In search of the perfect geotextile/geocomposite filter for retro-fitting old embankment dams

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SYNOPSIS. Increased use of quantitative risk assessment techniques to determine the probability of failure of the various threats posed to reservoir embankments has highlighted the potential risk of internal erosion occurring in many older embankment dams. In dams where an internal erosion threat has been identified retofit filters are commonly incorporated into the downstream shoulder of the dam. The variability of the materials used in the construction of the dams makes conventional filter designs difficult. Locally sourcing and placing of consistent quality filter materials on slopes also poses difficulties. This paper investigates the potential of designing using geotextile filters to retrofit old embankment dams identified as being vulnerable to internal erosion.

INTRODUCTION

In recent years the concepts of reservoir risk assessment have advanced considerably (ICE, 1996, Hughes et al, 2000, Brown and Gosden, 2002, 2004, 2005, Brown and Carter, 2004, Brown and Bridle, 2005). These assessments have identified inadequate overflow capacities of many dams. As a result those dams which were below the current standard have had their spillways upgraded to acceptable levels. This has left the internal behaviour of dams designed and built before the development of soil mechanics and modern compaction plant as a major cause of concern (Charles, 1998, 2001, Vaughan, 2000a). This concern is enhanced by the number of internal erosion incidents which occur each year (e.g. Gardiner et al, 2004, Bridle, 2004). Internal erosion is the damaging process by which seepage flow through the body of an embankment dam carries away fine particles of soil. The flow paths may progressively enlarge resulting in the material carried away becoming larger, increasing in quantity and eventually leading to breaching of the dam. The final stages can be very rapid. Internal erosion

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can be contained by 'filters' which are sized to retain the soil particles eroded from the soil to be protected (the 'base soil') while allowing water to pass through. Such filters are designed to prevent erosion of the watertight element of the dam and prevents the development of erosion 'pipes'.

DESIGN OF GRANULAR FILTERS

Vaughan and Bridle (2004) have recently published an update on methods of filter design to resist internal erosion. They recognise that most have been developed in relation to coarse granular materials. The application of these methods 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. Such an approach was used in the construction of graded filters and weighted stability berms used in the upgrading of dams in Northern Ireland (Cooper, 1987).

Filter designs are based on the principle that the pore spaces between particles should be just small enough to prevent the passage of the smallest of the protected grains and rely on a 'self-filtering' effect whereby some the protected material is allowed into the filter to make it effective.

In dams, the element most vulnerable to erosion is the waterproofing element, the core, typically 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.

Vaughan and Bridle (2004) recognise that the filter design principles used for granular soils do not apply to the protection of clay cores. They identify two approaches to the design of filters to resist internal erosion of clay cores The first is known as the 'critical filter' approach developed by USDA Soil Conservation Service (1986) and Sherrard & Dunnigan (1989) and quoted in ICOLD (1994). This is based on the 'no erosion' test where 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. Various filter gradings were proposed for different core materials based on the results of conventional particle size distribution tests undertaken on dispersed and flocculated soil.

Vaughan et al 1970; Vaughan & Soares, 1982 and Vaughan, 2000b have proposed an alternative design method for filters for clay cores known as the 'perfect' filter method. This is based upon an assessment of the finest material which might be eroded from the walls of a crack in the core. Vaughan and Soares, 1982 determined the size of particle retained by a given filter experimentally by preparing different sizes of particle and passing them in dilute suspension through the filter. They discovered that this was usually clay flocs of around 10 μm (0.01 mm) particle size.

The filter grading which is required to retain these flocs is based on the finer sizes present, usually the 15% size. A comparison of critical and perfect filter designs has been undertaken by Vaughan (2000b). Vaughan and Bridle (2004) note that 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.

DESIGN OF GEOTEXTILE FILTERS

Geotextile filters are manufactured in a variety of forms either single geotextile membranes or as a prefabricated geocomposite comprising two filter geotextiles bonded either side of the water-carrying core. For ease of reference the following terms will be used in subsequent sections when referring to the components of the filter.

