**PDHonline Course C660 (2 PDH)**

# An Introduction to Geotextiles for Soil Wall Reinforcement

*Instructor: J. Paul Guyer, P.E., R.A., Fellow ASCE, Fellow AEI*

**2020**

**PDH Online | PDH Center**

5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
www.PDHonline.com

An Approved Continuing Education Provider

# An Introduction to Geotextiles for Soil Wall Reinforcement

*J. Paul Guyer, P.E., R.A.*

## CONTENTS



 

(This publication is adapted from the *Unified Facilities Criteria* of the United States government which are in the public domain, have been authorized for unlimited distribution, and are not copyrighted.)

(Figures, tables and equations in this publication may at times be a little difficult to read, but they are the best available. **DO NOT PURCHASE THIS PUBLICATION IF THIS LIMITATION IS UNACCEPTABLE TO YOU.**)

**1. INTRODUCTION.** Soil, especially granular, is relatively strong under compressive stresses. When reinforced, significant tensile stresses can be carried by the reinforcement, resulting in a composite structure which possesses wider margins of strength. This extra strength means that steeper slopes can be built. Geotextiles have been utilized in the construction of reinforced soil walls since the early 1970's. Geotextile sheets are used to wrap compacted soil in layers producing a stable composite structure. Geotextile-reinforced soil walls somewhat resemble the popular sandbag walls which have been used for some decades. However, geotextile-reinforced walls can be constructed to significant height because of the geotextile's higher strength and a simple mechanized construction procedure.

**2. ADVANTAGES OF GEOTEXTILE-REINFORCED WALLS.** Some advantages of geotextile-reinforced walls over conventional concrete walls are the following:

a. They are economical.

b. Construction usually is easy and rapid. It does not require skilled labor or specialized equipment. Many of the components are prefabricated allowing relatively quick construction.

c. Regardless of the height or length of the wall, support of the structure is not required during construction as for conventional retaining walls.

d. They are relatively flexible and can tolerate large lateral deformations and large differential vertical settlements. The flexibility of geotextile reinforced walls allows the use of a lower factor of safety for bearing capacity design than for conventional more rigid structures.

e. They are potentially better suited for earthquake loading because of the flexibility and inherent energy absorption capacity of the coherent earth mass.

**3. DISADVANTAGES OF GEOTEXTILE-REINFORCED WALLS.** Some disadvantages of geotextile-reinforced walls over conventional concrete walls are the following:

a. Some decrease in geotextile strength may occur because of possible damage during construction.

b. Some decrease in geotextile strength may occur with time at constant load and soil temperature.

c. The construction of geotextile-reinforced walls in cut regions requires a wider excavation than conventional retaining walls.

d. Excavation behind the geotextile-reinforced wall is restricted.

 

**4. USES.** Geotextile-reinforced walls can be substantially more economical to construct than conventional walls. However, since geotextile application to walls is relatively new, long term effects such as creep, aging, and durability are not known based on actual experience. Therefore, a short life, serious consequences of failure, or high repair or replacement costs could offset a lower first cost. Serious consideration should be given before utilization in critical structures. Applications of geotextile-reinforced walls range from construction of temporary road embankments to permanent structures remedying slide problems and widening, highways effectively. Such walls can be constructed as noise barriers or even as abutments for secondary bridges. Because of their flexibility, these walls can be constructed in areas where poor foundation material exists or areas susceptible to earthquake activity.

## 5. GENERAL CONSIDERATIONS.

a. The wall face may be vertical or inclined. This can be because of structural reasons (internal stability), ease of construction, or architectural purposes. All geotextiles are equally spaced so that construction is simplified. All geotextile sheets, except perhaps for the lowest one, usually extend to the same vertical plane.

b. Geotextiles exposed to UV light may degrade quite rapidly. At the end of construction, a protective coating should be applied to the exposed face of the wall. An application of 0.25 gallon per square yard of CSS-1 emulsified asphalt or spraying with a low viscosity water-cement mixture is recommended. This cement mixture bonds well and provides satisfactory protection even for smooth geotextiles. To protect the face of the wall from vandalism, a 3-inch layer of gunnite can be applied. This can be done by projecting concrete over a reinforcing mesh manufactured from No. 12 wires, spaced 2 inches in each direction, supported by No. 3 rebars inserted between geotextile layers
to a depth of 3 feet.

c. When aesthetic appearance is important, a low-cost solution like the facing system comprised of used railroad ties or other such materials can be used.

d. No weepholes are specified, although after UV and vandal protection measures the wall face may be rather impermeable. To ensure the fast removal of seeping water in a permanent structure, it is recommended to replace 1 to 2 feet of the natural foundation soil (in case it is not free-draining) with a crushed-stone foundation layer to facilitate drainage from within and behind the wall. The crushed rock may be separated from the natural soil by a heavy weight geotextile.

