34

Evapotranspirative Cover Systems for Waste Containment

Jorge G. Zornberg and
John S. McCartney
University of Texas at Austin

34.1 Introduction

The management of hazardous and municipal wastes may have important implications on groundwater quality. The current trend in waste management in the United States involves its disposal and isolation within containment facilities to minimize human and environmental contact. One of the key engineered components in municipal and hazardous waste containment systems is the cover system. The cover system is the surface culmination of a landfill, so it interacts closely with the atmosphere. Cover design and analysis involves concepts from various disciplines such as geotechnical engineering, environmental engineering, soil science, agriculture engineering, climatology, biology, and hydrology. Integration of concepts from these various disciplines presents important challenges to researchers, designers, regulators, and stakeholders. This is particularly the case in evapotranspirative covers, the understanding of which relies heavily on the quantification of atmospheric processes at the land surface and of water flow though unsaturated soil.

The water balance components used to quantify the conservation of water mass in an engineered cover may include evaporation and plant transpiration (together referred to as evapotranspiration), precipitation, overland runoff, soil moisture storage, lateral drainage, and basal percolation. Basal percolation, an important variable to quantify the overall performance of landfill covers, is the volume of water that exits the lower boundary of the engineered cover with time. The water that cannot be removed from the cover by evapotranspiration or lateral drainage reaches the underlying waste mass, possibly mobilizing contaminants that may eventually reach the groundwater. Accordingly, one of the primary objectives of a landfill cover system is to control basal percolation. Additional objectives of landfill covers include accommodating differential settlements without compromising its performance, and controlling landfill gas release. In addition, the cover should remain stable under static and seismic conditions, minimize long-term maintenance, allow land re-use, and provide an aesthetic appearance.

The design of final cover systems for new municipal and hazardous waste containment systems in the United States is prescribed by the US Resource Conservation and Recovery Act (RCRA) Subtitles D and C, respectively. Federal- and state-mandated cover systems for municipal and hazardous waste landfills have endorsed the use of resistive barriers. Resistive cover systems involve a liner (e.g., a compacted clay layer) constructed with a low saturated hydraulic conductivity soil (typically 10^{-9} m/sec or less) to reduce basal percolation. Figure 34.1(a) shows the water balance components in a resistive system, in which basal percolation control is achieved by maximizing overland runoff. To enhance cover performance and lower construction costs, RCRA regulations allow the use of alternative cover systems if comparative analyses and field demonstrations can satisfactorily show their equivalence with prescriptive systems. Evapotranspirative covers are alternative systems that have been recently proposed and successfully implemented in several high-profile sites. Evapotranspirative covers are vegetated with native plants that survive on the natural precipitation and have been shown to be stable over long periods of time. Figure 34.1(b) shows the water balance components in an evapotranspirative cover system. Evapotranspiration and moisture storage are components that influence significantly the performance of this system. Internal lateral drainage may also be a relevant component in some cover types (capillary barriers on steep slopes). The novelty of this approach is the mechanism by which basal percolation control is achieved: an evapotranspirative cover acts not as a barrier, but as a sponge or a reservoir that stores moisture during precipitation events, and then releases it back to the atmosphere as evapotranspiration or lateral drainage. Silts and clays of low plasticity are the soils most commonly used in evapotranspirative covers, as they can store water while minimizing the potential for cracking upon desiccation.

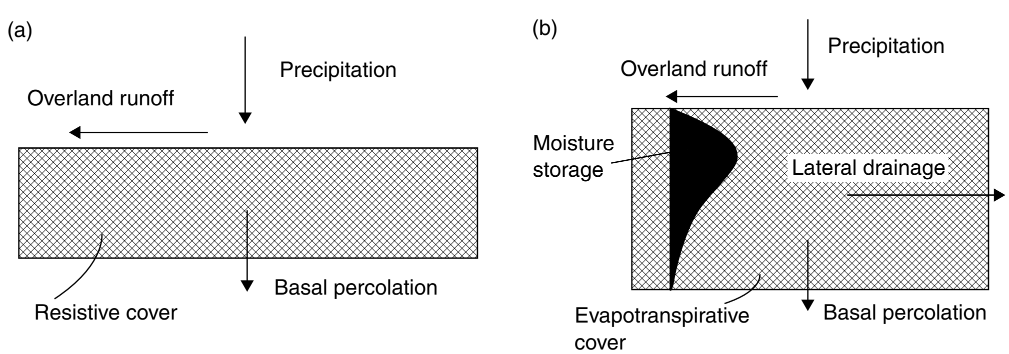

FIGURE 34.1 Water balance components: (a) in a resistive barrier and (b) in an evapotranspirative cover

Additional advantages of evapotranspirative covers over typical clay barrier systems include minimizing desiccation cracking, ease of construction, and low maintenance. Also, effective evapotranspirative covers can be constructed with a reasonably broad range of soils, which can lead to significant cost savings. The adequacy of evapotranspirative cover systems has been verified by field experimental assessments (Anderson et al., 1993; Dwyer, 1998), and procedures have been developed for quantitative evaluation of the variables governing their performance (Khire et al., 1999; Zornberg et al., 2003). The scope of this chapter includes: (i) basic hydraulic concepts for unsaturated soils relevant to evapotranspirative covers, (ii) types of evapotranspirative covers, (iii) design and modeling issues, (iv) field monitoring approaches, and (v) case studies.

34.2 Unsaturated Soil Hydraulic Concepts Relevant to Evapotranspirative Cover Performance

34.2.1 Water Flow through Unsaturated Porous Media

Designing a truly impermeable barrier (i.e., one leading to zero basal percolation) should not be within an engineer's expectations. Instead, the objective of the cover should be to minimize the basal percolation of water to acceptable levels. Quantification of the basal percolation is challenging as it involves analysis of water flow through unsaturated soils subject to complex atmospheric boundary conditions. Both air and water are present in the voids of unsaturated soils. The relative amounts of water and air in the soil, typically quantified on a volumetric basis, highly influence the soil hydraulic behavior. Figure 34.2 illustrates some of the common phase relationships used for the analysis of water flow processes in unsaturated soils. The volumetric moisture content θ, is defined as the ratio between the volume of water and the total control volume. The porosity n, which is the ratio between the volume of voids and the total control volume, corresponds to the volumetric moisture content at saturation (i.e., $n = \theta_s$). The degree of saturation S, commonly used to normalize the moisture content of a soil is the ratio between the volumetric moisture content and the porosity. Finally, the volumetric air content is the difference between the porosity and the volumetric moisture content.

In an unsaturated soil, water is held within the pores against the pull of gravity by a combination of adsorptive and capillary pressures (Olson and Langfelder, 1965). Adsorptive pressures are present in soils due to electrical fields and short-range attractive forces (van Der Waal forces) that tend to draw water toward the soil particles in highly plastic clays, where the net negative charges on water dipoles and surface of clay particles interact with the cations in the pore water. The capillary pressure is quantified as the difference between the pore air pressure and the pore water pressure. Water is a wetting fluid for most soil particles, which implies that the air-water menisci between individual soil particles are convex, tensioned membranes. Accordingly, the air pressure is greater than the water pressure, which has a negative magnitude. The adsorptive and capillary pressures are typically considered together as a single

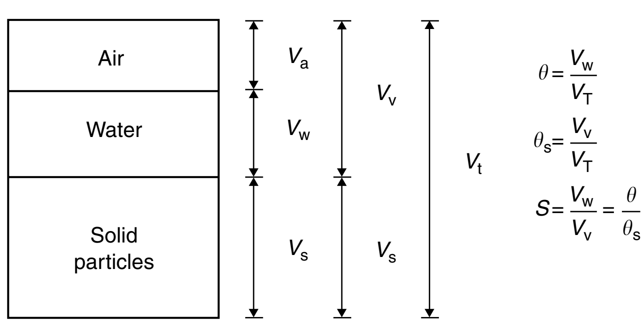

FIGURE 34.2 Volumetric phase diagram for unsaturated soils.

variable, referred to as the matric suction, ψ, which has units of pressure (kPa). The capillary rise in a pipette provides an analogy useful to assess the influence of pore sizes on the matric suction, given by the following expression

$$\psi = P_a - P_w = h_c \rho_w g = \frac{2\sigma_{aw} \cos \gamma}{R} \tag{34.1}$$

where P_a is the pore air pressure, P_w is the pore water pressure, h_c is the height of capillary rise in a pipette of radius R, ρ_w is the density of water, g is the acceleration of gravity, σ_{aw} is the surface tension between water and air, and γ is the wetting contact angle (typically 10° for quartz minerals). Equation 34.1 assumes that air is under atmospheric pressure ($P_a = 0$) and indicates that the suction is inversely proportional to the pore radius. Accordingly, for the same volumetric moisture content, a fine-grained soil (with comparatively small pore radii) will have a higher suction than a coarse-grained soil. The relationship between moisture content and suction is thus related to the pore size distribution of the soil as discussed in Section 34.2.2.