Filter	a geotextile filter or geocomposite prefabricated filter.
Geotextile	a single geotextile or the geotextile bonded on either side of the water-carrying core.
Core	the water-carrying core of a geocomposite between the geotextiles outer layers which are bonded to it.

A variety of methods for designing geotextile filters have been summarised by ICOLD (1986), Christopher et al (1991) and Giroud (1982, 1988,1996, 1998). As with granular filters, the methods of design of geotextile filters are predominantly based on filtration rules for granular materials. The main requirements are to provide efficient filtration without clogging or piping and adequate flow capacity under the design loads to provide the maximum anticipated seepage during the design life.

Vaughan (2001) states that geotextile filter design involves the use of maximum openings in lieu of d_{15} size or equivalent in granular filter design.

A variety of other criteria have been produced by others examples of which are detailed in Table 1.

Table 1 - Published Retention Criteria

Geotextile Retention Criteria		
Source	Criterion	Remarks
Rankilor (1991)	$O_{50}/D_{85} \leq 1$	Nonwovens & soils with $0.02<D_{85}<0.25$
	$O_{15}/D_{15} \leq 1$	Nonwovens & soils with $D_{85}0.25$
Giroud (1982, 1984,1992)	$O_{95}/D_{85} \leq$ [(9-18)/Cu]	Dependent on Cu of soil and assumes fines will migrate for large/low Cu soils
French Committee on Geotextiles and Geomembranes (CFGG, 1986)	$O_f / D_{85} \leq 0.38 - 1.25$	Dependent on soil type, compaction, and hydraulic conditions of the site
Fischer, Christopher and Holtz (1990)	$O_{50}/D_{85} \leq 0.8$ $O_{50}/D_{15} \leq 1.8 - 7.0$ $O_{50}/D_{50} \leq 0.8 - 2.0$	Based on geotextile pore size distribution and dependent on Cu of the soil
Terram Design Guide (Anon, 1996)	Piping Limit - Minimum Aperture Opening Size (AOS) less than or equal to 120µm	
American Standard on Geotextile in Highway Applications (AASHTO, 1999)	Maximum A0S, ASTM D-4491 - 200µm	

where:
O_{95} = 95% opening size of geotextile
O_{50} = 50% opening size of geotextile
D_{85} = grain size in millimetres of 15 percent finer by weight
$Cu = D_{60}/D_{10}$

Giroud (1984) points out that such criteria are probably too restrictive for highly cohesive soils. However, cohesive soils are not usually problematic, and Giroud's retention criterion handles worst case (i.e., cohesionless) conditions. ICOLD (1996) has published a list of known applications of geotextiles in embankment dams from twelve countries. Nominal Pore Size of Geotextile Filters used range from 29 -180 µm.

For long term performance, the filtering system development between a geotextile and an adjacent stable soil performs the filtering function for fine particle movement. From a design standpoint, there needs to be as many possible paths per unit area available for water to pass through the soil/geotextile system. The adjacent soil will comprise a percentage of these paths once the filtering mechanism is developed. From a conservative design approach, the more paths available per unit area the more efficient the filtration system will be over time.

In addition to designing a geotextile with sufficient soil retention and filtration properties to control piping, some other important design objectives must be fulfilled. These include:

- sufficient drainage capacity and the ability to dissipate excess hydrostatic pore pressure
- long term effectiveness (ability to resist clogging)
- stability of geosynthetic soil filter systems laid on slopes
- survivability and durability of geotextiles

<u>Sufficient drainage capability</u>

Darcy's equation is the foundation for determining sufficient water passage capability of a soil/geotextile filter system. The adjacent soil's hydraulic properties govern the initial and long term filtration behaviour of a soil/geotextile filter system.

In geotextile design, the adequacy of water passage, rather than Darcy's coefficient of permeability, is considered the important design parameter. Water passage normal to the plane of the geotextile (permitivitivity, Ψ) and in-plane flow along the line of the geotextile (transmissivity, θ) need to be considered.

