Earth embankments 3

3 Earth embankments

3.1 INTRODUCTION

Earth embankments have been used since the earliest times to impound and divert water. They are simple compacted structures that rely on their mass to resist sliding and overturning and are the most common type of dam found worldwide. Modern haulage methods and developments in soil mechanics since the end of the nineteenth century have greatly increased the safety and life of these structures.

The main advantages involved in the construction of small earth dams are:

- Local natural materials are used.
- Design procedures are straightforward.
- Comparatively small plant and equipment are required.
- Foundation requirements are less stringent than for other types of dam. The broad base of an earth dam spreads the load on the foundation.
- Earthfill dams resist settlement and movement better than more rigid structures and can be more suitable for areas where earth movements are common.

However, disadvantages also exist and these are:

- An earth embankment is easily damaged or destroyed by water flowing on, over or against it. Thus, a spillway and adequate upstream protection are essential for any earth dam.
- Designing and constructing adequate spillways is usually the most technically difficult part of any dam building work. Any site with a poor quality spillway should not be used.
- If not adequately compacted during construction, the dam will offer weak structural integrity, offering possible pathways for preferential seepage.
- Earth dams require continual maintenance to prevent erosion, tree growth, subsidence, animal and insect damage and seepage.

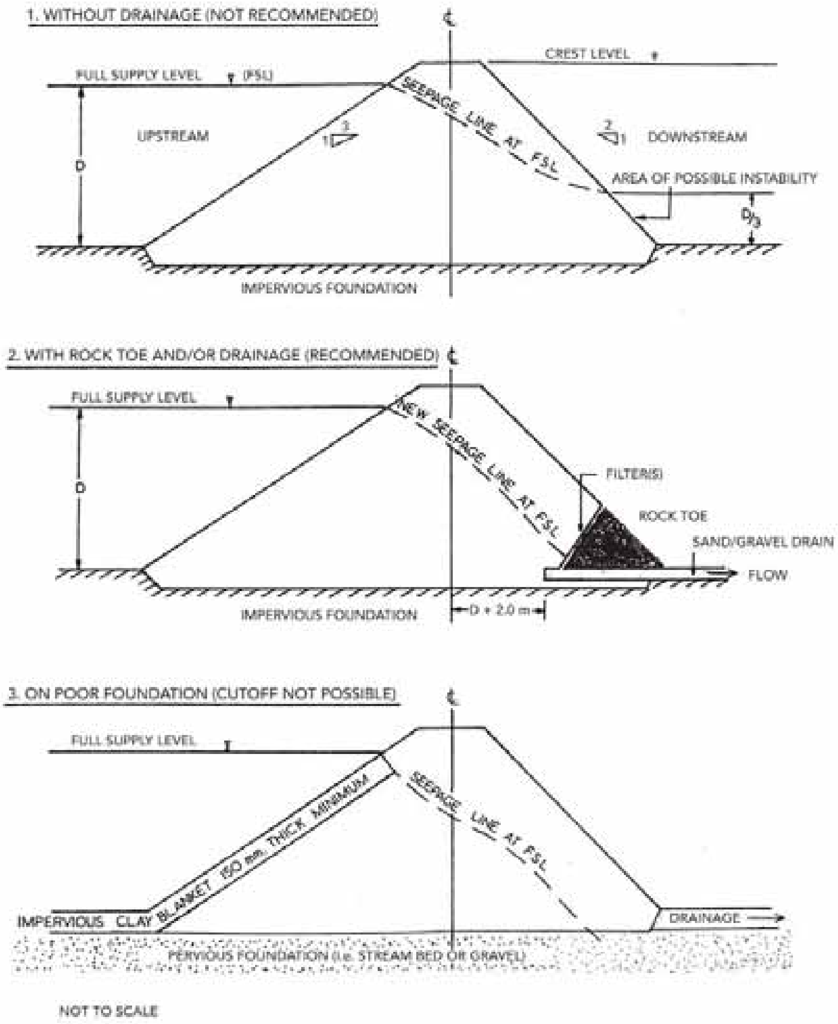
The earliest embankments were constructed on the principle of a solid wall of earth, whether impervious or not, across a stream or river. When built properly, such homogeneous embankments can still be cheap and reliable. They are, however, generally inferior to the modern method of zoned construction in which an embankment is built in three sections:

- upstream and relatively impermeable section;
- central core or hearting of highly impermeable material (which, with any below ground cutoff, will effectively seal the dam against seepage); and
- downstream section of poorer, coarser material that allows freer drainage of the structure and which, by its weight, anchors the complete embankment to its foundation and prevents slip and other movement.

3.2 THE HOMOGENEOUS EMBANKMENT

With this older type of dam, the build up of excess pore pressures within the embankment and seepage can be a problem, especially for a reservoir having high, or rapidly fluctuating water levels for long periods; or for a dam having impervious foundations. If seepage is excessive this can lead to instability and eventual failure of all or part of the downstream face. **Figure 1** illustrates the problem and offers some solutions.

Figure 1 - Homogeneous dams



Either a rock toe or drainage layer ('blanket') of gravel or similar material will help relieve seepage problems in the downstream areas of an embankment on impervious foundations. The rock toe should be overlain by coarse sand and gravel to prevent embankment materials being drawn into it, a situation that could ultimately reduce the permeability of the toe and cause subsidence of the dam. In more pervious foundations (which often exist where dams are constructed on stream beds) exposure of a natural drainage layer can have the same effect of relieving seepage as an artificial gravel blanket or drainage layer.

Any seepage relief structure should only underlie the downstream section of the dam and should not extend into areas of the embankment that could permit percolation or direct seepage from upstream.

Generally, homogeneous dams should have relatively flat slopes (1:3 upstream and 1:2 downstream) as insurance against possible instability. A flatter upstream slope, required by all earth dams, allows the saturated section below water level to resist slumping. Also the weight of the water stored above it exerts a downforce which, when combined with the weight of the dam, equals or exceeds the horizontal thrust exerted by the depth of the water against the embankment. Note that the latter is dependent on the depth, not the volume of water, and that the horizontal thrust increases according to the square of the depth of the water. Therefore, building higher dams becomes more critical as, for example, doubling the water depth of a dam from 2 m to 4 m would increase the thrust fourfold.

Water levels should not be allowed to fall or rise too fast, especially if the embankment material is impermeable. This is because a rapid lowering of the reservoir could lead to slumping of the upstream face or, if the wall has been allowed to dry, a rapid rise in level could lead to erosion through cracks and fissures. Both may eventually result in erosion, loss of material and, in a worst case scenario, a breach.

