Water for the World

Designing Small Dams

Technical Note No. RWS. 1.D.5

Dams can be built across small streams and rivers to back up the flow of water and create a reservoir for a community water supply. Water from a reservoir is used by installing intakes and pumping the water to the community. (See "Designing Intakes for Ponds, Lakes and Reservoirs," RWS.1.D.2). Dams are generally made from concrete, reinforced concrete, masonry or earth.

The design of concrete and masonry dams is complex and should only be attempted by an engineering expert with experience in the design of dams. The design of small earthen dams is simpler and their construction is much easier. This technical note outlines the steps that must be taken to design small earth dams: (a) location of a suitable site, (b) design of the dam embankment and (c) design of the spillway.

The design process should result in the following three items which should be given to the construction supervisor:

1. A survey map of the area including the exact location of the dam. Figure 1 shows the type of location map that should be prepared.

2. A list of all labor, materials and tools needed as shown in Table 1. This will help make sure that adequate quantities of materials are available so construction delays can be prevented.

3. A detailed plan of the dam and related structures with all dimensions similar to that shown in Figure 2.

Useful Definitions

BASALT - A dark heavy volcanic rock.

CREST - The highest point or level top of a dam.

EROSION - The wearing away of soil, rock or other material by the flow of water.

EVAPORATION - Loss of water to the air as heat changes it from liquid form to vapor.

FREEBOARD - The height added to a dam as a safety factor to prevent waves or run-off caused by storms from overtopping the embankment.

OVERTOPPING - Water flowing over the crest of a dam due to inadequate spillways.

PERCOLATION - Movement of water downward through the pores of the soil.

RIP-RAP - Blanket foundation or wall made of large stones thrown together irregularly or loosely.

SEEPAGE - Water leaking from the ground or a dam embankment.

SILT - Sediment made up of fine particles carried or laid down by moving water.

SPILLWAY - A channel built to control the level of water in a dam reservoir; flood water is drained from a dam through spillways.

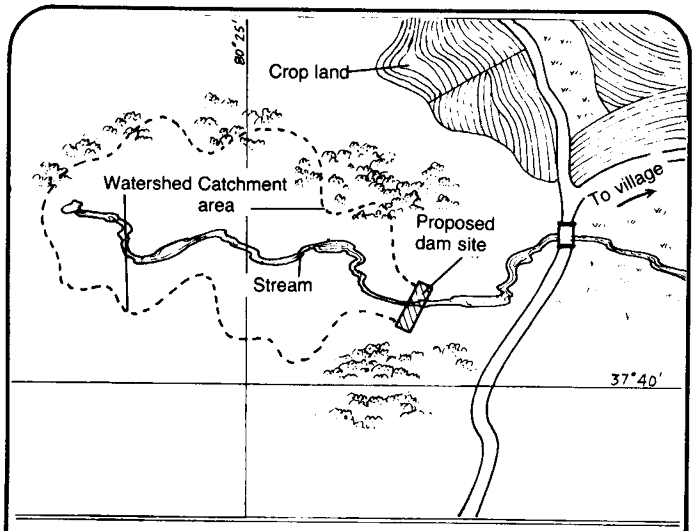

Figure 1. Dam Location Map

Table 1. Sample Materials List

Item	Description	Quantity	Estimated Cost
Labor	Foreman Laborers	____ ____	____ ____
Supplies	Clay soil Flat rocks Grass seed Stakes Rope	____ ____ ____ ____ ____	____ ____ ____ ____ ____
Tools	Surveying equipment Digging tools A small tractor or backhoe (if possible) Soil compaction device Levels Earth moving equipment	____ ____ ____ ____ ____ ____	____ ____ ____ ____ ____ ____

Total Estimated Cost = ____

Location of a Site

The first step in designing a dam is choosing an appropriate site. See Figure 3. The choice of a site depends on six factors:

