Chapter 5
Dams and Spillways

A dam is an impervious barrier built across a water course to:

- store water
- create a head
- form a lake

Atatürk Dam

Classification of dams on type and material

- Gravity Dams
- Arch Dams
- Buttress Dams
- Embankment (Fill) Dams

Classification of dams on size

- Large Dams
- High Dams
- Small Dams

Additional classification by ICOLD (International Commission on Large Dams)

- Large Dam: ($H_f > 15$ m)

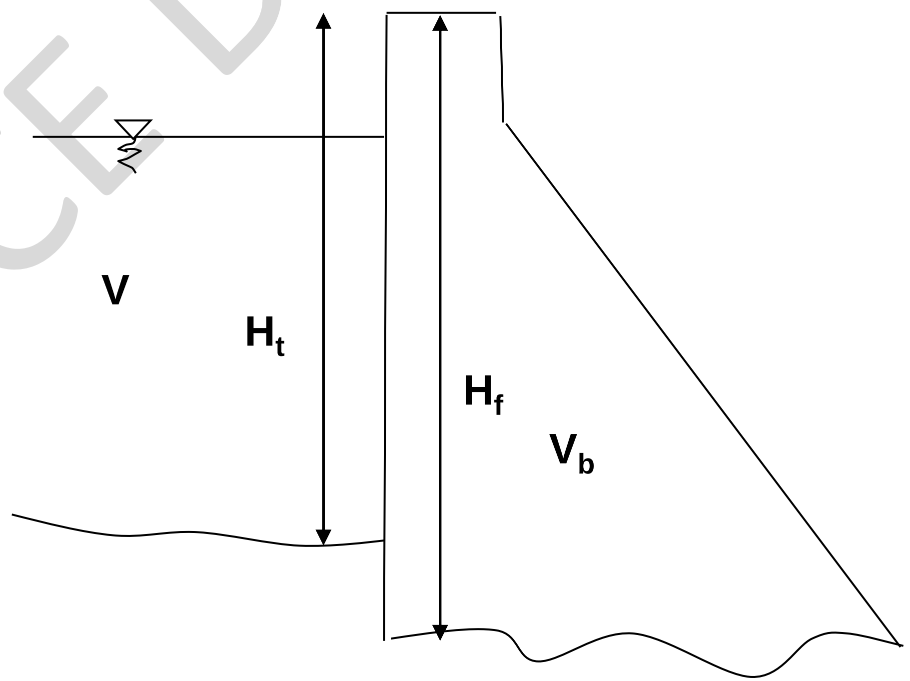
or $\left\{ \begin{array}{l} 10 \text{ m} \leq H_f \leq 15 \text{ m} \\ V > 10^6 \text{ m}^3 \\ L > 500 \text{ m} \end{array} \right.$

- Small Dam:

  $H_f < 10$ m

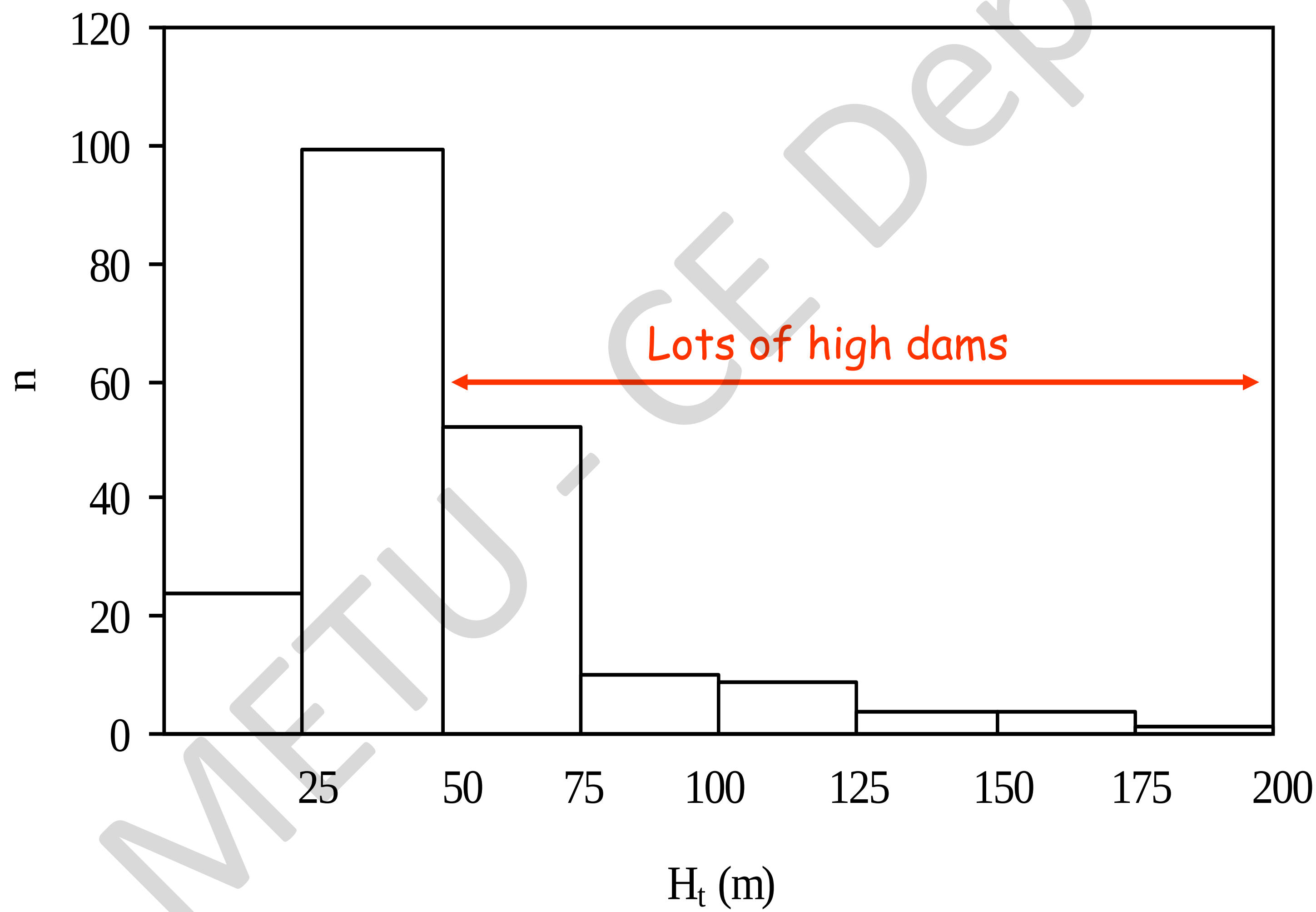
- High Dam

  $H_t > 50$ m



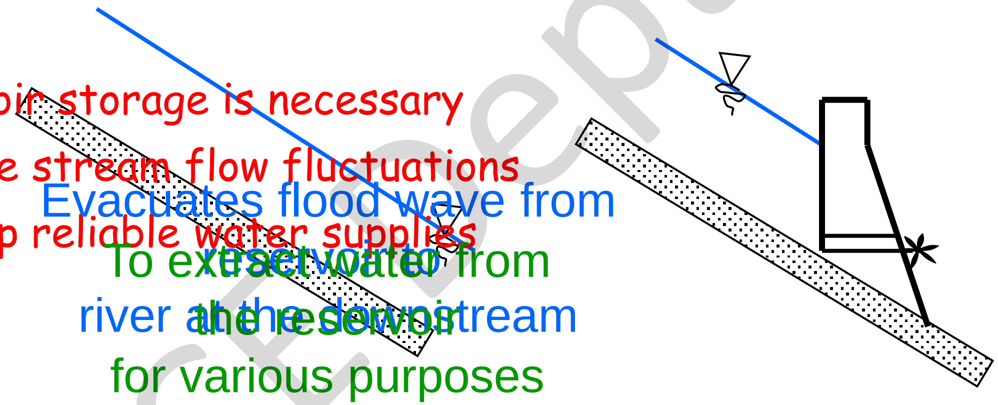
V = reservoir storage
L = crest length

Dams in Turkey



Parts of dams:

- Body
- Reservoir
- Spillway
- Water intake
- Diversion facilities
- Others
  - Hydropower station
  - Site installations
  - Roads
  - Locks
  - Fish ladders

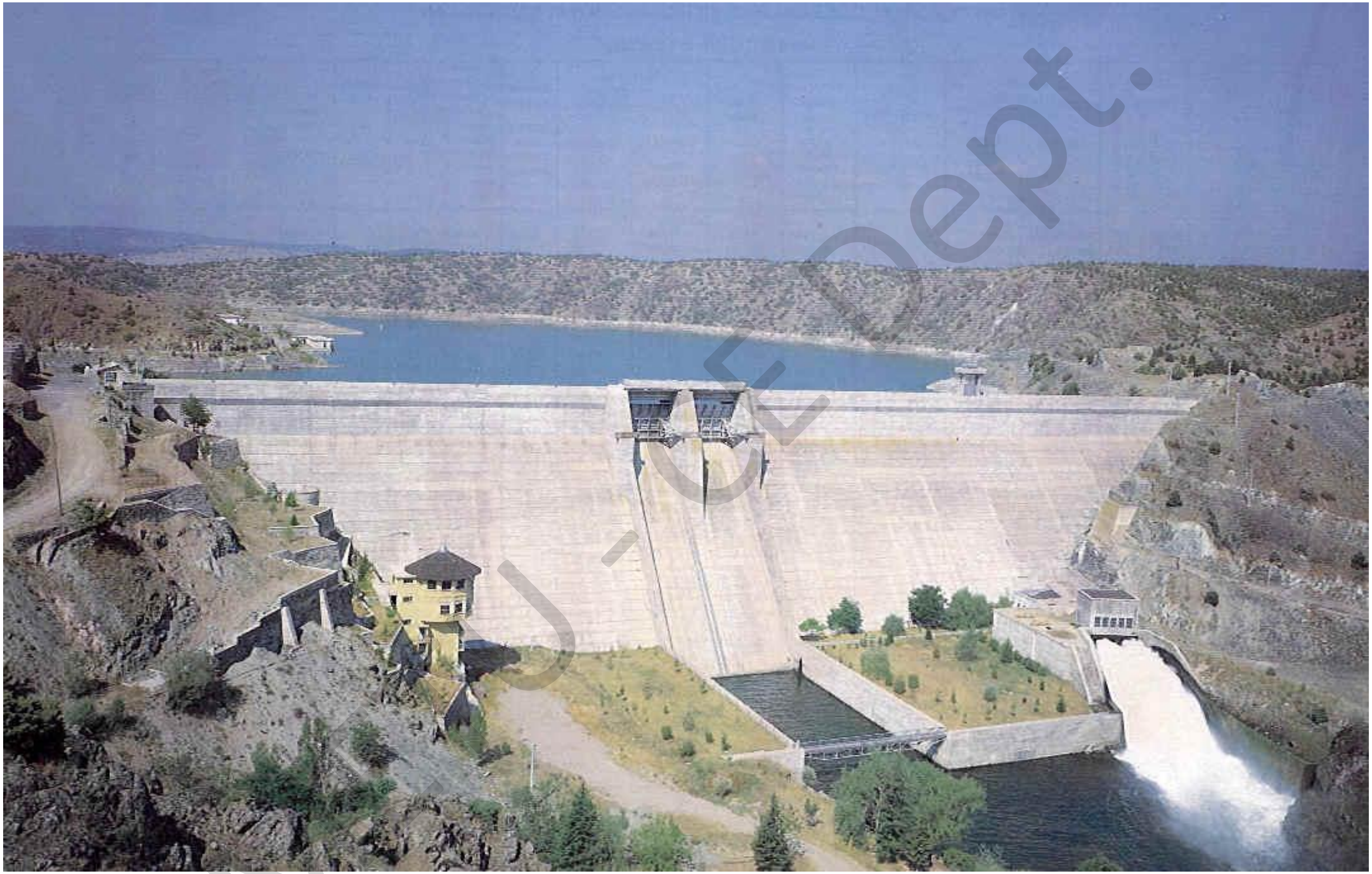


Classification of dams

a) GRAVITY DAMS

- Concrete gravity
- Prestressed concrete
- Roller compacted concrete (RCC)

- Hardfill – most recent type
  Ex: Cindere Dam



Porsuk Dam (Concrete Gravity) on Porsuk River

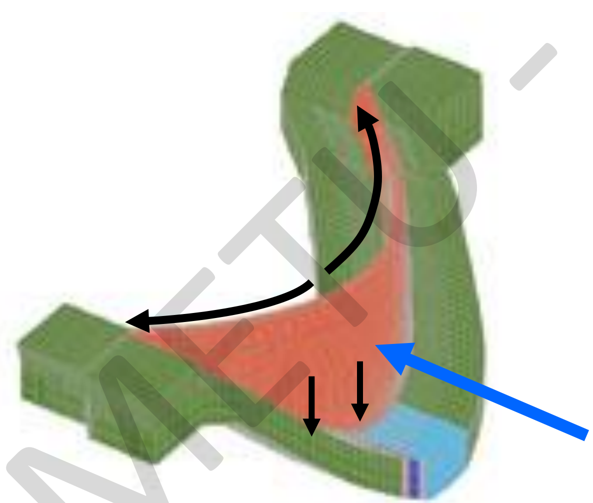
Sarıyar Dam (Concrete Gravity) on Sakarya River

Suçatı Dam (Roller Compacted Concrete, RCC)
on Güredin (Ceyhan) River

Suçatı Dam (Roller Compacted Concrete, RCC)
on Güredin (Ceyhan) River

b) ARCH DAMS

- Constant-angle arch
- Constant-center arch
- Variable-angle, variable center arch

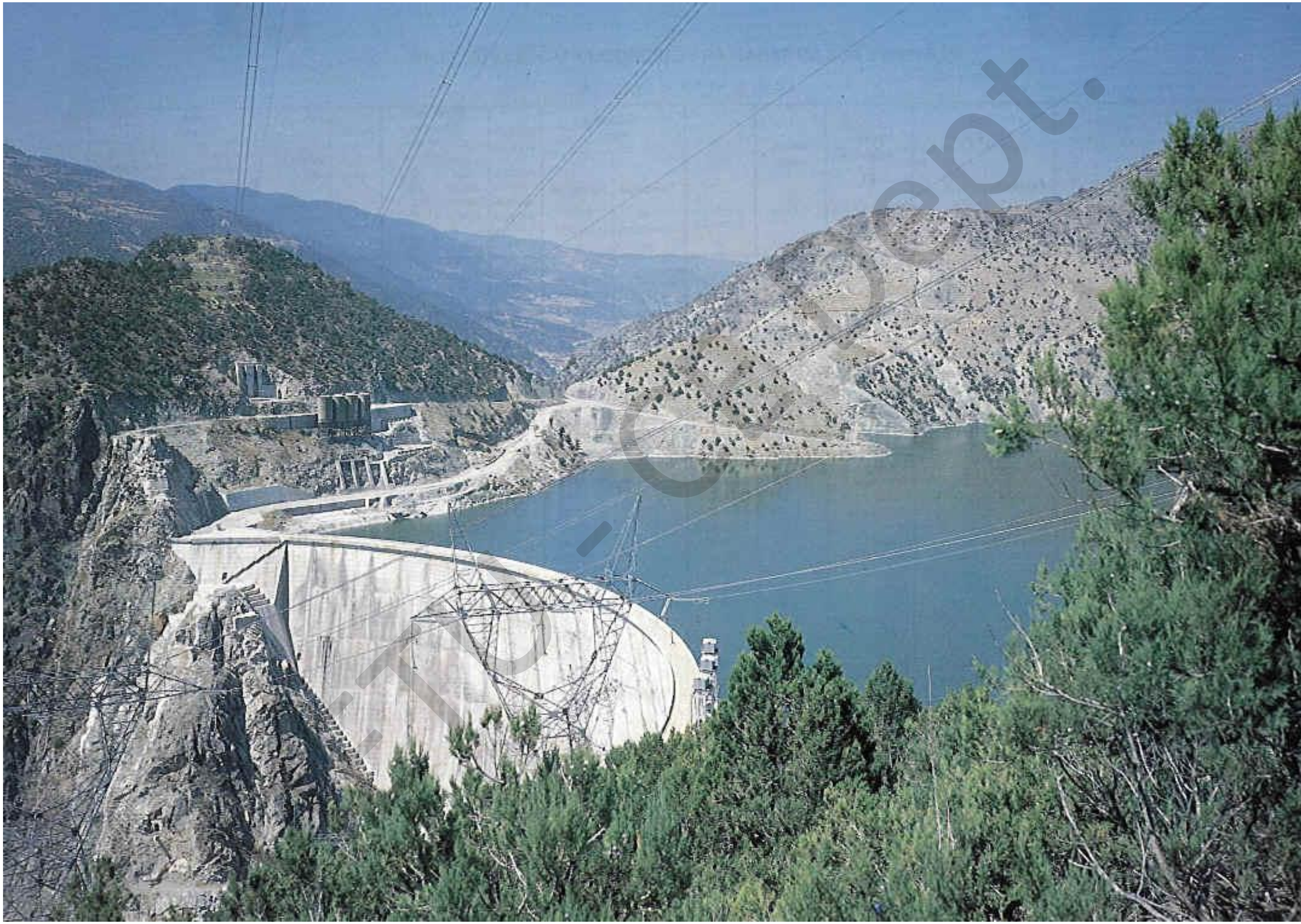


http://www.minstroy.com/images/proekti/caknkov_kamak/stenata.jpg

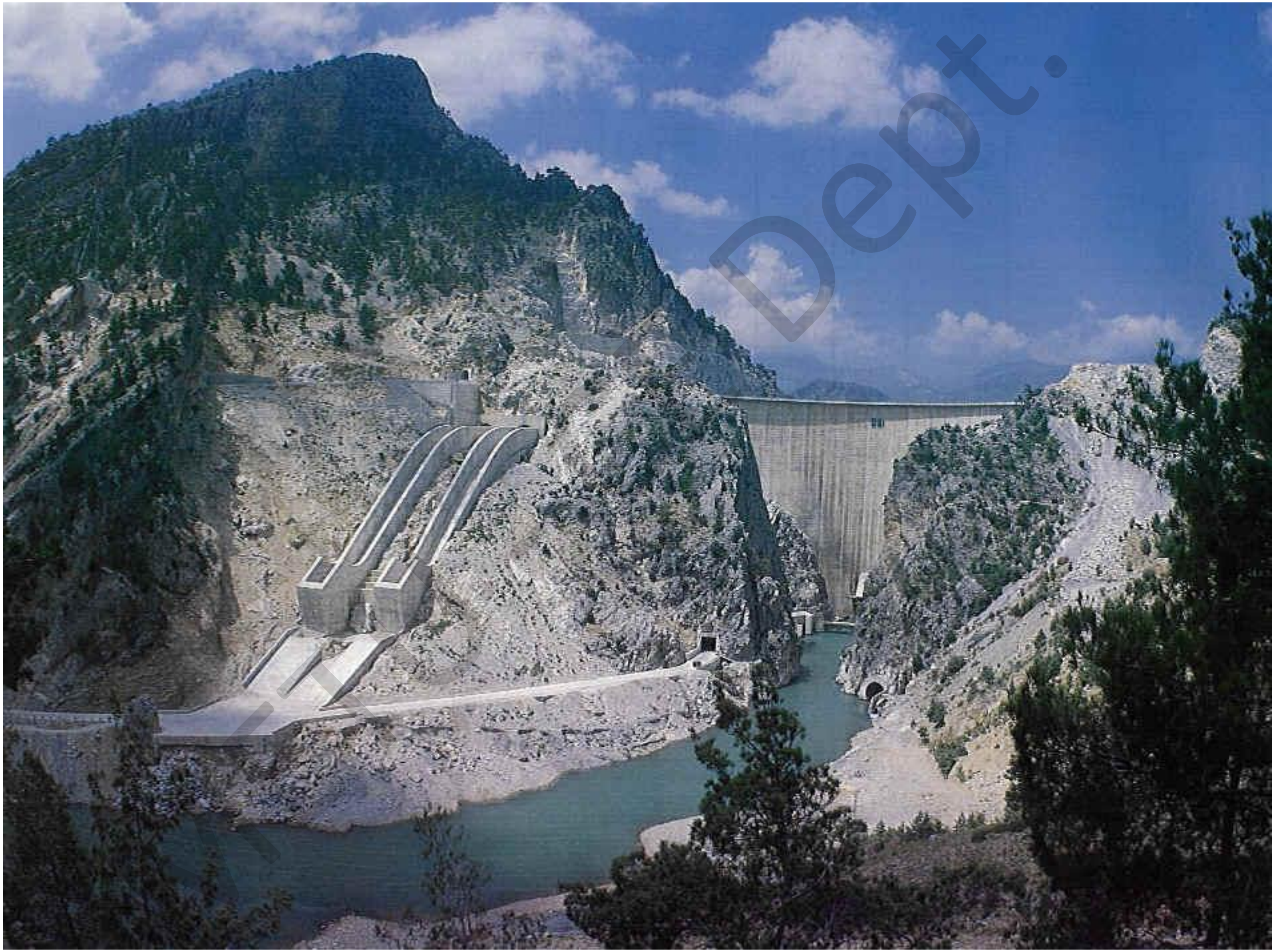
Most of the forces are transferred to the sides/slopes of the valley

