Earthen Dams for Small Catchments

A Compilation of Design, Analysis, and Construction Techniques Suitable for the Developing World

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by

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Introduction

This design manual was written to aid engineers and others with technical training in the design and construction of small dams. It assumes basic technical competence, confidence, and understanding of physics, mathematics, surveying, and the philosophy of engineering.

Individuals with different levels of education and experience will be able to use this guide in different ways. Someone with a basic technical or scientific background with some construction experience may be able to use the standard plans and rules of thumb to produce an acceptable design. A person with a background in engineering may be able to go further in the design process and refine the design to the specific situations. And, someone who is a trained and experienced civil or geotechnical engineer may use this as only a rough road map and a reminder using primarily their experience and knowledge to make informed design decisions.

Retaining large amounts of water is a potentially dangerous undertaking that even the professionals fail at occasionally. All care must be taken to assure safety in such an endeavor. Good luck and happy damming.

About the Author

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1 Layout and Sitting

The first step in building a dam is to identify the best location. There will be many factors that affect this. Ultimately it is up to the judgment of the engineer to balance all the trade-offs involved in the site selection. Luckily, there are some tools that can assist in the decision.

1.1 Storage Ratio

The storage ratio is defined as the ratio of the amount of water retained to the amount of soil used to retain it. It's a good way to compare sites in a cost per benefit analysis. It is only a rough estimate and should not take the place of a detailed estimation once a site has been selected.

Table 1-1: Comparison of Storage Ratios

Volume of Storage/Volume of Earthwork	Site Rating
<2	Poor
2-4	Moderate
4.1-6	High
>6	Excellent

1.1.1 Volume of Storage

For the quickest and easiest method for determining the storage capacity find the length of the dam, the fetch (this is the longest distance on the reservoir measured strait back from the dam face, sometimes called the throwback), and the maximum depth. These values can be found using either a topographical map or during a simple survey using a hand level. Multiplying these together and then dividing by 6 provides an estimation of the storage volume. For a little better estimation the total surface area of the reservoir can be found using similar techniques. The area multiplied by the deepest depth and divided by 3 (this echoes the formula for a conical shape) will provide a volume estimation. (Nelson)

If the gully or valley is of an unusual shape the following formula may provide a better estimate.

Volume of Storage = (0.22)(K)(Length of Dam)(Fetch)(Depth)

Where K is a unitless coefficient based on the shape of the valley, and the length of the dam is measured perpendicular to the stream. (Stephens)

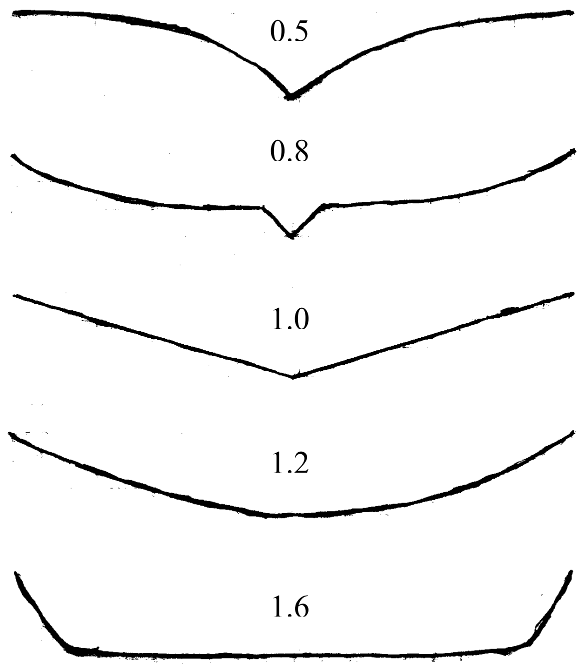

Figure 1-1:Gully Profiles with Shape Factor K

1.1.2 Volume of Earthwork

The calculation for the volume of the earthwork required is a little more involved. A good estimate is:

Volume of Earthwork = (0.216)(Height)(Length)[2(Crest Width)+(Height)(Slope)]

Where the slope equals the sum of both upstream and downstream slopes. For example a dam with an upstream slope of 2:1 and a downstream slope of 1.75:1 would use 2 + 1.75 (3.75) for the calculation. See the section on slope stability for acceptable slopes. (Nelson)

For unusually shaped valleys use:

Volume of Earthwork = (1.05)(K)(Length of Dam)(Height of Dam)((Height of Dam)+1)

Where K is the same shape coefficient from the last section. This method assumes an average dam slope of 2.5:1. (Stephens)

1.2 Additional Considerations

There are additional things to consider in the planning of a dam site. Most of these can be better understood once a little more is known about the design of a dam. It is important to keep sight of the big picture and still pay attention to details. Some questions that should be asked and answered about any site are:

- What will be the effects of a catastrophic failure and how much of a safety factor is warranted?
- What kind of spillway will be required at this site?
- How will the water be distributed from the reservoir?
- What are the upstream/downstream ecological impacts?
- How far must the soil and building materials be transported?
- What is the window of opportunity for construction? (When will the rainy season come?)
- Will there be enough labor to finish in time?
- Will there be enough materials to finish at all?
- What can go wrong that I haven't thought of yet?

This is just a partial list of questions a good designer may or may not have to answer in the planning of dam project.

2 Design of Dam

2.1 Basic Earthwork Cross-Section

The following plans and dimensions represent good rules of thumb for the design of a dam. These are suitable as guidelines for the novice designer and as a starting point for an engineer with more experience in hydraulics and geotechnics. Each dam design has its strengths and limitations based on availability of materials, space limitations, and existing surface conditions. The design guidelines are a combination of typical designs presented by Nelson (1985) and Stephens (1991).

2.1.1 Homogeneous Dam with Toe Drain

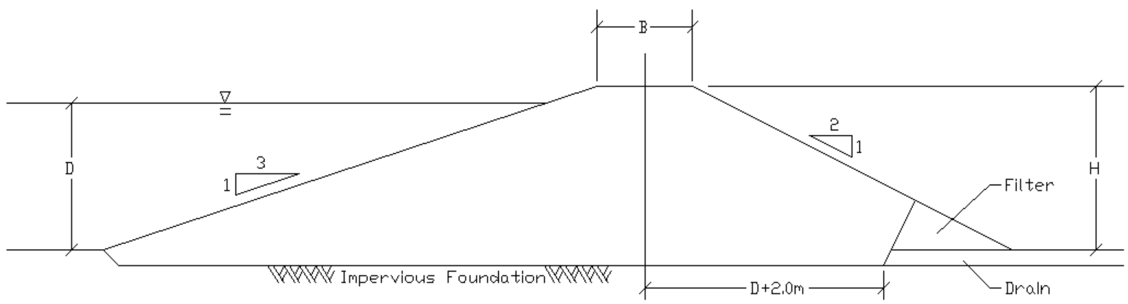

Figure 2-1: Cross-Section of Homogenous Dam with Toe Drain

For this basic type of dam, there are two main components: the impervious to semi-pervious structure and the toe filter and drain. More detail will be given to the types of soil required in Section 2.3. It is required that this dam be placed on an impervious foundation such as solid rock or clay. The purpose of the filter and drain is to provide a way for seepage to exit the dam without causing excessive erosion of the dam material.

The two basic dimensions for this dam are the height (H) and the crest width (B). The height chosen will depend on the depth of water at full supply level (D) and the freeboard required. Crest width will depend on the height.