1. There must be enough water to fill the reservoir.

2. The reservoir must store the maximum amount of water behind the smallest feasible dam.

3. A sound foundation for the dam and an impervious reservoir must be available.

4. The stored water must be as free from sources of contamination as possible.

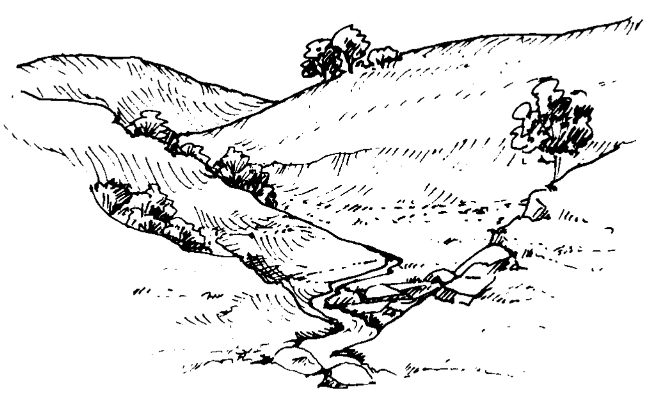

Figure 3. Appropriate Dam Site

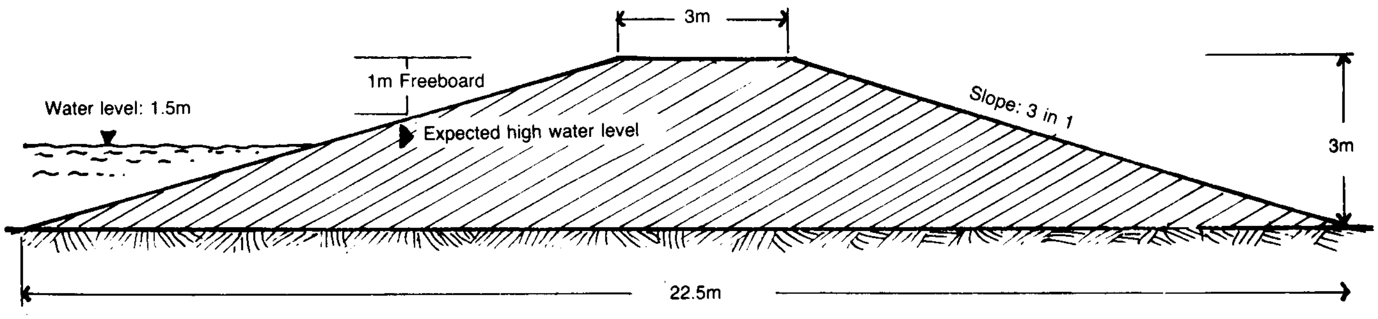

Figure 2. Clay Dam Embankment

Caution!

The proper design and construction of a dam requires some engineering and geological knowledge. No dam holding more than about a 3.0m depth of water should be attempted by anyone without qualified advice, and even smaller dams should be constructed only with technical advice.

Failure of a dam can cause tremendous damage. The most common causes of failure are:

Overtopping or the flowing of water over the top of the dam due to inadequate spillways.

Undermining, the flowing of water below the embankment.

Fissures and cracks caused by the use of poorly compacted material.

Percolation along tree roots that have not been properly removed.

Erosion which is caused by heavy rains.

A dam may not wash away but there are other factors which contribute to the failure of a dam. If the catchment area above the dam is inadequate, it will not fill. If the soil in the catchment area is porous, water will soak into the ground. A stream that contains suspended matter may silt up the dam unless silt traps are built. Further, if allowance for evaporation is not made, the reservoir may dry up during the dry season.

Be sure to consider all these factors when attempting to design a dam. Failure to do so may cause failure of the project, loss of money and possibly even destruction of surrounding areas.

