Geosynthetic Institute
475 Kedron Avenue
Folsom, PA 19033-1208 USA
TEL (610) 522-8440
FAX (610) 522-8441

GSI White Paper #35

"A Primer on Soil and Geotextile Filter Design as Applies to MSE Walls"

by

Robert M. Koerner, Ph.D., P.E., NAE
Director Emeritus - Geosynthetic Institute
robert.koerner@coe.drexel.edu

George R. Koerner, Ph.D., P.E., CQA
Director - Geosynthetic Institute
gsigeokoerner@gmail.com

December 7, 2016

A Primer on Soil and Geotextile Filter Design as Applies to MSE Walls

The practice of *soil filtration* should be quite familiar to those readers with a geotechnical engineering background (note that *geotextile filtration* is much more recent). As such, the information on soil filtration is available in most current geotechnical textbooks as well as older textbooks under the title of soil mechanics and foundation engineering. Furthermore, specialty books, conference proceedings, and technical papers dealing with earth dams and earth/rock dams treat the subject matter extensively. It, that is earth dams, was the impetus for the initial developments of soil filtration concepts and design. Regarding the newer use of geotextiles for filtration, the *Designing With Geosynthetics* (2012) book covers the topic, as well as many references in the open literature, e.g., the GSI data base has the following citations:

- geotextile-filtration-<u>design</u>: 96 citations
- geotextile-filtration-<u>theory</u>: 37 citations
- geotextile-filtration-laboratory-<u>clogging</u>: 101 citations
- geotextile-filtration-laboratory-<u>general</u>: 131 citations
- geotextile-filtration-laboratory-<u>opening size</u>: 52 citations
- geotextile-filtration-laboratory-<u>permeability</u>: 47 citations

<u>Total (through 2016) = 464+</u>

The above said, the basic reason for this White Paper dealing with both soil and geotextile filtration is its necessary application to mechanically stabilized walls (MSW) using geosynthetic reinforcement. In this regard, filtration is rarely addressed (much less installed) leading to a large number of wall failures. See Koerner and Koerner (2013) for 171 MSE wall failures where filtration materials were completely absent as though no such thing ever existed. Incidentally, we now have 301 such failures and filtration materials are still not utilized.

Thus, this White Paper is subdivided into three parts… a review of soil filtration, a review of geotextile filtration and filtration applications with respect to MSE walls.

Part I - Soil Filter Concepts and Design

Earth and earth-rock impoundment dams undoubtedly date from ancient times. Such dams likely consisted of a large mass of locally available soil to the desired mass and height according to the perceived site-specific needs. It is unknown who eventually decided to include a clay corewall for seepage control between discrete upstream and downstream soil embankments but it was an important advance. As a result, earth dam design was probably understood to be that the upstream and downstream soil embankments resulted in overall lateral stability from the impounded water, while the intermediate clay resulted in some degree of watertightness. Eventually, it was recognized that some seepage through and/or around the clay corewall would have to be accommodated. This seepage was to be captured and transmitted internal within the dam's cross section using a chimney drain leading to an outlet drain as shown in Figure 1.

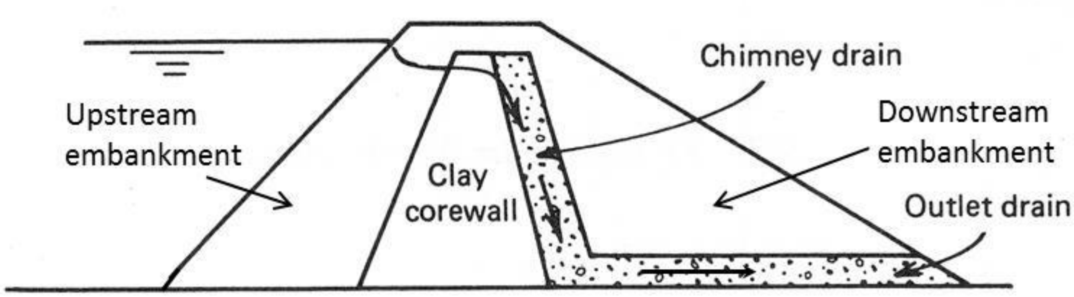


Figure 1. Zoned earth dam with chimney and outlet drain.
(ref. Koerner and Welsh, 1980)

The above said, the incompatibility of the vastly different particle size soils of the embankment soil and the gravel drains was quickly realized in light of long-term mixing, particularly the fine embankment soils invading the coarse drainage soils rendering the latter ineffective. This, in turn, eventually required intermediate soil layers, called "filters", in the dashed line locations shown in Figure 2. This was certainly the status of dam construction in the early 1900s when earth dam construction was extremely active in America and elsewhere.

