Appendix E - SOILS - CLASSIFICATION, TESTING AND SUITABILITY

E.1 Introduction

Soil holds water in most farm dams and makes up the construction material for embankments. Therefore the ability to identify various soil types for their engineering properties is crucial. This is carried out through on-site soil testing as well as through laboratory testing of the samples collected.

E.2 Soil Properties

The important properties of soils used in farm dams are strength, hydraulic conductivity (or permeability), compressibility, and interaction with water. Compaction has an effect on all of these properties.

Compressive strength to support the weight of the dam and water, and shear strength to resist the force of the water tending to slide the embankment downstream are the obvious requirements. The tendency of fill material in steeply sloping batters to slide downhill is also resisted by shear strength. The strength of soils has two components, cohesion and friction.

Cohesion arises from the physical (and chemical) properties of clay. At the correct moisture content, clay particles stick together and require force to separate them. This does not occur with separated and extremely dry particles, and may also disappear when the clay is fully saturated with water. It depends on the particles being close together and thus on the state of compaction of the soil.

Friction occurs between all types of soil particles and depends on their shape and type of material. It is similar to all other forms of friction in that the strength developed depends on the load applied at right angles to the contact and therefore reduces the load at right angles to the contact. Water pressure in the spaces between the particles reduces the

load at right angles to the contact and therefore reduces the friction strength. Friction strength also depends on contact between the particles and is thus affected by the state of compaction of the soils.
Practical dam building materials range from clays through sandy clays, to sand and gravel use for free draining parts of the dam. Clays have relatively low friction strength and high cohesion at normal moisture contents. Their low cohesion when saturated makes the use of fairly flat batters necessary. Sandy clay materials have a useful combination of high friction-strength and some cohesion, and may be used on steeper slopes because they retain at least their friction strength when saturated.

E.2.1 Soil Permeability

Hydraulic conductivity or permeability is usually expressed as K, indicating the relative ease with which a fluid can move through the material.

K is defined by the Darcy equation

$$K = \frac{Q}{I\,A} \qquad \text{cm / s or m / day}$$

where Q = quantity of flow per unit time
A = area of material normal to the flow direction
I = hydraulic gradient (head loss per unit distance) in the flow direction

In most of the materials normally encountered, the rate of flow is directly proportional to the hydraulic gradient as indicated by the equation, but this may not be so in extremely permeable material with larger voids.

Values of K vary from about 100 cm / s (86,400 m / day) for gravels through about 0.01 cm / s (8.64 m / day) for some fine sands to as low as 10^{-9} (0.000008 m / day) for extremely impermeable clays.

Values of around 10^{-6} cm / s or about 0.01 m / day should be satisfactory in farm dams depending on the hydraulic gradient conditions and the water losses that can be tolerated. Most clay soils can achieve this if well compacted, and may achieve it easily.

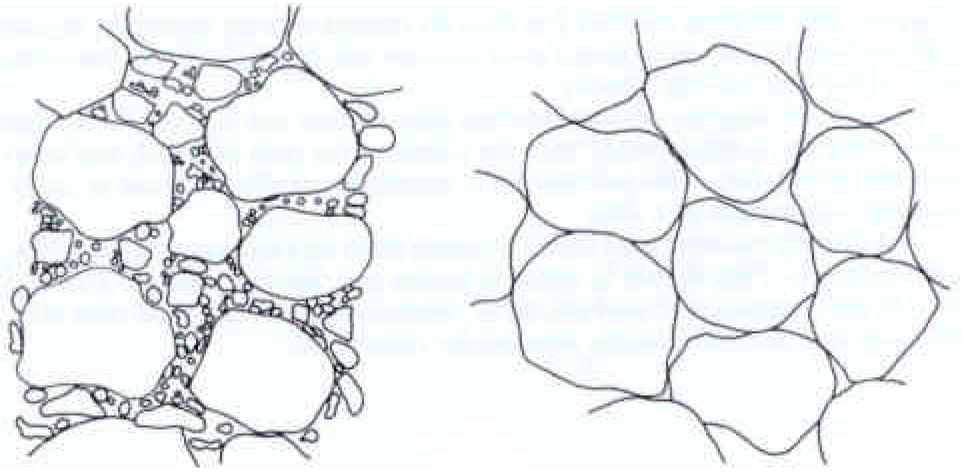
Measurement of permeability, particularly of low permeability clays, is difficult and time consuming. Laboratory measurement is done on prepared samples and directly measures the water flow at either a constant head loss or a recorded falling head loss. However, laboratory measurement on remoulded samples often does not reflect in-situ permeability.