5. The reservoir must be easily accessible to the users.

6. Needed construction materials must be close to the site.

The amount of water available to the reservoir depends on the amount of rainfall, the size of the catchment area or watershed, and the soil conditions. The best catchment area is one with steep, rocky slopes where the rain runs down to the reservoir quickly. In this type of watershed, water is not lost through seepage or evaporation. Special attention must be given to the danger of flooding, however. Another excellent catchment area is one where a thin layer of pervious soil overlays impervious rock. The rainfall seeps through the pervious layer and flows downhill over the rock to form springs lower in the valley. The springs then feed the reservoir. The advantage of this type of catchment is that water flowing underground does not evaporate, is not easily contaminated, and flows out slowly. The amount of water available can be increased by planting trees. Trees slow down run-off but allow water to percolate downwards. Trees planted on steep, rocky hillsides will help prevent possible flooding.

Determining the amount of run-off available from a catchment area requires very specific information about soil types, rainfall, land slopes and other factors. Very complicated mathematical formulas must be used. Worksheet A shows how to determine the quantity of water from a catchment area. The size of the catchment area is best estimated by using a map of the area. A general rule for estimation is that the catchment area is at least 15 times the area of the reservoir formed by the dam. The average catchment area drains about 1000 liters of water for every millimeter of rainfall on a hectare. This figure represents 10 percent of the total rainfall.

Worksheet A. Quantity of Water Available from a Catchment Area	
Area of watershed in hectares	5
Area in meters (5 hectares x 100m x 100m)	50000 m^2
Amount of annual rainfall	700 mm
Volume of rainfall (area in m^2 x rainfall = 50000 m^2 x 700 mm)	35000000 liters
Volume of available water = 10% x total volume of rainfall (0.10 x 35000000 liters)	3500000 liters

The volume of water to be stored can be determined by finding the area of the reservoir and multiplying it first by the average depth of water in the reservoir and then by 80 percent to take into account losses due to evaporation, percolation and transpiration. The area of the reservoir is found by multiplying the length of the reservoir (length of the dam) by the upstream distance. The upstream distance is found by using a hand level and finding a point upstream that is level with the top of the dam. The distance from that point to the top of the dam is the upstream distance. Use the formula Volume = upstream distance x length x average depth x 80 percent to find the volume of stored water. The reservoir should be at least 2m deep at the deepest point. To get the average depth, multiply the greatest depth by 0.4. Figure 4 shows the sample dimensions.

The total volume is multiplied by 80 percent to allow for evaporation and percolation. Evaporation rates vary with climate and wind conditions. In very hot climates and where ponds are unprotected from the wind, evaporation rates are high. Percolation rates depend on the type of soil forming the reservoir floor. These soils should be as impervious as possible.

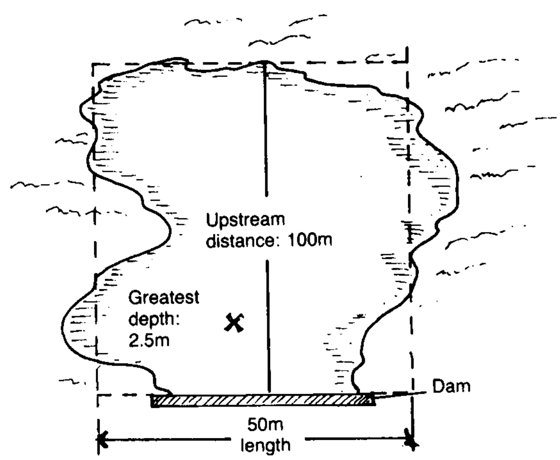

Figure 4. Determining Water Volume

Generally, losses from percolation decrease in time as the reservoir floor is sealed with sediment settling out of the water.

If the reservoir and catchment areas provide sufficient water, then the best location for the dam must be determined. The most economical site is a steep-sided valley where the dam will be shorter and easier to build. The storage capacity is good in this type of location because the water backs up a long way behind the dam. A very good site is where a broad valley suddenly narrows. The dam will not be too long and the valley will provide good storage.

