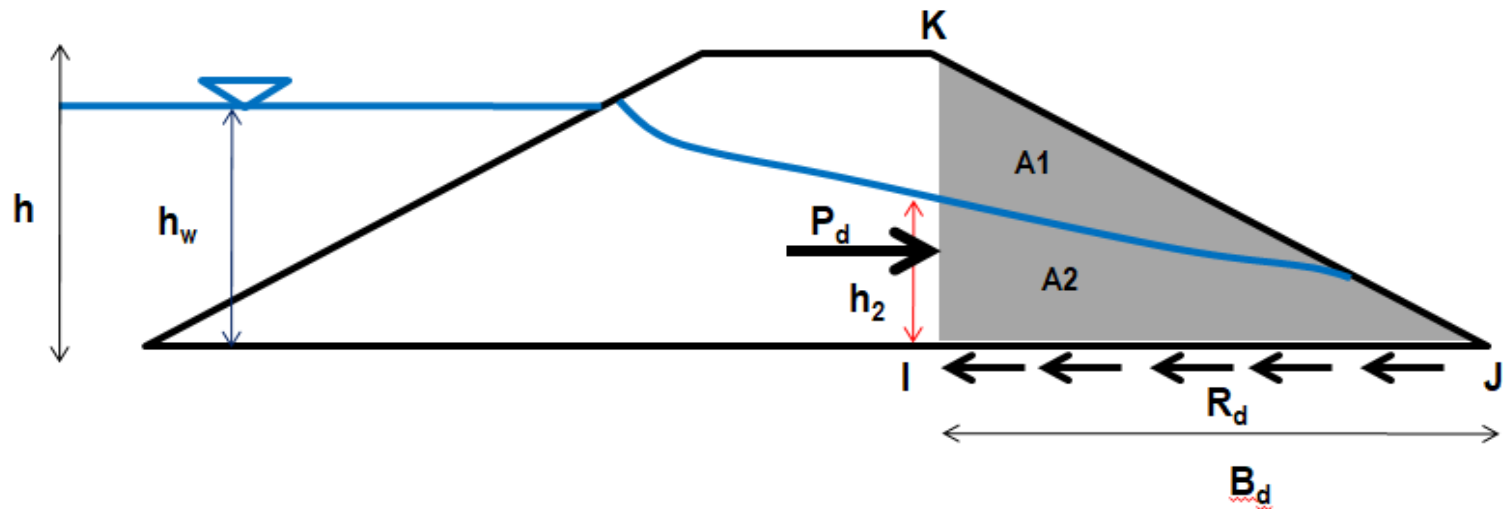
f) Critical safety against sliding

$$F.S._{\text{crit}} = \frac{\tau_{\text{cr}}}{\tau_{\max}} \geq 1$$

Cont....

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Case 5: Stability of the d/s slope of the dam under steady seepage from the consideration of horizontal shear developed at base under the d/s slope of the dam.



Downstream shoulder – KJI

h – dam height

B_d – width

h_w – u/s water depth

h_2 – saturated height

A2 – saturated soil

A1 – dry soil

P_d - Horizontal Destabilizing Force

R_d – Resisting shear strength

Cont....

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A) Horizontal Force / Destabilizing Force

A.1. Effective lateral earth pressure

$$P_e = \frac{\gamma_2}{2} h^2 \tan^2(45 - \frac{\phi}{2}) \quad \gamma_2 = \frac{\gamma_{\text{sub}} h_2 + \gamma_{\text{dry}} (h - h_2)}{h}$$

A.2. Pore water pressure

$$P_p = \frac{\gamma_w h_2^2}{2}$$

A.3. Total destabilizing Force

$$P_d = P_e + P_p = \frac{\gamma_2 h^2}{2} \tan^2(45 - \frac{\phi}{2}) + \frac{\gamma_w h_2^2}{2}$$

A.5. Average Shear Stress

$$\tau_{\text{avg}} = \frac{P_d}{B_d \times 1} = \frac{P_d}{B_d}$$

Cont....

