Composite filters for critical applications

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ABSTRACT: The development of technology defining the filters for the critical internal drainage of water retaining structures has emerged in the last two centuries with finite definitions of granular filters by Karl Terzaghi. Further refinement has been made over the past twenty years by Sherard et al (1986). At the same time the use of geotextiles as filters emerged, and filter criteria were developed for such materials. This paper also reflects on what is considered as "problem" soils' behaviour which includes low density or loose base material; dispersive and/or erodible or non-cohesive base material as well as gap-graded or non-uniformly graded base material. An analysis and subsequent comparison of modern granular filter and geotextile filter criteria emphasises the difference in porosity of filter materials and hence natural filters' tendency to fail in piping, whereas geotextile filters' weakness tends to be in clogging. Laboratory investigations into geosynthetic performance under low and high hydraulic gradients, as well as the effect of density and deformation on performance are described. Through combining the advantages of granular filters and geosynthetic filters into the design of composite filter systems the performance of critical filter systems are enhanced and overcome historical reticence for relatively recent technologies and provides for competent, cost-effective filter systems. Examples of such systems' design, construction, installation and performance in critical civil, mining and environmental applications are illustrated.

1 INTRODUCTION

The developments in water retaining structure design over the past 2000 years has shown a change from rubble mounds with ashlar facings to more economical, steeper slope, earth embankments, for which internal drainage is critical.

The history of dam engineering demonstrates that filter technology is a relatively young science. This is due in part to the changes in form of structure with time.

The oldest known large dam is the ancient Sadd el-Kafara dam which is situated in one of the numerous wadis in the desert to the east of the Nile Valley, some 30km south of Cairo, Egypt. The dam was originally 113m long and 14m high when built about 4500 years ago. Today only the northern wing which extends about 23m into the wadi and the southern wing which is about 27m long still stand, separated by a breach of some 50 to 60m wide which has been formed by the numerous floods of the past 45 centuries.

The Sadd el-Kafara dam consists of three construction material types within its 98-metre total cross section width, which have differing composition and function. These are:

- A central core of rubble, gravel and weathered material,
- Two sections of rockfill on either side (upstream and downstream) of the core and
- Layers of ashlars placed in steps on the slopes of the rockfill.

It has been estimated that the construction took 10 to 12 years based on the volumes of material that had to be transported from the wadi edges and terraces. No presence of filters is recorded. Assessments of the dam's stability by modern methods lead to the conclusion that the design was basically correct, although very conservative. This, it is assumed, indicates that no experience with structures of this kind was available when it was built. Analysis of pottery and radio carbon dates obtained from samples of charcoal and textiles found in the remains of the building to the north-west of the dam, which was probably a workers camp accommodation during the construction of the dam, indicate that the dam was constructed in the early old kingdom i.e. about 2700 to 2600BC. More recent examples of dam engineering achievement include the Roman reservoirs of Merida, Spain, which are still in use today and are so well preserved that they can be considered unique.

The reservoir of Proserpine lies some 5km outside of Merida. The dam is a gravity structure which, in principle, is made of earth with an outer covering of small ashlars, concrete and rubble. No distinctive filter system is present. The dam has a crest length of 400m and height of 14.5m; is situated on the stream called Lus Pardillas and has a storage reservoir of 4 million cubic metres and supplied water to the city via a winding 12km canal and aqueducts.

The early type of dam construction shows essentially the use of a semi-impermeable solid facing with supporting soil. Some 2000 years later, dam engineering has advanced through making use of various soils for flexibility and impermeability allowing for a greater diversity of foundation conditions. It is this relatively recent advancement in dam engineering that brought with it the development of granular and still more recently geosynthetic filters.

To this day, internationally, there is a wide range of geotextile filter criteria which have regional preferences, and they are often aligned with their locally manufactured geosynthetic types (e.g. nonwoven or woven).

Independent of the filter material, i.e. whether sand or synthetic (including woven or nonwoven), the mechanism by which a successful filter is established is the same.

That process is that at the interface zone the fine fraction of the base material must be allowed to depart from the interface zone in an adequate quantity so as to leave a more pervious base material immediately adjacent to the filter material. Likewise the filter may have its permeability reduced but not to the extent that it is lower than the modified permeability of the base material.

