SECTION 5 – FILTER DESIGN

Design Guideline 16 – Filter Design

DESIGN GUIDELINE 16

FILTER DESIGN

(page intentionally left blank)

DESIGN GUIDELINE 16

FILTER DESIGN

16.1 INTRODUCTION

National Cooperative Highway Research Program (NCHRP) Reports 568 and 593 (Lagasse et al. 2006, 2007) describe the importance of filters to the successful long-term performance of armoring-type countermeasures. Based on a survey of the existing state of practice, these reports indicate that filter design criteria has typically been the most overlooked aspect of revetment riprap design, and recommend that more emphasis be given to ensuring compatibility between the filter and the soil.

Correct filter design reduces the effects of piping by limiting the loss of fines, while simultaneously maintaining a permeable, free-flowing interface. Seepage flow and turbulence at the water-filter interface induces the migration of soil particles. The particle size distribution of the base soil underlying an armor layer must be determined to properly design a filter for particle retention. For example, when a filter with relatively large pores overlies a uniform fine-grained soil, piping of the fine particles may continue unabated, since there are no particles of large and intermediate sizes to prevent their migration. The presence of large and intermediate sized particles in the soil matrix prevents clogging from occurring at the soil-filter interface when filters with relatively small pores are used.

In addition to particle retention, filters must be have sufficient hydraulic conductivity (sometimes referred to as "permeability") to allow unimpeded flow of water from the base soil through the filter material. This is necessary for two reasons: (1) regulating the particle migration process at the soil-filter interface, and (2) minimizing hydrostatic pressure buildup from seepage out of the channel bed and banks, typically caused by seasonal groundwater fluctuations or flood events.

The hydraulic conductivity of the filter should never be less than the material below it (whether base soil or another filter layer). Figures 16.1 (a) through (c) illustrate the typical process that occurs during and after a flood event. Seepage forces can result in piping of the base soil through the armor layer. If a filter is less permeable than the base soil, an increase of hydrostatic pressure can build beneath the armor layer. A permeable filter material, properly designed, will alleviate problems associated with fluctuating water levels.

Base Soil Properties: Base soil is defined here as the subgrade material upon which the filter and armor layer (riprap, for example) will be placed. Base soil can be native in-place material, or imported and recompacted fill. The following properties of the base soil should be obtained for proper design of the filter, whether using a geotextile or a granular filter.

General Soil Classification. Soils are classified based on laboratory determinations of particle size characteristics and the physical effects of varying water content on soil consistency. Typically, soils are described as coarse-grained if more than 50% by weight of the particles is larger than a #200 sieve (0.075 mm mesh), and fine-grained if more than 50% by weight is smaller than this size. Sands and gravels are examples of coarse-grained soils, while silts and clays are examples of fine-grained soils.

The fine-grained fraction of a soil is further described by changes in its consistency caused by varying water content and by the percentage of organic matter present. Soil classification procedures are described in ASTM D 2487 "Standard Practice for Classification of Soils for Engineering Purposes: Unified Soil Classification System" (ASTM 2003a).

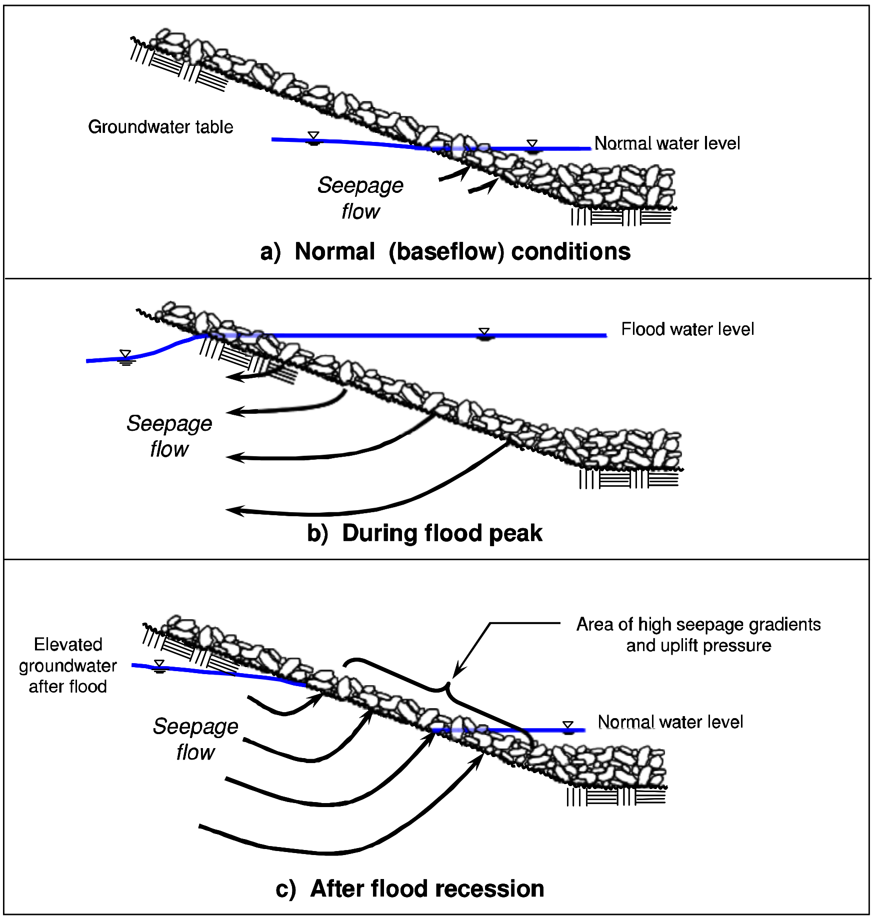


Figure 16.1. Changes in water levels and seepage patterns during a flood.

Particle Size Distribution. The single most important soil property for filter design is the range of particle sizes in the soil. Particle size is a simple and convenient way to assess soil properties. Also, particle size tends to be an indication of other properties such as hydraulic conductivity. Characterizing soil particle size involves determining the relative proportions of gravel, sand, silt, and clay in the soil. This characterization is usually done by sieve analysis for coarse-grained soils or sedimentation (hydrometer) analysis for fine-grained soils. ASTM D 422 "Standard Test Method for Particle-Size Analysis of Soils" describes the specific procedure (ASTM 2003a).

