An update on perfect filters

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SYNOPSIS. Recent work shows that the probability of failure of dams resulting from internal erosion is often higher than that resulting from other threats. Filters to protect dams against erosion are therefore important. Most of our existing dams are not protected from internal erosion by filters. The 'perfect' filter equation links permeability of filters to the floc size of the soil they will retain. This permeability approach is useful in establishing the vulnerability or otherwise of existing dams to internal erosion because the permeability of fills can be determined by in-situ permeability measurements in boreholes. Floc sizes can also be simply determined using the principles of Stokes' Law in the laboratory. Some samples display murkiness which obscures the results. Examples of the use of perfect filters are given, including examples of retro-fitting of filters in dams in which they were not originally installed.

GUARDING AGAINST INTERNAL EROSION

It has long been suspected, and recent reservoir safety work for Defra (KBR & BRE, 2002) has demonstrated, that the probability of failure resulting from internal erosion of existing British dams is often greater than from the two other major threats, overtopping and earthquakes. Internal erosion is the process in which soil particles are eroded from the walls of cracks and discontinuities in earth dams by water flowing through them, often at high velocity because of the high hydraulic gradients through dams. Continued erosion leads to enlargement of the discontinuity, often as 'pipes' through the structure, which may erode back from the downstream end initiating a process of slope instability, crest lowering and overtopping that may ultimately cause failure. Internal erosion can be contained by 'filters', non-cohesive soils, usually medium silts to sands, which are sized to retain the soil particles eroded from the soil to be protected (the 'base soil') while allowing water to pass through. This prevents the development of erosion 'pipes' and thereby protects the structure.

Long-term benefits and performance of dams. Thomas Telford, London, 2004

How to design filters, particularly filters for existing dams, is likely to become an important dam safety issue in the coming years, and it is timely to update the information available.

CORES, COHESIVE SOILS, CRACKS AND EROSION

In dams, the element most vulnerable to erosion is the waterproofing element, the core, usually of clay. The protection of a dam core is probably the most critical function that a filter must perform. The consequences of failure can be severe damage and even catastrophe.

The vulnerability of cohesive clay cores to erosion arises because cohesive soils are able to sustain open cracks. Cracks or other leakage paths may form through cores during construction, during first filling, because of settlement, arching, hydraulic fracture or other causes. Filters should ensure that the presence of openings does not lead to loss of material from them.

VULNERABILITY OF EXISTING BRITISH DAMS TO INTERNAL EROSION

Most British dams are not equipped with filters and are therefore not equipped to resist internal erosion should it arise. Measures such as puddling, using very wet fill and wetting clay fills to make them softer, were all intended to make these vulnerable soils flexible and able to deform without cracking as the dam deformed in response to foundation settlement, water level variations, earthquakes and other loads.

To further reduce the vulnerability of narrow puddle clay cores in the older British dams, a zone of 'selected fill' was often placed on either side of the core. It was easier for early dam builders to use finer but non-cohesive soil as transition. It was easy to dig and compact and, following the exhaustive discussion at the inquest on the disaster at Dale Dyke dam, which failed in 1864 (Binnie, 1978), the desirability of well rammed fine-grained transition fills was understood and acted upon, more often than not. The 'selected fill' in the transitions may be of a grading that would provide filter protection to the core, as Vaughan (2000a) found at Ladybower, but it may often be cohesive and therefore able to sustain open cracks, making it too vulnerable to erosion and unable to act as a filter.

Fortunately, instances of internal erosion proceeding to serious damage are rare (Charles, 2001). Cohesive cores have considerable resistance to erosion unless they crack or develop concentrated leakage paths for other reasons. Thus satisfactory behaviour in operation may continue for ever. However, erosion may be occurring very slowly and not yet been revealed. Although the general experience is that dams grow safer with time, there is no justification for assuming that because they have not leaked or failed after a given time, they will never leak or fail.

In assessing the risks of internal erosion of dams, one of Vaughan's (2000a) conclusions was that 'usually there is considerable warning, allowing corrective action to be taken'. However, this is not always the case. Catastrophic wash out before remedial action can be taken is the big danger. The risks should be assessed by investigating the dam and, from a knowledge of its properties, evaluating the mechanisms by which internal erosion might develop and the speed at which it might occur. Appropriate defensive measures and surveillance routines can then be put in place.