 

## 6. PROPERTIES OF MATERIALS.

**6.1 RETAINED SOIL.** The soil wrapped by the geotextile sheets is termed “retained soil.” This soil must be free-draining and nonplastic. The ranking (most desirable to less desirable) of various retained soils for permanent walls using the Unified Soil Classification System is as follows: SW, SP, GW, GP, and any of these as a borderline classification which is dual designated with GM or SM. The amount of fines in the soil is limited to 12 percent passing sieve No. 200. This restriction is imposed because of possible migration of fines being washed by seeping water. The fines may be trapped by geotextile sheets, thus eventually creating low permeability liners. Generally, the permeability of the retained soil must be more than 10-3 centimeters per second. The ranking order indicates that gravels are not at the top. Although they posses high permeability and, possibly, high strength, their utilization requires special attention. Gravel, especially if it contains angular grains, can puncture the geotextile sheets during construction. Consequently, consideration must be given to geotextile selection so as to resist possible damage. If a geotextile possessing high puncture resistance is available, then GP and GW should replace SP and SW, respectively, in their ranking order. The retained soil unit weight should be specified based on conventional laboratory compaction tests. A minimum of 95 percent of the maximum dry unit weight, as determined by ASTM D 698 should be attained during construction. Since the retained soil will probably be further densified as additional layers are placed and compacted, and may be subjected to transitional external sources of water, such as rainfall, it is recommended for design purposes that the saturated unite weight be used.

**6.2 BACKFILL SOIL.** The soil supported by the reinforced wall (the soil to the right of L in figure 1) is termed “backfill soil.” This soil has a direct effect on the external stability of the wall. Therefore, it should be carefully selected. Generally, backfill specifications used for conventional retaining walls should be employed here as well.

Clay, silt, or any other material with low permeability should be avoided next to a permanent wall. If low quality materials are used, then a geotextile filter

 

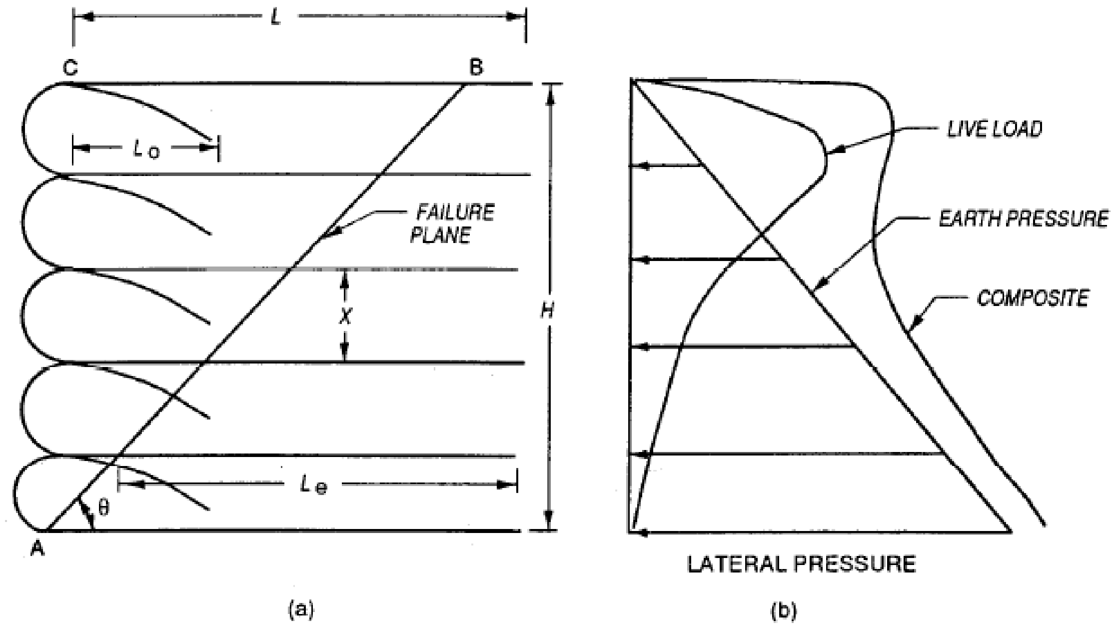


Figure 1
General Configuration of a Geotextile Retained Soil Wall
and Typical Pressure Diagrams

meeting filtration requirements should be placed to separate the fines from the free draining backfills, thus preventing fouling of the higher quality material. Since the retained soil and backfill may have an effect on the external stability of the reinforced wall, the properties of both materials are needed. The unit weight should be estimated as for the retained soil; use the maximum density at zero air voids. The strength parameters should be determined using drained direct shear tests (ASTM D 3080) for the permeable backfill. The backfill and the retained soil must have similar gradation at their interface so as to minimize the potential for lateral migration of soil particles. If such requirement is not practical, then a conventional soil filter should be designed, or a geotextile filter used along the interface.

**7. DESIGN METHOD.** The design method recommended for retaining walls reinforced with geotextiles is basically the U.S. Forest Service method as developed by Steward, Williamson, and Mahoney (1977) using the Rankine approach. The method considers the earth pressure, line load pressure, fabric tension, and pullout resistance as the primary design parameters.