Flow of water through soils is driven by a gradient in the hydraulic energy, which is quantified by the fluid potential (energy per unit mass of water). The fluid potential is given by an expanded form of Bernoulli's equation:

$$\Phi = gz + \frac{1}{2}\left(\frac{v}{n}\right)^2 + \frac{-\psi}{\rho_w} + \frac{P_o}{\rho_w} \tag{34.2}$$

where Φ is the fluid potential, z is the vertical distance from the datum, v is the water discharge velocity, n is the porosity, and P_o is the osmotic suction. In Equation 34.2, the four terms on the right-hand side correspond to the potential energy, the kinetic energy, the energy due to the water pressure ($\psi = -P_w$ if $P_a = 0$), and the energy due to osmosis. The discharge velocity (v/n) is comparatively small, leading to a negligible kinetic energy component. The osmotic suction is typically considered constant throughout an evapotranspirative cover, and consequently does not lead to a contribution to the hydraulic gradient. As in the case of water-saturated soils, Darcy's law for unsaturated soils indicates that flow is driven by the gradient in total hydraulic potential. However, the available pathways for water flow in unsaturated soil decrease as the moisture content decreases (or as suction increases). This is quantified by the hydraulic conductivity function $K(\psi)$, which accounts for the decrease in conductivity with increasing suction (or decreasing moisture content). The K-function is discussed in Section 34.2.2.2. The discharge velocity through a soil in the vertical direction z can be estimated using Darcy's law and Equation 34.2, as follows:

$$v = \frac{Q}{A} = -\frac{K(\psi)}{g}\frac{\partial \Phi}{\partial z} = -K(\psi)\frac{\partial}{\partial z}\left(1 - \frac{1}{\rho_w g}\frac{\partial \psi}{\partial z}\right) \tag{34.3}$$

where Q is the volumetric flow rate, and A is the area of soil perpendicular to the flow direction. Figure 34.3 shows a control volume of thickness dz for one-dimensional (1-D) water flow through a soil layer with thickness L using the base of the soil layer as datum. The continuity principle in this control volume can be expressed by:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial v}{\partial z} \tag{34.4}$$

where the left-hand side represents the change in moisture storage in the control volume, and the right-hand side represents the change in flow rate across the control volume. Substitution of Equation 34.3 into Equation 34.4 leads to the governing equation for 1-D flow through unsaturated porous materials, referred to as Richards' equation:

$$\frac{\partial \theta}{\partial \psi}\frac{\partial \psi}{\partial t} = \frac{\partial}{\partial z}\left[K(\psi)\left(1 - \frac{1}{\rho_w g}\frac{\partial \psi}{\partial z}\right)\right] \tag{34.5}$$

Richards' equation is a coupled, nonlinear parabolic equation, which can be solved using finite differences or finite elements. Numerical solutions to Richards' equation can be challenging because the constitutive function [$K(\psi)$ and $\theta(\psi)$] are highly nonlinear and may have undefined or zero derivatives. Further,

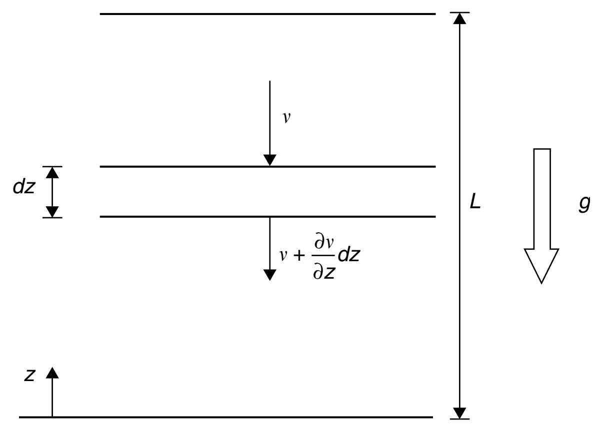

FIGURE 34.3 Control volume for vertical flow through an evapotranspirative cover

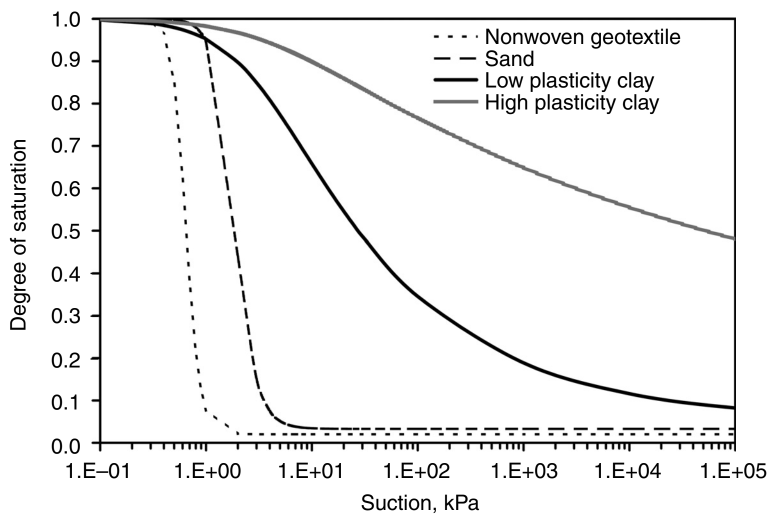

FIGURE 34.4 Typical SWRCs for different geotechnical materials

selection of boundary conditions may not be straightforward for several practical problems. Boundary conditions typically used for evapotranspirative covers include atmospheric flux boundary conditions at the surface (infiltration or evaporation), and unit hydraulic gradient (i.e., zero change in suction with depth) at the base. A discussion on the boundary conditions for evapotranspirative covers may be found in Fayer and Jones (1990). Additional difficulties for solving water flow problems for unsaturated soils arise when considering moisture removal from plant roots, desiccation cracking, animal intrusion, and volumetric changes.

34.2.2 Unsaturated Soil Hydraulic Properties

34.2.2.1 Soil Water Retention Curve

The moisture storage of the soil is an important performance variable of evapotranspirative covers. The moisture storage is typically quantified using the relationship between volumetric moisture content and soil suction, referred to as the Soil Water Retention Curve (SWRC). Figure 34.4 shows the SWRCs for different geotechnical materials. The coarser materials (sand and geotextile) show a highly nonlinear response, with a significant decrease in moisture content (or degree of saturation) in a narrow range in suction. The fine-grained materials (silt and clay) show a more gradual decrease in moisture content with increasing suction. The nonlinearity observed in these relationships is partly caused by the range of pore size distributions for these materials. An important characteristic in a SWRC is the air entry value. During initial drying of a fully saturated soil specimen water does not flow from the soil until the suction corresponding to the air entry value is reached. When this suction is reached, air enters the specimen and the moisture content decreases. Once the air entry value is reached, the moisture content drops from saturation to a value that remains approximately constant with increasing suction. This low moisture content value is often referred to as the residual moisture content. The residual condition occurs because the water becomes occluded (or disconnected) within the soil pores, with no available pathways for water flow to occur.

The SWRC for a given material is not only sensitive to the pore size distribution, but also the soil mineralogy, density, and pore structure (Hillel, 1988). The SWRC can show significantly different wetting and drying paths, a phenomenon referred to as hysteresis (Topp and Miller, 1966; Kool and Parker, 1987). During drying, the largest pores drain first, followed by the smaller pores. During wetting, the smaller pores fill first, but the presence of large pores may prevent some from filling. Also, wetting of a dry media often leads to entrapment of air in the larger pores, which prevents saturation of the media unless positive pressure is applied to the water. Air entrapment causes the wetting path to be relatively flat for high suctions (e.g., over 100 kPa), with a steep increase in volumetric moisture content at lower suctions.

Several techniques are available to determine the SWRC experimentally (Klute et al., 1986; Wang and Benson, 2004). Two main groups of techniques have been used to define the SWRC. The first group of techniques ("physical" techniques) involves an initially water-saturated material from which water is slowly expelled by imposing a suction to a specimen boundary. Flow continues until it reaches a condition at which the moisture content and suction are in equilibrium. The most commonly used physical technique is the axis translation technique. A common test that is based on this technique is the pressure plate test (Figure 34.5(a)), which involves placing a soil specimen on a high air-entry ceramic plate and applying air pressure to the specimen. The air pressure causes the pore water to pass through the ceramic plate since the water pressure on the effluent side of the plate is kept at atmospheric pressure (zero). At equilibrium, the air pressure corresponds to the suction. The outflow volume is measured using a constant head Mariotte bottle. This approach is repeated for successively higher pressures that gradually dry the specimen, after which the pressure may be decreased to measure the wetting behavior. At the end of the testing, the gravimetric moisture content may be measured destructively, and the moisture content at each pressure increment can be back-calculated from the outflow measurements. Additional details can be found in the ASTM standard for SWRC determination (ASTM D6836 2002). Another technique, the hanging column, is shown in Figure 34.5(b). This test also involves a ceramic plate, but connects the bottom of the plate to a manometer tube. A negative water pressure is imposed on the water level in the ceramic plate by holding the manometer tube beneath the plate.

The second group of techniques ("thermodynamic" techniques) involves allowing water to evaporate from a specimen in a closed chamber under controlled relative humidity. The relative humidity is controlled by allowing water to evaporate from a saturated salt solution placed within the chamber, as shown in Figure 34.5(c). Another commonly used thermodynamic technique is the chilled mirror

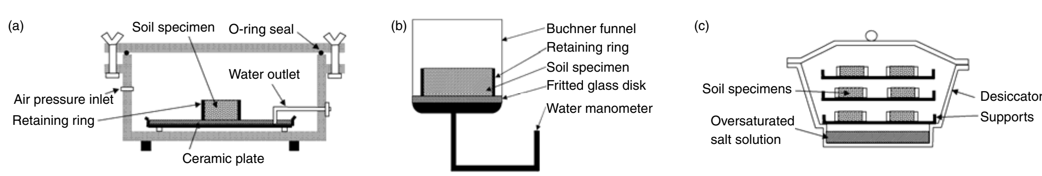

FIGURE 34.5 Conventional methods to determine the SWRC: (a) pressure plate; (b) hanging column; and (c) saturated salt solutions.

hygrometer (Wang and Benson, 2001). This device infers the total soil suction (matric and osmotic) by measuring the vapor pressure in the soil, which is related to the temperature at which moisture condenses on a mirror. When condensation occurs, a change in the optical properties of the mirror is detected. In general, physical techniques are used for relatively low suctions (e.g., under 1500 kPa), while thermodynamic techniques are used for higher suctions.