Plasticity. Plasticity is defined as the property of a material that allows it to be deformed rapidly, without rupture, without elastic rebound, and without volume change. A standard measure of the plasticity of soil is the Plasticity Index (PI), which should be determined for soils with a significant percentage of clay. The results associated with plasticity testing are referred to as the Atterberg Limits. ASTM D 4318 "Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils" defines the testing procedure (ASTM 2003a).

Porosity: Porosity is that portion of a representative volume of soil that is interconnected void space. It is typically reported as a dimensionless fraction or a percentage. The porosity of soils is affected by the particle size distribution, the particle shape (e.g., round vs. angular), and degree of compaction and/or cementation.

Hydraulic conductivity. Hydraulic conductivity, sometimes referred to as permeability, is a measure of the ability of soil to transmit water. ASTM provides two standard laboratory test methods for determining hydraulic conductivity. They are ASTM D 2434 "Standard Test Method for Permeability of Granular Soils (Constant Head)" and ASTM D 5084 "Standard Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter" (ASTM 2003b). In these tests, the amount of water passing through a saturated soil sample is measured over a specified time interval, along with the sample's cross-sectional area and the hydraulic head at specific locations. The soil's hydraulic conductivity is then calculated from these measured values. Hydraulic conductivity is related more to particle size distribution than to porosity, as water moves through large and interconnected voids more easily than small or isolated voids. Various equations are available to estimate hydraulic conductivity based on the grain size distribution, and the practitioner is encouraged to consult with geotechnical and materials engineers on estimating this property. Table 16.1 lists typical values of porosity and hydraulic conductivity for alluvial soils.

Table 16.1. Typical Porosity and Hydraulic conductivity of Alluvial Soils (after McWhorter and Sunada 1977).

Type of Material	Porosity (vol/vol)	Hydraulic conductivity (cm/s)
Gravel, coarse	0.28	4×10^{-1}
Gravel, fine	0.34	
Sand, coarse	0.39	5×10^{-2}
Sand, fine	0.43	3×10^{-3}
Silt	0.46	3×10^{-5}
Clay	0.42	9×10^{-8}

Granular Filter Properties: Generally speaking, most required granular filter properties can be obtained from the particle size distribution curve for the material. Granular filters may be used alone or as a transitional layer between a predominantly fine-grained base soil and a geotextile.

Particle Size Distribution. As a rule of thumb, the gradation curve of the granular filter material should be approximately parallel to that of the base soil. Parallel gradation curves minimize the migration of particles from the finer material into the coarser material. Heibaum (2004) presents a summary of a procedure originally developed by Cistin and Ziems whereby the d_{50} size of the filter is selected based on the coefficients of uniformity (d_{60}/d_{10}) of both the base soil and the filter material. With this method, the grain size distribution curves do not necessarily need to be approximately parallel.

Hydraulic conductivity. Hydraulic conductivity of a granular filter material is determined by laboratory test, or estimated using relationships relating hydraulic conductivity to the particle size distribution. The hydraulic conductivity of a granular layer is used to select a geotextile when designing a composite filter. For countermeasure installations, the hydraulic conductivity of the filter should be at least 10 times the hydraulic conductivity of the underlying material.

Porosity: Porosity is that portion of a representative volume of soil that is interconnected void space. It is typically reported as a dimensionless fraction or a percentage. The porosity of soils is affected by the particle size distribution, the particle shape (e.g., round vs. angular), and degree of compaction and/or cementation.

Thickness. Practical issues of placing a granular filter indicate that a typical minimum thickness of 6 to 8 inches should be specified. For placement under water, thickness should be increased by 50%.

Quality and Durability. Aggregate used for a granular filter should be hard, dense, and durable.

Geotextile Filter Properties: For compatibility with site-specific soils, geotextiles must exhibit the appropriate values of hydraulic conductivity, pore size (otherwise known as Apparent Opening Size, or AOS), and porosity (or percent open area). In addition, geotextiles must be sufficiently strong to withstand the stresses during installation. Values of these properties are available from manufacturers.

Only woven monofilament or nonwoven needle-punched geotextiles should be considered for filter applications. Slit-film, spun-bonded, or other types of geotextiles are not suitable as filters. If a woven monofilament fabric is chosen, it should have a Percent Open Area (POA) greater than, or equal to, 4%. If a nonwoven needle-punched fabric is chosen, it should have a porosity greater than, or equal to 30%, and a mass per unit area of at least 400 grams per square meter (12 ounces per square yard). The following list briefly describes the most relevant properties of geotextiles for filter applications.

Hydraulic conductivity: The hydraulic conductivity, K, of a geotextile is a tested property of geotextiles that is reported by manufacturers for their products. The hydraulic conductivity is a measure of the ability of a geotextile to transmit water across its thickness. It is typically reported in units of centimeters per second (cm/s). This property is directly related to the filtration function that a geotextile must perform, where water flows perpendicularly through the geotextile into a crushed stone bedding layer, perforated pipe, or other more permeable medium. The geotextile must allow this flow to occur without being impeded. A value known as the permittivity, ψ, is used by the geotextile industry to more readily compare geotextiles of different thicknesses. Permittivity, ψ, is defined as K divided by the geotextile thickness, t, in centimeters; therefore, permittivity has a value of $(s)^{-1}$. Hydraulic conductivity (and permittivity) are extremely important in filter design.

Transmissivity: The transmissivity, θ, of a geotextile is a calculated value that indicates the ability of a geotextile to transmit water within the plane of the fabric. It is typically reported in units of cm^2/s. This property is directly related to the drainage function, and is most often used for high-flow drainage nets and geocomposites, not geotextiles. Woven monofilament geotextiles have very little capacity to transmit water in the plane of the fabric, whereas non-woven needle punched fabric have a much greater capacity due to their 3-dimensional microstructure. Transmissivity is not particularly relevant to filter design.

Apparent Opening Size (AOS). Also known as Equivalent Opening Size, this measure is generally reported as O_{95}, which represents the aperture size such that 95% of the openings are smaller. In similar fashion to a soil gradation curve, a geotextile hole distribution curve can be derived. The AOS is typically reported in millimeters, or in equivalent U.S. standard sieve size.

Porosity. Porosity is a comparison of the total volume of voids to the total volume of geotextile. This measure is applicable to non-woven geotextiles only. Porosity is used to estimate the potential for long term clogging, and is typically reported as a percentage.

Percent Open Area (POA). POA is a comparison of the total open area to the total geotextile area. This measure is applicable to woven geotextiles only. POA is used to estimate the potential for long term clogging, and is typically reported as a percentage.