Freeboard is the distance from the top of the water to the top of the dam. It is a safe guard against overtopping by floods or by wave action. A typical freeboard allowance is 1.0 m. In the case of long reservoirs, waves may be larger. Wave height is a function of the fetch, the longest exposed water surface on the reservoir. The freeboard may have to be increased in such cases. Table 2-1 shows typical values for extreme fetches.

Table 2-1: Typical Freeboard Values for Various Fetches

Fetch (m)	Freeboard (m)
Up to 600	1.0
1000	1.2

2000	1.3
3000	1.5
4000	1.6
5000	1.7

Adding the required freeboard to the height of the water at full supply level (D) the height (H) can be found. A height of 10.0 m is pushing the boundaries of what is considered a "small" dam and the scope of this guide. If the dam approaches or passes 10.0 m it is suggested that a professional engineer with experience in dam design be consulted.

The crest width should increase with the height. Table 2-2 shows the minimum suggested crest widths for different heights. As shown, the gravel filter should be placed at roughly at the length D plus 2.0 m from the centerline and be constructed to a height of D/3.

Table 2-2: Minimum Crest Widths

Height of Dam (H) (m)	Crest Width (B) (m)
Up to 2.0	2.5
2.1 to 3.0	2.8
3.1 to 4.0	3.0
4.1 to 5.0	3.3
5.1 to 6.0	3.5
6.1 to 7.0	3.7
7.1 to 8.0	3.9
8.1 to 9.0	4.0
9.1 to 10.0	4.2

2.1.2 Diaphragm Dam

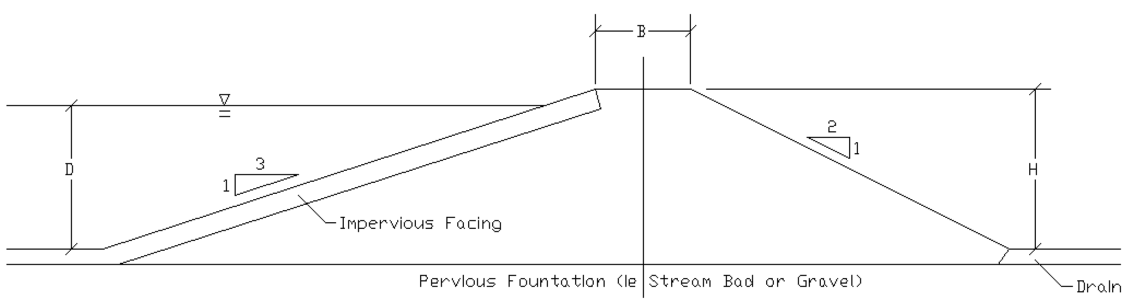

Figure 2-2: Cross-Section of Diaphragm Dam

A diaphragm dam such as this can be used when there is no impervious layer below the dam. A slightly modified version can be used when there is an impervious layer below the dam.

Height (H) and crest width (B) can be determined the same as the previous dam. This type of dam should be limited to a height of 8.0 m to keep seepage forces at safe levels in this unusual configuration.

The major difference here is the facing. In this dam water is retained at the face of the dam and the main material only supports the facing. A drain is still important to direct seepage because no impervious material is perfect. It does not have to be as large and can be just a thin (0.3 m) layer that protrudes into the dam.

The thickness of the impervious facing is based on the height of the dam. Table 2-3 shows the typical minimum thickness for different dam heights.

Table 2-3: Typical Facing Thickness

Height of Dam (H) (m)	Facing Thickness (m)
Up to 5	0.60
6	0.75
7	0.90
8	1.05

If this type of dam being built above an impervious foundation, the facing can be stopped at the upstream toe and a cut off trench installed as in the zoned dam directly beneath the facing. If the foundation is a pervious material such as sand or gravel, the facing should be extended upstream, as shown. The impervious material upstream should be extended at least 35m and have a thickness of at least 0.6m. It should also be thicker at the toe to account for any settling of the dam. Because of the extreme impracticality of the impervious blanket, it is usually favorable to find a better site than use this type of dam.

2.1.3 Zoned Dam

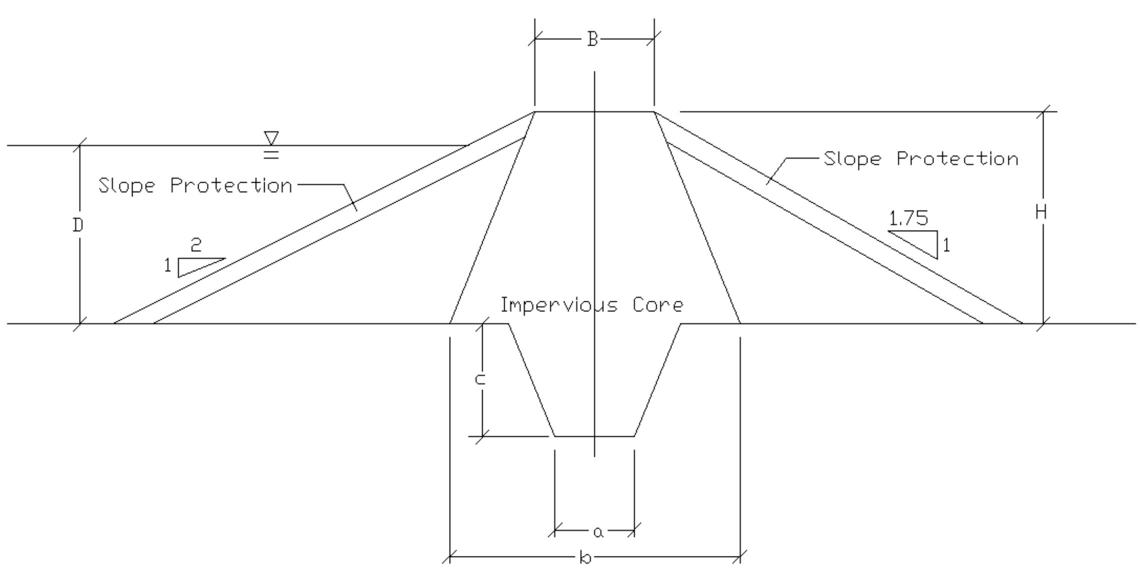

Figure 2-3: Cross-Section of Zoned Dam

A zoned dam can be the most efficient use of soil. Each material is used to its greatest potential. The slope protection protects the shoulders form erosion. The core retains the water and the shoulders stabilize the core.

The typical height and width are determined as in the other cases. The width of the impervious core (b) should be at least equal to the height (H). The cut off trench, dimensions (a) and (c), must be constructed to prevent dangerous seepage conditions. The width (a) is recommended to be between 1.5 m and 2.5 m. The depth (c) should be at least ¾ the dam height (H) when there is no solid impervious layer below the dam. If a solid impervious clay layer exists below the dam the core depth (c) should be extended at least 0.6 m into the clay. If a solid rock foundation is encountered below the dam, the dimensions of the trench can be reduced to 0.3 m by 0.3 m.

The slope protection is to stop the effects of erosion and wave action. This can be rip-rap (large rocks), cobbles, or even bricks. On the downstream face it can be vegetation, provided that it covers the face adequately. When placing cobbles or rip-rap make sure it is thick enough to handle any settling of the dam. When finished the protected soil should not be visible.