⇩

Sides of the valley need to be strong



Gökçekaya Dam (Arch) on Sakarya River



Oymapınar Dam (Arch) on Manavgat River

Karakaya Dam (Arch-Gravity) on Fırat River

b) BUTRESS DAMS

- Flat-slab buttress
- Multiple-arch butress

Elmalı II Dam (Flat-Slab Buttress) on Çavuşbaşı River

d) EMBANKMENT (FILL) DAMS – composed of earth material at the dam site

- Earth-fill (>50% of fill is soil)
  - Simple embankment
  - Zoned embankment
  - Diaphragm-type embankment
- Rock-fill (>50% of fill is of rock)
  - Impermeable-face
  - Impermeable earth-core

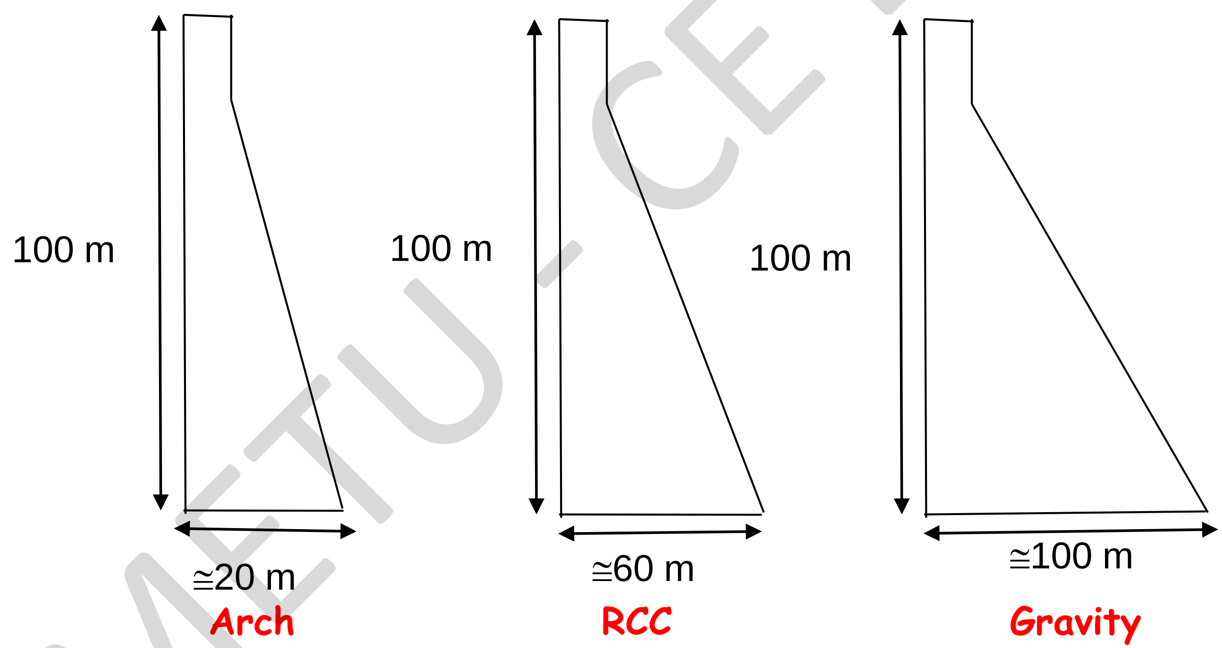
Atatürk Dam (Rockfill) on Fırat River

Hasan Uğurlu Dam (Rockfill) on Yeşilırmak

Kılıçkaya Dam (Rockfill) on Kelkit River

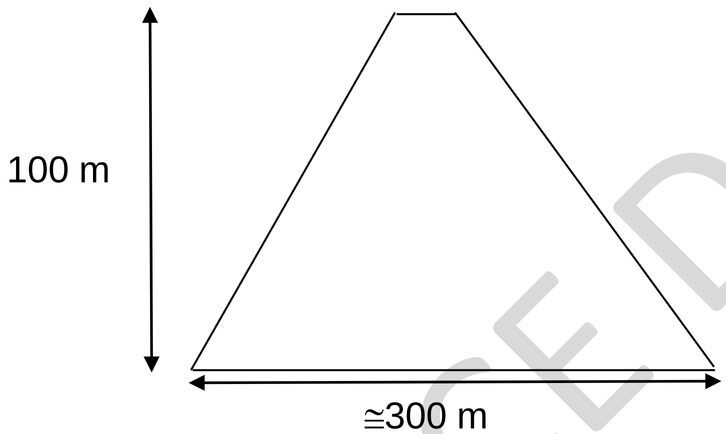
Comparison of dams according to V_b

Concrete dams

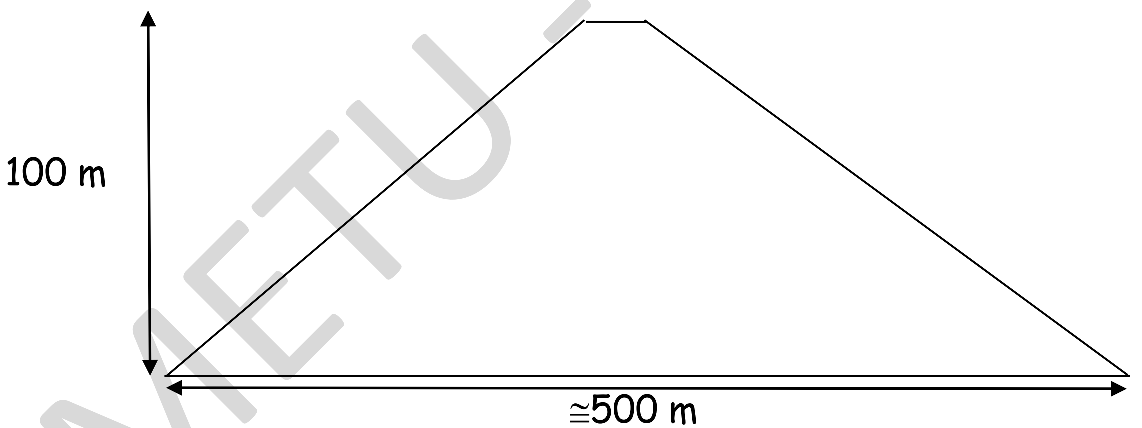


less economic in terms of material required

Fill dams



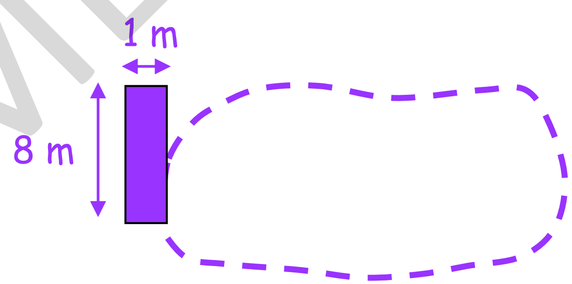
Rockfill



Earthfill

Comparison of some dams

Dam	Type	H_f (m)	V_b ($\times 10^6$ m^3)
Boyabat	Gravity	193	2.3
Berke	Arch	186	0.74
Atatürk	Rockfill	166	84.5



1×8 m^2 wall along Turkey's border!

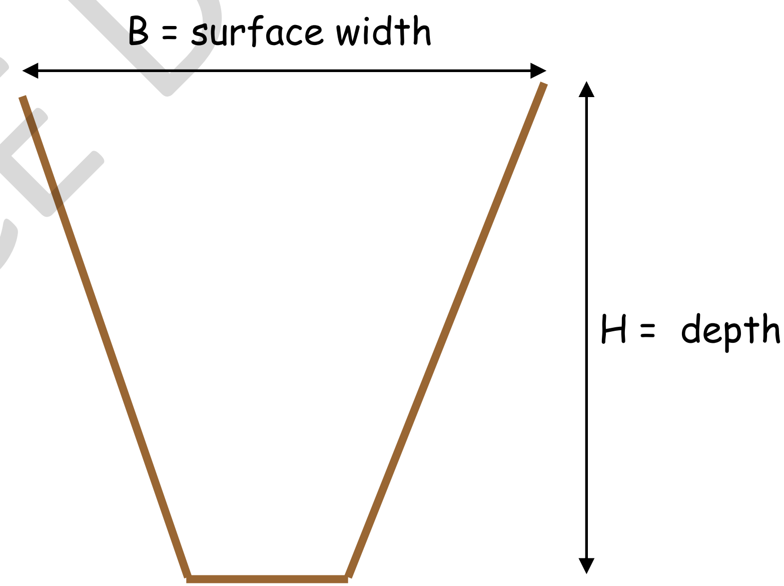
Shape of valley → Type of dam

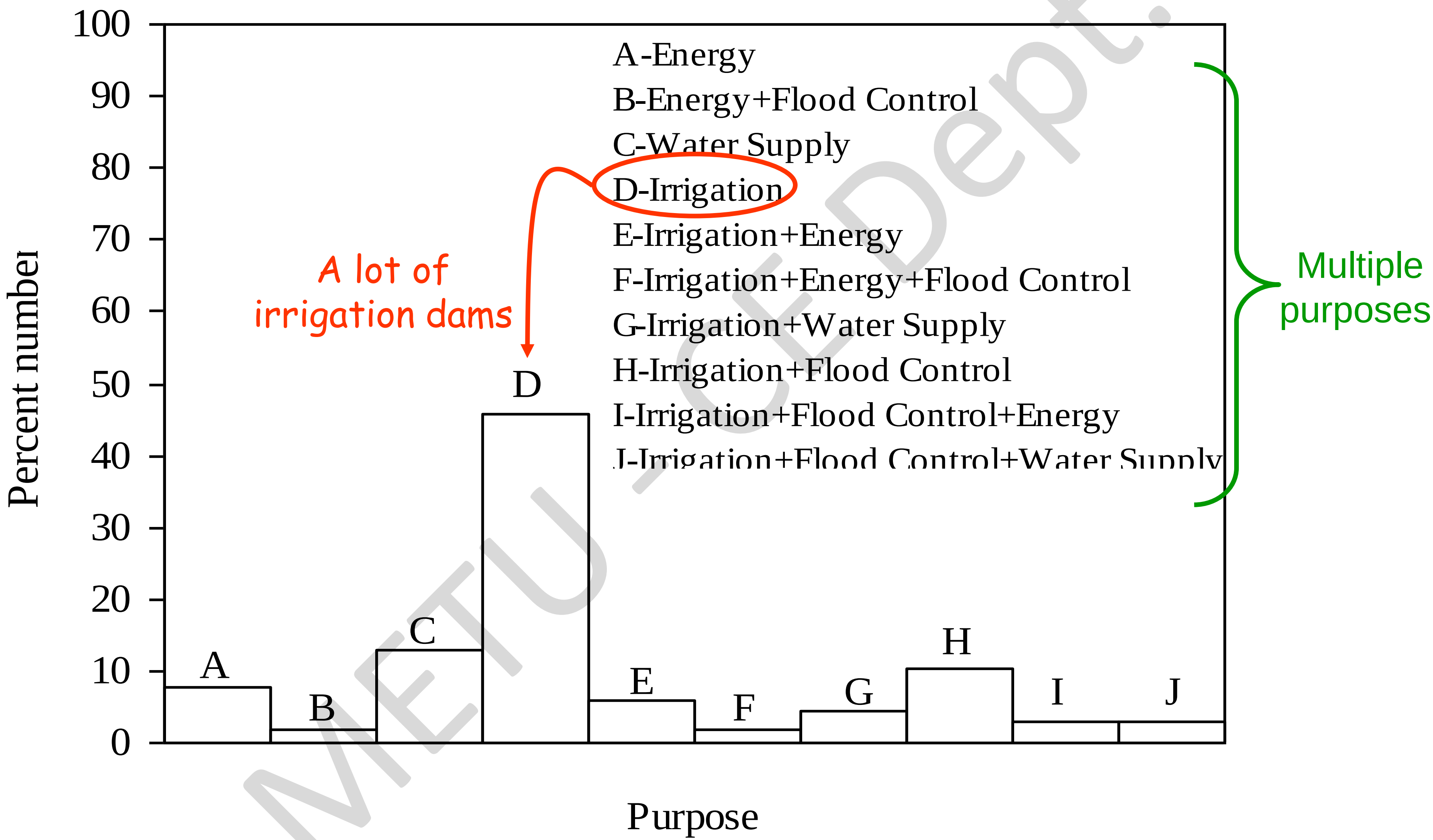
B/H < 3, gorge

3 ≤ B/H ≤ 6, narrow canyon

B/H > 6, wide valley

Characterized the valley → dam type

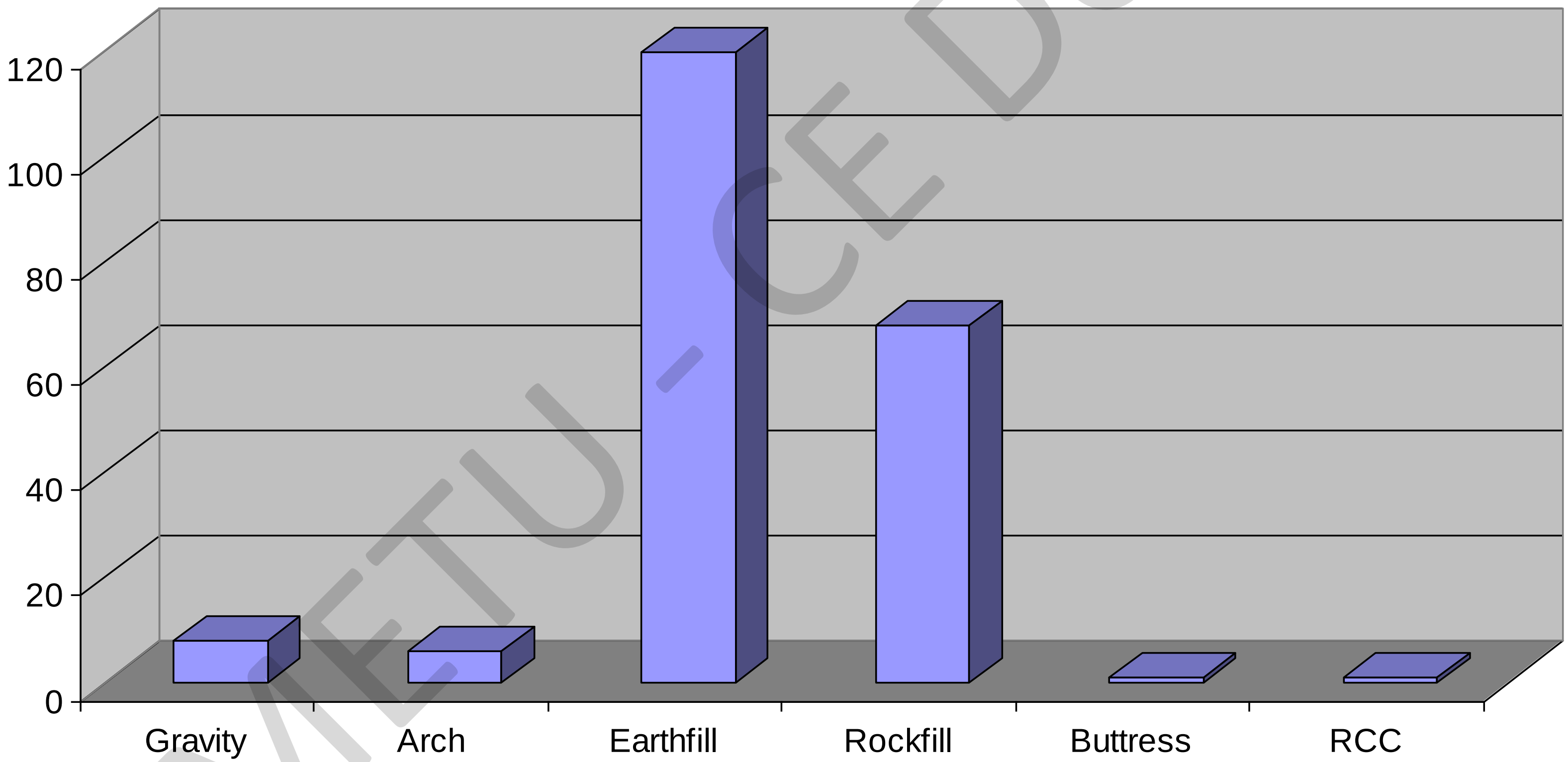




100
90
80
70
60
50
40
30
20
10
0
Percent number
Purpose
A
B
C
D
E
F
G
H
I
J
A-Energy
B-Energy+Flood Control
C-Water Supply
D-Irrigation
E-Irrigation+Energy
F-Irrigation+Energy+Flood Control
G-Irrigation+Water Supply
H-Irrigation+Flood Control
I-Irrigation+Flood Control+Energy
J-Irrigation+Flood Control+Water Supply
A lot of irrigation dams
Multiple purposes!

Statistical values on Turkish Dams (As of 2002)

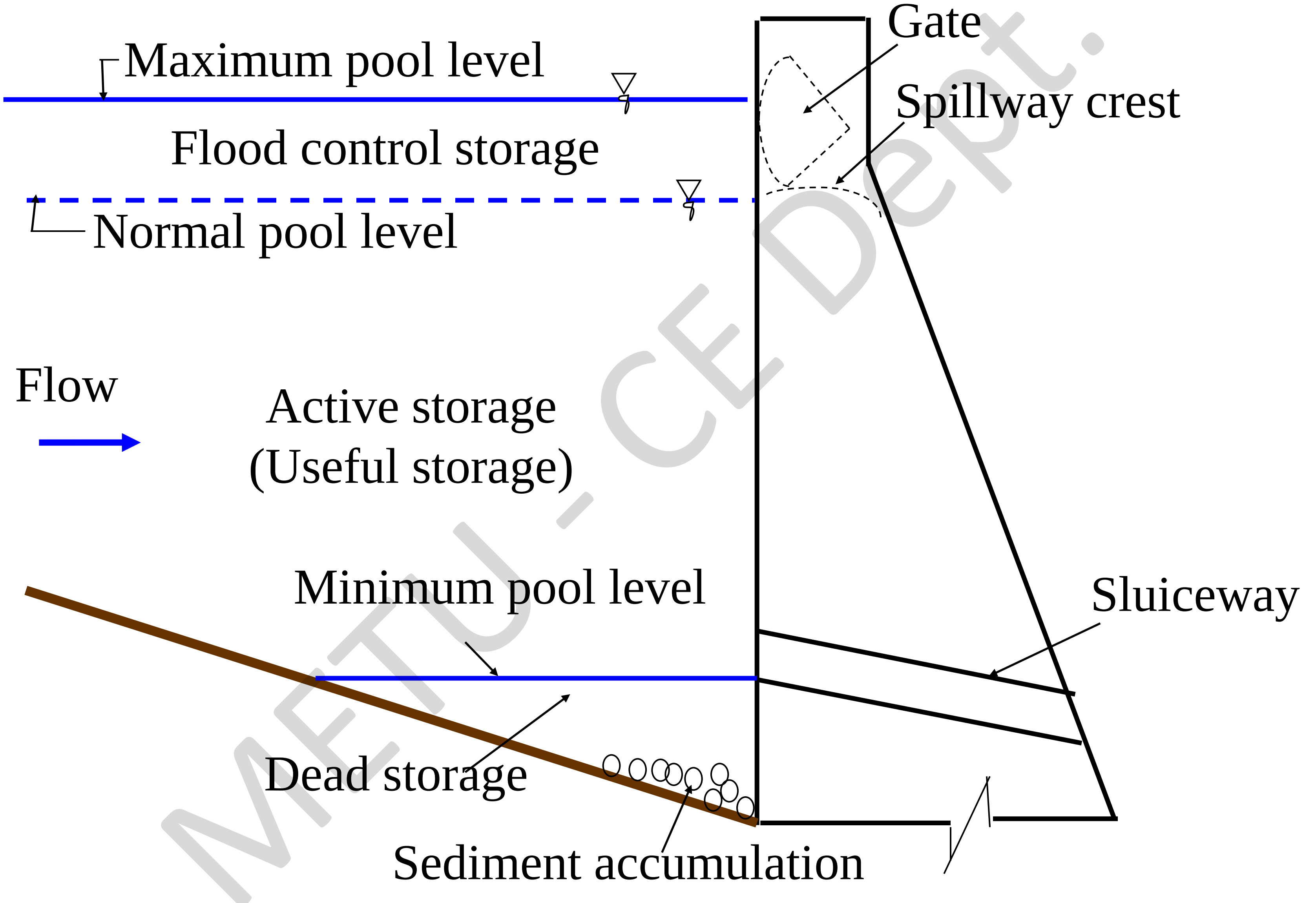
Number of dams under operation: 204



Most of the dams are fill type!

