

GEOTEXTILES IN WATER-BALANCE FINAL COVERS SYSTEMS FOR ARID AND SEMI-ARID REGIONS

Gregory N. Richardson, Ph.D., P.E.
G.N. Richardson & Associates
Raleigh, North Carolina

Fess Foster, Ph.D.
Golden Sunlight Mine
Whitehall, Montana

ABSTRACT

During the past decade, considerable research has demonstrated the applicability of reclamation, i.e., final, covers that limit infiltration through manipulation of water storage capacities of the soil layers and natural evapotranspiration (ET) effects, i.e., water-balance principles, as opposed to incorporating barriers such as compacted clay liners. Water balance covers rely on a two layered system to limit penetration of surface waters. The upper layer is a well graded loamy soil that will support vegetation and has sufficient water storage to typically hold a full season's precipitation. The premise is very simple: if we can hold all of the infiltration in the upper loam layer at times when the ET is minimal, the water will be removed by ET when the vegetative growth is maximum. Most arid and semi-arid vegetation are limited by the amount of stored water typically available in the ground; i.e., they run out of moisture in late summer or fall and become stressed. This paper presents background information and research being conducted to demonstrate the beneficial roles of geotextiles in such covers.

INTRODUCTION

During the past decade, considerable research has been performed to demonstrate the applicability of final covers that limit infiltration through manipulation of water-balance principles (Anderson et al., 1993; Melchior et al., 1994; Wing et al., 1993) as opposed to incorporating barriers such as compacted clay liners. The basic water balance equation is

$$\Delta S = P - Q - ET - L \quad (1)$$

where ΔS is the change in water storage in the upper soil layer, P is precipitation, Q is the runoff, ET is evapotranspiration, and L is seepage or percolation through the final cover. The design objective is to minimize L. As shown on Figure 1, water balance covers rely on a two layered system to limit penetration of surface waters. The upper layer is a well graded loamy soil that will support vegetation and has sufficient water storage to typically hold more than a full season's precipitation. The premise is very simple: if we can hold all of the infiltration in the upper loam layer at times when the ET is minimal, the water will be removed by ET when the vegetative growth is maximum. Most arid and semi-arid vegetation are limited by the amount of stored water typically available in the ground; i.e., they run out of moisture in late summer or fall and become stressed.

To keep the moisture in the loam layer in a water-balance cover, we use a simple phenomena first

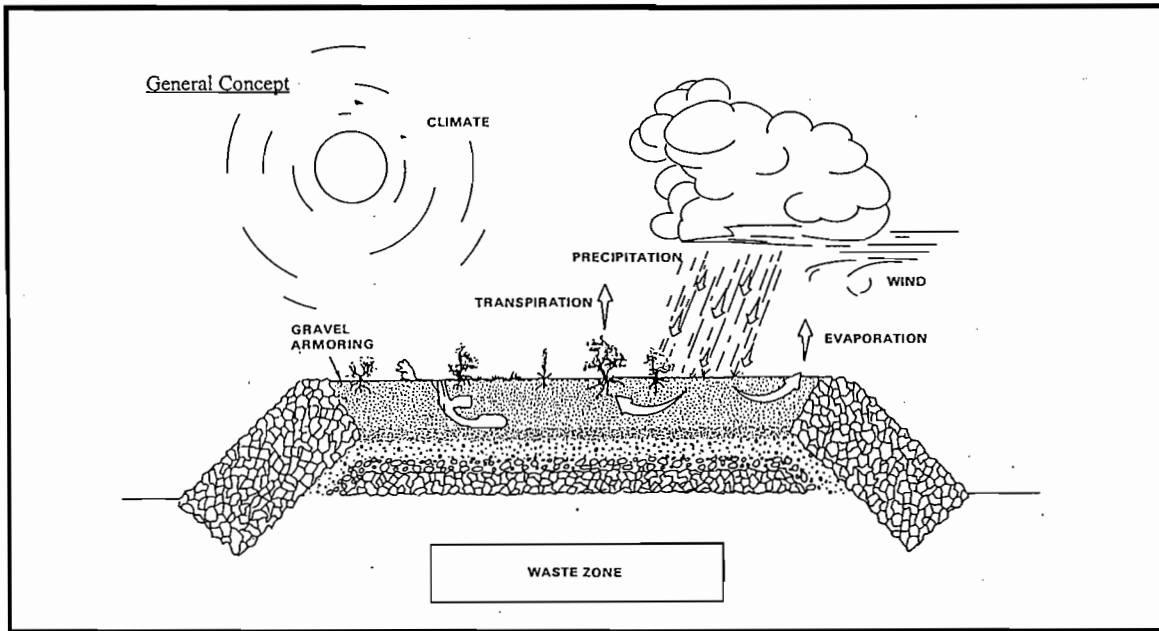


Figure 1. Two-Layer Water Balance Final Cover System

explored by L.A. Richards in the 30s. Richards observed that loamy soil layers in nature that were underlain by a coarse grained soil layer were always wetter than those that were underlain by a fine grained layer. His explanation, what is now referred to as Richard's Effect, essentially is that water is held in the loam by capillary tension. The coarse lower layer forms a capillary break that prevents moisture from being drawn downward by capillary forces and aids in retention of moisture in the upper loam. An excellent summary of such water-balance covers is presented by Benson et al. (1995).

