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GEOTEXTILES IN FILTRATION APPLICATIONS

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ABSTRACT

Geotextile filters are rapidly replacing graded granular filters as the standard of practice in geotechnical design. However, as with graded granular filters, their performance cannot be assured without proper design. This paper presents the application and design of geotextile filters used in drainage and erosion control systems. Design is presented in generic form such that national standards and local conditions can be considered in evaluating the properties required for the geotextile. A step-by-step design approach is included.

BACKGROUND

One major area of geotextile use is as filters in drain applications such as trench and interception drains, blanket drains, pavement edge drains, structure drains, and beneath permeable roadway bases. The *filter* restricts movement of soil particles as water flows into the *drain* structure and is collected and/or transported downstream. Geocomposites consisting of a drainage core surrounded by a geotextile filter are often used as the drain itself in these applications. Geotextiles are also used as filters beneath hard armor erosion control systems.

Because of their comparable performance, improved economy, consistent properties, and ease of placement, geotextiles have been used successfully to replace graded granular filters in almost all drainage applications. Thus, they must perform the same functions as graded granular filters:

- to allow water to flow through the filter into the drain, and to continue doing this throughout the life of the project; and

- to retain the soil particles in place and prevent their migration (*piping*) through the filter (if some soil particles do move, they must be able to pass through the filter without blinding or clogging the downstream media during the life of the project).

Geotextiles, like graded granular filters, require proper engineering design or they may not perform as desired. Unless flow requirements, piping resistance, clogging resistance and constructability requirements (defined later) are properly specified, the geotextile/soil filtration system may not perform properly. In addition, construction must be monitored to ensure that materials are installed correctly. This paper reviews the application of and design requirements for geotextiles used as filters. This guidance is edited from the recently published book "Geosynthetic Engineering" by Holtz, Christopher and Berg (1997) which contains detailed recommendations for complete design of geotextile filters as well as most other applications.

APPLICATIONS

Properly designed geotextiles can be used as a replacement for (or in conjunction with) conventional graded granular filters in almost any drainage application. Properly designed geocomposites can be used as a replacement for granular drains in many applications (*e.g.*, pavement edge drains). In most drainage and filtration applications, geotextile use can be justified over conventional graded granular filter material use because of cost advantages from:

- Use of less-costly drainage aggregate;
- Possible use of smaller-sized drains;
- Possible elimination of collector pipes;
- Expedient construction;
- Lower risk of contamination and segregation of drainage aggregate during construction; and,
- Reduced excavation.

Examples of drainage applications include:

- Filters around trench drains and edge drains -- to prevent soil from migrating into the drainage aggregate or system, while allowing water to exit from the soil.
- Filters beneath pavement permeable bases, blanket drains and base courses. Prefabricated geocomposite drains and geotextile-wrapped trenches are used in pavement edge drain construction.
- Drains for structures such as retaining walls and bridge abutments. The geotextile separates the drainage aggregate or system from the backfill soil, while allowing free drainage of ground and infiltration water. Geocomposite drains are especially useful in this application.
- Geotextile wraps for slotted or jointed drain and well pipes -- to prevent filter aggregate from entering the pipe, while allowing the free flow of water into the pipe.
- Interceptor, toe drains, and surface drains -- to aid in the stabilization of slopes by allowing excess pore pressures within the slope to dissipate, and by preventing surface erosion. Again, geocomposites have been successfully used in this application.
- Chimney and toe drains for earth dams and levees -- to provide seepage control.

Examples of geotextiles used as filters in erosion control systems include:

- Riprap armor stone placed over geotextile filters have found successful application in protecting precipitation runoff collection and high-velocity diversion ditches.
- Geotextiles may be used in slope protection to prevent or reduce erosion from precipitation, surface runoff, and internal seepage or piping. In this instance, the geotextile may replace one or more layers of granular filter materials which would be placed on the slope in conventional applications.
- Riprap-geotextile erosion control systems may also be required along streambanks to prevent encroachment of roadways or appurtenant facilities.
- Similarly, riprap-geotextile systems may be used for scour protection around structures.
- A riprap-geotextile system can also be effective in reducing erosion caused by wave attack or tidal variations when facilities are constructed across or adjacent to large bodies of water.
- Finally, hydraulic structures such as culverts, drop inlets, and artificial stream channels may require protection from erosion. In such applications, if vegetation cannot be established or the natural soil is highly erodible, a geotextile can be used beneath armor materials to increase erosion resistance.

In several of the above applications, placement of the filter layer may be required below water. In these cases, in comparison with conventional granular filter layers, geotextiles provide easier placement and continuity of the filter medium is assured.

In each of these applications, flow is through the geotextile -- that is, perpendicular to the plane of the fabric. In other applications, such as vertical drains in soft foundation soils, lateral drains below slabs and behind retaining walls, and gas transfer media, flow may occur both perpendicular to and transversely in the plane of the geotextile. In many of these applications, geocomposite drains may be appropriate.

All geosynthetic designs should begin with a criticality and severity assessment of the project conditions (see Table 1) for a particular application. First developed by Carroll (1983) for drainage and filtration applications, the concept of critical-severe projects -- and, thus, the level of engineering responsibility required -- should be applied to all geosynthetic applications.