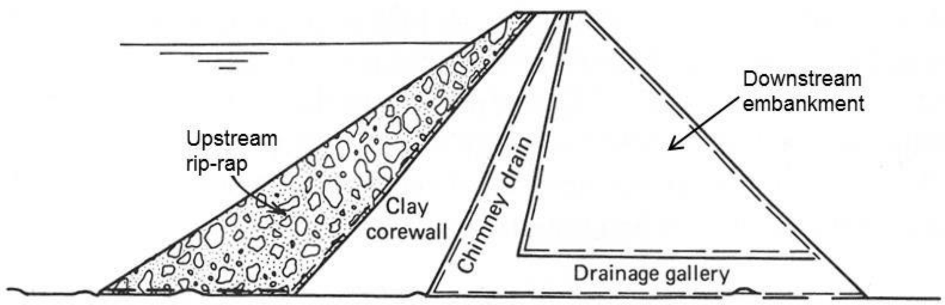


Figure 2. Dashed lines show various locations for soil or geotextile filters used within a zoned earth/rock dam (ref. Koerner and Welsh, 1980).

On a conceptual basis several governmental agencies (e.g., the U.S. Bureau of Reclamation and the U. S. Army Corps of Engineers) began experiments using various particle size distribution curves of many different soil types. The goal was to include an intermediate size soil (the filter) between the two greatly dissimilar sized ones, e.g., between the embankment soil and the gravel drains. Since embankment and drainage soil types are so extremely different, as shown in Figure 3, it sometimes required two soil filters, i.e., a coarser one and a finer one.

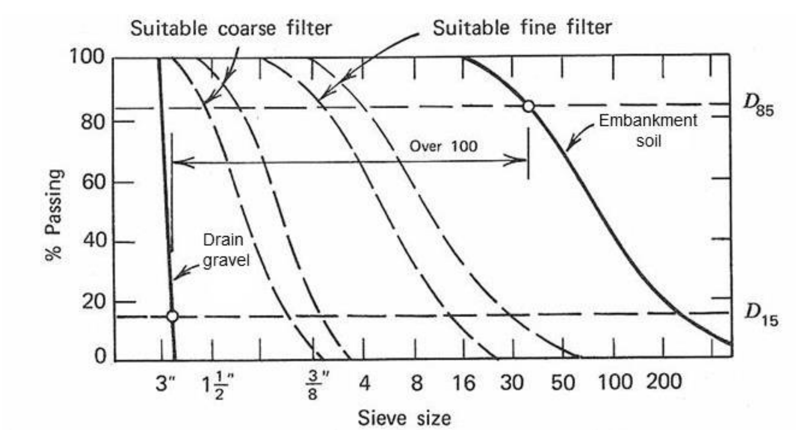


Figure 3. Concept of a graded soil filter design between fine grained embankment soil and drainage gravel (ref. Cedegren, 1973).

Credit for associating numeric particle size values for filter soils is given to Terzaghi (1925), Bertram (1940) and then verified by considerable experimental work at the U.S. Army Corps of

Engineers, Vicksburg Experimental Station. This laboratory testing helped to stimulate the growth of soils and hydraulic laboratories in civil engineering consultancies and universities worldwide. As reported by Lambe and Whitman (1969), the requirements of a filter to keep fine soil particles from invading the adjacent coarse soil being protected are based on particle sizes. The resulting filter specifications relate the grading of the protective "filter" to that of the "soil" being protected by the following three equations:

$$\frac{D_{15}\,Filter}{D_{85}\,Soil} < 5 \tag{1}$$

$$4 < \frac{D_{15}\,Filter}{D_{15}\,Soil} < 20 \tag{2}$$

$$\frac{D_{50}\,Filter}{D_{50}\,Soil} < 25 \tag{3}$$

where D_{15}, D_{50}, and D_{85} are the particle sizes from a particle size distribution plot at 15, 50, and 85% passing the particular sieve. See https://en.wikipedia.org/wiki/sieve_analysis for a nice description of the above and ASTM D6913 for the standard sieve analysis test method. It should also be mentioned that a soil filter manufactured to the three equations presented above provides for two seemingly opposite functions. They are (i) filter voids tight enough to prevent embankment soil particles from clogging the gravel drainage soil, and (ii) filter voids open enough to allow for water flow without inducing hydrostatic pressure in the embankment soil. This balance of tight and yet sufficiently open voids of the filter is essential to provide. The previous equations are such that this balance is accomplished accordingly since all three must be satisfied. These equations are indeed the current state-of-the-practice in soil filtration applications and design. Needless to say, the "manufacturing" of a filter soil (or two or even three of them) to specific grading in a large scale field operation is challenging and very expensive to say the least. In this regard, we feel that geotextile filters have made tremendous strides in replacing soil filters in myriad applications. An overview of geotextiles used as filters in this regard follows:

Part II - Geotextile Filter Concepts and Design

A geotextile filter mimics a soil filter insofar as sufficient tightness (closed voids) must be provided so as to avoid excessive downstreaming clogging, yet adequate permeability (open voids) must also be achieved. It is the same type of balance as with soil filters, however, the design formulations are quite different between the two materials.

The retention process is accomodated by making the geotextile voids tight enough to retain the soil on the upstream side of the fabric. It is the coarser soil fraction that must initially be retained and that is the targeted soil size in the design process. These coarser-sized particles eventually block the finer-sized particles from moving and build up a stable upstream soil structure. *In a sense, the geotextile is acting as a catalyst to make the upstream soil do its own filtration.*

There are many formulas that can be applied to soil retention design, most of which use the soil particle size characteristics and compare them to the 95% opening size of the geotextile, which is defined as the O_{95}-value. The test methods used in the United States (ASTM D4751 or ASTM D6767) to determine this value are called the *apparent opening size* (AOS) and are obtained using a dry-sieving method or a capillary flow method. In Europe and Canada, the test method is called *filtration opening size* (FOS), and is accomplished by wet or hydrodynamic sieving.

The simplest of the design procedures for geotextile filters examine the percentage of soil passing the No. 200 sieve, whose openings are 0.074 mm. According to AASHTO [1991], the following is recommended:

- For soil with ≤ 50% passing the No. 200 sieve use $O_{95} < 0.60$ mm—i.e., AOS of the geotextile ≥ No. 30 sieve.
- For soil > 50% passing the No. 200 sieve use $O_{95} < 0.30$ mm—i.e., AOS of the geotextile ≥ No. 50 sieve

To extend this further, a series of direct comparisons of geotextile-opening size (O_{95}, O_{50} or O_{15}) has also been made in ratio form to some soil particle size to be retained (D_{90}, D_{85}, D_{50} or D_{15}; see Christopher and Fischer [1992]). The numeric value of the ratio depends upon the geotextile type, the soil type, the flow regime, etc. For example, Carroll [1983] recommended the following:

$$0_{95} < (2 \;\; or \; 3) D_{85}$$

where D_{85} is the soil particle size in mm, for which 85% of the total soil is finer.

In contrast to the simplified methods stated above, a more comprehensive approach toward soil-retention criteria is given in Figure 4, for steady-state flow conditions, Luettich, et al. [1992]. To utilize the figure, one must first fully characterize the upstream soil from which flow is originating. A particle-size distribution, along with Atterberg limits, plasticity, dispersity and relative density characteristics are necessary. The design is then straightforward by having these properties and beginning from the left side of the figure, going progressively through the diagram, until the O_{95}-value on the right side is obtained. The method is highly recommended.