FILTER DESIGN METHODS

Many methods have been put forward for filter design (e.g. CIRIA/CUR, 1991). Most apply to coarse materials, such as used in coastal protection, but the application of them results in the design of successively coarser layers, each of which is sized so that grains or particles from the adjoining layer will not pass through its neighbour. In an ideal filter, the pore spaces between particles should be just small enough to prevent the passage of the smallest of the protected grains. There is a wide range of sizes in the any granular material and a similar range of pore sizes. Consequently, most filters depend on some of the protected material moving into the filter to make it effective. This is called 'self-filtering'. Most filter rules for non-cohesive soils allow for this.

FILTER DESIGN FOR CLAY CORES

In dams, the element most vulnerable to erosion is the waterproofing element, the core, usually of clay. This poses special problems in filter design because using traditional rules to design filters to protect cohesive soils usually leads to filters of sizes which are themselves likely to be cohesive. These would be capable of keeping cracks open like the core they are intended to protect. Clearly, this offers no effective protection to vulnerable cohesive clay cores and it is generally accepted that different design principles should be applied.

These different principles address the issue of the actual size of the clay particles that filters must retain. Clay particles exist in nature in flocs, groups of individual particles. The floc size is related to the clay type and the pore water chemistry. In some circumstances, such as changes in pore water chemistry brought about by introducing water with differing chemistry, the flocs can be dispersed, partially to form smaller flocs, or completely to be dispersed into individual clay particles. In laboratory particle size distribution tests, the clay portion is artificially dispersed using a dispersant, and the sizes of individual clay particles are determined. Clays are defined as being 2 microns (0.002 mm) or smaller. Clay flocs are larger than this, often around 10 microns (0.01 mm), the medium silt size in the standard particle size distribution.

DISPERSION OF BASE SOILS

Chemical dispersion of the clay in dam cores has a history of causing erosion and washout in arid parts of Australia, Brazil, the U.S. and elsewhere. It is produced by a combination of the chemistry of the clay and the percolating water. Several chemical situations have been identified as causing it (Aitcheson & Wood, 1965; Emmerson, 1967; Stratton & Mitchell, 1976; Perry, 1987). Aicheson & Wood (1965) refer to a dam in Australia which washed out immediately when the water impounded was changed to relatively pure fresh water after several years of successful operation while holding water of a higher salt concentration. They also describe how arid conditions can lead to a ped structure with a much higher permeability than is expected in a clay fill. The large voids in such fill allow the dispersed particles which have been eroded to pass through them.

Dispersive soil is a special case. The authors know of no examples encountered in UK. However, as a precaution, all soils likely to be used in dams should be tested in prospective reservoir waters to demonstrate non-dispersion.

CRITICAL FILTER DESIGN

The most commonly used filter design method is the 'critical filter' approach developed by USDA Soil Conservation Service (1986) and Sherrard & Dunnigan (1989), also given in ICOLD (1994).

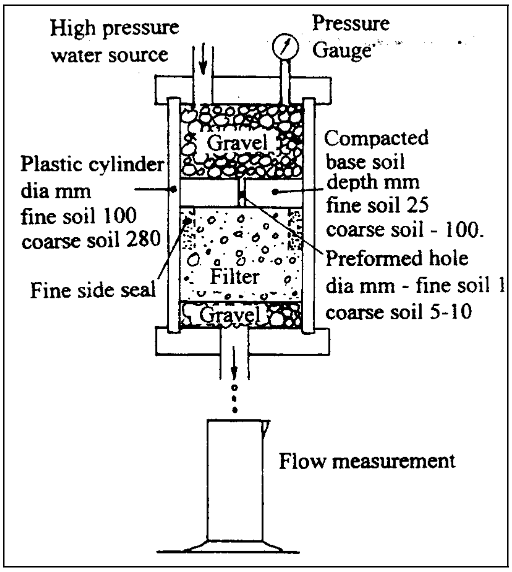

Figure 1 'No erosion' apparatus for the critical filter test

The method was based on an empirical laboratory 'no erosion' test, using the apparatus shown in Figure 1. Samples of base soil and prospective filter were tested by passing water under pressure through a small diameter hole in the base soil into the filter. If water discharged from the filter is clear, it is judged adequate; if water discharged from the filter is not clear, the filter is inadequate. From the results of many tests, the filter gradings that would protect the several groups of core materials were recommended. The groups of core materials are defined using the conventional (i.e. the dispersed, de-flocculated) particle size distribution.