TABLE 1
GUIDELINES FOR EVALUATING THE CRITICAL NATURE OR SEVERITY OF DRAINAGE AND EROSION CONTROL APPLICATIONS
(after Carroll, 1983)

A. Critical Nature of the Project		
Item	Critical	Less Critical
1. Risk of loss of life and/or structural damage due to drain failure:	High	None
2. Repair costs versus installation costs of drain:	>>>	= or <
3. Evidence of drain clogging before potential catastrophic failure:	None	Yes
B. Severity of the Conditions		
Item	Severe	Less Severe
1. Soil to be drained:	Gap-graded, pipable, or dispersible	Well-graded or uniform
2. Hydraulic gradient:	High	Low
3. Flow conditions:	Dynamic, cyclic, or pulsating	Steady state

A few words about the condition of the soil to be drained (Table 1) are in order. First, gap-graded, well-graded and uniform soils are illustrated in Figure 1. Certain gap-graded and very well-graded soils may be *internally unstable*; that is, they can experience piping or internal erosion. Unstable soils include gap-graded, broadly graded and dispersive soils such as sugar sands, rock flour, and other highly erodible soils. On the other hand, a soil is *internally stable* if it is self-filtering and if its own fine particles do not move through the pores of its coarser fraction (Lafleur, et al., 1993). Most of the design criteria assumes that the soil to be filtered is internally stable -- it will not pipe internally. If unstable soil conditions are encountered, performance tests should be conducted to select suitable geotextiles.

An evaluation of the grain size curve will provide a good indication of the stability of the soil. In gap-graded soils, there exists a coarse and fine fraction, but very little medium fraction. If there is an insufficient quantity of soil particles in the medium fraction, fine soil particles pipe through the coarse fraction.

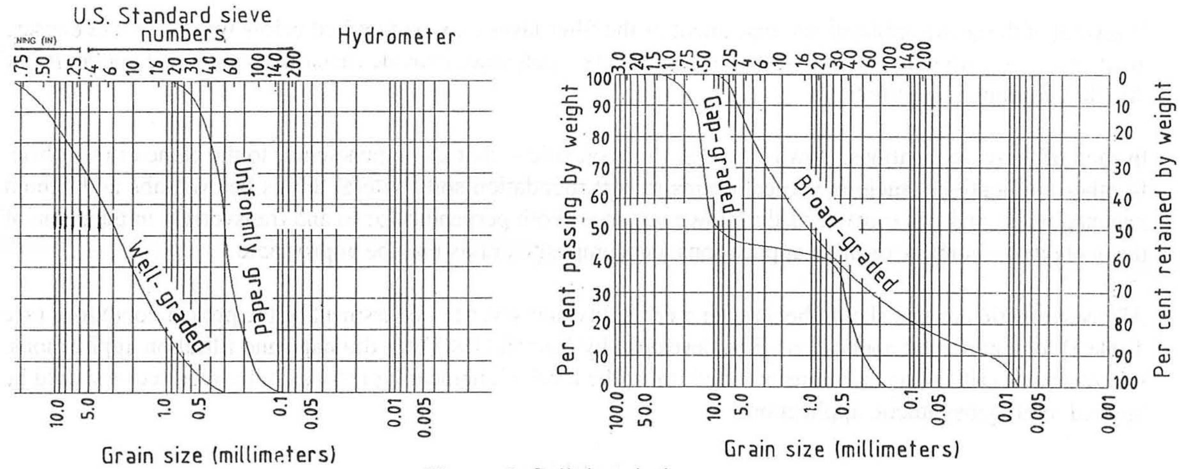

Figure 1 Soil descriptions.

In broadly graded soils, the gradation is distributed over a very wide range of particle sizes such that fine soil tends to pipe through coarser particles. According to Kenney and Lau (1985, 1986) and Lafleur, et al. (1989), broadly graded ($C_u > 20$) soils with concave upward grain size distributions tend to be internally unstable. The Kenney and Lau (1985, 1986) procedure utilizes a mass fraction analysis. Research by Skempton and Brogan (1994) verified the Kenney and Lau (1985, 1986) procedure.

Dispersible soils are fine-grained natural soils which deflocculate in the presence of water and, therefore, are highly susceptible to erosion and piping (Sherard, et al., 1972). See also Sherard and Decker (1977) for more information on dispersible soils.

GEOTEXTILE FILTER DESIGN

Designing with geotextiles for filtration is essentially the same as designing graded granular filters. A geotextile is similar to a soil in that it has voids (pores) and particles (filaments and fibers). However, because of the shape and arrangement of the filaments and the compressibility of the structure with geotextiles, the geometric relationships between filaments and voids are more complex than in soils. In geotextiles, pore size is measured directly, rather than using particle size as an estimate of pore size, as is done with soils. Since pore size can be directly measured, relatively simple relationships between the pore sizes and particle sizes of the soil to be retained can be developed. Three simple filtration concepts are used in the design process:

1. If the size of the largest pore in the geotextile filter is smaller than the larger particles of soil, the soil will be retained by the filter. As with graded granular filters, the larger particles of soil will form a filter bridge over the hole, which in turn filters smaller particles of soil, which then retain the soil and prevent piping (Figure 2).
2. If the smaller openings in the geotextile are sufficiently large enough to allow smaller particles of soil to pass through the filter, then the geotextile will not *blind* or *clog* (see Figure 3).
3. A large number of openings should be present in the geotextile so proper flow can be maintained even if some of the openings later become plugged.