This paper also reflects on what is considered as "problem" soils' behaviour which includes low density or loose base material; dispersive and/or erodible or non-cohesive base material as well as gap-graded or non-uniformly graded base material.

An analysis and subsequent comparison of modern granular filter and geotextile filter criteria emphasises the difference in porosity of filter materials and hence natural filters' tendency when inadequate to fail in piping, whereas geotextile filters' weakness tends to be in clogging.

2 THE SAFETY OF DAMS

While dams form an integral part of society's infrastructure having provided humanity for several centuries with benefits such as water supply, flood control, irrigation, power generation and recreation, some major dam failures have aroused awareness of the potential hazard caused by dams.

Many of the older dams are characterised by increased hazard potential due to downstream development and increased risk due to structural deterioration or inadequate spillway capacity. The three main causes of dam failure are given as overtopping; foundation defects and piping, and that while foundation failures occur relatively early in the performance life the other causes may take much longer to materialise (National Research Council, 1983).

The modes and causes of dam failures are varied, multiple and often complex and interrelated. Thus it cannot be assumed that the triggering mechanism alone caused the failure, had the dam not had secondary weaknesses. Therefore there is a need for a careful, critical review of all facets of a dam. Such reviews should be based on a competent understanding of causes and weaknesses, both individually and collectively and should be made periodically by experts in the field of dam engineering. Hence, it is correct to give thorough consideration to both natural and synthetic filters, and their inter-relationship in dams and other fluid retention structures.

3 EMBANKMENT LEAKAGE AND PIPING

Piping and foundation seepage can lead to high hydraulic gradients across core or shell material, which requires protection so as to avoid contributing to a failure. This protection is provided by way of a filter and drain in most instances. In some cases impermeable barriers are used.

The path along which piping takes place may vary. While experience has shown piping readily chooses a route along an outlet conduit or adjacent to an abutment or concrete gravity structure, other routes readily encountered include positions of low stress; zones exposed to high hydraulic gradients and/or windows in the filter system. An example of the latter is the Zoeknog Dam which failed on first filling in 1993 (Keller et al, 1993). This 40m high homogeneous embankment dam having a morning-glory spillway was constructed with the embankment ahead of the outlet conduit. The embankment filter system was then not tied into the outlet conduit competently.

Because permeability can vary over a range of many billions of times it is important to have a practical understanding of this property for materials used in engineering drainage. Soil, aggregates and jointed, cracked or vesicular rocks are often permeable to air and water. Many materials allow the movement of fluids by diffusion process but that is outside the scope of this paper. The permeability of most rock abutments and dam foundations is determined almost entirely by the joint and cracked patterns, and many clays are extremely resistant to the flow of water yet shrinkage cracks or interbeds of silts or sand may increase their permeabilities thousands of times (Cedergren, 1989). Controlled removal of seepage water from hydraulic structures by filters is desired for structural stability.

Factors which affect the permeability of soil include:

- Viscosity of the permeant which for water varies by about 100% over the range of temperatures ordinarily encountered in seepage.
- Pore spaces and hence particle sizes affect permeability factors proportional to the square of their dimension. The permeability of soils thus varies significantly with grain size and is extremely sensitive to the quantity, character and distribution of the finest fractions.
- Soil type and density. The denser the soil the smaller the pores and hence the lower the permeability. Density can thus vary the permeability by 2-1000 times, but generally the smaller the range of particles the lower the difference induced by compaction.
- Particle arrangement. If soil particles are sorted or stratified into layers or lenses, or, if a particular orientation of particles is encountered or if fines ball up as opposed to being broadly dispersed throughout the mass, the permeability for that soil will be affected.
- Open work gravel, if present, will increase soil mass permeability.
- Dispersion of fines.
- Moisture content at compaction (can vary permeability by as much as a 1000 times for a 2% variation in moisture content).
- Influence of discontinuities. Joints, seams or strata of different material can lead to serious variations. These discontinuities could be in the form of shrinkage or shear cracks.
- Chemical character of particles and permeant. Water soluble rocks such as limestone or gypsum can lead to the development of solution channels with time hence increase permeability. Conversely, deposition of oxides or organisms can reduce permeability.
- Size of soil or rock mass. The presence of one or more of the above factors in various zones, or combinations, will require the evaluation of a representative portion of the mass.