**7.1 EARTH PRESSURE.** Lateral earth pressure at any depth below the top of the wall (fig 1a) is given by:

$$\sigma_{ho} = K_o \gamma d$$

where

$\sigma_{ho}$ = lateral earth pressure acting on the wall
$K^o$ = at rest pressure coefficient
$\gamma$ = soil unit weight
d = depth below the top of the wall

(eq 1)

A typical earth pressure distribution is shown in figure 1b. Use of the "at rest" pressure coefficient, $K^o$ , is recommended and is determined by the following equation:

$$k_o = 1 - \sin \phi$$

(eq 2)

where $\phi$ is the angle of internal friction of the soil. The failure surface, AB in figure 1a, slopes upward at an angle of $\Theta = 45 + \Theta/2$.

**7.2 LIVE LOAD PRESSURE.** Lateral pressures from live loads are calculated for a point load acting on the surface of the backfill using the following equation:

$$\sigma_{hl} = Px^2z/R^5 \quad \text{(eq 3)}$$

where

P = vertical load

x = horizontal distance from load to wall and perpendicular to the wall

z = vertical distance from load to point where stress is being calculated

$R = \sqrt{x^2 + y^2 + z^2}$

y = horizontal distance from load to wall, and parallel to the wall

A typical live load pressure distribution is shown in figure 1b. Figure 2 illustrates live load stress calculations.

**7.3 FABRIC TENSION.** Tension in any fabric layer is equal to the lateral stress at the depth of the layer times the face area that the fabric must support. For a vertical fabric spacing of X , a unit width of fabric at depth d must support a force of , where is the average total lateral pressure (composite of dead plus live load) over the vertical interval X .

**7.4 PULLOUT RESISTANCE.** A sufficient length of geotextile must be embedded behind the failure plane to resist pullout. Thus, in Figure 1a, only the length, Le, of fabric behind the failure plane AB would be used to resist pullout. Pullout resistance can be calculated from:

$$P_A = 2d\gamma \text{ TAN } 2/3\ \phi$$

where

$P_A$ = pullout resistance

d = depth of retained soil below top of retaining wall

$\gamma$ = unit weight of retained soil

$\phi$ = angle of internal friction of retained soil

$L_e$ = length of embedment behind the failure plane

(eq 4)

It can be seen from this expression that pullout resistance is the product of overburden pressure, γd, and the coefficient of friction between retained soil and fabric which is assumed to be TAN 2/3 Φ. This resistance is in pounds per square foot which is multiplied by the surface area of $2L_e$ for a unit width. Where different soils are used above and below the fabric layer, the expression is modified to account for different coefficients of friction for each soil:

$$P_A = d\ \gamma\ (\text{TAN } 2/3\ \phi_1 + \text{TAN } 2/3\ \gamma_2)$$

(eq 5)

**8. DESIGN PROCEDURE.** The recommended design procedure is discussed in the following steps. The calculations for the fabric dimensions for overlap, embedment length and vertical spacing should include a safety factor of 1.5 to 1.75 depending upon the confidence level in the strength parameters.

**8.1 RETAINED SOIL PROPERTIES Φ AND γ.** Only freedraining granular materials should be used as retained soil. The friction angle, Φ, will be determined using the direct shear (ASTM D 3080)

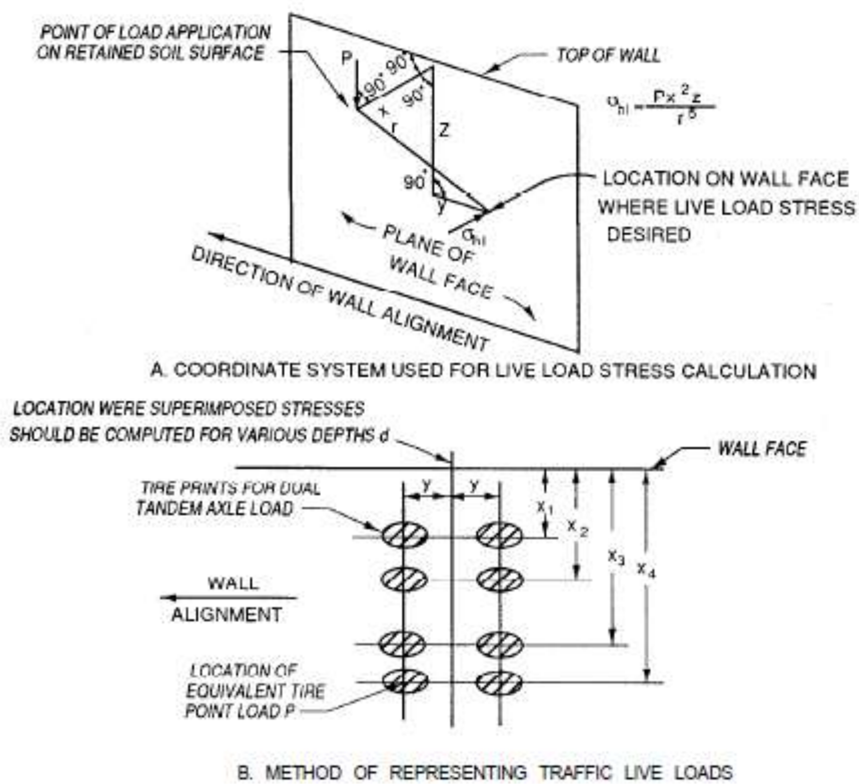


Figure 2

Procedures for Computing Live Load Stresses on

Geotextile Reinforced Retaining Walls

or triaxial tests (ASTM D 2850). The unit weight, γ, will be determined in a moisture density test (ASTM D 698). Generally, 95 percent of ASTM D 698 maximum density can be easily attained with granular materials. However, other densities can be specified so long as the friction angle used is consistent with that density. The saturated unit weight is used in lateral pressure calculations.