Field measurement is done by measuring the rate of flow into a hole (in saturated materials) or out of a hole (in dry materials). The latter case often applies in Queensland and is unfortunately less reliable than the former. The results are likely to be under rather than overestimates of the true value.

In any dam embankment, but especially in larger ones, it is desirable to have a high permeability in the downstream zone of the wall, allied with a low permeability zone further upstream. This is to ensure that the water that could seep through the low permeability material can drain away without reducing the strength and stability of the downstream part of the wall, especially if the water in the dam is likely to be reduced quickly (rapid drawdown) so that the excess water in the material drains back to the storage. This design method is discussed in the Chapter 4.

E.2.2 Unified Soil Classification System

In terms of their engineering properties, soils are classified under the Unified Soil Classification System (USCS). The system is fully described in AS 1726-1993 (Geotechnical site investigations). Soil types are assigned a symbol: gravels (G), sands (S), silts (M), clays (C), organic soils (O) and peats (Pt). Sands and gravels are subdivided into well graded (W) and poorly graded (P). Well-graded sands and gravels have a favourable spread of particle size with a good representation of all particle sizes from the largest to the smallest. Poorly graded is to have an unbalanced particle size distribution or an altogether uniform grade.



Well-graded (W) Poorly-graded (P)

FIGURE E-1 - GRADATION OF SOILS

Silts and clays are subdivided into those with high (H) or low (L) liquid limits. The liquid limit is the moisture content at which the silt or clay becomes a slurry. This is determined by the Atterberg test. At a water content over 50 per cent of the dry weight, the silt or clay is considered to have a high liquid limit and a low liquid limit at percentages below 50. Plastic limit is the moisture content at which a soil looses its plasticity and crumbles. This is determined by rolling the material (at different moisture contents) into 3 mm ‘pencils’.

Table E-1 displays the complete Unified Soils Classification System. Table E-2 shows typical engineering properties for each of the different soil type classifications. Table E-3 shows the suitability of different materials for earth dams. This table, taken from US texts on large earth dams, indicates that a GC (clayey gravel) is the preferred material for a dam. It is rare to use this material in a farm dam in Queensland. The most common soils are SC, CL and CH (i.e. good clays).

TABLE E-1 – UNIFIED SOIL CLASSIFICATION SYSTEM

Group symbol	Description
GW	Well graded gravels
GP	Poorly graded gravels
GM	Silty gravels
GC	Clayey gravels
SW	Well graded sands
SP	Poorly graded sands
SM	Silty sands
SC	Clayey sands
ML	Inorganic silts with low liquid limits
CL	Inorganic clays with low liquid limits
OL	Organic silts with low liquid limits
MH	Inorganic silts with high liquid limits
CH	Inorganic clays with high liquid limits
OH	Organic clays with high liquid limits
Pt	Peat and highly organic soils