Conventional techniques to define the SWRC require significant time to obtain limited data. For example, determination of the SWRC for a high-plasticity clay specimen may take several months. Also, conventional determination methods require the use of several specimens and destructive measurement of moisture content. Problems specific to SWRC testing involve diffusion of air across porous ceramics, lack of control of volume change during drying and wetting (e.g., Cabral et al., 2004), and inability to impose a stress state representative of field conditions.

Centrifugation can be used to alleviate shortcomings of conventional characterization of the SWRC. Centrifugation increases the body forces on a porous media, accelerating fluid flow as time increases quadratically with g-level. Centrifuges were first used in the early 1930s to define the SWRC by soil scientists and petroleum engineers (Gardner, 1937; Hassler and Bruner, 1945). Saturated specimens can be placed upon a saturated ceramic plate that conducts only liquid. During centrifugation, the increased body force causes water to exit the specimen through the ceramic while air enters the surface of the specimen. The suction profile within the specimen can be defined if the bottom boundary is maintained saturated (zero suction). The suction distribution obtained at equilibrium (i.e., when flow ceases) is:

$$\psi(r) = \frac{\rho_{\mathrm{w}}\omega^2}{2}[r_0^2 - r^2] + \psi(0) \tag{34.6}$$

where r_0 is the outer radius of the centrifuge specimen, r is the distance toward the center of rotation with a datum at the outer radius, ω is the angular velocity, and $\psi(0)$ is the suction at the bottom boundary of the specimen (zero if a saturated ceramic plate is used as the bottom boundary condition). Analytical techniques can be used to associate the average moisture content (measured destructively) with the suction at the soil surface (Forbes, 1994).

A SWRC is typically quantified by fitting experimental data to power law, hyperbolic, or polynomial functions (Brooks and Corey, 1946; van Genuchten, 1980; Fredlund and Xing, 1994). Although the Brooks and Corey (1946) model is able to represent a sharp air entry suction, the van Genuchten (1980) model is most commonly used in numerical analyses because it is differentiable for the full range of suctions. The van Genuchten model is given by:

$$\theta = \theta_{\mathrm{r}} + (\theta_{\mathrm{s}} - \theta_{\mathrm{r}})[1 + (\alpha\psi)^N]^{-(1-(1/N))} \tag{34.7}$$

where θ_{r} is the residual moisture content, θ_{s} is the saturated moisture content (porosity), and α (units of kPa^{-1}) and N (dimensionless) are fitting parameters. Preliminary estimates of the SWRC could be obtained using databases that rely on the granulametric distribution of soils (Fredlund and Xing, 1994).

34.2.2.2 Hydraulic Conductivity Function

The relationship between hydraulic conductivity and suction, also referred to as the K-function, provides a measure of the increased impedance to moisture flow with decreasing moisture content. The saturated hydraulic conductivity K_{s} provides a measure of the minimum impedance to moisture flow through soil. Figure 34.6 shows K-functions for different geotechnical materials. Near saturation, the coarser materials (sand and geotextile) have high hydraulic conductivity, while the fine-grained materials (silt and clay) have lower hydraulic conductivity. However, as the soil dries, the coarse materials end up being less conductive than the fine-grained materials. That is, as the fine-grained materials can retain more water in the pores as suction increases, they still have available pathways for water flow, and are thus more conductive than coarser materials. The superior performance in arid climates of evapotranspirative covers relative to conventional resistive covers can be attributed to the lower unsaturated hydraulic conductivity of the selected cover soils.

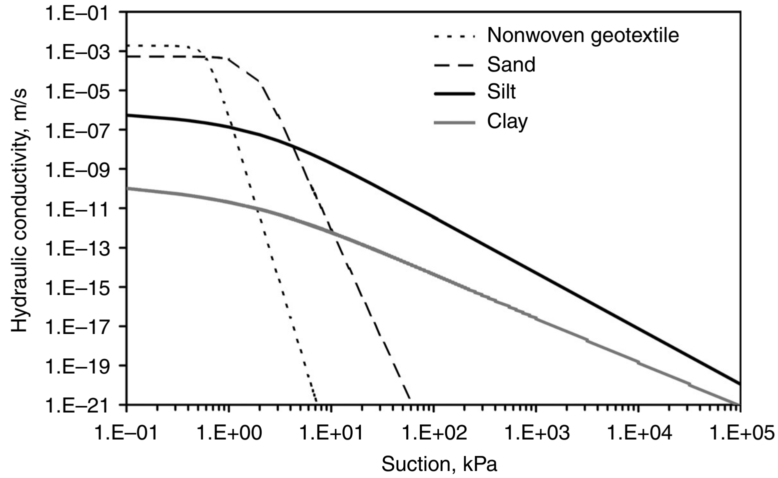

FIGURE 34.6 Typical K-functions for different geotechnical materials.

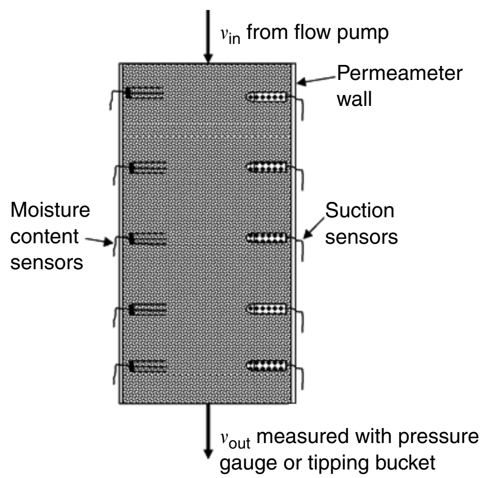

FIGURE 34.7 Parameter set up for measurement of K-function.

Conventional methods used to define the K-function are costly, time consuming, and prone to experimental error. Accordingly, the K-functions (e.g., such as those in Figure 34.6) are often predicted based on pore size distributions such as van Genuchten–Mualem model (1980), as follows:

$$K(\theta) = K_{\text{sat}}\sqrt{\frac{\theta-\theta_{\text{r}}}{\theta_{\text{s}}-\theta_{\text{r}}}}\left[1-\left(1-\left(\frac{\theta-\theta_{\text{r}}}{\theta_{\text{s}}-\theta_{\text{r}}}\right)^{1-\text{N}}\right)^{1/(1-\text{N})}\right]^2 \qquad (34.8)$$

$K(\psi)$ can be defined by substituting Equation 34.7 for θ into Equation 34.8. Other predictive relationships for the K-function are given by Burdine (1953) and Campbell (1974).

Several techniques have been proposed for direct determination of the K-function in the laboratory (Benson and Gribb, 1997). Conventional techniques to measure the K-function involve flow of liquid through a specimen confined within a permeameter. Flow is applied using either ceramic plates or flow pumps. Figure 34.7 shows a typical permeameter setup used to measure the hydraulic conductivity (Meerdink et al., 1996; Lu and Likos, 2005; McCartney et al., 2005b). Permeameters have differed in specimen confinement and size, control of boundary conditions, and availability of instrumentation. The K-function can be estimated using steady or transient flow processes. During steady moisture infiltration with a deep water table, a unit hydraulic gradient (e.g., $i = 1$) is typically observed in the soil profile, sufficiently far from a water table boundary. Accordingly, suction does not change with depth and water flow is driven only by gravity. In this case, the hydraulic conductivity equals the imposed steady-state discharge velocity. Additional points are obtained by changing the imposed flow. During transient flow processes, the suction and moisture content profiles are measured as a function of depth and time, and the K-function can be estimated using the instantaneous profile method (Watson, 1966; Olson and Daniel, 1979; Meerdink et al., 1996). While techniques based on transient processes yield more information about the K-function, steady state techniques provide more reliable information. As for the SWRC, conventional techniques used to define the K-function require significant time to obtain limited data. Problems specific to K-function testing include boundary effects on the flow process, difficulties in uniformly distributing water from flow pumps to the specimen, and tedious testing procedures.

To alleviate these shortcomings, centrifuge testing has been used to define the K-function in geotechnical projects involving the design of ET covers (Zornberg et al., 2003; Dell'Avanzi et al., 2004). Nimmo et al. (1987) developed the Internal Flow Control Steady-State Centrifuge (IFC-SSC) method, which uses a system of reservoirs to control the fluid flow rate and suction at the upper and lower surfaces of a specimen. Conca and Wright (1994) developed the Unsaturated Flow Apparatus (UFA), which uses a sophisticated rotary joint to a low fluid flow rate into the specimen. The UFA uses open-flow centrifugation, which does not impose a suction value on the specimen. For steady state conditions, the SSC and UFA use Darcy's law to determine the K-function:

$$K(\psi) = \frac{-v}{[-(1/(\rho_w g))(d\psi/dz) - ((\omega^2 r)/g)]} \tag{34.9}$$

where v is the imposed discharge velocity. Points on the K-function curve are defined using Equation 34.9 after reaching steady state flow conditions. The SSC and UFA do not allow the direct monitoring of the relevant variables (suction, moisture, discharge velocity) in-flight during testing. If the suction gradient in Equation 34.9 is assumed to be negligible, the hydraulic conductivity becomes inversely proportional to ω^2. The SSC and UFA centrifuges must be periodically stopped to measure the specimen mass to ensure steady state flow, and the moisture content must be measured destructively at the end of the test.

