CHAPTER 3 ROCKFILL DAMS

Rockfill dam

- rock fragments (or rockfill) is the main construction material
- *dam that contains more than 50% of compacted or dumped pervious fill*
- stability mainly developed by the friction and interaction of the particles

Advantages of Rockfill Construction

- **Economical** - due to the use of cheap local materials (when large quantities of rock are readily available)
- Suitable where the foundation conditions are not good, especially where high hydrostatic uplift is likely to be a factor in design.
- The rock filling is especially adapted **to construction during wet and cold weather** and permits continuous work under weather conditions that would not permit earth or concrete construction and hence **rapid constructions** are possible.
- The rockfill dam with an upstream diaphragm is very well **adapted to stage construction**. The dam height can be increased merely by dumping more rock behind the impervious diaphragm without interfering with or encroaching on the reservoir. The dam is then made water-tight by continuing the impervious face upward.

Disadvantages

- Rockfill dams require more strong foundations than earth dams
- Rockfill dams require heavy machines for transporting, dumping and compacting rocks.

A rockfill dam consists of two basic structural elements:

i. An embankment built of rockfill, and
ii. An impervious element/Membrane

Rockfill dams may be classified into three groups, depending on the location of the membrane:

- Central core, | Internal membrane
- Sloping core, and |
- Upstream membrane, or “decked.”

67 meters high, concrete faced rock fill dam CFRD on Glennies Creek (Australia)

FOUNDATION DESIGN

Foundation requirements

- more severe than earthfill dam but less severe than concrete gravity dam.
- Hard erosion resistant bed rock is most suitable.
- Rockfill dams are not suitable in soft foundation of sand, silt and clay.
- Foundation with river gravel + rock fragments is acceptable

Foundation treatment must be sufficient to satisfy the following criteria:

- Minimum leakage
- Prevention of piping
- Limited settlement
- Sufficient friction development between abutments and foundation to ensure sliding stability

MEMBRANE DESIGN

- Seepage membrane is required to stop the seepage through the dam embankment.

Types:

- Central core (vertical or sloping/inclined)
- u/s membrane

Materials for the membrane

- reinforced cement concrete (RC)
- steel
- timber
- stone / rubble or masonry
- asphalt concrete for u/s face membrane and
- earth/clay

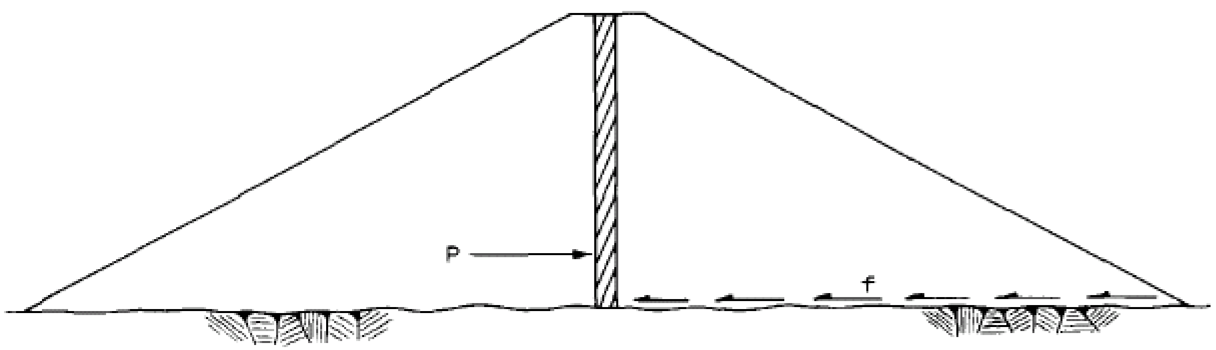
Internal membrane

Advantages of the internal membrane include

- less total area exposed to water,
- protection from the effects of weathering and external damage.

The prime disadvantages of an internal membrane are

- the inability to place rockfill material without the **simultaneous placement** of impervious core material and filters (Simultaneous construction is must both for membrane and rockfill)
- the **inaccessibility** of the membrane for damage inspection and correction,
- the dependence on a **smaller section** of the dam for **stability** against sliding
- Filters/transition zone required for earth core
- Adequate **construction control** required if several filter zones are required due to coarse shell