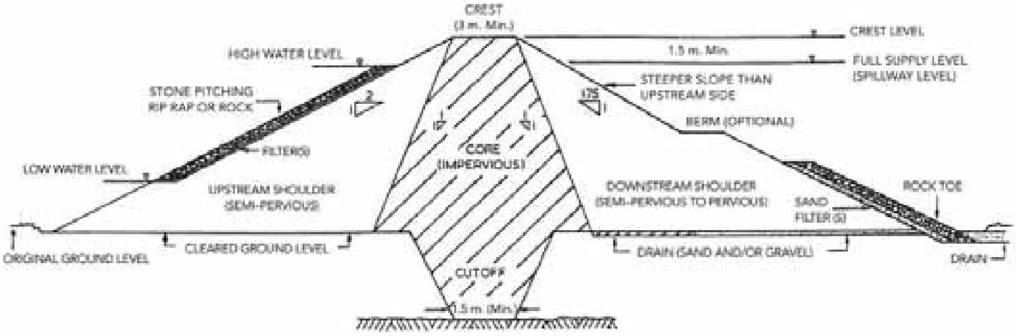
3.3 THE ZONED EMBANKMENT

This is a better alternative, particularly for larger dams that readily allow the use of construction machinery. With this type of dam, possible seepage hazards are reduced to a minimum. Compared with homogeneous embankments, costs are likely to be higher, mainly because the earthworks material is divided into three categories: pervious for the downstream section, impervious for the core (or hearting) and semi-impervious for the upstream section, all of which has to be excavated from separate borrow areas (preferably within the reservoir area), thus increasing excavation and movement costs. Slopes, however, can be reduced to around 1:2 upstream and 1:1.75 downstream (or 1:2.25 upstream and 1:2 downstream for sites where only relatively poor impermeable material is available) and the material excavated in construction of the core can be used in the embankment, thus economizing on the use of earthworks.

Figure 2 illustrates an ideal example of a zoned dam. Note should be made of the rock toe, which may be required for stability and to drain the downstream section (gravel drains may be necessary) and the stone pitching on the upstream face which, in this case, is necessary for protection of the wall from wave action. When laid correctly, stone pitching (**Figure 3** provides an example) can prove an inexpensive (if available locally) and efficient means of protection but should not be used on the ends of embankments and abutments and along the sides of spillways. These areas of a dam are extremely sensitive to erosion and may need to be concreted or shielded by gabions for maximum protection. The FAO publication on small dams and weirs in earth and gabion materials (FAO, 2001) provides guidelines on this.

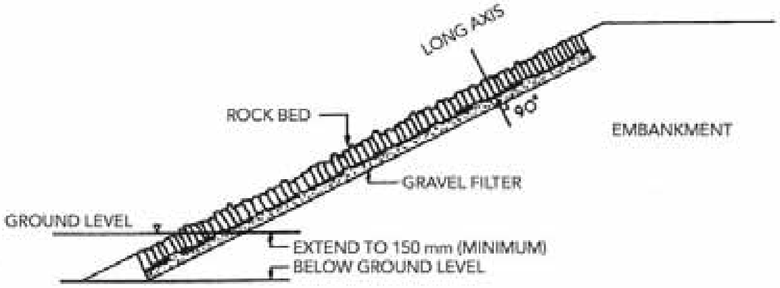
Artificial impermeable materials, such as heavy duty plastic sheeting, have successfully been used in many parts of the world as an alternative to clay cores. In the tropics, however, such materials have been found to attract termites and rodents; have been burrowed into by animals and have not resisted settlement of the embankment after construction. Similarly, ant hill/termite mound material, often

Figure 2 - Section of a typical zoned dam



CUTOFF EXTENDED TO GOOD, STABLE, IMPERVIOUS FOUNDATION (ROCK OR FIRM CLAY LAYER) OR TO DEPTH EQUAL TO MINIMUM 3/4 HEIGHT OF DAM.

Figure 3 - Stone pitching detail



NOTE: STONES MUST BE LAID WITH LONG AXIS CORRECTLY ALIGNED. THEY WILL THEN WITHSTAND SETTLEMENT AND REDUCE THE RISK OF EROSION.

used because of its relatively high clay content, is losing favour beacause of its undesirable organic and mineral constituents; its variability within a small area and, once used, its subsequent attraction to termites (and their predators) despite its being treated with insecticide or mixed with diesel fuel. Where suitable core material is unavailable within economic limits, such material may have to be used, but must be analysed if possible; well 'killed' before excavation and treated when being installed.

Care is needed in the use of insecticides that could contaminate watercourses when absorbed by seepage or other water.

3.4 CUTOFF TRENCH AND CORE

Most dams, homogenous or zoned, can benefit from the construction of a cutoff in the foundation. A cutoff will reduce seepage and improve stability.

Whether stable clay, or other material is being used, the cutoff trench must be excavated to a depth that will minimize all possible seepage. Ideally, the cutoff trench should be dug down to solid rock that extends to great depths. If underlying rock is fissured or uneven it can be cleaned off and concreted to offer a good surface on which the clay can be laid. For larger indentations or cracks, slush grouting should be used, which is a thick slurry mix of cement and water poured and broomed into the larger cracks and fissures before any concrete is laid to fill the remaining indentations and to offer an eventual mostly flat surface. For more even surfaces with smaller cracks, a cement wash (a weaker mix of cement and water to form a creamy texture) can be brushed across a surface to seal it and again establish a mostly flat surface layer.

The cutoff material should be placed in layers to a maximum 50-75 mm thick and to a minimum width of 1 m for small dams (i.e. hand laid cores) and layers 75-150 mm thick and 2-3 m wide for larger dams (i.e. material laid by scoop or scraper and compacted by machinery).

Every layer must be well compacted and if the whole dam length cannot be completed at any one time. Each section must be well keyed and bonded to the next since the cutoff trench and core are designed as one homogeneous unit to avoid seepage and structural problems. Compaction can be carried out by hand (tamping damp material by ramming poles 100-150 mm diameter) or by machinery (rollers or vibrators), or a combination of both. If farm tractors are being used, the tyres can be filled with water and, if a staggered track is followed across the width of the cutoff trench at the time of back filling, much compaction time can be saved. Light irrigation of the borrow area, some hours before excavation, can often assist in the scraping and scooping of the material, as long as it is not too wet.

Rain on the site can cause problems and an over-wet clay will prove difficult to compact. In this situation it is better to wait for the soil to dry before continuing with construction.

Continual or, at least frequent, monitoring of core material quality, moisture content and layering procedures is advisable, especially where inexperienced plant operators and labourers are being employed.

The importance of correct core construction cannot be over-emphasized. Failure to correctly carry out these comparatively inexpensive procedures could lead to expensive problems later that remedial measures will rarely completely resolve. If the core and cutoff trench have not been taken down to a firm foundation, or laid in layers thin and moist enough to allow compaction, it will be too late to introduce corrective measures after construction. In severe cases the dam can fail or not attain legislative approval – in either case an expensive mistake. The cutoff trench, and core of a zoned embankment, must be constructed of impervious material. Use of a soil that will not allow the passage of any water (i.e. impervious) is not necessarily desirable. This is explained in more detail in Section 4.

Earth works 4

4 Earth works

4.1 INVESTIGATIONS

Ideally, the entire earth fill should be drawn from within the reservoir area and, if required, from any cut spillway areas. The importance of a correct analytical approach to determine the various soil types for a zoned embankment cannot be stressed too much. Although using a soil laboratory is expensive, the results can more than repay the cost involved and, more often than not, will ensure the exclusion of doubtful material in the construction process. This approach will include selecting the soils to be used, laboratory testing and mechanical analysis (if such facilities are available) to ensure the selected materials are suitable and interpretation of the results of these tests by an experienced engineer or technician to permit the appropriate materials to be used.