Other geological conditions are important. The site must have a solid foundation. The foundation must provide stable support for the embankment and sufficient resistance to seepage. Granite or basalt beds extending across a valley and thick layers of silty or sandy clay make good dam foundations. The best foundation is a thick layer of impervious material.

The suitability of a reservoir site depends on the ability of the soil to hold water. Soil must be impervious enough to prevent high seepage losses. Clays and silty clays generally are the best soils for a reservoir.

When choosing the most appropriate site, keep in mind the need to avoid contamination. By building the dam above inhabitated areas, the problem of contamination by people is reduced.

Design of the Dam Embankment

Once a suitable site is located, design of the dam embankment can proceed. The major design considerations are the foundation and foundation cut-offs, the embankment side slopes, the top and bottom widths, the freeboard, and the quantity and quality of material to be used in construction.

The best foundation is a thick layer of stable, impervious material. If a suitable layer is found at the surface, no special measures are required. Top soil should be removed and the foundation surface loosened to improve the bond between the foundation and the embankment. If a foundation is pervious material at or near the surface with rock or impervious material at a greater depth, seepage through the pervious layer may occur and must be controlled. For large dams a cut-off joining the impervious layer in the foundation to the base of the dam is needed. Figure 5 shows one example of a typical cut-off trench. A trench is dug parallel to the centerline of the dam into the impervious layer. The trench should have a bottom width of at least 1.2m. The sides should be no steeper than 1:1. The trench should be filled with thin layers of clay soil and compacted.

The slope of the sides of the dam depends on the stability of the material in the embankment. If the fill material is stable, the side can have steeper slopes. Table 2 shows maximum slopes for upstream and downstream faces of a dam built from different fill materials. For safety's sake, especially when dams are being built by people with little experience, the slopes should be at least 3:1 and possibly even 4:1.

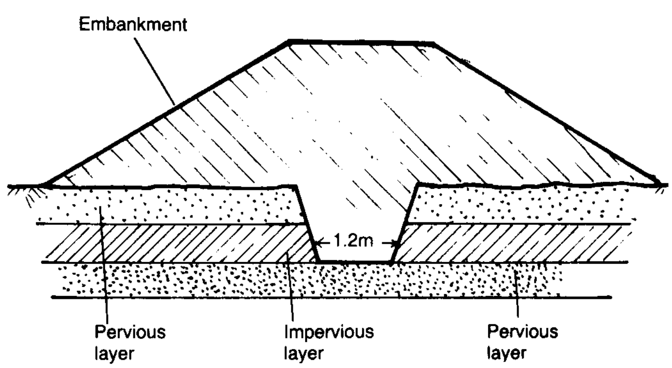

Figure 5. Cut-off Trench in Dam Embankment

Table 2. Side Slopes for Earth Embankments

Fill Material	Side Slopes* Horizontal to Vertical Upstream	Downstream
Clay, Clayey sand, Sandy clay, Silty sand	3:1-3.5:1	2.5:1-3:1
Silty clay, Clayey gravel, Silty gravel	3:1-3.5:1	2.5:1-3:1
Silt or Clayey silt	3.5:1-4:1	3:1-3.5:1

* A 3:1 slope means 3m horizontal distance for every 1m in height.

Each dam has a flat section at the top. The width of this top section depends on the height of the dam. Table 3 shows the relationship between the height of the dam and the width of the top section.

Table 3. Top Widths for Earth Embankments

Height of Dam	Top Width
Under 3m	2.5m
3-4.5m	3.0m
4.5-6m	3.5m
6-7.5m	4.0m

The height of the dam depends on the freeboard. Freeboard is the height added to the dam to prevent waves or heavy run-off from flowing over it. Freeboard is the vertical distance between the top of the dam and the water surface in the reservoir at flood level. Generally, the freeboard height should be at least 0.9m above the flood level of the water. For added safety, the freeboard should be at least 1.5m above the flood level.

The dimensions of the entire dam embankment can be determined by using the following formulas:

Height of the dam = Depth of water at deepest point + maximum depth at flood level + height of freeboard.