2.2 Material and Soil Properties

The designs in the preceding section break down the types of soil into three categories: impervious, pervious (drains), and semi-pervious (usually unlabelled, general fill). This refers to the soil's ability to drain or retain water. This is an important feature in a soil. The other feature of the soil that will be needed is the strength of the soil. The properties that effect both permeability and strength are numerous and complex. But, they do not have to be understood completely to perform some simple tests to determine if a soil is suitable for a certain application.

2.2.1 Basic Soil Classification

There are many different ways to classify soil. The method presented here is an extreme simplification of the Unified Soil Classification System (USCS). It has been reduced to the point that the tests can be performed in the field with little difficulty but the results are still useful. It is worth noting that the USCS is different from the methods agriculturists and soil scientists use to classify soils.

Soil can be broken down in to two basic categories: organic soils (such as peat) and non-organic soils (sand, gravel, silt, and clay). Organic soils are formed from rotting and decomposing plant and animal mater and are characterized by high compressibility, dark color, and occasionally an organic smell. Because of their instable nature and extreme variability it is considered to be completely useless for foundations, embankments, and other forms of engineering. Soils with small amounts of organic matter don't have to be discarded completely, but the amount should be as little as possible.

Non-organic soils are soils that have been produced through erosion and other geologic processes. The four basic types are: clay, silt, sand, and gravel. The differences between these types of soils are the size of the grains. Clay and silt also have chemical and shape properties that separate them, but since neither can be seen with the naked eye they must be differentiated based on feel and other factors. Since almost all soils contain a combination of these grain sizes, soils can be classified based on how much of each type is present.

Table 2-4: Description of Basic Soil Grains

Grain Type	Size	Comments
Clay	0.0005-0.002 mm	Sticky and gooey when wet. Can be molded and rolled without breaking apart. Very hard when completely dried as in an oven.
Silt	0.002-0.06 mm	Very fine material, individual grains can't be seen with the naked eye. When dry silt feels like talcum powder. When wet, clumps break apart and disperse.
Sand	0.06-2 mm	Loose grains over a range of sizes. Even the smallest sand grains can be seen with the naked eye. The soil will feel gritty.
Gravel	2-64 mm	Large grains, easily distinguished.

It is possible to get a rough idea of the distribution of the grain sizes using a glass jar. Take a narrow glass jar with a tight lid. Fill it half way up with a representative soil sample (gravel is easy to spot and can be removed and noted ahead of time). Fill to the top with water and then shake vigorously to put all particles into solution. Let sit for 24 hours or until the water is clear. The soil will sink to the bottom with the largest grains first. It is now possible to make a rough estimate of the percentages of each grain type and size. The USCS states that the soil sizes percentages are determined by weight. Given the rough nature of this test a volume estimate would be adequate.

If there is a large amount of clay in the sample, it may not all settle out in 24 hours. In fact, the clay may never settle out. It would be a fairly safe assumption that all the material that is still in solution after 24 hours is clay. It would also be possible to let the water evaporate off (if an oven is used, be careful not to boil the water) to isolate the fine (clay and silt) particles for further analysis. If the fine material hard when dry and is sticky and malleable when mixed with water there is a good amount of clay in it. If it breaks apart easily when dry and falls apart when wet it has more silt than clay.

2.2.2 Suitable Impervious Material

Soils with large amounts of clay are naturally impervious. To be suitable for the impervious sections on a dam the soil will need at least 55% clay particles (USCS classification of . A quick test for clay is to cut a lump of soil with a knife. If there is a bit of a shine to the soil it has a fair amount of clay in it. Also, a good clay soil will be able to roll into a "snake" about 1.5 mm thick and 40 mm long without breaking. Some experimenting with different amounts of water may be required.

Once a potential impervious soil is found, a good final check is to actually test its permeability. Take a 750 ml plastic bottle (or something similar) and cut the bottom off. Turn it upside-down and fill the bottom (previously the top) third with soil. Fill the rest with water. If no water leaks in 24 hours then the soil should be fine. If the sample breaks apart and disperses in the water it is unsuitable for any part of the dam and should be avoided completely.

If a suitable natural soil can't be found there are alternatives. It has been suggested that concrete or asphalt can take the place of the impervious layers. This has worked in many places, but it's not recommended. Unlike a thick sticky clay, these materials can and will crack under settlement. When a crack forms, extra measures must be taken to control the flow through the dam. It has been proposed in some literature that ant or termite hill material is acceptable or even desirable because of the cementing chemicals these insects excrete. Unfortunately, this material has been found to break down over time and to be unsuitable. More current guides recommend avoiding the material.

Plastic sheeting is an acceptable alternative. It can be used to either provide all impermeable resistance or just to supplement marginal material. One layer can supplement soil with some clay in it provided the sheets are overlapped at least 15 cm and the soil is well compacted around it. If the soil is completely devoid of clay and any water retaining capabilities two layers could be used. The layers should be spaced about a third of a meter apart with the seams offset. The same 15 cm overlap applies.

The sheeting should be placed in the center or slightly upstream of where the impervious layer should be. The sheeting should be placed either vertically, parallel to the upstream face or somewhere in between. Never place the layer sloping in the same direction as the downstream face. The seepage pressure acts perpendicular to the sheeting. That force should be directed down to the foundation not up towards the face.

2.2.3 Suitable Drain Material

Gravel is used for drain material. The ideal gravel for a drain would be completely free of all other particles (clean gravel) and have particles in the range of 1-5cm. This will provide plenty of space between the particles for water to flow through. Sand and gravel is considered "clean" when it has less than 5% clay and silt.

The key to a successful drain is not so much to have the space for water to flow, but to keep the space from clogging. If the soil that is being drained is fine grained the drain may need a graduated filter. For example if the main dam material is a small grained sand with a good portion of fine materials (clay, silt) the drain may be made of two parts, a coarse clean sand layer (about 0.3 m) that is placed between the main section of the dam and the gravel drain.

If gravel is limited or additional drain age is needed, pipe may be used. It is possible to buy or fabricate slotted pipe for the use of drainage. If this method is used it is important to use materials around the drainpipe that will not clog the pipe. For example, if the only suitable drain material is a clean, coarse sand, then the pipe used should have many small slots (like those cut with a hacksaw) rather than large holes. If the only drainpipe available is the kind with large holes then it should be surrounded with coarse gravel and a filter system described above should be used to prevent silt up.

2.2.4 General Fill Material and Strength Tests

The quality of general fill material is based on what function it will perform. If it is only used to support the water-retaining layer (as in the zoned or diaphragm dam) then the major consideration will be strength. Granular materials with large amounts of sand and gravel generally have the highest strength. Silt is a much weaker soil and can lose nearly all it's strength when wet making it fairly useless and even dangerous for dam construction. If the fill material is required to retain some water (as in the homogeneous dam) it will need to have some clay particles in it. Usually this means at least over 15%. Once again, large amounts of silt can cause problems.

The two components to a soil's strength are its internal friction angle (ϕ) and its cohesion. Friction angle, for the most part, directly correlates to the soil's angle of repose. First, take the soil and break up any clods or clumps in the sample. Then form the soil into a cone by pouring it in a stream from the center. The cone should be about a 30-40 cm across the bottom. Observe the slope angle that the edge of the cone makes with the ground, this is roughly the friction angle of the soil.

The soil should be completely dry for this test. The performance while the soil is just slightly damp (like making a sand castle at the beach) will produce unusually high stable slopes but will not correlate to the completely dry or completely saturated situation found in a dam.

Cohesion is more difficult to measure in the field. It should really only be considered for soils that show plasticity. Just because the soil grains are stuck together doesn't mean the soil has cohesion. The soil must remain stuck together even after it has deformed and been remolded.