PHOTOGRAPH E-1 – ROLLING CLAY TO DETERMINE PLASTIC LIMIT

TABLE E-2 – ENGINEERING PROPERTIES OF EARTH DAM MATERIALS

Soil Class Group	Proctor Compaction		Permeability, k (m/day)	Compressibility		Shear Strength		
	Maximum Dry Density (t/m^3)	Optimum Water Content (%)		At 140 kPa (%)	At 350 kPa (%)	C_o (kPa)	C_{sat} (kPa)	Tan ϕ
GW	1.91	13.3	23 ± 11	1.4	*	*	*	0.79
GP	1.76	12.4	53 ± 28	0.8	*	*	*	1.74
GM	1.83	14.5	0.00025	1.2	3.0	*	*	0.67
GC	1.84	14.7	0.00025	1.2	2.4	*	*	0.60
SW	1.91 ± 008	13.3 ± 2.5	*	1.4 +	*	39.3 ± 4.1	*	0.79 ± 0.02
SP	1.76 ± 003	12.4 ± 1.0	0.0125	0.8 ± 0.3	*	22.8 ± 6.2	*	0.74 ± 0.02
SM	1.83 ± 002	14.5 ± 0.4	0.0063 ± 0.0040	1.2 ±0.1	3.0 ± 0.4	51.1 ± 6.2	20.0 ± 6.9	0.67 ± 0.02
SC	1.84 ± 002	14.7 ± 0.4	0.00025 ±0.00017	1.2 ± 0.2	2.4 ± 0.5	75.1 ± 15.2	11.0 ± 6.2	0.60 ± 0.07
ML	1.66 ± 002	19.2 ± 0.7	0.00049 ± 0.00019	1.5 ±0.2	2.6 ± 0.0	66.9 ± 10.3	9.0 (approx)	0.62 ± 0.04
CL	1.73 ± 002	17.3 ± 0.3	0.00007 ± 0.00025	1.4 ± 0.2	2.6 ± 0.4	87.0 ± 10.3	13.1 ± 2.1	0.54 ± 0.04
OL	*	*	*	*	*	*	*	*
MH	1.31 ± 006	36.3 ± 3.2	0.00013 ± 0.00008	2.0 ±1.2	3.8 ± 0.8	72.4 ± 29.7	20.0 ± 9.0	0.47 ± 0.05
CH	1.51 ± 003	25.5 ± 1.2	0.00004 ± 0.0004	2.6 ± 1.3	3.9 ± 1.5	102.8 ± 33.8	11.0 ± 5.9	0.35 ± 0.09
OH	*	*	*	*	*	*	*	*

Notes:

(a) * denotes insufficient data available:

(b) values given are averages and ± shows the 90% confidence limits of the averages of groups of samples

TABLE E-3 – SUITABILITY OF MATERIALS FOR EARTH DAM EMBANKMENTS

Group Symbols	Important Properties				Relative Desirability		
					Rolled Earth Dam		
	Permeability when Compacted	Shearing Strength when Compacted and Saturated	Compressibility when Compacted and Saturated	Workability as a Construction Material	Homogenous Embankment	Core	Shell
GW	Pervious	Excellent	Negligible	Excellent	-	-	1
GP	Very Pervious	Good	Negligible	Good	-	-	2
GM	Semi Pervious to impervious	Good	Negligible	Good	5	5	-
GC	Impervious	Good to Fair	Very Low	Good	1	1	-
SW	Pervious	Excellent	Negligible	Excellent	-	-	3 if gravelly
SP	Pervious	Good	Very Low	Fair	-	-	4 if gravelly
SM	Semi pervious to impervious	Good	Low	Fair	6	6	-
SC	Impervious	Good to Fair	Low	Good	2	2	-
ML	Semi pervious to impervious	Fair	Medium	Fair	7	7	-
CL	Impervious	Fair	Medium	Good to Fair	3	3	-
OL	Semi pervious to impervious	Poor	Medium	Fair	8	8	-
MH	Semi pervious to impervious	Fair to Poor	High	Poor	9	9	-
CH	Impervious	Poor	High	Poor	4	4	-
OH	Impervious	Poor	High	Poor	10	10	-

E.2.3 Soil Dispersion

Dispersive clays are those soils that disperse in the presence of water. These dispersive clays are also the soils that are readily erodible under the effects of rainfall or flowing water. In a water-retaining embankment, dispersive clays may cause a piping failure, which is defined as an open pipe or hole extending from the stored water though to the toe on the downstream slope. Photograph E-2 shows piping failure of a poorly-compacted embankment built from dispersive clays.

PHOTOGRAPH E-2 – DAM FAILURE DUE TO DISPERSION

Uniform or homogenous earth dams are especially susceptible to failure by piping. The typical piping failure typically starts with a very small initial leak. This is probably located at a narrow crack in one of the layers in the dam. A less likely cause with proper construction control is for the water to follow a path around loose hard clods in a dry dusty matrix. In some instances, foundation weaknesses not removed by stripping have been considered as the starting points for piping failures.

Determination of a soil's dispersive capability is therefore a crucial part of the site inspection. Dispersive soils have a high percentage of sodium in the clay fraction, which breaks down to form a suspension in water. These soils are common throughout Queensland and are marked by deep erosion gullies that are larger than expected given their catchment areas. Other indications of dispersive soils are eroded embankments with "rabbit warren" tunnels or other embankments that have failed by piping.

The Emerson Aggregate Test (AS 1289.3.8.1 1997) is a simple procedure for testing soil dispersion. The process is as follows:

- Place five air-dried soil crumbs, each about 5 mm diameter, in a squat beaker or glass jar containing 100 millilitres of demineralised water. Add the soil to the water, not the water to the soil.
- Allow to stand without shaking for at least one hour.
- Note the turbidity of the solution. If the solution is clear, the soil is non-dispersive and should be expected to provide little trouble assuming adequate compaction.
- Examine the interface between the crumb and the water. If there is a cloud, it is indicative of a dispersive soil. Any degree of dispersion should be treated with caution.