Width of the base = (Height of the dam x downstream slope) + (height of dam x upstream slope) + (width of the top). For example, consider a clay dam with a reservoir with the dimensions shown in Worksheet B. Assume a depth for flood channels of 0.5m, a freeboard of 1m, and a top width of 3m. Worksheet B shows how to determine the dimensions of the embankment. Figure 2 shows a dam embankment with the dimensions from Worksheet B.

Worksheet B. Determining Embankment Dimensions

1. Maximum depth of reservoir	1.5 m
2. Maximum depth of flood channels	0.5 m
3. Height of freeboard	1.0 m
4. Total height of dam (sum of 1, 2, 3)	3.0 m
5. Width of top (See Table 3)	3 m
6. Upstream slope	3.5:1
7. Downstream slope	3:1
8. Width of base = 3.0 (height) x 3.5 (upstream slope) + 3.0 (height x 3 (downstream slope) + 3m (width of top) =	22.5m

Knowing the embankment slopes, the width of the top, and the height of the dam, it is possible to determine the volume of fill needed for the embankment by using the sum of the areas method shown in Table 4. Determine the height of fill at any level along the dam and find this number in the left hand column. Then, find the side slope column with the slopes corresponding to the dam. Move down the column until you are across from the fill height you are using. This number is the area that corresponds to the fill height at slope sides are 3.5:1, 3:1 and fill height is 3.0m, the area is $32m^2$. Add to this the number in the column under the appropriate top width for the fill height you are using. If the dam has a top width of 3m, the number corresponding to a 3.0m fill is $9.0m^2$. The total end area is $32m^2 + 9.0m^2 = 41.0m^2$.

The volume of earth fill is the sum of volumes for several cross-sectional areas. Figure 6 and Table 5 should be used for reference. Figure 6 is a profile of a dam embankment 22.5m long with a 3m top width. Eight stations or cross-sectional areas are shown. Each is located at a different distance from the other and each has a different fill height. To find the fill height at each station, look to the scale at the right. Then locate the end area of the cross-section by using Table 4 and adding together the area under the slope column and the area under the width column. Add all the cross-sectional areas together to get the total area. The volume of each cross-section is determined by multiplying the area of the cross-section by the length of each section (the distance between each station). For total volume, add all the volumes together and divide by two. This process is shown in Table 5. The total is divided by two because the calculated volume is twice as big as the volume desired.

Table 4. End Area Table for Embankment Sections for Various Side Slopes and Top Widths

Fill Height (m)	Side Slopes Upstream Slope Downstream Slope					Top Width				
	2.5:1 2.5:1 2:1 3:1	2.5:1 3:1 2:1 3.5:1	3:1 3:1 2.5:1 3.5:1	3.5:1 3.5:1 3:1 4:1	4:1 4:1 3:1 5:1	2m	2.5m	3m	3.5m	4m
1.0	$3m^2$	$3m^2$	$3m^2$	$4m^2$	$4m^2$	$2m^2$	$2.5m^2$	$3m^2$	$3.5m^2$	$4m^2$
1.2	4	4	4	5	6	2.4	3.0	3.6	4.2	4.8
1.4	5	5	6	7	8	2.8	3.5	4.2	4.9	5.6
1.6	6	7	8	9	10	3.2	4.0	4.8	5.6	6.4
1.8	8	9	10	11	13	3.6	4.5	5.4	6.3	7.2
2.0	10	11	12	14	16	4.0	5.0	6.0	7.0	8.0
2.2	12	13	15	17	19	4.4	5.5	6.6	7.7	8.8
2.4	14	16	17	20	23	4.8	6.0	7.2	8.4	9.6
2.6	17	19	20	24	27	5.2	6.5	7.8	9.1	10.4
2.8	20	22	23	27	31	5.6	7.0	8.4	9.8	11.2
3.0	22	25	27	32	36	6.0	7.5	9.0	10.5	12.0
3.2	26	28	31	36	41	6.4	8.0	9.6	11.2	12.8
3.4	29	32	35	40	46	6.8	8.5	10.2	11.9	13.6
3.6	32	36	39	45	52	7.2	9.0	10.8	12.6	14.1
3.8	36	40	43	50	58	7.6	9.5	11.4	13.3	15.2
4.0	40	44	48	56	64	8.0	10.0	12.0	14.0	16.0