These simple concepts and analogies with soil filter design criteria are used to establish design criteria for geotextiles. Specifically, these criteria state:

- the geotextile must retain the soil (retention criterion), while
- allowing water to pass (permeability criterion), throughout
- the life of the structure (clogging resistance criterion).

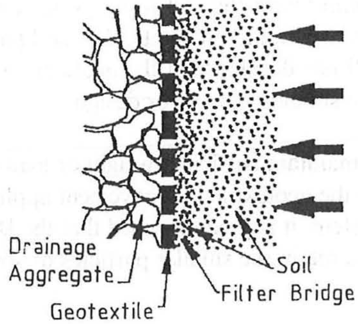

Figure 2 Filter bridge formation.

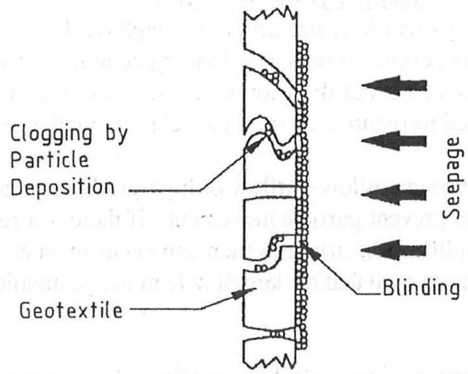

Figure 3 Definitions of clogging and blinding (Bell and Hicks, 1980).

To perform effectively, the geotextile must also survive the installation process (survivability criterion).

After a detailed study of research carried out both in North America and in Europe on conventional and geotextile filters, Christopher and Holtz (1985) developed the following design procedure for geotextile filters for drainage and permanent erosion control applications. The original, specific criteria were based on the ASTM dry sieve procedure for determining the opening size of the geotextile. In this paper, the criteria are presented in generic form to allow the use of alternate opening size procedures and to adopt local conditions. For a summary of international design criteria, any of which can be adapted to the recommended design approach, please refer to Christopher and Fischer (1991). A step-by-step procedure which incorporates the filtration criteria in a complete drainage or erosion control system design is presented in an appendix to this paper.

The level of design required depends on the critical nature of the project and the severity of the hydraulic and soil conditions (Table 1). Especially for critical projects, consideration of the risks and the consequences of geotextile filter failure require great care in selecting the appropriate geotextile. For such projects, and for severe hydraulic conditions, conservative designs are recommended. **Geotextile selection should not be based on cost alone.** The cost of the geotextile is usually minor in comparison to the other components and the construction costs of a drainage system. Also, do not try to save money by eliminating laboratory soil-geotextile performance testing when such testing is required by the design procedure.

Retention Criteria

Steady state flow conditions

$$O_{e(geotextile)} \leq B\, D_{(soil)} \qquad [1]$$

where:

O_e = effective opening size in the geotextile for which e is the percent openings that are smaller than the opening size O (mm), usually the O_{90} or O_{95};

B = a coefficient (dimensionless); and

$D_{(soil)}$ = representative soil particle size (mm), usually the medium to larger fractions (e.g. D_{50} or D_{85}).

The coefficient B generally ranges from 0.5 to 5 and is a function of the method used to evaluate the opening size (e.g. wet versus dry methods), the characteristic O_e value, type of soil to be filtered, its density, its representative particle size, the uniformity coefficient C_u if the soil is granular, the type of geotextile (woven or nonwoven), and the flow conditions.

Dynamic flow conditions

If the geotextile is not properly weighted down and in *intimate contact* with the soil to be protected, or if dynamic, cyclic, or pulsating loading conditions produce high localized hydraulic gradients, then soil particles can move behind the geotextile. Because the bridging network will not develop and the geotextile will be required to retain even finer particles, a smaller, conservative B value should be used for design..

For reversing inflow-outflow or high-gradient situations, it is best to maintain sufficient weight or load on the filter to prevent particle movement. If there is a risk of movement of the geotextile in a pavement application or if uplift of the armor system can occur in an erosion protection system, it is recommended that the B value be reduced such that the largest hole in the geotextile is small enough to retain the smaller particles of soil (e.g. D_{15}).

In many erosion control applications it is common to have high hydraulic stresses induced by wave or tidal action. The geotextile may be loose when it spans between large armor stone or large joints in block-type armor systems. For these conditions, it is recommended that an intermediate layer of finer stone or gravel be placed over the geotextile and that riprap of sufficient weight be placed to prevent wave action from moving either stone or geotextile. For all applications where the geotextile can move, and when it is used as sandbags, it is recommended that samples of the site soils be washed through the geotextile to determine its particle-retention capabilities.

Stable versus unstable soils

The above retention criteria assumes that the soil to be filtered is internally stable -- it will not pipe internally. If unstable soil conditions are encountered, performance tests should be conducted to select suitable geotextiles.