At this investigatory stage possible borrow areas should be identified – initially by eye, trying to ascertain soil type from vegetation, visible soil, position on slope and so on.

Preliminary exploration to determine suitable borrow areas for dam construction would:

- Explore areas for large quantities of soil material for inclusion in the embankment and any training walls. Ideally trials should indicate at least 150 percent of the estimated material needed for the dam is available (i.e. to cater for losses and wastage and poorer than estimated materials being found) and that the haul distances are not excessive.
- Explore areas for the provision of more specialized materials such as gravels (for drainage), aggregates (for concrete), filter materials, stone (for rip-rap or stone pitching) and high-quality clays for lining upstream surfaces and any canals.

The FAO Manual, on small dams and weirs in earth and gabion materials (FAO, 2001) has a detailed section on borrow materials, sampling and testing. The section below however provides basic details to follow in ascertaining the more favourable areas for investigation.

4.1.1 Soil pits and trenches

Dig soil pits and auger holes to assess the top and subsoil layers and the foundation condition in the embankment area. Auger holes dug on a grid to depths of 3 m throughout a potential source area will allow a general assessment of soil types to be made. A series of trial pits and trenches can then be dug in more promising areas to allow a visual assessment of the soil profile to be made in line with local soil coding and classification techniques. Samples can be taken for subsequent texture and laboratory analysis.

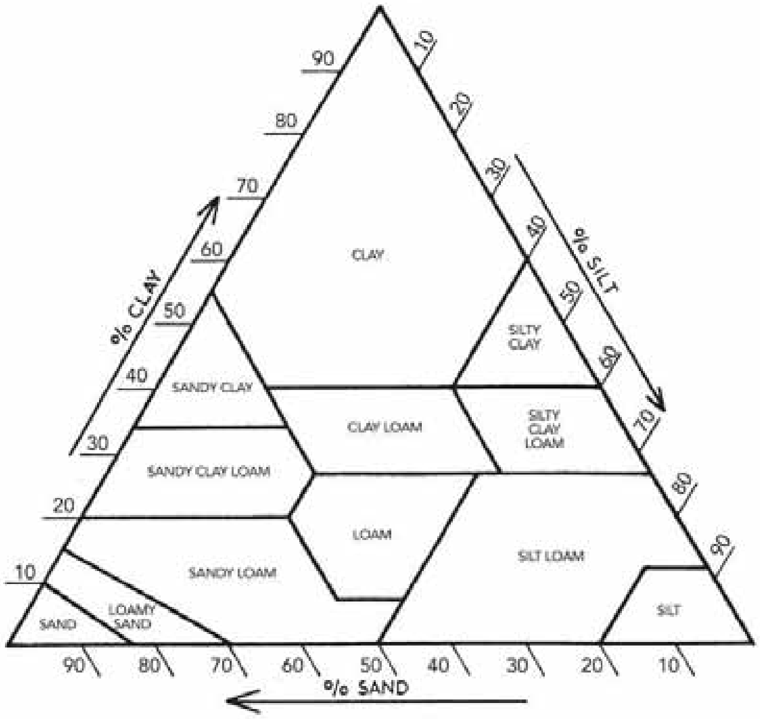
4.1.2 Texture tests

Texture tests are carried out to determine soil types. Excluding stones and gravels, the mineral part of the soil is made up of particles in three size ranges[4]:

Clay:	less than 0.002 mm diameter.
Silt:	0.002-0.05 mm diameter.
Sand:	0.05-2.00 mm diameter.

The relative proportions of sand, silt and clay are used to determine the textural class of a soil. The internationally accepted United States Department of Agriculture (USDA) Texture Diagram (refer to **Figure 4)** is a useful tool for initially demarcating soils for dam building. The USDA system is widely used throughout the world[5].

Figure 4 - Soil textural class



SOURCE: US BUREAU OF RECLAMATION ADAPTED FROM SUPPLEMENT TO SOIL CLASSIFICATION SYSTEM (7TH APPROXIMATION), SCS., USDA, SECOND PRINTING, MARCH 1967

Basically, the textural classes involved are as follows:

Any soil with more than 55 percent clay can be considered as a 'clay'. A 'sandy clay' is a soil with between 33 percent and 55 percent clay and up to 65 percent sand. A 'sandy clay loam' has between 20 percent and 30 percent clay and up to 80 percent sand and loam.

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[4] The figures vary according to who is defining: geotechnical engineers, sedimentologists, soil scientists and so on. The definition here is that for the USDA and adopted by FAO.

[5] The United Kingdom system varies slightly from this, mainly with minor differences in the classification of clays and clay-based soils.

Sands can be further defined according to the size of the grains (i.e. fine, medium and coarse) in the sand fraction.

Sands and clays, and combinations of them, are most suitable for earth dam construction. Generally, however, silty soils are unsuitable because of their inherent instability when wet and should not be included in any of the earthworks.

To precisely define textural classes requires laboratory techniques but, with experience and specific local knowledge, hand testing to determine texture can prove important for the initial stages of identifying appropriate earth fill materials. Clay soil areas can be demarcated in the field with the better soils (i.e. higher percentage clays) being reserved for the core and upstream shoulder of the embankment. Silts are often similar in both appearance and feel to wet clays when dry but can usually be differentiated when wet as the clay will exhibit sticky, plastic-like characteristics while silt has a silky, smooth feeling with a tendency to disperse.

Hand-testing techniques involve the taking of a small sample of a soil – usually in the hand not required for making notes – dampening it (avoid soaking it) and rolling it into a ball to examine its cohesive constituents.

A better quality clay can be manipulated into a thin strip without breaking up, rolled into a ball and dropped onto a flat surface from waist height without cracking unduly. Also, when cut it will exhibit a shiny, smooth surface.

The latest USBR Manual on small earth dams (USBR, 2006) has updated the section on soils according to types, defines a ‘Unified Classification’ and makes recommendations on slopes for dam construction (albeit for larger dams than this handbook will target) according to soil type. Compaction rates are also indicated to guide designers and constructors for smaller, simpler dams on smaller catchments and to reduce the needs for mechanical and laboratory testing of such soils.

4.1.3 Infiltration tests

At this stage, preliminary infiltration tests to obtain an indication of the soil’s permeability can be performed. The simplest way to carry out such tests involves filling auger holes or small pits with water, taking care not to over compact the soil within. A comparative evaluation of falling water levels over an area can then provide an indication of permeability and may indicate relative clay contents. Infiltration rings, which are used in the assessment of infiltration capacity for irrigation design purposes, can be used for the upper surface layers of soil.

4.1.4 Core and cutoff material

A soil is required that will limit the passage of water but not to such an extent that undesirable differential pressures could build up across and within the embankment. The impermeability of the soil used will vary between localities, but some standardization of water tightness can be achieved through varying the degree of compaction involved. A more pervious material will require greater compaction and vice versa. Generally, soils containing a significant percentage of clay are ideal for the core but clays with a tendency to crack should be avoided. If the latter are used they should be carefully compacted, placed in lower parts of the dam that are unlikely to dry out (such as in the cutoff trench) or covered by a gravel layer or topsoil with grass.