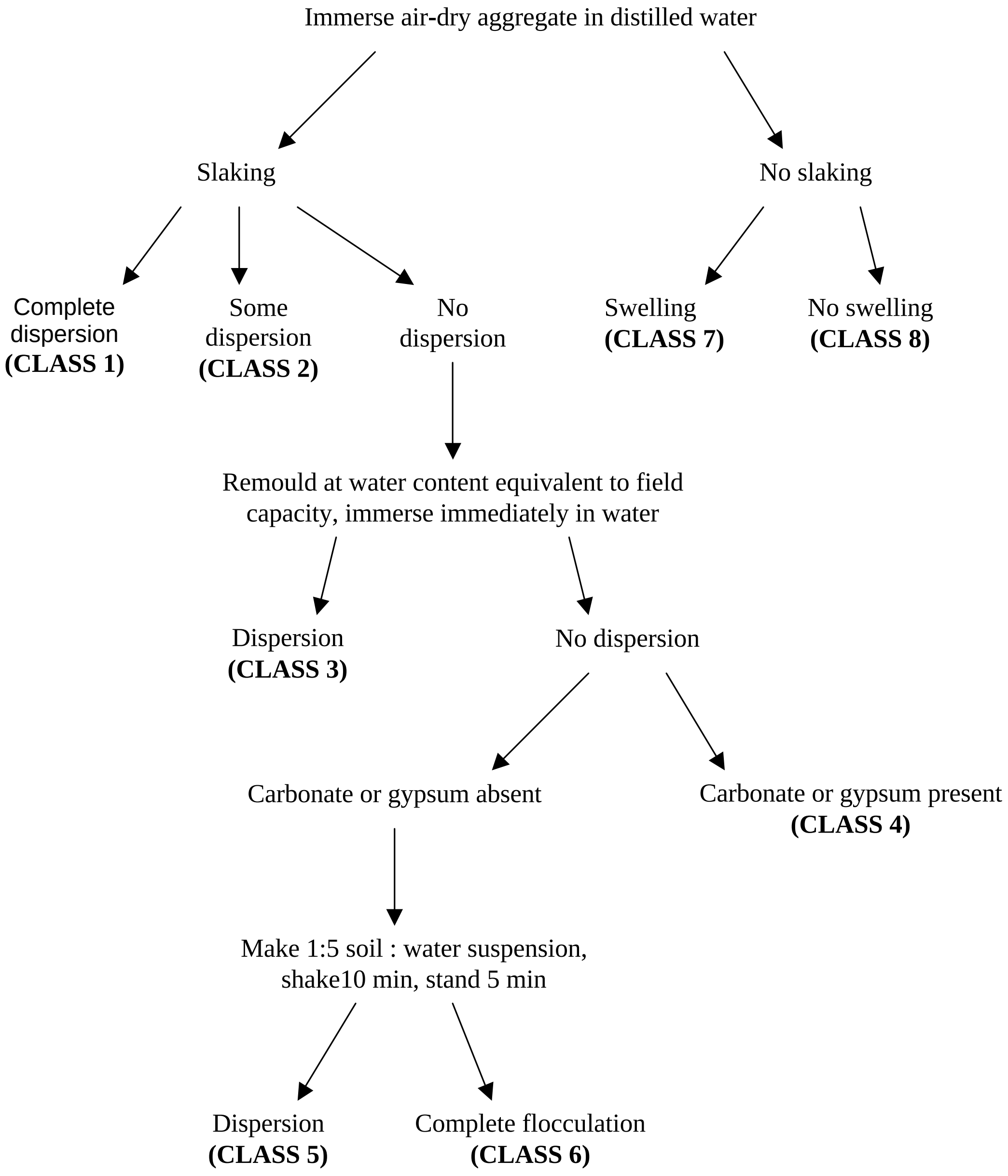


FIGURE E-2 - DETERMINATION OF EMERSON CLASS (ADAPTED FROM AS 1289.3.8.1 -1997)

Soils with an Emerson Class of 1 or 2 should be regarded as very suspect. Good moisture control and compaction is required to use these materials in an embankment.