Permeability/Permittivity Criteria

Permeability requirements:
The general equation for permeability is:

$$k_{geotextile} \geq FS \bullet k_{soil} \qquad [2]$$

$$\psi_{allow} \geq FS \bullet \psi_{required} \qquad [3]$$

-- for *less critical applications* and *less severe conditions, typically the following relation is used*:

$$k_{geotextile} \geq k_{soil} \qquad [4]$$

-- and, for *critical applications* and *severe conditions, the factor of safety should be increased an order of magnitude or greater*:

$$k_{geotextile} \geq 10\, k_{soil} \qquad [5]$$

Minimum permittivity requirements (to make sure that a geotextile with a sufficient flow capacity is used):

$$\psi \geq 0.1 \text{ to } 1 \text{ sec}^{-1} \qquad [6]$$

In these equations:

k	=	Darcy coefficient of permeability (m/s); and
ψ	=	geotextile permittivity, which is equal to $k_{geotextile}/t_{geotextile}$ (1/s) and is a function of the hydraulic head.

For actual flow capacity, the permeability criteria for noncritical applications is conservative, since an equal quantity of flow through a relatively thin geotextile takes significantly less time than through a thick granular filter. Even so, some pores in the geotextile may become blocked or plugged with time. Thus, for critical or severe applications, Equation 5 is recommended to provide additional conservatism.

The required flow rate, q, through the system should also be determined, and the geotextile and drainage aggregate selected to provide adequate capacity. As indicated above, flow capacities should not be a problem for most applications, provided the geotextile permeability is greater than the soil permeability. However, in certain situations, such as where geotextiles are used to span joints in rigid structures and where they are used as pipe wraps, portions of the geotextile may be blocked. Also, in certain erosion control systems, portions of the geotextile may be covered by the armor stone or concrete block revetment systems, or the geotextile may be used to span joints in sheet pile bulkheads. For such systems, it is especially important to evaluate the flow rate required through the open portion of the system and select a geotextile that meets those flow requirements. For these applications, the following criteria should be used together with the permeability criteria:

$$q_{required} = q_{geotextile}(A_g/A_t) \qquad [7]$$

where:

A_g = geotextile area available for flow; and
A_t = total geotextile area.

Clogging Resistance

Less critical/less severe conditions

For *less critical/less severe* conditions:

$$O_{e\,(geotextile)} \geq 3\ D_{15\,(soil)} \qquad [8]$$

Equation 8 applies to soils with $C_u > 3$. For $C_u \leq 3$, select a geotextile with the maximum O_e value from retention criterion.

In situations where clogging is a possibility (*e.g.*, gap-graded or silty soils), the following *optional* qualifiers may be applied:

for *nonwovens* -

$$\text{porosity of the geotextile, } n \geq 50\% \text{ to } 70\% \qquad [9]$$

for *woven monofilament wovens* -

$$\text{percent open area, POA} \geq 4\% \text{ to } 10\% \qquad [10]$$

Most common nonwovens have porosities much greater than 70%. Most woven monofilaments easily meet the criterion of Equation 2-12; woven slit films typically do not, and are therefore not recommended for subsurface drainage or erosion control applications.

For *less critical/less severe* conditions, a simple way to avoid clogging, especially with silty soils, is to allow fine particles already in suspension to pass through the geotextile. Then the *bridge network* (Figure 2) formed by the larger particles retains the smaller particles. The bridge network should develop rather quickly, and the quantity of fine particles actually passing through the geotextile is relatively small. This is why the *less critical/less severe* clogging resistance criteria requires an AOS (O_{95}) sufficiently larger than the finer soil particles (D_{15}). Those are the particles that will pass through the geotextile. Unfortunately, the AOS value only indicates the size and not the number of O_{95}-sized holes available. Thus, the finer soil particles will be retained by the smaller holes in the geotextile, and if there are sufficient fines, a significant reduction in flow rate can occur.

Consequently, to control the number of holes in the geotextile, it may be desirable to increase other qualifiers such as the porosity and open area requirements. There should always be a sufficient number of holes in the geotextile to maintain permeability and drainage, even if some of them clog.

Filtration tests provide another option for consideration, especially by *inexperienced users*. A simple method to check the geotextile is to mix the fines with water to form a slurry. If the fines will pass though the geotextile it will not clog. However, if fines are retained on the geotextile, this does not necessarily mean that it will clog, only that a better test should be performed as discussed in the next section.

Critical/severe conditions

For *critical/severe* conditions, select geotextiles that meet the retention and permeability criteria. Then perform a filtration test using samples of on-site soils and hydraulic conditions. Since erosion control systems are often used on highly erodible soils with reversing and cyclic flow conditions, severe hydraulic conditions often exist. Accordingly, designs should reflect these conditions, and soil-geotextile filtration tests should always be conducted.

