EARTHEN DAMS

i) OBJECTIVES:

Earthen dams can be of 2 major types depending on their primary objective:

a) Irrigation Dam: Such dams can be constructed to meet two different kinds of Demands of:

- Storing water during the rainy season to be used for irrigation in the Post-monsoon period.
- Providing protective irrigation during dry spells within the rainy season. Most parts of India typically receive rainfall between June and September, very intensively within a few hours and a few days. The number of rainy days does not average more than 40-50 Therefore we may need structure for providing protective irrigation for kharif season.

b) Percolation Dam: Percolation dams are constructed for recharging groundwater. Such structures are usually made on the upper part of the catchment area. Water stored here percolates to wells and tube wells located in the lower part of the catchment. Such dams can also be made in the immediate upstream portion of wells and tube wells. Depending on the capacity of the dam and duration of water storage, the dam can have secondary benefits (such as pisciculture) that are vital for the livelihood security of marginal farmers and landless laborers.

ii) LOCATION:

Deciding how to locate an earthen dam requires balancing many considerations and arriving at the best possible solution.

a) Balance between Catchment Area and Storage Capacity: The first is to create the best possible match between the storage capacity of the dam and its catchment area.

b) Side banks of the Drainage Line: We must also try to ensure that where the dam is located the drainage line should have well-defined embankments so that we can anchor the dam into them.

c) Slope of the Drainage Line: Ideally, upstream of this site, the drainage line should be relatively flat (bed slope not more than 5%). This helps maximize storage capacity.

d) Upstream Width of the Drainage Line: As we move upstream of the dam site, it would be good if the width of the drainage line increases, so as to contain maximum storage within its banks.

e) Geology: In an irrigation dam, the water spread area and the natural embankments should be impermeable. In a percolation structure, the natural embankments should be impermeable but the water spread area should comprise relatively more permeable material.

f) Availability of Materials: Even with all other factors favoring a site, we may be compelled to abandon it if the requisite materials (earth, boulders, water etc.) are not easily available. This could make costs of transporting material prohibitively high.

g) Waste weir: It is very important to be able to find a proper location for the surplus weir at the dam site. We know that if water flows over the top of an earthen dam it will break. Hence, the surplus weir is required to channelize excess runoff safely out of the structure.

iii) Design

It is neither desirable nor possible to capture the entire surface water run-off within the watershed. In any case, no single earthen dam can do this. A thumb rule we have devised to make an earthen dam cost-effective is that it should aim to capture no more than 40% to 70%[1] of the season's total surface water run-off.

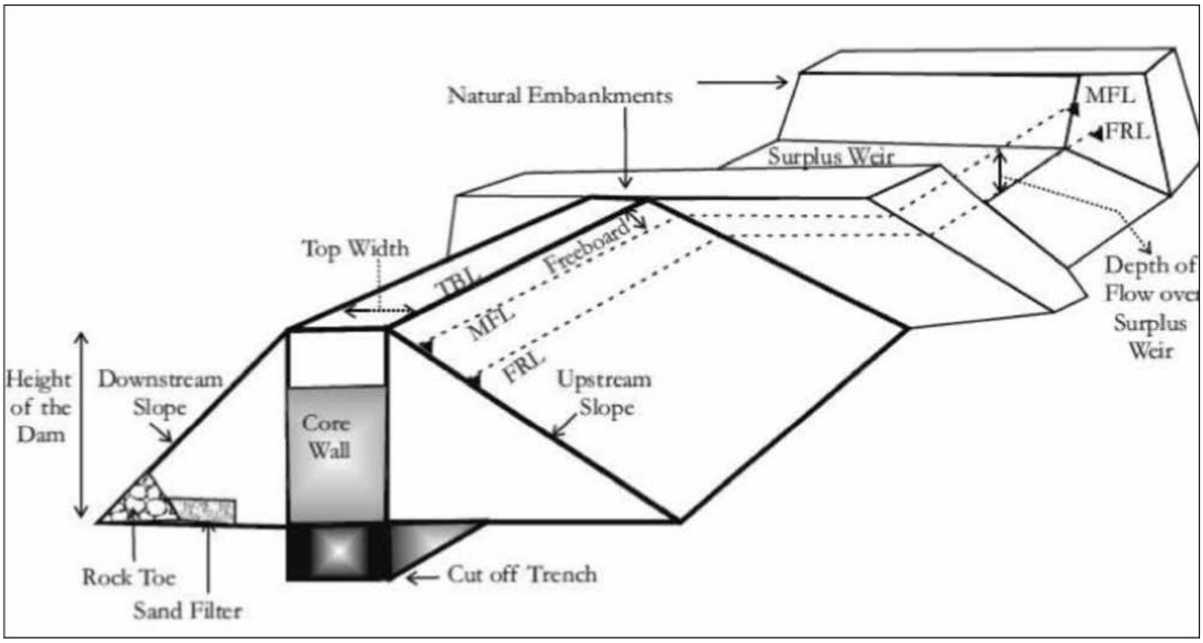


Fig: The design of an earthen dam and its main parts

a) Full Reservoir Level (FRL):