Table 2-5: Cohesion Strength for Different Consistencies of Cohesive Soils

Consistency	Cohesion (kPa)	Feel or Touch
Soft	<24	Blunt end of pencil-sized object makes deep penetration easily.
Medium	24-48	Blunt end of pencil-sized object makes 12 mm penetration with moderate effort.
Stiff	48-96	Blunt end of pencil-sized object makes moderate penetration or about 6 mm.
Very Stiff	96-190	Blunt end of pencil-sized object makes slight indentation; fingernail easily penetrates.

Hard	>190	Blunt end of pencil-sized object makes no indentation; fingernail barely penetrates.

Choosing a good fill material is relative. Almost any soil that shows moderate strength characteristics can be used. The slopes will just we shallower for weaker soils. The goal is to find the best soil that's practical and know its limitations.

2.3 Forces and Failures

The key to designing a dam is to understand the forces on the structure and the potential failures they can cause. Previously this design manual provided general rules and dimensions that would produce stable dams in a variety of cases. For cases that are not typical, analysis must be performed to assure that the dam will be stable and sufficiently safe.

Situations that would cause a need to complete additional analysis include, but are not limited to:

- Less than ideal soil properties
- Excessive size
- Extreme cost of failure, i.e. potential loss of life, extreme ecological impact, structures downstream, etc.

2.3.1 Seepage and Piping Failures

Seepage occurs through soils when water pressure on one side is greater than the water pressure on the other side. The nature of a dam is that this is always the case. A dam will still be useful with some water flowing through the soil. Too much water flowing through can be potentially damaging and dangerous. The flow can erode the dam eternally, causing more flow and more erosion until the dam fails. This phenomenon is called piping or piping failure. Dams have failed in a matter of minutes due to piping.

Seepage can be controlled and the risk of a piping failure can be reduced in a number of ways. Materials can be used that slow the flow of water through a dam by either forcing through a different path or by providing a greater resistance to flow. A safe path can also be provided for the flow of water. The water can be directed into areas less susceptible to erosion.

2.3.1.1 Measuring Seepage

The most accurate method for determining seepage is through the use of flow nets. The theory and application of flow nets is fairly complicated and this manual should be considered a refresher for those who have been exposed to the topic before hand, not as a lesson to those who are learning for the first time.

For a very rough estimate of seepage through a homogeneous dam, the following equation can be used:

$$q = k(\sqrt{(L^2 + D^2)} - L)$$

Where:
q = Flow through dam per unit width.
k = Hydraulic conductivity of soil.
D = Depth of reservoir.
L = Horizontal distance from where the top of the reservoir intersects the dam to the center of the filter.

Construction of a Flow Net

These are just a few reminders on the construction of a flow net. Any good textbook on general geotechnical engineering or groundwater will provide a more detailed description along with the theory.

1. Start with scale drawing of cross section.
2. Observe the general nature of flow. Where does the water enter and exit the soil? What general path does it follow?
3. Locate the boundary flow lines (longest and shortest) and constant head lines (water entrance and exit).
4. Sketch a couple intermediate flow lines.
5. Start at the boundary constant head line where the water enters (or exits) the soil and sketch as many constant head lines as required to reach the exit (or entrance) constant head line by drawing curvilinear squares and 90° intersections with flow lines.
6. Adjust these flow lines and constant headlines as necessary to produce curvilinear squares and 90° intersections.
7. If needed, sketch additional flow lines and constant head lines to reduce the size of the curvilinear squares.

Don't forget:

- Flow lines and constant head lines intersect at 90°.
- Flow lines and constant head lines form curvilinear squares where the sum of opposite sides are roughly equal.
- Flow lines cannot terminate before hitting the last constant head line.

Finding the Upper Flow Line in a Homogeneous Earth Dam

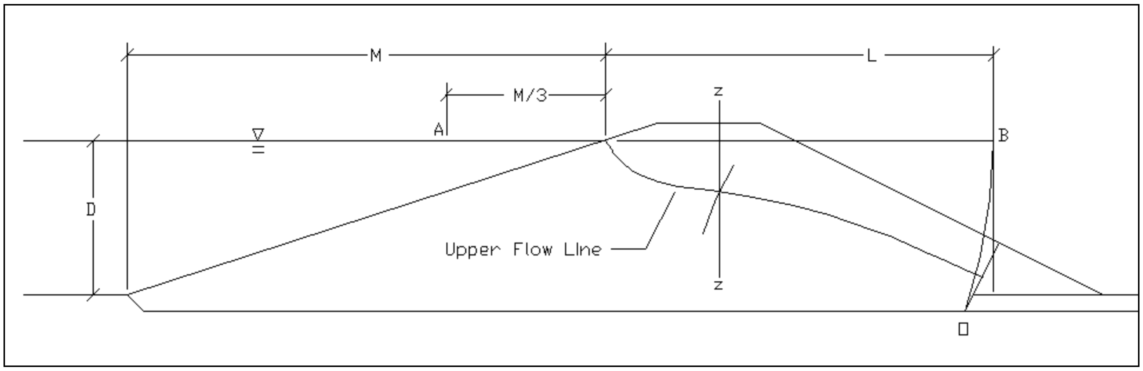

Figure 2-4: Diagram Illustrating the Procedure for finding the Upper Flow line of a Homogeneous Dam

1. Find point A and swing an arc OB having the radius AO
2. Draw vertical line B
3. Draw vertical line z-z in the general location shown and determine distance from zz to line B
4. Using O as the center, swing an arc radius zB to intersect line zz. This point is a point on the upper flow line.
5. Repeat steps 3 and 4 until enough points are established on the line to rough in the shape.
6. Draw the beginning of the flow line by hand. It should intersect the face at a right angle and ease into the flow line.

2.3.2 Slope Stability and Slope Failures

The stability of the upstream and downstream slopes is the most important factor in the design of a safe dam. It can also be one of the most difficult. The analysis of granular material (sand gravel) is fairly strait forward, but materials with cohesion (clay) can be more difficult to predict.

Professional engineers with a complete analysis and good lab results of soil properties rarely design slopes with a safety factor of less than 1.5. Nelson (1985) recommends using the following values for slopes in different conditions.

Table 2-6: Recommended slopes for various soil conditions and dam dimensions

Dam Height (m)	Dam Face	Soil Conditions		
		>50% Gravel >15% Clay	>50% Sand >15% Clay	>55% Clay
3	Upstream	2.5:1	2.5:1	3:1
	Downstream	2:1	2:1	2.5:1
3.1-6	Upstream	2.5:1	2.5:1	3:1
	Downstream	2.5:1	2.5:1	3:1
6.1-10	Upstream	3:1	3:1	3.5:1
	Downstream	2.5:1	3:1	3:1

Slope stability is a fairly involved subject that builds on specific engineering knowledge. It's recommended that only designers who have had at least an exposure to soil mechanics and geotechnics deviate from the standard slope grades and alignments, and even then only if necessary.

2.3.2.1 Granular Soils

For granular materials with no cohesion the maximum allowable slope is equal to the fiction angle. But, this will not allow any factor of safety and the slope may degenerate with something as simple as someone walking across the face.