**8.2 LATERAL EARTH PRESSURE DIAGRAM.** Using the properties of the retained soil, calculate the pressure coefficient $K_o$ = I x SIN Φ. The lateral earth pressure expression: $\sigma_{ho} = K_o\gamma h$ is used to calculate the triangular shaped pressure distribution curve for the height of retaining wall desired.

**8.3 LIVE LOAD LATERAL PRESSURE DIAGRAM.** It is first necessary to determine the design load. Lateral pressure diagrams must be developed for each vehicle or other equipment expected to apply loads to the retaining wall using equation 3. The equation is solved for each wheel and the results added to obtain the lateral pressure. This pressure is calculated at 2-foot vertical intervals over the height of the retaining wall. Normally, from one to three locations along the wall are checked to determine the most critical.

**8.4 COMPOSITE PRESSURE DIAGRAM.** The earth pressure and live load pressure diagrams are combined to develop the composite diagram used for design as shown in Figure 1b.

**8.5 VERTICAL SPACING OF THE FABRIC LAYER.** To determine the vertical strength of the fabric layer, the fabric allowable tensile strength, S, is set equal to the lateral force calculated from $\sigma_h X$, where $\sigma_h$ is the lateral pressure at the middle of the layer. Thus, knowing the fabric tensile strength, and value of the fabric vertical spacing, X , can be calculated. The fabric strength should be divided by the appropriate safety factor. The equation for fabric spacing is:

$$X = \frac{S}{(F.S.)\sigma_h} \qquad \text{(eq 6)}$$

**8.6 LENGTH OF FABRIC REQUIRED TO DEVELOP PULLOUT RESISTANCE.** The formula for pullout resistance, $P_A = 2d\gamma TAN\ 2/3\Phi\ L_e$, is used to solve for the pullout resistance which can be developed at a given depth geotextile length combination or to solve for d, the depth required to develop $P_a$. The usual case for walls is to set $P_a$ equal to the geotextile strength and solve for , the length of geotextile required. Thus, the expression would be:

$$L_e = \frac{P_A\ (F.S.)}{(2\ d\ \gamma\ TAN\ 2/3\ \phi)}$$

where

$P_A$ = fabric tensile strength

F.S. = safety factor of 1.5 to 1.75

The minimum length of the fabric required is 3 feet.

**8.7 LENGTH OF FABRIC OVERLAP FOR THE FOLDED PORTION OF FABRIC AT THE FACE.** The overlap, $L_o$ , must be long enough to transfer the stress from the lower section of geotextile to the longer layer above. The pullout resistance of the geotextile is given by:

$$f = d_F\ \gamma\ TAN\ 2/3\ \phi\ L_o\ 2 \qquad \text{(eq 8)}$$

Where $d_f$ = depth to overlap. Tension in the geotextile is:

$$T = \sigma_h\left(\frac{X}{2}\right) \qquad \text{(eq 9)}$$

Since the factor of safety can be expressed as:

$$F.S. = \frac{f}{T} = \frac{d_F\ \gamma\ TAN\ 2/3\ \phi\ L_o}{\sigma_h\left(\frac{x}{2}\right)} \qquad \text{(eq 10)}$$

This can be solved for the length of overlap required:

$$L_o = \frac{\sigma_h X \text{ (F.S.)}}{2\, d_F\, \gamma\, \text{TAN } 2/3\, \phi}$$

The minimum length of overlap should be 3 feet to ensure adequate contact between layers.

**8.8 EXTERNAL WALL STABILITY.** Once the internal stability of the structure is satisfied, the external stability against overturning, sliding and foundation bearing capacity should be checked. This is accomplished in the same manner as for a retaining wall without a geotextile. Overturning loads are developed from the lateral pressure diagram for the back of the wall. This may be different from the lateral pressure diagram used in checking internal stability, particularly due to placement of live loads. Overturning is checked by summing moments of external forces about the bottom at the face of the wall. Sliding along the base is checked by summing external horizontal forces. Bearing capacity is checked using standard foundation bearing capacity analysis. Theoretically, the fabric layers at the base could be shorter than at the top. However, because of external stability considerations, particularly sliding and bearing capacity, all fabric layers are normally of uniform width.