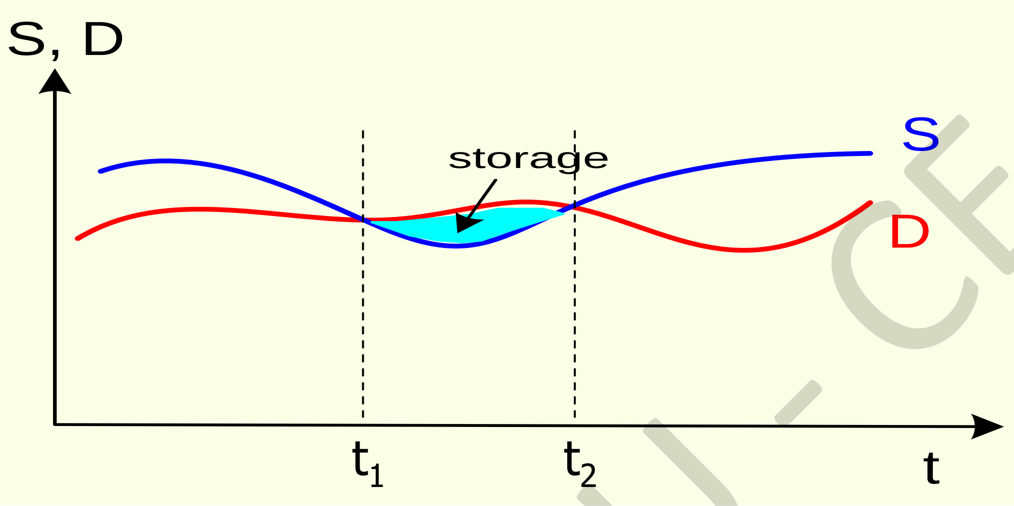
Hasan Uğurlu Dam

Çamlıdere Dam’s water intake



Gate
Maximum pool level
Spillway crest
Flood control storage
Normal pool level
Flow
Active storage
(Useful storage)
Minimum pool level
Sluiceway
Dead storage
Sediment accumulation

Reservoir Capacity Determination



Sometimes S < D

Storage is necessary

Critical period = [t_1 , t_2]

$$\text{Storage} = \int_{t_1}^{t_2} (D - S)\, dt$$

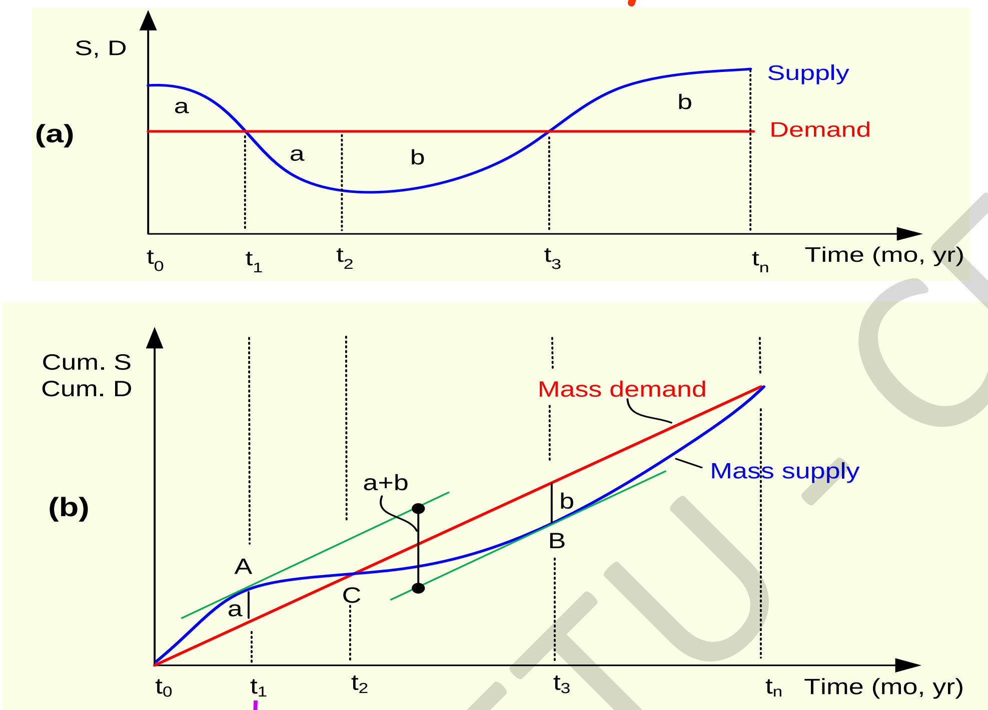
S : Supply

D : Demand

$\Sigma S \geq \Sigma D$

Reservoir Capacity Determination

Mass curve analysis



$\sum S = \sum D$

S: varying
D: constant

$t_0 - t_1 \rightarrow S > D \rightarrow$ (a)
$t_1 - t_2 \rightarrow S < D \rightarrow$ (a)
$t_2 - t_3 \rightarrow S < D \rightarrow$ (b)
$t_3 - t_n \rightarrow S > D \rightarrow$ (b)

$\left.\begin{matrix} t_1 - t_2 \\ t_2 - t_3 \end{matrix}\right\}$ (a+b)

Critical period = [t_1 , t_3]

Required storage = a + b

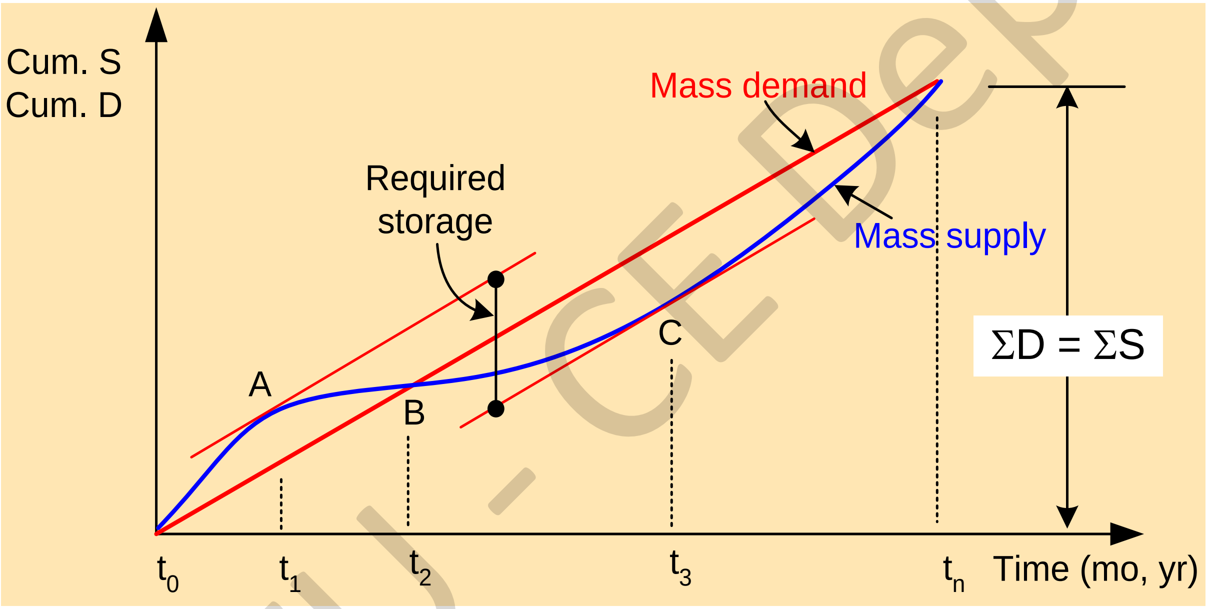
$$\text{Storage} = \int_{t_1}^{t_3} (D - S)\,dt$$

from second year on there will not be any shortage

Discharge S at t_1 = Discharge D at t_1

From t_0 to t_1 reservoir will store a amount of water.
From t_1 to t_2 the stored amount a will be used.
At t_2 reservoir will be empty.
From t_2 to t_3 there will be b amount of shortage of water.
At t_3 the reservoir will start to fill again.
At t_n the reservoir will store b amount of water.

Reservoir Capacity Determination



100 % regulation ($\Sigma S = \Sigma D$)

Example 11 Determine the capacity of storage reservoir with given monthly flows using mass curve analysis. Assume yield is equal to average flow. Also find the monthly contents of the reservoir and monthly changes in the reservoir volume.

a) Tabular solution:

Month	St (10^6 m^3)	Dt (10^6 m^3)	ΣSt (10^6 m^3)	Σ Dt (10^6 m^3)	Σ St- Σ Dt (10^6 m^3)	Change in res.vol. (10^6 m^3)	Res. content (10^6 m^3)
1	2	3	4	5	6	7	8
Oct.	2,3	5,5	2,3	5,5	- 3,2	-3.2	2.1
Nov.	3,8	5,5	6,1	11,0	- 4,9	-1.7	0.4
Dec.	5,1	5,5	11,2	16,5	- 5,3 *	-0.4	0
Jan.	7,1	5,5	18,3	22,0	- 3,7	1.6	1.6
Feb.	8,2	5,5	26,5	27,5	- 1,0	2.7	4.3
March	11,5	5,5	38,0	33,0	5,0	6	10.3
April	7,2	5,5	45,2	38,5	6,7	1.7	12
May	11,8	5,5	57,0	44,0	13,0 *	6.3	18.3
June	3,5	5,5	60,5	49,5	11,0	-2	16.3
July	1,5	5,5	62,0	55,0	7,0	-4	12.3
Aug.	2,2	5,5	64,2	60,5	3,7	-3.3	9
Sep.	1,8	5,5	66,0	66,0	0,0	-3.7	5.3
S	66	66					

start here

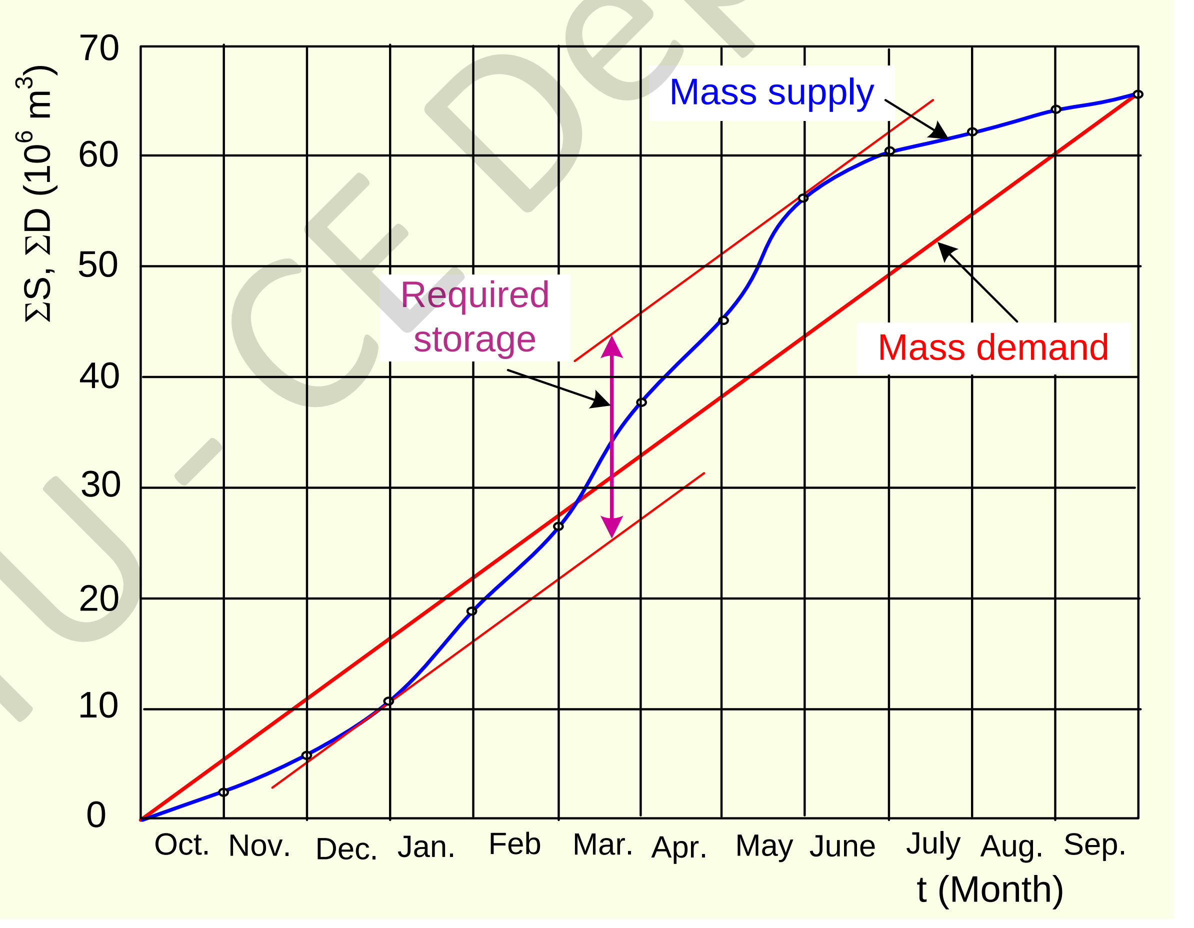
given

66/12 = 5.5

S = 5.3 + 13.0 = 18.3*10^6 m^3
(sum of highest negative and highest positive values in column 6)

b) Graphical solution

Month	ΣS_t ($10^6\ m^3$)	ΣD_t ($10^6\ m^3$)
(1)	(2)	(3)
Oct.	2,3	5,5
Nov.	6,1	11,0
Dec.	11,2	16,5
Jan.	18,3	22,0
Feb.	26,5	27,5
March	38,0	33,0
April	45,2	38,5
May	57,0	44,0
June	60,5	49,5
July	62,0	55,0
Aug.	64,2	60,5
Sep.	66,0	66,0



$$S = 18.3 * 10^6\ m^3$$

Some examples – people impacted from dam projects in Turkey

	KEBAN	KARAKAYA	ATATÜRK
# of people directly and indirectly impacted	46167	45000	50000
# of families resetteled	159	250	344
# of villages impacted	126	105	142 + 1 district

Ref: TRCOLD (1999). Dam Engineering in Turkey, Turkish National Committee On Large Dams, Ankara.

Planning of dams:

- Reconnaissance surveys $\Rightarrow$ eliminate infeasible alternatives
- Feasibility study $\Rightarrow$ select the best dam type & site
  - Economical &
  - Technical feasibility
- Planning study $\Rightarrow$ design the selected alternative
  - Final design
  - Operational policy
  - Management requirements, etc.

Feasibility study:

- estimation of water demand, D → HARD!
- determination of water potential, S → HARD!
- optimal plans, D ⇔ S → VERY IMPORTANT
  - For ex: If D>>S then a large reservoir is required
- determination of dam site
- determination of dam type
  - foundation conditions
  - availability of material
  - spillway type
  - earthquake zone, etc.
- project design → DIMENSIONS

Feasibility study-Determination of dam site

- topography
- geologic formation → effect foundati
- flood hazard → storage capacity shoul
- spillway location & possibilities
- climate
- diversion facilities
- sediment problem → impacts lifetime of the project
- water quality → upstream reaches of river are preferable for dams
- transportation facilities → locations that require min. cost for road construction
- right of way cost → relocation of too many people is NOT GOOD (istimlak bedeli)

narrow valley with rock abutments → arch dams

low rolling hills → fill dams

If large flood evacuation

In a rainy climate, construction of an earthfill dam is not easy thus a rockfill dam is preferable

NOT good location for a dam due to sedimentation prob.

Feasibility study-Project design

- Hydrologic design
  - determination of maximum design lake elevation
  - determination of spillway capacity
  - determination of crest elevation of the dam

- Hydraulic design
  - determination of static and dynamic loads
  - design of spillway and energy dissipating facilities
  - design of outlet works

- Structural design
  - determination of stress distributions
  - determination of required reinforcement
  - structural checks for the body, spillway, and outlet works

Dam break scenarios!

St. Francis Dam (California, USA) → arch dam
collapsed during a heavy flood (1928)

Teton Dam (Idaho, USA) → earhfill dam
collapsed due to seepage (1976)
it was 1 year old when collapsed

14 lives
+
1 billion $
lost

1. Reconnaissance surveys
2. Feasibility

3. Planning study:

- topographic surveys → reservoir area-elevation-volume curves are determined
- foundation studies → are carried out for seepage, permeability, grouting, etc.
- details on materials & constructional facilities → quantity of mat'ls req'd, # and type of construction equipment, etc.
- hydrologic study → measurement of rainfall, discharge, temp., etc., a stream-gauging station is established.
- reservoir operation study → performed periodically

Construction of dams

a) evaluation of time schedule & required equipment

- Coordination of various companies

b) diversion of river flow

- To provide a dry area for construction

c) foundation treatment

- Less deformation
- ↓ permeability & seepage
- ↑ shearing strength
- Slope stability for side hills

- Concrete & rock-fill dams should be adapted for hard formations like rock & granite
- Earth-fill dams can be choosen for most type of foundation conditions.

d) formation of dam body

a) Time schedule & equipment:

- map of dam site: 1/500 - 1/5000
- the approximate quantities of work
  - excavation
  - concrete pouring
  - filling
  - explosions
  - grouting
- diversion facilities
- urgency of work ⇒ national project !

