Chapter 4
Construction of earth and rockfill dams (Overview)

Phases of Construction

- Evaluation of plans, specifications, basic requirement, and features of the site.
- Planning and scheduling of the job
- Making the site ready
- Building up the structure
- Clean Up

A typical construction sequence for a fill dam is:
Stage 1: Excavate diversion tunnel and build coffer dams. The end of this stage is marked by the milestone of diverting the river through the diversion tunnel.

Stage 2: Strip dam foundation of overburden. Carry out foundation treatment and grouting.

Stage 3. Excavate and haul fill construction materials from their sources and place and compact in the dam embankment. The end of this stage is marked by the milestone of closure of the diversion tunnel to start the storage of water in the dam reservoir. Excavation of the spillway will also be under way during this stage.

Stage 4: Complete outlet works, spillway and all other parts of dam project
RIVER DIVERSION

The **magnitude**, **method** and **cost** of river diversion works will depend upon
- the cross-section of the valley
- the bed material in the river
- the type of dam
- the expected hydrological conditions during the time required for this phase of the work
- and finally upon the consequences of failure of any part of the temporary works.

**Possibilities**

**Cofferdams**: Large discharges require cofferdams and different structures of the **diversion system**

An **upstream main cofferdam** serves to retain the anticipated construction floods and to conduct the permanent river discharge and the construction floods to the diversion structures.
A **downstream cofferdam** serves to protect the construction area from inundation by tail water.

The other components of the diversion system may be **channels** and **lateral tunnels** through one of the abutments.
Foundation and Abutment treatment

The preparation of the foundation and abutments for an earth or rock-fill dam is the most difficult and important phase of construction.

The degree of foundation preparation depends on the:

- Type of dam
- Height of dam and the consequences of failure
- Topography of the dam site
- Erodibility, strength, permeability, compressibility of the soil or rock in the dam foundation
- Groundwater inflows to excavations
- Climate and river flows

Purpose of foundation and abutment treatment

- to obtain positive control of under seepage
- prepare surfaces to achieve satisfactory contact with overlying compacted fill
- and minimize differential settlements and thereby prevent cracking in the fill

The main activities under the foundation and abutment treatment works are:

- Stripping of the foundation and abutments to depths sufficient to remove soft, organic, fractured, weathered, or otherwise undesirable materials;
- Cleaning and adequately filling of depressions and joints in rock surfaces
- Rock surfaces are made relatively smooth and uniform by shaping and filling
- subsurface cavities are detected and grouted
- cutoffs extend to suitable impervious materials
Cutoff in rock

- Remove rock with **open joints and other fractures** which would otherwise lead to a highly permeable structure.
- Remove rock with **clay infilled joints, roots** etc., which may erode under seepage flows to yield a high permeability rock.
- Carry out **slope modification and treatment**
- Where the exposed rock is susceptible to slaking by wetting and drying (e.g. many shales) or breakdown under trafficking, it should be **covered with a cement-sand grout** (thickness usually 10 mm to 25 mm)
- Remove from the surface **all loose soil and rock**, and debris from grouting (using light equipment and with an air or air-water jet). Hand cleanup may be necessary. The surface may need to be moistened immediately before placing earthfill to maintain the earthfill moisture content.
- If the rock in the floor or the sides of the cutoff trench displays **open joints** or other features which would allow erosion of the earthfill into them, it should be cleaned of loose material and covered by a **cement-sand grout**, pneumatically applied mortar or concrete.
Excavation of sheared zones prior to filling with dental concrete in the cutoff foundation

Application of pneumatically applied mortar on seams in the cutoff foundation
Cutoff in soil

- Remove soil with open fissures, open joints, roots, root-holes, permeable layers (e.g. sand and gravel) and other permeable structure (e.g. leached zones in lateritic soils)
- Remove dispersive soils if possible
- Carry out slope modification (next slide)
- If the soil on the sides of the cutoff trench displays permeable layers or features which would allow erosion of the earthfill into them, it should be trimmed and cleaned and covered with a filter layer or layers which are designed to control such erosion
- Remove loose and dry soil and other debris with light equipment, possibly with the aid of an air jet
- The base of the cutoff should be watered to within 2% dry and 1% wet of optimum water content and rolled before placing the first layer of fill, to compact any soil loosened by the construction work
**Slope modification**

- Excavation of near vertical or overhanging surfaces and/or backfilling with concrete is required.