## 9. REFERENCES


Al-Hussaini, M. M., "Field Experiment of Fabric Reinforced Earth Wall," *Proceedings of the International Conference on the Use of Fabrics in Geotechnics,* Paris, Apr 20-22, Vol. 1, pp. 119-121, 1977.

Al-Hussaini, M., and Perry, E. B., "Analysis of A Rubber- Membrane Strip Reinforced Earth Wall," SoilReinforcing and Stabilizing Techniques in Engineering Practice, *Proceedings of a Symposium Jointly Organized by the New South Wales Institute of Technology and the University of New South Wales,*Sydney, Australia, 1978.

Andrawes, K. Z., McGowan, A., Wilson-Fahmy, R. F., and Mashhour, M. M., "The Finite-Element Method of Analysis Applied to Soil-Geotextile Systems," *Proceedings of the 2nd International Conference on Geotextiles,* Las Vegas, Aug l-6, Vol. 3, pp. 695-700, 1982.

Baker, R., "Tensile Strength, Tension Cracks and Stability of Slopes," *Soils and Foundations, Journal of the Japanese Society of Soil Mechanics and Foundations Engineering,* Vol. 21, No. 2, pp. 1-17, 1981.

Baker, R., and Garber, M., "Variational Approach to Slope Stability," *Proceedings of the 9th International Conference on Soil Mechanics and Foundation Engineering,* Vol. 2, pp. 9-12, Tokyo, 1977.

Baker, R., and Garber, M., "Theoretical Analysis of the Stability of Slopes," *Geotechnique,* Vol. 28, No. 4, pp. 395-411, 1978.

Barrett, R. K., "Geotextiles in Earth Reinforcement," *Geotechnical Fabrics Report,* Mar/Apr, Vol. 3, No. 2, pp. 15-99, 1988.

Bell, J. R., Barrett, R. K., and Ruckman, A. C., "Geotextile Earth-Reinforced Retaining Wall Tests: Glenwood Canyon, Colorado," *Transportation Research Record, 916,* pp. 59-69, 1983.

Bell, J. R., Greenway, D. R., and Vischer, W., "Construction and Analysis of a Fabric-Reinforced Low Embankment on Muskeg," *Proceedings, International Conference on the Use of Fabrics in Geotechniques,* Paris, Vol. 1, pp. 71-76, 1977.

Bell, J. R., and Hicks, R. G., "Evaluation of Test Methods and Use Criteria for Geotechnical Fabrics in Highway Applications, Final Report," Federal Highway Administration, Washington, DC, 1983.

Bell, J. R., and Steward, J. E., "Construction and Observation of Fabric Retained Soil Walls," *Proceedings of the International Conference on the Use of Fabrics in Geotechnics,* April 20-22, Vol. 1, pp. 123-128, 1977.

Bell, J. R., Stilley, A. N., and Vandre, B., "Fabric Retained Earth Walls," *Proceedings of the 13th Annual Engineering Geology and Soils Engineering Symposium,* University of Idaho, Moscow, Idaho, April 2-4, pp. 271-287, 1975.

Blair, J. C., Bell, J. R., and Hicks, R. G., "Permeability Testing of Geotextiles," *Transportation Research Record, 826,* pp. 1-6, 1981.

Broms, B. B., “Design of Fabric Reinforced Retaining Structures,” *Proceedings of the Symposium on Earth Reinforcement,* American Society of Civil Engineers, Pittsburgh, Penn., 1978.

Campbell, D. H., et al., “Erosion Objective: Storm Water Drainage Channel Needs Erosion Protection,” Geotechnical Fabrics Report, p. 20, 1985.

Cedergren, H. R., *Seepage, Drainage, and Flownets,* Wiley, New York, 1977.

Chassie, R. G., “Geotextile Retaining Walls: Some Case History Examples,” paper prepared for presentation at the 1984 NW Roads and Streets Conference, Corvalis, Oreg., 1984.

Chen, W. F., *Limit Analysis and Soil Plasticity,* Elsevier Pub., Amsterdam, The Netherlands, 1975.

Christie, I. F., and E-Hadi, K. M., “Some Aspects of the Design of Earth Dams Reinforced with Fabric,” *Proceedings of the International Conference on the Use of Fabrics in Geotechnics,* Paris, April 20-22, Vol. 1, pp. 99-103, 1977.

Christopher, B. R. 1983. “Evaluation of Two Geotextile Installations in Excess of a Decade Old,” *Transportation Research Record 916,* National Academy of Sciences, Washington, DC, p 79-88.

Christopher, B. R., and Holtz, R. D., “Geotextile Engineering Manual,” Report No. FHWA-TS-861203, STS Consultants Ltd, Northbrook, Ill under contract FHWA No. DTFH61-83-C-00094, 1984.

Civil Works Construction Guide Specification, No. CW 02215, “Plastic Filter Fabric,” Department of the Army Corps of Engineers, Office of the Chief of Engineers, Washington, DC, 1986.

Couch, F. B., Jr., “Geotextile Applications to Slope Protection for the Tennessee-Tombigbee Waterway Divide Cut,” Second International Conference on Geotextiles, Las Vegas, Nev., 1982.