Various structural units of a dam may be constructed by different companies

⇓

coordination is IMPORTANT

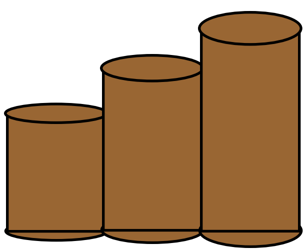
b) Diversion of river flow

- diversion by side tunnel or channel
  - tunnel – preferable for narrow & stiff valley
  - channel – preferable for wide valley

- two-stage diversion

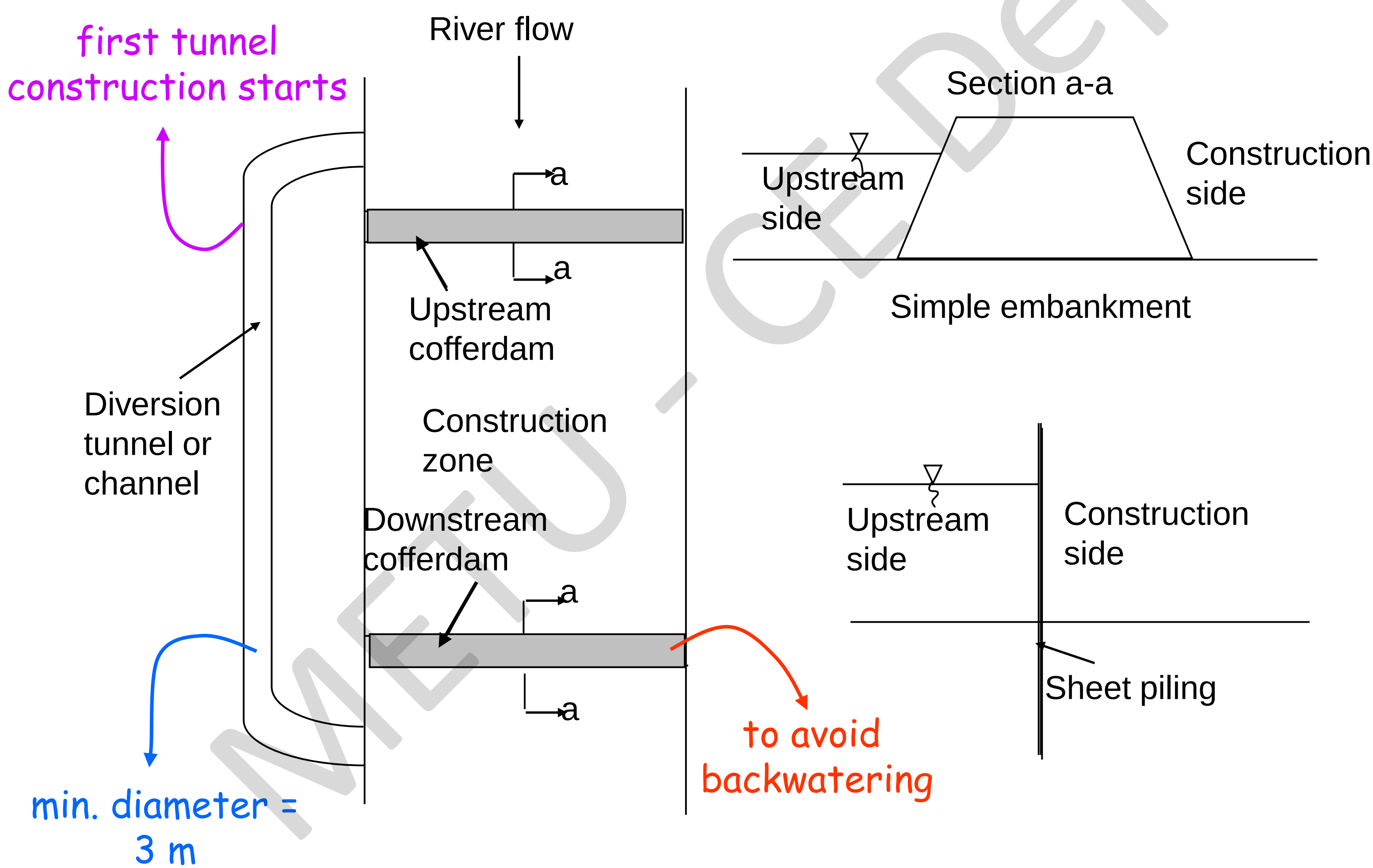
A diversion facility is composed of:

- a conduit
  - a tunnel of a diameter of D_{min}= 3 m → so that a small truck can fit in
  - a lined trapezoidal channel
- upstream and downstream cofferdams
  - embankment
    - homogeneous fill
    - zoned fill
  - sheet pile
  - cellular

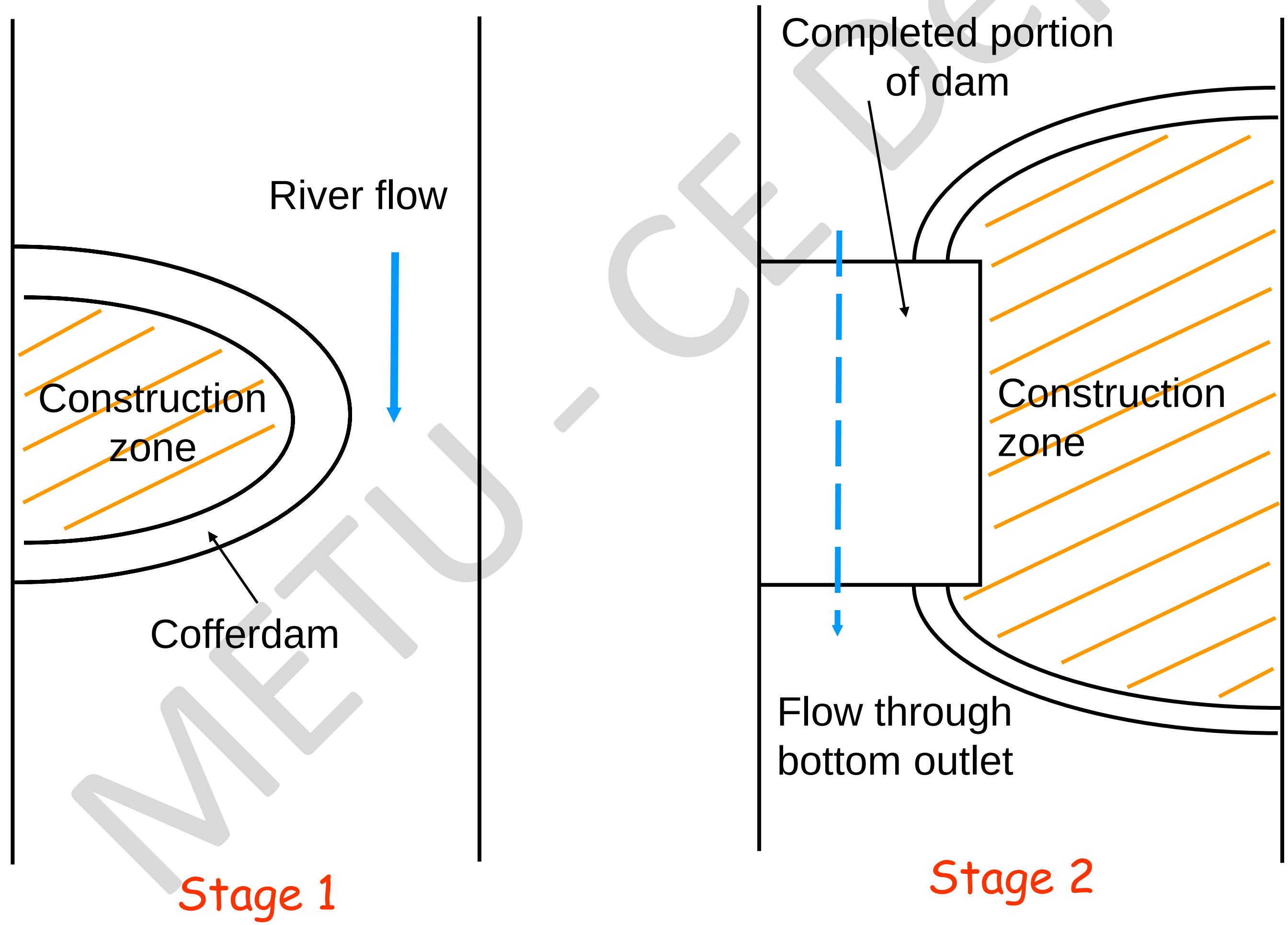


containers filled with earth material

Diversion by side tunnel or channel



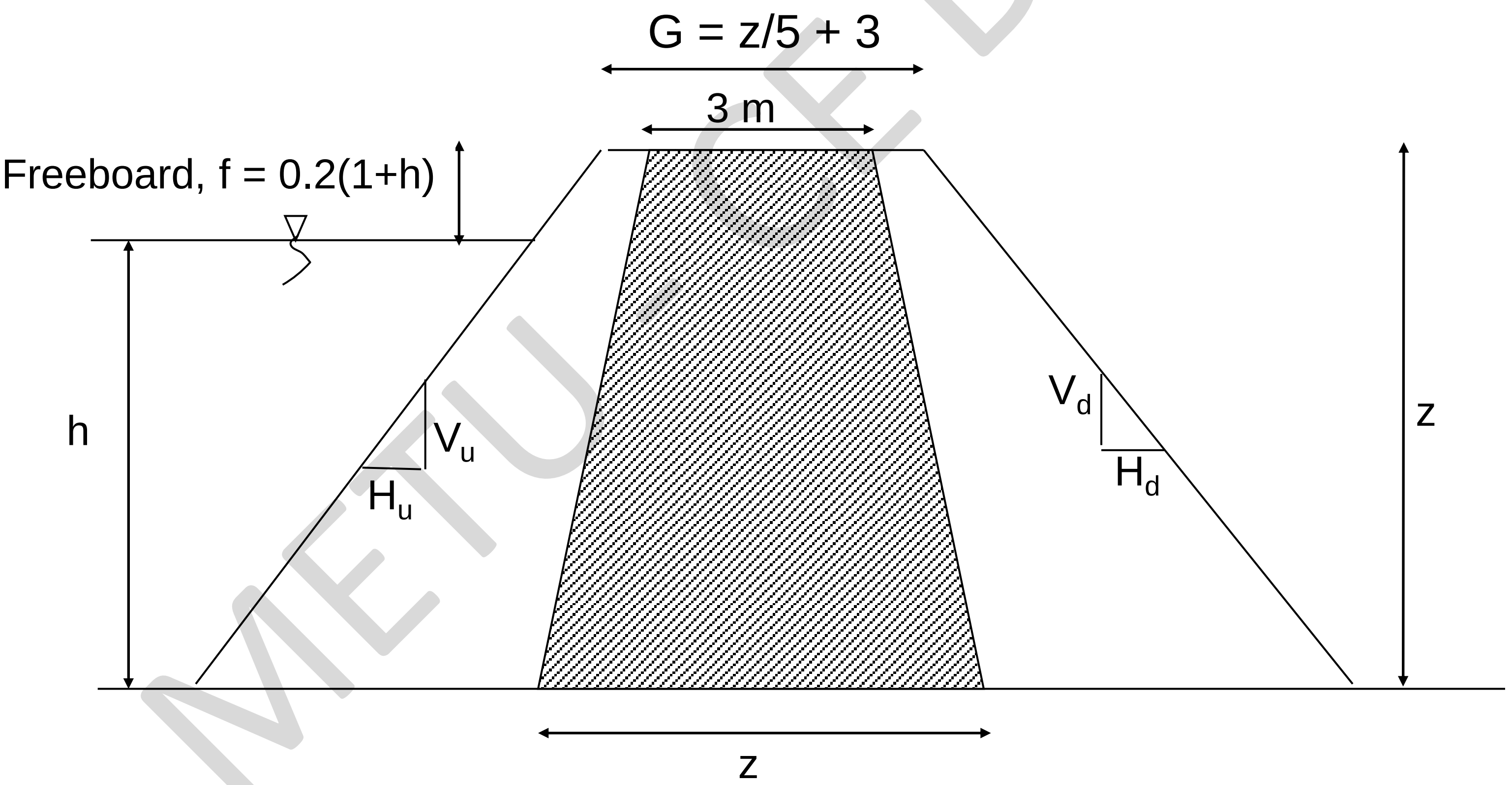
Two-stage diversion - practiced especially in wide valleys good for concrete dams



Earth cofferdam on impervious foundation

Generally designed for 20 yr flood

should be constructed during low flow season



c) Foundation treatment

- the foundation must be excavated to solid rock before any concrete is poured.
- after excavation the cavities or faults in the underlying strata are sealed with concrete or grout.

a) Clearing:

- leveling of reservoir site → dam will fill evenly
- stripping of dam site → increase shear resistance
- removal of organic material and wastes → avoid taste & odor and also to avoid increase of porosity in embankment dams

Foundation treatment

b) Grouting operation:

Grout mix → cement, water & aggregate

Grout mix is injected under pressure (so that the mix will reach deaper regions)

- to increase the foundation bearing capacity
- to reduce foundation porosity
- to solidify the formation underlying the dam & the reservoir

c) Relief drainage:

- use of proper drainage facility, e.g. downstream wells

d) Formation of dam body

a) Concrete dams
- are built of mainly plain concrete to take compressive stresses
- their own weight resists the forces exerted on them

- concrete is poured in isolated blocks of
  * 1.5 m high
  * 15 m long

- Care: Minimize heat generation!

  shrinkage ⇒ cracking

  ⇓

  * reduced bearing capacity !
  * increased seepage !

  ∴ Use of low-heat cement

Hydration: process by which cement reacts with water

↓

Heat is generated

↓

During dissipation of this heat in long term, the concrete cools & shrinks

↓

May cause cracks

↓

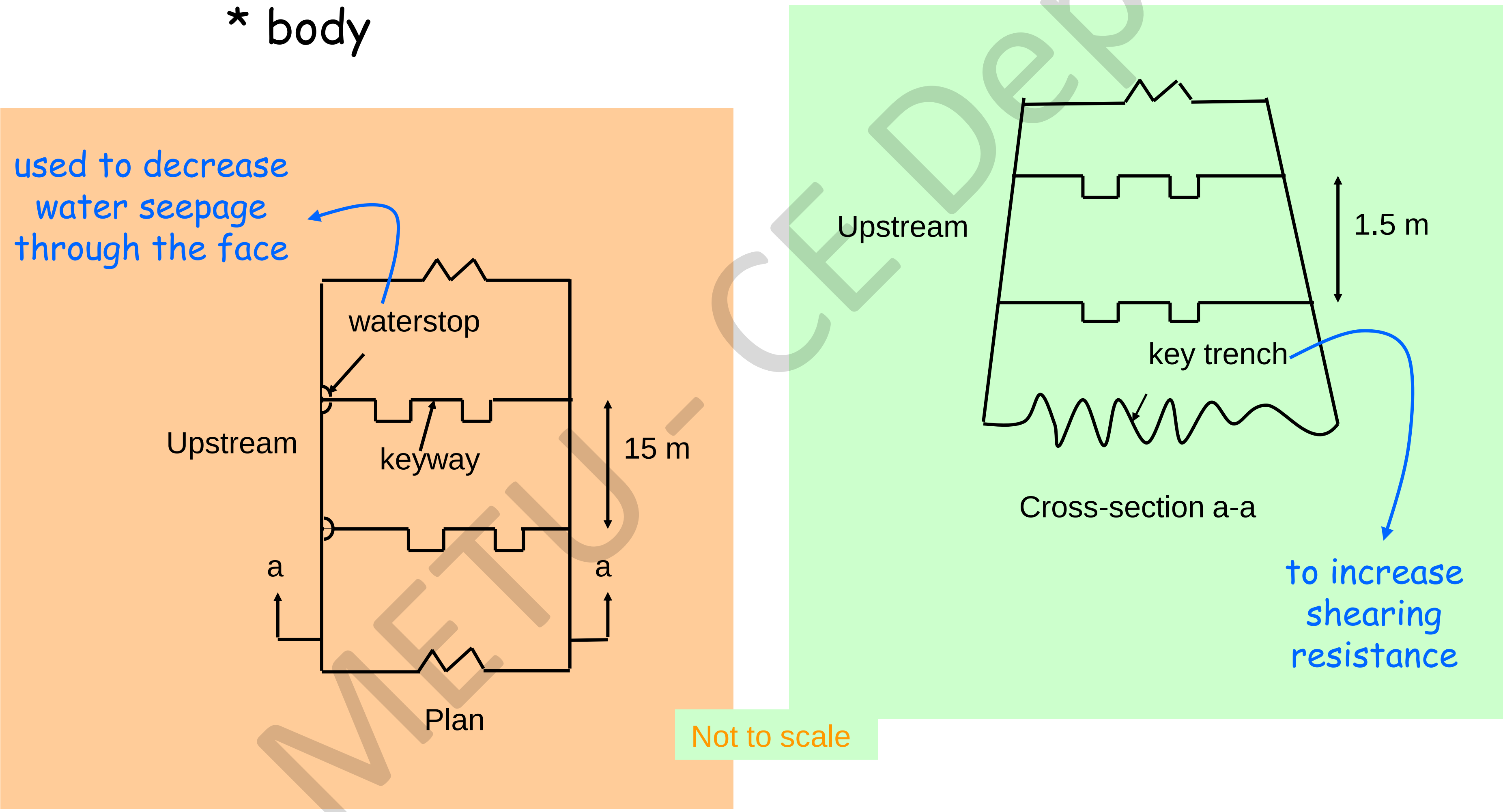
To meet crack control requirements, placement of concrete is done using monoliths

↓

Individual monoliths are seperated by contraction joints

Placement technique: key-trench formation

* foundation
* body



- contraction joints

  * control of internal (temperature) stresses !

- Painting lateral surfaces causes elimination of adherence of adjacent blocks

- Implementation of

  * Waterstops
  * Inspection galleries
  * Internal drainage facilities

seepage control

Concrete is a brittle material & is susceptible to cracking due to its low tensile strength

↓

To avoid development of tensile stresses due to shrinkage & temperature drop in mass concrete, concrete dams are built as assemblages of monoliths seperated by contraction joints

b) Prestressed concrete dams: (tension + compression)

- prefabricated elements of pre-tensioned bars

  prestressing elements minimize the tensile stresses in the concrete

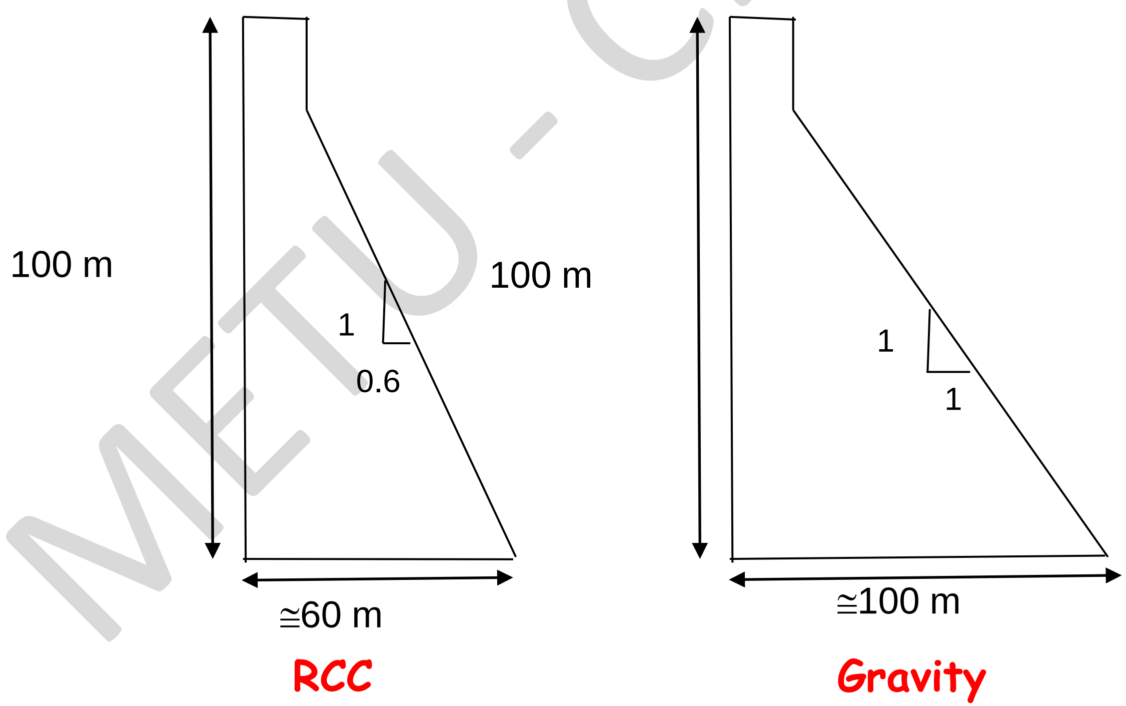
c) RCC dams: (compression)

- Preparation of a rather dry mix composed of
  - * limited cement → decreases cost
  - * fine & coarse aggregate → coarse agg. from explosions
  - * fly ash → reduces generation of heat during settling of concrete

    → less shirankage & craking
  - * limited water → dry mix
- Pouring this mix in ≈ 20 - 45 cm layers
- Compaction of layers by static or vibrating rollers

Advantages of RCC over Conventional Concrete Gravity:

- Economical
  - use of coarse aggregate and limited cement
  - specific weight of RCC is high → less volume of concrete required wrt conventional concrete gravity dam



- Greatly reduced heat generation during setting (fly ash)

↓

minimized shrinkage problem

↓

no need for vertical contraction joints

- Shorter construction duration than other types !