The effectiveness of a capillary break depends essentially upon the difference in capillary suction between the loam and the granular layers at the capillary break. This effectiveness can be significantly diminished by the presence of fines in the coarse lower layer. It is particularly important that fines do not migrate vertically downward out of the loam. This will lead to a gradual blurring of the capillary break and reduced effectiveness of the capillary break. To prevent fines migration, a designer must incorporate either a graded natural filter zone or a geosynthetic alternative. Graded natural filter zones are constructed using relationships first established by Terzaghi (1922) as follows:

$$R_{15} = \frac{D_{15} \text{ of filter material}}{D_{15} \text{ of material protected}}$$

$$R_{50} = \frac{D_{50} \text{ of filter material}}{D_{50} \text{ of material protected}} \quad (2)$$

In general, current guidance for R_{15} and R_{50} (U.S.B.R., 1974) provide that R_{15} varies from 12 to 40 for subrounded particles and 6 to 18 for angular particles, and R_{50} varies from 12 to 58 for subrounded particles and 9 to 30 for angular particles. Separation of typical gravels and loams associated with a capillary break may require more than two layers of graded natural soil layers to satisfy the natural filter zone criteria, see Figure 2. Each filter layer must be a minimum of 15 cm (6-inch) thick for construction reasons. The development of a graded natural filter dulls the distinction between the two layers forming the water-balance final cover and adds to both the thickness and cost of the final cover.

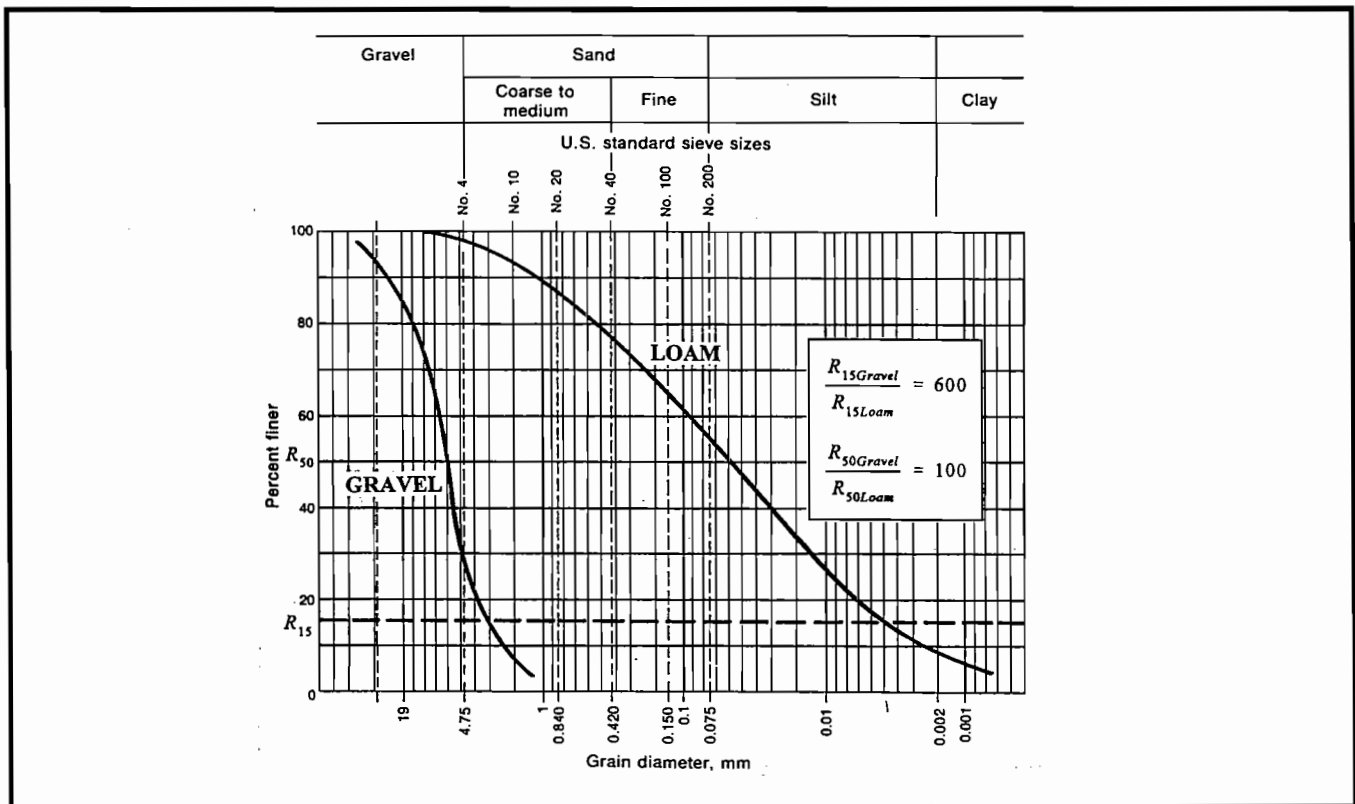


Figure 2. Grade Soil Filter Criteria

Geotextile filter criteria for soil retention is generally expressed as follows:

$$O_{95} < R_{95} d_{85} \quad (3)$$

where O_{95} is the maximum AOS of the geotextile, R_{95} ranges from 1 to 3, and d_{85} is the grainsize with 85% finer than for the loam. Interestingly, the geotextile does not have to be designed to resist clogging since the design goal is to prevent movement of water across the capillary break. Fines from the loam can migrate down to the geotextile and form a soil cake that has a permeability less than that of the loam (and therefore a greater soil suction) while water passing through the geotextile will wash the fines from the coarser stone beneath. Thus, the effectiveness of the capillary break using a geotextile may actually improve with time.