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B) Resisting Shear Strength

$$R_d = C + W \tan \phi$$

$$W = \gamma_{dm} A_1 + \gamma_{sub} A_2$$

$$R_d = c B_d + \frac{1}{2} \gamma_{sub} B_d h \tan \phi \quad \approx \quad \gamma_{sub} (A_1 + A_2) = \frac{1}{2} \gamma_{sub} B_d h$$

c) Safety against sliding

$$F.S = \frac{R_d}{P_d} > 1.5$$

d) Critical Shear Stress

□ Shear stress is at $0.6 B_d$

$$\eta \quad \tau_{max} = 1.4 \tau_{avg}$$

Cont....

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e) Shear strength at critical point

$$\tau_{crit} = c + 0.5bh \gamma_{sub} \tan \phi$$

f) Critical safety against ~~the~~ sliding

$$F.S._{crit} = \frac{\tau_{crit}}{\tau_{max}} > 1$$

Cont....

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ROCKFILL DAMS

- this type of dam economical only in remote areas where the cost of concrete would be high or in areas where there is a scarcity of earth fill materials and where the only material available for construction of the structure consists of durable hard rock.
- Uses variable size of rock to provide stability and impervious membrane to provide water tightness.

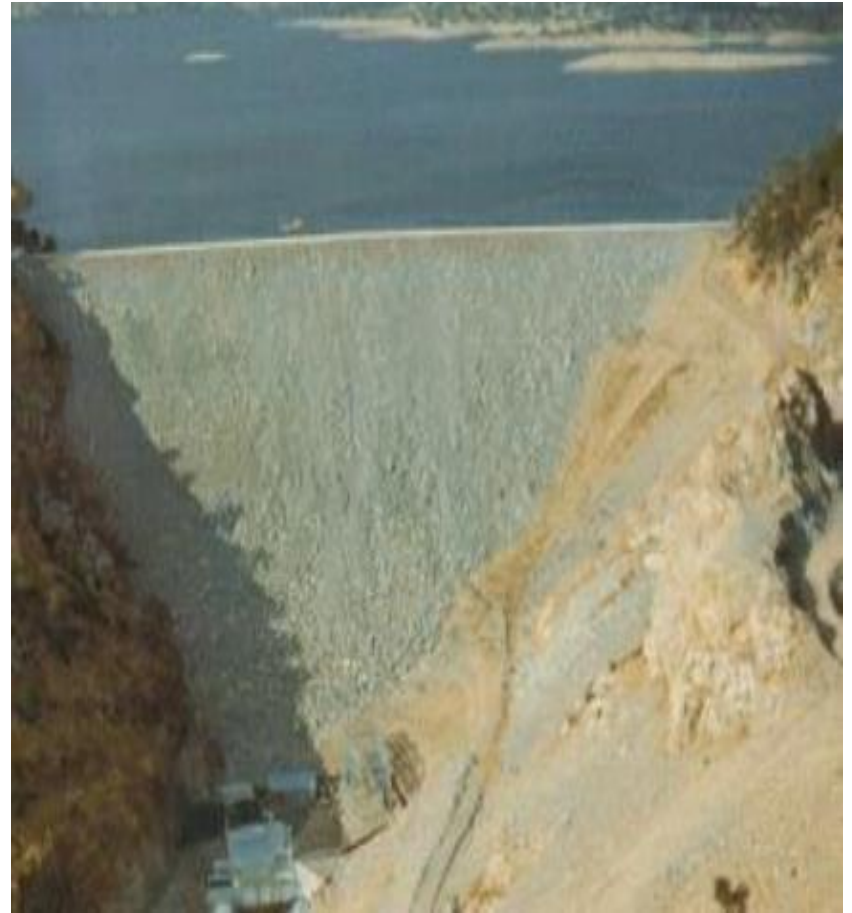
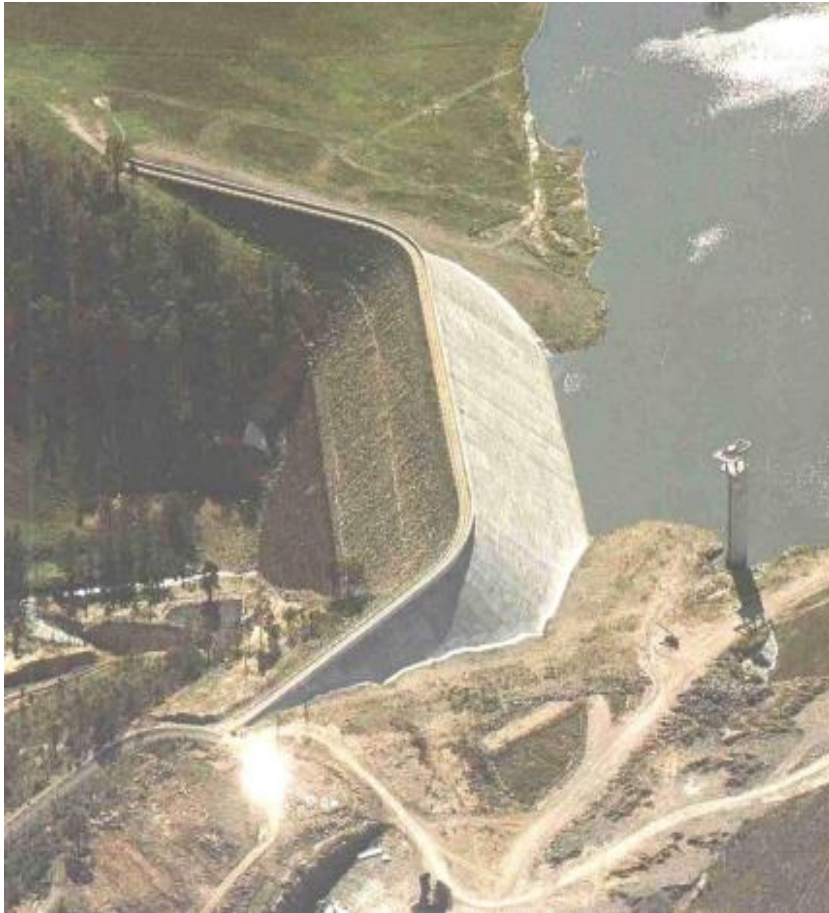
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- Rock fill dams can prove economical when any of the following conditions exist.
 - ✚ Large quantities of rocks are available or will be excavated in the area.
 - ✚ Earth fill materials are difficult to obtain or require much processing to be used
 - ✚ Short construction season prevails
 - ✚ Excessively wet climatic condition limit the placement of large quantities of earth fill materials.

Cont....