Thickness. As mentioned above, thickness is used to calculate hydraulic conductivity. It is typically reported in millimeters or mils (thousandths of an inch).

Grab Strength and Elongation. Force required to initiate a tear in the fabric when pulled in tension. Typically reported in Newtons or pounds as measured in a testing apparatus having standardized dimensions. The elongation measures the amount the material stretches before it tears, and is reported as a percent of its original (unstretched) length.

Tear Strength. Force required to propagate a tear once initiated. Typically reported in Newtons or pounds.

Puncture Strength. Force required to puncture a geotextile using a standard penetration apparatus. Typically reported in Newtons or pounds.

There are many other tests to determine various characteristics of geotextiles; only those deemed most relevant to applications involving countermeasures have been discussed here. As previously mentioned, geotextiles should be able to withstand the rigors of installation without suffering degradation of any kind. Long-term endurance to stresses such as ultraviolet solar radiation or continual abrasion are considered of secondary importance, because once the geotextile has been installed and covered by the armor layer, these stresses do not represent the long-term environment that the geotextile will experience. Table 16.2 provides recommended tests and allowable values for various geotextile properties.

16.2 FILTER DESIGN PROCEDURES

16.2.1 Granular Filter Design Procedure

Numerous texts and handbooks provide details on the well-known Terzaghi approach to designing a granular filter. That approach was developed for subsoils consisting of well-graded sands, and may not be widely applicable to other soil types. An alternative approach that is considered more robust in this regard is the Cistin – Ziems method.

The suggested steps for proper design of a granular filter using this method are outlined below. Note that "d_s" is used to represent the base (finer) soil, and an "d_f" is used to represent the filter (coarser) layer.

Step 1. Obtain Base Soil Information. Typically, the required base soil information consists simply of a grain size distribution curve, a measurement (or estimate) of hydraulic conductivity, and the Plasticity Index (PI is required only if the base soil is more than 20% clay).

Table 16.2. Recommended Tests and Allowable Values for Geotextile Properties.

Test Designation	Property	Allowable value (1)		Comments
		Elongation < 50%(2)	Elongation > 50%(2)	
ASTM D 4632	Grab Strength	> 315 lbs (Class 1) > 250 lbs (Class 2) > 180 lbs (Class 3)	> 200 lbs (Class 1) > 160 lbs (Class 2) > 110 lbs (Class 3)	From AASHTO M 288
ASTM D 4632	Sewn Seam Strength (3)	> 270 lbs (Class 1) > 220 lbs (Class 2) > 160 lbs (Class 3)	> 180 lbs (Class 1) > 140 lbs (Class 2) > 100 lbs (Class 3)	From AASHTO M 288
ASTM D 4533	Tear Strength (4)	> 110 lbs (Class 1) > 90 lbs (Class 2) > 70 lbs (Class 3)	> 110 lbs (Class 1) > 90 lbs (Class 2) > 70 lbs (Class 3)	From AASHTO M 288
ASTM D 4833	Puncture Strength	> 110 lbs (Class 1) > 90 lbs (Class 2) > 70 lbs (Class 3)	> 110 lbs (Class 1) > 90 lbs (Class 2) > 70 lbs (Class 3)	From AASHTO M 288
ASTM D 4751	Apparent Opening Size	Per design criteria (See section 16.2)		Maximum allowable value
ASTM D 4491	Permittivity and Hydraulic Conductivity	Per design criteria (See section 16.2)		Minimum allowable value
ASTM D 4355	Degradation by Ultraviolet Light	> 50% strength retained after 500 hours of exposure		Minimum allowable value
ASTM D 4873	Guide for Identification, Storage, and Handling			Provides information on identification, storage, and handling of geotextiles.
ASTM D 4759	Practice for the Specification Conformance of Geosynthetics			Provides information on procedures for ensuring that geotextiles at the jobsite meet the design specifications.

1) Required geotextile class for permanent erosion control design is designated below for the indicated application. The severity of installation conditions generally dictates the required geotextile class. The following descriptions have been modified from AASHTO M 288:

   Class 1 is recommended for harsh or severe installation conditions where there is a greater potential for geotextile damage, including placement of riprap that must occur in multiple lifts, drop heights that may exceed 1 foot (0.3m) or when repeated vehicular traffic on the installation is anticipated.

   Class 2 is recommended for installation conditions where placement in regular, single lifts is expected and little or no vehicular traffic on the installation will occur, or when placing individual rocks by clamshell, orange peel grapple or specially-equipped hydraulic excavator with drop heights less than 1 foot.

   Class 3 is specified for the least severe installation environments, with drop heights less than 1 foot onto a bedding layer of select sand, gravel or other select imported material.

2) As measured in accordance with ASTM D 4632.

3) When seams are required.

4) The required Minimum Average Roll Value (MARV) tear strength for woven monofilament geotextiles is 55 pounds. The MARV corresponds to a statistical measure whereby 2.5% of the tested values are less than the mean value minus two standard deviations (Koerner 1998).

Step 2. Determine Key Indices for Base Soil. From the grain size information, determine the median grain size d_{50} and the Coefficient of Uniformity d_{60}/d_{10} of the base soil. Due to the inherent variability of natural soils, these parameters should be determined for a number of samples and a representative value, or range of values, should be used for design based on engineering judgment.

Step 3. Determine Key Indices for Granular Filter. One or more locally available aggregates should be identified as potential candidates for use as a filter material. The median grain size d_{50} and the Coefficient of Uniformity d_{60}/d_{10} should be determined for each candidate material. Alternatively, candidate materials may be identified from standard aggregate specifications (e.g., AASHTO, ASTM, DOT, etc.). A range of values corresponding to the allowable gradation limits should be evaluated to determine an appropriate value for design.

Step 4. Determine Maximum Allowable d_{50f} for Filter. Enter the Cistin - Ziems design chart (Figure 16.2) with the Coefficient of Uniformity for the base soil on the x-axis. Find the curve that corresponds to the Coefficient of Uniformity for the filter in the body of the chart, and from that point determine the maximum allowable A_{50} from the y-axis. Compute the maximum allowable d_{50f} of the filter using $d_{50f(max)} = A_{50max}$ times d_{50s}. Check to see if the candidate filter material conforms to this requirement. If it does not, continue checking alternate candidates until a suitable material is identified.

Step 5. Determine Hydraulic Conductivity Criterion. Check to ensure that the hydraulic conductivity of the filter is at least 10 times greater than that of the base soil.