In light of the aforementioned, filters and drains need to give recognition to the extreme variation that can be encountered, both with respect to location and with respect to time. Thus the filter design which needs to cater for both particle retention and permeant removal requires a conservative approach.

4 FILTER CRITERIA

The criteria typically used for filter design are based on opposing extremes for granular and geosynthetic filters.

Irrespective of the base soil to be drained, the opposing principles with which the granular filter needs to comply are:

1. The pore sizes between the filter particle medium must be coarse enough to allow the seepage water to drain away freely, and
2. The pore openings between the filter particle medium must be small enough to retain the coarse fraction of the base soil (which in turn is to retain the remainder of the base soil).

This is done by setting a limit to the ratio between the fine (D_{15}) fraction of the filter material and the coarse (d_{85}) particle range of the base soil. The filter criteria for sands and gravels have been well established but it was the advancement by Sherard and his co-workers who further developed criteria for silts and clays in the 1980's that has established the basic principles of granular filter criteria used today (see Table 1.) Sherard and Dunnigan (1989) found that fine grain materials having between 40 and 85% passing the 0.075mm sieve (cohesion of base soil does not influence filter requirements) require a limit to the D_{15} of the filter at 0.7mm. Still finer material requires special consideration while material falling in the category between 15 and 40% passing the 0.75mm sieve is considered intermediate and extrapolation between criteria is required.

Table 1: Summary of Soil Granular Filter Criteria

Group	Soil type as % passing through the 0.075 mm sieve	Filter Criteria
1	≥ 85	D15 ≤ 9xd85, but not smaller than 0.2 mm
2	40 to 85	D15 = 0.7 mm
3	0 to 15	D15 ≤ 4xd85
4	15 to 40	D15 ≤ (40 - A) / (40 – 15) (4xd85 – 0.7 mm) + 0.7 mm where A is the % between 15 and 40

This would mean that for draining fine grained (impervious or semi pervious) typical core material the D_{15} of a filter having a requirement of being less or equal to 0.7mm nominal diameter will have the characteristic pore spaces controlling piping i.e. retention, of less than 0.116mm. This can be shown by assuming that the particles are spherical and using Pythagoras to ascertain that the diameter of a sphere, which will just pass between three equal diameter spheres having diameter "D", is d=D/6). The rest of the granular filter's characteristic pore spaces would be larger.

For all base soil groups, the granular filter criteria are based on the smallest characteristic pore size of the granular filter.

The advent of geotextiles for use in civil engineering has realised numerous filter criteria for geotextiles which are typically based on some characteristic opening size of the geotextile which reflects the diameter of the largest pore size and some finer soil particle size (John, 1987). The generic types of geotextile used in filter applications in embankment dams, tailings dams and mine backfilling nowadays cover the full spectrum of nonwoven; woven and knitted products. The latter have been restricted in use primarily to underground workings. Designers need to recognise the distinct differences in characteristics of the geotextile types, such as their percentage open area, porosity and tortuosity of flow paths through the fabric, over and above the range of criteria. See Table 2.

Table 2: Regional Geotextile Filter Design Criteria (after John, 1989)

American Practice	
Soil Description	Geotextile Criteria
$d_{50} > 0.075$ mm	$0.297 \text{ mm} \le O_{95} \le d_{85}$ (wovens)
	$0.297 \text{ mm} \le O_{95} \le 1.8d_{85}$ (nonwovens)
$d_{50} \le 0.075$ mm, $U \le 2$	$O_{95} \le d_{85}$
$2 \le U \le 4$	$O_{95} \le 0.5Ud_{85}$
$4 \le U \le 8$	$O_{95} \le 8d_{85} / U$
$U \ge 8$	$O_{95} \le d_{85}$
Where U is the base soil Coefficient of Uniformity.	

Dutch Practice
For static unidirectional flow, originally $O_{90} < d_{90}$ for wovens and $O_{90} < 1.8d_{90}$ for nonwovens, both these are relaxed by the Dutch Coastal Works Association to $O_{90} < 2d_{90}$.