4.1.5 Other embankment materials

Semi-pervious materials such as sandy clays and clay loams with a proportion of fines, such as clay or perhaps silt particles, are suitable for inclusion in the upstream shoulder. These will allow a limited passage of water and, in a properly constructed embankment, will resist slumping when wet. Where poorer soils are used, special attention to compaction techniques will have to be given to minimize the volume of air spaces in the soil and to maximize its stability when wet.

Pervious materials such as coarser grained sand and gravels – suitably washed and screened/sieved for size and grade – are used in the downstream shoulder and sections of the embankment requiring mass and drainage. Always seek specialist advice for use of these materials in drainage and filter works. These can often be better compacted dry or if only slightly damp. Once completed, a dry downstream face will prevent slippage and reduce risk of failure.

4.2 SOILS

Within a river valley a cross-section of soils may be available. The valley sides, where less leaching has occurred, can provide soils with a higher proportion of clay. The more heavily leached areas can provide amounts of sands, gravels and/ or silts. The streambed proper should be a source for silts, sands and gravels, the latter being useful for drains and concrete work. Of great economic importance is the need to find such materials close to the dam site, preferably within the reservoir area, and in large enough quantities to justify their removal. Avoid complete removal of impervious materials, as exposure of more permeable layers beneath could lead to seepage problems in later years, especially when under pressure of several metres of water.

Investigation of proposed borrow areas is a necessary feature of any dam survey. This is carried out using auger holes, soil pits, boreholes and utilizing existing features such as wells and animal burrows to gain an extensive knowledge of the area.

4.2.1 Clays

The best clay soil is always reserved for the core and cutoff and must be well compacted. Basically, the lower the clay percentage (to an arbitrary minimum as low as 3-5 percent), the more compaction and care in construction is required.

The upstream shoulder does not require highly impermeable clays as these could lead to undesirable uplift pressures developing beneath this section of embankment. More permeable clays usually have a good crumb or granular structure and include the typical red (but not lateritic) soils and the lighter self-ploughing basalt soils of central and southern Africa with their ability to move topsoil (when dry and crumbly) down through cracks in the profile. Sandy clay soils are most suited for inclusion in this upstream section as they compact well, have much reduced seepage characteristics but do not allow the build up of high soil–water pressures. Clays are not required in the downstream shoulder as it is essential that this section is free draining.

4.2.2 Silts

Avoid including silts in any section of the embankment. The lack of cohesion, poor structure, fine material and difficulty in compaction are their main drawbacks. A small proportion of silt is permissible, say in a silty-clay, but care must be taken in its use and application to ensure it is balanced with other soils and to keep percentage contents low.

As they can be confused with fine clays, it is important to differentiate the two when testing for texture. Laboratory analysis may, therefore, be required.

4.2.3 Sands

A soil with a predominance of sand should not be used in dam construction. A sandy soil can be used in the downstream shoulder but should not be used elsewhere unless there is no alternative. If a sandy soil is used in the rest of the dam special attention must be paid to compaction, the best soil reserved for the core, and some consideration given to obtaining embankment water tightness by other means.

Sands do have an important role in larger dams as a filter material.

4.2.4 Materials to avoid

Should there be any question about a soil's suitability, it is safest to avoid using it. Some materials should never be used in dam construction, in particular the following:

- ➔ Organic material (except when used to top dress the embankment and other parts of the dam site at the end of the construction period).
- ➔ Decomposing material.
- ➔ Material with a high proportion of mica, which forms slip surfaces in soils of low clay percentages.
- ➔ Calcitic soils such as clays derived from limestone which, although generally stable, are usually very permeable.
- ➔ Fine silts, which are unsuitable for any zone of the dam.
- ➔ Schists and shales which, although often gravelly in texture, tend to disintegrate when wet. Schists may also contain a high proportion of mica.
- ➔ Cracking clays that fracture when dry and may not seal up when wetted in time to prevent piping through them.
- ➔ Sodic soils, which are fine clays with a high proportion of sodium. They are difficult to identify in the field, so any fine clay should be analysed.

Sodic soils

Contact between a sodic soil and water leads to deflocculation occurring in the profile in which sodium has accumulated, entered the exchange complex and caused dispersion of the colloids. Consequently, reduction occurs in pore spaces affecting infiltration, permeability and aeration. The pH[6] and electrical conductivity (affected by soil salinity – sodium, magnesium and calcium being important) measured are in most cases high. Basically this leads to highly dispersive behaviour when wet (i.e. as most dam soils would be) and thus these soils do not act at all like clays (which bond together when wet) and are completely unsuitable to use in any embankment.

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[6] pH is the standard measure of acidity related to the concentration of hydrogen ions. A pH of 7 is neutral, soils with a pH between 1 and 7 are acidic and those above 7 (to 14) are alkaline.

Any clays with a predominance of sodium (and, to a lesser extent, magnesium) among the exchangeable cations should be avoided as earthworks' materials. Laboratory results will generally show exchangeable sodium percentage (ESP) values higher than 15 and pH in the range 8.5 to 10 although lime-free soils can show pH values as low as 6. Structure will have significantly deteriorated and compaction tests will indicate easily mobilized soils that are structurally unstable when wet and under load. The proportion of clay to exchangeable sodium will also be important in so much that a sandy-clay soil with lower ESP values (i.e. 8 or above) will prove more unstable than a clayey soil with a higher ESP value.

Sodic soils are virtually cohesionless when wet and are responsible for many catastrophic earth dam collapses. Such failures usually occur soon after first filling of a dam reservoir and it is normally not advisable to attempt repair work as the embankment and foundation may still have sodic areas as yet unaffected. If sodicity is suspected the best rule is not to use any of the soil concerned and avoid such areas when extending dam, core or foundation work. However, for soils with low levels of sodicity, chemical treatment with gypsum and higher levels of compaction to increase the *in situ* impermeability (i.e. to keep the sodic soils dryer than normal) may help maintain stability where such soils have inadvertently been included in earth fill materials. Drainage will also be important to lower the phreatic surface within the embankment and to reduce pore pressures.

In central and southern Africa, sodic soils are most commonly found in 'mopane' (*Colophospermum mopane*) woodland and scrubland, which develop on granitic bedrock-derived soils (these have higher sodium-releasing mineral contents than their basaltic equivalents, which tend to be richer in calcium materials) in the lower rainfall and relatively hotter climates that allow sodium to accumulate in the upper soil horizons.

Marine clays found in Canada, Norway and Sweden, termed 'quick clays' and renowned for their viscosity and ability to flow great distances when wet are similar to mopane soils and have been created by the deposition of sodium within the soil horizons as pore water levels decline.

4.3 MECHANICAL ANALYSIS

Mechanical analysis of soil samples to assess constituents, mineral content, compaction characteristics and to check for other factors such as mica, silt, sodicity, etc., that may make apparently good soil unsuitable, should be carried out. Correlation of these results, which accurately assess silt, clay, sand and other particles in a soil, with previous work will allow estimates to be made of earth fill available, overburden to be removed and unsuitable areas to be avoided.

The importance of a correct analytical approach to determine the various soil types for a zoned embankment cannot be over stressed. Although using a soil laboratory is expensive, the results can more than repay the cost involved and, more often than not, will ensure the exclusion of doubtful material in the construction process.