Permittivity is defined as:

The volumetric flow rate of water per unit cross-section area, per unit head, under laminar flow conditions, in the normal direction through the geotextile.

$$q = \Delta h \, A \, K_n/t = \Delta h \, A\Psi$$

A geotextile's ultimate permittivity, Ψ_{ult}, is determined using ASTM D-4491 (2004). This permittivity result is often used to develop a geotextile permeability value which is dependent on geotextile thickness. De Berardino (1992) Bhatia (1998), Rollin, Mlynarek and Bolduc (1990), and others have commented on the complete lack of a role that thickness plays in soil/geotextile filtration design. Koerner (1990) also uses permittivity for design.
Using Darcy's Law, Koerner has developed the following required soil permittivity:

$\Psi_r = q / \Delta h A$

where:
Ψ_r = required permittivity
q = flow rate
Δh = head loss
A = area of geotextile

Flow net analysis can be used to determine the required permittivity (Cedergren, 1989).

A factor of safety applied to the required permittivity as follows:
$\Psi_g \geq F.S.\ \Psi_r$ (Koerner, 1990)

where:
Ψ_g = design allowable geotextile permittivity
F.S. = Factor of safety
Ψ_r = required permittivity

The factor of safety is based on experience. A factor of safety of 5 is recommended for geotextile erosion control structures. A number of similar criteria based on permittivity have also been published a summary of which are given in Christopher and Fischer, 1991.

The transmissivity, in-plane flow within the geotextile, is defined as the in plane permeability times the geotextile thickness.

Transmissivity, $\theta = k_p t$

Thus applying Darcy's law:

$$q = k_p\, i\, A = \frac{\theta}{t}\, i\, w\, t = \theta\, w\, i$$

where
q = flow rate
k_p = In plane flow rate
t = thickness of geotextile
w = width of geotextile

When a granular drain or filter layer is replaced by a geosynthetic layer, it is often assumed that the two have the same hydraulic transmissivity. In the United States, this approach is often mandated by regulations for the case of leachate collection layers used in landfills. This is true only in the case of confined flow (i.e. if the liquid collection layer is completely filled with liquid). In reality, liquid collection layers should be designed for unconfined flow, (Giroud et al. 2000). To be equivalent under the unconfined flow condition, the geosynthetic liquid collection layer should have a greater hydraulic transmissivity than the granular liquid collection layer (Giroud et al. 2000).

$\theta_{geocomposite} = E\,\theta_{graular\ drain}$

$E = 1/0.88\ [\ 1+ (t_{soildrain/}\ 0.88L)\ .\ (\cos\beta/\tan\beta)]$

E - Equivalency factor
$t_{soildrain}$ - Thickness of soil drain(m).
L - Slope length (m)
β - Slope angle
$\theta_{soildrain}$ - Soil drainage transmissivity m^2/s
$\theta_{geocomposite}$ - Geosynthetic drainage transmissivity m^2/s

A typical granular filter thickness of 300mm with a permeability of $1x10^{-4}$ m/s equates to a geotextile in plane flow rate that requires either a cuspated or geonet drainage core to provide the sufficient drainage capacity. The high water carrying capacity of the drainage core allows for economic provision of drainage capacity in the geocomposite filter.

<u>Long term effectiveness (ability to resist clogging)</u>

The ultimate long term performance concern is potential clogging of the geotextile. A number of additional criteria have been proposed to resist clogging as detailed in Christopher and Fischer, 1991.

Giroud (1996) maintains that an effective filter must be able to retain larger soil particles whilst, at the same time, it must allow very fine particles close to the geotextile to pass which would otherwise block the geotextile. So the geotextile effectively supports the formation of a natural, stable grain structure within the adjacent soil to produce a self filtering effect. To pass through a nonwoven geotextile, a particle must pass between fibres. Giroud (1998) modelled the filtering effects of geotextiles, defining the term constriction, as a passage contained between three or more fibres which are nearly, but not necessarily exactly, in the same plane. The size is defined as the diameter of the sphere which can just pass through the constriction. A soil particle that travels in a nonwoven geotextile follows a certain path until it meets a constriction which is smaller than it is. The level at which a particle is stopped depends on the filtration path. If the particle is not stopped by a constriction, it passes through the geotextile.