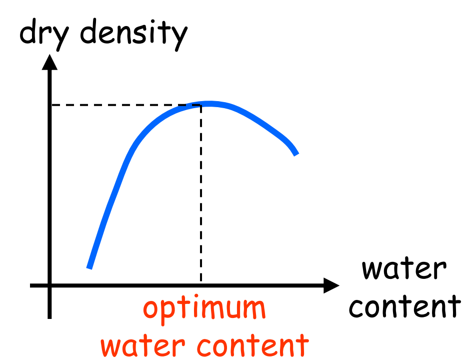
c2) Recent developments: Hardfill dams

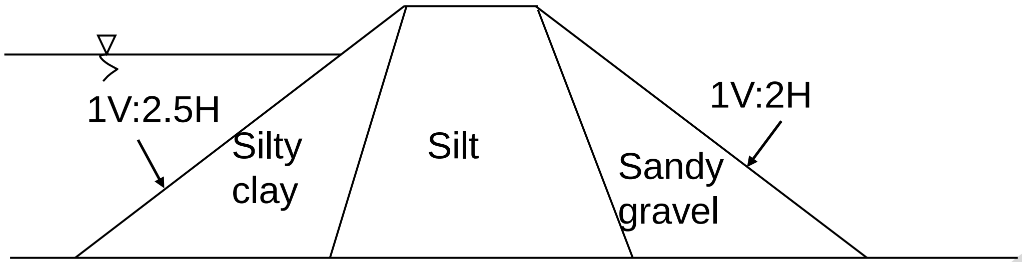
- Requires symmetrical cross-section → more stable but more material thus more expensive
- Very little or no binding material is used thus cheaper

d) Earth fill dams – more than 50% earth material

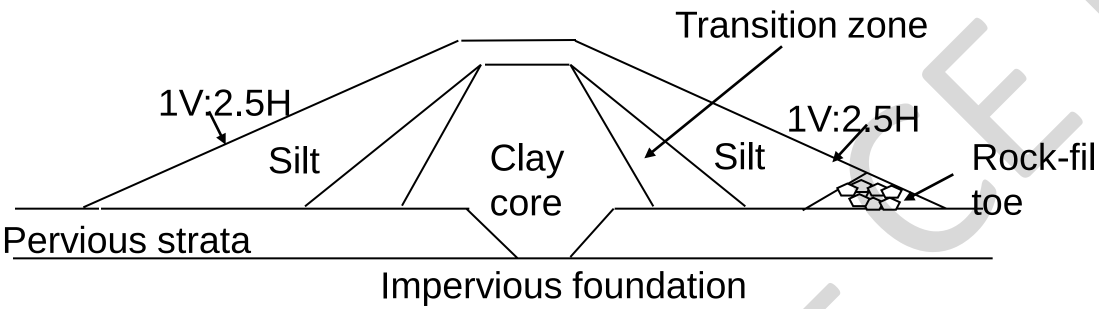
- Placement of fill material composed of
  - non-organic soil → decay causes posoristy to increase
  - non-plastic to low-plasticity soil → to avoid deformation
- Compaction of layers of ≈ 50 cm using sheep-foot rollers (fine aggregate) or vibrating rollers (coarse aggregate)
  - to increase compressive & shear strength and
  - to decrease voids
- Compaction under optimum moisture content

→ To obtain max. dry density for a desired compaction

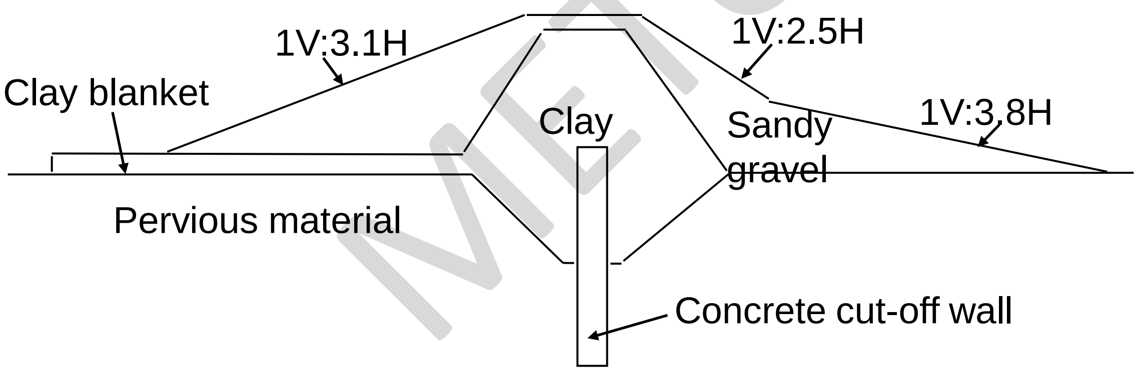




(a) Simple zoned embankment



(b) Earth dam with core extending to impervious foundation



(c) Earth dam on pervious foundation

- mass of the dam that will make it
- clay ← low permeability
  - gravel particles can be introduced into clay core to increase the shear strength of the core
- erosion protection at the UPSTREAM FACE

Slope stability

- choose proper side slopes for no sliding
- take proper slope-protection remedies:
  - Upstream face: protect against wave induced erosion
    - use rock/rip-rap or concrete
    - rip rap → to decrease water erosion by dissipating the energy of the waves
  - Downstream face: protect against wind/rainfall erosion
    - use grass, but not trees since big rooted plants increase seepage

e) Rock-fill dams – more than 50% is rock

- Formation of core and filter is similar to earth-fill dam!
- Compaction of saturated rock → better than just dumping because compaction provides better interlocking
- PROBLEM: Subject to considerable settlement ← dam is heavy

↓

Cracking of membrane

↓

periodic repair

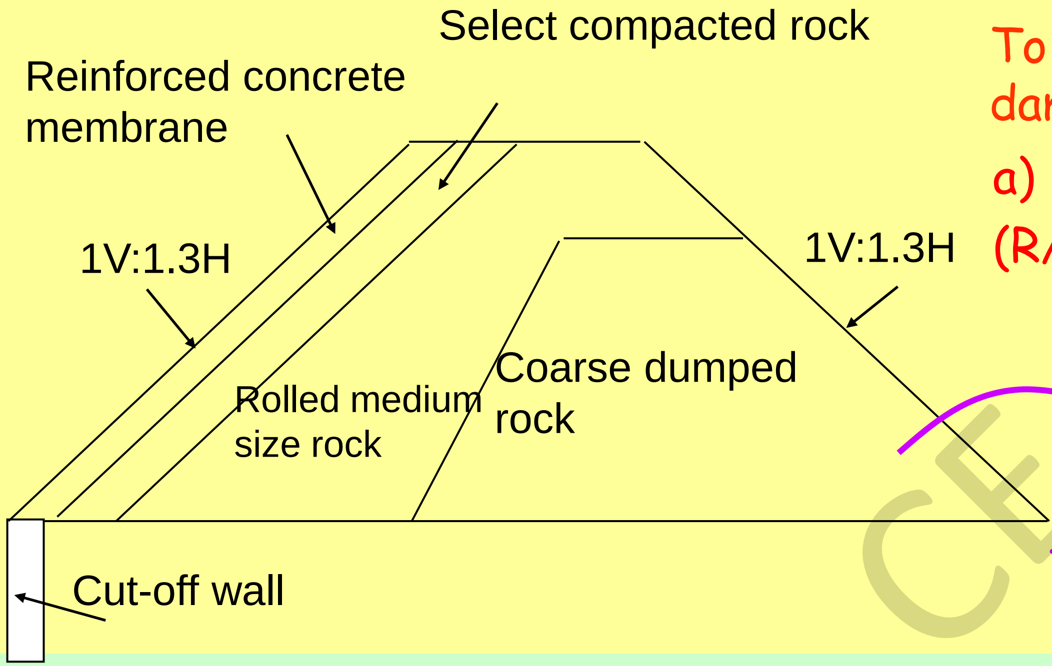
e) Rock-fill dams – more than 50% is rock

- Steeper side slopes than earth-fill dam → less material
- Rigid foundation conditions are required!
- Speedy construction, easy to increase crest elevation
  - in a rainy region rock-fill may be preferable
- Normally cheaper than a concrete gravity dam if proper material and equipment are available

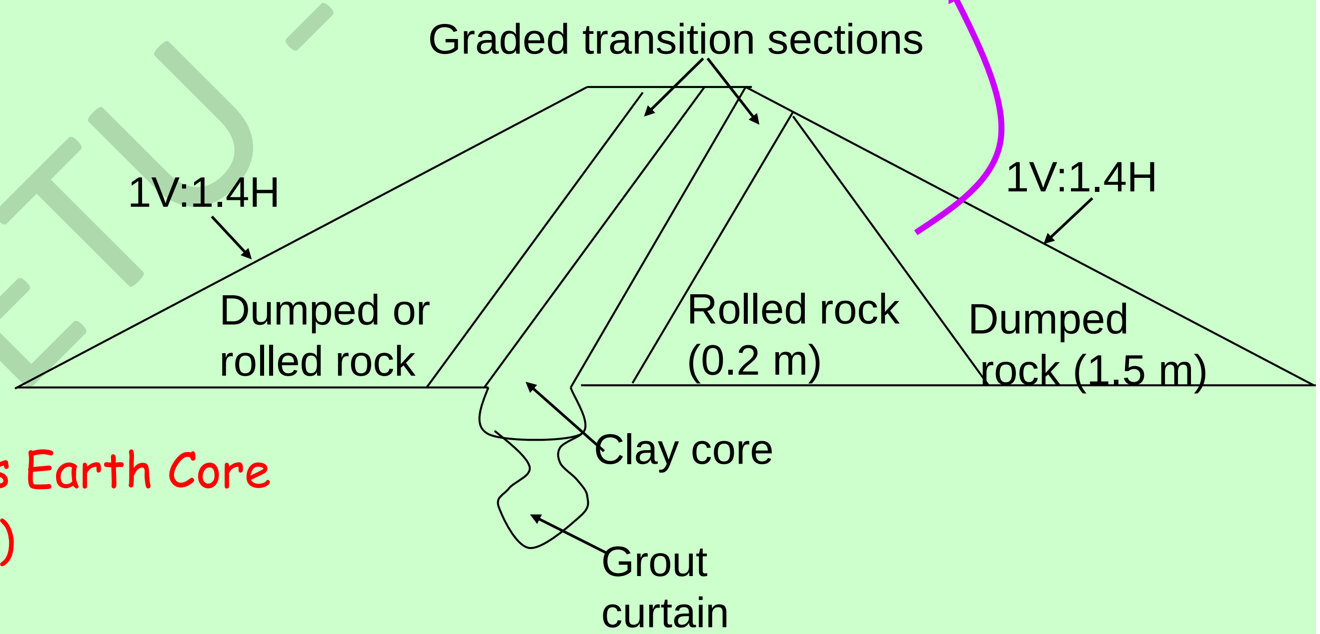
To control seepage through rock-fill dams:

a) Impervious Face

(R/C Membrane, Asphalt Facing, etc.)



dumped rock
to increase weight of the dam
(to increase stability)



b) Impervious Earth Core (Conventional)

Concrete gravity dams → Proportioned such that its own weight resists the forces exerted upon it

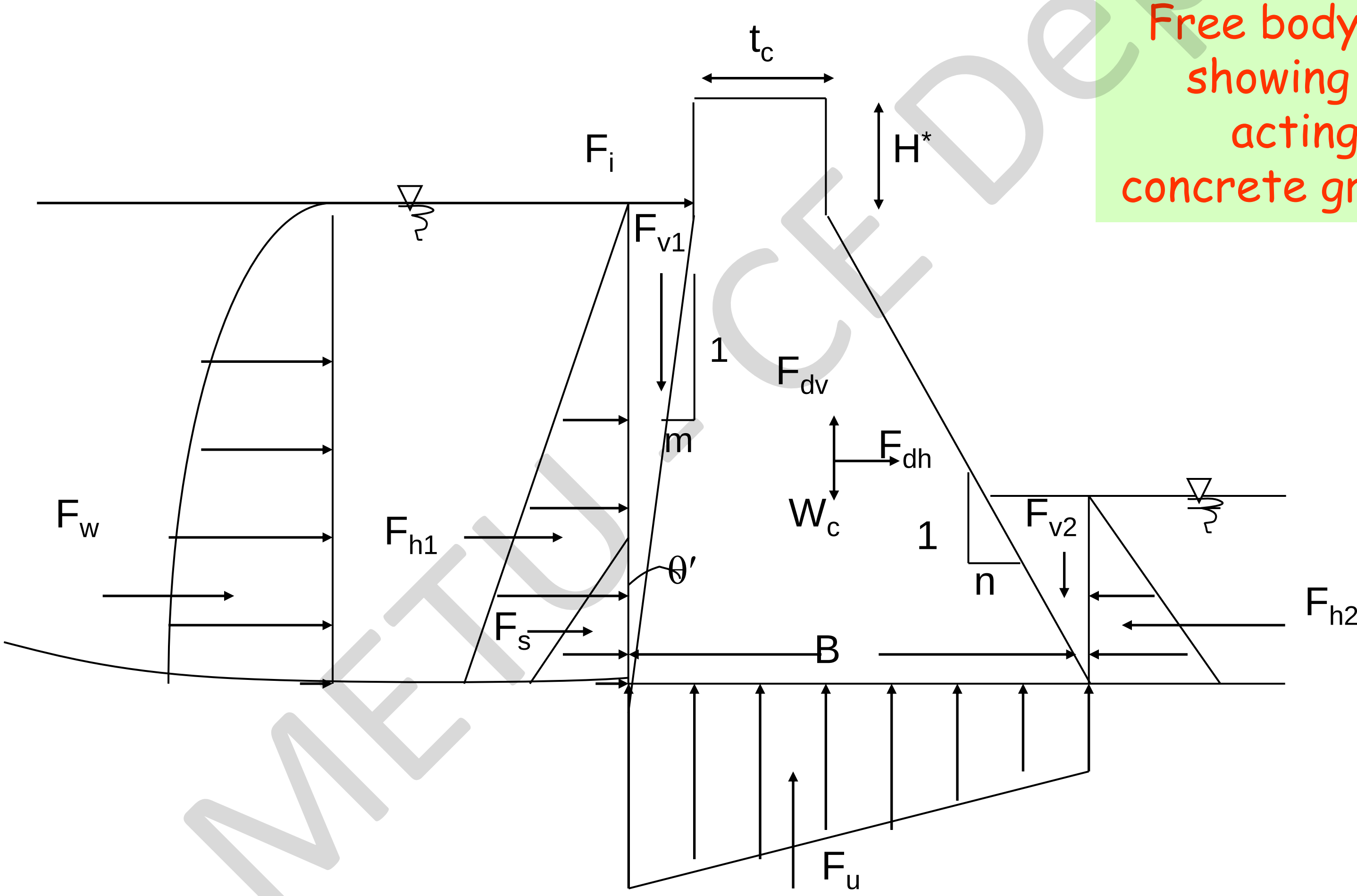
Gravity load satisfies the stability (its own weight)

Designed to

- take compressive stresses only
- be safe under all loading conditions against
  - overturning
  - shear and sliding
  - stresses in the body and at foundation

dimensions are chosen s.t. only compressive stresses develop under all loading conditions.

Forces acting on a concrete gravity dam



Free body diagram showing forces acting on a concrete gravity dam

- Weight of dam – acts at center of gravity of the dam

$$W_c = \gamma_c V$$

γ_c: specific weight of concrete

V: body volume

- Hydrostatic forces

$$F_{h1} = \frac{1}{2}\gamma h_1^2 \qquad F_{v1} = \frac{1}{2}\gamma m h_1^2$$

- Uplift force

$$F_u = \left[h_2 + \frac{\phi}{2}(h_1 - h_2)\right] B\gamma$$

ϕ: uplift reduction coefficient

Ex: If uplift forces reduction is 40% due to installation of drains, then Φ = 1- 0.4 = 0.6

- Lateral earth force – acts at $h_s/3$ above reservoir bottom

$$F_s = \frac{1}{2}\gamma_s h_s^2 K_a$$

active earth pressure coeff.

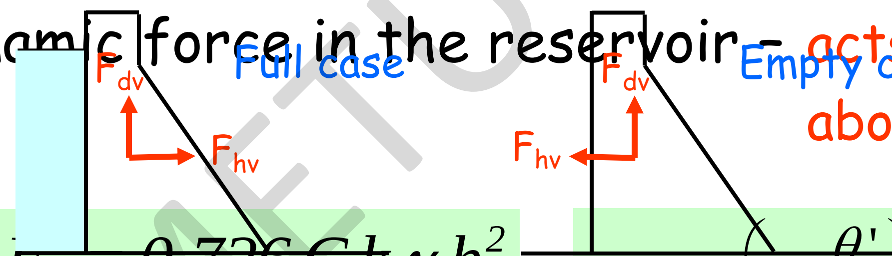
specific weight of sediment

- Earthquake force on the dam body – acts at center of gravity of the dam

$$F_{dh} = k_h W_c \qquad F_{dv} = k_v W_c$$

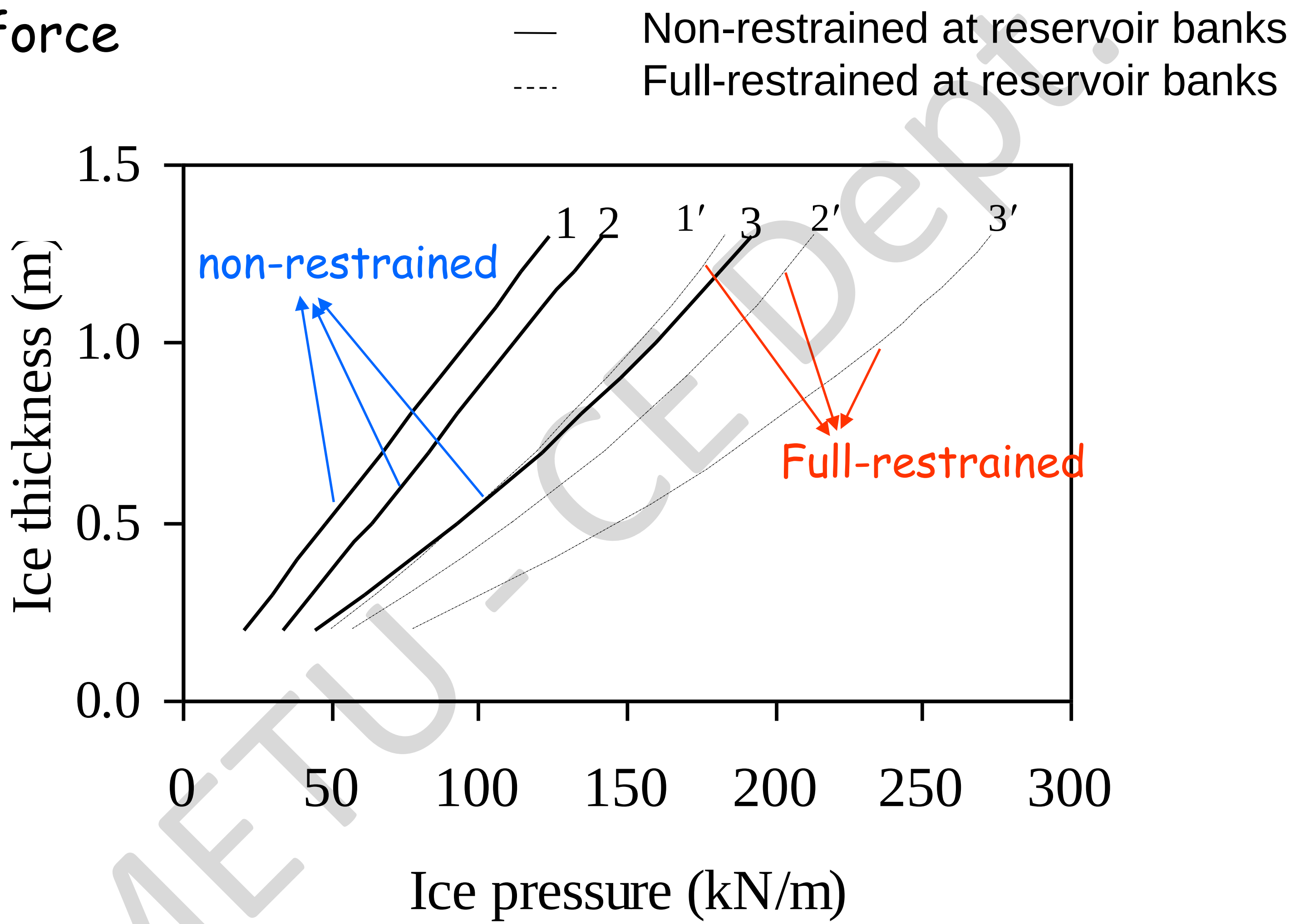
earthquake coeff.s

- Dynamic force in the reservoir – acts at a distance $0.412h_1$ above reservoir bed



$$F_w = 0.726\, C\, k\, \gamma\, h_1^2 \qquad C = 0.7\left(1 - \frac{\theta'}{90}\right)$$

Ice force

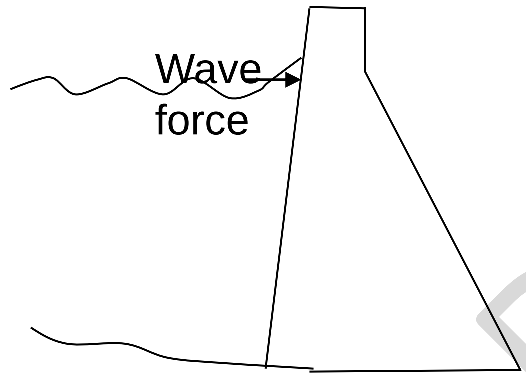


1- Temperature rising at 2.8°/hr

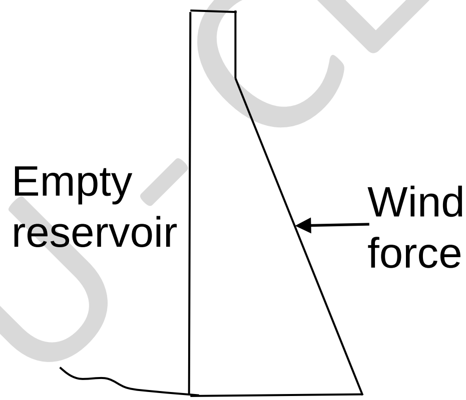
2- Temperature rising at 5.6°/hr

3- Temperature rising at 8.4°/hr

- Wave forces



- Wind forces



- Dynamic forces on spillways, $\Sigma F = \rho Q \Delta u$

Q	=	flow rate over spillway
Δu	=	change in velocity
ρ	=	density of water

Loading combinations

Stability analysis are conducted for various loading conditions & dam must prove its safety under all loading conditons.