Step 6. Check for Compatibility with Armor Layer. Repeat steps 1 through 4 above, considering that the filter material is now the "finer" soil and the particles comprising the armor are the "coarser" material. This check ensures that the particles of the granular filter will not be winnowed out through the voids of the armor layer. If the Cistin-Ziems criterion is not met, then multiple layers of granular filter materials should be considered.

Step 7. Filter Layer Thickness. For practicality of placement, the nominal thickness of a single filter layer should not be less than 6 inches (15 cm). Single-layer thicknesses up to 15 inches (38 cm) may be warranted where large riprap particle sizes are used as armor. When multiple filter layers are required, each individual layer should range from 4 to 8 inches (10 to 20 cm) in thickness (HEC-11 (Brown and Clyde 1989)).

16.2.2 Geotextile Filter Design Procedure

The suggested steps for proper design of a geotextile filter are outlined below:

Step 1. Obtain Base Soil Information. Typically, the required base soil information consists simply of a grain size distribution curve, a measurement (or estimate) of hydraulic conductivity, and the Plasticity Index (PI is required only if the base soil is more than 20% clay).

Step 2. Determine Particle Retention Criterion. A decision tree is provided as Figure 16.3 to assist in determining the appropriate soil retention criterion for the geotextile. The figure has been modified to include guidance when a granular transition layer (i.e., composite filter) is necessary. A composite filter is typically required when the base soil is greater than 30% clay having relatively low cohesion, or is predominantly fine-grained soil (more than 50% passing the #200 sieve). If a granular transition layer is required, the geotextile should be designed to be compatible with the properties of the granular layer.

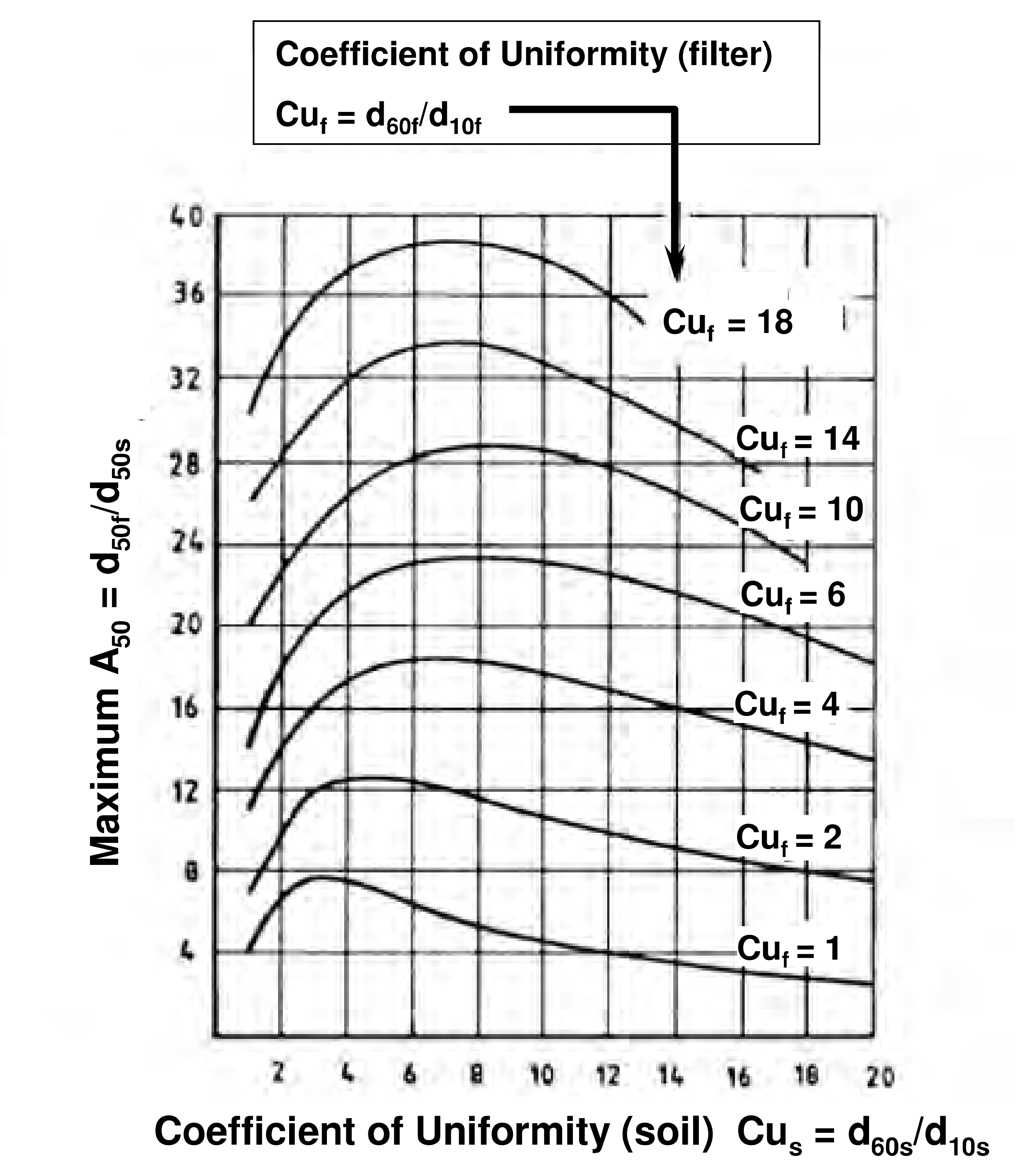
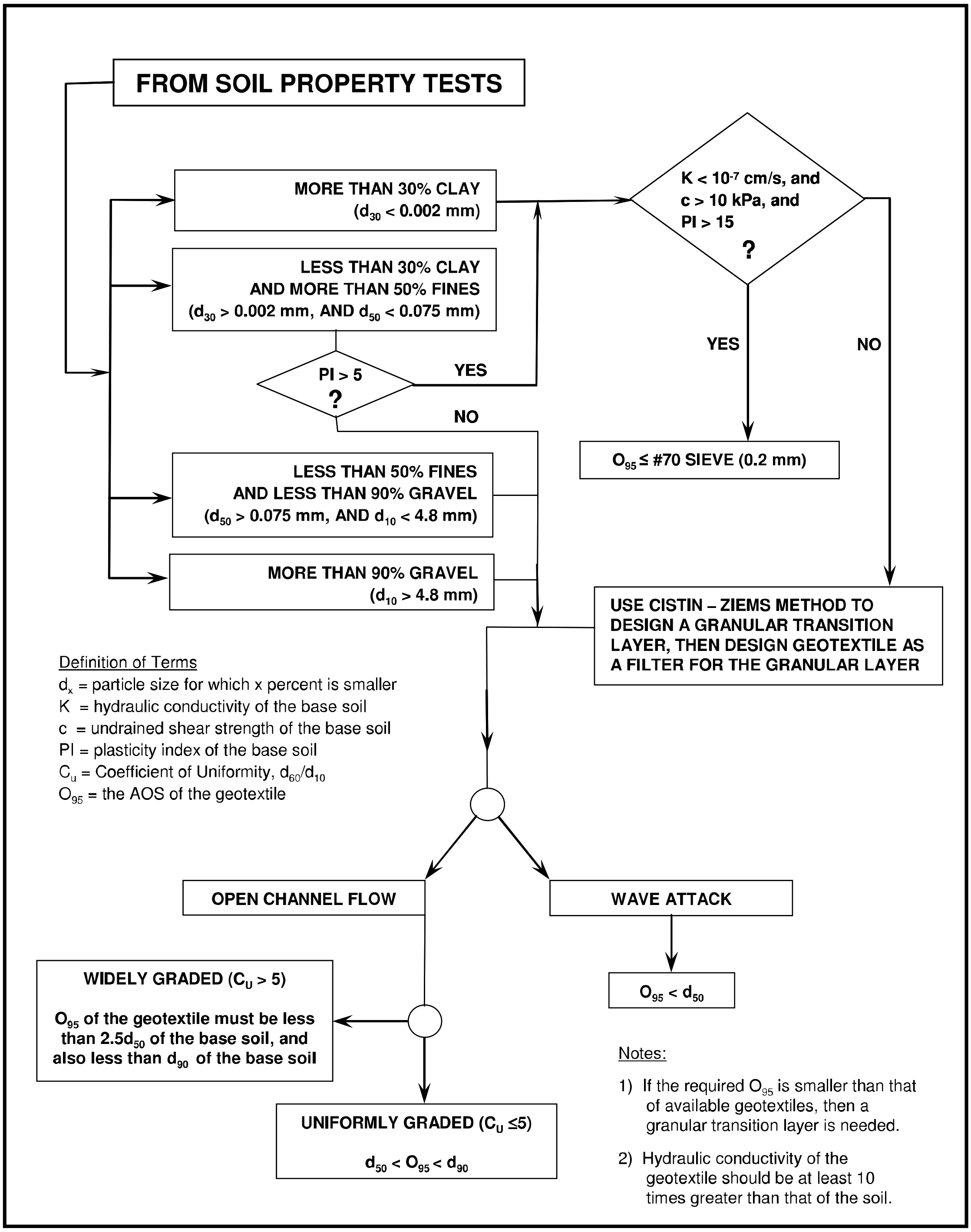