'PERFECT' FILTER DESIGN

The alternative design method for filters for clay cores is the 'perfect filter' method. It was devised after sinkholes developed at Balderhead dam on first filling in 1967, as shown on Figure 2 (Vaughan et al 1970; Vaughan & Soares, 1982; Vaughan, 2000b). Segregation was identified in the erosion debris from the clay core found in the damage zone. The sand found in the eroded crack was the remains of the core fill, as the particle size distribution diagram on Figure 2 shows. The sand had been retained by the filter (designed to methods that precede both perfect and critical methods) but finer silt and clay-sized materials had passed through the filter because it was too coarse.

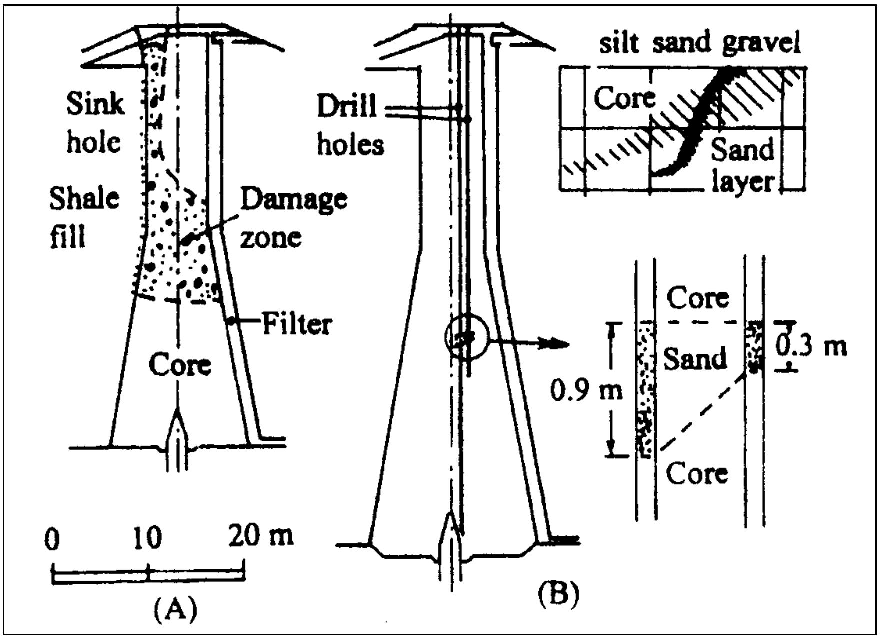

Figure 2 Balderhead dam, showing A - Damage zone where sink hole formed and B – Erosion hole filled with water washed sand

The perfect filter is required to retain the finest material which might be eroded from the walls of a crack in the core. This was taken to be the finest material obtained by mechanical dispersion of the clay in the appropriate water. This was usually clay flocs of around 10 μm (0.01 mm) particle size. Since this was a lower bound approach, no safety factor was required.

The design of a perfect filter involves two steps: first, the determination of the size of particle which must be retained and, second, the filter grading which is required to retain it. The filter grading required in design rules for non-cohesive soils is based on the finer sizes present, usually the 15% size. When the filter design was evolved it was found that the size of particle retained correlated well with filter permeability. The permeability of a filter is determined by the size of the continuous pores through it. Moreover the permeability is likely to vary with particle shape and it will vary with density of packing. While for uniform soils the permeability correlates with such an approach quite well, for well-graded soils the permeability depends on finer sizes and cannot be correlated with a particular percentage size.

The size of particle retained by a given filter was found experimentally by preparing different sizes of particle and passing them in dilute suspension through the filter (Vaughan and Soares, 1982). Either the sediment passed through the filter immediately or it sealed the surface, causing the flow rate to decrease rapidly. There was a small zone where the sediment clogged the surface more slowly. This was counted as retention. The test was more difficult to interpret when it was performed at a larger scale on filters containing gravel-sized particles. The results are summarised on Figure 3:

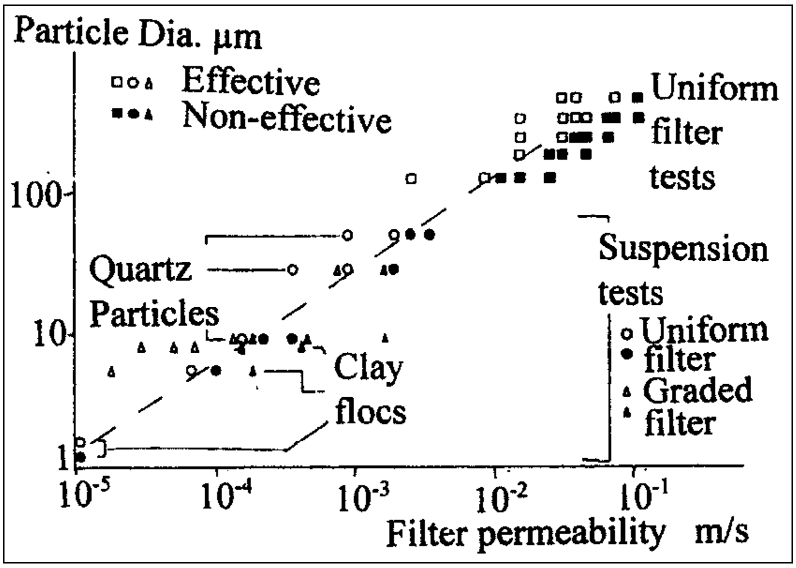

Figure 3 Summary of 'perfect' filter tests determining filter permeability required to retain base soils of various particle (and floc) sizes

Vaughan and Soares (1982) found that the relationship between filter permeability and the size of particles retained could be expressed as:

$$\delta_R = 1.49 * 10^3 (k)^{0.658}$$

where: δ_R = size of smallest particle retained in microns (10^{-6} mm)
k = permeability of filter (m/s)

The application of these findings to the erosion at Balderhead is illustrated on Figure 4. The grading of the core is shown, as is the grading of the portion of the core material retained by the 'actual' filter. This is the sand shown on Figure 2 above. The D_{15} range of the 'critical' filter that would have been provided to protect the core is also shown, as is the grading of the 'perfect filter'. It can be seen that the critical filter would have been too coarse to prevent the erosion that occurred through the cracks. Note also the modified core grading showing how it curtails at the minimum floc size, about 7 microns (0.007 mm), medium silt size.

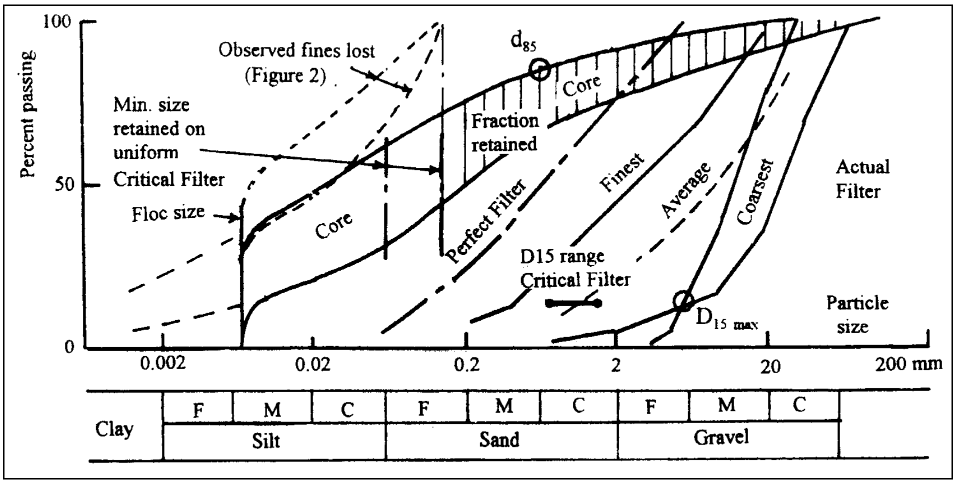

Figure 4 Filter base soil combination at Balderhead dam showing perfect filter, critical filter and observed segregation

COMPARISON OF PERFECT FILTERS WITH CRITICAL FILTERS

It is of interest to compare critical filters with perfect filters. This has been done by Vaughan (2000b) and the results are summarised on Table A below. The results are for filters of the appropriate critical filter base soil groups. No critical filter method 'no erosion' tests have been performed. The comparison has been made in terms of the minimum size of particle retained. This has been deduced from Sherrard & Dunnigan (1989) for the critical filters by first estimating the permeability of the critical filter from the relationship between permeability and the D_{15} size (Vaughan, 2000b).