The FRL indicates the maximum level up to which water will rise when the structure is full. The FRL is determined bearing in mind the total runoff in relation to the effective storage potential of the site, which in turn depends on the shape of the side embankments, the upstream bed slope and geology of the drainage line and its width. The precise method of determining the storage potential of the site is provided in the Appendix to this chapter. Once we know the storage potential, how high we keep the FRL is determined by specific conditions at the site, such as height of the embankments, upstream bed slope, width of the drainage line and maximum permissible submergence. The submergence permissible in any such structure would depend upon the nature of the catchment: in particular, whether it is inhabited, forested or whether it includes fertile agricultural land. The permission of those whose lands may be getting submerged would also need to be obtained prior to fixing the FRL. They should be actively involved in the planning and design of such structures from beginning to end. In case they suffer a loss due to the structure, they must be adequately compensated, possibly through sharing the benefits from the structure with them

b)The Maximum Flood Level (MFL):

The MFL is the maximum level up to which water is allowed to rise in a structure after an intense spell of rain. This provision takes care of extraordinarily high floods, which might damage the structure because it takes time for flood water to move out of the surplus weir. This may happen especially when there are temporary obstructions in the surplus weir due to accumulation of fallen tree trunks, leaves etc. This is particularly important after the first rains.

c)The Freeboard:

Over and above the MFL, we provide an extra height to the dam, which is called the freeboard. Freeboard is the difference in height between the top of the bund and the maximum level up to which floodwater rises in a dam. Normally, the freeboard should be at least double the difference between FRL and MFL. It has been found through years of experience that for earthen structures with height less than 5m, a freeboard of 1m would be adequate.

[1] We know that rain in most parts of India falls in spells within a 4-month monsoon period. An examination of data on intensity of rainfall from all over the country suggests that any one spell is unlikely to yield more than 40% of the season's total run-off. Our small dams should not, therefore, be designed to capture more than this. As Tideman says "In engineering design it is uneconomical to design structures to cope with extreme events. A designer takes a calculated risk and designs a structure that will accommodate the largest rain storm that can be expected during a particular time interval" (Tideman, 1996).

d) Top bund level (TBL):

MFL + freeboard = TBL. The TBL refers to the top level of the dam. If water flows over the top of the bund in an earthen dam, the dam will break. Hence, unlike in masonry or boulder structures, the excess water cannot be directed over the top of an earthen structure. Therefore, the TBL in all earthen structures has to be kept higher than the FRL/MFL.

e) Top Width:

Top width of dams varies with the height and purpose of the dam. For earthen dams in the range of 3 to 6 meters height, top width is kept in the range of 1 to 2 meters. If the top is to serve as a road, the top width will need to be more than 2m. The top width may be determined by the empirical formula,

$W = 0.4 \times h + 1$ where, W = top width of bund

h = maximum height of bund

f) Hydraulic Gradient:

Saturation Gradient; Percolation Gradient: Line of saturation or Seepage and percolation line are all synonymous terms. It is a line inside an embankment marking the boundary between wet earth and damp or dry earth.

In the case of earthen embankments which hold up a depth of water against one face, the bank becomes gradually saturated by percolation up to certain level constituting a gradient or an inclined line falling from the point where the water touches the embankments on the upstream side. This inclined line is called the Hydraulic Gradient or Seepage Line for that soil and below which the embankment portion is saturated. This is due to the pressure of water, and the more the soil is porous the less is the resistance to percolation, and the flatter the hydraulic gradient.

The plane of the surface of percolation is called the plane of saturation or percolation and if this cuts the outer face of the bank, visible flow will appear along and below the line of intersection. The hydraulic grade line must fall within the toe of the bank and be covered by at least 100 cm of soil and which should be much more in the case of Core walls of puddle-clay etc. reduce the seepage line and prevent the flow lines from cutting the downstream face of the embankment. Sometimes filler materials are placed on the downstream toe to provide free drainage, which will force the seepage line down. Filter materials can be placed in several layers, each layer coarser than the last.