To calculate the safety factor for dry granular slopes, a rough estimate can be found using the following formula:

$$SF = \frac{\tan(\phi)}{\tan(i)}$$

SF= Safety Factor
ϕ= Friction Angle
i= Slope Angle

When the soil is completely submerged it is subject to different amounts of pressures and the effect of the internal friction angle is limited. In this case the safety factor is expressed as follows:

$$SF = \frac{\gamma_{sub} \tan(\phi)}{\gamma_{total} \tan(i)}$$

γ_{sub}= Buoyant weight of soil
γ_{total}= Total weight of soil

The buoyant weight of soil is typically about half of its total weight. It would not be unreasonable to use that approximation.

2.3.2.2 Soils with Cohesion

Taylor (1937) derived a method for determining the safety factor for simple slopes. The charts he created are based on simple slopes with cohesion. Under these conditions a circular failure plane will occur. Even though this method is fairly simplified it can provide insight to more complex slopes.

In Taylor's method the safety factor is found as follows:

$$SF = \frac{c}{N\gamma H}$$

c= Cohesion in Pa (N/m^2)
γ= Unit weight of soil (N/m^3)
H= The height of the slope (m)

N= The Stability Number found on Taylor's charts (See Appendix)

N is a function slope angle (i), friction angle (ϕ), and depth factor (D). The depth factor is the ratio of the height of the slope to the depth of a "strong" stratum and is only used for soils without any friction angle. A strong stratum can be bedrock or just another soil that is stronger than the soil of the slope. It can also be a deep soil with an appreciable amount of internal friction.

When a soil is analyzed with both cohesion and a friction angle some iteration is required. It is assumed that the safety factor of the cohesion and the safety factor of the friction angle are equal. To start, assume a safety factor of 1.0 and use the actual value of the friction angle. Use the chart to find the stability number and use it in the formula. This calculated safety factor is the safety factor of the cohesion. Use this to guess a value for the safety factor for the friction angle. The new friction angle can be calculated as follows:

$$\phi_{new} = \tan^{-1}\left(\frac{\tan\phi_{original}}{SF}\right)$$

Continue trying values for the safety factor until the safety factor used for the friction angle matches the safety factor calculated for the cohesion.

2.3.2.3 Method of Slices

If there is a specific failure plane that is of concern, a method of slices can be useful. In this approach the slope is analyzed by assuming a failure plane and equilibrium equations are applied to finite slices above the failure plane.

This method is long and involved and even after it is completed and a safety factor is found, there is no guarantee that the failure surface selected will be the critical failure surface. It is best used to check week areas. This method also requires that a full seepage analysis be performed and pore water pressure is taken into account as well. Water is the main cause of slope failures and in a dam water is a given. Once again, this should really be considered a reminder for those who have experience in the subject, not as a first exposure to the topic.

The first step is to get a scale drawing of the slope cross-section and draw in the failure surface of interest. Above the failure surface slice the failure mass (the part that would be moving in the even of a failure) into multiple vertical sections. Make a new section every time the failure surface is enters a new type of soil or the slope changes direction. It's a good idea to number these slices because the analysis and calculations tends to get complicated. For convenience an example table is provided to help with the calculations (see Appendix C).

Directions for using the table:

1. Start by calculating the weight of each slice (a).

2. Then find the angle at the base of the slice where it hits the failure plane (b).
3. The next column (c) is the weight multiplied by the sine of the base angle.
4. Sum this column to find value A.
5. Next column (d) is the weight multiplied by the cosine of the base angle.
6. Calculate the pore water force (not pressure), which is the pore water pressure multiplied by the slice thickness (e).
7. The column for base length is summed to find the value B, this is should be the length of the failure surface.
8. Column g is N, column d minus column e. This column sums to value C.
9. The Swedish method of slices states that the safety factor of that particular plane is cohesion multiplied by value B (for different cohesion values multiply each slice individually then sum) plus value C multiplied by the tangent of the friction angle (for different friction angles multiply each slice individually then sum) divided by value A. This is usually close enough. And considering the level of uncertainty from the soil properties it's as close as can be reasonably expected. If more precision is required the analysis can be extended to Bishop's method.
10. The columns from here on out are self-explanatory based on the formula in the heading.
11. Before calculating the next column, make an educated guess at a safety factor (F). The result of the Swedish method is a good start.
12. Calculate to column and then sum for value D. The first shot at a final safety factor is found by dividing value D by value A.
13. Chose a new factor F a little higher than the value just calculated. And repeat the 11 and 12 for the next two columns.
14. The final safety factor can be found using the equation for linear interpolation at the bottom of the page.

2.4 Outlet Works

Water will have to be removed from the reservoir under two conditions, normal use and emergency spillway. The normal use outlets will depend on how much flow is required. These can be sized and designed as either pumped or gravity fed water systems. In some cases, such as an animal watering hole, flood control, or a groundwater dam, normal use outlets might not be needed at all. All earthen dams will require an emergency spillway to prevent overtopping.

2.4.1 Channel Spillway

Spillways protect the dam from overtopping. The purpose is to direct flow that would exceed the design full storage level around the dam. The easiest form of spillway is just a channel that bypasses the dam at the full storage elevation. Channel spillways are primarily for floodwaters. Small flows over a channel spillway can erode it over time. If a constant flow is expected, such as a dam across a continuously running stream, a trickle tube or a drop inlet will have to be installed as well to accommodate that flow.

Channels are should have good erosion protection. The best erosion protection is a creeping type of grass that will cover the spillway. If grass will not grow well, cobbles and riprap can be used.

It is recommended that the sides be constructed at a slope of 2:1. The inlet size of the spillway is based on the amount of flow. The outlet width is based on the flow and the slope that the flow takes to return to the natural streambed. It is important that the flood flow is returned in such a way that it will not erode the downstream face of the dam. In the figure the dam is shown with an extra wing wall to deflect flow from the face of the dam.

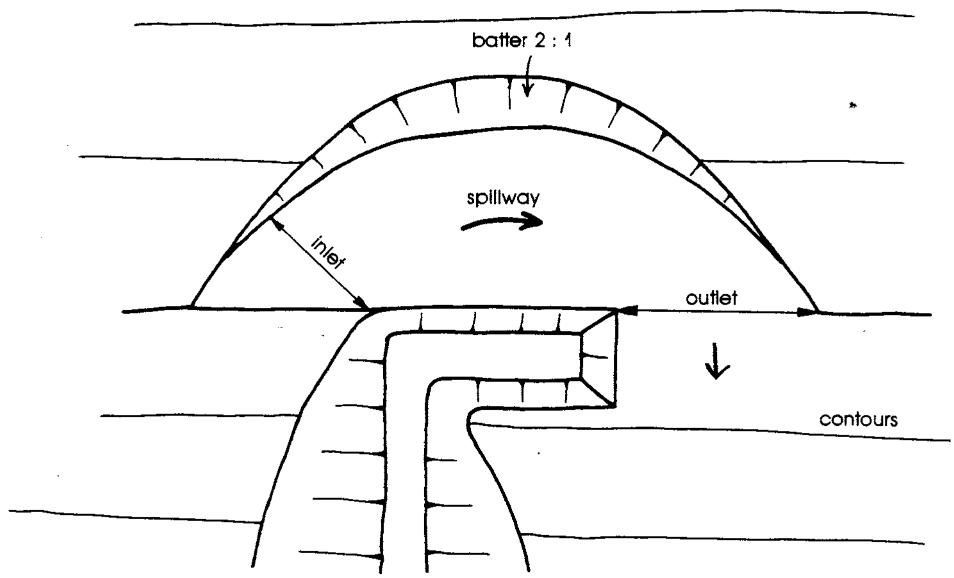

Figure 2-5: Plan View of Spillway Layout with Wing Wall (Nelson)