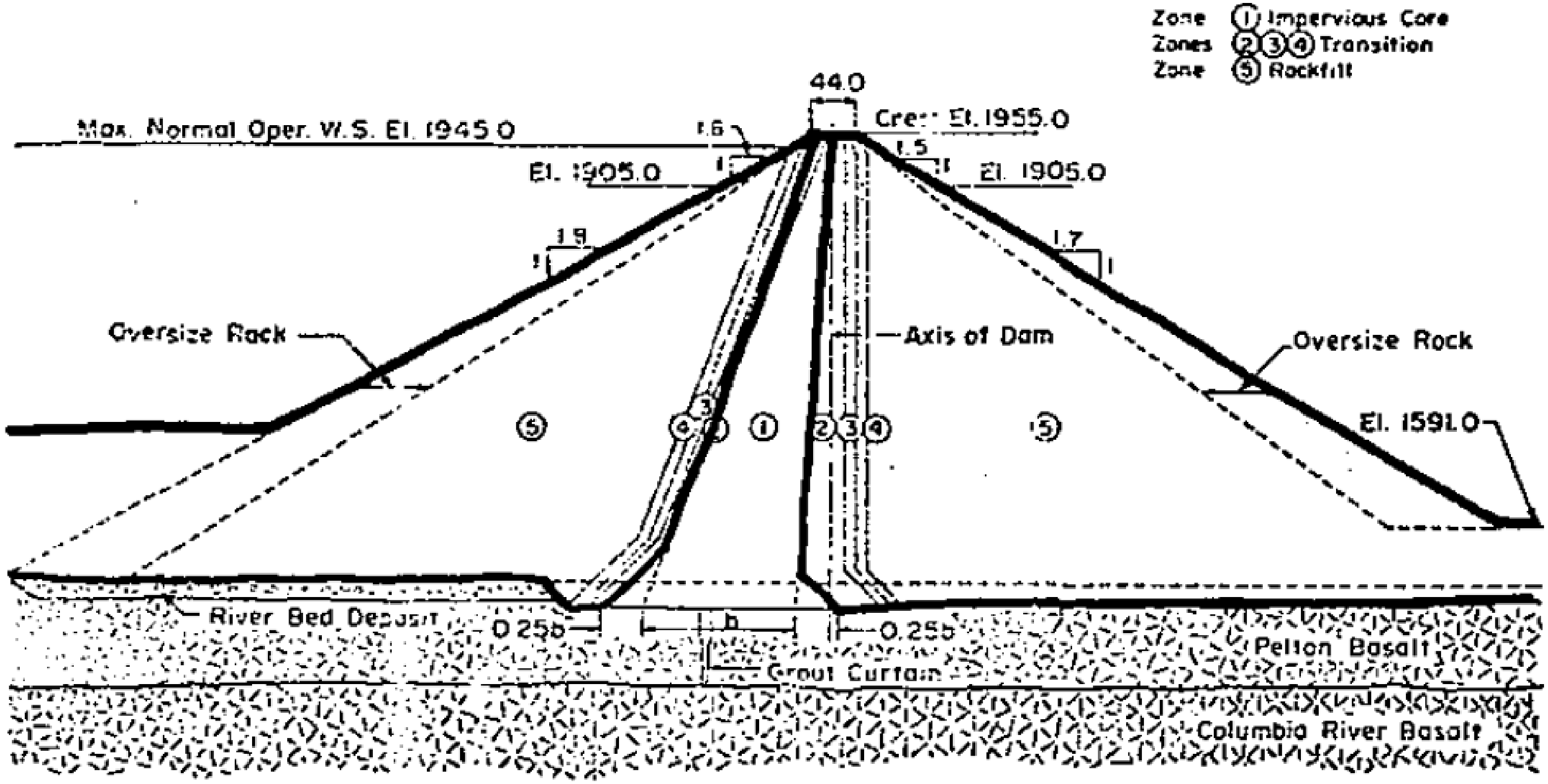


(B) CENTRAL MEMBRANE

Earth Core

a. Impervious Central Core of Earth

- Enough quantity of earthfill available for core
- Used when u/s abutments are widely apart in comparison to dam axis length
- Or show highly weathered rock to great depth and require adequate grouting /cutoff.
- Design same as for earthfill dam, seepage and stability analysis required.
- Material placed in 6” lifts and compacted by tampering rollers
- Core material to have enough plasticity to allow it to deform without cracking on dam deflection.
- Filter zones provided (one or multiple zone of 8-15 ft thick)
- Foundations and abutments opposite to core be treated to prevent piping
- Joints, cracks, fissures in core area be cleaned out and filled with concrete or grouted;
- Bottom width 0.5 h to 2.5 h
- U/s and d/s slopes symmetrical (0.3 H:1V → 1.5H:1V), or u/s flatter than d/s face
- Dam slopes as x+1 H:1V (minimum 2:1) [x = core slope]
- Chimney/blanket drain to drain off seepage flow (from the earth core and other core / membranes.
- Location is central vertical position

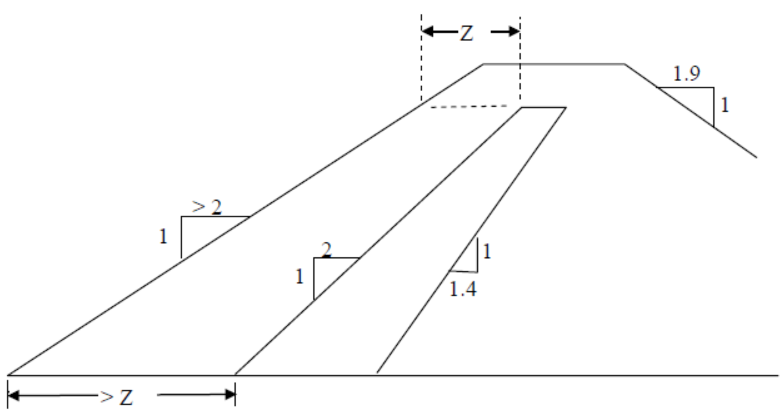


Round Butte Dam in USA

- The core zone varied in thickness from 10 ft (3 meters) at the crest to 220 ft (67 meters) at its flared foundation contact 440 ft (134 meters) below.
- Its downstream face was nearly vertical, and its upstream face sloped at 0.45H: 1 *V.*
- The core zone was conservatively protected on both faces by three layers of progressively coarser filter or transition materials, each layer being 10ft (3 meters) thick

b. Sloping Earth Cores

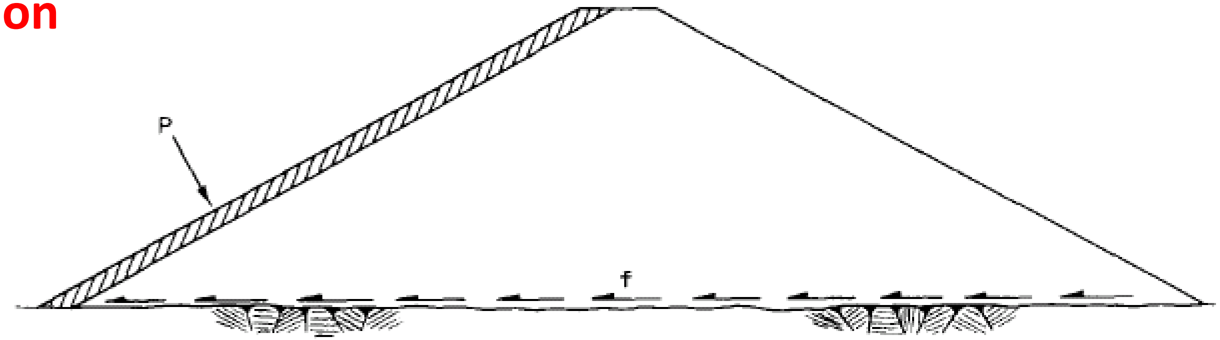
- These cores located closer to u/s face, almost paralleling the u/s face
- Filter zones on u/s & d/s of core
- Usually thin width, width decreases at top
- Bottom width 30 to 50 ft
- Top width 15 to 20 ft
- Advantages: foundation grouting can be carried out while the embankment is being placed
- U/S face: core = 1.4H:1V Dam: u/s face 2:1 or flatter, d/s face = 1.4:1
- Core can be placed after initial settlement of rockfill (less subsequent cracking risk)
- Due to lower contact pressure at foundation → more susceptible to seepage and piping
- Works as **u/s earth face rockfill dam** with face protected by dumped quarry rock.



Upstream membranes

Upstream membranes have the following advantages:

- Readily available for inspection and repair
- Can be constructed *after completion* of the rockfill section
- Foundation **grouting** can be performed **simultaneously** with rockfill placement
- A larger portion of the dam is available for **stability** against sliding
- Can be used as slope protection
- It is relatively **easy to raise** the dam at a later date
- In wet climates, the absence of impervious soil fill simplifies and **speeds construction**



(A) UPSTREAM MEMBRANE

U/s face membrane (cont'd)

1. Concrete Faced Rockfill Dam (CFRD)

- RCC slabs placed at face over bedding layer
- Slab thickness and reinforcement requirements by **experience**, **precedent and judgment**
- Criteria :
  - Low permeability
  - Sufficient strength to permit large subsided areas beneath the facing
  - High resistant to weathering
  - Flexible to adjust to small embankment settlements

- Best suited for **compacted rockfill dams** due to lesser chance of settlement and deflection.
- Well compacting **bedding layer** reduce bridging requirements and provide more uniform support to the face layer.
- Concrete to be dense, durable, weather/chemical resistant
- Slab placed in blocks 20-60 ft square
- Horizontal + vertical **expansion joints** and construction joints are provided. Gaps filled with flexible bitumen.
- Metal or rubber **water stops** (1 or more layers) in joints