1) Usual loading

- hydrostatic forces at normal operating level (F_h, F_v)
- uplift force (F_u)
- temperature stresses
- dead loads (W_c)
- ice load (F_i)
- silt load (F_s)

2) Unusual Loading – flood condition

- hydrostatic forces at full upstream level (F_h, F_v)
- uplift force (F_u)
- temperature stresses
- dead loads (W_c)
- silt load (F_s)

3) Extreme or Severe Loading

- forces in usual loading + earthquake forces

Requirements for stability

A dam may fail by

- Overturning
- Sliding
- Combined shear and sliding
- Stresses

- Rotation about the toe

- Sliding over a horizontal plane

- Failure of the material

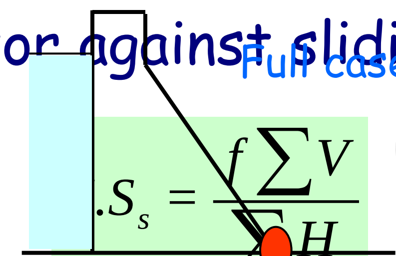
- Safety factor against overturning:

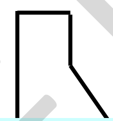
$$F.S_o = \frac{\sum M_r}{\sum M_o}$$

$\sum M_r$ → Total resisting moment about the toe

$\sum M_o$ → Total overturning moment about the toe

- Safety factor against sliding:





$$F.S_s = \frac{f \sum V}{\sum H}$$

f = coefficient of friction
$\sum V$ = sum of vertical forces
$\sum H$ = sum of horizontal forces

for empty case take moments wrt the toe

for empty case take moments wrt the heel

- Safety factor against shear-sliding:

$$F.S_{ss} = \frac{f \sum V + rA\tau_s}{\sum H}$$

$f \sum V$ → sliding

$rA\tau_s$ → shear

A = area of the shear plane
τ_s = shear strength of concrete
r = factor to express the max. allowable average shear stress

Stresses:

normal stress

vertical normal stress

$$\sigma = \frac{\sum V}{A} \pm \frac{Mc}{I}$$

bending stress

net moment about the center of base

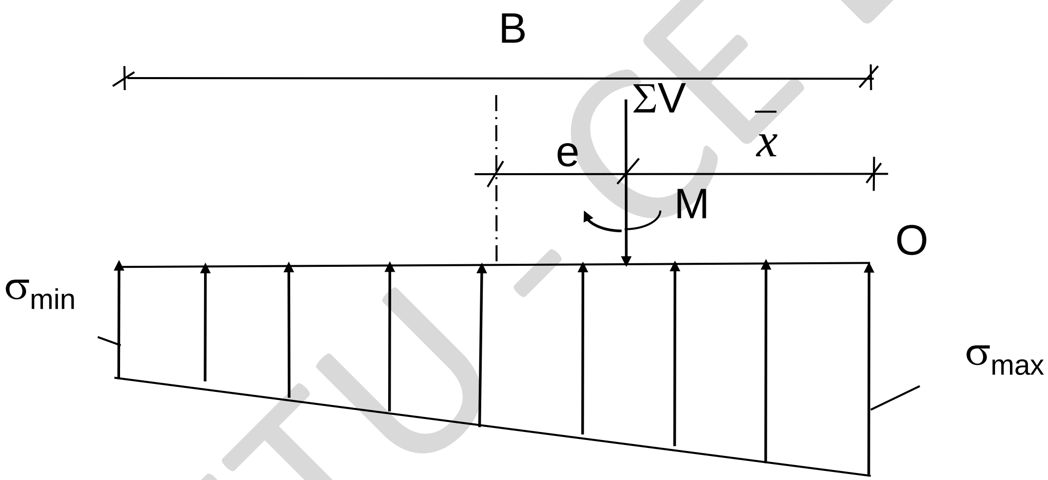
$$M = \sum Ve$$

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

$$c = \frac{B}{2}$$

$$I = \frac{B^3}{12}$$

moment of inertia



minimum normal stress per unit width

$$\sigma_{\min} = \frac{\sum V}{B} - \frac{\sum V * e * B/2}{B^3/12} = \frac{\sum V}{B}\left(1 - \frac{6e}{B}\right) \geq 0$$

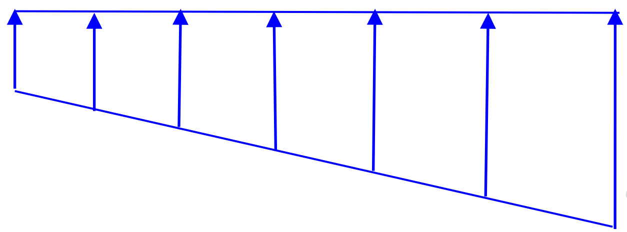
in order to obtain compressive stresses the min. pressure should be ≥ 0

- $e < B/6 \Rightarrow$ Compression

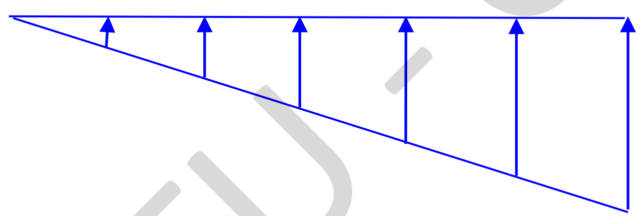
$$\frac{\sum V}{B} \geq 0 \quad or \quad 1 - \frac{6e}{B} \geq 0$$

$$1 \geq \frac{6e}{B}$$

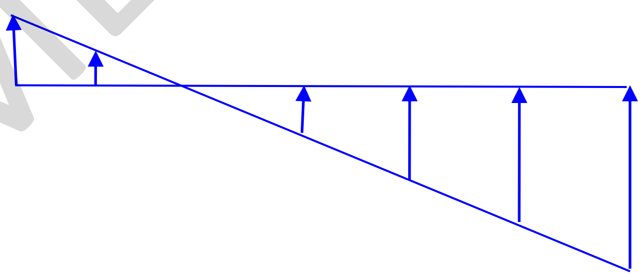
$$\frac{B}{6} \geq e$$



- $e = B/6 \Rightarrow$ Triangular distribution



- $e > B/6 \Rightarrow$ Tension $(\sigma_t \approx (5\text{-}10)\%$ of $\sigma_{ac})$



Tensile strength is approximately
5-10% of the compressive strength

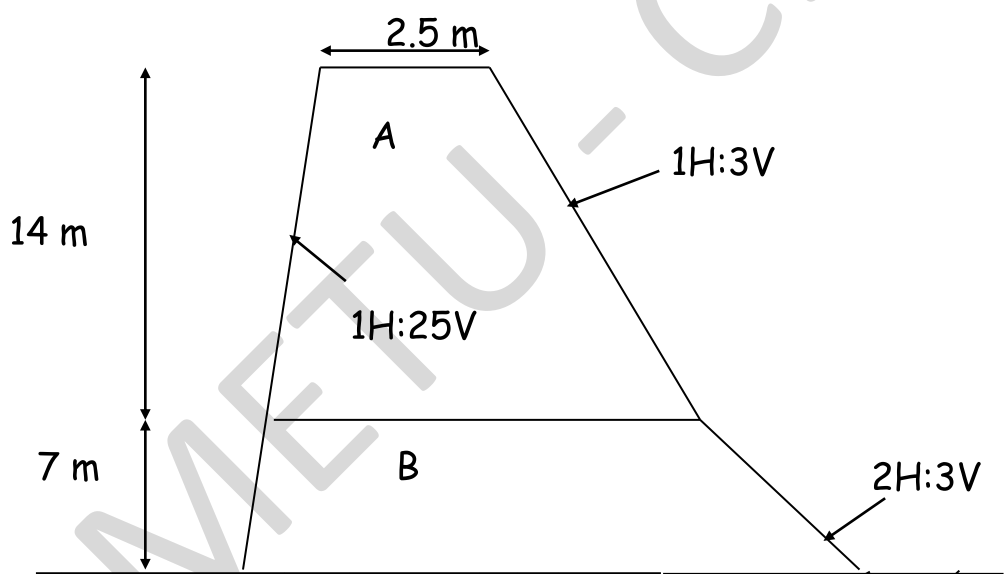
Safety criteria

Loading	$F.S_s$	$F.S_o$	$F.S_{ss}$	σ_{max}	
Usual	≥ 1.5	≥ 2.0	≥ 3.0	$\leq \sigma_c/3.0$	$\leq \sigma_f/4.0$
Unusual	≥ 1.2	≥ 1.5	≥ 2.0	$\leq \sigma_c/2.0$	$\leq \sigma_f/2.7$
Extreme	> 1.0	≥ 1.2	≥ 1.0	$\leq \sigma_c$	$\leq \sigma_f/1.3$

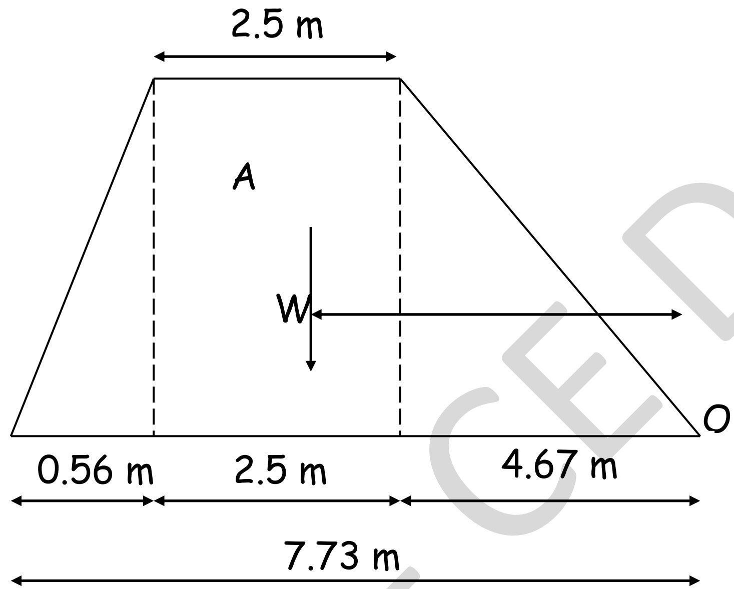
compressive strenght of concrete

compressive strenght of foundation

Example 12 A cross-section of a concrete gravity dam is shown in Figure 3.42. Analyze the stability of block A for full and empty upstream reservoir cases, separately. Ignore earthquake, silt, and ice forces. Specific weights of concrete and water are 23 kN/m^3 and 10 kN/m^3, respectively. Compressive and shear strengths of concrete are 35000 kN/m^2, and 6000 kN/m^2, respectively. The coefficient of friction between concrete blocks is 0.65. There is no tailwater in the downstream. Required safety factors can be taken as those of a usual loading.



a) <u>Empty reservoir case:</u> Free-body diagram for block A is shown below



In case of empty upstream reservoir, since there is no horizontal force acting on block A, such as earthquake force, the block will be infinitely safe against sliding and overturning. However, the stresses in concrete should be checked. The weight of the block is

$$W = (0.5*0.56 + 2.5 + 0.5*4.67)*14*23 = 1647.03 \text{ kN/m}.$$

Point of application of W with respect to point O in Figure 3.43 is computed as

$\bar{x}$ = 4.72 m. The eccentricity of W around the center of the base is

$$e = 4.72 - \frac{7.73}{2} = 0.86m$$

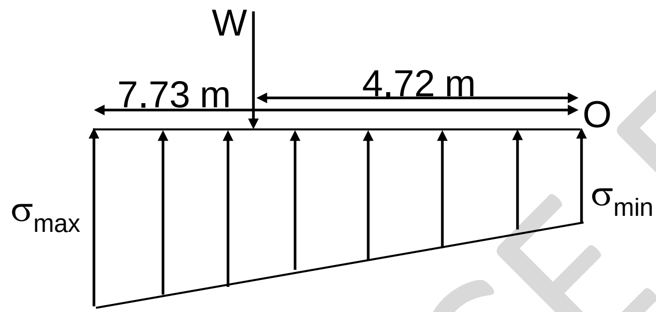
Since e = 0.86 $m<B/6=1.29$, compressive stresses develop at the base of block A. Values of c and I are as follows:

c = 7.73 /2 = 3.87 m and I = $(7.73)^3$ /12 = 38.49 m^3

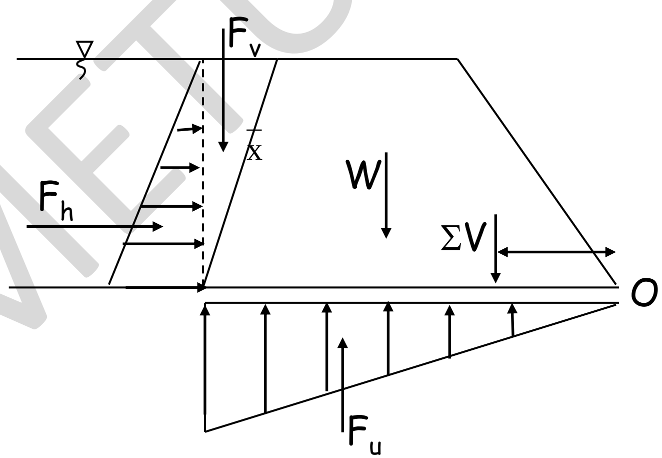
M = W*e = 1647.03*0.86 = 1416.4 kN.m /m.

$$\sigma = \frac{1647.03}{7.73} \pm \frac{1416.4 * 3.87}{38.49} = 213.07 \pm 142.41$$

σ_{max}=355.48 kN/m²<<35000 kN/m². For usual loading, $\sigma_{max}<\sigma_c/3$=11166.7 kN/m² and σ_{min}=70.66 kN/m² >0, O.K. So, block A is safe for empty reservoir case. Note that the major principle compressive stresses at the upstream and downstream faces are also acceptable. A linear stress distribution is assumed at the base



b) <u>Full reservoir case:</u> For a conservative approach, it is assumed that water might seep through joints and possible cracks in the concrete and exert internal hydrostatic pressures. Therefore, uplift pressures in the dam body should be considered at any level below the reservoir water surface. A free-body diagram is shown



F_h = 0.5*10*(14)^2 = 980 kN/m
F_v = 0.5*14*0.56*10 = 39.2 kN/m
F_u = 0.5*10*14*7.73 = 541.1 kN/m.
Overturning moments about the toe:
ΣM_o = 980*(14/3) + 541.1*(2/3)*7.73 = 7361.8 kN.M/m
Resisting moments about the toe:
ΣM_r = 1647.03*4.72 + 39.2*7.54 = 8069.55 kN.m/m.

$$F.S_o = \frac{\Sigma M_r}{\Sigma M_0} = \frac{8069.55}{7361.8} = 1.1 < 2.0$$ NOT O.K.

$\Sigma V = W + F_v - F_u$ = 1647.03 + 39.2 - 541.1 = 1145.13 kN/m.
$\Sigma H = F_h$ = 980 kN/m.

$$F.S_{ss} = \frac{0.65*1145.13 + 0.33*7.73*6000}{980} = 16.4 > 3.0$$ O.K.

$F.S_s$ = 0.76 < 1.5, NOT O.K. Net moment:
$\Sigma M = \Sigma M_r - \Sigma M_o$ = 707.75 kN.m/m.

Point of application of ΣV with respect to toe:

$$\bar{x}' = \frac{\Sigma M}{\Sigma V} = \frac{707.75}{1145.13} = 0.62m \qquad e = \frac{7.73}{2} - 0.62 = 3.25m$$

e > 7.73 / 6 (tension)

M = ΣV.e = 1145.13*3.25 = 3721.7 kN.m/m.

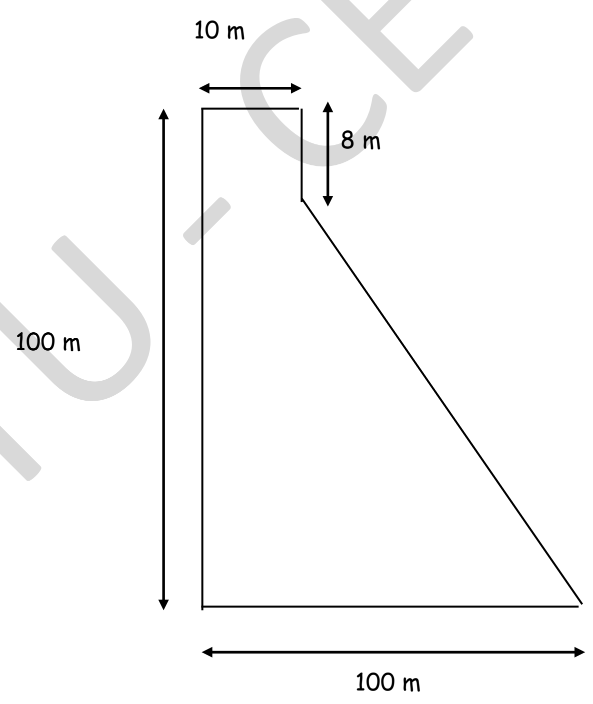
$$\sigma = \frac{1145.13}{7.73} \pm \frac{3721.7 * 3.87}{38.49} = 148.14 \pm 374.2$$

σ_{max}=522.34 kN/m^2<11166.7 kN/m^2, σ_{min}=-226.06 kN/m^2<0, $\sigma_{min} < \sigma_t$, O.K.

where σ_t is the tensile strength. Block A, and hence the dam, is not stable when the reservoir is full. Dimensions may be increased or measures may be taken to reduce the uplift force.

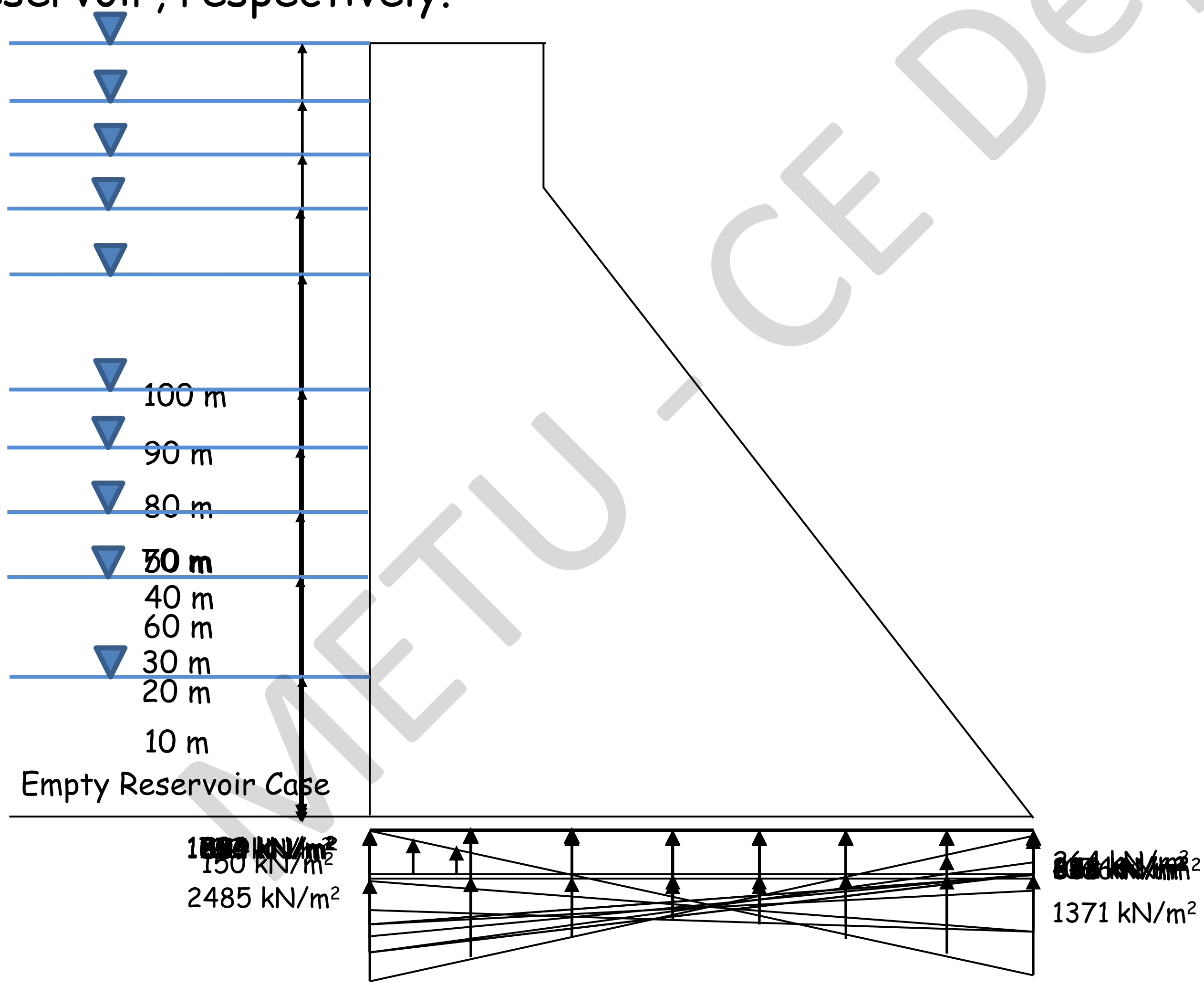
Example 13

By carrying out a stability analysis of the concrete gravity dam shown in the figure, determine the variation of safety factors and stresses at the foundation level for various operating depths of the reservoir. Ignore silt and ice forces. Take $k_h=k_v=0.1$, $f=0.7$, $\gamma_{con}=24$ kN/m^3, $\gamma=10$ kN/m^3, $\tau_s=6$ MPa, $\sigma_c=25$ MPa, σ_f = 90 MPa, and ϕ = 1.0. The required safety factors can be taken as those of the extreme loading case.