For the Loam soil shown on Figure 2, the maximum AOS of the geotextile is approximately 1.4 mm or a #14 sieve. Most woven or nonwoven geotextile satisfy this criteria.

Based on the above considerations, it is felt that a geotextile filter placed at the capillary break would reduce the cost and thickness of a water-balance final cover and provide a system that would actually improve in performance with time. This paper presents research being conducted to demonstrate the beneficial roles of geotextiles in such covers.

Water-Balance Evaluation of Final Cover Performance

The accepted approach for evaluating the performance of a water-balance final cover is the use of an analytical model and either actual or synthetic site weather data. This procedure is similar to that used in the EPA HELP (Schroeder et al., 1994) model commonly used to evaluate barrier style final covers. The HELP model cannot be used for evaluation of thick water-balance covers because it provides for capillarity related removal of soil water from only the upper evaporative zone (Fleenor, 1995). This causes HELP to over predict the amount of infiltration through thick final covers in arid and semi-arid regions. Alternative water balance models used in previous investigations by others include UNSAT-H (Fayer, 1990), TRACER3D (Morris et al., 1996), and RMA42 (Fleenor et al., 1995). These models attempted to provide improved algorithms for capillary forces within thick covers in arid regions. It is generally assumed that the HELP model will over predict infiltration through all final covers in arid and semi-arid regions.

Because of its conservative nature, the HELP model was used to estimate infiltration through potential mining reclamation final covers for waste rock. The cover profiles include 1) a vegetative layer directly over waste rock, 2) a capillary break cover constructed using a geotextile and a gravel layer, and 3) a capillary break cover constructed using a graded soil filter break as shown on Figure 3. The