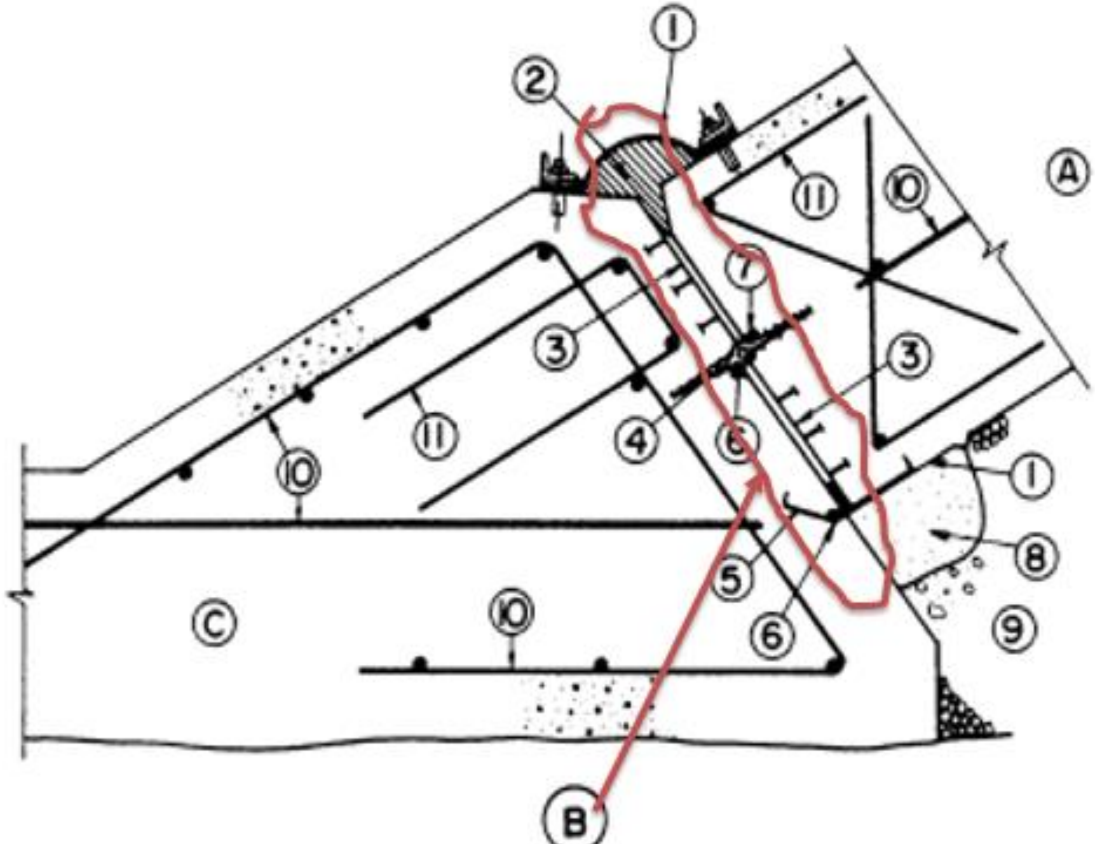
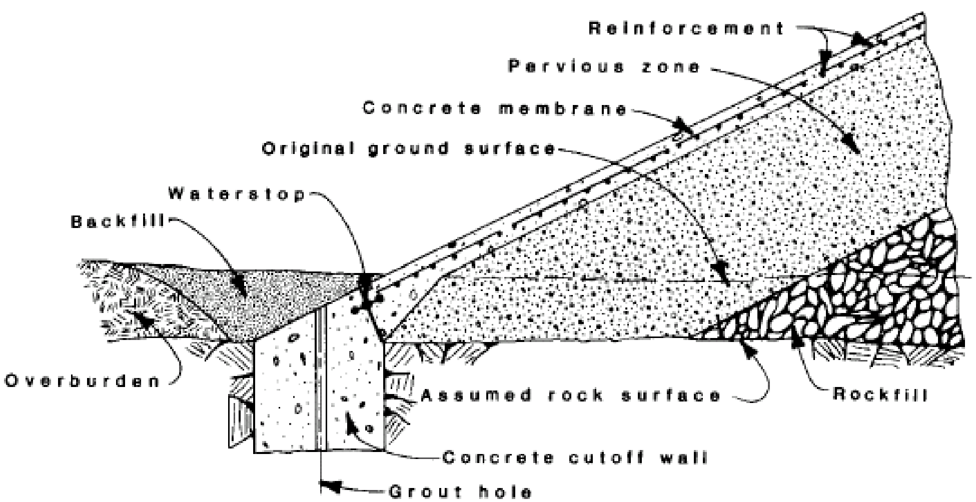


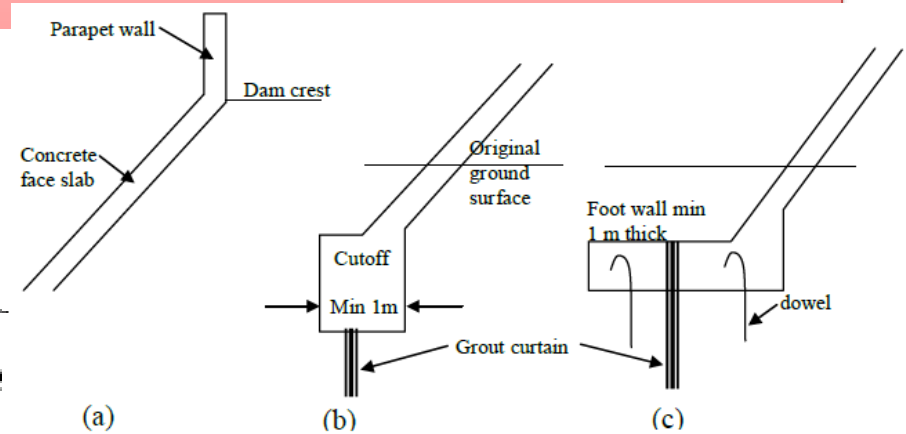
Fig Concrete face sealing. Junction of the concrete face sealing and the plinth (perimetric joint)

(A) Face slab, (B) Perimetric joint, (C) Plinth
(1) Hypalon band, (2) Mastic filler, (3) Compressible wood filler, (4) PVC water stop, (5) Copper water stop, (6) Neoprene cylinder, (7) Styrofoam filler, (8) Sand-asphalt mixture, (9) Zone 2, (10) Steel reinforcement, (11) Steel reinforcement to protect concrete against crushing and to protect water stop : (ICOLD, 1989a)

Concrete Faced Rockfill Dam (CFRD)- **continued**

- Concrete facing result in smooth surface and increase wave run up (but due to steeper slopes, net run up may not increase much)
- Coping or **parapet walls** (5-10 ft) (Fig. (a)) in continuation of face concrete to reduce height of embankment by containing wave run up.
- Concrete facing anchored to the foundation cutoff wall through continuous reinforcement (Fig. (b))
- May be anchored to flat bottom with dowel anchored footwall which also serve as grout cap (Fig. (c)).
- Minimum temperature reinforcement 0.5%