(NOTE: To find the end area for any fill height, add square meter found under "side slopes" column to that under "top width" column. Example: If a dam at a fill height of 3.0m has a 3.5:1 upstream slope, 3:1 downstream slope and a top width of 3m, the end area is: $32m^2 + 9m^2 = 41.0m^2$.)

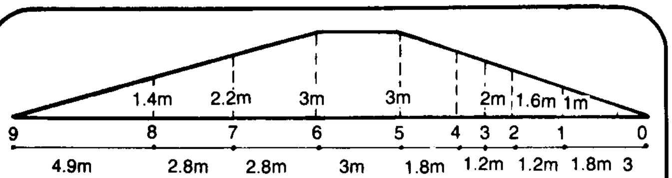

Figure 6. Determining Volume of Fill in Dam Embankment

In the example shown in Table 5, a dam with a base 22.5m long, a top width of 3m, a height of 30m, and 3.5:1 and 3:1 slopes requires $426.4m^3$ of earth backfill. To allow for a 5 percent loss from settlement, add $21.32m^3$ to the total. The final total volume is $447.72m^3$.

When backfilling the dam, keep in mind that the material used should be of uniform quality. If there are

Table 5. Sample Volume of Embankment in Figure 6 Using Sum of Area Method

Station	Fill Height	End Area (from Table 4)	Sum of Areas	Distance	Double Volume = Distance x Sum of Areas
0	0m	0m	---	---	---
1	1.0m	$7m^2$	$7m^2$ (STA 0 + 1)	3m	$21m^3$
2	1.6m	$12.8m^2$	$19.8m^2$ (STA 1 + 2)	1.8m	$35.64m^3$
3	2.0m	$20m^2$	$32.8m^2$ (STA 2 + 3)	1.2m	$39.36m^3$
4	2.4m	$27.2m^2$	$47.2m^2$ (STA 3 + 4)	1.2m	$56.64m^3$
5	3.0m	$41.0m^2$	$67.2m^2$ (STA 4 + 5)	1.8m	$120.96m^3$
6	3.0m	$41.0m^2$	$82.0m^2$ (STA 5 + 6)	3.0m	$246m^3$
7	2.2m	$23.6m^2$	$64.6m^2$ (STA 6 + 7)	2.8m	$180.88m^3$
8	1.4m	$11.2m^2$	$34.8m^2$ (STA 7 + 8)	2.8m	$97.44m^3$
9	0m	0	$11.2m^2$	4.9m	$54.88m^3$
				Total Volume	$852.8m^3$

(NOTE: Divide double volume by two to get volume of fill in embankment.)

$$\frac{852.8m^3}{2} = 426.4m3$$

Allowance of 5 percent for settlement + 21.32

Total 447.72m3

doubts about the porosity of any of the soil, it should be placed on the downslope side. The best type of soil is clay material containing some silt or sand. If only clay is used, it may crack when dry or slip when wet. Be careful that there is not too much sand in the material. If too much sand is present, water may percolate through. To ensure the strength of the dam, the earth fill must be well compacted. If not, leakage is likely to occur and failure of the dam is possible. Figure 7 shows a way that the earth can be compacted manually. The log must be raised up and down to pound the soil. Compaction done this way is a very slow process but must be done in the absence of other methods.