Giroud demonstrated that in order that the filter is neither too permeable for the soil nor too prone to clogging, the geotextile must possess an optimum number of constrictions m where:

$$m = \frac{\text{Geotextile Thickness}}{\text{Fibre Diameter}} \times \sqrt{(1 - \text{porosity})}$$

Geotextile fibre diameters vary from 25-50 μm for fine to coarse fibres.

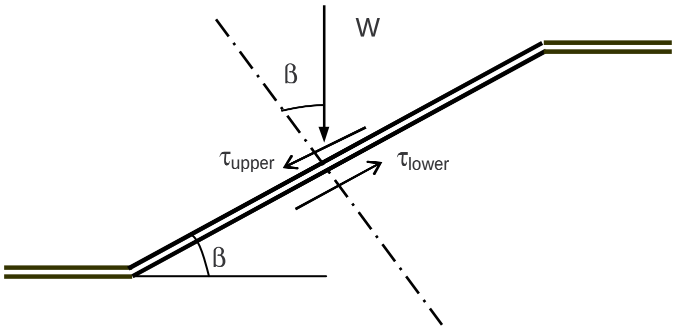
Giroud (1996) produced a performance model of a geotextile in contact with soil which shows that the number of constrictions between the filaments which a soil particle must pass during its way through the geotextile is a significant characteristic. He demonstrated that the optimum number of constrictions for geotextile filters is between 25 and 40. The range of 25 to 40 constrictions guarantees the homogeneity of the geotextile opening size, and the retention and stabilisation of the grain structure at the surface of the geotextile, resulting in the quick formation of a stable, natural filter without internal clogging. At less than 25 constrictions (typical for thin heat-bonded geotextiles) the retention capacity under turbulent flow conditions is no longer guaranteed, and as a consequence the homogeneity of the geotextile filter is too low. At more than 40 constrictions (typical for thick, single-layer geotextiles) soil particles can clog the geotextile (so-called "internal clogging).

Stability of geotextile soil filter systems laid on slopes

The stability of a geotextile filter system is often controlled by the shear strength between the various interfaces, i.e. geotextile/soil and geotextile/geocomposite interface shear strengths. The importance of interface shear strength was illustrated by the slope failure in Phase IA of Landfill B-19 at Kettleman Hills in the USA, which instigated a major investigation carried out by the University of California at Berkeley (Seed et al., 1988). It has also played an important role in a number of UK failures (Jones and Dixon, 2003). Various authors have produced simplified methods of establishing the stability of geotextiles on slopes (Giroud et al., 1995 and Koerner and Hwu, 1991). The analysis can be undertaken on conventional slope stability programmes. It is important to obtain data on the geotextile interface shear strength from shear testing to BS6906:1991. Some typical results are quoted by Jones and Dixon, 2003.

A further consideration is the potential to build up tension forces due to unbalanced friction forces above and below the geotextile liner (Koerner and Hwu, 1991 and Bourdeau et al. 1993). The situation is shown in Figure 1.

Figure 1 – Frictional Forces on Geotextiles placed on slopes



Three different conditions need to be considered as follows:

$\tau_{upper} = \tau_{lower}$	The geotextile goes into a state of pure shear which should not be of great concern for most geotextiles
$\tau_{upper} < \tau_{lower}$	The geotextile goes into a state of pure shear up to a magnitude of τ_{upper} and the balance of $\tau_{lower} - \tau_{upper}$ will not be mobilised
$\tau_{upper} > \tau_{lower}$	The geotextile goes into a state of pure shear up to a magnitude of τ_{lower} and the balance of $\tau_{upper} - \tau_{lower}$ will not be mobilised