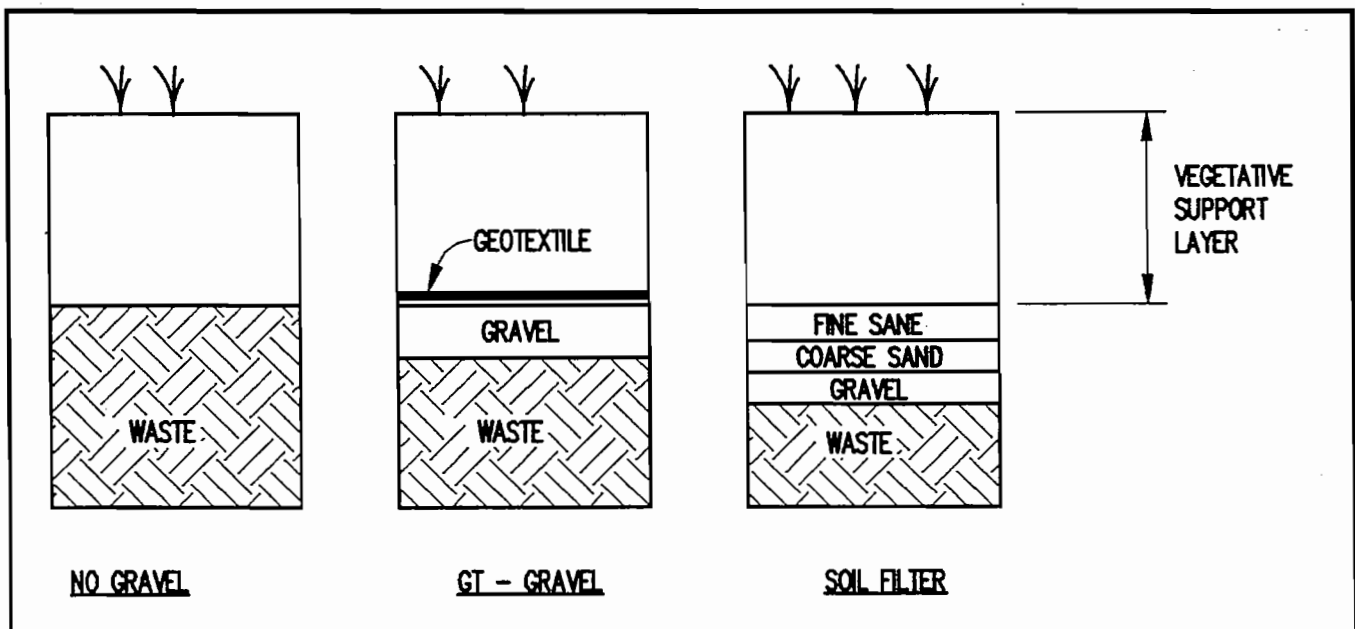


Figure 3. Cover Profiles Evaluated with HELP Model

thickness of the vegetative layer was varied from 24 to 48 inches. The average infiltration through the covers over a five year period is shown on Figure 4. The average annual precipitation during the five year period is 17.9 inches. The use of a 36 inch thick vegetative support layer and a geotextile/gravel capillary break system reduces the average annual infiltration to approximately 0.13 inch or 0.7% of the rainfall striking the cover. UNSAT-H analyses performed at this same site indicated an annual infiltration of only 2.49E-5 inches (Schafer & Associates, 1996) using a gravel capillary break layer that would also require a geotextile filter to construct and survive. This very small difference in predicted infiltrations between the HELP model and UNSAT-H must be examined with reference to the accuracy that important soil properties used in the evaluations can be defined.

The analysis of infiltration through a capillary break cover requires an accurate definition of the unsaturated hydraulic conductivity and volumetric moisture content for each soil as a function of the matrix suction, i.e., the capillary tension within the soil. A excellent summary of the difficulties of measuring these properties is presented by Meerdink et al. (1996). Typical examples of these relationships from applications at the Department of Energy Hanford facility are shown on Figure 5. The work of Meerdink et al., 1996 showed that significant difficulties exist in accurately defining the unsaturated hydraulic conductivity and volumetric moisture content relationships for an unsaturated soil even under research level field and laboratory efforts. This work did suggest the these relationships were reasonably well portrayed by empirical models developed by Brooks and Corey (1964, 1966) and Fredlund et al. (1994). The Brooks and Corey Model for volumetric moisture content verses soil suction, i.e., tension head, is incorporated in the HELP model commonly used for water-balance evaluations. All the models represent simple (complex?) Curve fitting algorithms used to best-fit available laboratory and field data. A discussion of testing methods to determine such data follows this section. These empirical models are expressed as follows:

Brooks-Corey Model

Volumetric Water Content vs. Matrix Suction

$$\frac{\Theta - \Theta_r}{\Theta_s - \Theta_r} = \left[\frac{\psi_b}{\psi} \right]^\lambda \quad \text{when } \psi > \psi_b \quad (4)$$

$$\Theta = \Theta_s \quad \text{when } \psi \leq \psi_b$$

where Θ is the volumetric water content (volume water divided by total volume), Θ_r is the residual water content, Θ_s is the saturated water content, ψ is the matrix soil suction, ψ_b is the air-entry suction pressure on the drying cycle (desorption) or the water-entry pressure on the wetting cycle (sorption), and λ is an empirical pore size distribution index.