Although several empirical methods have been proposed to evaluate geotextile filtration characteristics (*i.e.*, the clogging potential), the most realistic approach for all applications is to perform a laboratory test which simulates or models field conditions. One type of filtration test is the gradient ratio test, ASTM D 5101, "Measuring the Soil-Geotextile System Clogging Potential by the Gradient Ratio" (1994). This test utilizes a rigid-wall soil permeameter with piezometer taps that allow for simultaneous measurement of the head loss in the soil and the head loss across the soil/geotextile interface. The ratio of the head loss across this interface (nominally 25 mm) to the head loss across 50 mm of soil is termed the *gradient ratio*. As fine soil particles adjacent to the geotextile become trapped inside or blind the surface, the gradient ratio will increase. A gradient ratio less than 3 is recommended by the U.S. Army Corps of Engineers (1977), based upon limited testing with severely gap-graded soils. Because the test is conducted in a rigid-wall permeameter, it is most appropriate for sandy and silty soils with $k \geq 10^{-7}$ m/s.

For soils with permeabilities less than about 10^{-7} m/s, long-term filtration tests should be conducted in a flexible wall or triaxial type apparatus to insure that flow is through the soil rather than along the sides of the specimen. The soil flexible wall test is ASTM D 5084, while the Hydraulic Conductivity Ratio (HCR) test (ASTM D 5567) has been suggested for geotextiles (see Section 1.5). Unfortunately, neither test is able to measure the permeability near the soil-geotextile interface nor determine changes in permeability and hydraulic gradient within the soil sample itself - a serious disadvantage (Fischer, 1994). Fortunately, very fine-grained, low-permeability soils rarely present a filtration problem unless they are dispersive (Sherard and Decker, 1977) or subject to hydraulic fracturing, such as might occur in dams under high hydraulic gradients (Sherard, 1986).

Again, it is emphasized that these filtration tests are *performance tests*. They must be conducted on samples of project site soil by the specifying agency or its representative. These tests are the responsibility of the engineer because manufacturers generally do not have soil laboratories or samples of on-site soils. Therefore, realistically, the manufacturers are unable to certify the clogging resistance of a geotextile.

Biological clogging can also occur, especially in landfill applications. The potential for biological clogging can be examined with ASTM D 1987, "Standard Test Method for Biological Clogging of Geotextile or Soil/Geotextile Filters" (1991). If biological clogging is a concern, a higher-porosity geotextile may be used, and/or the drain design and operation can include an inspection and maintenance program to flush the drainage system.

Survivability and Endurance Criteria

To be sure the geotextile will survive the construction process, certain geotextile strength and endurance properties are required for filtration and drainage applications. Several national codes have been established that provide specific guidance to minimum property requirements for both drainage and erosion control applications (e.g. USA, AASHTO M288, 1996).

As placement of armor stone is generally more severe than placement of drainage aggregate, required property values should be higher for erosion control applications. Also , in addition to standard strength requirements, consideration must be given to the potential for geotextile abrasion by the armor stone. Riprap or armor stone should be large enough to withstand wave action and thus not abrade the geotextile. The specific site conditions should be reviewed, and if such movement cannot be avoided, then an abrasion requirement should be included in the specifications. Allowable physical property reduction due to abrasion should be specified. No reduction in piping resistance, permeability, or clogging resistance should be allowed after exposure to abrasion.

Geotextile endurance relates to its longevity. Geotextiles have been shown to be basically inert materials for most environments and applications. However, certain applications may expose the geotextile to chemical or biological activity that could drastically influence its filtration properties or durability. For example, in drains, granular filters and geotextiles can become chemically clogged by iron or carbonate precipitates, and biologically clogged by algae, mosses, etc. Biological clogging is a potential problem when filters and drains are periodically inundated, then exposed to air. Excessive chemical and biological clogging can significantly influence filter and drain performance. These conditions are present, for example, in landfills.

ADDITIONAL SELECTION CONSIDERATIONS

The late Dr. Allan Haliburton, a geotextile pioneer, noted that all geotextiles will work in some applications, but no one geotextile will work in all applications. Even though several types of geotextiles (monofilament wovens and an array of light- to heavy-weight nonwovens) may meet all of the desired design criteria, it may be preferable to use one type over another to enhance system performance. Selection will depend on the actual soil and hydraulic conditions, as well as the intended function of the design. Intuitively, the following considerations seem appropriate for the soil conditions given:

1. Graded gravels and coarse sands -- Very open geotextiles may be required to permit high rates of flow and low-risk of blinding.
2. Sands and gravels with less than 20% fines -- Open monofilament wovens and needlepunched nonwovens with large openings are preferable to reduce the risk of blinding. For thin, heat-bonded and thick, needlepunched nonwoven geotextiles, filtration tests should be performed.
3. Soils with 20% to 60% fines -- Filtration tests should be performed on all types of geotextiles.
4. Soils with greater than 60% fines -- Heavy-weight, needlepunched geotextiles and heat-bonded geotextiles tend to work best as fines will not pass. If blinding does occur, the permeability of the blinding cake would equal that of the soil.
5. Gap-graded cohesionless soils -- Consider using a uniform sand filter with a very open geotextile designed to retain the sand but allow fines to pass.
6. Silts with sand seams -- Consider using a uniform sand filter over the soil with a very open geotextile, designed to allow the silt to pass but to prevent movement of the filter sand; alternatively, consider using a heavy-weight (thick) needlepunched nonwoven directly against soil so water can flow laterally through the geotextile should it become locally clogged.