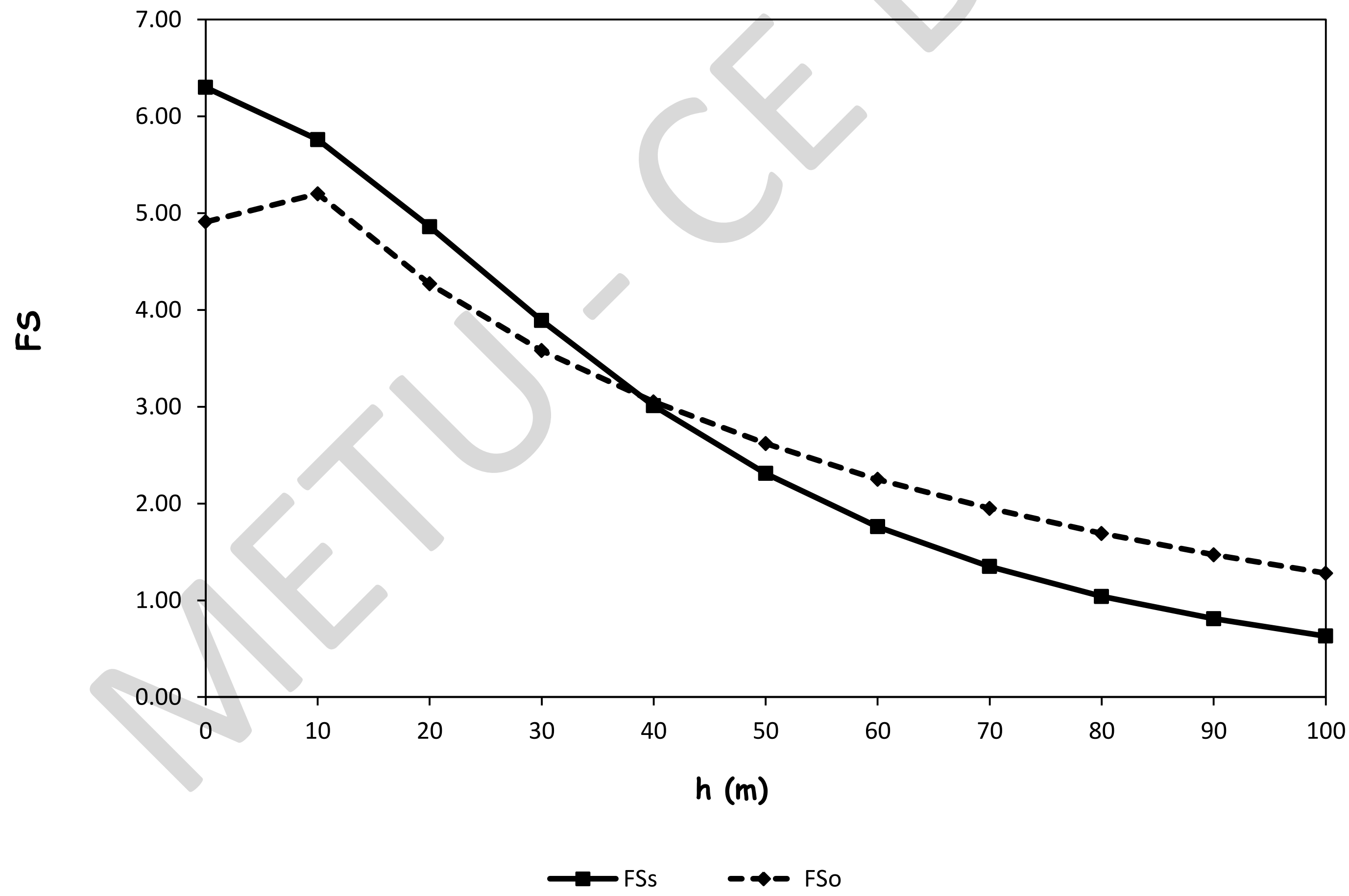


Solution

The results of the analysis are given in the following animation for various water depths. In the computations, moments are taken with respect to the toe and heel for the cases with water in the upstream and empty reservoir, respectively.



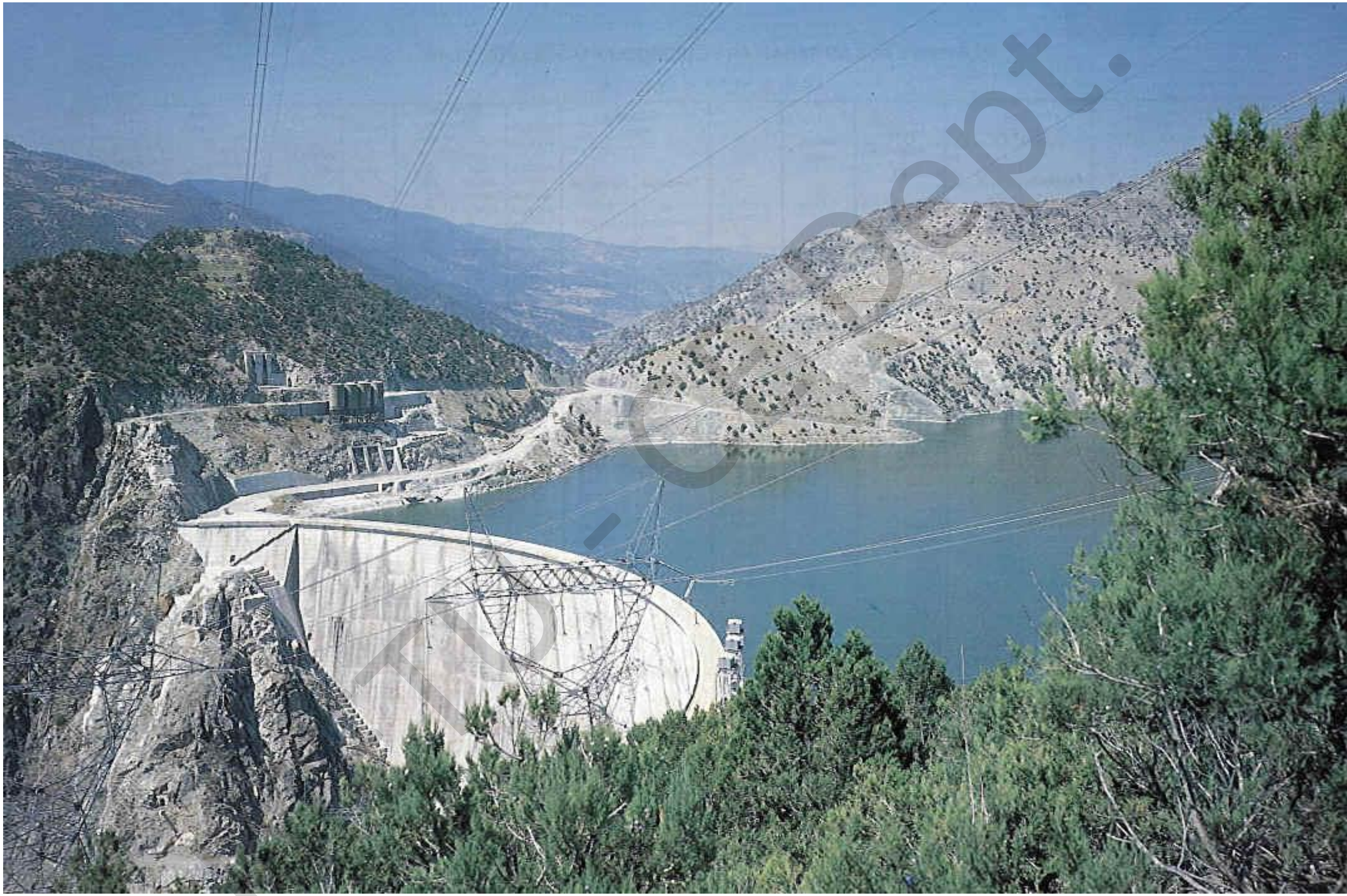
The variation of water depth in the reservoir causes significant changes in the overall stability. The stress distribution at the foundation level was shown in the previous slide. Assuming that the safety criterion for extreme loading is also applicable for this example, the dam is found safe for h $\leq$ 80 m.



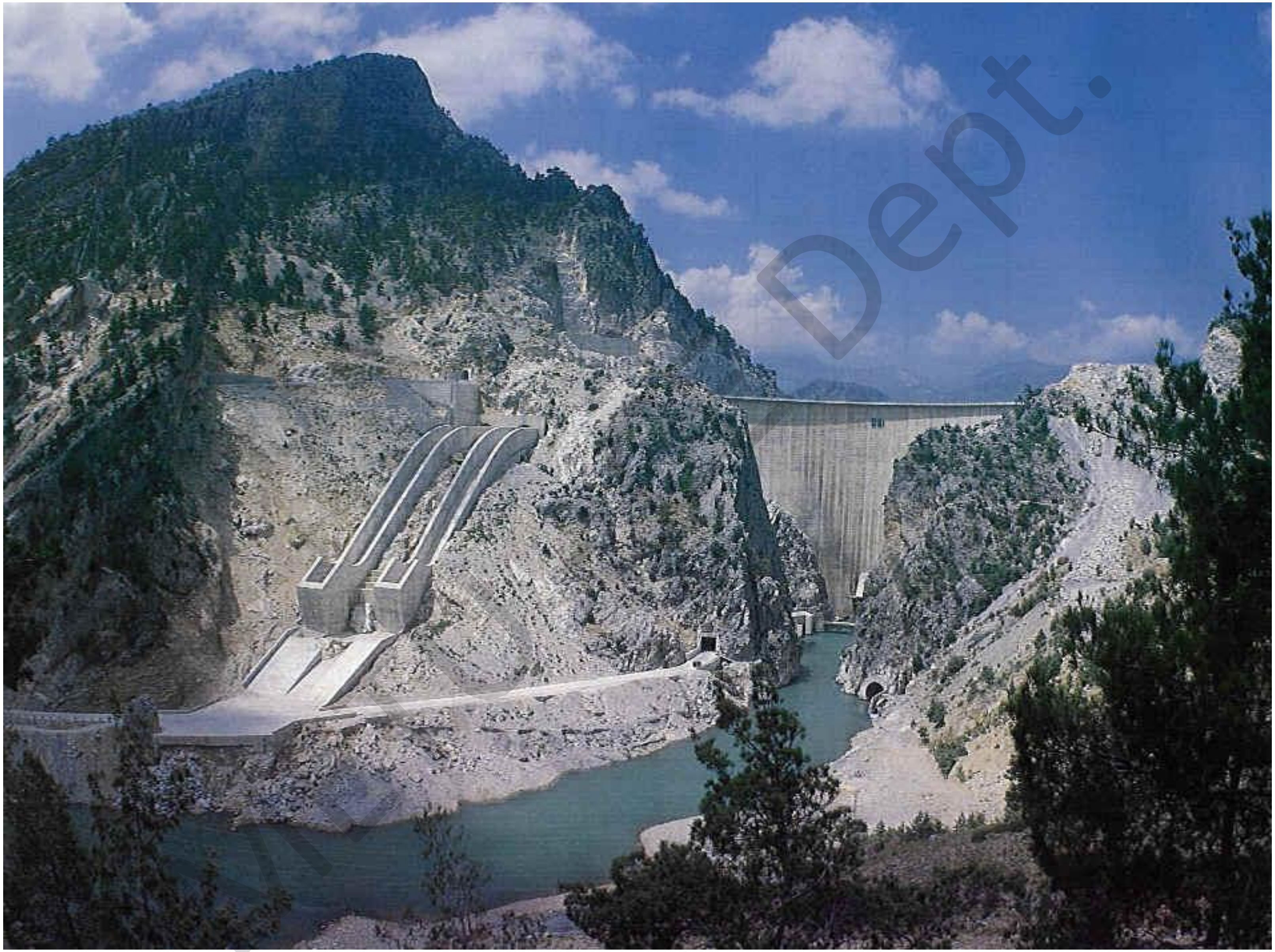
Arch dams

Stability is based on
- its self weight &
- ability to transmit water load to valley walls by arch action

- Thin slender structures curved in plan
- They are usually suited to valleys where the valley width to height ratio, B/H<6.0.
- Water thrust is transmitted partially
  - by arch action to the sides - Stiff side formation &
  - by cantilever action to the foundation - Stiff foundation is required



Gökçekaya Dam on Sakarya River



Oymapınar Dam on Manavgat River

- From structures and construction view points, an arch dam is composed of series of
  - horizontal beams
  - vertical cantilevers

- Construction technique is similar t
  - temperature stresses are pronc
  - uplift force is small
    (since base width is small)

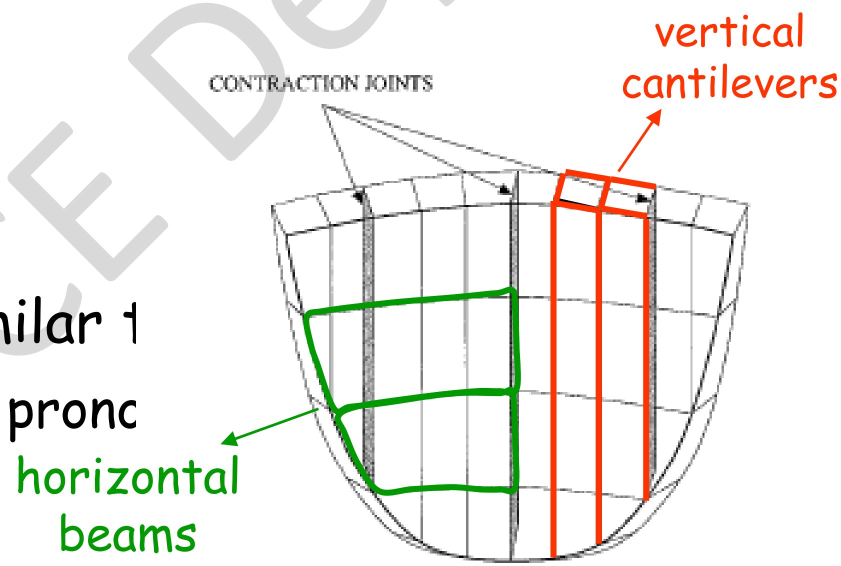


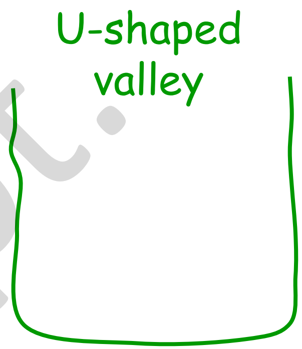
Figure 1. Vertical contraction joints in an arch dam

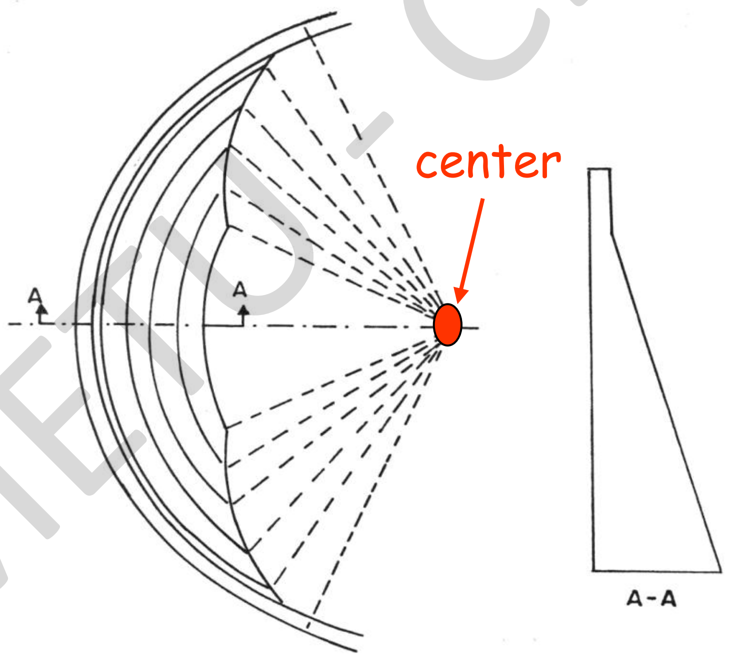
D. T. LAU, B. NORUZIAAN AND A. G. RAZAQPUR

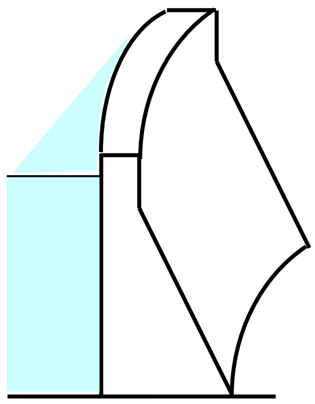
Types of arch dams:

A) Constant-center (variable angle):

- U-shaped valley
- dams of medium height





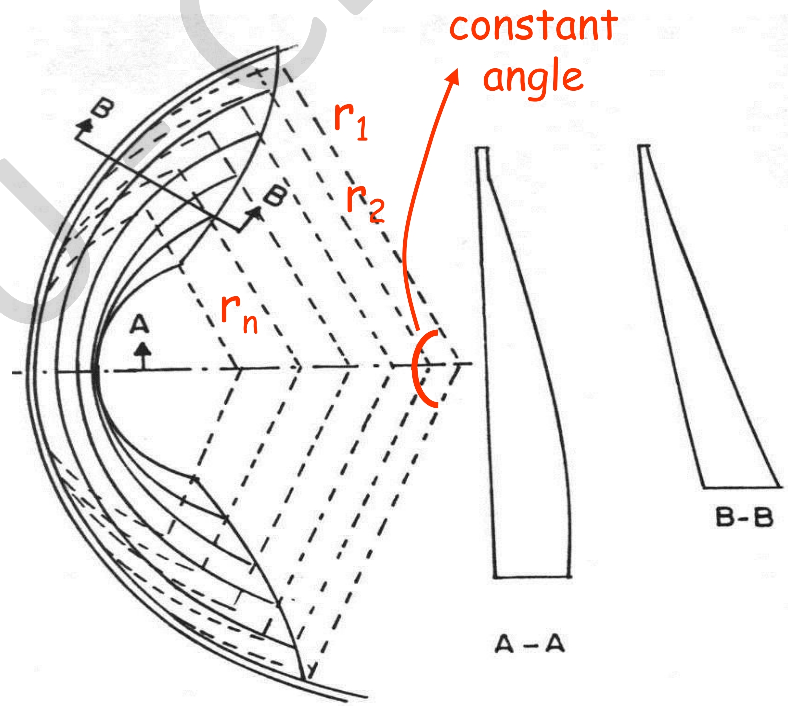


B) Variable-center (constant angle)

- V-shaped valleys
- Radius decreases with depth. So arching action is more pronounced at low depths.
- Thinner than constant-center dams. So they are more elastic and safer