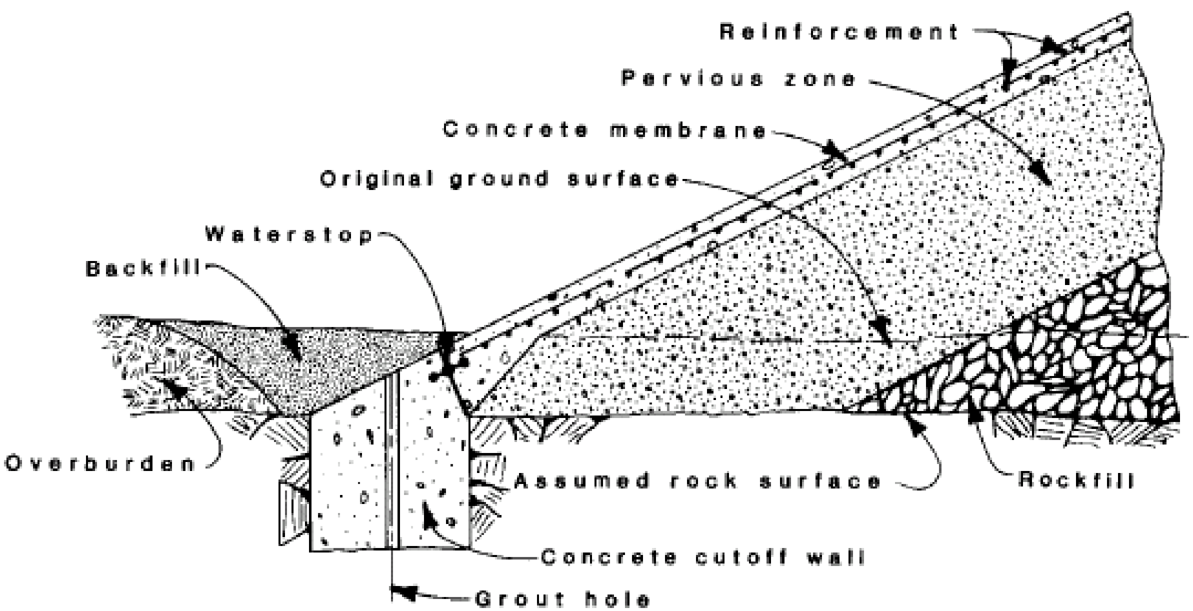




- The reinforced concrete slab is the most commonly used membrane in rockfill dams. The thickness of the membrane increases with depth below the water surface and is usually determined from the relation, **$t = 0.3 + 0.0025\,h$,** t is the thickness (m) and h is the depth measured below the water surface (m)

Membrane Cutoffs:

- To prevent seepage beneath the dam, foundations are usually grouted. For rock foundation grouting is done to seal-off rock imperfections. The need for grouting and the extent required should be based on
  - careful study of the site geology,
  - on a visual examination of the drill cores from the rock foundation,
  - and on drill-hole water-loss values.



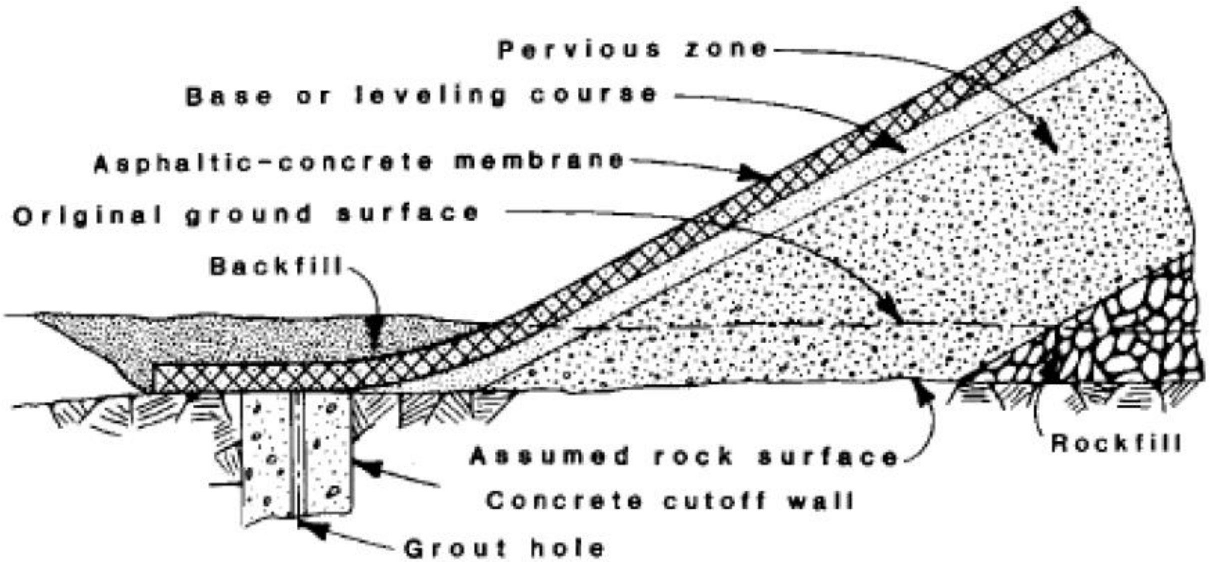
Detail of concrete membrane at cutoff wall.

Membrane Cutoffs (cont'd)

- Provides leakage control in the upper few meters of the foundation
- facilitate grouting operation (as grout cap)
- provide water tight seal with membrane, and take downward thrust of membrane
- When uncertainty concerning the permeability of upper portions of the foundation contact exist, such as for soft rock, a cutoff wall into bedrock can provide increased protection
- A minimum width and depth of 3 feet is recommended for cutoff walls in sound rock

2. Asphaltic Concrete

- provides more flexibility and tolerates larger settlement
- Dam u/s slope 1.7:1 or flatter for easy placement



- Good bedding layer to eliminate uplift pressures and piping if cracks
- If bedding layer B zone (next fig of max. rockfill section) not used , provide a 6" thick leveling layer to fill surface voids, provide easy travel of paving machinery, and smooth bedding surface for asphalt membrane
- Penetration coat over leveling layer to bind and stabilize it
- Membrane thickness 20 to 25 cm. Asphalt 8.5% by weight of dry aggregates
- Standard road paver used and asphalt placed in 3 layers
- Seal coat on the finished surface (for water proofing) and increased durability

- The controlled face is a sandwich-like structure of two units of asphaltic concrete with an intermediate drain layer which allows control of the seepage quantity, e.g. in an inspection gallery.