4.4 LABORATORY TESTS

Laboratory tests on selected samples should be undertaken to confirm the field evaluations and to determine the physical properties of the soils. The following tests (refer to the methods and procedures detailed in the nine documents comprising the British Standard[7] 1377 of 1990 (and 2007 amendments) for definitive information on compaction, compressibility, permeability and durability and shear strength) are recommended:

- ➔ Gradings: both mechanical sieving and hydrometer tests to determine the particle size distribution, identify the predominant soil type and the likely permeability of the material.
- ➔ Atterberg tests: measure the plastic limit and liquid limit of soil to enable the material to be classified and its suitability as a fill material assessed.
- ➔ Proctor test: to determine the maximum dry density and the optimum moisture content for use in compaction control during construction. Soils compacted to the maximum dry density are then at their maximum strength.
- ➔ Crumb test: to determine the disposition of the soil to disperse.

Examples of typical soils materials envelopes, based on a southern African laboratory (sieve) analysis, and according to particle size are given in **Figure 5**. In this figure, any soil materials meeting the specifications found between the heavy black lines would be suitable for inclusion in the parts of the dam embankment noted on the graphs. 'Shell zone material' refers to the upstream and downstream sections of a zoned embankment: they may need to be differentiated further where different materials are recommended for each section.

4.5 BORROW AREAS

Borrow areas within the reservoir area should be given first preference, followed by those located on the valley sides close to the proposed embankment. Borrow pits in the reservoir have the advantage of increasing the upstream storage capacity and require no remedial work once the dam is completed.

Borrow pits should never be located close to the downstream toe area of the dam, the spillway or outfall or in any area prone to erosion.

Borrow pits located some distance from the dam site will increase construction costs, wear and tear on plant and machinery and the timing of the construction so always identify source materials as close to the dam site as possible.

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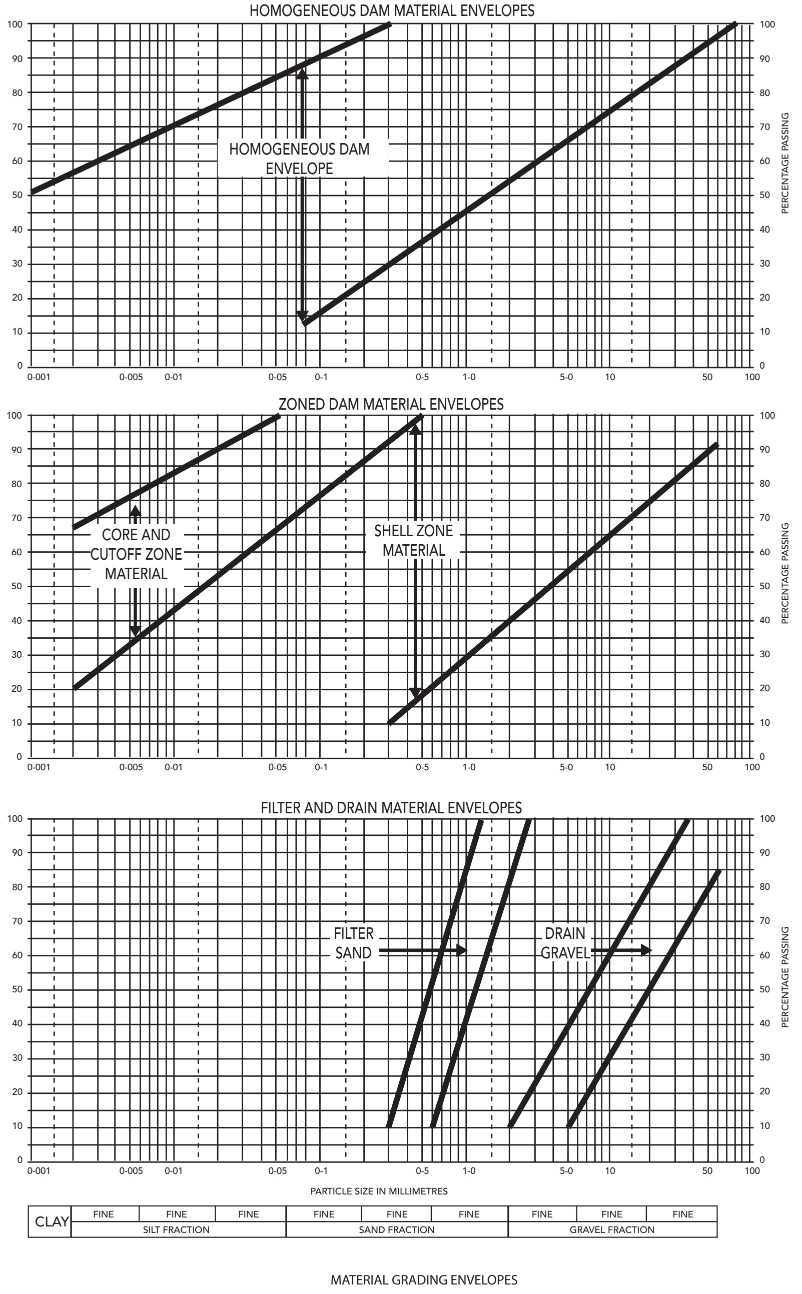
[7] British Standards are available on line from the BSI Group website or from other websites and booksellers.

Figure 5 - Material grading envelopes



5

Site selection and preliminary investigations

5 Site selection and preliminary investigations

5.1 INTRODUCTION

Although the selection of a suitable site is essentially a field exercise, the use of aerial photographs[8] and large-scale maps can provide a useful assessment of the local topography and hydrological conditions before any field visit takes place. This is especially important on larger sites and catchments where much field time can be saved by allowing the poorest sites to be excluded and a list of the more promising sites to be drawn up.

Once the aerial photography interpretation has been completed and possible sites identified, a field visit is essential. Use of an accurate global positioning system (GPS) at this stage can prove useful. If the site proves difficult it should not be considered unless other overriding reasons demand that the dam be located in a specific area – in all such cases competent engineering advice is needed before any further work is done. It is important to identify where the water to be stored is to be used: irrigation, for example, involves the conveyance of large quantities of water and, if the dam-site is a long distance away from the cultivated area, much expenditure on pipelines and pumping may be required. For large irrigable areas, large diameter and costly high pressure pipes may be required and it may prove more economic to choose a poorer, more expensive dam site close to the land involved than a better site further away.

Other factors, such as access, availability of materials, land tenure issues, environmental concerns, community needs, the distance to the nearest power source and inundation of roads, bridges, and buildings should all be considered at this stage so that costly investigation work is not wasted.

5.2 AERIAL PHOTOGRAPHY

The procedure for using aerial photography is as follows:

- ➔ Area boundaries must be identified and delineated.
- ➔ Irrigable areas, pasture and developed land must be marked to allow the best location of potential sites. Catchment areas – outlined from following hill crests and other features – are normally taken from maps as catchments may extend beyond the limits of available photography. If the photograph is becoming crowded with detail, non-essential details can be erased to aid easier interpretation.
- ➔ Stream lines should be drawn in and areas that appear to have flatter gradients should be more heavily marked. Dam sites on steep slopes are rarely economic as embankments give limited storage so, where steep slopes (i.e. over 4-5 percent) are seen on the photograph or the map, such areas should be given low priority.