Class 1 Class2 Class 3

Class 4 Class 5 Class 6 Class 7

Class 8

PHOTOGRAPH E-3 – EMERSON TESTS FOR DISPERSION

Photograph E-3 shows a range of Emerson Classes. When doing the test, there is a degree of subjectivity in determining the distinction between classes. A distinction between slaking (mechanical breakdown of clods) and dispersion needs to be noted.

Severe erosion gullies around the site might be indicative of dispersive soils, but might only indicate rapidly slaking soils. Local knowledge is important, for if the size of a gully is out of proportion to what would normally be expected, the cause could be due to erosion of dispersive soils. Local knowledge will also indicate whether dams in the area fail frequently. While such failures are usually due to poor design or construction, they are usually an indication that poor (dispersive) soils persist in the area. The shape of the erosion of a particular layer can indicate the occurrence of a dispersive soil. Normally, it would be wise to avoid a site where active erosion gullies exist. Sink-hole formations and the occurrence of natural tunnels in the soil profile also indicate dispersive soils.

E.2.4 Soil Compaction

Compaction has an enormous effect on permeability, and this effect is the main reason for compacting materials in earth dams.

The value of permeability depends on the total area of voids between soil particles for water to pass through and depends inversely on the size of the voids. Sands have a higher permeability than clays because they have larger void spaces, even though the clay may have a greater total void space.

Uncompacted clays have more void space. If the clay is in the form of strong clods when placed, the voids may be very large (as large as for coarse sand or gravel) and the initial permeability will be very high. This is the usual reason for piping or tunnelling failure of dams, associated with dispersive soils.

If the uncompacted clay has time to become wet when the water enters, it may soften, collapse, or swell thus blocking the large voids and the final permeability will become quite low. This is probably the reason why so many uncompacted dams with non-dispersive soils are successful. This experience tends to convince inexperienced earthmoving contractors that they can build cheap dams on any site.

If the final value of permeability is still fairly high, then there will be noticeable seepage, and the downstream batter may become saturated. If this happens, partial or complete failure of the slope may occur.

Compaction of clay materials removes the risks associated with high permeability.

Low permeability material can be used throughout the wall. It usually requires flatter batter slopes and thus extra earthworks. If the permeability is so low that the rate of water movement is always less than the evaporation loss from the downstream batter, then steep downstream batters may be quite successful. This is probably the case with many heavy clay soils.

It is desirable to achieve maximum compaction for dams. This is equivalent to obtaining a maximum dry density of the soil. The maximum dry density can be obtained at an optimum moisture content for each type of soil. This optimum moisture content can be determined using the **Proctor Test**, which is a standardized method. The Proctor test comprises two levels of compaction. These are **standard** compaction (AS 1289.5.1.1 –1993) and **modified** compaction (AS 1289.5.2.1 –1993).

The method for each is similar, varying only in the compactive effort used. The method is as follows:

(i) obtain sufficient soil (approx. 12.5 kg) to give five or more representative samples of the soil

(ii) thoroughly mix each of the samples with a suitable amount of water. The quantities of water should be selected so that the optimum moisture content (O.M.C.) is straddled and the moisture steps are not excessive for the soil type. The steps for clay soil are approximately 3%;

(iii) allow the wetted soil portions to cure for an adequate time. Sands may be satisfactorily cured in several hours but heavy clays may require at least a week;

(iv) weigh and assemble the mould;

(v) take one portion of the wetted soil, mix it thoroughly and compact it into the mould in 3 layers (5 layers for modified compaction) not varying in compacted thickness by more than 5 mm. For standard compaction, compact each layer by 25 uniformly distributed blows of a 2.7 kg rammer falling freely from a height of 300 mm. For modified compaction, compact each layer by 25 uniformly distributed blows of 450 mm. Use only sufficient soil to slightly overfill the mould leaving not more than 5 mm to be struck off after removing the top collar;

PHOTOGRAPH E-4 – UNDERTAKING COMPACTION TEST IN LABORATORY

(vi) carefully remove the top collar;

(vii) level the compacted soil to the top of the mould;

(viii) weigh the mould plus compacted soil

(ix) remove the soil from the mould and obtain a representative sample. Determine the moisture content of this sample;

(x) calculate the density of the wet soil as:

$$\rho = \frac{\text{mass of wet soil}}{\text{volume of container}}$$

$$= \frac{M2 - M1}{V}$$

where M2 = mass of mould, base plate and wet soil
M1 = mass of mould and baseplate
V = internal volume of the mould

(xi) calculate the density of dry soil (dry density) as:

$$\rho d = \frac{\text{mass of dry soil}}{\text{volume of container}}$$

$$= \frac{\rho \text{ x } 100}{100 + w}$$

where ρ = density of wet soil
w = moisture content of soil expressed as a percentage on a dry basis

(xii) plot the dry densities for each compacted sample against their corresponding moisture content. Draw a smooth curve through these points and determine the maximum dry density and O.M.C.