The size of particle retained is then deduced from the perfect filter relationship.

Table A: Comparison of perfect and critical filters

Dam	Perfect Filter Design		Critical filter details deduced from Sherrard & Dunnigan (1989) Filter Provided			
	Floc Size δ_R (µm)	Permea-bility k (10^{-5} m/s)	Core Soil Group	D_{15} of filter (µm)	Permeability (10^{-5} m/s)	Size re-tained δ_R (µm)
Ardingly, UK	10	22	2	700-1500	319 - 1228	34-82
Carsington, UK	8	16	1	180	29	7
Cow Green, UK	6	10	2	700-1500	319-1228	34-82
Dhypotamus, Cyprus	6	10	2	700-1500	319-1228	34-82
Empingham, UK	10	22	1	90	9	3
Evinos, Greece	11	26	2	700-1500	319-1228	34-82
Kalavasos, Cyprus	5	8	2	700-1500	319-1228	34-82
Monasavu, Fiji	20	13	1	70	5	2
Balderhead, UK	7	13	2	700-1500	319-1500	34-82

The Critical Filters are more conservative than Perfect Filters for Group 1 cores (plastic clays) (e.g. 3 microns against 10 microns actual floc size at Empingham) and significantly less conservative for Group 2 cores (well graded sandy clays) (e.g. 34-82 microns against 7 microns at Balderhead). This is despite Group 2 cores giving poorer field performance. For the Group 1 cores the critical filters are more conservative than the perfect filters, despite the latter being able to arrest the smallest particle which may develop during erosion.

DETERMINATION OF FLOC SIZE

To use the perfect filter design method, the floc size of the core soil must be known. It is commonly determined using standard particle size analysis techniques (e.g. hydrometer) on samples slaked in reservoir water only, NOT subjected to the usual chemical dispersion process. Figure 2 above shows the results for the Balderhead core material. Often samples with and without dispersion, and sometimes without dispersion but in distilled, not reservoir, water, are also tested; these are the so-called 'double' and 'triple', respectively, dispersion tests. While the minimum floc size often shows up well in these tests, it is not always clear.

A simpler test (Head, 1992), which normally shows the floc size clearly, is based on Stokes Law, which relates the size of bodies falling through a liquid to their size. In our case, the smallest flocs sink slowest and can be seen as a falling front above which is clear water. The rate of fall of the front can then be used to determine the size of the smallest flocs present by using the version of the Stokes Law formula below:

$$D = 0.005\,531\ \{(\eta\ H) / (t\ (\rho_S - 1))\}^{0.5}$$

where: D = minimum floc size (mm)
H = distance floc front falls (mm) in time t (mins)
t = time (mins) to fall H (mm)
ρ_S = mass density of soil particles, should be measured, but is commonly in the range 2.6-2.7

The dynamic viscosity of water, η, varies with temperature, as follows:

Temperature (˚ C)	Dynamic Viscosity, η (mPa-s)
10	1.3037
15	1.1369
20	1.0019
25	0.8909

The rate of fall of flocs of the sizes normally encountered is quite rapid and Stokes law tests can be done quickly. The table below shows the time that flocs of various sizes take to fall 300 mm and gives information on the floc sizes and the filters required to retain them:

Mins to drop 300 mm	Terminal velocity mm/s	Floc size microns	Floc texture	Perme-ability perfect filter m/s	D_{15} uniform perfect filter mm	Texture D_{15} perfect filter
5	1.00	32.9	Coarse silt	3.04E-03	0.681	Coarse sand
15	0.33	19.0	Medium silt	1.32E-03	0.424	Medium sand
45	0.11	11.0	Medium silt	5.73E-04	0.265	Medium sand
90	0.0556	7.8	Medium silt	3.38E-04	0.196	Fine sand
180	0.0278	5.5	Fine silt	2.00E-04	0.146	Fine sand
360	0.0139	3.9	Fine silt	1.18E-04	0.108	Fine sand
1080	0.0046	2.2	Clay (deflocculated)	5.12E-05	0.067	Fine sand

THE 'MURKINESS' PROBLEM

Sometimes in the Stokes Law test the falling front is not visible. The sediment can be seen to arrive at the base of the measuring cylinder, but the water above remains 'murky' and opaque, so that the falling front cannot be seen. The source of the murk is not known. It usually persists for extremely long periods, longer than even the smallest clay particles would take to settle, and it seems unlikely it comprises dispersed clay flocs. Its source may be the same as the source of 'colour' in treated water, although it is more severe, making the water opaque, not transparent as 'coloured' waters are. It seems prevalent in alluvial soils, perhaps because organic materials are present. It complicates a simple and useful test, easily done in the field, and research into its source and how to overcome the murkiness without affecting the validity of results would be valuable.