Table 2-10: The hydraulic grade line in different types of soils:

S. No.	Soil Type	hydraulic grade/seepage line
1.	Good clay	3:1
2.	Good compacted soil	4:1
3.	Average soil (sandy loam)	5:1
4.	Bad soil	6:1
5.	Fine silt	6:1
6.	Fine sand	8:1
7.	Coarse sand	10:1

(Source: Indian Practical Civil Engineers Hand book, by P.N. Khanna)

g) Upstream and Downstream Slopes of the Dam:

The upstream slope of the dam is subject to erosion by the sloughing action of waves and by receding water. The downstream slope of the bund is subject to erosion by intense rainfall and the scouring action of flowing water. In order to protect the dam from such erosive action, the slopes of the dams must be very carefully determined. The precise upstream and downstream slopes of the bund depend on the angle of repose and erodability of the materials used in the outermost face. However, it is necessary to provide a lower slope on the upstream side than the downstream side to counter the sloughing action. Through experience it has been found that for a stable earthen structure, the upstream slope should range from 2.5:1 to 4:1. The downstream slope should range from 2:1 to 3:1.

h) Settlement Allowance:

The soil used on an earthen dam is usually compacted to a certain degree. Even the, this artificial compaction can never match the state of natural compaction in which the materials are found on earth’s surface. Hence, a certain allowance has to be made for natural process of compaction due to the weight of the dam, movement of its materials towards their natural angle of repose, the increased moisture caused by water storage and the direct impact of rainfall. This allowance to be provided for this settlement depends on the type of fill material and the method of compaction used. Thus, the earthen dam must be made convex shaped with the middle portion being higher than the sides.

i) Waste weir:

Water in excess of the FRL is drained out by the waste weir. The base of the waste weir is at the FRL. Spells of rain can vary greatly in intensity. There may be a sudden storm and dangerous amounts of water may have to be dealt with. A safety valve is required that lets some of the runoff go as soon as the dam is filled up to the designed FRL.

The dimensions of the surplus weir are determined by taking into consideration the peak runoff from the catchment. The surplus weir must have the capacity to drain out safely the peak runoff when the water is at FRL of the dam. Peak runoff from a watershed is estimated as per the Rational Formula:

Peak Runoff $Q = C \times I \times A / 360$

Where,

Q = peak runoff in cubic meters per second C
= coefficient of runoff

I = intensity of rainfall in millimeters per hour

A = catchment area of the structure in hectares

The discharge capacity of the surplus weir has to be equal to the peak run-off. The surplus weir is given by the Crested Weir formula:

$Q = 1.711 \times L \times H^{3/2}$

where,

L = Length of the Weir (m)

H = Depth of flow through the weir (the height to which we would allow water to rise inside a surplus weir) (m)

iv) CONSTRUCTION STEP BY STEP:

a) Trial Pits:

At three or four places in the proposed dam site, experimental pits of 1m. x 1m. should be dug. Fill water in these pits to get an idea of the percolation rate of the proposed site. The site should be abandoned if the percolation rate is too high. Trial pits also help us determine the depth of the cut-off trench along the base of the dam. A third purpose of the trial pit is to assess the strength of the strata underlying the dam.

b) Site Clearance:

Remove all vegetation at the proposed site. Scrape the location to 10 -20cm depth. All tree roots as well as sand; stones etc., at the site should be removed. “Toothing” should be provided at the proposed site by making the base of the dam uneven. This helps better grip of the structure on the ground.

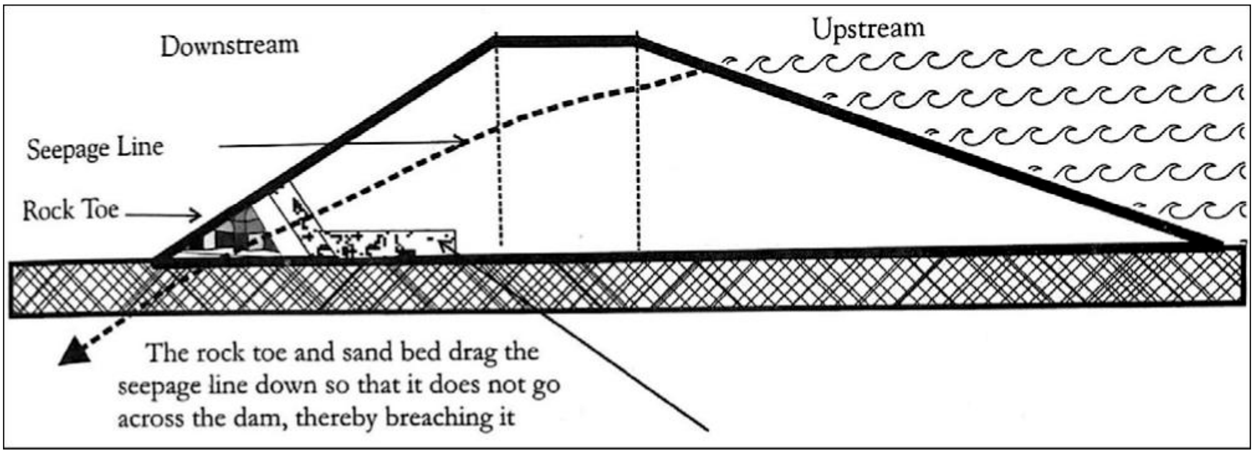
c) Layout:

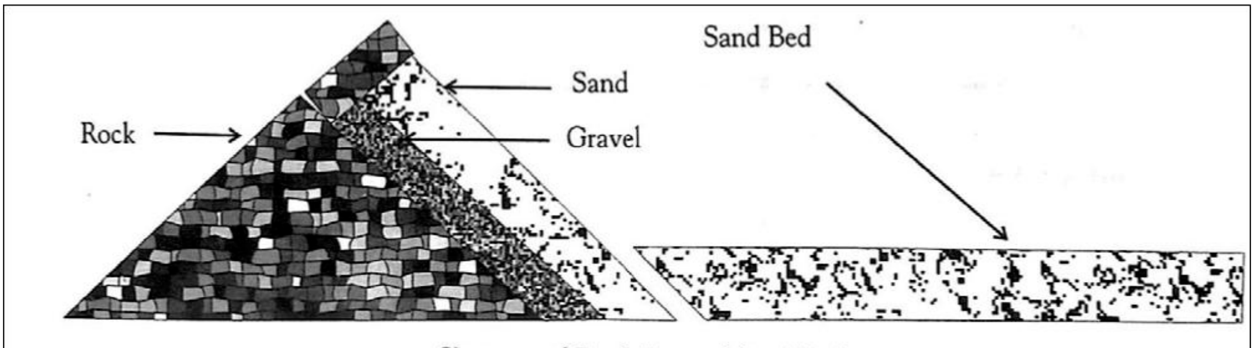
Draw a line along the center of the proposed bund from embankment to embankment (center line). Determine the FRL and TBL of the structure. At 4 meter intervals on the center line, use the dumpy level to mark a series of points where the dam will be raised to TBL. Settlement allowance must be added to this height at each point. On the basis of the slope parameters decided, indicate distances on the upstream and downstream side at each point and draw lines through these points. Care must be taken to provide the required top width exactly in the middle of the bund. For instance, if the maximum dam height is 5m, top width 2m and upstream and downstream slopes 2.5:1 and 2:1 respectively, the upstream edge of the dam must be marked at (5x2.5)+1=13.5m distance and the downstream edge at (5x2)+1=11m distance

d) Cut-off Trench:

We need to prevent the water from leakage and seepage we have stored in an earthen dam. For this we dig a cut-off trench and fill it with puddled clay the purpose of the cut-off trench is not to provide a foundation but to control excessive seepage below the dam wall.

Dig a 1m wide trench of required depth along the center line of the proposed dam. In earthen dams, the depth of the cut-off trench is usually fixed as 25% of the TBL or till impervious strata is reached, whichever comes earlier. After excavation, the base of the cut-off trench should be rammed thoroughly by watering. Fill the trench with 30-35 cm thick layers of puddled clay. Each layer should be properly watered and rammed into the layer below. Ramming inside the trench is usually done by laborers walking on the puddled clay.





Close-up of Rock Toe and Sand Bed

Fig: The seepage line and rock toe - Horizontal Sand Filter/Rock Toe Drain

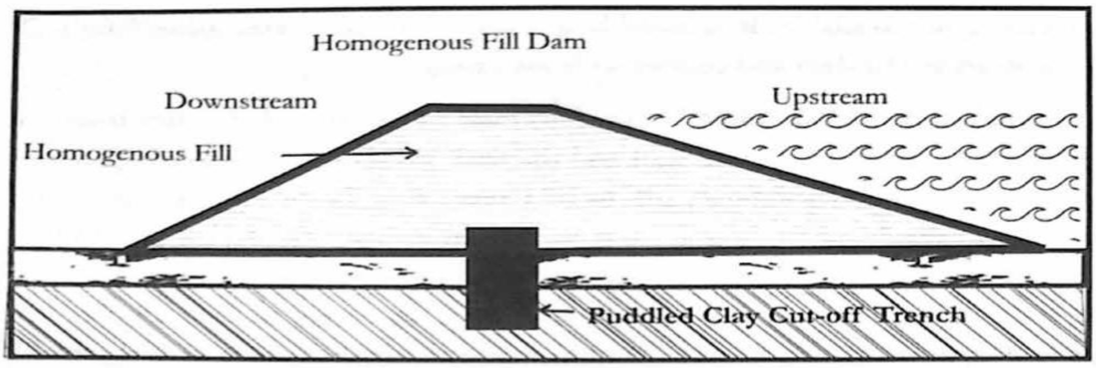
Even in a relatively impervious structure, some amount of water stored in a reservoir percolates from the upstream side to the downstream through the body of the dam, thus forming a seepage line. If this line emerges above the base of the dam, it would slowly cut into the downstream side and gradually erode it. This would pose a serious threat to the stability of the structure. In order to drag the seepage line downwards so that the water is drained within the base of the dam, 30 to 50 cm thick sand layers are placed inside the dam, at the base of the downstream portion, forming a horizontal sand filter. On the outermost side of the downstream portion, boulders are placed to drag the seepage line down, which forms the rock toe drain. The rock toe is usually constructed in the design of a reverse filter with each subsequent layer increasingly coarser than the previous layer. The filter material must be more pervious than the bund material so that the seeping water can be rapidly removed.