German Practice	
Soil Description	Geotextile Criteria
$d_{40} < 0.06$ mm, stable soil	$D_w < 10d_{50}$ and $D_w < 2d_{90}$
$d_{40} < 0.06$ mm, problem soil	$D_w < 10d_{50}$ and $D_w < d_{90}$
$d_{40} > 0.06$ mm, stable soil	$D_w < 5d_{10}U^{1/2}$ and $D_w < 2d_{90}$
$d_{40} > 0.06$ mm, problem soil	$D_w < 5d_{10}U^{1/2}$ and $D_w < d_{90}$
Note: Problem soils are defined as those falling in any of the following three categories: Fine grained soils with a plasticity index of less than 0.15 % Soils whose average particle size (d_{50}) lies between 0.02 and 0.1mm Soils with a uniformity coefficient of less than 15 that also contain clay- or silt- sized particles.	

French Practice	
These criteria recognise the base soil's co-efficient of Uniformity (U); soil "tightness" or density, and hydraulic gradient (i).	
Soil Description	Geotextile Criteria
Well graded (U > 4) and dense	$4d_{15} \le O_f \le 1.25d_{85}$
Well graded (U > 4) and loose	$4d_{15} \le O_f \le d_{85}$
Uniformly graded ($U \le 4$) and dense	$O_f \le d_{85}$
Uniformly graded ($U \le 4$) and loose	$O_f \le 0.8d_{85}$
Note: When the hydraulic gradient (i) in the vicinity of the geotextile lies between 5 and 20, then the geotextile pore sizes specified above should be reduced by 20%. Similarly, if it exceeds 20, or reversing flow conditions are present, then the pore size should be reduced by 40%. (The 0_f values used above are the geotextile's characteristic pore sizes as measured by the French AFNOR 38017 test).	

English Criteria	
Based on the principle that if a characteristic particle size is retained (e.g. d_{95}), a reverse filter will form, even for broadly graded soils (having a high coefficient of uniformity U). This is summarised as:	
Minimum size of soil particle to be positively restrained	Maximum value for O_{95}
d_5	$d_{50}U'^{-0.9}$
d_{15}	$d_{50}U'^{-0.7}$
d_{50}	d_{50}
d_{60}	$d_{50}U'^{0.2}$
d_{85}	$d_{50}U'^{0.7}$
d_{90}	$d_{50}U'^{0.8}$
d_{95}	$d_{50}U'^{0.9}$
	where U' is the modified coefficient of uniformity

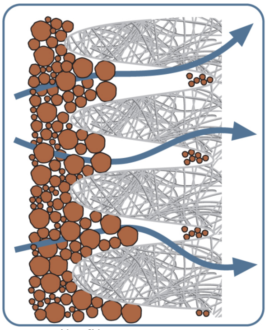
Other Criteria
In the USA, the permeability criteria laid down by AASHTO-AGC-ARTBA Task Force 25 for critical or severe applications is: $k_g > 10k_s$ (where k_g = permeability of the geotextile and k_s = permeability of the base soil). In addition, Task Force 25 specifies that for woven monofilament geotextiles, the percentage open area should be greater than 4% and the $0_{95}>2d_{15}$ may sometimes also be used in the USA. (John, 1989, pp174). The additional criteria of $O_{95} > 2d_{15}$ may sometimes also be used in the USA. All these criteria consider a characteristic particle size, e.g. (d_{50}) of the base soil or typically a larger fraction, and compare it to the (larger) characteristic opening size of the geotextile (e.g. O_{95}, O_f, D_w). These criteria demonstrate the significant difference between natural and synthetic filter criteria as: Granular filters are based on the smallest characteristic opening size. Geotextile filters are based on their largest characteristic opening size.