Figure E-3 shows examples of Proctor curves determined using the standard compaction method for a range of Darling Downs soils. It is clear that each soil type used has a different maximum dry density and optimum moisture content. Due to their inherent large void space volumes, clays have a lower dry density and a higher optimum moisture content. Figure E-3 also shows that compaction in some soil types is more sensitive to moisture content (e.g. red laterite) than others.

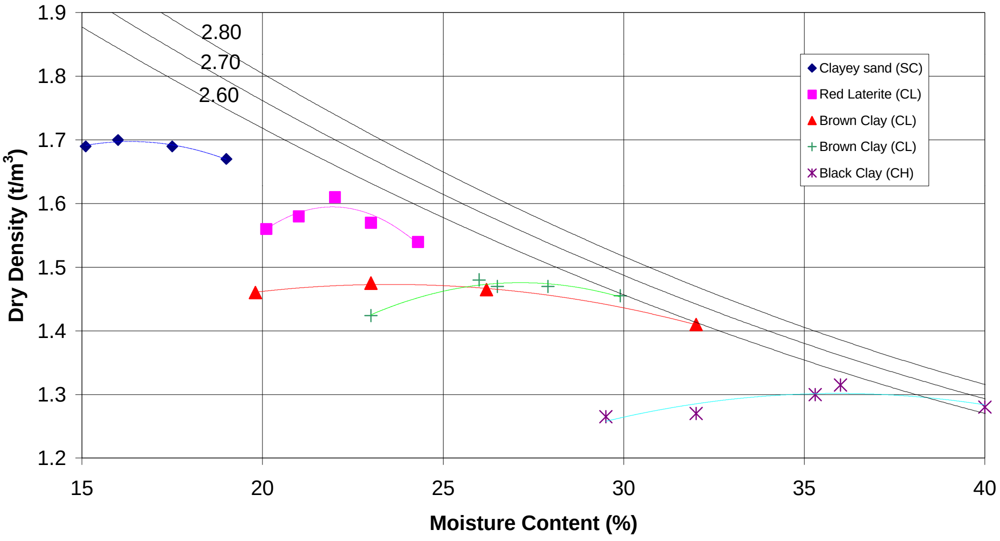


FIGURE E-3 – STANDARD COMPACTION FOR VARIOUS DARLING DOWNS SOILS

Table E-4 shows the optimum moisture content for the maximum dry densities of each soil shown in Figure E-3. This data is similar to the US data presented in Table E-2.

TABLE E-4 – SUMMARY OF FIGURE E-3 DATA

Soil Type	Optimum Moisture Content on a dry basis (%)	Maximum Dry Density (t/m^3)
Clayey Sand (SC)	16.0	1.70
Red Laterite (CL)	22.0	1.61
Brown Clay (CL)	23.0	1.48
Brown Clay (CL)	26.0	1.47
Black Clay (CH)	35.5	1.30

E.3 Initial On-Site Soil Investigations

When assessing a potential farm dam site, there are different aspects of the soils that need to be considered.

E.3.1 Foundations

Embankment foundations must be capable of supporting the embankment weight without any substantial settlement and must be sufficiently impervious to prevent excess seepage beneath the dam. Sites that have springs, soaks or landslip areas should be avoided because they signify unstable soil conditions and the likelihood of seepage losses. Boulders and rock outcroppings are also to be avoided since they are difficult to work around and make it difficult to form a tight “key” with the embankment. The four materials can be encountered in embankment foundations are rock, clay, and sand and gravel.

If a rock foundation is being considered, farmers are strongly advised to contact a consulting engineer. Rock foundations can present complications such as seepage along the seam of the rock foundation and the embankment, weathering of the rock causing weakness and the creation of permeable zones in open joints, faults and bedding planes.