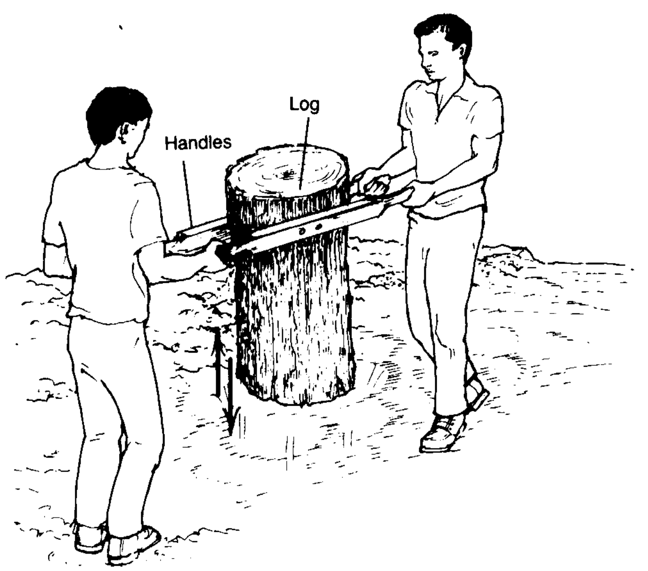

Figure 7. Manually Compacting Soil

Design of a Drain

Before the construction of the dam begins, a large diameter pipe should be placed in the stream bed as shown in Figure 8. The water flow is channeled into this pipe and carried further downstream. In this way, the construction area stays dry without the need for digging a long diversion ditch.

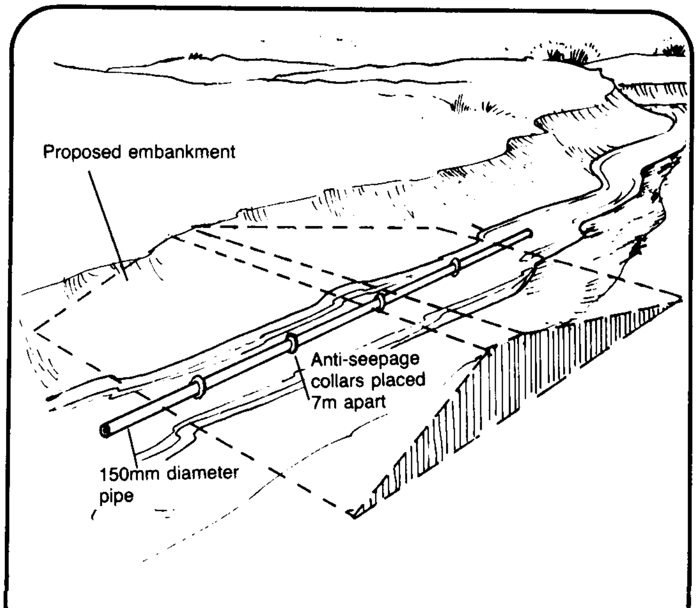

Figure 8. Installation of Drain Pipe in Stream Bed

The pipe serves a further purpose. The pipe, with anti-seepage collars attached, remains in place during the construction of the embankment. Therefore, once the embankment is completed, a drain pipe passing from the reservoir through the dam to the downstream side of the dam is in place. On the downstream side, a cut-off valve is placed on the pipe. In times of heavy rain or flooding, the valve can be opened to drain the reservoir and prevent overtopping. The drain pipe is very important in preventing dam failure.

Design of the Spillway

Water must never be allowed to spill over the top of an earth dam. To prevent overtopping, spillways are built to channel the flood water away. They must be built clear of the dam in solid ground. Often, two spillways are built. One is located lower for regular overflow, the other higher for safety during times of abnormal flooding. Spillway channels should be continued downstream away from the downstream edge of the base in order to prevent erosion of the dam by flood water. Figure 9 shows an example of a dam and spillway design.