Table 2-7: Minimum Inlet and Outlet Widths for Channel Spillways given Certain Flood Flows and Return Slopes (Nelson)

Flood Flow (m^3/s)	Inlet Width (m)	Outlet Width for Various Return Slopes (m)										
		24%	22%	20%	18%	16%	14%	12%	10%	8%	6%	<4%
< 3	5.5	20	19	18	16	15	13	12	10	9	7	6
4	7.5	27	25	23	22	20	18	16	14	12	9	8
5	9.0	34	31	29	27	25	22	20	17	14	11	10
6	11.0	40	38	35	32	30	27	24	21	17	14	12
7	12.5	47	44	41	38	35	31	28	24	20	16	14
8	14.5	54	50	47	43	39	36	32	28	23	19	16
9	16.5	60	56	53	49	44	40	36	31	26	21	17
10	18.5	67	63	58	54	49	45	40	35	29	23	19
11	20.0	74	69	64	59	54	49	44	38	32	26	22
12	22.0	80	75	70	65	59	54	48	41	35	28	24
13	23.5	87	81	76	70	64	58	52	45	38	30	26
14	25.5	94	88	82	75	69	62	56	48	41	33	28
15	27.5	100	94	87	81	74	67	59	52	44	35	30

Manning's equation and channel geometry can be used to refine the design of the spillway. Manning's equation and the appropriate constants are provided in Appendix B.

2.4.2 Continuous Overflows and Use Outlets

In some cases water must to be released continuously from the reservoir for either water use, maintaining downstream flows, or compensating for continuous upstream flows. It is also a good idea to have a method for draining the reservoir in a safe and controlled manner.

These outlets are simply pipes running through the center of the dam. They can be sized using the same techniques used to size pipes for gravity fed water systems. These outlets should be placed at the opposite side of the dam from the spillway, especially in the case of a drop inlet. This will help prevent interference if both are operating at the same time.

If the flow is large, a drop inlet may have to be used. Stephens (1991) recommends this design for drop inlets based on recommendations from the Zimbabwe Ministry of Agriculture.

Table 2-8: Minimum Dimensions of Drop Inlet Chamber Based on Figure 2-6 and 2-7 (Stephens)

Capacity (m^3/s)	Dimension D1 (m)	Dimension D2 (m)	Dimension D3 (mm)
0.015	0.3	0.3	100
0.030	0.5	0.3	150
0.070	0.6	0.5	225
0.125	1.2	0.5	300
0.200	2.0	1.0	375
0.250	3.0	1.6	400
Based on a maximum flow velocity of 2.0 m/s or a maximum friction head loss of 2m per 100m of pipe			

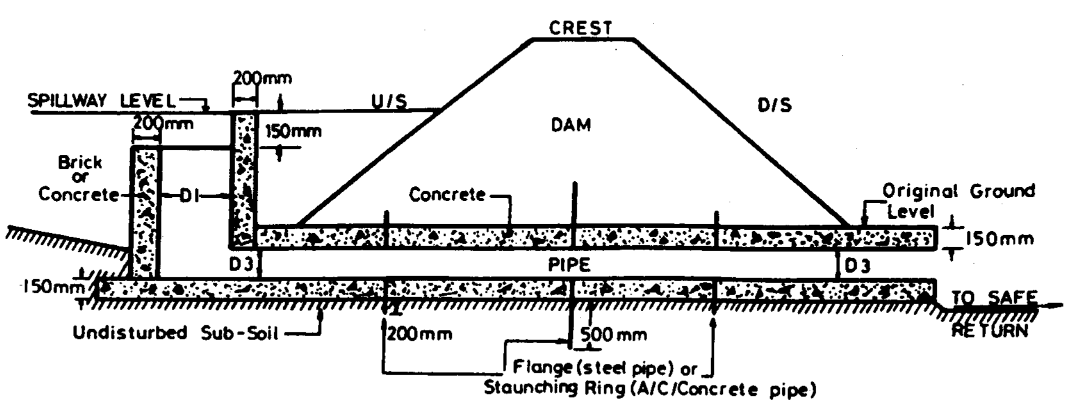

Figure 2-6: Elevation View of Standard Drop Inlet (Stephens)

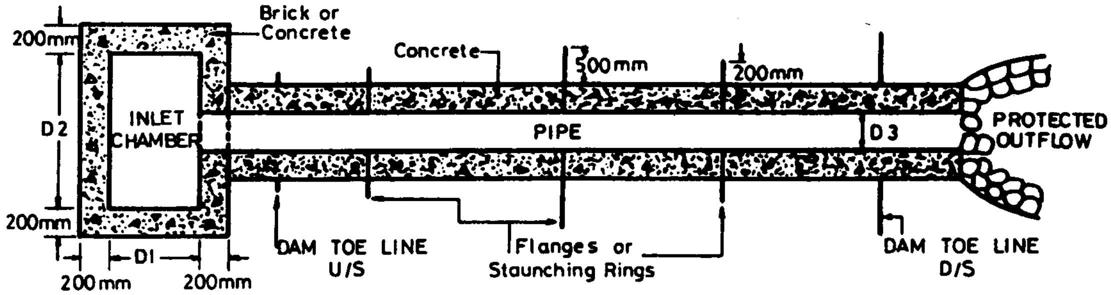

Figure 2-7: Plan View of Standard Drop Inlet (Stephens)

No matter what type of pipe or structure protrudes through the dam, a cut off collar must be installed. A cut off collar prevents water from seeping through the dam along the outside edge of the structure. The boundary between concrete and soil or a pipe and soil is more permeable than the soil itself. It can cause a short-circuit for the water and increase the seepage to a dangerous level. Cut off collars, some times called staunching rings, wrap around the pipe and force seepage to take a longer slower route through the dam.

A good size cut off collar for a standard size plastic pipe (40 – 100 mm) would be 1.2 m by 1.2 m square with a thickness of 150 mm. The collars should be spaced about 2.5 m apart and centered in the dam. Longer pipes will require more cut off collars. (Nelson)

Table 2-9: Number of Cut Off Collars Required for Different Lengths of Pipe (Nelson)

Length of Pipe (m)	Number of Cut Off Collars
20	3
25	4
30	5
35	6
40	7
50	8

There are two schools of thought about placing a valve on the dam outlet. Some suggest placing the valve on the downstream side of the dam. This makes for easy operation and repair of the valve. Some suggest placing the valve on the upstream side. This has the disadvantage of placing the valve underwater and thus making operation difficult. It has the advantage however of keeping the pressure off of the pipe and possibly extending it's life. This is a decision that will have to be made by the engineer based on the materials available. Regardless of the side it's placed on, the control is a good idea to help lower the level in the case of an expected rain or to close off and help fill the reservoir in the case of low flow.

3 Construction

It doesn't matter how good the design is if the construction is sub par. Similarly it is a useless design if it cannot be constructed. An engineer wiser than the author of this manual once stated, "Do not design something that must be wished into the ground." It is important to think about construction during all stages of the design. Each aspect of the design must have a plan behind it to get it built.

The dam will be built like a layer cake, one piece right on top of another. Once the soil is placed there is no sneaking back to install something that was forgotten. Before any construction is started, thoroughly review the plans and make a list of what must be placed first, second, etc. Digging up soil and attempting to re-compact it will cause weak spots in the embankment.