Hydraulic Conductivity vs. Matrix Suction

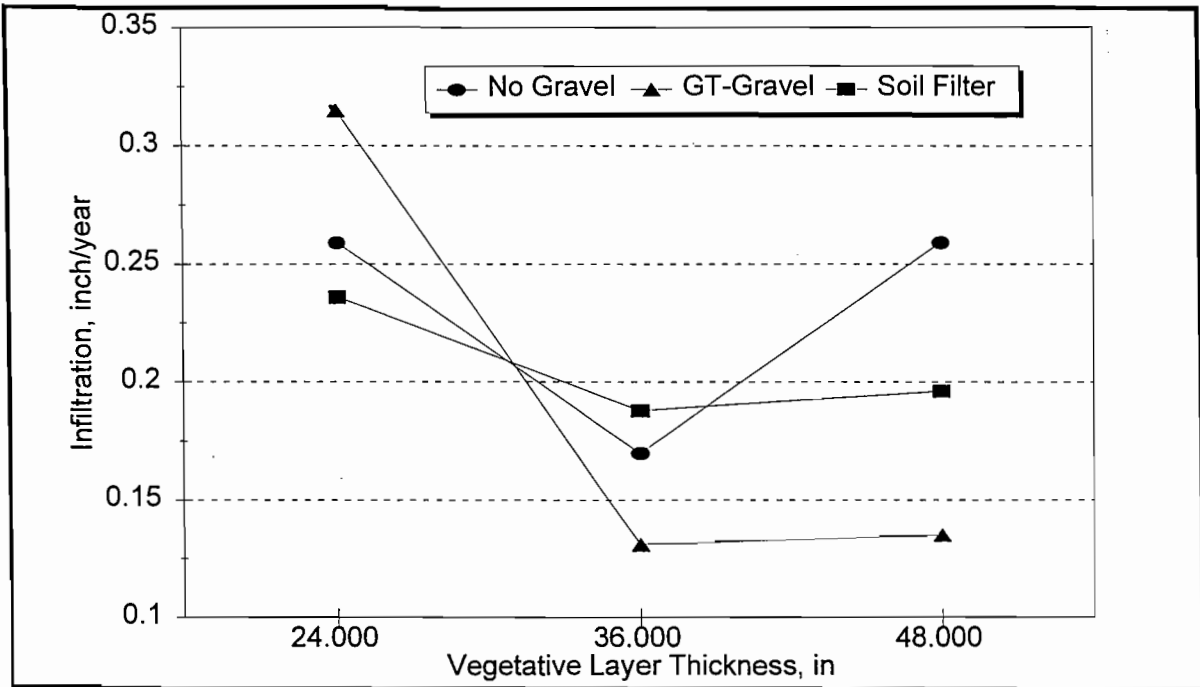


Figure 4. HELP Model Predicted Infiltration

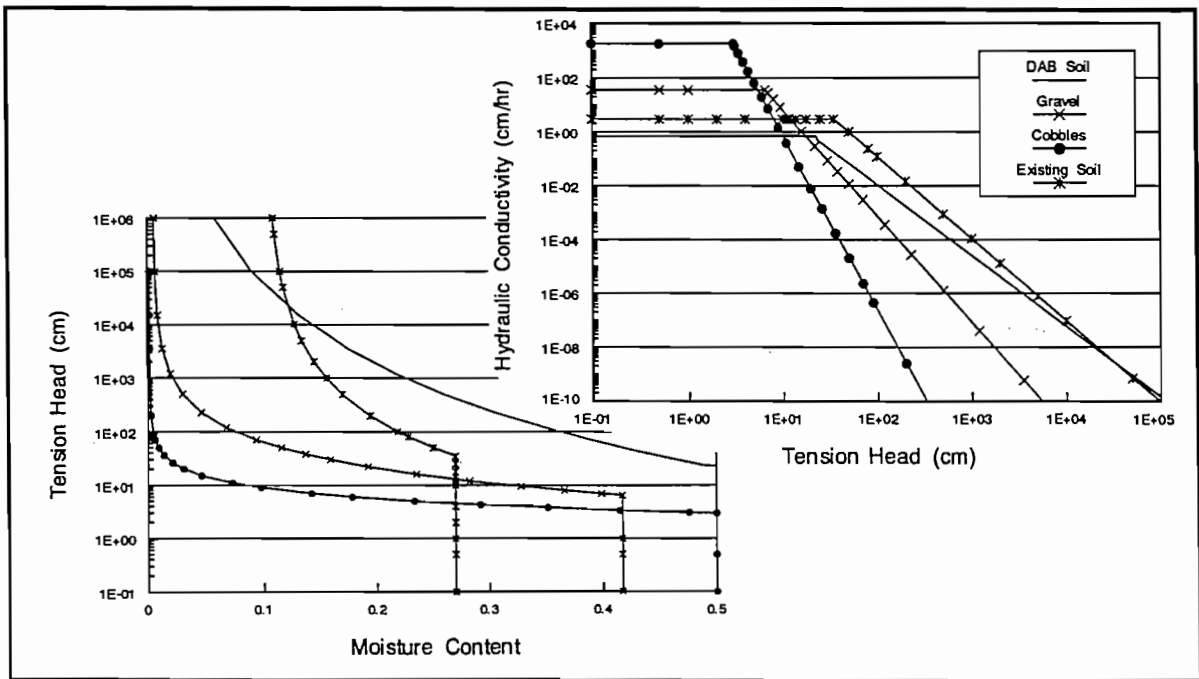


Figure 5. Unsaturated Soil Properties

$$K_r = K_s \left[\frac{\psi_b}{\psi} \right]^{2 + (5\lambda/2)} \quad \text{when } \psi > \psi_b \quad (5)$$

$$K_r = K_s \quad \text{when } \psi \leq \psi_b$$

where K_r is the permeability of the partially saturated soil and K_s is the permeability of the saturated soil.

Fredlund et al. Model

Volumetric Water Content vs. Matrix Suction

$$\Theta = C(\psi) \frac{\Theta_s}{\left[\ln \left(e + \left(\frac{\psi}{a} \right)^p \right) \right]^q} \quad (6)$$

where a , p , and q are empirical curve fitting parameters, and $C(\psi)$ is given as follows:

$$C(\psi) = 1 - \frac{\ln \left(1 + \frac{\psi}{C_r} \right)}{\ln \left(1 + \frac{1 \times 10^6}{C_r} \right)} \quad (7)$$

where C_r is related to the soil matrix suction at the residual water content.

Hydraulic Conductivity vs. Matrix Suction

$$K(\psi) = \frac{\int_{\ln \psi}^b \frac{\Theta(e^y) - \Theta(\psi)}{e^y} \Theta'(e^y) d\psi}{\int_{\ln \psi_a}^b \frac{\Theta(e^y) - \Theta_0}{e^y} \Theta'(e^y) d\psi} \quad (8)$$

where y = a dummy variable of integration representing $\ln \psi$, $b = \ln(106 \text{ kPa})$, ψ_a = air-entry pressure, and Θ' is the derivative of Equation 4 with respect to ψ .

Both the laboratory generation of empirical data and the empirical models for water content and permeability of partially saturated soils are complex and subject to considerable error. Given that the differences in water-balance models is commonly less than 1%, it is questionable whether the quality of soil data available for such analyses meets the mathematical accuracy of the models. It is also questionable that actual field construction will produce consistent properties within individual soil strata, i.e, the mathematics may be

more precise than life justifies.