- The uncontrolled face is only one unit of asphaltic concrete which consists of one or more individual layers

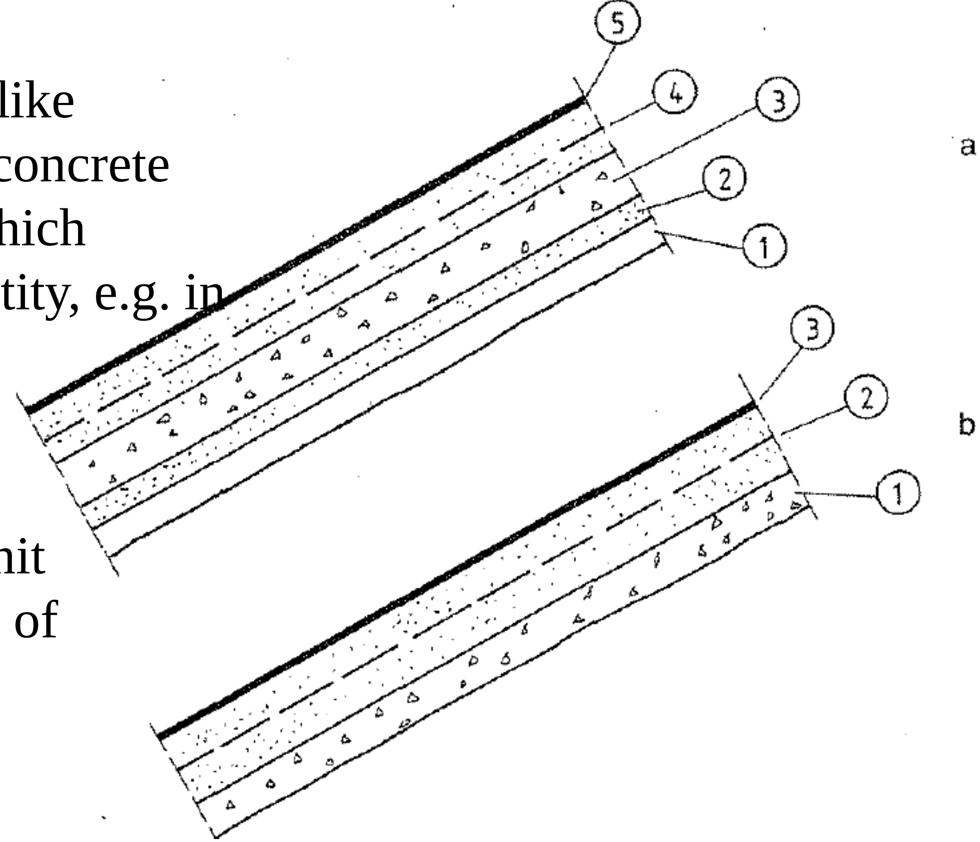
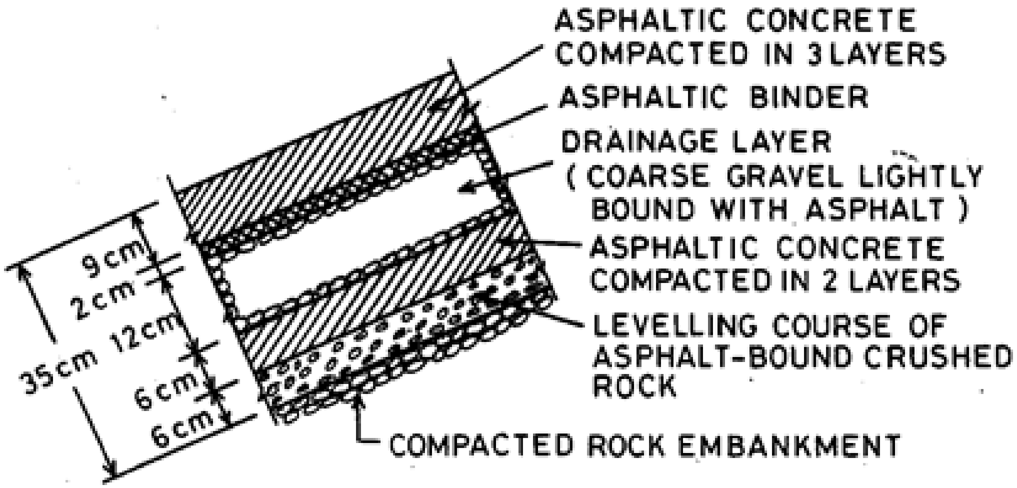


Fig. Face sealings of asphaltic concrete, typical design

a Controlled face sealing
(with drainage, ICOLD 1982: Type A)
1 Bituminous binder course, 5 to 15 cm
2 Asphaltic concrete, 3 to 8 cm
3 Bituminous drainage layer, 5 to 15 cm
4 Asphaltic concrete, one or more layers, 5 to 12 cm
5 Bituminous seal coat, 0.2 to 0.4 cm

b Uncontrolled face sealing
(without drainage, ICOLD 1982: Type B)
1 Bituminous binder course, 5 to 15 cm
2 Asphaltic concrete, one or more layers, 6 to 12 cm
3 Bituminous seal coat, 0.2 to 0.4 cm

Asphaltic Concrete



Asphaltic concrete membrane for Genkel dam (Germany).

- Placed in 3 to 4 m (10-12’) wide strip – at right angle to dam axis
- Rolling operation follow placement
- Smooth wheel rollers, vibratory or tandem type
- Layers compacted to min of 97% density
- Tight joints between adjacent strips