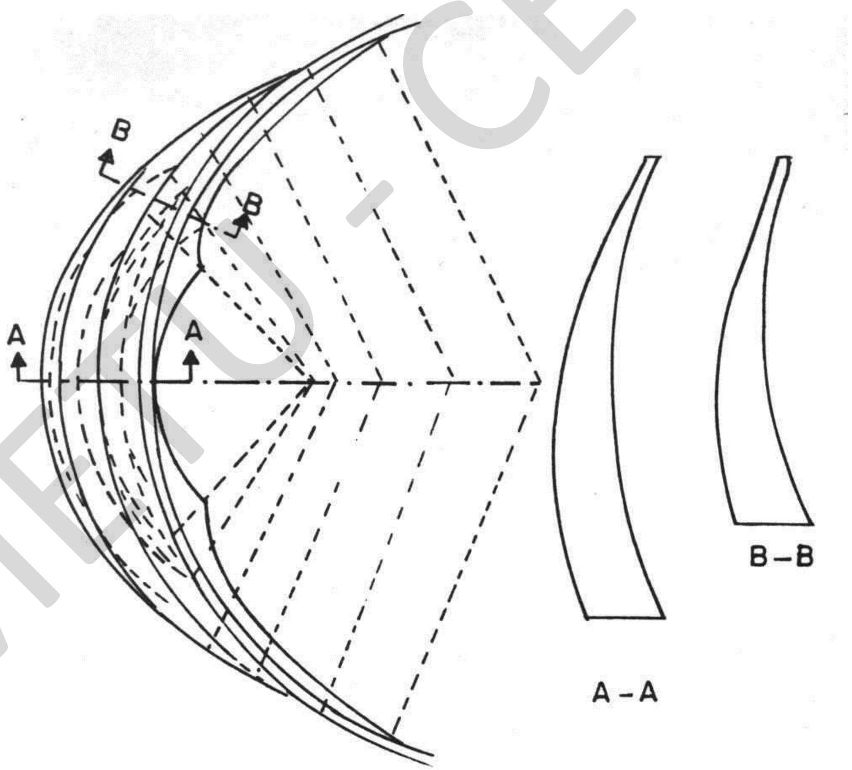
radius of arch ↓es with depth

arching action is more pronounced at low depths



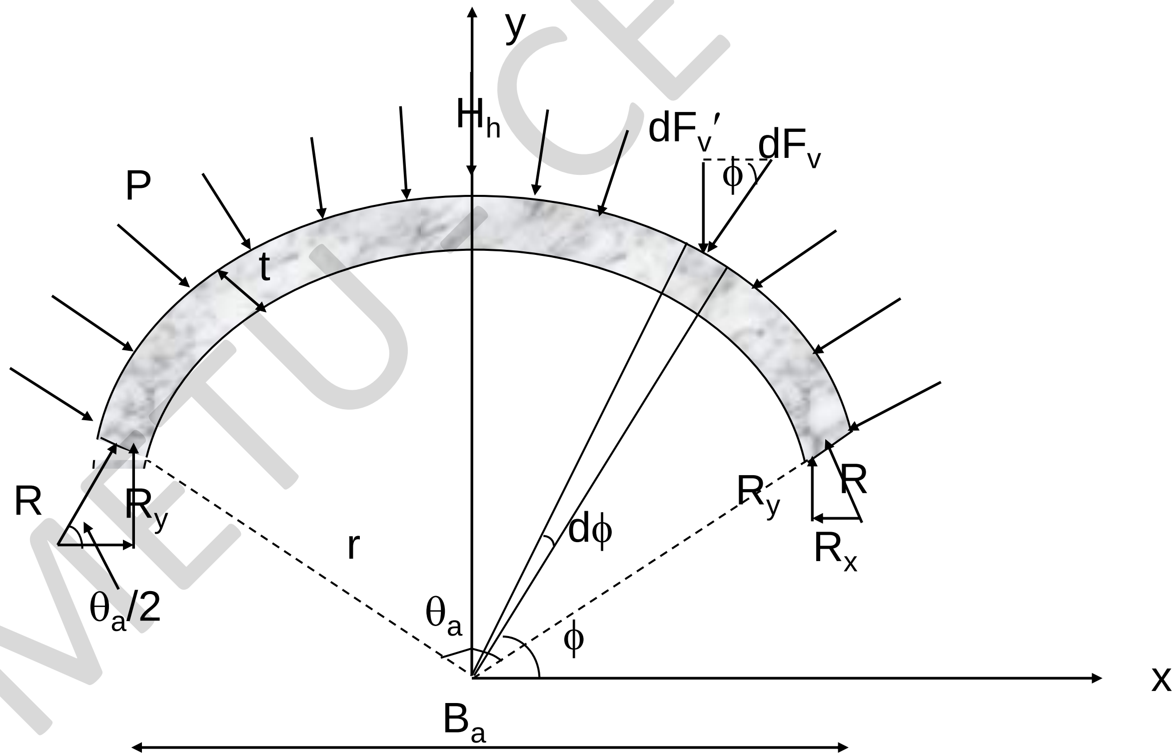
C) Variable-center, variable-angle arch dams:

- Combination of two types described above.
- Load distribution in vertical direction governs the cross-sectional shape of the dam.



Simplified design – arch rib analysis: determination of thickness at any elevation for an arch dam whose crest elevation is already determined

Assumption: water trust induced by hydrostatic pressure is taken by ARCH ACTION ONLY



$$dF_v = p(r\,d\Phi) \xrightarrow[\text{component}]{\text{Horizontal}} dF'_v = p(r\,d\Phi)\sin\Phi$$

$2\pi \quad 2\pi r$

$d\Phi \quad x$

$x = r\,d\Phi$

$F = pA$

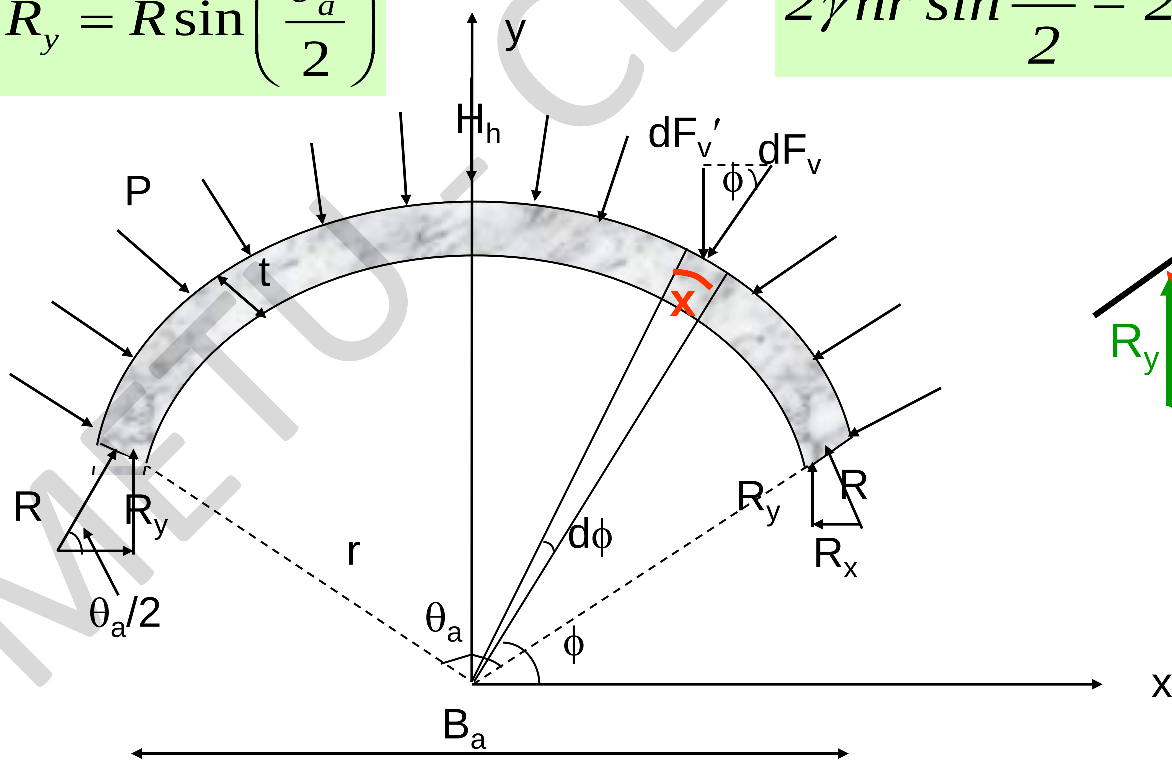
$dF_v = p(r\,d\Phi)1$

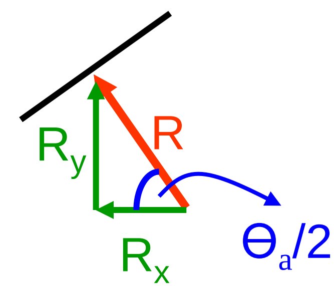
$$H_h = 2\int_{\left(\frac{\pi}{2}-\frac{\theta_a}{2}\right)}^{\frac{\pi}{2}} \gamma h r \sin\phi\, d\phi = -2\gamma h r\left(\cos\left(\frac{\pi}{2}\right) - \cos\left(\frac{\pi}{2}-\frac{\theta_a}{2}\right)\right) = 2\gamma h r \sin\frac{\theta_a}{2}$$

$p = \gamma h$

$$H_h = 2R_y \qquad R_y = R\sin\left(\frac{\theta_a}{2}\right)$$

$$2\gamma h r\, \sin\frac{\theta_a}{2} = 2R\,\sin\frac{\theta_a}{2}$$





$R = \gamma hr$

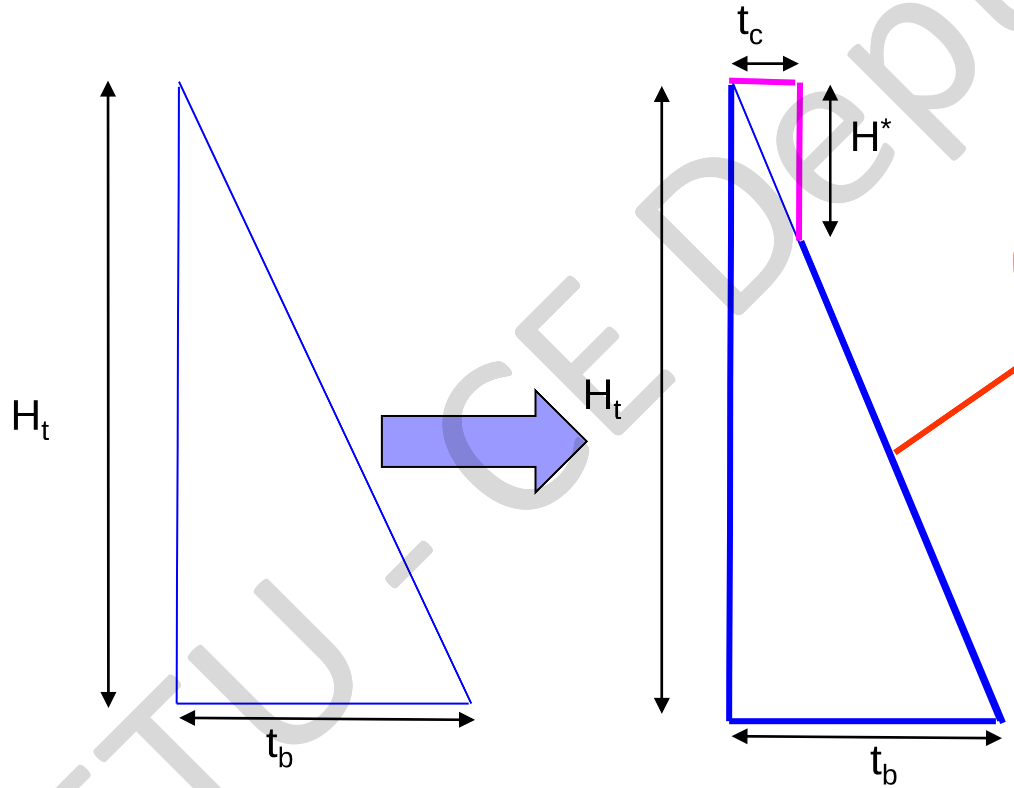
$t << r$

if t<<r → avr. compresive stress in the rib ≈ max. compresive stress in the rib

$$\sigma_{all} \approx \frac{R}{t} = \frac{\gamma hr}{t}$$

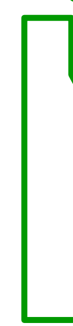
$$t = \frac{\gamma hr}{\sigma_{all}}$$

allowable working stress for concrete in compression



x-section for U-shaped valley $t = f(h)$

x-section for V-shaped valley $t = f(h^2)$



$V = Lt$

$$V = \frac{\gamma h}{\sigma_{all}} r^2 \theta_a$$

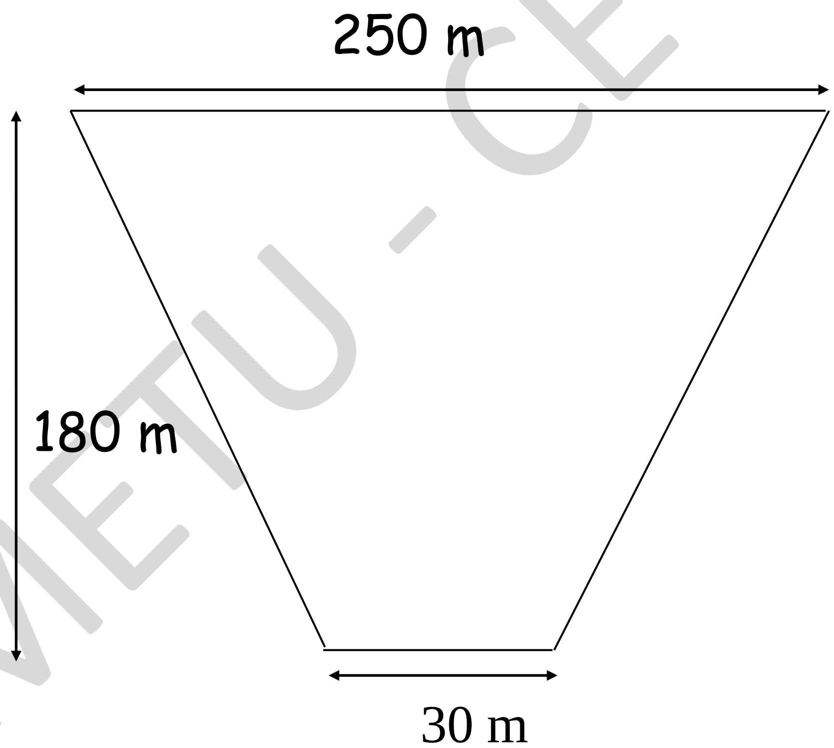
Optimum $\theta_a = 133°34'$

In practice, $\theta_a = 100°$ to $140°$

V = volume of concrete per unit height

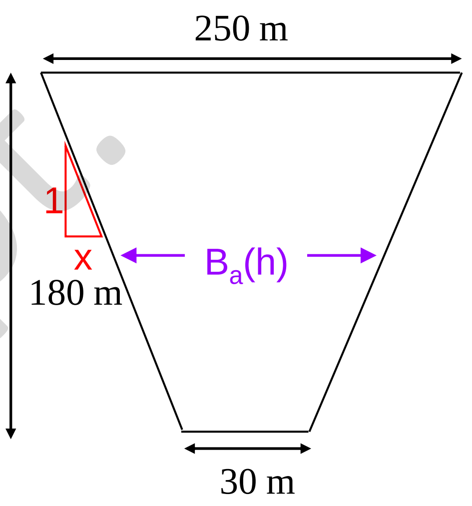
Example 14

- Using the simplified arch rib analysis, design an arch dam 180 m high for a trapezoidal canyon shown below, Upstream face is vertical. Thickness at the crest is 3 m. Take σ_{all} = 4000 kN/m^2 and θ_a = 120°.



180   (250-30)/2
1   x
----
x = 0.611

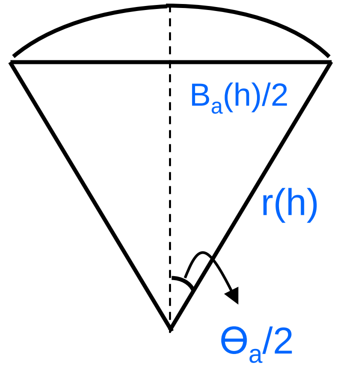
Solution



$$B_a(h) = 250 - 1.222h$$

$$r(h) = \frac{B_a(h)}{2\sin\frac{\theta_a}{2}} = 0.577B_a(h) = 144.25 - 0.705h$$

$$t = \frac{\gamma h r(h)}{\sigma_{all}} = \frac{\gamma(144.25h - 0.705h^2)}{\sigma_{all}}$$



Maximum thickness is obtained from → dt/dh = 0

$$\frac{dt}{dh} = \frac{\gamma}{\sigma_{all}}(144.25 - 1.41h) = 0 \longrightarrow h_{max} = 102.3m$$

$$t = \frac{\gamma h r(h)}{\sigma_{all}} = \frac{\gamma(144.25h - 0.705h^2)}{\sigma_{all}}$$

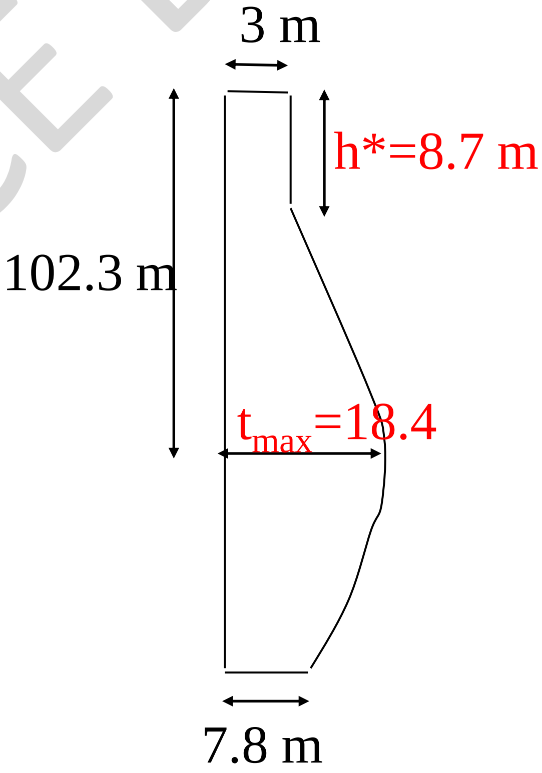
$$t_{max} = \frac{10\left(144.25 \times 102.3 - 0.705(102.3)^2\right)}{4000}$$

$$t_{max} = 18.4\ m$$

$$t = \frac{\gamma h r(h)}{\sigma_{all}} = \frac{\gamma(144.25h - 0.705h^2)}{\sigma_{all}}$$

$$3 = \frac{10\left(144.25 \times h^* - 0.705(h^*)^2\right)}{4000}$$

$$h^* = 8.7\ m$$



- A constant-angle arch dam is preferable since volume is less!
  - It requires less concrete than a constant-center dam
  - However, its formwork is more difficult

Constructional details:

- Foundation must be excavated to solid rock
- Abutments should be stripped to join the dam at right angle to the line of thrust to prevent sliding of the dam
- Grouting is usually required at the foundation
- Excessive care for constructional quality!

Characteristics of dams

Dam Type	Foundation Conditions	Construction Materials
earth-fill	every type	non-organic, non-plastic all soils
rock-fill	hard sandy, gravely or rock	rock and clay
concrete gravity	rock foundation	concrete
arch	rock foundation and abutments	concrete
buttress	rock foundation	plain/reinforced concrete

Dam Type	Construction Conditions	Critical Factor
earth-fill	earth construction equipment needed; average workmanship	overtopping, settlement, excessive seepage, sliding of slopes, earthquake
rock-fill	earth construction equipment needed; average workmanship	overtopping, settlement, excessive seepage, sliding of slopes, earthquake
concrete gravity	concrete mixing plants; skilled workmanship	sliding, settlement, overturning, earthquake
arch	concrete mixing plants; skilled workmanship	sliding, settlement, overturning, earthquake, sliding on abutments
buttress	concrete mixing plants; skilled workmanship	settlement, overturning, earthquake

Dam safety and rehabilitation

Possible causes of dam failure (break):

- Inadequate spillway capacity
- Piping & settlement due to fault movement
- Improper protection, stability failure

Remedies:

- Proper design
- Use of sound and proper material
- Proper construction
- Surveillance and continuous monitoring

proper design
&
construction
+
continuous inspection
&
monitoring

Indicators of problems

- large horizontal and vertical movements of crest,
- tilting of the roadway along the crest,
- deformation of embankment slopes,
- higher than usual pore water pressures in embankment dams,
- unusual seepage at the toe or edges of an embankment dam,
- seepage flows not decreasing with low flow conditions,
- turbid outflows through the embankment,
- tilting of the spillway crest,
- increased leakage into inspection galleries in concrete dams, etc.

settlement

crest may be tilted due to differential settlement

piezometers placed in earth-fill dams indicate the locus of line of saturation which indicates the degree of seepage thru the embankment

Monitoring:

most of the problems
are due to excessive seepage

- Placement of piozemeters in earthfill dams
  - pore water pressure
  - locus of line of saturation → indicates seepage

- Placement of strain gages and stress meters in inspection galleries in concrete dams

Rehabilitation:

- Further grouting after construction ⇒ earth-fill dams
- Enlarged toe drain ⇒ embankment dams
- Placement of
  - cutoff wall
  - impermeable blanket

  } Embankment dams

- Supporting measures against slope failure
  - rip-rap
  - grass
  - concrete blocks/slabs

- Handling downstream scour holes after floods

Now spillways !