Coutermarsh, B. A. and G. Phetteplace, *“Numerical Analysis of Frost Shields,”* in Proceedings, American Society of Civil Engineers/Canadian Geotechnical Society Sixth International Cold Regions Specialty Conference, W. Lebanon, NH, February 26-28, 1991, p. 178-190.

Coutermarsh, B. A. and G. Phetteplace, *“Analysis of Frost Shields Using the Finite Element Method,”* Seventh International Conference on Numerical Methods in Thermal Problems, Stanford, CA, Pineridge Press, Swansea, UK, p. 123-132.

De Ment, L. E., “Two New Methods of Erosion Protection for Louisiana,” *Shore Beach,* Vol. 45, No. 1, p. 8, 1977.

Douglas, G. E., “Design and Construction of Fabric-Reinforced Retaining Walls by New York State,” *Transportation Research Record, 872,* pp. 32-37, 1982.

El-Fermaoui, A., and Nowatzki, E., “Effect of Confining Pressure on Performance of Geotextiles in Soils,” *Proceedings of the 2nd International Conference on Geotextiles,* Las Vegas, Aug l-6, Vol. 3, pp. 799-804, 1982.

Engineering and Design, "Use of Geotextiles Under Riprap," Engineer Technical Letter No. 1110-2-286, Department of the Army, US Army Corps of Engineers, Washington, DC, 1984.

Ford, H. W., "Estimating the Potential for Ochre Clogging Before Installing Drains," *Transactions of the American Society of Civil Engineers 25(6),* pp. 1597-1600, 1982a.

Ford, H. W., "Some Fundamentals of Iron and Slime Deposition in Drains," *Proceedings of the Second International Drainage Workshop,* Washington, DC, pp. 207-212, 1982b.

Fowler, Jack, "Analysis of Fabric-Reinforced Embankment Test Section at Pinto Pass, Mobile, Alabama," thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, Oklahoma State University, Stillwater, Okla., 1979.

Fowler, J., "Theoretical Design Considerations for Fabric-Reinforced Embankments," *Proceedings of the 2nd International Conference on Geotextiles,* Las Vegas, Aug I-6, Vol. 3, pp. 665-670, 1982.

*Geotextiles and Geomembranes,* T. S. Ingold, Ed., published by Elsevier Applied Science Publishers, Essex, England, containing articles on geotextiles and geomembranes, began publication in 1984.

*Geotechnical Fabrics Report,* Published by Industrial Fabrics Association International since 1981, St. Paul, Minn.

Giroud, J. P., "Filter Criteria for Geotextiles," *Proceedings of the Second International Conference on Geotextiles,* Vol. I, pp. 103-108, 1982.

Gulden, W., and Brown, D., "Treatments for Reduction of Reflective Cracking of Asphalt Overlays on Jointed-Concrete Pavements in Georgia," *Transportation Research Record 916,* Transportation Research Board, Washington, DC, 1983.

Haliburton, T. A., "Design of Test Section for Pinto Pass Dike, Mobile, Alabama," Report prepared by Haliburton Associates, Stillwater, Okla., under Contract No. DACW0l-78-C-0092, for US Army Engineer District, Mobile, Mobile, Ala., 1978.

Haliburton, T. A., "Evaluation of Construction Procedure for Fabric-Reinforced Embankment Test Section, Pinto Pass, Mobile Harbor, Alabama," conducted by Haliburton Associates, Stillwater, Okla., under Contract No. DACW39-78-M-4002, for US Army Engineer Waterways Experiment Station, Vicksburg, Miss., 1979.

Haliburton, T. A., Anglin, C. C., and Lawmaster, J. D., "Selection of Geotechnical Fabrics for Embankment Reinforcement," School of Civil Engineering, Oklahoma State University, Stillwater, Okla., 1978.

Haliburton, T. A., Fowler, J., and Langan, J. P., "Design and Construction of Fabric-Reinforced Embankment Test Section at Pinto Pass, Mobile, Alabama," *Transportation Research Record, 249,* pp. 27-34, Washington, DC, 1980.

Haliburton, T. A., Lawmaster, J. D., and King, J. J., "Potential Use of Geotechnical Fabric in Airfield Runway Design," Contract No. AFOSR79-00871, Air Force Office of Scientific Research, School of Civil Engineering, Oklahoma State University, Stillwater, Okla., 1980.

Haliburton, T. A., Lawmaster, J. D., and McGuffie, V. C., "Use of Engineering Fabrics in Transportation Related Applications," Haliburton Associates Engineering Consultants, Under Contract No. DTFH-80-C-0094, Stillwater, Okla., 1981.

Hammer, D. P., and Blackburn, E. D., "Design and Construction of Retaining Dikes for Containment of Dredged Material," Technical Report TR-D-77-9, US Army Engineer District, Savannah, Savannah, Ga., 1977.

Henry, K. S., *"Geotextiles as Capillary Barriers,"* Geotechnical Fabrics Report, March/April, pp. 30-36.