PERMEABILITY AND GRADING OF FILTERS

The use of a relationship that relates retained floc size to the permeability of the filter reflects the fact that permeability is related to pore sizes. However, measuring the permeability of a potential filter is less convenient than measuring its grading and the expression below (Vaughan 2000b), which is for uniform filters, is useful to give an early indication of the grading of potentially suitable filters:

$$k = 3 * 10^{-8} (D_{15})^{1.767}$$

where: D_{15} = D_{15} size of uniform filter (in µm, microns)
k = permeability of filter (in m/s)

Note that the actual filter, if not uniform (i.e. $D_{60}/D_{10} > 1$), will have a different permeability, and therefore a different filtering capability, and the permeability of candidate filters should be measured before they are used.

The permeabilities of filters retaining clays flocs are low and their drainage capacity is therefore limited. If filters are protecting fills that include permeable layers that may allow substantial quantities of seepage to pass, it may be necessary to provide a coarser drainage filter downstream of them to allow the seepage to escape freely. To pass the quantity, the hydraulic gradient across the low permeability, low capacity filter is high, and the gradient along the high permeability, high capacity drainage filter is low.

FILTER PROPERTIES

Filters should be non-cohesive, at least as placed. The 'sand-castle test' described by Vaughan & Soares (1982) is a convenient and quick means of proving non-cohesiveness at source. Granular soils may bond with age and develop cohesion, although so far as the authors know, no problems have been reported from this cause.

Filters must be internally stable and self-healing. Kenney & Lau (1985) and Lafleur et al (1989) give methods to check the internal stability of non-uniform filters.

A further check on the suitability of filters can be made by passing 'muddy' water made from (reservoir) water containing the base soil through a layer of the filter in a permeameter. Adequate filters retain the 'mud' and clear water passes through. Inadequate filters allow the muddy water to pass.

IN-SITU PERMEABILITY AS A GUIDE TO THE VULNERABILITY OF EXISTING DAMS TO INTERNAL EROSION

The filtering capacity of non-cohesive shoulder fills can be assessed from in-situ permeability measurements. For example, Vaughan (2000a) found non-cohesive silty sandy gravel transition fill at Ladybower to have a maximum permeability of $4*10^{-6}$ m/s. This provides perfect filter protection to the adjoining clay core in which the minimum floc size is about 10 microns. As the fill tested may not be uniform, use of a lower bound to the permeabilities measured may be appropriate. The filter relationship between the transition and the general shoulder fill should also be checked as transition fills may erode into coarse shoulder fills.

The perfect filter equation makes the connection between floc size retained and filter permeability, as follows:

$$\delta_R = 1.49 * 10^3 (k)^{0.658}$$

where: δ_R = size of smallest particle retained in microns (10^{-6} mm)
k = permeability of filter (m/s)

The equation was derived for non-cohesive filters with permeabilities ranging upwards from 1×10^{-5} m/s. Use of the equation to determine the floc size of soils that would be retained by soils with in-situ permeability less than 1×10^{-5} m/s should be cautious. If the soils are cohesive, improbable results emerge (Tedd et al, 1988). In practice, this means that in low permeability fills, the cohesiveness of the soil should be checked, and the floc size of cohesive materials should be determined in the laboratory.

Note that samples taken from boreholes in fills with substantial proportions of granular materials are likely to have lost fines and not be properly representative of the in-situ fill, consequently laboratory permeability tests do not give usable results. In-situ tests are needed, usually from piezometers installed in boreholes. These may also serve for measuring pore pressure in the investigation of old dams

However, as Charles et al (1996) point out, the sand in the sand-pockets in piezometers installed in fill will usually have a permeability up to about $2*10^{-5}$ m/s. If this is less than the fill in which the piezometer is sited, it will appear that the fill will retain smaller flocs than it is capable of retaining, an unsafe situation. A progressive approach to determining the permeability, and hence the filtering capacity, of fills that may be required to protect against internal erosion is therefore recommended, commencing with in-situ permeability tests in boreholes.