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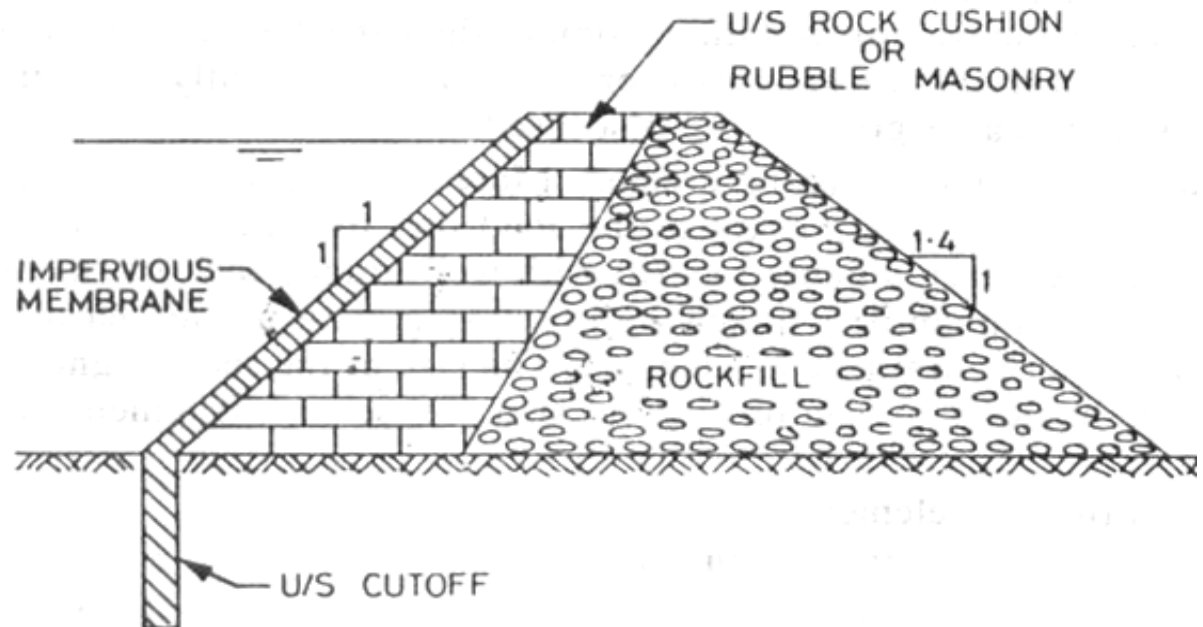


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The major components of Rock fill dam may consist of:

- ✓ Rock rubble masonry
- ✓ Impermeable membrane
- ✓ Rock fill
- ✓ U/S cut-off



2.3 River diversion during construction

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River Diversion

River diversion is a technique of diverting river water away from downstream part into the canal or tunnel or to particular confined side.

River diversion takes place for two purposes:

- For construction purpose
- For water use purpose

Cont....

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River Diversion for construction purpose

- During construction of gravity or embankment dam, concreting of dam or placing of earthen material cannot be done in water.
- Therefore, before starting construction of major dam, the river water has to be diverted away from the dam site so that the construction can be done in dry condition.

Cont....

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- Cofferdam: usually earthen embankment (for economic purpose) is constructed on the U/S and D/S of the dam site to isolate the construction area which is to be kept dry.
- ❖ The diversion tunnel or canal takes off U/S of the coffer dam on the U/S and then joins on the D/S of the coffer dam in the D/S side.
- ❖ Some water usually seeps into the construction area, which has to be pumped out to keep the area dry.

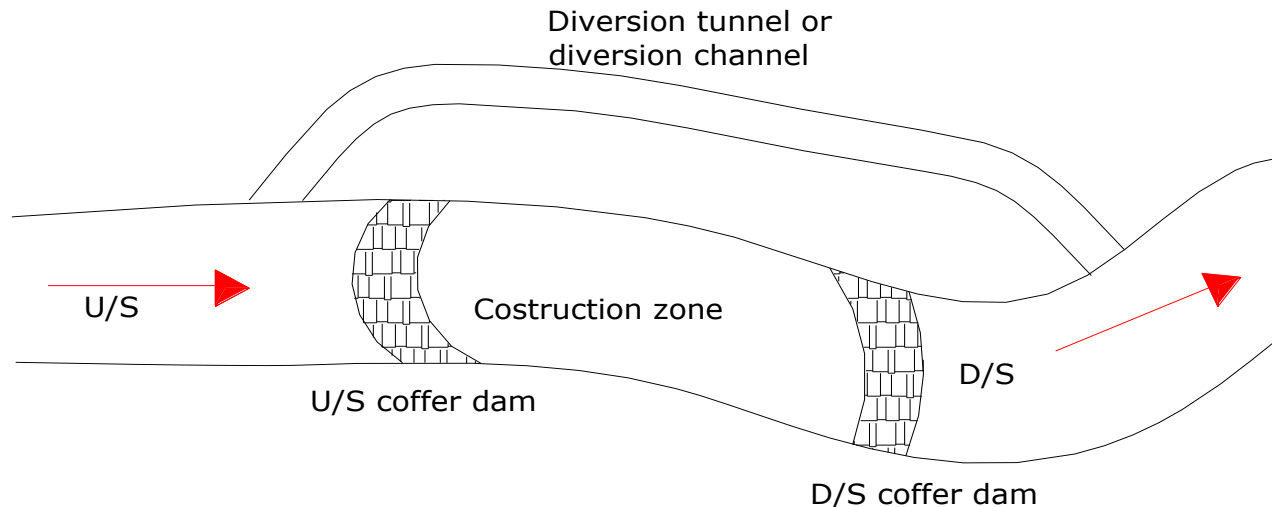
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- The diversion of river water can be accomplished in either of the following ways:

I. Provision of diversion tunnel or Channel

- Used during construction of both concrete & embankment dams



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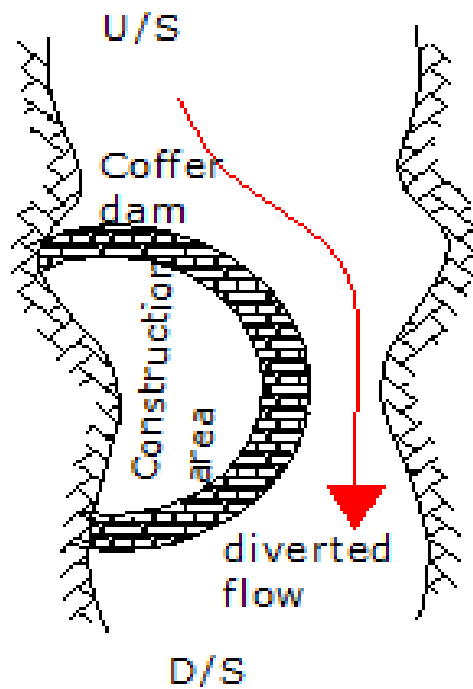
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II. Two stage construction

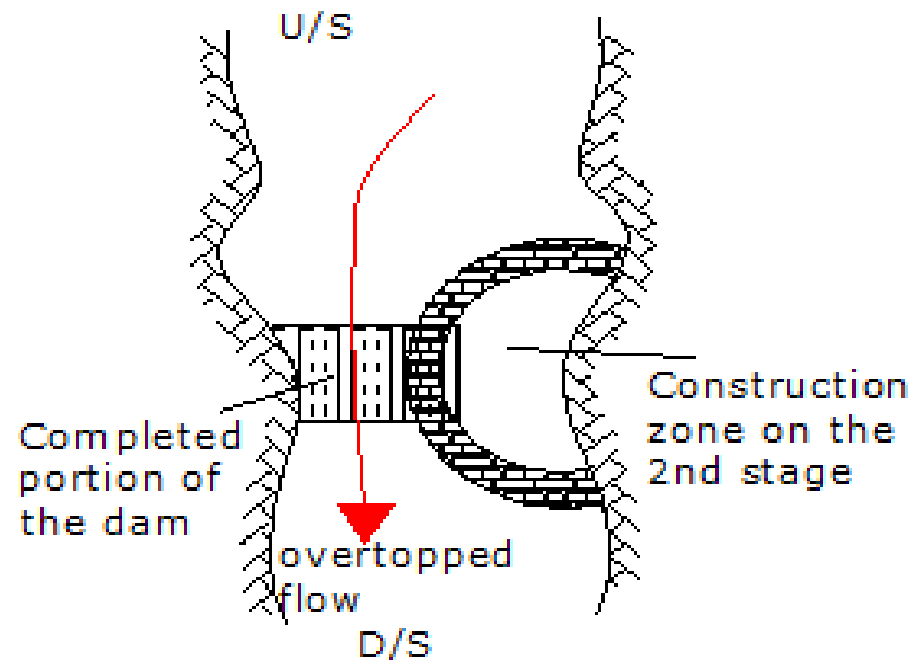
- Instead of diverting the river into a tunnel or channel, it is some times more economical to have two stage construction of gravity dam.
- In such a case, the flow is, first of all, diverted and confined to one side of the channel by constructing semi circular coffer dam.
- Then construction progresses in free water zone. On the next stage the diverted water is allowed to overtop or to pass through outlet on the side of already constructed portion of the dam.
- This method is suitable only during construction of concrete dam.