Figure 16.2. Granular filter design chart according to Cistin and Ziems (Heibaum 2004).



Definition of Terms

d_x = particle size for which x percent is smaller
K = hydraulic conductivity of the base soil
c = undrained shear strength of the base soil
PI = plasticity index of the base soil
C_u = Coefficient of Uniformity, d_{60}/d_{10}
O_{95} = the AOS of the geotextile

Notes:

1) If the required O_{95} is smaller than that of available geotextiles, then a granular transition layer is needed.
2) Hydraulic conductivity of the geotextile should be at least 10 times greater than that of the soil.

Figure 16.3. Geotextile selection for soil retention (modified from NCHRP Report 593).

Note: If the required AOS is smaller than that of available geotextiles, then a granular transition layer is required, even if the base soil is not clay. However, this requirement can be waived if the base soil exhibits the following conditions for hydraulic conductivity K, plasticity index PI, and undrained shear strength c:

$K < 1 \times 10^{-7}$ cm/s
$PI > 15$
$c > 10$ kPa

Under these soil conditions there is sufficient cohesion to prevent soil loss through the geotextile. A geotextile with an AOS less than a #70 sieve (approximately 0.2 mm) can be used with soils meeting these conditions, and essentially functions more as a separation layer than a filter.

Step 3. Determine Geotextile Hydraulic Conductivity Criterion. The hydraulic conductivity criterion requires that the filter exhibit a hydraulic conductivity at least 4 times greater than that of the base soil (Koerner 1998) and for critical or severe applications, up to 10 times greater (Holtz et al. 1995). In riverine or coastal revetment works where floods or wave attack can create high seepage gradients, the application is considered severe and a minimum hydraulic conductivity ratio of 10 is adopted for filter design. Generally speaking, if the hydraulic conductivity of the base soil or granular filter has been determined from laboratory testing, that value should be used. If lab testing was not conducted, then an estimate of hydraulic conductivity based on the particle size distribution should be used.

To obtain the hydraulic conductivity of a geotextile in cm/s, multiply the thickness of the geotextile in cm by its permittivity in s^{-1}. Typically, the designer will need to contact the geotextile manufacturer to obtain values of permittivity and thickness.

Step 4. Minimize Long-Term Clogging Potential. When a woven geotextile is used, its percent open area (POA) should be greater than, or equal to, 4% by area. If a non-woven geotextile is used, its porosity should be greater than, or equal to, 30% by volume. A good rule of thumb suggests that the geotextile having the largest AOS that satisfies the particle retention criteria should be used (provided of course that all other minimum allowable values described in this section are met as well).

Step 5. Select a Geotextile that Meets the Required Strength Criteria. Strength and durability requirements depend on the installation environment and the construction equipment that is being used. AASHTO M-288, "Geotextile Specification for Highway Construction" provides guidance on allowable strength and elongation values for three categories of installation severity. These criteria are reflected in Table 16.2, presented previously. For additional guidelines regarding the selection of durability test methods, refer to ASTM D 5819, "Standard Guide for Selecting Test Methods for Experimental Evaluation of Geosynthetic Durability" (2003b).

16.3 DESIGN EXAMPLES

16.3.1 Granular filter

Revetment riprap using Class II riprap (nominal d_{50} = 225 mm, or 9 inches) is to be placed on a channel bank. The native soil on the channel banks is a silty sand. A locally produced medium to coarse sand is proposed as a granular filter material for the riprap. A number of samples of both the native soil and the candidate filter material have been collected and engineering properties determined. From the test results, representative values have been developed for designing the filter.

The grain size distribution curves for the native soil, candidate filter material, and riprap are shown in Figure 16.4. From this figure and supplemental laboratory tests, the other relevant characteristics of the materials in the design are summarized in Table 16.3.