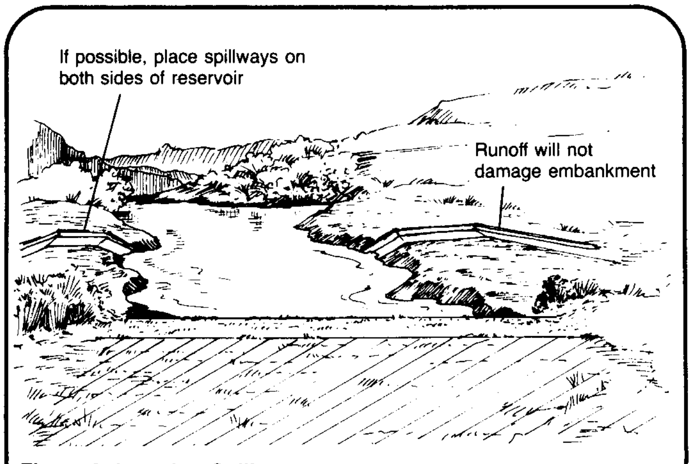

Figure 9. Locating Spillways

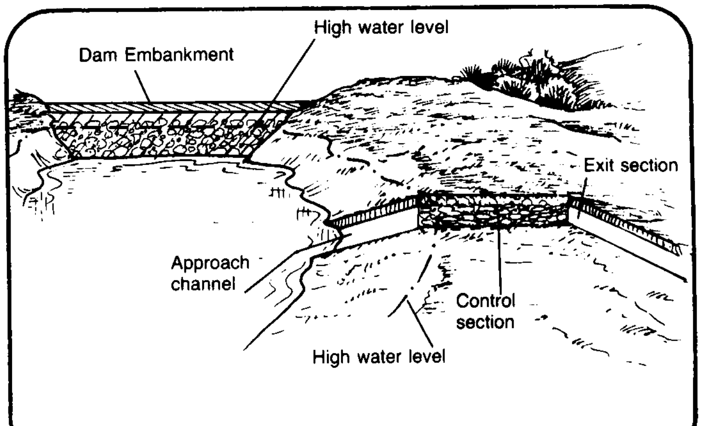

Figure 10. Design of Spillway

Calculate the spillway size by obtaining local information and making a good guess. Find out how high the stream rises at the wettest time of the year and estimate the width of a similar stream running 60cm deep. Allow for extra width according to whether last year was dry, wet or average and then double the amount to allow for a heavy storm. This is the minimum size of the spillway. If there are doubts, widen the spillway.

There are three sections to the spillway as shown in Figure 10. These are the approach channel, control section, and exit channel. The flow enters the spillway through the approach channel. It should be short with smooth easy curves. It should have a slope toward the reservoir of not less than two percent to ensure drainage. The width of the spillway is the same as the width of the channel in the control section (the high, flat section in line with the crest of the dam). This section should be lined with stone or concrete to prevent erosion. The channel should widen a little below the crest to prevent flood water from backing up.

The first part of the exit channel should have a fairly steep slope to move water away from the crest rapidly. It may be necessary to line this section with rough stone. Further downstream, the channel should flatten and move the overflow far away from the dam.

Other Design Considerations

Rainfall and waves in the reservoir cause dam erosion. Rain that falls on the dam crest, on the entire downstream slope, or on the upstream slope above water level will cause damage to the dam. The best way to prevent erosion is to plant a suitable type of creeping grass. The grass should be planted in horizontal rows in top soil mixed with manure.

On the upstream side, the dam should be paved or lined with stone to a height of 0.6m above water level. Riprap walls will help prevent erosion from waves in the reservoir.

Summary

The design of a dam is not easy and generally requires engineering skill. A poorly designed dam may break down or wash away and cause great damage to property and lives. The most common causes of failure are overtopping, undermining caused by water flowing below the embankment, fissures caused by shrinkage or badly compacted materials, percolation along tree roots that have not been cleared from the site, and weaknesses from erosion of the dam by rainfall and wave action. To avoid all these problems, much care and effort must go into the design of the dam.

A well-designed dam will provide a good source of water for a small community. Before deciding to build a dam, however, always be sure that a suitable site exists, that construction materials are available, and that the water can reach the users easily and less expensively than through another method. If these criteria are met, a successful dam project can be developed.