These general observations are not meant to serve as recommendations, but are offered to provide insight for selecting optimum materials. They are **not** intended to exclude other possible geotextiles that you may want to consider.

CONCLUSIONS

Experience has found geotextiles to be more forgiving than granular filters. However, in spite of their good performance, situations have arisen where they have failed to perform properly. Most often poor performance has occurred when geotextiles have not been properly designed for the specific site conditions. Proper design, as outlined in this paper, is fundamental to eliminating poor performance.

REFERENCES

ASTM (1994), *Annual Books of ASTM Standards,* American Society for Testing and Materials, Philadelphia, Pennsylvania:

Volume 4.08 (I), Soil and Rock

Volume 4.08 (II), Soil and Rock; Geosynthetics

AASHTO (1996), Standard Specifications for Geotextiles - M 288, *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, American Association of State Transportation and Highway Officials, Washington, D.C., pp 689-692.

AASHTO (1990), Guide Specifications and Test Procedures for Geotextiles, *Task Force 25 Report*, Subcommittee on New Highway Materials, American Association of State Transportation and Highway Officials, Washington, D.C.

AASHTO (1991), *Model Drainage Manual*, 1st Ed., American Association of State Highway and Transportation Officials, Washington, D.C.

Bell, J.R. and Hicks, R.G. (1980), *Evaluation of Test Methods and Use Criteria for Geotechnical Fabrics in Highway Applications - Interim Report*, Report No. FHWA/RD-80/021, Federal Highway Administration, Washington, D.C., June 190 p.

Berg, R.R. (1993), *Guidelines for Design, Specification, & Contracting of Geosynthetic Mechanically Stabilized Earth Slopes on Firm Foundations*, Report No. FHWA-SA-93-025, Federal Highway Administration, Washington, D.C., 87p.

Carroll, R.G., Jr. (1983), Geotextile Filter Criteria, *Engineering Fabrics in Transportation Construction, Transportation Research Record 916*, Transportation Research Board, Washington, D.C., January, pp. 46-53.

Cedergren, H.R. (1989), *Seepage, Drainage, and Flow Nets*, Third Edition, John Wiley and Sons, New York, 465 p.

Christopher, B.R. and Fisher, G.R. (1991), "Geotextile Filtration Principles, Practices and Problems", Proceedings of the 5th GRI Seminar on Geosynthetics in Filtration, Drainage and Erosion Control, Geosynthetic Research Institute, Philadelphia, PA, pp. 1-17.

Christopher, B.R. and Holtz, R.D. (1985), *Geotextile Engineering Manual*, Report No. FHWA-TS-86/203, Federal Highway Administration, Washington, D.C., March, 1044 p.

Dunham, J.W. and Barrett, R.J. (1974), Woven Plastic Cloth Filters for Stone Seawalls, *Journal of the Waterways, Harbors, and Coastal Engineering Division*, American Society of Civil Engineers, New York, February.

FHWA (1992), *Evaluation Scour at Bridges*, Hydraulic Engineering Circular No. 18, Federal Highway Administration IP-90-017.

FHWA (1989), *Design of Riprap Revetment*, Hydraulic Engineering Circular No. 11, Federal Highway Administration.

FHWA (1988), *Design of Roadside Channels with Flexible Linings*, Hydraulic Engineering Circular No. 15, Federal Highway Administration.

FHWA (1975), *Hydraulic Design of Energy Dissipators for Culvert and Channels*, Hydraulic Engineering Circular No. 14, Federal Highway Administration.

Fischer, G.R. (1994), *The Influence of Fabric Pore Structure on the Behavior of Geotextile Filters*, Ph.D. Dissertation, University of Washington, 498 p.

Giroud, J.P. (1980), Introduction to Geotextiles and Their Applications, *Proceedings of the First Canadian Symposium on Geotextiles*, Calgary, Alberta, September, pp. 3-31.

GRI Test Method GT1 (1993), Geotextile Filter Performance via Long Term Flow (LTF) Tests, Standard Test Method, Geosynthetic Research Institute, Drexel University, Philadelphia, PA.

Holtz, R.D., Christopher, B.R. and Berg, R.R., Geosynthetic Engineering, BiTech Publishers Ltd., Richmond, British Columbia, Canada, 1997, 452 p..

Hunt, J.R. (1982), The Development of Fin Drains for Structure Drainage, *Proceedings of the Second International Conference on Geotextiles*, Las Vegas, Nevada, Vol. 1, August, pp. 25-36.

Kenney, T.C. and Lau, D. (1985), Internal Stability of Granular Filters, *Canadian Geotechnical Journal*, Vol. 22, No. 2, pp. 215-225.

Kenney, T.C. and Lau, D. (1986), Reply (to discussions) - Internal Stability of Granular Filters, *Canadian Geotechnical Journal*, Vol. 23, No. 3, pp. 420-423.

Keown, M.P. and Dardeau, E.A., Jr. (1980), *Utilization of Filter Fabric for Streambank Protection Applications*, TR HL-80-12, Hydraulics Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Koerner, R.M., *Designing With Geosynthetics*, 3rd Edition, Prentice-Hall Inc., Englewood Cliffs, NJ, 1994, 783p.