Tension will occur in a situation when a material with high interface friction (e.g. sand and gravel) is placed above a geotextile and a material with low interface friction (e.g. a soft clay) is placed beneath the geotextile. The tension developed in this case is given by the equation (Bourdeau et al., 1993)

$$T = \left\{ \left[\frac{\alpha_{upper} - \alpha_{lower}}{F} \right] + \gamma H \cos\beta \left[\frac{\tan\delta_{upper} - \tan\delta_{lower}}{F} \right] \right\} L$$

where:
T = Tension force in geotextile
α_{upper} = adhesion between geotextile and upper soil
α_{lower} = adhesion between geotextile and lower soil
γ = soil density
H = slope height
β = slope angle
δ_{upper} = friction angle between geotextile and upper slope
δ_{lower} = friction angle between geotextile and upper slope
L = length of geotextile

Placing the geotextile to limit tension stresses developing during laying of geotextiles will also need to be specified.

Survivability and Durability of Geotextile

Giroud et al. (1998) recognised that a geotextile with adequate and homogenous filtering properties can be specified. However a geotextile will also need appropriate mechanical properties to resist mechanical damage and deformation when being placed. To achieve this, Giroud considered a two-layer non-woven needle punched geotextile; a filter layer constructed with fine fibres to give the required filter properties and a protective layer providing the required mechanical properties to protect the filter layer from construction activities. Such products are now commercially available from a number of suppliers. Indeed multi-layered composites can be constructed by several manufacturers using lamination or needle-punching with project specific elements. Composites may also comprise a geo-net drain or cuspated plastic sheet (fin drain) with a geotextile bonded on one or both sides to provide filtration, separation and/or protection.

One of the first applications of two-layer filter geotextiles in embankment dams was on the Valcros dam in France (Artieres and Tcherniavsky, 2002). The dam incorporated some sampling points whereby the long term performance of the geotextiles could be monitored. These allowed visual monitoring of the soil particle retention mechanism. The observed particles retained inside the first filament were consistent with Giroud’s (1996) constriction concept to achieve filtering requirements (Anon, 2001)

Durability of geotextiles over time is an important consideration for long term effectiveness. Polypropylenes and polyesters are long chain polymers in which structural degradation can be initiated by heat, light and chemical/biological action. The resistance properties are therefore important in specifying a filter and method statements must limit the exposure to ultra violet light during storage and installation of materials to avoid early deterioration.

Koerner (2005) provides a methodology to define as-manufactured properties of geosynthetics for design purposes. Strength should be reduced using the equation:

$$T_{allow} = T_{ult} \left[\frac{1}{RF_{ID} \times RF_{CR} \times RF_{CBD} \times RF_{SM}} \right]$$

The Reduction Factors (RF) are for installation damage (ID), creep (CR), chemical and biological degradation (CBD) and seams (if appropriate)

(SM). Koerner (2005) lists many common uses with recommended reduction factors. These numerical values are site specific and material specific and can be changed dependent upon the risk assessment of the construction methods and anticipated service within the project.

Allowable flow rates also require a range of reduction factors:

$$q_{allow} = q_{ult} \left[\frac{1}{RF_{SCB} \times RF_{CR} \times RF_{IV} \times RF_{CC} \times RF_{BC}} \right]$$

Here the Reduction Factors are for soil clogging and blinding (SCB), creep into void space (CP), intrusion into voids (IV), chemical clogging (CC) and biological clogging (BC). Again appropriate ranges are provided by Koerner (2005).

CONCLUSIONS

Design methods are available to produce a perfect filter geotextile, however due consideration also needs to be given to providing sufficient drainage capacity, the ability to resist clogging, the stability of geotextile/geocomposite soil filter systems laid on slopes and the survivability and durability of geotextiles. Geotextile/geocomposite filter systems are more economical and simpler to lay than granular filters leading to quicker and simplified construction. They also require less site quality control compared to that required to achieve a properly graded granular filter. However they do require adequate design and specification, based on an understanding of the specific issues relating to geosynthetics to guarantee long term effectiveness.

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