Asphaltic Concrete

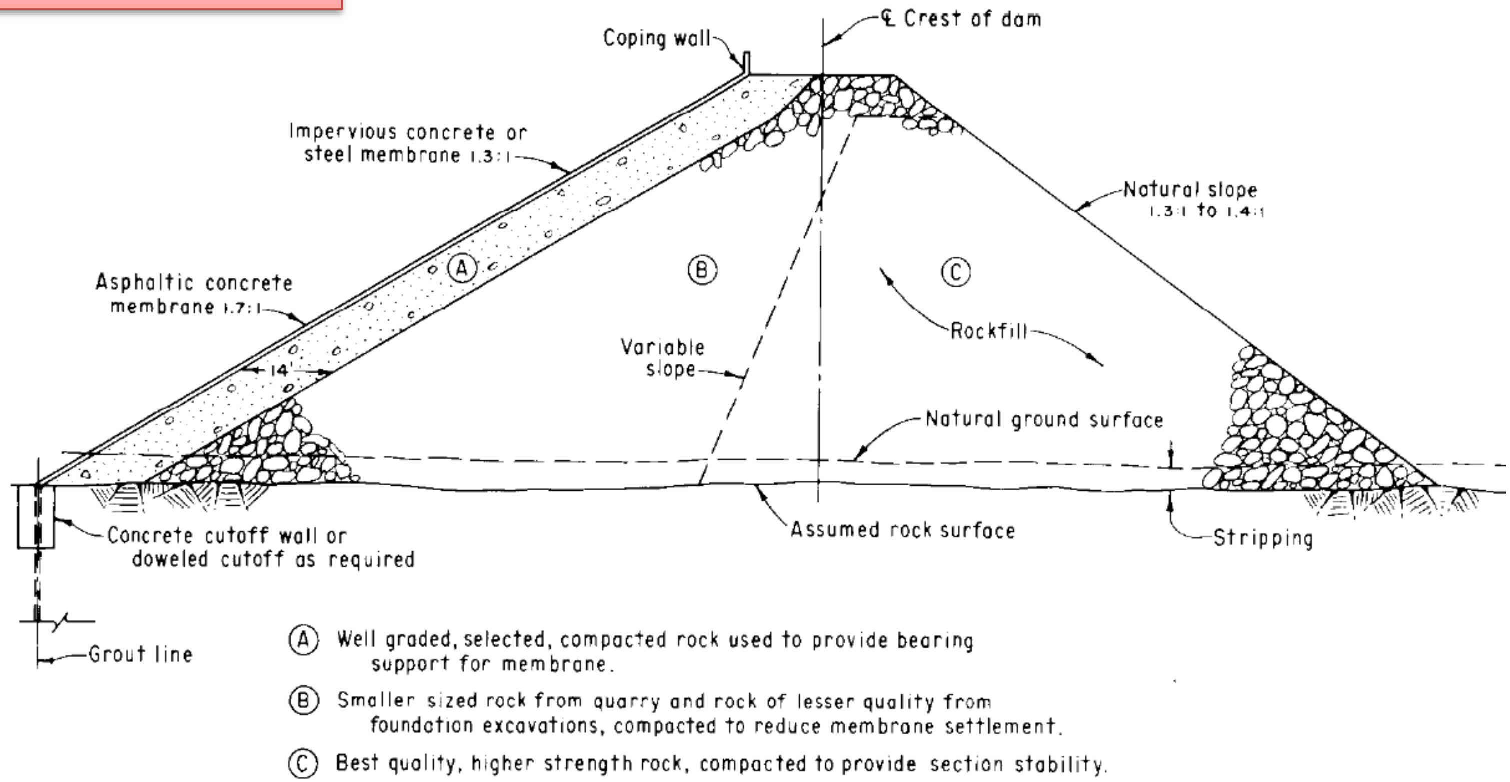
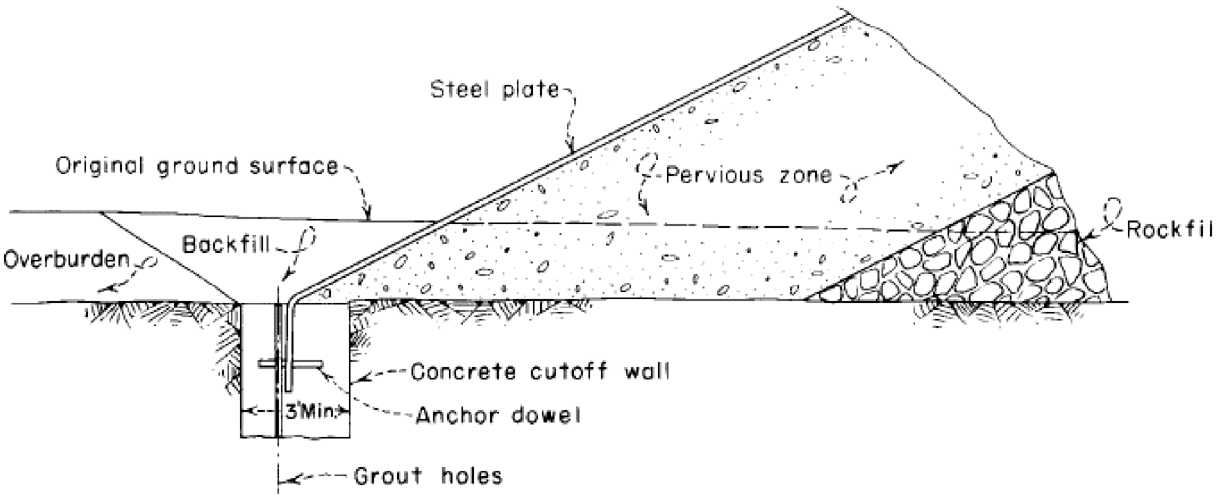


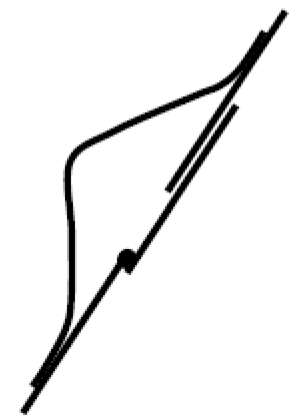
Fig Typical maximum section of a decked rockfill dam

- Membrane must be durable, flexible, impervious, does not creep, and resist weathering
- Membrane material must satisfy: sieve analysis, Sustained load test, Permeability, Wave action test , etc
- Special tests may be needed as: Slope flow, Coefficient of expansion, Flexural strength and Effect of reservoir ice
- Parapet walls may be used to contain wave action

3. Steel Face

- Used on few dams
- Performance satisfactory
- Can be rapidly constructed
- Can tolerate greater embankment reverts
- Disadvantage-probability of corrosion
- Proper maintenance can made facing as permanent
- Dam u/s Slopes 1.3-1.7