The dam should be built roughly 10% taller than designed. Soil will settle and consolidate over time. The 10% allowance will help assure that it will still be the size it was designed for years in the future. 10% is a rough and safe estimate for embankment settlement. If the conditions and soil suggest a different value it is up to the judgment of the engineer.

In addition to the dam and outlet works, a fence may also have to be constructed to keep animals out. Cattle and livestock can erode the dam by walking on it. They can also over graze the vegetative slope protection. Burrowing animals can also cause trouble for an embankment dam. Checking for burrows should be part of the routine maintenance and operation of the dam.

3.1 Surveying

Staking out the dam before construction begins will ensure that the bottom layers are placed correctly and that all outlet structures are in the right position.

Two reference stakes should be placed first. These will define the centerline of the dam. They should be placed close enough to the construction to be useful but far enough away as not to be disturbed. These will provide a reference point during construction. When the other stakes are removed or disturbed during construction, their location can be re-surveyed from these points.

Centerline pegs should be placed between the reference pegs. These should be place approximately every 15 m or every 1 m of elevation change. From these pegs the pegs outlining the upstream and downstream toe can be placed. The offset can be calculated based on the slope the height of that section and the crest width.

Offset Distance = (Slope, i.e. 2 for 2:1)(Height, including settlement allowance)
+(0.5)(Crest Width)

The spillway can be pegged out in a similar fashion. The pegs defining the spillway will be placed at the top of the excavation.

3.2 Site Preparation

Before construction is to begin the ground must be prepared. Topsoil is not the optimal foundation to build on. Before the embankment is to be built up, the foundation should be excavated to a depth of at least 1 m and possibly deeper depending on conditions. This soil may be used for the embankment if it is clear of organic material and is of good quality, but it must be compacted to the specifications described in the next section. This applies the abutment of the dam as well, all the way up to the very edge.

The reservoir will also have to be cleared. If excessive organic mater is submerged in the reservoir it can taint the water supply. A quick survey with a hand level at the full supply level will show what brush will have to be cleared.

A good route between the borrow pit and the dam site needs to be prepared. This is what will limit the speed of construction. The best location for a borrow pit is just on the other side of the dam in the reservoir. Not only is this close, but also it doesn't disturb any extra ground and it increases the capacity of the reservoir. If this is possible be sure to keep the edge of the pit about 5 to 10 m from the upstream toe of the dam and don't cut the sides of the borrow pit any steeper than that of the downstream slope.

If the stream is flowing in the gully while the dam is being constructed, it must be diverted. It's best to divert the stream as far from the dam as possible and sent it down a neighboring gully. If this is not possible it can be directed directly to the trickle tube or other continuous outlet. If this is not in the design, it should be. This is a continuous flow that needs to be dealt with over the live of the dam. This is a good test for the design of the trickle tube or outlet. If it can't handle the constant flow while the dam is being built, it won't handle the constant flow when the dam is completed.

3.3 Compaction

In order for the soil to act as predicted, it must be fully compacted. Compaction is the process of removing the voids from the soil and making it as dense as possible. The key to good compaction is, small lifts, good energy, and the right amount of water.

Placing the soil in layers (or lifts) that are too big is a problem that plagues even professionals in developing countries. Even heavy equipment can't make up for layers that are too thick. For hand compaction methods and even medium sized farm equipment, the lifts should be limited to 75 – 100 mm. This is before the compaction is started. When it's done it will be even smaller.

The energy applied to the soil will also affect compaction. Typical heavy machinery used in construction will apply 550 kilojoules of energy to every cubic meter of soil. To get similar results from hand compaction, this would roughly be equivalent pounding the soil 5-6 times with a 10 kg pole 10 cm in diameter (or 3 times with a 20 kg pole). That is, if the lifts are 100 mm or less. Getting plenty of people to walk and stomp across the surface will also help.

The greatest challenge to achieving the best compaction possible is getting the soil damp enough to pack, but not to wet. The optimum moisture content (the weight of the water in a soil divided by the weight of the dry soil grains) for compaction will vary for different soils, it is important to have a good feel for it. If the soil is too dry, water can easily be added. If it is too wet, drying the soil is a pain and can put an operation behind schedule. It is better to work with soil that is a little to dry than a little to wet. The consequences of poorly compacted soil are far worse than falling behind schedule.

Table 3-1: Typical Values for Optimum Moisture Content for Compaction

Soil Type	Typical Value of Optimum Moisture
Sand	6-10%
Sand-Silt Mixture	8-12%
Silt	11-15%
Clay	13-21%

To get a good feel for when a cohesionless soil such as silt or sand is at its optimum moisture content grab a small handful. Squeeze the soil firmly. If water squeezes out or your hand is wet, there is too much water. A soil with the right amount of water will form a clod when squeezed. When you open your hand the soil should break into two or three clumps. If it falls apart it could use some more water.

For clay soils with cohesion the clay should be able to be rolled into a snake about 15 cm long and the diameter of a pencil or about 1 cm. If the soil can be looped around to touch the other end without breaking its at a good moisture content. This may take some experimenting. If it can't be done at all, the soil may not be as cohesive as originally thought and the design may have to be reconsidered.

Use these tests to approximate how much water should be added. Mix up a test batch. Keep track of how much water is added to a certain volume of soil and extrapolate. It's best to add the water in the borrow pit, this allows the best mixing. If water is added on sight, it should be sprinkled lightly.

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Appendix A: Taylor's Friction Circle Charts