Although the SSC and UFA allow a faster testing time than conventional K-function testing methods, their shortcomings led to the development of an improved centrifuge device, referred to as the Centrifuge Permeameter for Unsaturated Soils (CPUS) (McCartney and Zornberg, 2005a). This device incorporates the use of a low-flow hydraulic permeameter and a high-g centrifuge capable of continuously, non-destructively, and non-intrusively measuring suction, moisture content, and fluid flow rate in a single specimen during centrifugation. Accordingly, CPUS allows an expedited determination of both the SWRC and K-function from a single specimen in a single test. Measuring the SWRC and K-function during a flow process is consistent with actual flow problems, unlike conventional techniques such as the axis-translation technique. Figure 34.8(a) shows a view of the CPUS centrifuge and Figure 34.8(b) shows a schematic view of the CPUS permeameter and its instrumentation layout. A special low-flow fluid union is used to supply fluid from the stationary environment to the rotating specimen within the centrifuge. CPUS facilitates the use of experimentally obtained, rather than theoretically derived hydraulic properties in the design of evapotranspirative cover systems.

34.3 Types of Evapotranspirative Covers

34.3.1 Monolithic Covers

Monolithic covers are evapotranspirative covers that consist of a single soil layer placed directly over the waste (Zornberg et al., 2003). Figure 34.9a shows a schematic view of a monolithic soil cover. The soil layer

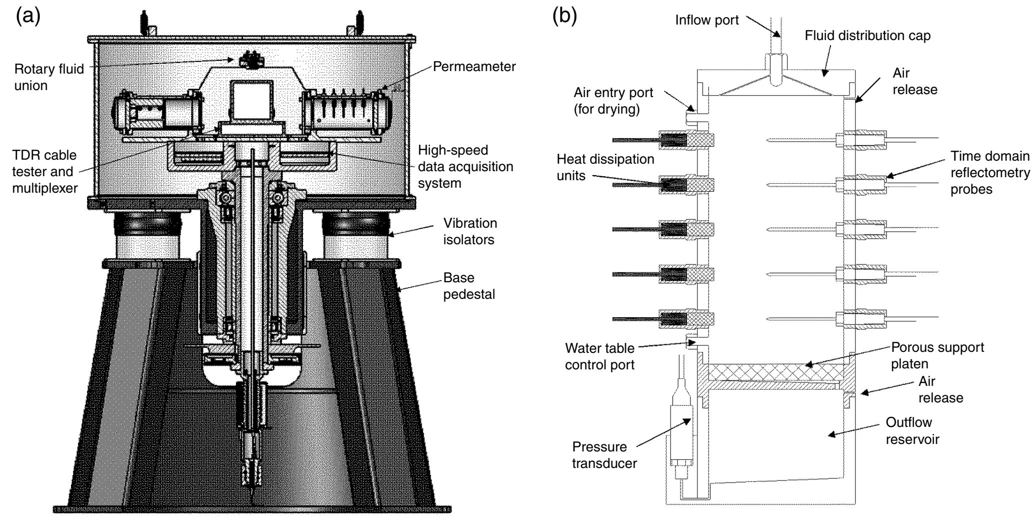

FIGURE 34.8 Centrifuge parameter for unsaturated soils: (a) centrifuge layout and (b) Permeameter.

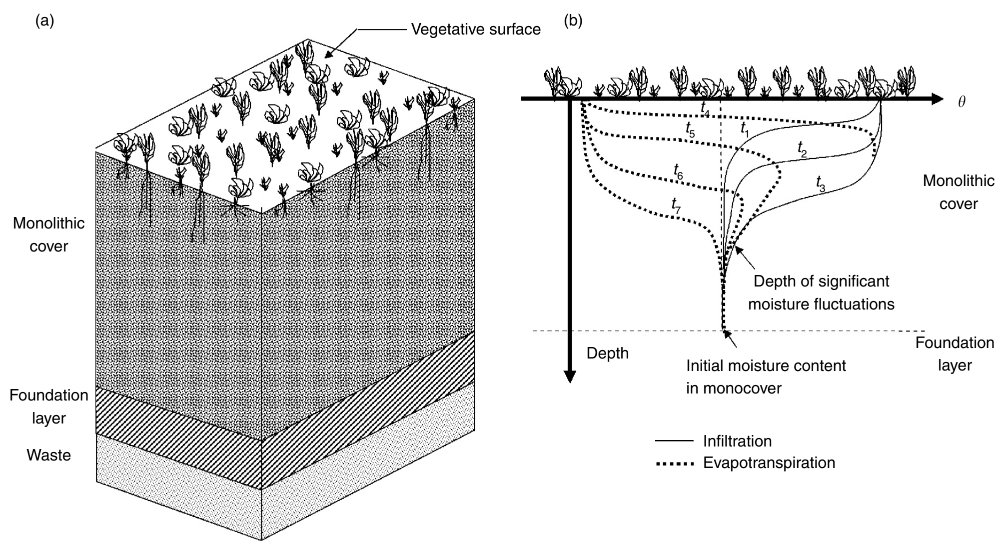

FIGURE 34.9 Monolithic cover: (a) soil profile and (b) typical seasonal moisture content fluctuations.

acts both as a substrate for vegetation and a hydraulic barrier. A foundation layer consisting of the same soil type is typically used to provide a level surface above the waste. Early research focused on investigation of the long-term behavior of natural soil layers in arid regions, assuming that the behavior is analogous to that of an engineered monolithic cover (Waugh et al., 1994). These studies found that moisture content fluctuations in natural analogues in recent geologic history are typically confined to the upper few feet of soil, indicating the adequacy of monolithic covers as an acceptable long-term solution to waste disposal.

The major aspects in monolithic covers are the proper characterization of the hydraulic properties (K-function and SWRC) of the soils as well as the determination of the appropriate thickness of the engineered soil cover. Figure 34.9b shows schematic moisture profiles, illustrating typical seasonal fluctuations in a properly performing monolithic cover. The moisture profiles illustrate wetting during infiltration events and subsequent drying due to evapotranspiration. Although some moisture fluctuations are expected to reach the base of the cover in extreme events, most of the moisture fluctuations are expected to take place only within the upper portion of the cover. Monolithic cover design requires selection of the cover thickness and soil moisture storage necessary to keep the basal percolation below a minimum allowable (design) value, given the expected weather conditions for a site.

The soil moisture storage of a cover can be calculated as the integral of the volumetric moisture content profile with depth. The upper bound on soil moisture storage depend on the shape of the SWRC. The greater the moisture retained in a soil for the suction values expected in the field, the greater the moisture storage. A parameter that has been used to quantify the moisture storage is the field capacity, which is defined as the threshold moisture content value above which the soil no longer retains water by capillarity under the effects of gravity (Zornberg et al., 1999). When water is added to a soil that is at field capacity, drainage occurs. The field capacity may be obtained from infiltration tests, although a generally accepted value for silt and low plasticity clay soils is the moisture content corresponding to a suction of 33 kPa (Nachabe, 1998; Meyer and Gee, 1999). The storage capacity of a monolithic cover can be preliminarily estimated by multiplying the volumetric moisture content at field capacity (obtained using the SWRC) by the cover thickness.

34.3.2 Capillary Barriers

Capillary barriers are evapotranspirative covers that consist of a layered soil system typically involving a fine-grained soil (silt, clay) placed over a coarse-grained material (sand, gravel, nonwoven geotextile). Capillary barriers use the contrast in hydraulic properties between the fine- and coarse-grained soils to enhance the ability of the fine-grained material to store moisture (Shackelford et al., 1994; Stormont and Anderson, 1999; Khire et al., 1999; 2000). Figure 34.10a and Figure 34.10b show SWRCs and *K*-functions for sand (coarse-grained component), and low plasticity clay (fine-grained component). The capillary break concept relies on the continuity of suction, even at the interface between two different materials. Figure 34.10a shows that when a clay–sand system is at an initially high suction (e.g., 1000 kPa), the clay has a degree of saturation of 0.2 while the underlying sand is at residual moisture content. Figure 34.10b indicates that at this high suction, the clay has a hydraulic conductivity of approximately 1×10^{-13} m/sec while the sand has an even higher impedance to flow. Consequently, if moisture infiltrates into the fine-grained material after a precipitation event and reaches the interface with the coarse-grained material it can only progress into the coarse-grained material at a very slow rate. Consequently, water will accumulate at the interface until the suction at the interface reaches a value at which the hydraulic conductivity of the coarse grained material is no longer below that of the fine-grained material (3.0 kPa in Figure 34.10b). This suction value is referred to as the breakthrough suction. A breakthrough suction of 3.0 kPa is significantly below the suction corresponding to field capacity (typically considered at 33 kPa for clay), which indicates that the degree of saturation in the clay will be relatively high (95%) when breakthrough occurs. For suction values less than that corresponding to field capacity, water would have drained downwards by gravity had the capillary break not been present. When the breakthrough suction is reached, leakage is observed in the coarse-grained layer at a rate approaching that corresponding to the saturated hydraulic conductivity of the barrier layer.