Laboratory Evaluation of Partially Saturated Soil

A rigorous application of water-balance design requires knowledge of the relationships between matrix pressure within a partially saturated soil and (1) water content, and (2) permeability. The methods used to determine these relationships are discussed here to demonstrate their approximate and tedious nature.

Matrix Suction vs. Water Content ---- This relationship is commonly evaluated in the laboratory using the “filter paper” test, ASTM D-5298 Test Method for Measuring Soil Potential (Suction) Using Filter Paper. The test involves placing the partially saturated soil sample in contact with the filter paper for a sufficient time to establish equilibrium. Moisture from the soil will migrate to the filter paper until the suctions are balanced between the soil and filter paper. The water content of the filter paper is then evaluated and the soil suction is determined from known calibration curves for the filter paper. This procedure is applicable for fine grained soils only. For coarse grained soils and gravels the suction vs. Water content relationship can be measured using ASTM D-2325 Test Method for Capillary-Moisture Relationships for Coarse- and Medium- Textured Soils by Porous Plate Apparatus. Alternatively, the matrix suction can be determined in the laboratory or field using a soil tensiometer. Deaerated water is maintained under a low vacuum within the tensiometer and is in contact with pore water in the soil via the ceramic tip. A vacuum gauge on the tensiometer allows direct measurement of the soil or matrix suction. Considerable skill and effort is required to successfully utilize field tensiometer and their use is limited to relatively fine grained soils.

Matrix Suction vs. Permeability ---- A excellent summary of field measurement methods related to the measurement of permeability in partially saturated soils is given in ASTM D-5126 Standard Guide for Comparison of Field Methods for Determining Hydraulic Conductivity in the Vadose Zone. No standards exist, however, for measurement of hydraulic conductivity of partially saturated soils for either field or laboratory testing. Most field and laboratory methods rely on knowing the suction profile and flow rate within a given soil sample. This may be performed as a steady-state test by regulating the rate of water flow through the monitored sample or may be an ‘instantaneous profile’ measurement. Both methods rely on

defining the hydraulic head at a point within the sample as $i_w = \frac{dh_w}{dx}$. Knowing the flow rate and head,

the permeability of the partially saturated soil can be evaluated using Darcy’s Law. This testing is very tedious and not generally available through commercial soils testing laboratories.

Alternative Laboratory Evaluation of Geotextile Enhanced Capillary Break

A simplified approach was taken to evaluate the benefits of a geotextile developed capillary break for mine reclamation covers. Simple flow lysimeters were constructed for the graded soil filter capillary break and geotextile filter alternatives as shown on Figure 6. The preferred capillary break alternative would simply be the capillary break that could retain the most water prior to allowing break through of the pore water. This was evaluated as follows:

- 1) The total dry unit weight of the soils placed within the lysimeters was obtained by knowing the water content and total weight of each soil placed.
- 2) The total weight of each lysimeter was monitored as water was gradually added to each lysimeter. Approximately .5 % water (by weight) was added to each lysimeter each increment of the wet up process. An approximately 48-hours increment between water additions was maintained. A tight fitting lid was placed over the samples to minimize evaporation during the tests.
- 3) The matrix suction near the geotextile enhanced capillary break was monitored for future field reference.
- 4) Water was added to each lysimeter until break through to the drainage layer occurred. The total water stored by each system prior to break through was obtained by subtracting the weight of the dry soil and lysimeter tank from the total final weight of the wetted lysimeter.