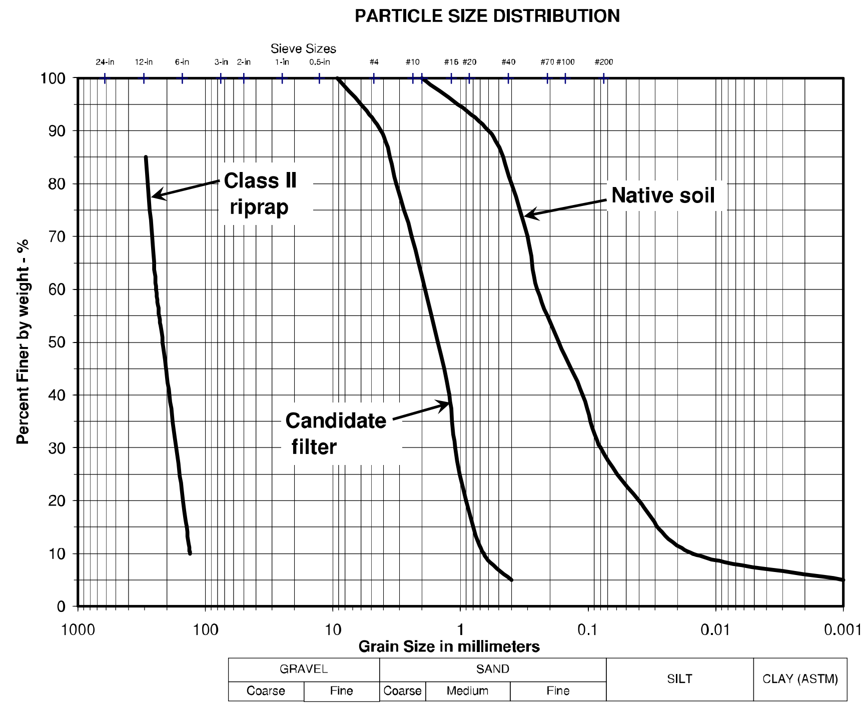


Figure 16.4. Grain size curves for design example.

Table 16.3. Soil, Filter, and Riprap Properties for Design Example.

Soil Property	Native Soil	Granular Filter	Riprap Class II
Median diameter d_{50}, mm	0.17	1.5	225 (9 in.)
Coefficient of uniformity $C_u = d_{60}/d_{10}$	0.24/0.014 = 17	1.9/0.7 = 2.7	230/120 = 1.9
Hydraulic conductivity K, cm/s	4.2×10^{-4}	2.3×10^{-2}	n/a
Plasticity Index	3.3	(np)	(np)

Step 1. Obtain Base Soil Information: Base soil information is provided in Figure 16.4 and Table 16.3.

Step 2. Determine Key Indices for Base Soil: Key indices for the base soil are:

d_{50} = 0.17 mm
C_u = 17
K = 4.2×10^{-4} cm/s
PI = 3.3

Step 3. Determine Key Indices for Granular Filter: Key indices for the candidate filter material are:

d_{50} = 1.5 mm
C_u = 2.7
K = 2.3×10^{-2} cm/s
PI = non-plastic

Step 4. Determine Maximum Allowable d_{50f} for Filter: Enter the Cisten – Ziems chart (Figure 16.2) with C_u = 17 of the native soil on the x-axis. Chart vertically up to a location corresponding to a C_u of 2.7 for the candidate filter material. Read a maximum allowable value A_{50} of approximately 11.5 on the y-axis.

Max. allowable $d_{50f} = A_{50}(d_{50s}) = 11.5 \times 0.17 = 1.96$ mm

Because the granular filter has a d_{50} less than this value, it is suitable as a filter based on its ability to provide particle retention.

Step 5. Determine Hydraulic Conductivity Criterion: The ratio K_f/K_s is 0.023/0.00042 = 55; therefore, the granular filter is suitable based on hydraulic conductivity considerations, because this ratio is greater than 10.

Step 6. Check for Compatibility with Armor Layer: Enter the Cisten – Ziems chart (Figure 16.2) with C_u = 2.7 of the filter material on the x-axis. Chart vertically up to a location corresponding to a C_u of 1.9 for the riprap. Read a maximum allowable value A_{50} of approximately 10 on the y-axis.

Max. allowable $d_{50r} = A_{50}(d_{50f}) = 10 \times 1.5 = 15$ mm

Because the riprap has a d_{50} greater than this value, a second (coarser) granular filter layer should be designed and placed on top of the first filter layer. In this case, the first filter layer is now considered the "base soil." Alternatively, a geotextile filter may be considered.

Step 7. Filter Layer Thickness: Because multiple layers of granular filter materials are required for this example, each individual layer should not be less than 4 inches thick, nor greater than 8 inches, in accordance with HEC-11 (see section 16.2.1).

16.3.2 Geotextile filter

This example will use the soil information from the previous section to determine the geotextile properties required for a filter that is compatible with the base soil beneath the Class II riprap.

Step 1. Obtain Base Soil Information. Base soil information is provided in Figure 16.4 and Table 16.3. From the grain size curve, the percentage (by weight) of material classified as "fines" (i.e., silt and clay) and the percentage classified as "gravel" is determined:

Fines: 26%
Gravel: None

Step 2. Determine Particle Retention Criterion. Knowing the base soil characteristics, enter the geotextile design flowchart (Figure 16.3) using the soil properties at the box labeled, "Less than 50% fines and less than 90% gravel."

Follow the appropriate branches of the decision tree until you get to the "Open Channel Flow" box. The criteria for soil retention based on the O_{95} aperture size of the geotextile are based on the Coefficient of Uniformity C_u of the native soil. Because C_u of the native soil is greater than 5, it is considered "widely graded."

Therefore,

$O_{95} < 2.5d_{50}$ and $O_{95} < d_{90}$

From these criteria, the O_{95} of the geotextile must be less than 2.5 times d_{50} and also less than d_{90} of the native soil.

$2.5 \times d_{50} = 2.5 \times 0.17 \text{ mm} = 0.425 \text{ mm}$

$D_{90} = 0.60 \text{ mm}$

Therefore, O_{95} must be less than or equal to 0.425 mm since this is the more stringent requirement. This is approximately equal to a No. 40 U.S. standard sieve size.

Step 3. Determine Geotextile Hydraulic Conductivity Criterion. The geotextile must be at least 10 times more permeable than the base soil.