Clay foundations are common and acceptable when they are of similar material to that placed in the bank. Inorganic clays are generally strong enough to support large dams of 8 metres in height. If the clay is malleable and saturated, it may be necessary to remove them or add stabilizing fills.

Gravel and sand sites are better avoided due to high seepage losses. Construction is also costly.

E.3.2 Permeability Testing

Sands and gravels are permeable and are highly prone to seepage. Rocks can also be permeable. Some dams have failed due to sinkholes, which have developed in the underlying rock, usually limestone. Permeability tests in the bed of storage can be conducted to identify pervious soils and therefore the potential for seepage losses. The procedure is as follows:

- Prepare three or four test holes with a 100 millimetre diameter and 3 metre depth
- Pre-soak each hole to a 2 metre depth (1 metre below the ground surface) for a minimum of one hour prior to starting the test
- Maintain each hole at this 2 metre level by adding water and record the amount required to do so.
- Continue this test for one day.

If the amount of water added exceeds 500 millilitres per minutes (30 litres per hour), the site is too permeable to accommodate a dam. If the rate falls between 500 and 50 millilitres, then the site is doubtful and should only be accepted on professional advice. Rates below 50 millilitres per minute should be suitable.

E.3.3 Adequate Embankment Material

When assessing a site for an embankment, it is necessary to determine that there is an adequate volume of suitable material available to construct the proposed embankment. Preferably, this material should be excavated from a borrow pit within the proposed storage area as this improves the S:E ratio.

E.3.4 Test Pit Protocol

Test pits are important for two reasons. Firstly, to ascertain information about foundations and seepage under the embankment in order to determine the necessary depth of the cut-off trench. Secondly, to determine locations of sufficient suitable embankment construction material, preferably within the storage area to improve the S:E ratio.

Soil maps can be used to plan site investigations before going on-site. These maps can indicate the type of soil that might be encountered and the possible number of different soil types.

Test pits are generally positioned under the expected embankment alignment. This information is used to determine required cut-off depths. Permeability tests in the bed of storage should also be examined as discussed above. The number of test pits depends on the size of the site and site variability. However, as a guide, position test pits at the extremities of the alignment with extra pits in between as required.

Test pits should be dug to a depth of at least 0.6 metres below the bottom of the proposed storage to ensure the floor is watertight.

E.3.5 Soil Sampling

Samples of approximately 12.5 kg should be taken from each different soil layer in the test pit if Proctor tests are required. Smaller samples are adequate for Emerson tests. The samples should be kept in plastic bags that are well labelled. Labels should indicate:

- Landholder's name and location
- Test-hole number as shown on the test-hole plan
- Type of soil (e.g. topsoil, coarse sandy clay, brown clay, etc.);
- Depth from which the sample was taken; and
- Date

The samples taken can then be tested by an accredited soil testing laboratory for dispersion, liquid limit, plastic limit and optimum moisture content for compaction, if required.

E.3.6 Local Knowledge

Useful information about soils and their suitability for embankment construction can be obtained from locals. Questions should be asked about the success of the farm dams in the locality. Embankment failures or high seepage rates can indicate suspect soils.

E.4 Soil Testing during Construction

E.4.1 Embankment Material

During construction, the embankment soil compaction can be tested in the field and measured as a percentage against the results obtained in the laboratory (i.e. 95% compaction). There are relatively simple methods to monitor the level of compaction obtained throughout the embankment.

The first way of doing this is to extract a cylindrical block of soil from the bank using a core cutter. The mass of the soil can be determined by weighing. With the known inner volume of the core, one can determine the dry density of the soil in the embankment. Core cutters can only be used where there is no rock or gravel.

The second method is the sand replacement method. Remove a soil sample from the bank. Refill the hole from a cone containing a known volume of sand. Subtract the remaining sand in the cone from the initial amount to determine the volume of soil taken for the sample. The soil mass and water content can then be determined in the laboratory and the dry density calculated.

The third method is to use a nuclear density meter, which reads the wet density and the moisture content in the field from which the dry density can be calculated. This method has the advantage of giving instant feedback on site though it is more expensive.

PHOTOGRAPH E-5 – UNDERTAKING COMPACTION TEST IN THE FIELD (NUCLEAR DENSITY METER)

In the field, a quick way to verify that the soil on site has the proper moisture content is to roll a small amount of soil between your hands. If you can roll the clay to pencil thickness (4 mm) without crumbling, then the soil is at the correct moisture content for compaction.