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[8] 1:5 000 to 1:12 500 scale photos and 1:25 000 to 1:50 000 scale maps are most suitable for interpretation by eye and stereoscope. Satellite imagery to a suitable scale can also be considered.

A good dam site should have a catchment area that is not so big that an expensive spillway may be required but is also not so small that the yield from the reservoir is too low or erratic to be able to supply an economic area for any irrigation scheme.

Assessing the slope is difficult without a knowledge of the area and experience in aerial photography interpretation, so it may not prove feasible at this stage. Low gradients can be deduced from natural features such as meandering streams and ox-bow lakes, silt accumulations, swampy areas, right-angled tributary junctions and large-contour conservation and drainage spacings in nearby cultivated land Once streamlines have been marked in, and channel sections evaluated, the more favourable sites can be located.

Priorities can then be drawn up based upon the indications above and the following geographical points:

- ➔ Where one or more streams/tributaries meet the main channel, the site may offer maximum storage.
- ➔ A desirable site is one that is close to where the water is required or that can allow delivery by gravity flow, low pressure pipeline, or canal.
- ➔ Where narrow channel sections exist for the dam itself, and with wider reservoir areas immediately upstream, this would result in a short embankment and large storage capacity.
- ➔ Where rock bars are found either in the river (for weir sites or centre-spillway dams) and/or on the valley sides for safe spillways. They are virtually essential on larger catchment areas where grass spillways are not advised.
- ➔ Where sudden changes in streambed gradient (from flatter to steeper downstream) may indicate good storage potential and allow a free draining site to be chosen for the embankment.

Streambed gradients, and estimates of dam height and length, can be made from photographs using a parallax bar or from digital maps through appropriate software. Even for an experienced operator, revision of such estimates must be made in the field. The extent of the reservoir upstream of the dam (the throwback) can be assessed by eye from photos or, in the case of larger dams, from local topographic maps, but again this will require field confirmation.

5.3 FIELD VISITS

Once the sites have been located, a field visit to the area can be organized to allow the most suitable site to be chosen. There is no alternative to physically visiting each potential site, and any others that become apparent at the time, or can be sited by discussing the above factors with local people, as interpretation from the aerial photograph or map is only a tool for preliminary assessment. A rough reconnaissance of every site within the involved area including, if necessary, estimates of levels and gradients (a sufficiently accurate GPS or hand level will prove invaluable at this stage), with checks on spillways, borrow areas and foundation conditions, will allow the relative merits of each site to be assessed. The most favourable sites can then be determined and preliminary surveys carried out.

5.4 PRELIMINARY SURVEYS

The economic and design implications of each site can be determined from a brief preliminary survey, using a level/theodolite or accurate GPS equipment to take a line of spot heights across the profile (close to where the proposed embankment centre-line and spillway are estimated to be) and up the valley to provide indications of streambed gradient. The gradient is necessary to estimate the throwback of the dam and, for larger dams on flatter gradients, can often be estimated from contoured topographic maps of 1:50 000 scale.

For each site, the survey must be sufficiently accurate and detailed to enable comparative estimates to be made for various heights of dam. The most economic height is usually calculated on the basis of cost per unit volume of water. Comparison of the various alternative sites is then possible. More advice on surveying the site for later design work is given in Section 6.2.

5.5 CATCHMENT YIELD

The catchment yield, ‘Y’, is based on the expected annual runoff from a catchment and is an important factor in assessing the feasibility of a dam and in determining the required height of the embankment. The latter is important to allow the dam designer to size the dam to suit expected inflow and estimate the area that can be irrigated. It is estimated as follows:

- → Where the average percentage of runoff is not known, use, as a guide, a figure of 10 percent of the mean annual rainfall for the catchment area. If more information is known, take the rainfall on a return period of 1 in 10 years as a guideline.
- → Calculate the annual runoff for the catchment, in mm, based on the percentage determined above. This is ‘Rr’.
- → Measure[9] the catchment area ‘A’ in km^2, upstream of the proposed embankment. Ignore any upstream dams (as these may already be full at the time of a flood event – often at the end of a rainy season – and thus offer no retardation of any flood moving downstream) and calculate the area of the whole catchment.
- → The annual runoff for the catchment (the catchment yield in an average year), Y, in m3, is given by:

$$\mathbf{Y = Rr \times A \times 1\,000}$$

5.6 STORAGE CAPACITY

At this stage, this is worked out as follows:

$$Q = \frac{LTH'}{6}$$

Where:

Q is the storage capacity in m^3 and should not exceed Y above.

L is the length of the dam wall at full supply level (FSL) in m.

T is the throwback, in m and approximately in a straight line from the wall.

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[9] Use a planimeter for topographic maps or the appropriate computer software for digital maps derived from satellite imagery.

H’ is the maximum height of the dam, in m, at FSL.

6 is a factor (conservative generally) that can be adjusted (to 5 or 4) with experience and local knowledge.

All the above measurements can be determined by the use of a level or theodolite (or accurate GPS equipment) at the site, either in the form of a cross-section survey at the centre line of the proposed dam or, more accurately and more time consuming (but more useful where comparison of similar sites is involved), by a contour survey followed by a survey or estimate of the throwback.

The capacity estimated in this way is accurate to within about 20 percent, but it must be revised by a more detailed survey when the site has been approved for possible construction.

The formula considers the water volume to be an inverted pyramid with a triangular surface area (LT/2) and H’/3 for the height/depth, and is a simplification of reality. With experience, one is able to judge fairly accurately how an individual valley will compare with such an idealized picture and, therefore, to adjust the resulting conclusions.

5.7 PRELIMINARY VOLUME OF EARTHWORKS

The volume of earthwork can be estimated as follows:

$$V = 0.216\ HL\ (2C+HS)$$

Where:

V is the volume of earthworks in m^3.
H is the crest height (FSL+ freeboard) of the dam in m.
L is the length of the dam, at crest height H, in m (including spillway).
C is the crest width in m.
S is the combined slope value.
For example, if the slopes of the embankment are 1: 2 and 1:1.75, S = 3.75.

This formula is based on areal equations for the cross-section and longitudinal section with the inclusion of an empirically developed adjustment factor. Again, it presents an idealized solution and as for the capacity formula should only be used at the preliminary survey stage. The formula is, however, reasonably accurate and if a general average figure is known for costs of earthworks, a guide cost for the total embankment can be derived.

5.8 CATCHMENT AREA AND SPILLWAY DIMENSIONS

Accurate estimation of catchment area, either from an aerial photograph or a large-scale topographic map, is essential in the calculation of catchment yield and peak flood. For both, hydrological data (mainly rainfall and runoff), topographical factors and the shape of the catchment will be the main influences. The maximum design capacity of the reservoir is directly related to the catchment yield multiplied by a design factor that has usually been derived locally from the history of other dams. In the case where a series of small dams is built in a catchment, the size of the catchment area for each dam should be taken as the total catchment area above the dam under consideration, not only the area between it and the one above it. The dam designer has to assume that the peak flood will occur when all the dams above are full and therefore will not have significant retardation or retention effects on the flood – this is most important for designing the spillway to safely pass the peak flood.