Figure 34.10c shows a schematic view of a capillary break cover. Similar to the monolithic cover, the soil layer acts both as a substrate for vegetation and a hydraulic CRL (or capillary retention layer, CRL). However, a coarse-grained material (capillary break layer, CBL) is placed over the foundation material to create a capillary break at the interface between the CRL and the CBL). Figure 34.10d shows schematic moisture profiles illustrating the expected seasonal fluctuations in a properly performing capillary break cover. Unlike the monolithic cover, the moisture front can reach the bottom of the barrier layer without resulting in basal percolation, provided that the moisture at the interface does not exceed the breakthrough value. An important benefit of capillary breaks is that the moisture storage within the fine-grained soil can exceed its freely draining state (field capacity). Consequently, more water can be stored in a capillary break cover than in a monolithic cover of equivalent thickness. Alternatively, a thinner fine-grained layer can be used in a capillary break cover to obtain the same moisture storage as in a monolithic cover. The magnitude

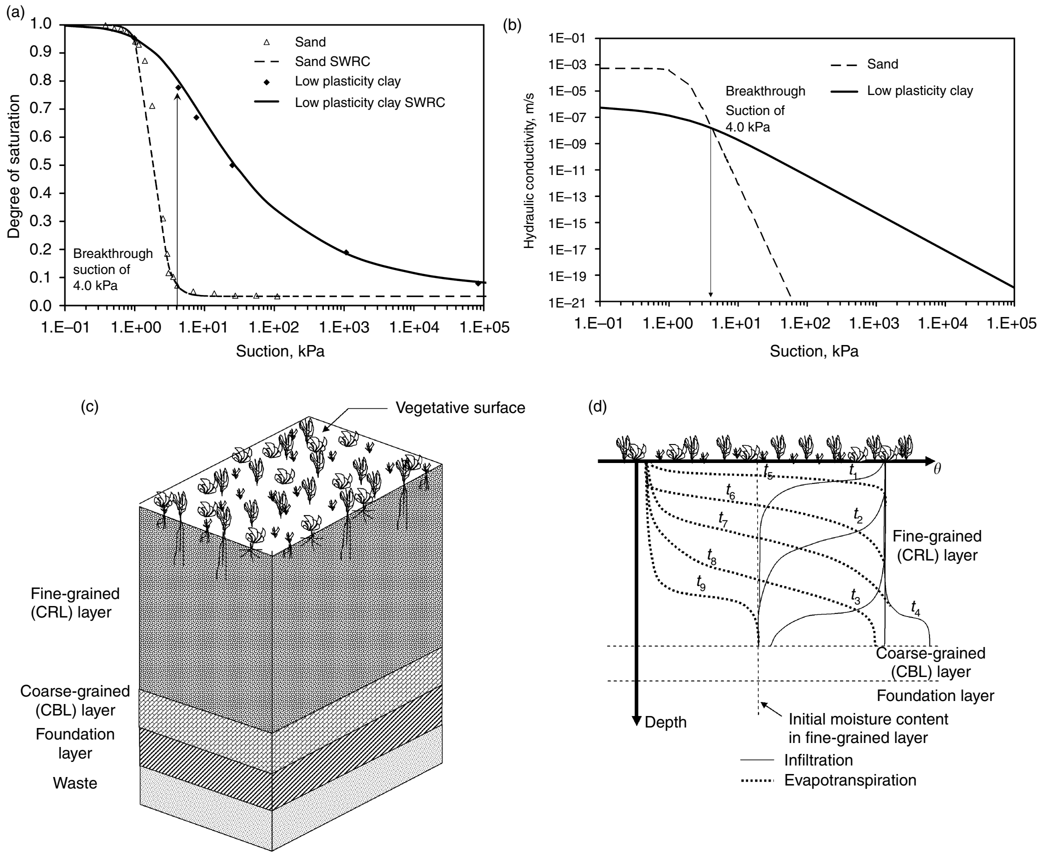

FIGURE 34.10 Capillary barrier details: (a) conceptual SWRC illustration of the capillary break effect; (b) conceptual K-function illustration of capillary break effect; (c) capillary break soil profile; and (d) typical seasonal moisture content fluctuations.

and long-term changes in the conditions leading to breakthrough are aspects under current investigation, especially in inclined covers (Parent and Cabral, 2004). Inclined covers may experience lateral diversion, which leads to greater moisture contents in the lower portion of a slope, resulting in a greater likelihood for breakthrough. Conservatism should be used in capillary barrier design, as these barriers have typically been reported to experience breakthrough during spring snowmelt when plant evapotranspiration is at a minimum (Khire et al., 1999; 2000). In addition, preferential flow through larger pores may lead to significant variability in the breakthrough suction (Kampf and Holfelder, 1999).

34.3.3 Anisotropic Barriers

Anisotropic barriers are similar to capillary barriers, but their design accounts for the internal lateral drainage through one or more drainage layers resulting from the inclination of the cover (Stormont, 1995; Bussiere et al., 2003; Parent and Cabral 2005). Figure 34.11a shows a schematic view of an anisotropic barrier. Anisotropic layers typically involve a soil vegetation substrate overlying a coarse-grained drainage layer, which are in turn underlain by a primary barrier layer and a second coarse-grained layer to provide a capillary break. The coarse-grained drainage layer functions both as a capillary break to the vegetation substrate and as a drainage layer for breakthrough water. The water collected by the drainage layer, along with moisture migrating laterally within the vegetation substrate is typically diverted to a ditch before a significant amount of water can infiltrate into the primary barrier. Figure 34.11b shows moisture profiles

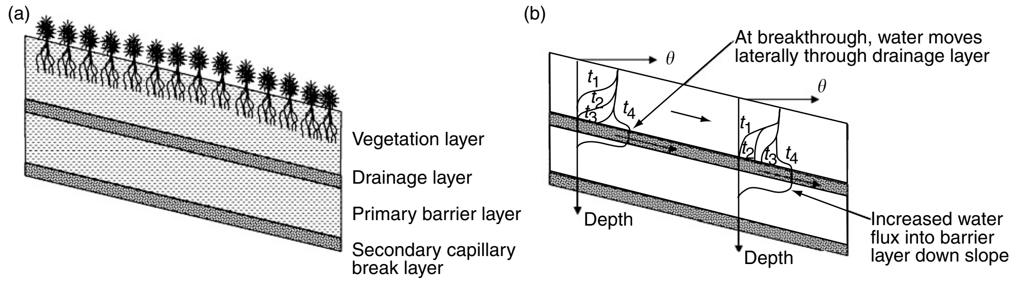

FIGURE 34.11 Anisotropic barrier: (a) soil profile and (b) typical moisture content fluctuations during infiltration.

illustrating the expected trends along the length of an anisotropic barrier during a wet season. The capillary break at the drainage layer increases the moisture storage capacity of the vegetative substrate. Infiltration of water into the barrier layer generally occurs toward the toe of the slope due to water accumulation from infiltration and lateral drainage. Design of anisotropic covers is more complex than that of monolithic or capillary break covers due to the need to quantify the required hydraulic properties for the layered profile as well as the volume of laterally diverted water. Field comparisons between the performance of test-scale capillary break, anisotropic, and monolithic covers performed by Dwyer (1998) indicate that the anisotropic cover performed well compared to the other covers for the same weather conditions over a five-year monitoring program. However, its construction was the most difficult of the three covers.

34.4 Relevant Issues for Design of Evapotranspirative Covers

34.4.1 Design Strategies

Despite the conceptual simplicity of evapotranspirative covers, their design is not trivial and typically involves numerical and field demonstration components. The design of an evapotranspirative cover involves the identification of performance criteria that are used to evaluate the suitability of different design alternatives. This phase typically requires close interaction between the designer, site stakeholders, and local regulators. The goal is to identify the criteria that will provide for human safety, constructability, and cost effectiveness. The design process typically involves identification of different cover design alternatives. This includes: (i) identification of suitable local borrow soil sources, (ii) characterization of the hydraulic properties of pre-selected soils under different placement conditions, (iii) determination of the cover geometry, (iv) identification of site-specific critical meteorological conditions, and (v) identification of suitable plant communities and vegetative cover properties. Design typically involves use of numerical models to predict the cover performance and field demonstrations aimed at evaluating the different design alternatives. Performance monitoring programs have been typically implemented after construction to verify the adequacy of the selected design alternative. Recent developments in evapotranspirative cover design have employed decision analysis, statistical characterization of design variables, and cost estimations to identify the optimal combination of performance variables. Such design approaches may help optimize the collection of laboratory data, identify if a site-specific field testing program is necessary, and quantify the risk of failure associated with design alternatives.

34.4.2 Performance Criteria and Regulatory Issues

Evapotranspirative covers are considered alternative covers and, as such, their design involves comparison of their performance with that of prescriptive cover systems (i.e., equivalency demonstration). Development of suitable performance criteria for ET cover systems generally involves equivalence demonstration with prescriptive covers (Morris and Stormont, 1997; McCartney and Zornberg, 2002; Albright et al., 2004). Because of the site-specific interactions between an evapotranspirative cover and the local climate and environment, performance criteria for evapotranspirative covers must account for site-specific conditions. This section outlines different types of performance criteria that have been put forth for evapotranspirative covers. The type of performance criteria will impact both the design procedures and the methods of post-closure monitoring.

Determination of a percolation criterion has been approached from two different perspectives, at least in recent evapotranspirative cover projects in the United States. The first involves defining a *quantitative* maximum value of basal percolation (e.g., expressed in mm/year) that should not be exceeded. The second involves a *comparative* approach aiming at achieving a basal percolation value in the evapotranspirative cover that is smaller than that through a prescriptive cover under the same weather conditions.

The maximum basal percolation value (quantitative percolation criterion) is typically defined in agreement with regulatory agencies, yet it should be based on actual performance data from prescriptive type covers or on the results of verified numerical models. A quantitative criterion establishes that the basal percolation through the evapotranspirative cover, P_e (mm/year), should be less than the Maximum Quantitative Percolation Value, MQPV (e.g., mm/year), deemed to satisfy equivalence, as follows:

$$P_e < \text{MQPV} \tag{34.10}$$

where MQPV is a predefined criterion and P_e is determined from field monitoring and from numerical simulations. The choice of a quantitative percolation criterion implies that the cover must be designed for a wide range of possible meteorological conditions to ensure fulfillment of the criterion for worst case scenarios. On the other hand, if the MQRV is selected conservatively, the cover design may lead to unrealistically high material and construction costs.