Cont....

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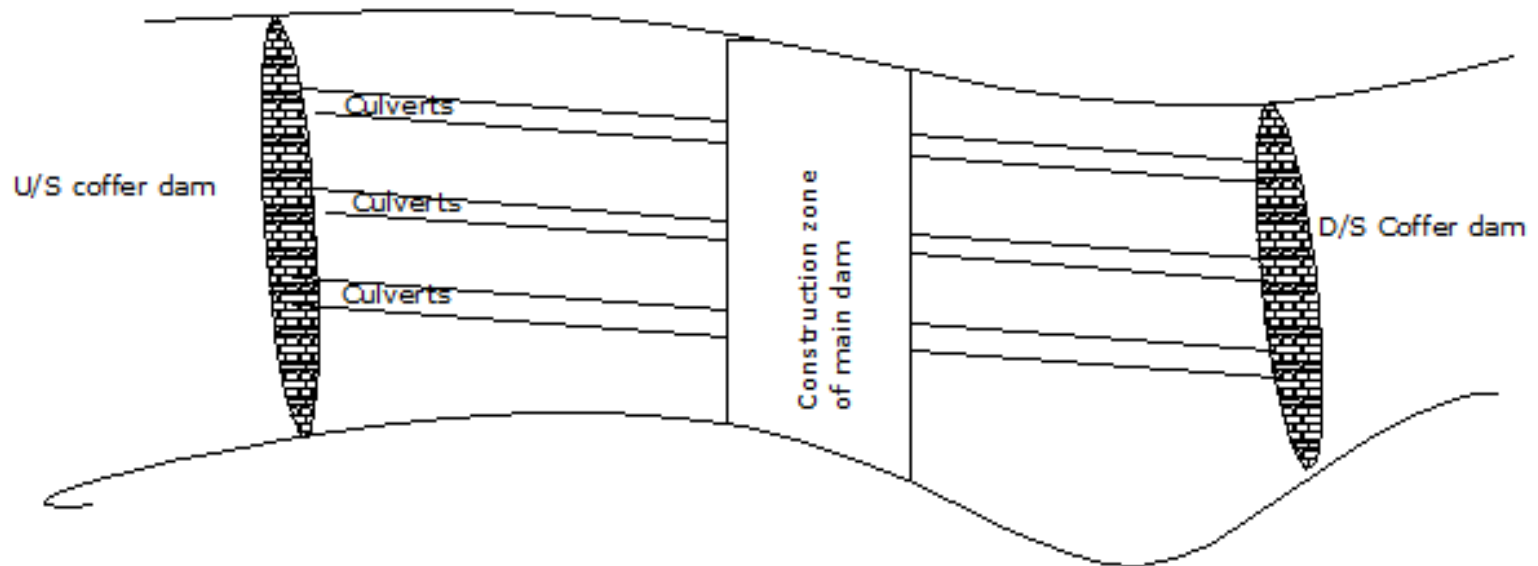


i. 1st stage diversion



ii. 2nd stage diversion

III. River diversion through the construction site (through culverts in the body of the dam) Example: Gilgel Gibe Hydroelectric project



THANK YOU