The inverse situation to requiring relatively small geotextile voids to prevent particle movement and subsequent excessive clogging of the geotextile or of the downstream gravel, is that there must be adequate flow of liquid through the geotextile filter, hence the void spaces in it must be sufficiently large. There is, however, a limit—that being when the upstream soil

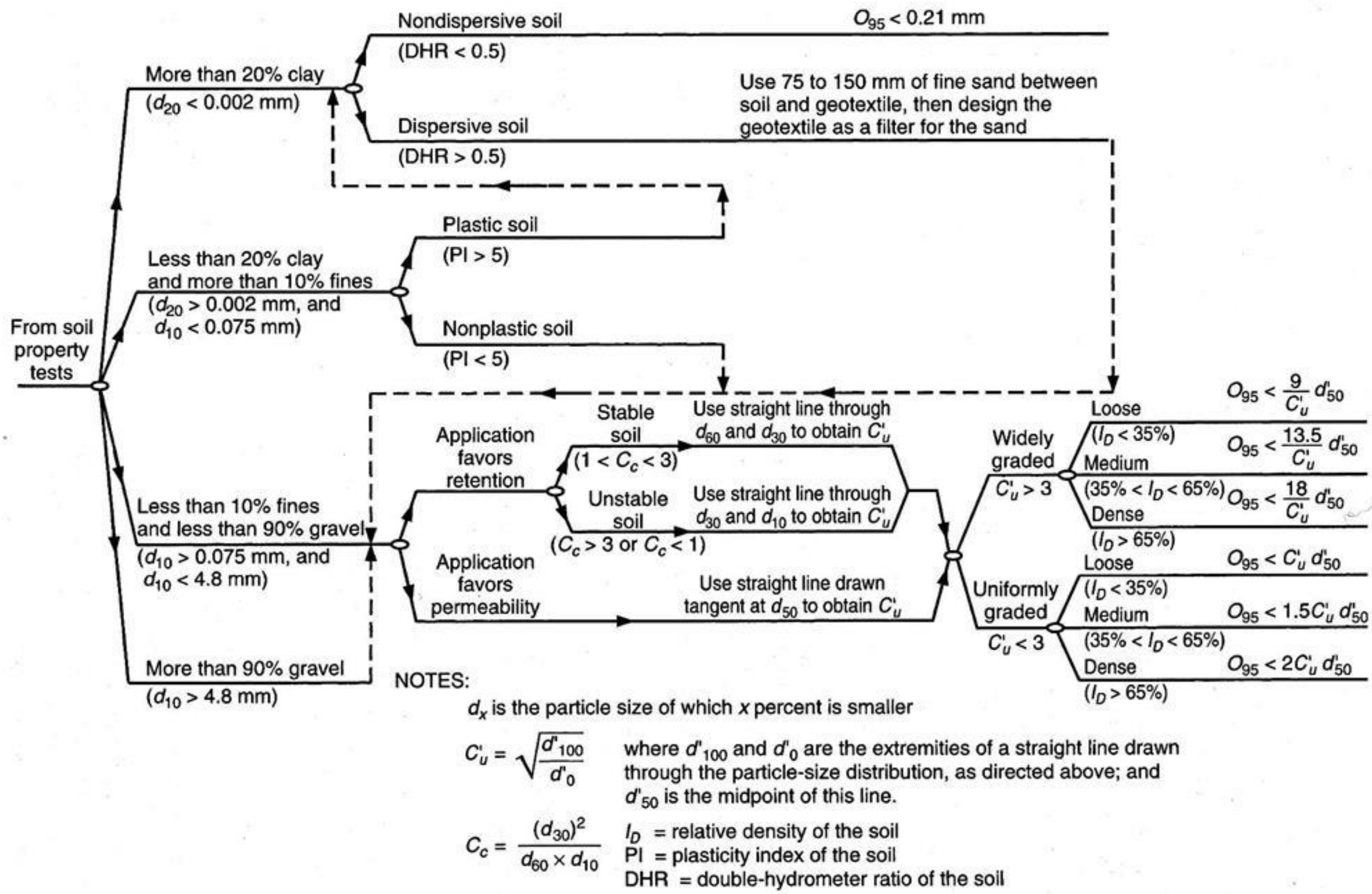


Figure 4. Soil retention criteria for geotextile filter design using *steady-state flow* conditions.
(After Luettich et al. [1992])

particles start to pass through the geotextile voids along with the flowing liquid. This can lead to an unacceptable situation called *soil piping*, in which upstream soil particles are carried through the geotextile, leaving unstable soil voids behind. The velocity of the liquid then increases, accelerating the process, until the upstream soil structure begins to collapse. This collapse often leads to small sinkhole-type patterns that grow larger with time.