A comparative percolation criterion for evapotranspirative covers involves defining the maximum ratio between the basal percolation through an evapotranspirative cover and that through a prescriptive cover. This percolation criterion recognizes that the performance of the evapotranspirative cover should be compared to that of a resistive cover under the same meteorological conditions. Specifically, the basal percolation through the evapotranspirative cover (P_e) should be less than that through the prescriptive cover (P_p), affected by the Maximum Comparative Percolation Ratio (MCPR) established for the project. That is, equivalence is deemed satisfied when the following condition is fulfilled:

$$P_e < \text{MCPR} \cdot P_p \tag{34.11}$$

where MCPR is dimensionless and P_e and P_p are basal percolation values (e.g., in mm/year). Adopting an MCPR of 1.0 implies that the evapotranspirative cover should perform better than a prescriptive cover under the same weather conditions. The methods used to define basal percolation values P_e and P_p may involve the use of a numerical model or of monitored field test plots. The first approach may not account for factors that are not adequately modeled using unsaturated flow models such as desiccation, surface settlement, animal burrowing, and fingering. The second approach may result in additional costs and may not account for critical weather conditions and long-term factors.

Performance criteria may also involve interpretation of the moisture profiles in the cover rather than quantification of percolation values. Specifically, quantitative criteria can involve comparison of the moisture storage within the cover with a certain threshold value. Similarly, criteria may involve comparison of the moisture at the base of the cover with a certain threshold moisture value (that can in turn correspond to a maximum value of $K(\theta)$ calculated from Equation 34.8). Ideally, performance criteria would involve interpretation of both basal percolation and moisture profile information (McCartney and Zornberg, 2002).

34.4.3 Important Design Variables

34.4.3.1 Soil Hydraulic Properties

The soil hydraulic properties relevant to the performance of evapotranspirative covers include the saturated hydraulic conductivity (K_s), the soil-water retention curve (SWRC), and the K-function.

Determining the required soil hydraulic properties is a challenging aspect of evapotranspirative cover design. Target values of the hydraulic properties are typically selected based on the required cover performance and on the expected weather conditions at the site. An important difficulty in the methods used to evaluate hydraulic properties in the laboratory is their high sensitivity to sample preparation and testing procedures. For example, the relative compaction of the soil and its compaction moisture content will typically affect the soil hydraulic properties. Finally, the differences between hydraulic properties determined in the laboratory and those in the field add to the difficulty in soil characterization. In addition to specimen preparation variability, the hydraulic properties in the field may change with time due to hysteresis (different behavior during wetting and drying), soil cracking, settlement, plant or animal intrusion, and erosion.

34.4.3.2 Cover Geometry

Cover geometry variables include the thickness of the cover, as well as the cover inclination. As the performance of the soil cover depends on its capacity to store liquid, a thicker cover will have a higher moisture storage capacity. The slope of the cover will impact its stability, the amount of water drained laterally, as well as the amount of overland runoff during precipitation events. Some evapotranspirative covers have been constructed with significantly high slope inclinations (as high as 1.5H:1V). This is the case of the OII landfill in Pomona, California (see Section 34.6.2). Steep slopes may require stabilization to account for seismic and static stability.

34.4.3.3 Critical Meteorological Variables

Critical meteorological conditions are site specific and play a significant role in the selection of the required soil properties, cover thickness, and slope inclination. A general guideline is that evapotranspirative covers are suitable for regions in which the potential evapotranspiration is greater than the precipitation. An important aspect of the design process involves identification of a worst-case precipitation record. Multi-year records must be obtained to consider the patterns in cover performance over both wet and dry years. In addition to the precipitation, the solar radiation, minimum and maximum air temperatures, wind speed, relative humidity, and percentage cloud cover are often used in numerical models to calculate the potential evapotranspiration. These variables are generally available from local or national weather station databases.

34.4.3.4 Vegetation Parameters

Vegetative cover properties determine the amount of water that can be removed from the cover by transpiration. Water uptake by plants has been quantified empirically as a function of variables such as the wilting point suction, leaf area index, evapotranspiration partitioning model parameters, and root density distribution. Although researchers have been incorporating plant behavior in numerical models since the 1950s, the quantification of these variables is still unclear. The wilting point suction is the suction above which the plants are unable to draw water from the soil. Plants will typically stop transpiring and grow dormant under such conditions. The leaf area index is the leaf area coverage per unit ground area, and is typically correlated with the moisture demand of plants. A plant with more foliage will be able to photosynthesize faster, leading to more transpiration. Evapotranspiration can be estimated using the Penman-Monteith model (Monteith, 1965), which requires knowledge of the daily maximum and minimum temperatures, dew point temperature, solar radiation, percent cloud cover, wind speed, and precipitation (Zornberg and McCartney, 2003). However, once the evapotranspiration has been estimated, it must be partitioned into evaporation and transpiration components for use in numerical models (Fayer et al., 1992). The Ritchie model can be used to correlate the relative contribution of the plant transpiration with the leaf area index. The root density distribution depends on the particular plant, although it is typically measured to avoid plants with roots deeper than the cover thickness. A diverse group of native shrubs and grasses is recommended. Selection of plants with different heights also prevents intrusion of burrowing animals while providing erosion control.

34.4.4 Numerical Modeling Issues

Analysis of the performance of alternative covers has been performed using: (i) unsaturated flow analyses, and (ii) simplified water balance analyses (Albright et al., 2002). Unsaturated flow analysis entails solving Richards' equation for certain surface boundary conditions (e.g., water infiltration, overland runoff, evaporation, transpiration) and bottom boundary conditions (e.g., unit hydraulic gradient, seepage face). The governing equations are solved using numerical techniques such as the finite element method or the finite difference method. Relevant outputs from these analyses include the transient moisture redistribution and basal percolation. Four commonly used Richards' equation-based codes that have been used in the analysis of evapotranspirative covers are UNSAT-H (Fayer and Jones, 1990), HYDRUS-1D (Simunek et al., 1998), LEACHM (Hutson and Wagenet, 1992), and Vadose/W (GeoSlope, 2004). The current version of UNSAT-H allows modeling of hysteresis in the SWRC, and was observed to have a close fit to observed data (Khire et al., 1999). HYDRUS-1D is more user-friendly and has built-in libraries for soil hydraulic properties and initial estimates for most performance variables. LEACHM has the distinct advantage of being an open-source code, while being particularly useful for conducting sensitivity analyses that allow identification of relevant variables (Zornberg et al., 2003). VADOSE/W is a commercial code that considers fully coupled heat and mass transfer with vapor flow, vegetation, gas diffusion and ground freezing in a finite element formulation in one or two dimensions. It solves a modified form of the Richards' equation with pressure as the dependent variable, not water content, which improves solution stability. Despite their ability to solve Equation 34.5 subject to complex boundary conditions, it is still challenging to use Richards' equation-based codes for predicting small basal percolation values with a high level of accuracy. It should be noted that the mass balance errors for numerical models may be of the same order of magnitude as basal percolation values of relevance for the analysis of evapotranspirative covers.

Analyses involving water balance use the conservation of mass at the soil surface to estimate the basal percolation through the cover. This approach treats the soil layer as a sponge, able to hold a certain maximum amount of water (at the field capacity suction) against the pull of gravity. Basal percolation is calculated as the volume of moisture in the cover that exceeds the field capacity moisture storage after accounting for moisture removed by evapotranspiration and lateral drainage. Water balance codes that have been used for evapotranspirative cover include the Hydrologic Evaluation of Landfill Performance (HELP) (Schroeder et al., 1994), which is distributed by the US Environmental Protection Agency (EPA), and the Erosion Productivity Impact Calculator (EPIC) (Williams et al., 1984). A significant limitation of the water balance approach is that it does not consider transient moisture redistribution, which plays an important role in moisture removal from the cover by evapotranspiration. Also, as the water balance approach considers that the only driving mechanism for water flow is gravity, it implicitly considers that the hydraulic gradient is always equal to 1.0.

34.5 Performance Monitoring of Evapotranspirative Covers

34.5.1 Monitoring Strategies

In the past decade, there has been a significant effort to expand the evapotranspirative cover knowledge base by constructing full-scale field test plots involving the monitoring of basal percolation and moisture profiles (Benson et al., 1999, 2001; Dwyer, 1998; O'Kane et al., 1998; Zornberg and McCartney, 2003). Monitoring schemes allow direct quantification of the response of evapotranspirative covers to atmospheric conditions. The field monitoring program should be consistent with the performance criteria used for the cover design. Different technologies have been considered to evaluate the basal percolation, moisture profiles, suction profiles, and meteorological variables, as discussed further in the following sections.

34.5.2 Regulatory Issues Specific to Compliance Demonstration

The selection of a quantitative or comparative percolation criterion for an evapotranspirative cover project (Section 34.4.2) may have significant implications on the compliance demonstration for the cover. As mentioned, the threshold basal percolation (MQPV) to be used in a quantitative percolation criterion is difficult to define. However, once the MQPV has been defined the monitoring program used for compliance demonstration phase using a quantitative percolation criterion is reasonably straightforward, as it involves monitoring the basal percolation to verify that it remains below the MQPV. Yet, limitations in field monitoring and numerical modeling must be understood to correctly interpret the data collected for compliance demonstration. On the other hand, the monitoring program used for compliance demonstration when using a comparative percolation criterion for the design may not be straightforward. For example, an approach could involve continued comparison monitored in the basal percolation values of two covers (prescriptive and alternative) over the lifetime of the evapotranspirative cover. Accordingly, the time period used for compliance demonstration is a key factor. For instance, compliance could be based on either the average basal percolation value during a time period or on the maximum basal percolation amounts associated with specific precipitation events.