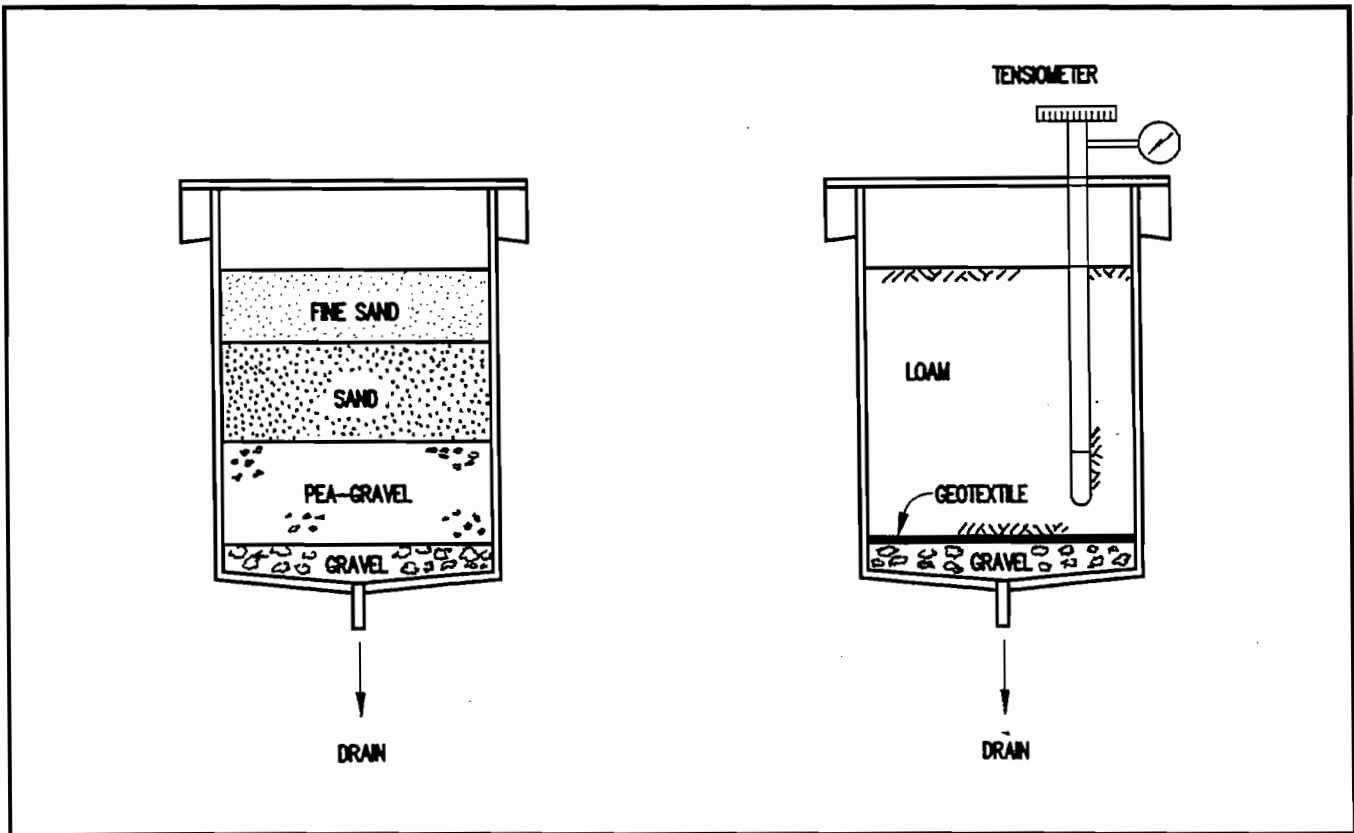


Figure 6. Lysimeters for Evaluating Capillary Break Performance

This test provides a quantitative estimate of the increased storage capacity provided by the use of a geotextile to form the capillary break. The results of the first series of tests are given in Table 2. All soils were placed in an air-dried state using minimal-compactive energy. Future tests will evaluate the influence of wet-dry cycles on the break through water content.

Table 2 Laboratory Evaluation of Capillary Break Alternatives

Variable Measured	Graded Soil Filter	Geotextile Filter
Total Dry Soil Weight, lb.	135.5	117.8
Total Soil/Water Weight at Break Through, lb.	139.5	130.6
Water Stored at Break Through, inches of water	0.9	4.3

The ability to store more than three additional inches of water is very important in systems where the difference in predicted performance between the theoretical models is approximately 0.13 inches. This increase in the storage capacity of the water-balance cover without a corresponding increase in the depth to the capillary break is very important.

Long-Term Considerations For the Capillary Break Cover

The long-term performance of the geotextile supported capillary break must restrict the movement of vegetative roots through the capillary break and into the waste. By retaining soil water close to the surface, the combined topsoil and capillary barrier create a habitat for relatively shallow-rooted plant species and, thus, function as a de facto root-intrusion barrier (Cline et al. 1980; Hakonson 1986). Root growth is generally limited to regions within the soil where extractable water is available. Thus plant roots have no reason to penetrate through the geotextile to the dry gravel below. Lysimeter tests performed by the Department of Energy (Link, 1994) showed that root mats tended to form at the capillary break interface. The root mat may provide a long-term alternative to the geotextile as the actual filter layer that maintains the capillary break.

Geotextile Selection Criteria

The geotextile used to create and maintain the capillary break must not be damaged during installation and must not allow the fines from the vegetative support layer to migrate to the coarse layer forming the capillary break. Thus clogging of the geotextile is not only acceptable, but actually preferred. Previously in this paper it was shown that almost all woven and nonwoven geotextiles satisfy the geotextile filter criteria for particle retention. To survive installation, the geotextile must have sufficient strength and ductility to resist the forces generated when the vegetative support layer is placed. Vegetative support layer soils may contain large stones since it is generally not economical to process these materials. Lacking field data on geotextile performance, it is recommended that the minimum strengths for separation as specified

by AASHTO M288-96 be used. These geotextile strength requirements are shown on Table 1. Note that no AOS requirement is required for this application other than the AOS must be less than approximately 1.4 mm. These conditions allow the user to select the most economical of geotextiles available.

Table 1 AASHTO M288-96 Geotextile Specifications (1)

Application	Separation	
Class/ Property	Woven	Non Woven
1. grab strength, lb	250	160
2. elongation, %	<50%	≥50%
3. puncture, lb	90	60
4. burst, psi	390	190
5. trap tear, lb	90	60

(1) Minimum average roll values (MARV)

Summary

Both HELP and UNSAT-H analyses indicates that the use of a natural graded filter to form the capillary break actually increases the amount of infiltration in comparison to the use of a geotextile filter to form the capillary break. The exception being only when a very thin vegetative support layer is used. The substitution of a graded soil filter for vegetative support layers is, however, not a reasonable financial alternative. Irrespective of water-balance modeling concerns, the performance of the geotextile/capillary break cover produces a predicted infiltration rate of only approximately 1×10^{-8} cm/sec. The difference between zero infiltration and this very small level of infiltration is only approximately a tenth of an inch of annual infiltration. This infiltration rate would be difficult to measure in the field and can be improved on only by the introduction of problematic compacted clay barriers that have questionable long-term survivability due to freezing and dessication forces acting on clays in these regions.