5 MECHANISM OF GEOTEXTILE FILTER PERFORMANCE

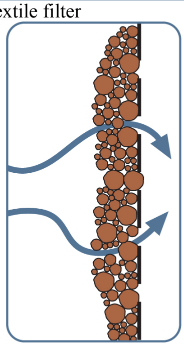
For a geotextile filter to work, a transition zone needs to be induced within the base soil by, and adjacent to, the geotextile upon movement of the permeant towards the drain. This happens provided that the fine fraction (controlling permeability) of the base soil does not build up at the interface of the base soil and geotextile filter, but rather passes beyond that interface. The geotextile openings must simultaneously also be fine enough merely to retain the coarse fraction of the soil, which in turn will retain its medium and fine fractions. Thus in the case of nonwoven geotextiles the fine fraction typically passes beyond the interface and whilst some material is often trapped within the geotextile thickness where the flow paths narrow, the permeant and ultra fine material passes around such trapped material, along often tortuous routes through the porous geotextile to exit into the drainage medium. Similarly for woven tape geotextiles the fine fraction departs from the base soil at the interface zone around the geotextile openings, and passes through the geotextile with very little entrapment taking place between tapes or filaments. Because the pores of woven textiles are usually relatively large compared to the base soil, the medium fraction also passes through the geotextile. Thus a cone of coarse particles is established around each opening in the woven tape material and the base soil drains through these cones of pervious transition material. In cross section it is almost the inverse of these cones of pervious material, which develop in the case of nonwoven geotextiles. (See Figure 1a and b).

Furthermore, in the case of nonwoven geotextiles, the base soil particles that enter the interface zone of the geotextile, give it a reinforcing effect. Thus, if deformed after initial performance, this type of geotextile maintains to a large extent the established more pervious interface zone. This is an important attribute when considering embankment settlement and more landfill filter loading.

Figure 1. Diagrammatic presentation of main generic types of geotextiles



(a) Nonwoven geotextile filter



(b) Woven mechanisms

There are however other factors to be taken into consideration when considering geotextiles as filters in critical and non critical applications. These include inter alia settlement induced changes; the construction procedure; durability of the polymer and the ease with which the product can be replaced in the event of failure.

5.1 *Construction Period Considerations*

Designers need to recognise whether the base soil is to be placed adjacent to the geotextile as hydraulic fill such as in tailings dams and mine back-fill, or as "dry material". In the event of the base material being placed hydraulically the fine fraction of the base soil is extremely mobile and a build up thereof within the geotextile structure would result in inadequate performance of the filter in many cases. Thus nonwovens are typically not used in backfill bag applications at present. In this sort of application specifically developed woven tape and knitted products are used to ensure drainage while allowing for the loss of larger volumes of fines. Typically the woven tape products used will allow 5-10 times the mass of fines to pass through the geotextile than for a nonwoven product, as shown by the Interface Flow Capacity Test (Legge, 1990).

Consideration should also be given to whether the fine fraction of the base soil could be windblown to the extent that it would contaminate either a filter or drain. Hence the authors are reticent to rely on filter criteria that refer to permeability alone (Giroud, 2006). Thus in the case of tailings dams in particular, a sacrificial layer of geotextile is used to cover the drain during construction and this is removed immediately prior to the placement of the tailings adjacent to the permanent granular filter. The sacrificial layer of geotextile used is typically a light nonwoven product and is used to trap the large volumes of windblown fine material so as to prevent them from contaminating the granular filter and drain. Thus in structures such as tailings dams and mono-waste landfills due to the relatively uniform particle grading and fine nature of the waste, only nonwoven products are fine enough to consider as suitable filters.

5.2 *Settlement Induced Deformation*

While overall settlements of structures are generally small the filter may be required to undergo larger local deformations. Thus the drainage material should not sustain an open crack and hence the criterion for granular filters is that there should not be more than 5% passing the 75 micron sieve. Bear in mind however, that in constructing the embankment dam or tailings dam the base material to be drained is placed adjacent to the geotextile and some intrusion takes place at this early stage. The reverse filter is then established at the interface; and across the entire interface area. Thus when time related settlements do occur the transition zone is already depleted of fine material. Furthermore the finer fraction finds itself entrapped in the geotextile and thus the deformation of the geotextile structures after exposure to the base soil, does not allow for significant change in pore size because the entrapped particles hold the geotextile to a large extent in the same form as when placed initially. In effect what is happening is the base soil is now acting as a "reinforcing" element within the nonwoven geotextile. Woven tapes however, when deforming, undergo an initial closing of the pore space and then an opening thereof. Because no soil is trapped within the woven fabric this reinforcing aspect cannot take place and the pore is essentially an unstable opening size, under deformation.