34.5.3 Lysimetry

Gravity lysimeters are the most common tools for directly monitoring basal percolation. They typically consist of a drainage layer underlain by a hydraulic barrier (Benson et al., 1999, 2001), such as a geocomposite or gravel drainage layer placed on top of a geomembrane. The geocomposites used in gravity lysimeters consist of a geonet sandwiched between two nonwoven geotextiles. A geonet is a thin polymeric sheet with slotted grooves that provide high lateral transmissivity. Geotextiles are polymeric fabrics used as filters, protection layers, and drainage layers. Geomembranes are polymeric sheets that have equivalent hydraulic conductivity values on the order of 10^{-15} m/sec. When a soil cover is placed above the lysimeter, it is intended that percolation through the cover soil will reach the geocomposite, and be transmitted down-slope to a collection bin. For effective performance, it is important to avoid that the presence of the lysimeter interferes with water flow (i.e., by introducing a capillary break).

The main advantage of lysimeters is that they can be constructed to cover large areas (10 to 100 ft on side), which allows a spatial averaging of the water flow through a potential system of saturated preferential pathways in the cover (areas with lower density, cracks, animal burrows, or decayed plant roots). However, lysimeters have several shortcomings, the most significant being that they provide little insight into reasons for poor or adequate cover performance. Another shortcoming is that, despite their high transmissivity and permittivity when saturated, the geotextile component of a lysimeter may cause a capillary break when in contact with unsaturated soils (Stormont and Morris, 2000; Zornberg and McCartney, 2003; McCartney et al., 2005b). A capillary break at the lysimeter–soil interface distorts the suction and moisture content profiles in an evapotranspirative cover and may lead to significant underestimation of basal percolation. In addition, lysimeters create barriers to upward flow from lower depths (Scanlon and Milly, 1994). This is typically caused by water vapor flow in response to thermal gradients, and may lead to overestimation of the basal percolation at the site.

34.5.4 Monitoring of Moisture and Suction Profiles

As the overall performance of an evapotranspirative cover system relies on its ability to store moisture until it is removed by evapotranspiration, moisture content or suction profiles can be monitored to assess why the evapotranspirative cover performs adequately (or not). Continued monitoring of *in situ* soil volumetric moisture content profiles is important in many geoenvironmental engineering and hydrological projects. In particular, monitoring of soil volumetric moisture content can provide relevant feedback on the migration of moisture through evapotranspirative covers.

Time Domain Reflectometry (TDR) technology has been used to measure the volumetric moisture content in evapotranspirative covers (Dwyer, 1998; O'Kane et al., 1998; Siddiqui et al., 2000; Albright and

Benson, 2002; Zornberg and McCartney, 2003). TDR involves measuring the velocity of an electromagnetic pulse applied to a transmission line that terminates in a shielded probe placed within the soil mass (Topp et al., 1980; Siddiqui et al., 2000; Suwansuwat and Benson, 1999). The pulse is reflected due to changes in impedance along the transmission line-probe system (e.g., the beginning of the probe and the end of the probe). The velocity of the reflected pulse is affected by the dielectric constant of the water within the soil mass, which is an order of magnitude greater than that of air and soil particles. The bulk dielectric constant of the soil mass, calculated from the velocity of the reflected pulse, can then be correlated with the soil volumetric moisture content. Conventional TDR systems use a cable tester to generate high frequency electromagnetic pulses (∼10 to 100 GHz) and measure the reflected waveform (with a resolution on the order of nanoseconds). Although conventional TDR systems are generally adequate for a wide range of soil types, their accuracy decreases for high moisture contents, saline soils, and highly conductive clays. Their shortcomings include the relatively high cost of probes and cable tester systems and comparatively complicated installation procedures to prevent probe damage.

Water content reflectometer (WCR) probes have often been used as an alternative to conventional TDR probes (Dwyer, 1998; Albright and Benson, 2002; Chandler et al., 2004). WCR probes infer the moisture content by measuring the dielectric content of the soil, similar to TDRs. However, WCRs use smaller electronic circuitry placed within the probe itself that generate a lower frequency electromagnetic pulse (∼40 MHz) (Chandler et al., 2004). WCR probes have lower power requirements and allow longer cable lengths than conventional TDRs. In addition, WCR probes can use conventional field dataloggers instead of cable testers, which makes them attractive for field applications. Despite these advantages, the use of comparatively low frequencies may lead to decreased resolution in volumetric moisture content measurements and to correlations that are more sensitive to the soil electrical conductivity and temperature than TDRs (Kim and Benson, 2002).

Suction measurements can also be made to complement moisture content evaluations. Concurrent suction and moisture content monitoring can provide data suitable to interpret evapotranspirative cover performance. Specifically, the suction and moisture content measurements can provide information for *in situ* determination of the SWRC. This can be used to interpret the SWRC during wetting and drying, interface phenomena like capillary breaks, and optimization of the SWRC to be used in numerical models. Suction measurements have been conducted in the field using several types of techniques, such as tensiometers (Ridley and Burland, 1995; Sisson et al., 2002; Tarantino and Mongiovì, 2003) and heat dissipation units (HDUs) (Flint et al., 2002; Nichol et al., 2003). Tensiometers consist of a pressure transducer with a porous ceramic stone filter. Due to continuity of suction, the suction within the ceramic stone will come into equilibrium with that of the surrounding soil. As water is drawn from the ceramic stone, the pressure transducer will measure a negative pressure value. HDUs consist of a heating unit and a thermocouple placed within a ceramic stone. The HDU infer the soil suction by applying a heat pulse to the heating unit in the ceramic stone, and measuring the transient changes in temperature of the ceramic stone using the thermocouple. The thermal properties of the ceramic are related to its moisture content, with a wet ceramic having higher thermal conductivity than a dry ceramic. Accordingly, the thermal response of the ceramic to the applied heat pulse can be calibrated against the suction in the ceramic, which is the same as the suction in the soil.

34.5.5 Monitoring of Meteorological Variables and Overland Runoff

Site-specific monitoring of meteorological variables is important to proper interpretation of evapotranspirative cover performance, as these variables vary on a regional and local scale. Precipitation is generally measured using tipping bucket rain gauges. These gauges collect water in a two-sided bucket with a capacity of approximately 4 ml. The bucket is placed on a pivot so that water flowing into the gauge is funneled into one side of the bucket. After the capacity of the bucket is reached, the weight of the water causes the bucket to tip on the pivot, spilling the water and allowing water to be funneled into the other side of the bucket. The gauge records the time of each tip. Overland runoff has been typically measured using geomembrane swales anchored on the soil surface on the perimeter of the cover. Difficulties have been encountered in the use of such swales due to thermal expansion of the exposed geomembranes. Other variables typically measured on the site include wind speed and direction using an anemometer, temperature, and solar radiation.

34.6 Case Studies

34.6.1 Site Survey

Table 34.1 shows a survey of evapotranspirative covers in the United States that have implemented field monitoring programs. A total of 53 evapotranspirative covers were identified at 48 sites in the United States. Among these, 19 of the sites have undergone or are undergoing construction or closure of an evapotranspirative cover, while the rest involve compliance demonstration using test covers. The number of sites with performance monitoring shown in this table reflects the growing number of alternative cover construction projects because of their technical and economic benefits. The table also provides the water balance variables monitored at each site and the study period. Although information is limited for some of the private covers, it appears that most covers have used lysimetry and moisture profile monitoring as part of compliance demonstration programs. Two of the sites, the OII landfill in Monterey Park, California, and the Rocky Mountain Arsenal, near Denver, Colorado, are discussed next.

34.6.2 OII Landfill

The first evapotranspirative cover system approved by the US EPA for a hazardous waste Superfund site was in 1997 (Zornberg et al., 2003). The cover was constructed at the OII Superfund site in Monterey Park, California, approximately 16 km east of downtown Los Angeles. The design of this cover involved five phases that were undertaken to define the cover layout configuration. The design phases included: (i) evaluation of a baseline evapotranspirative cover, (ii) equivalence demonstration of the baseline cover by comparison with the basal percolation through a prescriptive cover, (iii) evaluation of the sensitivity of different design parameters (e.g., cover thickness, soil characteristics, rooting depth, and potential use of irrigation schemes) on the basal percolation through the cover, (iv) use of compilation of the results of this analysis as basis for the design of the final evapotranspirative cover, and (v) equivalence demonstration using soil-specific hydraulic properties of each cover soil.

The criterion used for the design of the cover system at the OII Superfund site was comparative, and required that the basal percolation through the proposed evapotranspirative cover be less than the basal percolation through a prescriptive, resistive cover. That is, the Maximum Comparative Percolation Ratio (MCPR) at this project was 1.0. The prescriptive cover, defined by a consent decree, consisted of a 1200-mm thick system, which included a 300-mm thick vegetative layer, a 300-mm thick clay layer, and a 600-mm thick foundation layer. The vegetative and foundation layers both were considered to have a saturated hydraulic conductivity of 1×10^{-6} m/sec, and the clay layer to have a saturated hydraulic conductivity of 1×10^{-8} m/sec.