**For general foundation:**

- To **allow compaction of earthfill and avoid cavities** under rockfill due to overhangs in rock in the abutment.

**For cutoff foundation:**

- To **allow compaction of earthfill** to give a low permeability contact between the earthfill and the foundation.
- To **limit cracking of the earth core** due to differential settlement over large discontinuities in the abutments.
Slope modification in the cutoff foundation to reduce differential settlement and cracking of the earthfill core.

Foundation slope correction, Blue Mesa Dam (zoned earthfill dam on the Gunnison River in Colorado)
Seam treatment

It is common practice to require that seams of clay or extremely weathered rock which occur in the cutoff foundation should be excavated and filled with concrete. This is done to avoid erosion of the seams thus allowing seepage to bypass the earth core and filters. Thomas (1976) suggests that the depth of excavation and backfill should be 2 to 3 times the width of the seam.

Fig Slope modification and seam treatment in the cutoff foundation for interbedded sandstone and siltstone, near horizontal bedding
**Dental concrete, pneumatically applied mortar, and slush concrete**

**Dental concrete:** Dental concrete is used to fill irregularities in the foundation due to joints, bedding, sheared zones, overhangs, or excavated surfaces.

Dental treatment of weak seams in the plinth foundation of Kangaroo Creek Dam
The cohesive materials and rockfill material are usually excavated or quarried in dry conditions.

There is a range of equipment available to excavate, shift and place material in dams. Each type of equipment has been developed to suit particular requirements such as short haul distances or deep and narrow excavations.

PROCESSING OF NATURAL CONSTRUCTION MATERIALS

Processing may involve removal of oversize or undersize (fines) material, or obtaining a specific size range for use in a particular zone of the embankment such as a graded filter.

Material blending with sand and gravel

It is occasionally useful to blend cohesive material with sand and gravel to achieve the proper conditions for compaction and performance.

Material blending with clay

The properties of slightly cohesive soil with regard to their use as sealing material can be improved by adding clay. Usually bentonite is added, by adding bentonite the material is made more plastic. That means that the fill water content can be increased and hence better adjusted to the requirements of appropriate compaction.

Filter materials are treated like concrete aggregates. They are washed, screened and newly mixed according to specified gradations.
Embankment Construction

The embankment consists of a series of compacted layers or lifts of suitable material placed on top of each other until the level of the top of the embankment surface is reached.

The components of embankment construction are:
- Lift Thickness
- Material
- Degree of Compaction

The thickness of the lift is limited by the type and size of compaction equipment the contractor chooses to use.

<table>
<thead>
<tr>
<th>Material</th>
<th>Group symbol</th>
<th>Layer thickness uncompacted (cm)</th>
<th>Appropriate compactor</th>
<th>Number of passes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highly plastic clay</td>
<td>CH</td>
<td>15 to 20</td>
<td>SPR</td>
<td>6 to 10</td>
</tr>
<tr>
<td>Plastic silt</td>
<td>MH</td>
<td>20 to 25</td>
<td>SPR</td>
<td>4 to 8</td>
</tr>
<tr>
<td>Low plastic clay</td>
<td>CL</td>
<td>20 to 30</td>
<td>SPR, VPR</td>
<td>4 to 8</td>
</tr>
<tr>
<td>Low plastic silt</td>
<td>ML</td>
<td>20 to 30</td>
<td>SPR, VPR</td>
<td>4 to 6</td>
</tr>
<tr>
<td>Clayey sand</td>
<td>SC</td>
<td>20 to 30</td>
<td>SPR, VPR</td>
<td>4 to 6</td>
</tr>
<tr>
<td>Silty sand</td>
<td>SM</td>
<td>20 to 30</td>
<td>SPR, VPR</td>
<td>4 to 6</td>
</tr>
<tr>
<td>Sand and sand-gravel, poorly graded</td>
<td>SP</td>
<td>30 to 50</td>
<td>VSDR</td>
<td>4 to 6</td>
</tr>
<tr>
<td>Sand and sand-gravel, well graded</td>
<td>SW</td>
<td>40 to 60</td>
<td>VSDR</td>
<td>4 to 6</td>
</tr>
<tr>
<td>Clayey gravel</td>
<td>GC</td>
<td>20 to 30</td>
<td>SSDR, VPR, PR</td>
<td>6 to 8</td>
</tr>
<tr>
<td>Silty gravel</td>
<td>GM</td>
<td>30 to 40</td>
<td>SSDR, VPR, PR</td>
<td>6 to 8</td>
</tr>
<tr>
<td>Gravel, poorly graded</td>
<td>GP</td>
<td>40 to 50</td>
<td>VSDR</td>
<td>4 to 6</td>
</tr>
<tr>
<td>Gravel, well graded</td>
<td>GW</td>
<td>50 to 60</td>
<td>VSDR</td>
<td>4 to 6</td>
</tr>
<tr>
<td>Rockfill</td>
<td></td>
<td>60 to 150</td>
<td>VSDR</td>
<td>4 to 6</td>
</tr>
</tbody>
</table>