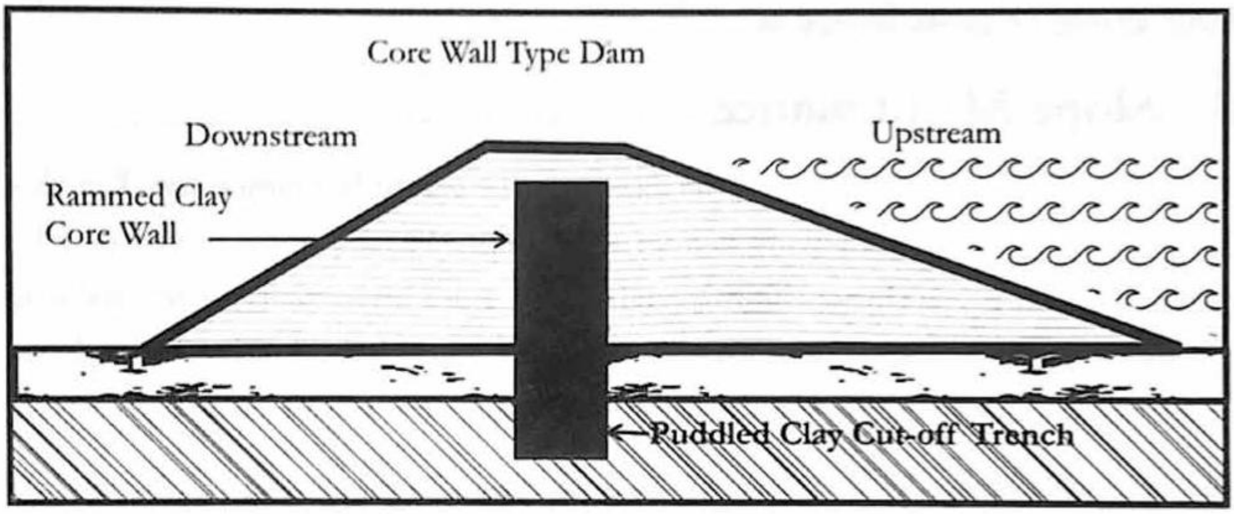
e) Embankment and core wall

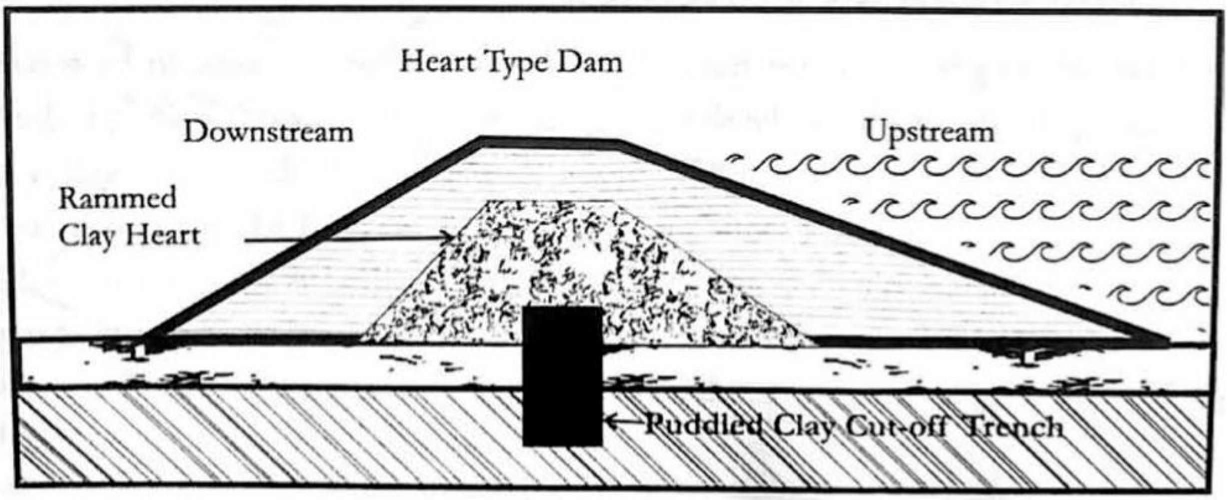
Depending on the construction materials used, earthen dams can be classified into three types:

- **Dams of Homogeneous Material:** In places with an impervious foundation where availability of clay is virtually nil, dams can be made from relatively more pervious material by increasing the cross-section area of the dam. Watering and ramming should be carefully done in such dams. The cross section of this type of dam should be made broader by providing lower slopes on the upstream and downstream, as well as by increasing the top width
- **Core Wall Type Dam: Where** both pervious and impervious materials are available, the dam wall can be partitioned between these according to their relative abundance. Where the availability of impervious clayey soil is limited, we can choose to economies on clay by watering and kneading by human labour (puddling). In the core wall type dam, there is a narrow, impermeable, puddled clay barrier, extending from side to side. The clay is soaked, kneaded and rammed to make a thin impermeable wall. This forms the core wall of the dam. The cut-off trench is filled with puddled clay till ground level is reached. This is a labour intensive method but it maximizes impermeability of clay. To support and protect this, the outer flanks of the dam are made of rammed coarser soils, which are arranged by grade. The finest particles are placed inside, graduating to the coarsest material on the outer face of the dam. The final shelter is provided by stone pitching, which involves placing a layer of boulders on the upstream face of the dam
- **Hearting and Casing Type Dam:** Where clay is available easily and in large quantities, it is possible to construct the heart of the dam with wetted and rammed clay, and provide a casing of coarser soils to protect it. Here, a thicker wall of clay is raised by laying, wetting and ramming (see Figure 2-36). The inner clay wall will also have side slopes, unlike the core wall, which is vertical. After the cut-off trench has been filled, the dam wall is raised in horizontal layers. Even in situations where pure clay is not available, it is possible to make an earthen dam using finer soils for the heart of the dam and coarser soils for casing.

In all three types of dams, care must be taken to raise all sections of the dam together. In a core wall type, the puddle core wall and the shell must be simultaneously raised. Core wall needs to be on structured only till the FRL is reached. In the hearting and casing type, both the hearting and the casing must be done together. The layers should be 6 to 8 inches on either side which are laid, wetted and rammed. While laying, it should be kept in mind that the finer soils should be laid inside, i.e., closer to the clay core, the coarser soils should graduate outwards. As layer after layer gets compacted, the width of the casing is reduced to create the slopes of the upstream and downstream sides of the dam till the desired height is arrived at.







f) Slope Maintenance:

Upstream and downstream slopes of the dam must be carefully maintained. For this, it is advisable that side slopes are made as a series of steps. These steps are necessary for the laborers to walk up to throw the material. Even more importantly, they allow us to make mid-term corrections in case the slopes go a little off the mark. Towards the end of the construction, the steps should be broken and a continuous slope provided.

g) Stone Pitching and Grass Turfing for Embankment Protection:

As mentioned already, the outer faces of the dam are subject to erosion by water. To protect the upstream face from the sloughing action of waves, stone pitching is done by using boulders of size 15-30 cm width. Use stones which are flat on one side and angular on the other. The area of stone pitching depends on the FRL of the dam and its upstream slope. Where boulders are not easily available, the freeboard zone on the upstream face and all of the downstream face can be protected by planting grass (grass turfing). The grass roots form a protective web that binds the soil together. The grass blades also cushion the force of raindrops making them less erosive. Grass turfing should be done before the monsoon begins on the down streamside of the dam.

h) Surplus Waste Weir:

After the construction of the main dam is over, surplus weir must be constructed[3] the site for surplus weir should be chosen in such a way that it minimizes excavation. As far as possible, the surplus weir should be connected to some natural drainage channel flowing nearby so that the excess runoff does not cause further erosion.