Dams should not be sited on catchments so small that they are unlikely to fill in an average year, except very rarely where other considerations, such as the provision of essential water supplies, are to be taken into account.

Estimations of peak flood are required for spillway design, the dimensions and physical characteristics of which are extremely important. If a suitable spillway of sufficient size is not available at a particular site, or would prove too expensive, it is advisable to move on to a better alternative site where spillway conditions can be met. On larger catchments (i.e. greater than 5-8 km^2) and rivers of a flashy nature, rock spillways are virtually essential. Therefore, good solid rock of adequate width must be available for all but the smallest dams and, as a very rough guide at this stage and subject to re-assessment at the detailed design stage, a minimum width of 15 m at 1.5 m freeboard for a dam on a catchment of around 5 km^2 may prove suitable. However, advice from local engineers and experienced local people should be sought if hydrological data and/or design charts are not available.

It is probable that more earth dams in southern and western African suffer problems through poor spillway design than for any other reason. If there is insufficient rock, the site should not be used for a dam.

Grass spillways, whether cut or natural, are really only suited to small catchments (i.e. up to 5 km^2) and low velocity flows (certainly below 1 m/s[10]) and even then may require continual maintenance throughout the life of the dam to prevent erosion from becoming too serious a problem. The ability of vegetation or soil to resist erosion is limited and maintenance of an even surface and uniform cover is very important. The stability of the channel as a whole will depend upon the stability of the most sparsely covered section and it is therefore wise to establish a good creeping grass cover throughout.

The grass cover condition will directly affect the channel's roughness coefficient, which will in turn depend upon flow. A low flow will meet high resistance while a high flow will flatten the grass and thus meet much lower resistance. Maximum allowable non-erosive velocities are highest in grass spillways that have been planted to shorter creeping varieties such as kikuyu, couch and star grasses. These can establish a uniform low cover offering minimum resistance to flow and maximum protection to the soil beneath.

However, where even normal flows are expected to constitute an erosion risk (i.e. if flow is expected to continue during the dry season and/or over a period of several months or more) a drop-inlet overflow spillway should be planned for and located at the opposite end of the embankment to the main spillway and at an elevation on the upstream side of the dam slightly lower (usually 50-100 mm) than full supply level.

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[10] Table 4 in Section 6.

Spillway design dimensions are linked to the size and the character of the catchment. A catchment with rocky or steep surfaces (and thus high runoff) of the same area will have higher peak floods than a catchment within the same climatological zone with flatter, well-vegetated slopes. Similarly, a long narrow catchment will have a greater time of concentration of flood water after a rainstorm than a broad catchment with the same characteristics and therefore produce lower peak floods from the same area.

5.9 PEAK FLOODS

The peak flood is the probable maximum flood (PMF) to be expected from a catchment following a rainfall of estimated intensity and duration for a selected return period[11] taking into account the hydrological characteristics of the catchment. In many parts of the world information is not available or smaller streams are not gauged to allow estimation of such floods for spillway design purposes. On bigger dams and catchments, where it is more important that the spillway is correctly and properly dimensioned, it is economic to study the hydrology, climate, topography and so on to arrive at reasonably accurate estimates of PMFs. However, for smaller dams and catchments, unless this information is already available, the engineer can rarely justify the cost of such an exercise and must resort to other means to safely estimate the PMF.

Where the designer cannot use a hydrologist, or detailed hydrological information is unavailable, the **Rational Method** – based on catchment area and an assumed uniform rainfall intensity and runoff – is a useful tool for the estimation of peak floods on small catchments. For this manual it is assumed that the Rational Method will be used for most cases.

The Rational Method is most appropriate for catchments under 15 km^2 and requires the engineer to know the catchment area and the maximum daily rainfall. Other factors such as topography (especially the slope), the shape of the catchment and the vegetation cover may also require consideration. These are generally taken into account in the calculation of the 'Time of concentration'.

Where other structures already exist in the catchment, ignore any flood reduction effects they may have as, in many countries, the maximum probable flood will occur at the end of the rainy season when all storage areas, natural or otherwise, are at full capacity and they will, therefore, have little effect in ameliorating runoff and retaining flood water.

5.10 CALCULATING THE PMF USING THE RATIONAL METHOD

The procedure to follow in calculating the probable maximum flood using the Rational Method is:

1. Locate the dam or new site on the appropriate topographic map (1:50 000 scale is normally suitable for all but the smallest catchments) and draw on the catchment boundary upstream of the embankment centre-line. Using a planimeter measure the catchment area, 'A', in km^2.
2. Using a linear measuring wheel or similar device, measure the 'actual length, L', of the main river/stream, upstream of the site and to the main river source, in km.
3. Estimate the elevation difference, 'h', in m, between the dam site and the

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[11] Usually 1 in 20, 25 or 50 years for small dams but it can be as high as 1 in 1 000 years for larger dams. In the case of Kariba dam, the spillway is designed for a 1 in 10 000 PMF.

main stream at its source. A contour map is essential for this and some extrapolation may be required where contour intervals are large.

4. Determine the time of concentration, 'Tc', in hours, using the formula:

$$\mathbf{Tc = (0.87\ L^3/h)^{0.385}}$$

5. From rainfall records or a rainfall distribution map, estimate the mean annual rainfall for the catchment. Using a graph similar to **Figure 6a**, estimate the one day storm rainfall, 'P', for the selected return period[12]. Use 1:20 to 1:25 year return periods for smaller catchments and 1:50 year return periods for larger dams, larger catchments or dams where safety issues are more important (i.e. near populated areas).
6. Derive the storm depth ratio, 'R', from the graph in **Figure 6b** and using the Tc determined above.
7. Calculate the extreme height channel slope as a percentage [100 h/(1 000 litres)] and estimate a runoff coefficient, "Cr", for the assumed return period using the graph in **Figure 6c**. If runoff is known to be excessive, such as on bare, eroded slopes, the runoff coefficient can be increased by up to 20 percent.
8. Determine the probable maximum flood (PMF), 'Qp', in m^3/s, using:

$$\mathbf{Qp = 0.278\ A\ P\ R\ Cr/Tc}$$

Where no other data are available and figures such as 6a to 6b cannot be drafted, a very approximate peak flood estimate can be made by taking the highest daily rainfall figure for the catchment and assuming that all dams in the same catchment are 100 percent full, the ground is saturated and that 100 percent runoff will occur. For example, if a rainfall of 223 mm fell on a catchment area of 19 km^2, the estimated peak flood would be in the region of 49 m^3/s over a 24 h period. Always stay on the conservative side when using approximations or estimates for peak floods; 2-4 m^3/s per km^2 of catchment area per 24 h period is a guide but this figure should always be adapted bearing in mind local topographic and climatic conditions.

In Zimbabwe, the appropriate government departments, using accumulated meteorological and hydrological data, provide dam designers with charts to estimate spillway dimensions on small dams up to 14 m high on catchments up to 120 km^2 in area and formulae and tables for medium dams on larger catchment[13] areas. The Ministry of Agriculture, in conjunction with its field staff and engineers and the Water Court, control the building of smaller, farm-type dams in Zimbabwe and the charts are provided to farmers and agricultural extension workers to allow the calculation of dimensions of most spillways with a good factor of safety. The procedure for using the charts is straightforward and they can prove an invaluable tool to the dam designer – engineer in that area, although in most cases they are used with some modification based on local knowledge and experience.