1 The average weight of all compactors is 100 to 150 kN. The heaviest available compactor should be used. Average operating speed is 5 km/h.

SSDR = Static smooth drum roller
VSDR = Vibratory smooth drum roller
PR = Pneumatic tired roller
VPR = Vibratory padfoot roller

Table: Standard procedures for compacting construction materials in the field;
(Large field tests are recommended to specify the details).
Smooth drum roller

Padfoot roller

Pneumatic tired roller
Compaction Fundamentals

- Place loose soil in the field and compact it to make soil strong and attain
  - Maximum shear strength
  - Very little settlement
  - Low hydraulic conductivity
  - Soil lowest emin ……highest dry unit weight

- The most important variables affecting **construction of earthfill embankments** are **the distribution of soils, method of placement, water content, and compaction**

- Soils containing fines can be compacted to a specific maximum dry density with a given amount of energy;
- Maximum density can be achieved only at a unique water content called **the optimum water content**.
- Maximum dry density and optimum water content are determined in the laboratory by compacting **five or more specimens of a soil at different water contents** using a **test procedure** which utilizes a standard amount of energy called “**standard compactive effort**”
- Most specifications require that the material is to be placed in the embankment at, or near, optimum moisture content and **at least 95% standard compaction** is to be achieved
Influence of water on compactability

- **low moisture content**
  - high internal friction
  - low density

- **optimum moisture content**
  - best compactability
  - max. density

- **high moisture content**
  - high water pressure
  - low density

Proctor curves of different soil types:

1. sandy gravel
2. Gravel - sand
3. uniform sand
4. sandy silt
5. heavy clay
Strength and Permeability of Compacted Soils

Compare the risks of dry side compaction with the wet side compaction.

Strength before reservoir filling with respect to moisture content.

Strength after reservoir filling (saturation).
The relative density $D$ can as well be expressed by:

$$D = \frac{\gamma_{\text{max}} (\gamma - \gamma_{\text{min}})}{\gamma (\gamma_{\text{max}} - \gamma_{\text{min}})} \times 100 \text{ (\%)}$$

where $\gamma_{\text{max}} = \text{unit weights of the soil in most compact state}$

$\gamma = \text{unit weights of the soil in place}$

$\gamma_{\text{min}} = \text{unit weights of the soil in loosest state}$

Compaction level (\%) $= \frac{\text{Insitu dry unit weight}}{\text{Max. dry unit weight (Proctor)}} \times 100$

Standard Proctor Specification 95 to 100 percent of MDUW( maximum dry unit weight)
The following is offered as a guide to practical minimum widths and also construction methods:

a) Filters upstream or downstream of an earth core, when constructed by end-dumping off a truck should be at least 2.5 and preferably 3 m wide.

b) If a spreader box such as that shown in Figure below is used, a minimum width of 1.5 m is practicable. The filter material is dumped off the truck into the spreader box, which spreads the filter out of its base as it is pulled along by a small bulldozer.

c) If filter materials are very scarce or high cost, formwork can be used to contain bands of filters as narrow as one meter. Sherard et al. (1963) show an example of such placement. This is very unusual and would only be contemplated in exceptional circumstances.

Figure . Typical spreader box and screed
Spreading sand filter material
(usually accomplished by graders or dozers)
spreader box
Placing the earthfill for up to 2m over the filter layer, and then excavating through the earthfill with a backhoe or excavator to expose the filter.

Dumping the filter on the trimmed downstream slope of the earthfill core.

Trenching method – backfilling trench.
Minimum recommendations

- Case (a) should be designed with a minimum horizontal dimension of 5 feet and 1 feet as shown.
- Case (b) should be designed with a minimum horizontal dimension of 3 feet and 1 feet.
**Sequence of placement**

Filters generally should be placed ahead of the adjacent earthfill or rockfill zones. This is desirable because it allows good control of the width of the filter zone compared to the specified width, and reduces the risk of contamination of the filter zone with materials from the adjacent zones, and from water eroding off adjacent areas generally.
Compaction of filters

Filters should be compacted in layers using a vibratory smooth steel drum roller. Filters are usually well graded granular materials and are readily compacted to a dense condition.