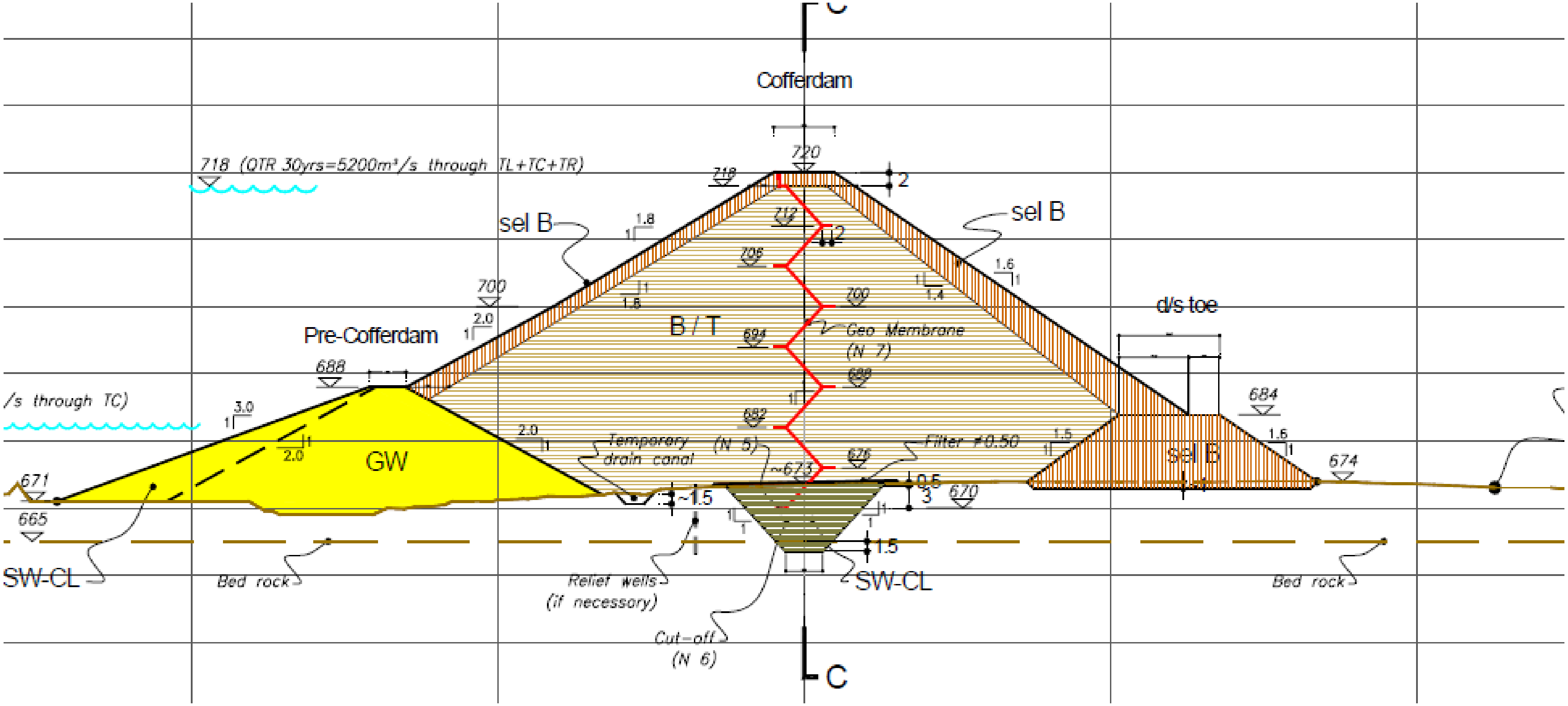




Steeper slopes construction difficulties

- Plate anchored to embankment by steel anchor rods grouted in bedding material
- Plate raised on a scaffolding, grid, bedding material placed after or during plate construction
- Plate thickness ¼-3/8”
- Jointed by bolts or continuous fillet weld,
- Expansion joints provided at regular interval
- Coping walls can be used to retard over splash

PVC geomembrane



Typical cross section of Gibe III cofferdam (Rockfill dam)

EMBANKMENT DESIGN

i. Rockfill Materials

The quality of the rock is a major factor in the choice of a rockfill dam and in the design of the structure. Extensive testing is necessary to judge whether the rock is suitable for construction.

Rock Quality

- Hard, durable and able to withstand disintegration due to weathering.
- Resist excessive breakage due to quarrying (rock blasted at quarry), loading, hauling and placing operations
- Free of unstable minerals
- Individual rocks of uniform size for good rock-to-rock contact.
- Igneous, sedimentary and metamorphic rocks all used successively.
- Each dam site a unique problem, thus General guidelines only.
- Rock quality determined by lab tests and/or in-situ inspections of weathering marks at the rock quarry site
- Test embankment to answer i. Use of marginal materials, ii. Performance of materials during compaction operation, iii. Correct compaction equipment, iv. Number of passes, v. Correct lift for each material

Rock Sources

Rock can be obtained from many sources as:

- Excavation for foundations, structures, spillway, stilling basin, tunnels, underground power houses etc.,
- Quarry rock near dam site
- Angular rock fragments can be obtained from the river bed

Rock Size

Use Rock of sp. gravity = 2.67 – 2.94 and weight not less than 160 lb/cft = 2560 kg/m3

Placement of Rockfill Materials

- Limiting settlement is critical in the construction of rockfill dams because excessive settlement may rupture the upstream membrane or cause joint separation with subsequent water loss

- Early rockfill dams were constructed by dumping the rock in high lifts; it was assumed that dropping rock from heights imparted compaction energy to the fill, decreased the void space and, thus, reduced embankment settlement (also sluicing used).

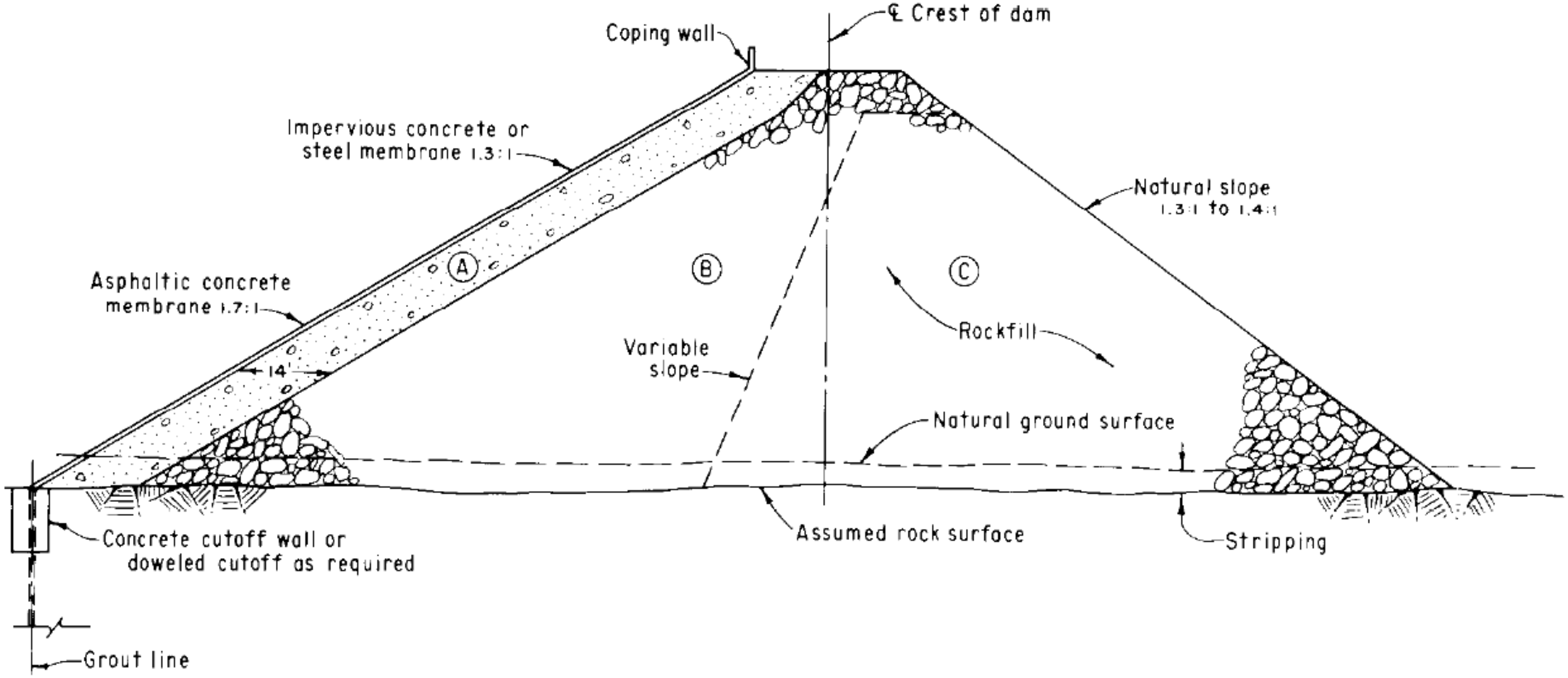
- Currently, placing rockfill in thin lifts and compacting it with a vibratory roller is the preferred construction method