Koerner, R.M., Koerner, G.R., Fahim, A.K. and Wilson-Fahmy, R.F. (1994), *Long Term Performance of Geosynthetics in Drainage Applications*, National Cooperative Highway Research Program, Report No. 367, 54 p.

Lafleur, J., Mlynarek, J. and Rollin, A.L. (1993), Filter Criteria for Well Graded Cohesionless Soils, Filters in Geotechnical and Hydraulic Engineering, *Proceedings of the First International Conference - Geo-Filters*, Karlsruhe, Brauns, Schuler, and Heibaum Eds., Balkema, pp. 97-106.

Lafleur, J., Mlynarek, J. and Rollin, A.L. (1989), Filtration of Broadly Graded Cohesionless Soils, *Journal of Geotechnical Engineering, American Society of Civil Engineers*, Vol. 115, No. 12, pp. 1747-1768.

Mansur, C.I. and Kaufman, R.I. (1962), Dewatering, Chapter 3 in *Foundation Engineering*, G.A. Leonards, Editor, McGraw-Hill, pp. 241-350.

Maré, A.D. (1994), *The Influence of Gradient Ratio Testing Procedures on the Filtration Behavior of Geotextiles*, MSCE Thesis, University of Washington.

Moulton, L.K. (1980), *Highway Subdrainage Design*, Report No. FHWA-TS-80-224, Federal Highway Administration, Washington, D.C.

Sherard, J.L. (1986), Hydraulic Fracturing in Embankment Dams, *Journal of Geotechnical Engineering*, American Society of Civil Engineers, Vol. 112, No. 10, pp. 905-927.

Sherard, J.L. and Decker, R.S., Editors (1977), Dispersive Clays, Related Piping, and Erosion in Geotechnical Projects, *ASTM Special Technical Publication 623*, American Society for Testing and Materials, Philadelphia, PA, 486 p.

Sherard, J.L., Decker, R.S. and Ryker, N.L. (1972), Piping in Earth Dams of Dispersive Clay, *Proceedings of the ASCE Specialty Conference on Performance of Earth and Earth -Supported Structures*, American Society of Civil Engineers, New York, Vol. I, Part 1, pp. 589-626.

Skempton, A.W. and Brogan, J.M. (1994), Experiments on Piping in Sandy Gravels, *Geotechnique*, Vol. XLIV, No. 3, pp. 461-478.

Terzaghi, K. and Peck, R.B. (1967), *Soil Mechanics in Engineering Practice*, John Wiley & Sons, New York, 729 p.

U.S. Army Corps of Engineers (1977), *Civil Works Construction Guide Specification for Plastic Filter Fabric*, Corps of Engineer Specifications No. CW-02215, Office, Chief of Engineers, U.S. Army Corps of Engineers, Washington, D.C.

U.S. Department of the Navy (1982), *Soil Mechanics*, Design Manual 7.1, Naval Facilities Engineering Command, Alexandria, VA.

U.S. Department of the Navy (1982), *Foundations and Earth Structures*, Design Manual 7.2, Naval Facilities Engineering Command, Alexandria, VA.

APPENDIX

DRAINAGE SYSTEM DESIGN GUIDELINES

In this section, step-by-step design procedures are given. As with a chain, the integrity of the resulting design will depend on its weakest link; thus, no steps should be compromised or omitted.

STEP 1. Evaluate the critical nature and site conditions (see Table 1) of the application.

Reasonable judgment should be used in categorizing a project, since there may be a significant cost difference for geotextiles required for critical/severe conditions. Final selection should *not* be based on the lowest material cost alone, nor should costs be reduced by eliminating laboratory soil-geotextile performance testing, if such testing is appropriate.

STEP 2. Obtain soil samples from the site and:

A. Perform grain size analyses.

- Calculate $C_u = D_{60}/D_{10}$ [11]

- Select the *worst case* soil for retention (*i.e.*, usually the soil with smallest $B \, x \, D_{85}$)

NOTE: When the soil contains particles 25 mm and larger, use only the gradation of soil passing the 4.75 mm sieve in selecting the geotextile (*i.e.*, scalp off the +4.75 mm material).

B. Perform field or laboratory permeability tests.

- Select worst case soil (*i.e.*, soil with highest coefficient of permeability, k).

- The permeability of clean sands with 0.1 mm < D_{10} < 3 mm and C_u < 5 can be estimated by the Hazen formula, $k = (D_{10})^2$ (k in cm/s; D_{10} in mm). This formula should **not** be used for soils with appreciable fines.

C1. *For drainage systems*, select drainage aggregate.

- Use free-draining, open-graded material and determine its permeability. If possible, sharp, angular aggregate should be avoided. If it must be used, then a geotextile meeting the property requirements for high survivability should be specified. For an accurate design cost comparison, compare cost of open-graded aggregate with select well-graded, free-draining filter aggregate.

C2. *For erosion control systems*, size armor stone or riprap.