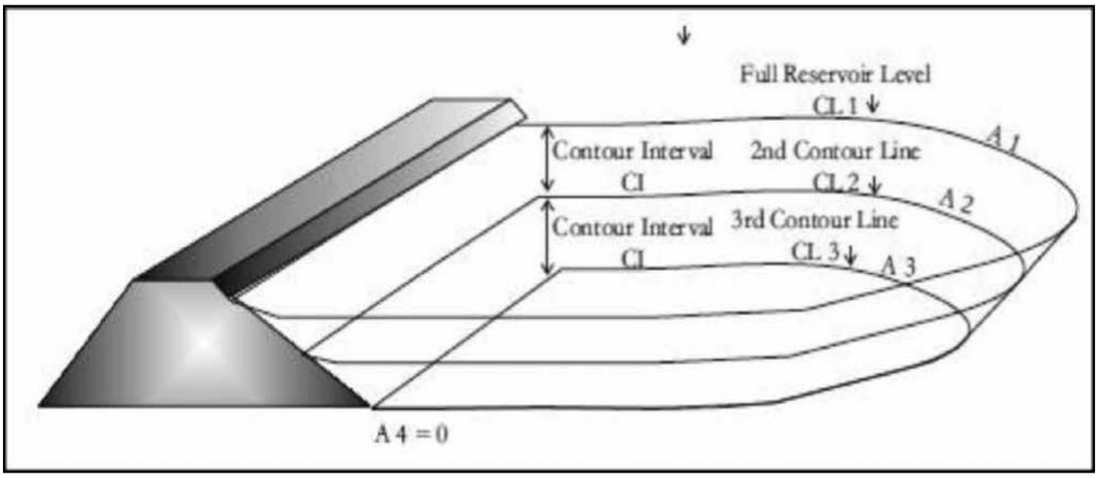
[3] In extraordinary circumstances where the monsoon is rapidly approaching and completing the dam before it appears difficult, we may also make the surplus weir first, in order to protect the work already done on the dam

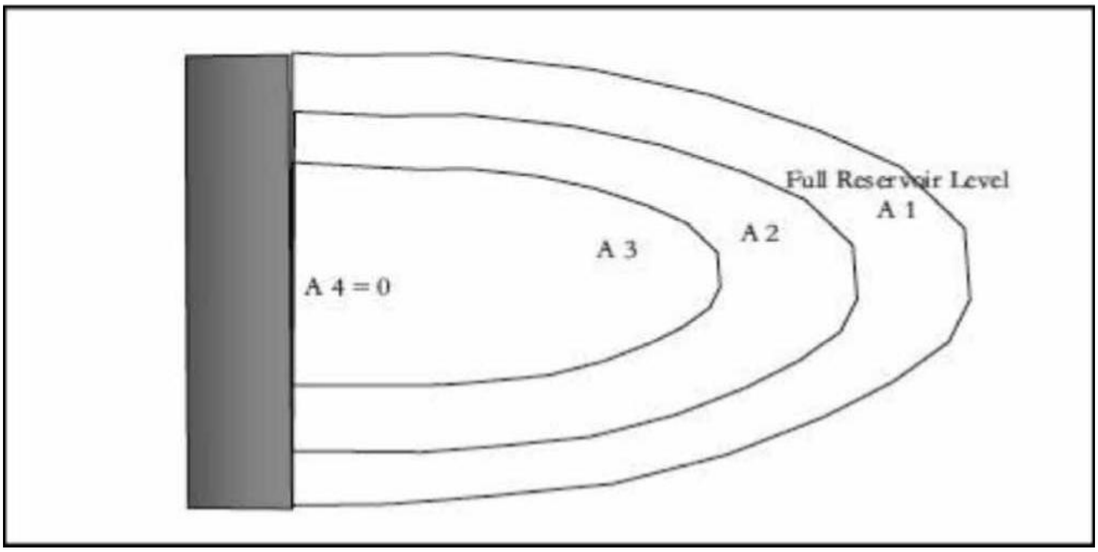
The following points also should be kept in mind while constructing surplus weirs:

- In some cases, it may be difficult to provide a surplus weir on the side of the dam due to adverse topography or geology. In such cases, a stone or cement masonry weir must be provided in the main body of the dam itself.
- All types of surplus weirs should have adequate protection of their sides and bed through stone pitching or stone/cement masonry.
- The surplus weir should not be very steep or have sharp curves. High slopes and sharp curves would both increase the danger of soil erosion.

v) ESTIMATION OF RESERVOIR CAPACITY:

To estimate the storage capacity of a dam, it is necessary to conduct a detailed contour survey of the proposed dam site. Multiplying the average of the area at two successive contours with the contour interval (CI) gives us the volume of water stored between two successive contour lines (see figure 2.36).
Effective storage capacity = Storage Capacity +Volume of water percolating from it during a season.