The charts are based upon data and formulae tailored for central and southern African climates and topography. In Zimbabwe (and Zambia), the rainfall intensity and duration is that expected in a subtropical, rainy-dry season climate with total precipitation rates varying between 450 and 850 mm and falling during the five or six cooler months of the year.

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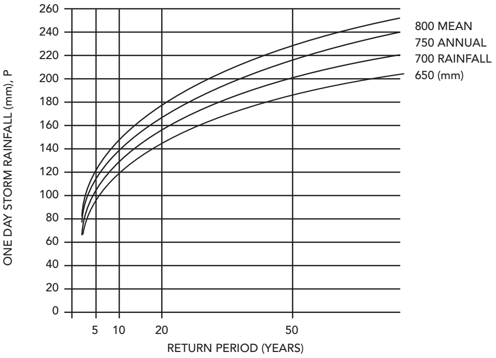
[12] The return period is the flood recurrence interval for a selected discharge in a stream or river.

[13] For larger more complex dams on larger catchments, the Ministry of Water Development produces probable maximum flood tables based on a range of return periods from 1 in 25 to 1 in 10 000 years plus other information to safely and accurately size spillways.

For climates with less intensive rainfalls such as lower, coastal African locations and some North American and Australian environments, the peak floods would be lower and the spillways that much smaller.

Figure 6a - One day storm rainfall



DETERMINE MEAN ANNUAL RAINFALL FOR LOCATION OF DAM. THIS EXAMPLE FOR SWAZILAND (LOW VELD AREA).

Figure 6b - Storm depth ratio

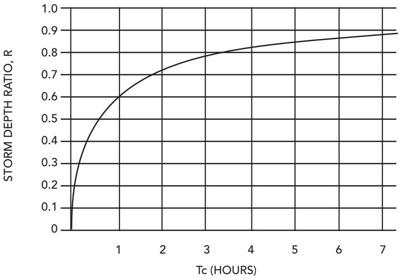
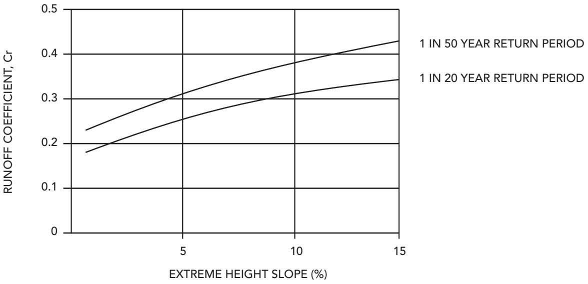


Figure 6c - Runoff coefficient



Where data are available, it would not be difficult to draw up similar charts or tables and once peak floods are determined, the hydraulic parameters for estimating spillway widths and depths are available.

In all cases, however, such charts and tables are by their nature generalized and should always be used with caution and, wherever possible, be adapted to suit local conditions.

Once the PMF has been estimated, the spillway width can be calculated using the formula:

$$\mathbf{Qp = 1.7\ b\ D^{1.5}}$$

where b and D are in m and Qp is in m^3/s

'1.7' is a factor derived for concrete ogee type crests and can vary up to 2.25 according to site conditions and factors of safety. 1.7 is generally used for spillways for small dams on small catchments.

'b' is the minimum width ('breadth') of the spillway and is calculated by introducing the values for Qp (estimated using the options above) and $D^{1.5}$. It is assumed that b is large when compared to D and that the spillway channel will thus be rectangular.

'D' is the depth of the spillway at the crest and will comprise all or part of the design freeboard. D is normally in the range 0.75 m to 1.5 m for small dams and comprises the total freeboard. However, where wave action or backing up of floods may affect the dam, an additional 'dry' freeboard of up to 0.75 m. should be added to the figure above for safety reasons.

Once all the other values are known, 'b' can then be calculated and the best option for varying depths, 'D', can be chosen.

The width 'b' is the minimum width for the spillway to accommodate the design flood. It assumes that there is no constriction downstream of the spillway. The width and depth may have to be adjusted to suit the local topography and spillway bed material later in the design process.

5.11 ESTIMATES OF STORAGE REQUIRED

At this time, it is wise to better assess the economic amount of water required from the dam.

This will, for irrigation dams, comprise irrigation requirement, other uses (livestock/domestic water), losses to seepage and evaporation and dead storage.

- Irrigation requirement can be calculated by multiplying the gross annual irrigation requirement per hectare by the area proposed. This may have to be adjusted once the estimated storage for the dam chosen is calculated.
- Environmental flows to release normal flows into the river or to comply with any legal requirements downstream.
- Other uses such as livestock water can be calculated by estimating water use for this. FAO can provide advice as well as locally based government and other organizations. As a guideline the following (assuming the animals are on dry pastures and good quality water is available) can be used:

– Cattle	40-80 litres/day for each animal (milking cows may need 100 litres/day).
– Young stock	25-50 litres/day.
– Pigs	25 litres/day.
– Poultry	30 litres/day per 100 adult birds.
– Bee hive	2 litres/day.
– Sheep	2-6 litres/day.
– Goats	3-8 litres/day.

– Camels	30-40 litres/day.
– Horses	40-50 litres/day.

Add 10 percent to any calculated total for water use by wild and feral animals and add a further 10 percent if the water is higher in salt content than recommended. Slightly saline waters can be tolerated by animals (but pigs and poultry are most sensitive) but they will have higher intakes to allow a greater water turnover to regulate body salt balances.

- ➔ Troughs are always recommended. Dams should be fenced off and no livestock allowed to drink directly from the reservoir or to damage the surroundings to the dam by overgrazing the catchment, tracking in the immediate surrounds of the reservoir and wallowing in the reservoir itself.
- ➔ Domestic water uses – opting for piped water supplies using filters or similar – can be calculated by determining the likely numbers of people who will use the dam for water and estimating total annual or dry season needs. A minimum of 20-50 litres/day per person in more rural areas can be used if piped water supplies are not to be provided but consideration for increases in use should be made in areas where populations are high and levels of urbanization may increase.
- ➔ Seepage losses are always difficult to estimate before the dam is built and to calculate after the dam has been constructed. As all dams will seep, it is best to estimate that a well constructed embankment will lose about 10 percent of its water to seepage in any one year.
- ➔ Evaporation losses can be calculated from local records noting that shallow large surface area reservoirs will have higher evaporation rates than narrow deep reservoirs. Wind is also an important factor in dry areas. Annual rates of evaporation from dams in Africa can exceed 30 percent but for calculating water uses (i.e. for irrigation), where actual figures are not known, dry season losses can be taken as 20 percent maximum.
- ➔ Dead storage is the amount of water retained in the dam that cannot be accessed. The dead storage will vary according to design, pumping suction heads and positions of any outlets in the embankment. It will also be more, proportionally, for a small dam than a larger dam and will offer an area in all dams for sediment to accumulate. For design purposes, a figure of 5 percent maximum of the total water stored can be used to estimate dead storage.

Once the above has been estimated the remaining amount available for irrigation can be calculated. It is at this stage the areas proposed under irrigation can be adjusted and any economic analysis made.