- Where minimum size of stone exceeds 100 mm, or gaps between blocks are greater than 100 mm, a 150 mm thick intermediate gravel layer should be used between the armor stone and geotextile. Gravel should be sized such that it will not wash through the armor stone ($D_{85\ gravel} \geq D_{15\ riprap}/5$).
- Determine armor stone placement technique (*i.e.*, maximum height of drop).

STEP 3. Calculate anticipated flow into and through drainage system and dimension of the system. Use collector pipe to reduce size of drain. For erosion control systems, calculate anticipated reverse flow. Estimate the maximum flow from seeps and weeps, maximum flow from wave runout, or maximum flow from rapid drawdown.

A. General Case

Use Darcy's Law

$$q = k\,i\,A \qquad [12]$$

where:

q	=	infiltration rate (L^3/T)
k	=	effective permeability of soil (from Step 2B above) (L/T)
i	=	average hydraulic gradient in soil and in drain (L/L) (Also, tangent of slope angle for wave runoff)
A	=	area of soil and drain material normal to the direction of flow (L^2)

Use conventional flow net analysis (Cedergren, 1989) and Darcy's Law for estimating infiltration rates into drain; then use Darcy's Law to design drain (*i.e.*, calculate cross-sectional area A for flow through open-graded aggregate). Use a conventional flow net analysis (Cedergren, 1989) for seepage through dikes and dams or from a rapid drawdown analysis.

B. Specific Drainage Systems

Estimates of surface infiltration, runoff infiltration rates, and drainage dimensions can be determined using accepted principles of hydraulic engineering (Moulton, 1980). Specific references are:

1. *Flow into trenches* -- Mansur and Kaufman (1962)
2. *Horizontal blanket drains* -- Cedergren (1989)
3. *Slope drains* -- Cedergren (1989)
4. *Erosion control systems* -- Hydraulic characteristics depend on expected precipitation, runoff volumes and flow rates, stream flow volumes and water level fluctuations, normal and maximum wave heights anticipated, direction of waves and tidal variations. For example, detailed information on determination of these parameters is available in the USA from FHWA (1989) Hydraulic Engineering Circular No. 11.

STEP 4. Determine geotextile requirements.

A. Retention Criteria

$$O_{e(geotextile)} \leq B\,D_{(soil)} \quad [1]$$

Soils with a C_u of greater than 20 may be unstable (see section 2.3-1.c): if so, performance tests are recommended to select suitable geotextiles.

B. Permeability/Permittivity Criteria

$$k_{geotextile} \geq FS \bullet k_{soil} \quad [2]$$

1. Less Critical/Less Severe: Use FS ≥ 1

2. Critical/Severe: Increase FS ≥ 10

3. Permittivity Requirements

$$\psi_{allow} \geq FS \bullet \psi_{required} \geq 0.1 \text{ to } 1.0 \text{ sec}^{-1} \quad [3]$$

3. Flow Capacity Requirement

$$q_{required} = q_{geotextile}(A_g/A_t), \text{ or} \quad [7]$$

$$(k_{geotextile}/t)\, h\, A_g \geq q_{required} \quad [14]$$

where:

$q_{required}$ is obtained from STEP 3B (Eq. 12) above;

$k_{geotextile}/t$ = ψ = permittivity;

t = geotextile thickness;

h = average head in field;

A_g = geotextile area available for flow (*i.e.*, if 80% of geotextile is covered by the wall of a pipe, A_g = 0.2 x total area); and

A_t = total area of geotextile.

C. Clogging Criteria

1. Less Critical/Less Severe

a. From Step 2A obtain D_{15}; then determine minimum pore size requirement from $O_e \geq 3\,D_{15}$, for $C_u > 3$ [8]

b. Other qualifiers:

Nonwovens: Porosity (geotextile)

Wovens: Percent open area

Alternative: Run filtration tests

2. Critical/Severe

Select geotextiles that meet retention, permeability, and survivability criteria, as well as the criteria in Step 4C.1 above, and perform a filtration test.

D. Survivability

Select geotextile properties required for survivability from national codes. Add durability requirements if appropriate.

STEP 5. Estimate costs.

For drainage systems, calculate the pipe size (if required), the volume of aggregate, and the area of the geotextile. Apply appropriate unit cost values.

Pipe (if required) (/m)	__________
Aggregate (/m^3)	__________
Geotextile (/m^2)	__________
Geotextile placement (/m^2)	__________
Construction (LS)	__________
Total Cost:	__________

For erosion control systems, calculate the volume of armor stone, the volume of aggregate and the area of the geotextile. Apply appropriate unit cost values.

Grading and site preparation (LS)	__________
Geotextile (/m^2)	__________
Geotextile placement (/m^2)	__________
In-place aggregate bedding layer (/m^2)	__________
Armor stone (/kg)	__________
Armor stone placement (/kg)	__________
Total cost	__________

STEP 6. Prepare specifications.

Include for the geotextile:

A. General requirements
B. Specific geotextile properties
C. Seams and overlaps
D. Placement procedures
E. Repairs
F. Testing and placement observation requirements

STEP 7. Collect samples of aggregate and geotextile before acceptance.

STEP 8. Monitor installation during and after construction.

STEP 9. Observe system during and after storm events.