Regarding adequate flow (permeability) through a geotextile filter, recognize that this property refers to cross-plane permeability wherein the liquid flow is perpendicular to the plane of the geotextile and not to in-plane permeability. Also, some of the geotextiles used for this purpose are relatively thick and compressible. For this reason the thickness is associated with the permeability coefficient and is used as *permittivity*, which is defined as follows:

$$\psi = \frac{k_n}{t} \tag{4}$$

where

ψ = permittivity

k_n = cross-plane permeability coefficient (the subscript n is often omitted), and

t = thickness at a specified normal pressure.

The testing for geotextile permittivity follows similar lines as used for testing soil permeability. It should be noted that some designers prefer to work directly with permeability and require the geotextile's permeability to be some multiple of the adjacent soil's permeability--e.g., 0.1, 1.0 or 10.0 (see Christopher and Fisher [1992]). Alternatively, one can formulate a factor-of-safety for adequate flow as follows:

$$FS = \psi_{allow}/\psi_{reqd} \tag{5}$$

The allowable permittivity is product-specific and evaluated per ASTM D4491 reduced by site-specific reduction factors, see Koerner (2012). The required permittivity is determined by a hydraulic design using Darcy's equation and is also illustrated and described in Koerner (2012).

Part III - MSE Wall Failures vis-à-vis the Lack of Filtration Design

Since 2001, GSI has been accumulating data on failures of geosynthetic reinforced mechanically stabilized earth (MSE) retaining walls. We presently have 301 cases, of which 191 (63%) have been caused in whole or part by water within, or adjacent to, the reinforced soil zone; see Figure 5. We sincerely hope that our past writings and webinars are helping to correct, or at least minimize, this unfortunate situation from continuing into the future.

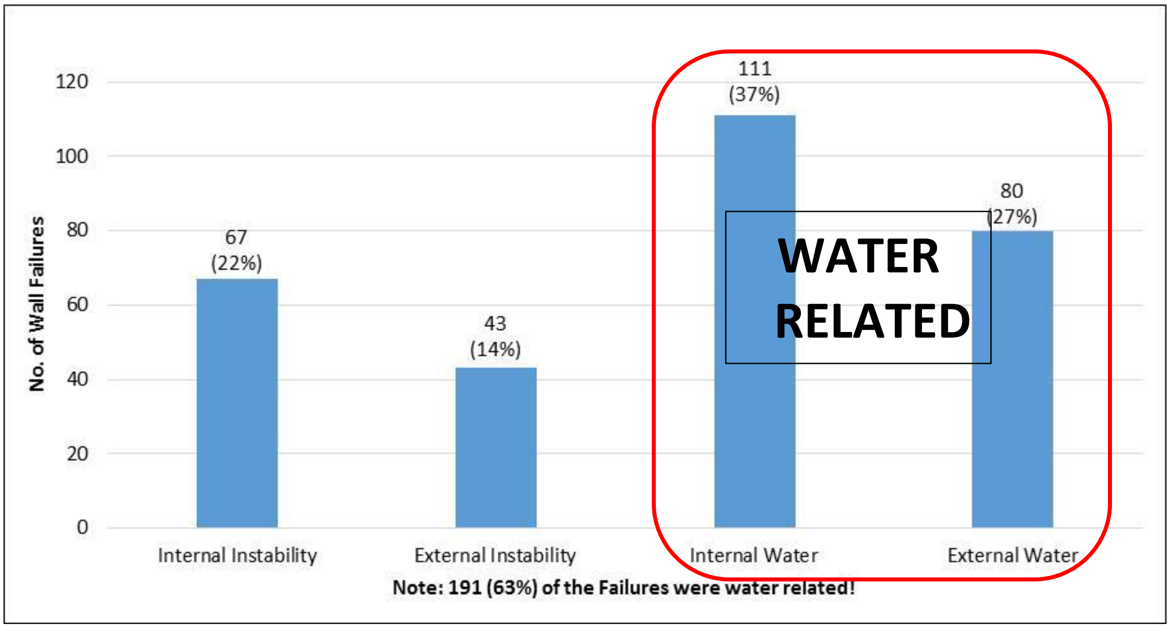


Figure 5. Basic failure mechanisms of 301 (100%) MSE wall failures.