5.3 *Porosity*

In considering woven geotextile porosity, it is impractical to determine as these products essentially act as two dimensional filter catalysts. The nonwoven products however act as three dimensional catalysts and porosity is a critical factor in ensuring performance, even when the base soil is poorly compacted. Note it is the fine fraction of the soil which generally controls its permeability. While there is some debate as to what the fine fraction is, it certainly should be noted that the soil which makes up less than 30% of the mass can be considered fine in respect to the rest. A larger percentage would then imply that, this fraction is more than filling the voids within the typical matrix of the soil.

Considering then what happens at the interface between the base soil and geotextile filter where the fine fraction is initially placed: for a geotextile having porosities as high as 90%, more than the characteristic amount of fine material found at the interface can be accepted by the geotextile without negative influence on its filter performance. The Interface Flow Capacity test has shown that up to 3 times the characteristic interface fine fraction soil mass can be accepted by a nonwoven geotextile before it shows noteworthy reduction in permeability.

5.4 *Laboratory Test Series*

Recognizing the variability and behavior of typical impervious and semi pervious soils in embankment dams, a series of tests were undertaken to ascertain the suitability of geotextiles as filters to such soils. A series of permeameter pot tests were undertaken, including Gradient Ratio tests, with a wide range of geotextile types and a semi pervious soil sample to ascertain filter performance. Although the results varied, the extremes were within a single order of magnitude, and showed no signs of excessive piping nor clogging. Although a predictable overall reduction in permeability was noted with time, a daily variation was noted which corresponded to changes in ambient temperature. It is believed that this variable flow followed a path between the soil sample and side wall of the permeameter.

The Interface Flow Capacity Test (IFC) was thus developed which separates a soil sample into a fine and a course fraction at the 30% particle size and measures the reduction in through-flow rate of the geotextile with exposure to increments in mass of a particular fraction. Such test clearly indicates susceptibility of a soil/geotextile combination to piping or clogging.

A further component of the series comprised using a modified large diameter triaxial cell to expose soil/geotextile combinations to high hydraulic gradients. This type of test revealed the vulnerability of some geofilters to piping failure, in particular following limited stress deformation.

5.5 *Other Considerations*

Organic clogging and chemical deposits (precipitates) may take place within the drainage medium irrespective of whether it is a synthetic or natural material. Designers need to design for such an event. In the case of ERGO, a large tailings dam, some experiences have been obtained in remediating biological clogging of geotextiles by inducing sudden changes to the environment within which this organic material develops. The occasional use of a "p-trap" on the outlet has been made to suddenly change the blanket drain from an aerobic to anaerobic condition on a regular basis, to control this growth as it is fitted and later removed from the outlet pipe.

Shrinkage cracks can develop in embankment dams, resulting in harsh hydraulic loading conditions on filters. In the remedial works at Kwaggaskloof Dam, regular cracks as wide as 40mm each were recorded, adjacent to the chimney drain. The remedial works were necessary as the dam had been constructed with an out of specification granular filter. Attempts at modifying the filter by using a foamed grout were investigated, but not implemented due to fear of leaving a window in the existing chimney drain and hence complete grouting with an additional down-stream berm was employed.

6 CONCLUSION

The ICOLD Bulletin on "Geotextiles as Filters and Transitions in Fill Dams" recommends that geotextiles not be used as critical filters in dams. This is due to the nature of their being thin and easily damaged, as well as the questions of durability, and in applications where they cannot be reached for replacement they are considered too high a risk for the sole defence against piping. The above however shows that geotextile filters significantly reduce the risk of contamination of drainage media and allow thus for thinner drains due to their mechanism of filtration. Furthermore, due to their tensile attributes geotextiles reduce the risk of sustaining an open crack in granular filters.

It is thus recommended that while geotextiles can be selected for use in non critical applications such as the outside of embankment dams under rip-rap etc, based on filter criteria and compatibility testing, nonwoven type geotextiles should be used as an adjunct to the filter drains within the embankment to reduce thickness thereof and hence cost; to reduce the risk of sustaining an open crack in the granular filter material, and provide added protection of the drain upon settlement in geotechnical structures.

So too is it recognised that due to the tensile resistance of a geotextile, they may readily span open cracks and thus induce early self-healing in the base material, particularly where marginal granular filters are used.

Through combining the advantages of granular filters and geosynthetic filters into the design of composite filter systems the performance of critical filter systems are enhanced and overcome historical reticence for relatively recent technologies and provides for competent, cost-effective filter systems.

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