ii. Embankment Sections

U/s , d/s Face Slopes and Zoning

- Slopes depend on type and location of membrane. Slopes evolved from steep (0.5 H: 1V) to flat (1.3-1.7:1)
- Steep slopes used to minimize rock volume and cost
- Steep slopes possible with u/s face membrane
- For past design the steep slopes were stabilized by thick crane-placed dry rubble masonry (and which provide as support zone for the bedding layer for u/s membrane). No derrick/crane placed rock work required for present design
- Slope flattened to match angle of repose
- Central sloping core: 2:1 to 4:1 both u/s & d/s (flatter slopes for central core)
- U/S face membrane: concrete u/s 1.3-1.7:1, d/s natural angle (1.3 – 1.4 :1), Asphalt concrete face 1.6 – 1.7:1, Steel, u/s 1.3-1.4:1, D/s – 1.3- 1.4

A) Section details for a typical decked (upstream membrane)rockfill dam

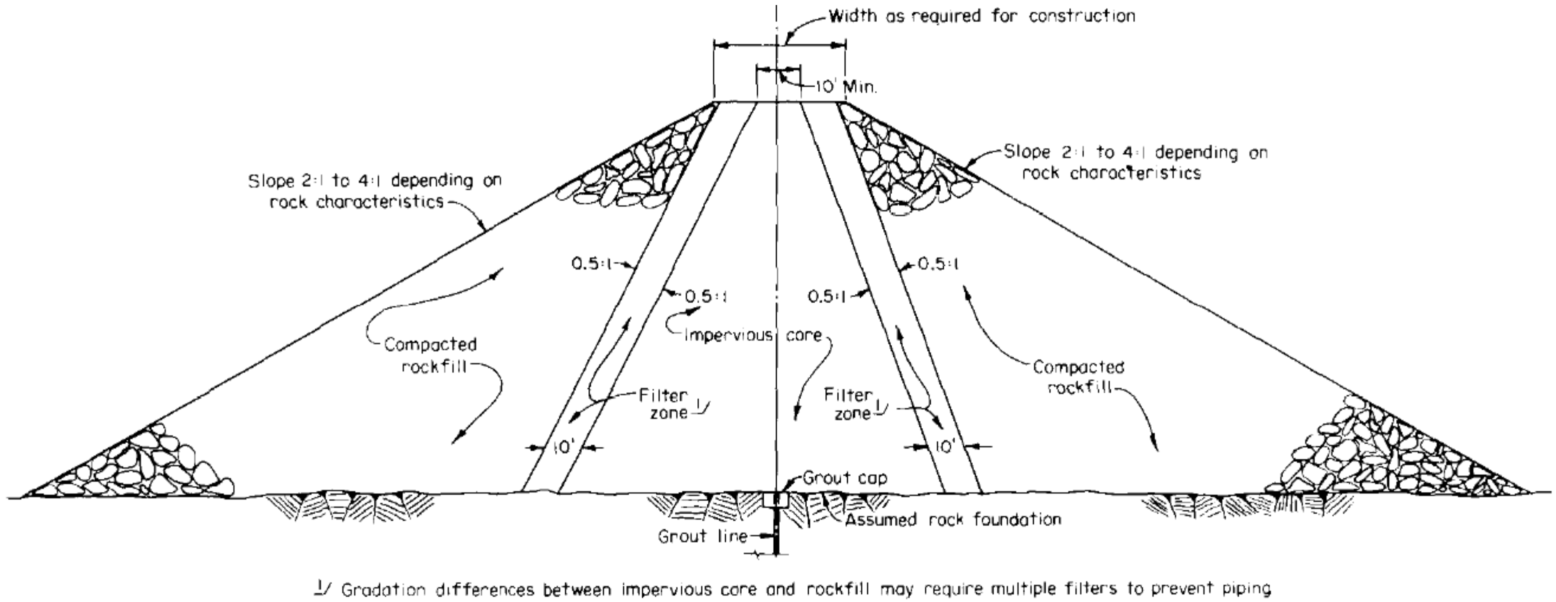


Zone C: The larger downstream zone of the dam, consisting of the best quality, larger, compacted rock; this zone provides high stability to the section.

Zone B: Rock of lesser quality than zone C, such as that excavated from the spillway; used to minimize total dam costs.

Zone A: Well-graded, smaller rock and gravel; used to provide bedding for the upstream membrane and to retard extreme water losses should the membrane crack.

B) With Central core:



- The u/s and d/s rock shell provide support to the core.
- Strongest and large rocks in d/s rockfill shell/zones.
- The u/s shell may be formed of lesser quality rock. For both u/s and d/s shells, the smaller size rock is placed nearer and adjacent to the core while larger size rocks is placed towards the outer faces.
- The rock material placed on u/s and d/s face to be of sufficient size and quality to satisfy the riprap requirements. No bedding layer is required below the riprap due to sufficient porous nature of the rockfill.
- General grading of rock material as: 0-10% - 0.6 mm, 0-40% -5 mm, 0-65% - 19 mm, 22-100% - 76 mm, 60-100% - 305 mm, 100 % - 610 mm

(B) With Central core (continued)

- The u/s and d/s shell rockfill is compacted in 1 m lifts with vibratory rollers. The sluicing is done in such a way that it will not clog filters or impermeable materials washed away
- The filter/transition zones are compacted in 30 cm lifts by crawler or vibratory rollers.
- The width of filter zone should be enough for placing and compaction. Filters materials prevent piping of the impervious materials into the rock shells.
- The core is compacted in 15 cm layers and compacted by sheep foot rollers + vibratory or tamping rollers.
- The top surface is scarified / roughened before the next layer to obtain an effective bond. The core material to have enough plasticity index to allow the core to deform without cracking.

Crest width

- should be determined by the type of membrane used and by its use after construction.
- The crest should, however, be wide enough to accommodate construction of the upstream membrane;
- A minimum width of 15 to 20 feet is recommended.
- Crest camber should be determined by the amount of foundation and embankment settlement anticipated. Because this is difficult to determine, a camber of 1 percent of the embankment height is recommended.

Freeboard

- Freeboard requirements depend on maximum wind velocity, fetch, reservoir operating conditions, spillway capacity, and whether coping walls are used.
- If a coping wall is used to provide wave run-up and over splash protection, the freeboard requirements of the embankment may be less than required for a riprapped earthfill dam
- If a coping wall is not used, the freeboard should be adequate to prevent wave run-up from flowing over the crest
- Good results have been obtained with coping walls, and their use is recommended.