(vi)ESTIMATION OF AN EARTHEN DAM:

The cost of an Earthen Dam 20 meters in length and a maximum height of 5 meters. The upstream and downstream slopes are 1:3 and 1:2 respectively. Top width of the dam is 2.5 meters; depth and width of the cutoff trench are 2.5m and 1m respectively. Freeboard = 1m. Height of the dam at different points along the dam is given below:

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Point	A	B	C	D	E
Height	0	2	5	3	0
Distance	0	5m	5m	5m	5m

<u>Solution</u>

Step 1 Volume of Cutoff Trench = Length x Width x Depth

= 20 x 1 x 2.5 = 50 cum

Step 2 Volume of Embankment

Volume of embankment is calculated by multiplying the cross section area with length. Cross section area at each point on the structure is calculated by the following formula for a trapezium:

Area of Cross Section = 1/2 x (S x H^2) + (TW x H) where, S = S_1 + S_2, (sum of upstream and downstream slopes), H = Height of the structure at any point, TW = Top width of structure = 2.5m

S_1 = 3 and S_2 = 2

Using the above formula, we calculate the area of cross section at each point. Multiplying

The average cross-sectional area between two points with the distance between the two points, we get the volume of the section.

Estimation of volume of embankment

Station (1)	Chainage (2)	Height (3)	Cross Section Area (4)	Average Cross section (5)	Length of Section (6)	Quantity (7 = 5x6)
A	0	0	0	-	-	-
B	5.0	2.0	15.0	7.5	5.0	37.5
C	10.0	5.0	75.0	45.0	5.0	225.0
D	15.0	3.0	30.0	52.5	5.0	262.5
E	20.0	0	0	15.0	5.0	75.0
Total volume of embankment						600.0 cum

Volume of Core wall

Cross section area of core wall = Width of core wall x Height of core wall
Height of core wall = Height of bund - Free board

Width of core wall = 1.00m

Free board = 1.00m

Cross section area of core wall = Width x (H - Freeboard) = 1.00 x (H - 1) = (H - 1) m

Estimation of volume of Corewall

Station (1)	Chainage (2)	Height (3)	Cross Section Area (4)	Average Cross section (5)	Length of Section (6)	Quantity (7 = 5x6)
A	0	0	0	-	-	-
B	5.00	2.00	1.00	0.50	5.00	2.50
C	10.00	5.00	4.00	2.50	5.00	12.50
D	15.00	3.00	2.00	3.00	5.00	15.00
E	20.00	0	0	1.00	5.00	5.00
Total volume of corewall						35.00 Cum

Volume of Rock toe

Cross section area of the Rock Toe = $(1 + S_2^2)/S_2$ X $(H^2/32$

We know that $S_2 = 2$

Cross section area = $(1 + 2^2)/2 \times (H^2/32) = 5/2 \times (H^2/32) = 5/64 \times H2$

Estimation of volume of Rock Toe

Station (1)	Chainage (2)	Height (3)	Cross Section Area (4)	Average Cross section (5)	Length of Section (6)	Quantity (7 = 5x6)
A	0	0	0	-	-	-
B	5.00	2.00	0.31	0.15	5.00	0.75
C	10.00	5.00	1.95	1.13	5.00	5.65
D	15.00	3.00	0.70	1.33	5.00	6.65
E	20.00	0	0	0.35	5.00	1.75
Total volume of rock toe						14.80 cum

Volume of casing/outer cover

Total volume of dam - (Volume of core wall + Volume of rock toe)

= 600 - (35 + 14.80) = 550.20 cum

Excavation for waste weir

The exit is rectangular in shape

Volume of excavation for waste weir = Length x Width x Height = 10m x 4m x 1.5m = 60 cum **Total Cost**

	Particulars of work	Unit	Volume/ Area	Rate/Unit (Rs.)	Amount (Rs.)
1	Excavation for Cutoff Trench in Hard Soil	Cum	50.00	23.20	1,160.00
2	Filling Cutoff Trench with Puddled Clay	Cum	50.00	104.00	5,220.00
3	Construction of Casing in Hard Soil	Cum	550.20	28.30	15,571.00
4	Construction of Clay Corewall	Cum	35.00	104.00	3,640.00
5	Construction of Rock Toe Filter	Cum	14.80	124.65	1,845.00
6	Excavation for Exit Weir	Cum	60.00	30.70	1,842.00
	Total Cost of Dam Construction				29,278.00

Other Rainwater Harvesting Techniques being followed in different parts of India by adopting similar technique as earthen dam.

vii) DOs AND DONTs:

DOs:

- The effective storage capacity of the dam should not be either too large or too small in relation to runoff.
- At the dam site, the drainage line must have well-defined embankments into which the dam can be

anchored.

- The upstream slope of the dam should be lower than the downstream slope
- The surplus weir must be properly designed to drain out the peak runoff safely when the water is at FRL.
- Adequate settlement allowance must be provided for in earthen dams.
- Rock toe must be provided to drag the seepage line downwards.
- The bed of the drainage line upstream the dam site should not have a high slope.

DONTs:

- Do not use highly erodible material like clay on the outer faces.
- Do not raise the core wall over the FRL of the dam.
- The surplus weir should not be very steep or have sharp curves.