Yet, there is one issue which has been, and continues to be, a serious omission in the design and construction of such walls. That is, the lack of a filter between fine-grained backfill soils and gravel drainage layers in the reinforced soil zone. To place fine grained backfill soils [note that 219 of the 301 failures (73%), used silt, clayey silt, silty clay or clay soils; see Figure 6] against gravel drainage layers with water moving from the fine-to-coarse *soils is a fundamental violation of filtration concepts.*

Figure 6. Backfill soils used in 301 (100%) MSW wall failures.

That said and focusing on MSE walls, there are three distinct locations within the standard MSE wall cross section which are deficient in this regard. Their locations are shown on Figure 7.

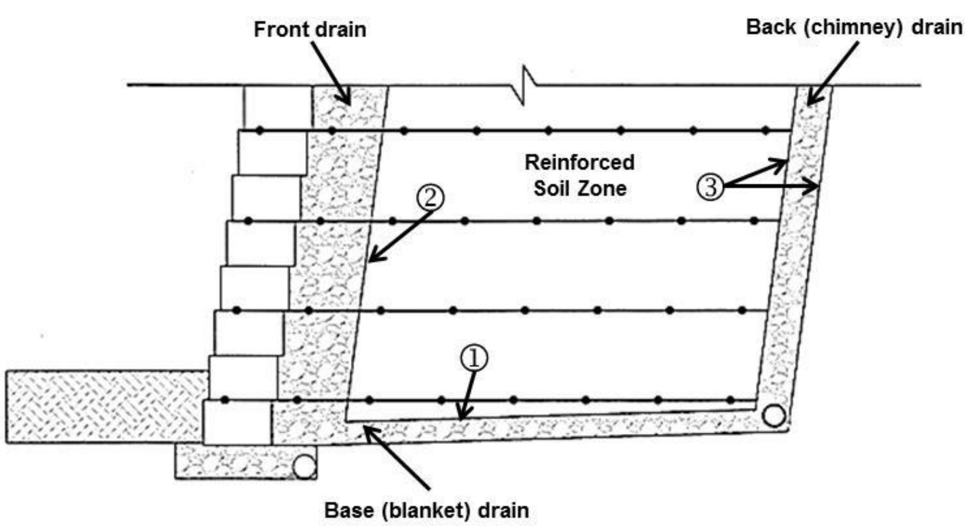
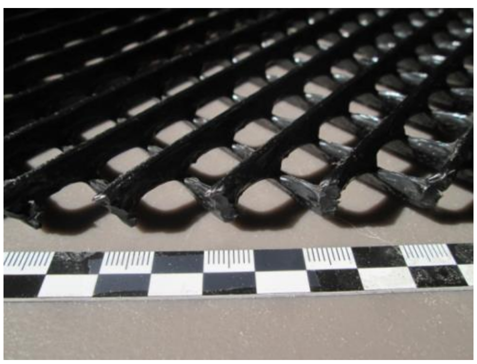


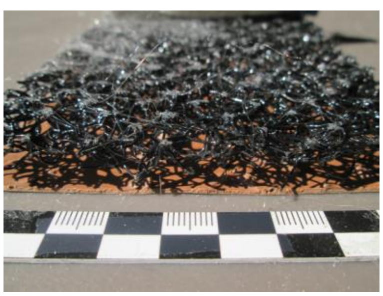
Figure 7. Base, Front and Back Drainage Locations
(mod. from National Concrete Masonry Association, Herndon, VA, Pub. No. TR308, 2016)

Location "1" is easy to accommodate using a geotextile filter since it is simply laid on top of the horizontal base (also called blanket) drain. Location "2" is more difficult construction-wise since each layer of soil between adjacent reinforcement layers must be wrapped accordingly. In so doing it becomes a wrap-around detail. In spite of the difficulty, it simply must be accommodated accordingly. Regarding location “3”, the geotextile filter must be on both sides of the back (also called chimney) drain. This becomes a nightmare to construct using gravel as the back drain. It begs the question, “why use gravel soil to begin with”? The straightforward answer to this situation is to omit the gravel drain and use a geocomposite drain. In this regard there are many types available under the two general categories of geonet composites and geospacer composites, see the photos of Figure 8. Let’s start using them on a regular basis and forget trying to stack a thin column of gravel vertically!