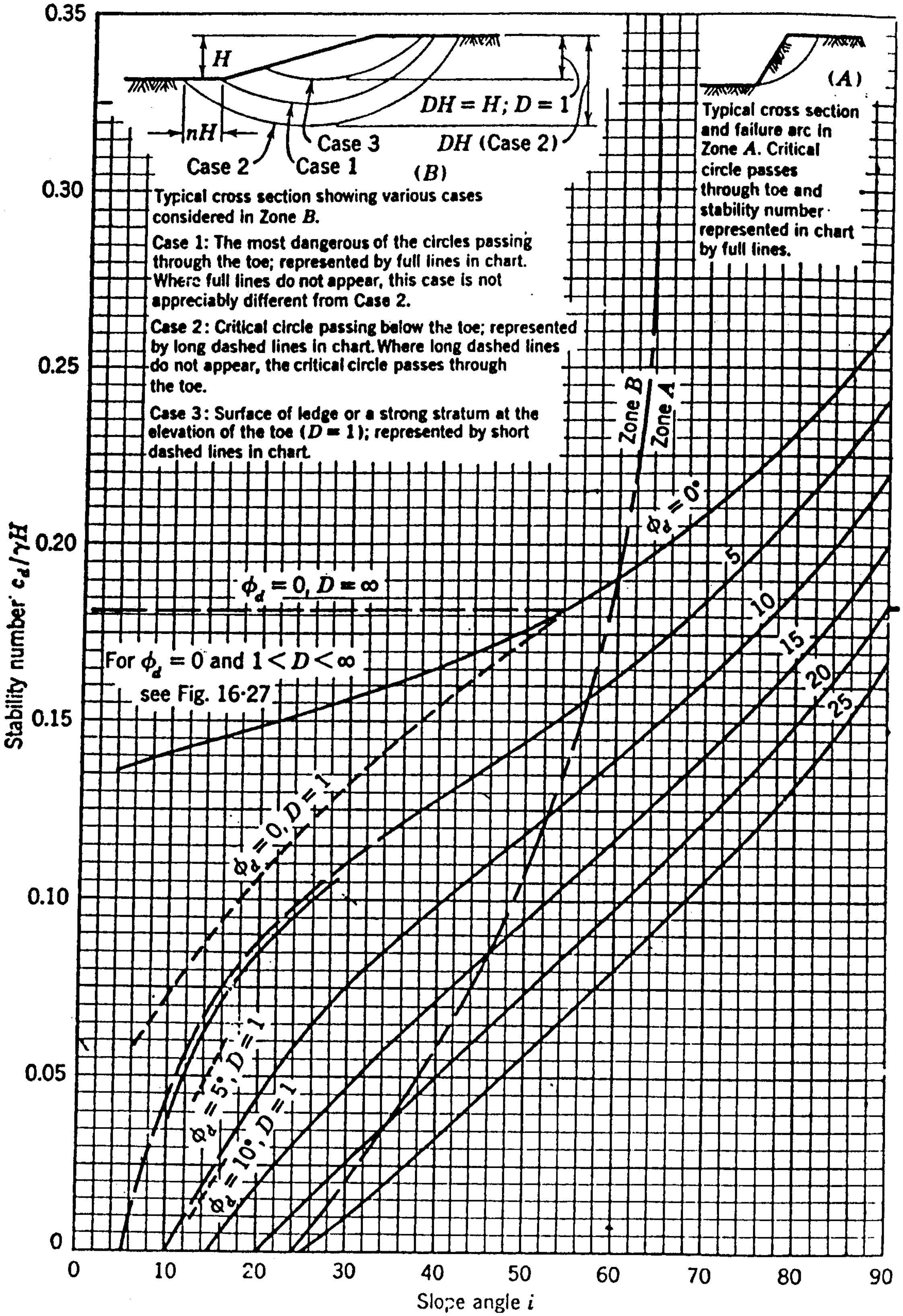

Figure A - 1: Taylor's Chart of Stability Numbers for Soils with a Friction Angle

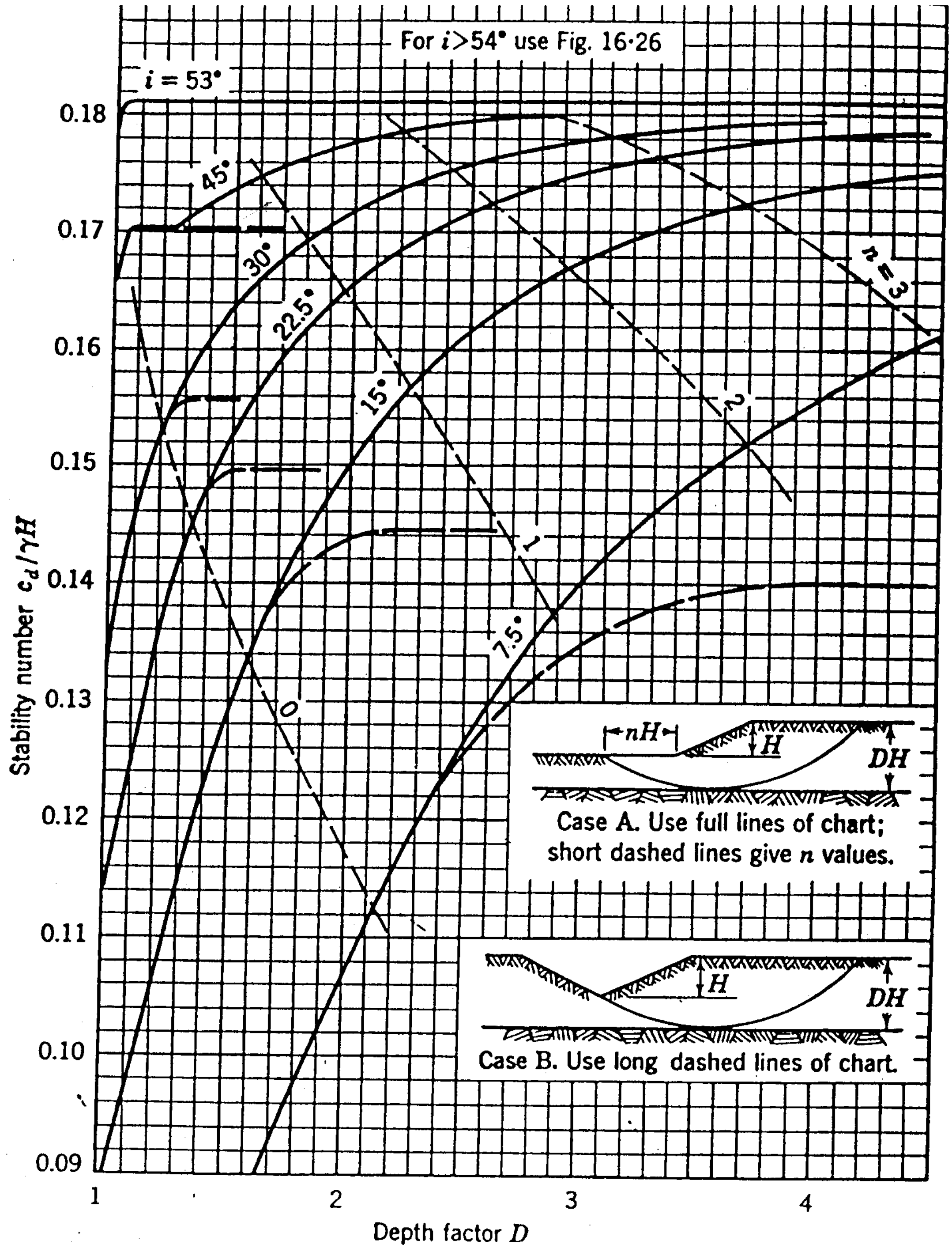

Figure A - 2: Taylor's Chart of Stability Numbers for Soils with No Friction Angle

Appendix B: Manning's Equation

Manning's Equation:

$$V = \frac{1}{n}\left(A/P\right)^{2/3} S^{1/2}$$

Where:

V= Velocity Q/A, in m/s
A= Cross sectional area of flow, in m^2
P= Wetted perimeter, in m
S= Slope of channel
n= Roughness Coefficient

Material	n
Earth	0.020-0.030
Rubble or Riprap	0.020-0.035
Vegetation	0.030-0.040

Geometry of trapezoidal Channel:

$$A = bd + zd^2$$

$$P = b + 2d\sqrt{1+z^2}$$

Where:

b= bottom width of channel
d= depth of flow
z= side slope (2:1 slope, z=2)

Appendix C: Calculation Chart for Method of Slices

Gamma= Phi= c= F1= F2=

Slice	Weight W	Base Angle Alpha	WsinAlpha	WcosAlpha	Pore Water Force u = Gamma H2O * b * H2O head	Base Length l	N = WcosAlpha - u	W - u	c*b	(W - u)*tan Phi	R=(c*b)+((W - u)*tan Phi)	M = cosAlpha*(1+((tanAlpha*tan Phi)/F))	R/M	M = cosAlpha*(1+((tanAlpha*tan Phi)/F))	R/M
	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o
1															
2															
3															
4															
5															
6															
7															
8															
9															
10															
11															
12															
13															
14															
15															
			[A]			[B]	[C]						[D]		[D]

SF1= SF2=

Swedish

F=(c*[B]+[C]tanPhi)/[A]

Bishop

SF=[D]/[A]

F=(SF1-((SF1-SF2)/(F1-F2))*F1)/(1-((SF1-SF2)/(F1-F2)))