$K_{geotextile} > 10K_s$

The hydraulic conductivity of the base soil in this example is 4.2×10^{-4} cm/s. Therefore, the geotextile must have a hydraulic conductivity greater than 4.2×10^{-3} cm/s.

Step 4. Minimize Long-Term Clogging Potential. For filter applications, the recommended criteria are:

Woven monofilament fabrics:	Percent Open Area (POA) ≥ 4%
Nonwoven needle-punched fabrics:	Porosity ≥ 30% Mass per Unit Area ≥ 400 g/m^2 (12 oz/yd^2)

Step 5. Select a Geotextile that Meets the Required Strength Criteria. The parameters regarding functional performance have been established via Steps 1 though 4. The strength properties of the geotextile are determined by the severity of the installation environment. For this example, assume that a severe installation environment is anticipated. This is referred to as a "Class 1" condition by AASHTO M288, and the associated minimum strength values are found in Table 16.2.

Summary: The recommended geotextile filter properties for the above example are summarized in Table 16.4. Examples of manufacturer's tables of woven and nonwoven geotextiles are provided in Tables 16.5 and 16.6 along with commentary that illustrates the selection process.

Table 16.4. Summary of Recommended Geotextile Properties for Example Problem.		
Geotextile Property	Nonwoven Needle-punched Fabric	Woven Monofilament Fabric
Maximum AOS, U.S. Standard Sieve	40	40
Minimum hydraulic conductivity, cm/s	4.2 x 10^{-3}	4.2 x 10^{-3}
Minimum mass per unit area, oz/yd^2	12	n/a
Minimum open area, percent	n/a	4.0
Minimum porosity, percent	30	n/a
Minimum strength properties	Per Table 16.2 "Class 1" condition	Per Table 16.2 "Class 1" condition

Table 16.5. Woven Monofilament Geotextile Filter Candidates.								
Property/Test Method	Units	W-Mf 300	W-Mf 400	W-Mf 402	W-Mf 403	W-Mf 404	W-Mf 500	W-Mf 700
MECHANICAL PROPERTIES								
Wide Width Tensile Strength								
ASTM D 4595								
MD @ Ultimate	kN/m (lbs/ft)	40 (2760)	26 (1800)	35 (2400)	47 (3240)	44 (3000)	32 (2200)	40 (2700)
CMD @ Ultimate	kN/m (lbs/ft)	39 (2700)	29 (1980)	24 (1680)	39 (2700)	40 (2760)	44 (3000)	26 (1740)
Grab Tensile Strength ASTM D 4632								
MD @ Ultimate	kN (lbs)	1.78 (400)	1.18 (265)	1.62 (365)	1.89 (425)	1.78 (400)	1.45 (325)	1.65 (370)
CMD @ Ultimate	kN (lbs)	1.49 (335)	1.13 (255)	0.89 (200)	1.56 (350)	1.40 (315)	1.89 (425)	1.11 (250)
MD Elongation @ Ultimate	%	20	16	24	21	15	15	16
CMD Elongation @ Ultimate	%	15	15	10	21	15	15	15
Mullen Burst Strength								
ASTM D 3786	kPa (psi)	4473 (650)	3441 (500)	3097 (450)	4479 (650)	5506 (800)	5171 (750)	3097 (450)
Trapezoidal Tear Strength								
ASTM D 4533								
MD @ Ultimate	kN (lbs)	0.65 (145)	0.36 (80)	0.51 (115)	0.65 (145)	0.67 (150)	0.60 (135)	0.45 (100)
CMD @ Ultimate	kN (lbs)	0.56 (125)	0.31 (70)	0.33 (75)	0.56 (125)	0.73 (165)	0.67 (150)	0.27 (60)
Puncture Strength								
ASTM D 4833	kN (lbs)	0.56 (125)	.56 (125)	0.40 (90)	0.67 (150)	0.67 (150)	0.62 (140)	0.53 (120)
UV Resistance after 500 hrs.								
ASTM D 4355	% Strength	90	90	90	90	90	70	90
HYDRAULIC PROPERTIES **Apparent Opening Size**								
(AOS) ASTM D 4751	mm (US Sieve)	0.600 (30)	0.425 (40)	0.425 (40)	0.425 (40)	0.425 (40)	0.300 (50)	0.212 (70)
Permittivity ASTM D 4491	sec	1.50	0.95	2.14	0.90	0.96	0.506	0.28
Percent Open Area								
COE-02215-86	%	8	10	10	6	1	4	4-6
Flow Rate	l/min/m^2	4685	2852	5907	2852	2852	1426	733
ASTM D 4491	(gal/min/ft^2)	(115)	(70)	(145)	(70)	(70)	(35)	(18)
Hydraulic Conductivity	cm/s	0.132	0.027	0.140	0.046	0.068	0.027	0.010
Note: Trade names shown in this table are fictitious and are provided for instructional purposes only.								

<u>Commentary regarding woven monofilament geotextiles in Table 16.5</u>:

W-Mf 300: No – AOS is too large an opening size
W-Mf 400: No – Grab tensile strength not high enough in the machine direction (MD) and also in the cross machine direction (CMD)
W-Mf 402: No – Grab tensile strength (cross machine direction or CMD) not high enough; Tear strength (cross machine direction or CMD) not high enough; Puncture strength not high enough
W-Mf 403: OK
W-Mf 404: No – Percent Open Area not high enough
W-Mf 500: OK, probably more expensive
W-Mf 700: No – Tensile strength and Tear strength (CMD) not high enough

Table 16.6. Nonwoven Needle-punched Geotextile Filter Candidates.