Henry, K. S., *"Laboratory Investigation of the Use of Geotextiles to Mitigate Frost Heave,"* CRREL Report 90-6, CRREL, Hanover, NH USA, 28 p.

Henry, K. S., *"Use of Geotextiles to Mitigate Frost Heave in Soils,',* in Proceedings, V International Conference on Permafrost in Trondheim, Norway, Vol. 2, p. 1096-1011.

Henry, K. S., S. Taylor and J. Ingersoll, *"Effects of Freezing on the Microstructure of Two Geotextiles,"* in Geosynthetics: Microstructure and Performance, ASTM STP 1076, pp. 147-164.

Henry, Karen S., *"Effect of Geotextiles on Water Migration in Freezing Soils and the Influence of Freezing on Performance,"* Proceedings, Geosynthetics, 91, Atlanta, GA, Industrial Fabrics Association International, St. Paul, MN.

Horz, R. C., "Geotextiles for Drainage, Gas Venting, and Erosion Control at Hazardous Waste Sites," *Report* No. *EPA/600/2-86/085,* US Environmental Protection Agency, Cincinnati, Ohio, 1986.

Ingold, T. S., "An Analytical Study of Geotextile Reinforced Embankments," *Proceedings of the 2nd International Conference on Geotextiles,* Las Vegas, Aug l-6, Vol. 3, pp. 683-688, 1982.

Instruction for Use of Construction Specification No. 210, "Plastic Filter Cloth," Department of the Army Corps of Engineers, Office of the Chief of Engineers, Washington, DC, 1981.

Jewell, R. A., "A Limit Equilibrium Design Method for Reinforced Embankments of Soft Foundations," *Proceedings of the 2nd International Conference on Geotextiles,* Las Vegas, Aug l-6, Vol. 3.) pp. 671-676, 1982.

Jones, *C.* J. F. P., *Earth Reinforcement and Soil Structures,* Butterworth and Co., Ltd., London, 1985.

Keown, M. P., and Oswalt, N. R., "US Army Corps of Engineers Experience with Filter Fabric for Streambank Protection Applications, Flexible Armored Revetments Incorporating Geotextiles," Pro*ceedings of the International Conference Organized by the Institution of Civil Engineers,* London, 1984.

Koerner, R. M., *Designing with Geosynthetics,* Prentice-Hall, Englewood Cliffs, N.J., 1986.

Koerner, R. M., and Bove, J. A., "In-Plane Hydraulic Properties of Geotextiles," *Geotechnical Testing Journal,* Vol. 6, No. 4, pp. 190-195, 1983.

Koerner, R. M., and Welsh, J. P., *Construction and Geotechnical Engineering Using Synthetic Fabrics,* Wiley, New York, 1980.

Lamb, T. W., and Whitman, R. V., *Soil Mechanics, SI Version,* Wiley, New York, 1979.

Lee, K. L., Adams, B. D., and Vagneron, J-M. J., "Reinforced Earth Retaining Walls," *Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers,* Vol. 99, No. SM10, pp. 745-764, 1973.

Leshchinsky, D., "Geotextile Reinforced Earth, Part I & II," Research Report Nos. CE 84-44/45, Department of Civil Engineering, University of Delaware, Newark, Del., 1984.

Leshchinsky, D., Baker, R., and Silver, M. L., "Three Dimensional Analysis of Slope Stability," *International Journal for Numerical and Analytical Methods in Geomechanics,* Vol. 9, pp. 199-223, 1985.

Leshchinsky, D., and Boedeker, R. H., "Geosynthetic Reinforced Soil Structures," *Journal of the Geotechnical Engineering,* American Society of Civil Engineers, Vol. 115, No. 10, pp. 1459-1478, 1989.

Leshchinsky, D., and Field, D. A., "In-Soil Load Elongation, Tensile Strength and Interface Friction of Nonwoven Geotextiles," *Proceedings of the Geosynthetics '87 Conference,* New Orleans, Feb 24-25, Vol. 1, pp. 238-249, 1987.

Leshchinsky, D., and Perry, E. B., "On the Design of Geosynthetic-Reinforced Walls," Geotextiles and Geomembranes, (in press), 1989.

Leshchinsky, D., and Reinschmidt, A. J., "Stability of Membrane Reinforced Slopes," *Journal of the Geotechnical Engineering, American Society of Civil Engineers,* Vol. 111, No. 11, pp. 1285-1300, 1985.

Leshchinsky, D., and Volk, J. C., "Stability Charts for Geotextile Reinforced Walls," *Transportation Research Record, 1031,* pp. 5-16, 1985.

McGhee, K. H., "Efforts to Reduce Reflective Cracking of Bituminous Concrete Overlays of Portland Cement Concrete Pavements," Virginia Highway and Transportation Research 'Council, Charlottesville, Va., 1975.

McGowan, A., Andrawes, K. Z., and Kabir, M. H., "Load-Extension Testing of Geotextiles Confined In-Soil," *Proceedings of the 2nd International Conference on Geotextiles,* Las Vegas, Aug l-6, Vol. 3, pp. 793-798, 1982.