The use of a geotextile to form the capillary break is recommended because of the following:

- The geotextile capillary break provides a significant increase in the water storage capacity above the capillary break without a corresponding increase in depth to the break,
- The geotextiles role is not diminished if it becomes clogged so the fabric can be selected based on known installation survivability criteria, and
- The long-term function of the capillary break does not depend upon the geotextile if the capillary break is placed within vegetation rooting depths.

The use of geotextile developed capillary breaks must of course be demonstrated through field trials and monitoring. It is reasonable, however, to begin such trials at this time.

References

Anderson, J.E., R.S. Nowak, T.D. Ratzlaff, and O.D. Markham, 1993. "Managing soil moisture on waste burial sites in arid regions," *J. Environ. Qual.*, 22:62-69.

Benson, C.H. and M.V. Khire, 1995, "Earthen Covers for Semi-Arid and Arid Climates," *Proceedings: Landfill Closures...Environmental Protection and Land Recovery, Geotechnical Special Publication No. 53, ASCE, NY, NY.*

Brooks, R., and A. Corey, 1964. "Hydraulic Properties of Porous Media," *Hydro. Paper No. 3, Civil Engineering Department, Colorado State University, Fort Collins, CO.*

Brooks, R., and A. Corey, 1966. "Properties of Porous Media Affecting Fluid Flow," *J. Irrigation and Drainage Div., ASCE, 92(2).*

Cline, J.F., K.A. Gano, and L.E. Rogers, 1980. "Loose rock as biobarriers in shallow land burial," *Health Physics, 39:497-504.*

Fleenor, W.E. and I.P. King, 1995. "Identifying Limitations on Use of the HELP Model," *Proceedings: Landfill Closures...Environmental Protection and Land Recovery, Geotechnical Special Publication No. 53, ASCE, NY, NY.*

Foxx, T.S., G.D. Tierney, and J.M. Williams, 1984. *Rooting Depths of Plants Relative to Biological and Environmental Factors, LA- I 0254-MS, Los Alamos National Laboratory, Los Alamos, NM.*

Hakonson, T.E., 1986. *Evaluation of Geologic Materials to Limit Biological Intrusion into Low-Level Radioactive Waste Disposal Sites, LA-10286-MS, Los Alamos National Laboratory, Los Alamos, NM.*

Link, S.O., W.J. Waugh, and J.L. Downs, 1994. "The Role of Plants in Isolation Barrier Systems," In G.W. Gee and N.R. Wing (eds.), *In-Situ Remediation: Scientific Basis for Current and Future Technologies*, pp. 561-592, Battelle Press, Richland, WA.

Melchior, K. Berger, B. Vielhaber, and G. Miehlich, 1994. "Multilayer Landfill Covers: Field Data on the Water Balance and Liner Performance," In G.W. Gee and N.R. Wing (eds.), *In-Situ Remediation: Scientific Basis for Current and Future Technologies*, pp. 411-425, Battelle Press, Richland, WA.

Meerdink, J.S., Benson, C.H., and M.V. Khire, 1996. "Unsaturated Hydraulic Conductivity of Two Compacted Barrier Soils," *Journal of Geotechnical Engineering, American Society of Civil Engineers, Vol. 122, No. 7, July, pp. 565-576.*

Morris, C.E. and J.C. Starmont, 1996. "Design of Capillary Barriers for Waste Site Containment," Proceedings 3rd International Symposium Environmental Geotechnology, San Diego, CA., pp. 513-522.

Reynolds, T.D., 1990. "Effectiveness of three natural biobarriers in reducing root intrusion by four semi-arid plant species," Health Physics, Vol. 59, pp.849-852.

Richards, L.A., 1931. "Capillary Conduction of Liquids in Porous Mediums," Physics Vol. 1, pp. 318-333.

Schafer & Associates, 1996. "Unsaturated Flow Modeling of Capillary Break Materials for Tailings Impoundment Reclamation," report to Golden Sunlight Mine, January 12.

Schroeder, P.R., et al, 1994. The Hydrologic Evaluation of Landfill Performance (HELP) Model: Engineering Documentation for Version 3, EPA/600/R-94/168b, Environmental Protection Agency, Cincinnati, OH.

Terzaghi, K., 1922. "Der Grundbruch an Stauwerken and seine Verhütung," Die Wasserkraft, Vol. 17, No. 24; Reprinted in From Theory to Practice in Soil Mechanics, John Wiley & Sons, New York, NY.

U.S.B.R., 1974. Earth Manual, 2 nd Edition, U.S. Bureau of Reclamation, Denver, CO.

Wing, N.R., and G.W. Gee, 1993. The Development of Permanent Isolation Surface Barriers: Hanford Site, Richland, Washington, U.S.A., WHC-SA-1799-FP, Westinghouse Hanford Company, Richland, WA.