Property	Test Method	Unit	Value	X31	X35	X40	X45	X50	X60	X70	X80	X100	X120	X160
MECHANICAL														
Grab Tensile Strength	ASTM D-4632	lb	MARV	80	95	115	120	150	160	180	205	250	300	380
Grab Elongation	ASTM D-4632	%	MARV	50	50	50	50	50	50	50	50	50	50	50
Puncture Strength	ASTM D-4833	lb	MARV	50	55	65	65	85	85	100	110	150	175	240
Mullen Burst	ASTM D-3786	psi	MARV	150	185	210	230	280	280	330	350	460	580	750
Trapezoidal Tear	ASTM D-4533	lb	MARV	30	40	50	50	60	60	75	85	100	115	150
HYDRAULIC														
Apparent Opening Size (AOS)	ASTM D-4751	US Sieve	MaxARV	50	50	70	70	70	70	70	80	100	100	100
Permittivity	ASTM D-4491	sec^{-1}	MARV	2.0	2.0	2.0	1.5	1.4	1.3	1.5	1.5	1.2	1.0	0.7
Hydraulic Conductivity	ASTM D-4491	cm/sec	MARV	0.22	0.25	0.22	0.22	0.23	0.24	0.34	0.38	0.30	0.29	0.27
Water Flow Rate	ASTM D-4491	gpm/ft^2	MARV	150	150	140	120	115	110	110	110	85	75	50
PHYSICAL														
Mass per Unit Area	ASTM D-5261	oz/yd^2	MARV	2.7	3.0	3.5	4.0	4.8	5.0	5.9	6.5	8.5	10.8	15.0
Thickness	ASTM D-5199	mils	MARV	30	40	50	45	55	60	70	70	100	105	145
ENDURANCE														
UV Resistance	ASTM D-4355	% Retained @ 500 hrs	MARV	70	70	70	70	70	70	70	70	70	70	70
Porosity		percent		38	38	36	36	36	36	36	34	32	32	32

Note: Trade names shown in this table are fictitious and are provided for instructional purposes only.

Commentary regarding nonwoven needle-punched geotextiles in Table 16.6: The X160 fabric is the only nonwoven geotextile from this manufacturer that has a mass per unit area greater than 12.0 ounces per square yard, which is the minimum recommended. The strength properties of this product are sufficient to resist stresses of a Class 1 installation environment.

16.4 BEARING CAPACITY

Geotextiles are often used to improve the bearing capacity of weak, compressible and often-saturated soils for purposes of improving roadways and other vehicular access points. It stands to reason that the bearing capacity of weak soils can also be improved by the use of geotextiles to withstand loading by heavy rock riprap.

In essence, bearing capacity relies upon the ability of a soil (or reinforced soil) substrate to effectively spread a loading from a relatively small point to a larger area. This results in a counteracting effect such that any potential deformation of the soil surface is resisted by lateral and vertical forces that are mobilized in the substrate.

Improvements in bearing capacity ranging from about 100% for loose sands, to over 700% for soft clayey silts, using one layer of geotextile have been reported (Koerner 1998). In the reported studies, the difference in bearing capacity was quantified using the settlement ratio ρ/B (settled distance divided by footing width) as a function of applied load, compared to a non-reinforced control. Use of multiple geotextile layers, with a specified vertical spacing, increased the bearing capacity in all cases.

Koerner identified four distinct modes of failure when using a geotextile to improve bearing capacity:

Excessive depth of geotextile: Geotextile is placed deeper than about 1 ft (300 mm) below the soil surface. Failure takes place in the soil above the geotextile.

Insufficient embedment length: Geotextile does not extend far enough beyond the load point to mobilize sufficient frictional resistance against slippage.

Tensile failure of geotextile: Geotextile is not strong enough to resist tensile forces without excessive elongation or outright tearing.

Excessive long-term (creep) settlement: Geotextile is vulnerable to long-term, sustained forces that result in gradual overextension, and thus undesirable settlement at the load point.

The U.S. Army Corps of Engineers (Henry 1999) provides in-depth background regarding the issue of soil bearing capacity, albeit in the context of vehicular wheel loadings on unpaved roadways. Primarily a geotechnical study, this document nonetheless provides some valuable information regarding the effect of geotextiles in improving the quality of subgrade bearing capacity, particularly with respect to load redistribution.

Henry (1999) provides design curves that relate the required road base aggregate thickness to the undrained shear strength of the subsoil, with and without a geotextile. In all cases, the use of a geotextile provides a significant reduction in the required amount of road base aggregate to effectively resist deformation by wheeled vehicles. Geotextile strength and elongation specifications are also provided, using existing ASTM testing standards.

It can be concluded that the use of geotextiles beneath a riprap armor layer will provide additional support to the bearing capacity of the underlying subsoils. The use of multiple layers of geotextiles, each separated by 6 to 12 inches (0.15 to 0.3 m) of compatible soil or suitable granular material, will serve to increase the bearing capacity to resist either static loading from rock riprap, or dynamic loading from wheeled (or tracked) maintenance vehicles. Geotextiles are often supplemented with a geogrid when bearing capacity is a significant consideration in the design of countermeasures.

16.5 REFERENCES

American Association of State Highway Officials (AASHTO), 2003, "Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Washington, D.C..

American Society for Testing of Materials (ASTM), 2003a, "Annual Book of ASTM Standards," Volume 4.08, West Conshohocken, PA.

American Society for Testing of Materials (ASTM), 2003b, "Annual Book of ASTM Standards," Volume 4.09, West Conshohocken, PA.

Brown, S.A. and Clyde, E.S., 1989, "Design of Riprap Revetment," Hydraulic Engineering Circular No. 11 (HEC-11), Report FHWA-IP-89-016, Federal Highway Administration, Washington, D.C.

Heibaum, M.H., "Geotechnical Filters – The Important Link in Scour Protection," 2004, Federal Waterways Engineering and Research Institute, Karlsruhe, Germany, 2nd International Conference on Scour and Erosion, Singapore (2004).

Henry, K.S., 1999, "Geotextile Reinforcement of Low-Bearing-Capacity Soils," Special Report 99-7, U.S. Army Corps of Engineers – Cold Regions Research and Engineering Laboratory, Hanover, NH 03755.

Holtz, D.H., Christopher, B.A., and Berg, R.E., 1995, "Geosynthetic Design and Construction Guidelines," Federal Highway Administration, Publication No. FHWA-HI-95-038, Washington, D.C.

Koerner, R.M., 1998, "Designing with Geosynthetics," 4th Edition, Prentice-Hall, Inc., Englewood Cliffs, NJ, 761 p.

Lagasse, P.F., Clopper, P.E., Zevenbergen, L.W., and Ruff, J.F., 2006, "Riprap Design Criteria, Recommended Specifications, and Quality Control," NCHRP Report 568, Transportation Research Board, National Academies of Science, Washington, D.C.

Lagasse, P.F., Clopper, P.E., and Zevenbergen, L.W., 2007, "Countermeasures to Protect Bridge Piers from Scour," NCHRP Report 593, Transportation Research Board, National Academies of Science, Washington, D.C.

McWhorter, D.B. and Sunada, D.K, 1977, "Ground-Water Hydrology and Hydraulics," 1st Edition, Water Resources Publications, Fort Collins, CO.