Meyerhof, G. G., "The Bearing Capacity of Foundations Under Eccentric and Inclined Loads," *Proceedings, 34th International Conference on Soil Mechanics and Foundation Engineering,* Zurich, Vol. 1, pp. 440-445, 1953.

Mitchell, J. K., "Earth Walls," *Transportation* News, Transportation Research Board, National Research Council, No. 114, pp. 24-31, 1984.

Mohney, J., "Fabric Retaining Wall-Olympic N. F.," *Highway Focus,* Vol. 9, No. 1, pp. 88-103, 1977.

Murray, R. T., "Fabric Reinforced Earth Walls: Development of Design Equations," *Ground Engineering,* Vol. 13, No. 7, pp. 29-36, 1980.

Murray, R. T., “Fabric Reinforced Earth Walls: Development of Design Equations,” Supplementary Report 496, Structures Department, Transport and Road Research Laboratory, Crowthorne, Berkshire, United Kingdom, 1981.

Murray, R., “Fabric Reinforcement of Embankments and Cuttings,” *Proceedings of the 2nd International Conference on Geotextiles,* Las Vegas, Aug l-6, Vol. 3, pp. 707-713, 1982.

Perloff, W. H., *Pressure Distribution and Settlement,* Chapter 4 in *Foundation Engineering Handbook,* ed. by Winterkorn and Fang, Van Nostrand Reinhold Company, New York, 1975.

Perloff, W. H., and Baron, W., *Soil Mechanics: Principles and Applications,* Wiley, 1976.

*Proceedings, International Conference on the Use of Fabrics in Geotechnics,* Ecole Nationale des Ponts et Chaussees, Paris, 3 Vol., 1977.

*Proceedings of the First Canadian Symposium on Geotextiles* (Calgary, Canada, Sep 1980), published by the Canadian Geotechnical Society, 700 EIC Bldg, 2050 Mansfield St., Montreal, Quebec, Canada, 1980.

*Proceedings, Second International Conference on Geotextiles,* Industrial Fabrics Association International, St. Paul, Minn., 4 Vol., 1982.

Rankilor, P. R., *Membranes in Ground Engineering,* Wiley, Chichester, United Kingdom, 1981.

Raymond, G. P., “Installation Factors that Affect Performance of Railroad Geotextiles,” *Transportation Research Record 1071,* Transportation Research Board, Washington, DC, 1986.

Richards, D. L., and Middleton, L. M., “Best Management Practices for Erosion and Sediment Control,” Federal Highway Administration, Arlington, Va., 1978.

Risseeuw, Ir. P., “Stabilenka Woven Reinforcement Fabric in Raising Mounds on Soft Soil,” Report NO. R.O. 5300.005, Akzo Research Laboratories, Department, C.T.I., Arnhem, The Netherlands, 1977.

Rowe, R. K., “Reinforced Embankments: Analysis and Design,” *Journal of the Geotechnical Engineering, American Society of Civil Engineers,* Vol. 110, No. 2, pp. 231-246, 1984.

Sherard, J. L., “Sinkholes in Dams of Coarse, Broadly Graded Soils,” *Thirteenth Conference of the International Congress on Large Dams, New* Delhi, India, Vol. 2, pp. 25-35, 1979.

Shoop, S. A. and K. Henry, *“The Effect of a Geotextile on Water Migration and Frost Heave in Large-Scale Tests,”* preprint 910532, Transportation Research Board, 70th Annual Meeting, January 13-17, 1991.

Spangler, M. G., *Soil Engineering,* International Textbook Company, New York, 1951.

Stilley, A. N., “A Model Study of Fabric Reinforced Earth Walls,” thesis submitted in partial fulfillment of the requirements for the Degree of Master of Science to Oregon State University, Corvalis, Oreg., 64 pp., 1974.

Terzaghi, K., and Peck, R. B., *Soil Mechanics in Engineering Practice,* 2nd Ed., Wiley, New York, 1967.

US Department of Transportation, “Sample Specifications for Engineering Fabrics,” FHWA Report TS-78-211, Federal Highway Administration, Washington, DC, 1978.

Van Zanten, R. V., *Geotextiles and Geomembranes in Civil Engineering,* A. A. Balkema, Rotterdam, The Netherlands, 1986.

Volk, J. C., “Analysis and Design of Geotextile Reinforced Walls,” thesis submitted in partial fulfillment of the requirements for the Degree of Master of Civil Engineering to the Faculty of the University of Delaware, Newark, Del., 1984.

Weimar, R. D., Jr., “Mechanism of the Geotextile Performance in Soil-Fabric Systems for Drainage and Erosion Control,” *Transportation Research Record No. 916,* pp. 37-40, Transportation Research Board, 1983.

Winterkorn, H. F., and Fang, H-Y, *Foundation Engineering Handbook,* Van Nostrand Reinhold Company, New York, 1975.

Wyant, David C., “Evaluation of Filter Fabrics for Use as Silt Fences,” Report No. VHTRC 80-R49, Virginia Highway and Transportation Research Council, Charlottesville, Va., 1980.

 