<table>
<thead>
<tr>
<th>Authority and dam</th>
<th>Zone</th>
<th>Standards specification</th>
<th>Methods specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Resources Commission of Queensland, Peter Faust Dam (1989)</td>
<td>2A and 2B</td>
<td>AS1289. Density index between 60% and 70%</td>
<td>At least one pass of a suitably smooth drum vibratory roller to give standards specification. Maximum layer thickness 350 mm after compaction</td>
</tr>
<tr>
<td>Water Authority of Western Australia, Harris Dam (1989)</td>
<td>2A Chimney drain 2A horizontal drain and 2B</td>
<td>AS1289. Density index &gt; 70%</td>
<td>Not given. Maximum thickness 500 mm before compaction 4 passes of a vibratory roller with static mass between 8 and 12 tonnes, and centrifugal force not less than 240 kN. Maximum thickness 600 mm before compaction 2 passes of a vibratory roller with static weight not less than 8 tonnes and a centrifugal force not less than 160 kN. Maximum layer thickness 450 mm after compaction 4 passes of a vibratory roller with static weight not less than 10 tonnes static weight and a centrifugal force not less than 350 kN. Maximum layer thickness 450 mm after compaction</td>
</tr>
<tr>
<td>Melbourne and Metropolitan Board of Works, Cardinia Creek Dam (1970)</td>
<td>2A and 2B</td>
<td>Not specified</td>
<td>Not specified</td>
</tr>
<tr>
<td>Snowy Mountains Hydroelectric Authority, Talbingo Dam (1967)</td>
<td>2A and 2B</td>
<td>Not specified</td>
<td>Not specified</td>
</tr>
</tbody>
</table>
i. Dumped Rockfill construction

- The main body of fill is placed by dumping. The initial part of the fill is dumped from clamshell cranes, cableways, or from ramps on the abutments to form a mound or bank. The remainder of the fill is dumped from the top of this mound, allowing the rock to fall down the sloping surface. The combined effect of sliding, tumbling and impact cause the pieces to become tightly wedged together. Not more than 15% fines should be in the dumped rockfill, since they prevent good compaction and make drainage of water difficult.

ii. Rolled Rockfill

- Modern day rockfill dam construction
- It is placed in layers and then rolled by heavy rubber tyred rollers and heavy vibrating rollers. Four to eight passes are required for compaction.
- Optimum rockfill loose lift thicknesses are generally about 18 to 30 inches (0.5 to 0.8 m) with maximum rock sizes limited to two thirds of the lift thickness
- Rockfills for compacted dam structures are generally placed in transitional zones with the most coarse and competent rock placed in the outer shell and finer more weathered rock placed in the interior or adjacent to earthfill filter drain and core materials

iii. Reshaping the Fill

- The dumped rockfill assumes side slopes of the angle of repose. If a flatter slope is required it can be formed by introducing horizontal berms as required
Rock dump loose lift placement in 45 ft (15 m) thickness
Compacted rockfill placement in relatively thin controlled lifts for heavy roller compaction
The possible sequence of works associated with the face slab are:

- Survey of the upstream face and the shotcrete protection applied to it.
  
  Due to movements of the embankment during the construction stage and probable bulging, it is necessary to trim the face back to its designed position, in order to enable the slab to be placed correctly and have the required thickness.

- Install the mortal pads along the vertical joints
  
  To be placed with a high degree of accuracy, because their position dictate the final shape, the thickness of the slab and also its surface specified tolerances. On these pads the cooper water stop will be placed along the full length of each bay

- Reinforcing mats.
  
  Can be transported down the face with the use of a trolley travelling on two rail lines. The reinforcing mats can be placed in the middle of the slab thickness. The work can start from the bottom of the bay and progress up towards the top of the face.

- Casting the slabs consecutively, one after the other
Placement of the mortar pads
Reinforcement placing trolley
Self climbing slip form with side discharger
Upstream Face Slab Concreting
General view of a completed Dam
GERDP LAYOUT

RCC Dam & Powerhouses

Reservoir

Spill Way

Saddle Dam (Rock fill)