DAMS WITH PERFECT FILTERS

There is a growing body of dams with perfect filters, as listed on Table B below:

Table B: Dams with perfect filters

Dam	Perfect Filter Design		Filter Provided			
	Floc Size (μm)	Permeability (10^{-5} m/s)	Filter Soil Type*	Permeability (10^{-5} m/s)	Size retained δ_R (μm)	D_{15} of filter (μm)
Ardingly, UK	10	22	ns	9	3	230
Carsington, UK	8	16	psg	1 to 10	1 to 3	80-170
Cow Green, UK	6	10	ns	2	1	110
Dhypotamus, Cyprus	6	10	sng	1	1	1000
Empingham, UK	10	22	ng	8	3	100
Evinos, Greece	11	26	sng	10	3	220
Kalavasos, Cyprus	5	8	sng	4	2	600
Monasavu, Fiji	20	13	cr	4	2	210
Balderhead, UK	7	13				
Melton Mowbray, UK	4	12	ns	10	3.5	150
Audenshaw, UK	6	23	ns	10	3.5	

* ns = natural sand psg = processed sand and gravel ng = natural gravel cr = crushed rock sng = natural sand and gravel screened to remove coarse sizes

It has always proved possible to find or make perfect filter gradings for the cases listed above, although this was sometimes difficult. Dounias et al (2000) describe how river gravels were used as the core filter at Evinos Dam. Hughes et al (2001) and Bridle (2003) describe the filter investigations at Audenshaw and Melton Mowbray respectively.

It must be emphasised that the perfect filter is only required to protect against erosion by continuous reservoir flow through cracks or other flow paths which are in cohesive soils, and which can sustain such an opening without sealing by collapse. This is typically a core, but where the foundation is of erodible clay, a short length of perfect filter blanket is often added on the foundation downstream of the core, where significant hydraulic gradients exist. The principle of the Perfect Filter for cohesive soil is that erosion through concentrated reservoir flow is prevented. Intrinsically, no cause for such flow is presumed. A relatively thin layer of filter has been considered acceptable.

It is inevitable that the filter provided is less permeable than the Perfect Filter required. This gives a safety factor, although one is not required.

RETRO-FITTING FILTERS

In dams which are found to be unacceptably vulnerable to internal erosion, filters will be required. This presents some challenges. Although perfect filters will protect fills for which they are designed, fills in old dams may be variable. Also, if the filters are incomplete and do not cover the entire exposed fill, erosion may still occur. Protecting against foundation erosion is particularly difficult. Methods of retro-fitting filters to meet these challenges will have to be devised, probably derived from previous experiences, a few examples of which are described here.

At Lower Tamar, a filter layer was placed below a weighting berm on the downstream slope to collect and filter seepage passing through the core (Kennard, 1972). Care should be taken to make sure that arrangements such as this have a sufficient weight to secure against a concentrated leak (Vaughan, 2000a). Bailey (1986) describes the provision of a filter wall to prevent erosion through tension cracks near the top of the core and the installation of a geotextile filter behind a retaining wall at the toe of the downstream slope to filter seepage passing through Upper Litton dam. Talbot & Ralston (1985) give examples of retro-fitting of filters to deal with cracks and potential internal erosion in dams, including flood dams.

Jairaj & Wesley (1995) describe the construction of a filter wall drain using a bio-polymer slurry at Hays Creek dam. The wall drain was excavated using slurry support in the usual way, and the trench filled with filter sand placed by tremie pipe, displacing much of the slurry. Water and sodium hypochlorite was pumped through the sand/slurry in the trench to break down and remove the remaining slurry, leaving the sand as a filter at the required permeability in the trench.

Filter collars can be provided near the downstream ends of culverts and pipes through dams to limit risks of erosion along the interface between these structures and the dam fill. Talbot & Ralston (1985) advocate filter collars, and give information on suitable dimensions and positioning.

CONCLUSION

The perfect filter approach to providing filter protection against internal erosion in dams provides a rigorous means to design safe, effective filters. It can also be conveniently used to assess the vulnerability to internal erosion and the need for filters in existing dams. The aim of this paper is to make the perfect filter approach accessible to European, including British, dam engineers to assist them in keeping their dams safe from damage through internal erosion in the long term.

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