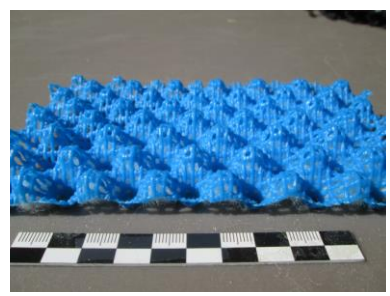
Biplanar Geonets

Triplanar Geonets



3-D mat geospacers

channel geospacers



protrusion, aka nubs/
columns/dimples geospacers

Figure 8. Geonet and geospacer drainage cores shown <u>without</u> their associated geotextile filters.

At this point in time we know that there are far too many MSE wall failures and that the majority are mobilized by water within or around the fine grained soil in the reinforced zone. By designing and placing geotextile filters, the high permeability gravel of the front drain and base drain will be indefinitely preserved. Even further, the use of drainage geocomposites for back drainage eliminates the contractors challenge of building a near vertical column of gravel and furthermore geosynthetic drainage composites automatically come with geotextile filters bonded onto both surfaces of the drainage core.

We feel that by not providing geotextile filter protected drainage to the front, base and back drainage systems of MSE walls it will result in long-term failures most likely in the lower regions of the wall where hydrostatic pressures are highest; see Figure 9. Incidentally, the repair of such toe failures is incredibly difficult and expensive, and certainly looks bad for all parties involved and for the industry as a whole.

Figure 9. Toe failures of MSE walls caused by hydrostatic pressures.
(see Wikipedia and Google)

References

American Association of State, Highway and Transportation Officials (AASHTO), (1991), Report of Task Force 25, Washington, DC.

ASTM D4991, "Standard Test Method for Water Permeability of Geotextiles by Permittivity," ASTM, West Conshohocken, PA.

ASTM D4751, "Standard Test Method for Determining Apparent Opening Size of a Geotextile," ASTM, West Conshohocken, PA.

ASTM D6767, "Standard Test Method for Pore Size Characteristics of Geotextiles by Capillary Flow Test," ASTM, West Conshohocken, PA.

ASTM D6913, "Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis," ASTM, West Conshohocken, PA.

Bertram, G. E. (1940), "An Experimental Investigation of Protection Filters," Publications of the Graduate School of Engineering, Harvard University, No. 267, January, 1940.

Carroll, R. G. Jr. (1983), "Geotextile Filter Criteria," TRR 916, Engineering Fabrics in Transportation Construction, Washington, DC, pp. 46-53.

Cedegren, H. R. (1973), "Seepage Control in Earth Dams," Chapter 1 in Embankment Dam Engineering, Hirschfeld, R. C. and Poulos, S. T. Eds., J. Wiley and Sons, NY, pp. 21-45.

Christopher, B. R. and Fisher, G. R. (1992), "Geotextile Filtration Principles, Practices and Problems," Jour. of Geotextiles and Geomembranes, Vol. 11, No. 4-6, pp. 337-354.

Koerner, R. M. (2016), *Designing With Geosynthetics,* 6th Edition, Xlibris Publ. Co., 914 pgs.

Koerner, R. M. and Koerner, G. R. (2013), "A Data Base Statistics and Recommendations Regarding 171 Failed Mechanically Stabilized Walls (MSW)," Jour. Geotextiles and Geomembranes, Vol. 40, October, pp. 20-27.

Koerner, R. M. and Welsh, J. P. (1980), "Construction and Geotechnical Engineering Using Synthetic Fabrics," J. Wiley and Sons, NY, 267 pgs.

Lambe, T. W. and Whitman, R. V. (1969), *Soil Mechanics*, J. Wiley & Sons, NY, 553 pgs.

Luettich, S., Giroud, J.-P. and Bachus, R. C. (1992), "Geotextile Filter Design Guide," Jour. Geotextiles and Geomembranes, Vol. 11, No. 4-6, pp. 19-34.

Terzaghi, K. (1925), *Erbaumechanik auf bodenphysikalis-cher Grundlage,* Deuticke, Vienna, 399 pgs.