A laboratory testing program was implemented to characterize the candidate borrow soils using soil specimens remolded under different compaction and moisture conditions. The experimental program included determination of hydraulic, shear strength, desiccation potential, and edaphic properties. Table 34.2 summarizes the laboratory test results for one of the candidate borrow soils measured in the laboratory for use in the equivalence demonstration. Following identification of the candidate soil borrow sources and determination of their hydraulic properties, soil-specific equivalence demonstrations were performed for the proposed evapotranspirative cover. Soil-specific parameters used in the unsaturated flow analyses included the SWRC, saturated hydraulic conductivity and K-function (obtained by centrifugation). In addition, soil-specific information from compaction tests was used in the analyses to define the soil placement conditions (unit weight and moisture content) that would optimize the performance of the cover.

TABLE 34.1 Survey of ET Cover Case Studies

	Cover details		Water balance variables measured					Study period		
Site name	Cover type	Cover location	Meterological variables	Percolation	Water content	Suction	Runoff	Start date	End date	Full scale or test section
Greater Wenatchee Regional Landfill[a]	Capillary break	Wentachee, WA	X	X	X		X	1992	1995	0 test sections
Greater Wenatchee Regional Landfill[a]	Monolithic	Wentachee, WA	X	X	X		X	1992	1995	1 test section
Live Oak Landfill[a]	Monolithic	Atlanta, GA	X	X	X		X	1993	1996	1 test section
Sacramento site[a]	Monolithic	Sacramento, CA		X				1999	2002	2 test sections
Beltsville facility[a]	Monolithic	MD	X	X	X		X	?	?	Test section
Phelan landfill[a]	Monolithic	Sacramento, CA	X	X	X		X	?	?	Test section
National Council for Air and Stream Improvement[a]	Monolithic	NM	X	X	X		X	?	?	Test section
Grede Foundries[a]	Monolithic	Reedsburg, WI	X	X	X		X	1995	1996	Test section
Texas Low-Level Radioactive Waste Disposal Authority Facility[a]	Monolithic	Sierra Blanca, TX	X	X	X		X	1995	1997	Test section
US Marine Corps Air and Ground Combat Center[a]	Monolithic	Twentynine Palms, CA	X	X	X		X	1998	1999	Test section
Marine Corps Base[a]	Monolithic	HI	X	X	X		X	?	?	Test section
US Ecology Co. Landfill[a]	Monolithic	Sheffield, IL	X	X	X		X	?	?	
Hamburg Test Site	Capillary break	Hamburg, Germany	X	X		X	X	1988	1992	1 test section
Omega Hills Landfill[a]	Capillary break	Milwaukee, WI		X			X	?	?	1 test section
Los Alamos National Laboratory[a]	Capillary break	Los Alamos, NM	X	X				1991	1995	1 test section
Los Alamos National Laboratory[a]	Capillary break	Los Alamos, NM	X	X	X		X	1991	1995	2 test sections
Arid Lands Ecology Reserve, Hanford[a]	Monolithic	Richland, WA	X	X	X			1985	1990	4 test sections
Hanford Field Lysimeter Test Facility[a]	Capillary break	Richland, WA	X	X	X		X	1987	1996	8 test sections
Hanford[a]	Capillary break	Richland, WA	X	X				?	?	2 test sections
Hanford[a]	Monolithic	Richland, WA	X		X			1987	1989	6 test sections
NMSU Las Cruces Site[a]	Monolithic	Las Cruces, NM	X	X	X	X		?	?	1 test section
Beatty Site[a]	Monolithic	Mojave Desert, NV	X	X	X	X		?	?	1 test section
Hanford Site[a]	Monolithic	Richland, WA	X	X	X	X		?	?	1 test section
Hill AFB[a]	Capillary break	UT	X	X	X	X	X	1990	1993	2 test sections

Sandia National Laboratories	Capillary break	Albuquerque, NM	X	X	X		X	1997	2002	1 test section
Sandia National Laboratories	Monolithic	Albuquerque, NM	X	X	X		X	1997	2002	1 test section
Sandia National Laboratories	Anisotropic	Albuquerque, NM	X	X	X		X	1997	2002	1 test section
Rocky Mountain Arsenal[a]	Monolithic	Denver, CO	X	X	X		X	1992	2003	4 test sections
Nevada test site	Monolithic	NV	X	[a]	X			1996	2002	2 test sections
Idaho National Engineering and Environmental Laboratory[a]	Monolithic	ID	X	X	X		X	1984	1995	1 test section
El Paso Site	Capillary break	El Paso, TX	X	X		X		2000	2001	1 test section
Questa Mine	Monolithic/ Oxygen cover	NM	X	X	X	X		2000	2001	1 test section
Equity Silver Mine	Monolithic/ Oxygen cover	BC, Canada	X	X	X	X	X	1992	1995	1 test section
Vereenigning Ash Dump	Ash Dump cover	South Africa	X		X	X	X	1995	1995	1 test section
F. R. Bowerman Landfill	Monolithic	CA			X			?	?	Full scale
Operating Industries, Inc. (OII)	Monolithic	Monterey Park, CA			X			?	?	Full scale
Puente Hills	Monolithic	CA			X			?	?	Full scale
Yucaipa	Monolithic	Orange Country, CA			X			?	?	Full scale
Lopez Canyon	Monolithic	Los Angeles, CA			X			?	?	Full scale
Yeermo	Monolithic	Los Angeles, CA			X			?	?	Full scale
Riverside Co.	Monolithic	Riverside Country, CA			X			?	?	Full scale
29 Palms Marine Base	Monolithic	CA			X			?	?	Full scale
Potrero Hills	Monolithic	CA	X		X		X	1997	1999	Full scale
Chiquita Canyon	Monolithic	CA			X			?	?	Full scale
Needles Landfill	Monolithic	CA			X			?	?	Full scale
Fairmead Landfill	Monolithic	CA			X			?	?	Full scale
Rocketdyne Site	Monolithic	Chattsworth, CA			X			?	?	Full scale
China Grade Landfill	Monolithic	Kern Country, CA		X	X			?	?	Full scale
McPherson Area Solid Waste Utility	Monolithic	McPherson, KS		X				?	?	Full scale
Ft. Carson	Monolithic	CO		X	X			?	?	Full scale
Lakeside Reclamation Landfill	Monolithic	Beaverton, OR			X			?	?	Full scale
MSW Landfill	Monolithic	NE			X			?	?	Full scale
Duvall Custodial Landfill	Monolithic	WA			X			?	?	Full scale

[a] ACAP Sites.

TABLE 34.2 Hydraulic and Geotechnical Properties for OII Landfill Cover Soils

Series	USCS classification (ASTM D2487)	Average % passing #200 sieve (% fines)	Atterberg limits Average PL (%)	Atterberg limits Average LL (%)	Saturated hydraulic conductivity (m/s)	Campbell model parameters a	Campbell model parameters b	Relative compaction[a] (%)
T1	CL	66	43	18	2.80E-06	−4.89	7.028	93.9
T2	CL	66	43	18	1.10E-05	−4.89	6.328	87.2
T3	CL	66	43	18	3.70E-05	−4.89	5.495	83.1
T4	CL	66	43	18	3.30E-06	−4.89	7.278	88.5
T5	CL	66	43	18	1.70E-05	−4.89	6.463	87.8
T6	CL	66	43	18	1.90E-04	−4.86	6.678	77.7

[a] In relation to standard Proctor test (ASTM 698).

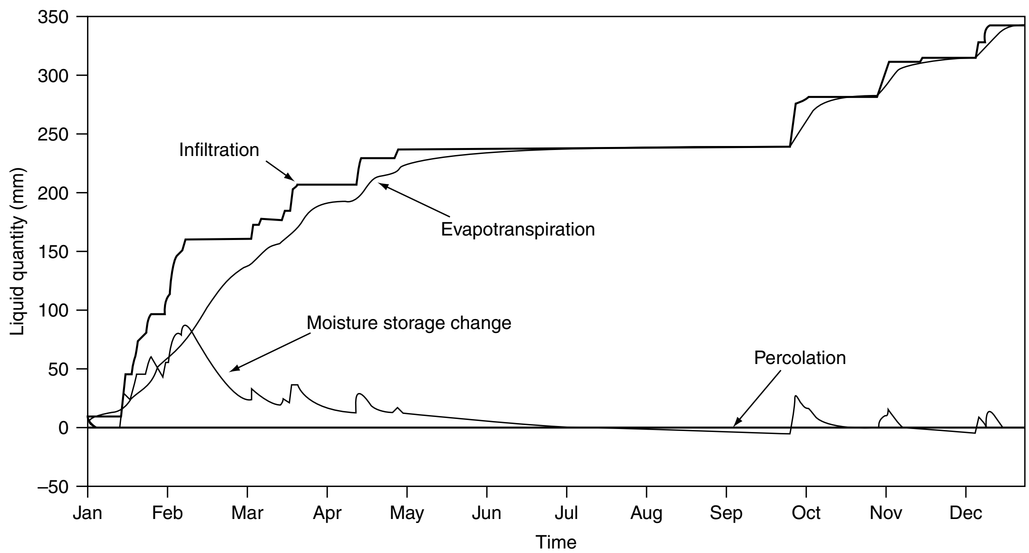

FIGURE 34.12 Seasonal variation in the water balance variables (Zornberg et al. 2003).

The code LEACHM (Hutson and Wagenet, 1992) was used to predict the basal percolation through both the prescriptive and the evapotranspirative covers to compare their performance using site-specific soil and meteorological conditions. LEACHM uses Campbell's (1974) equation to describe the relationship between suction and volumetric moisture content for soil:

$$\psi = a(\theta/\theta_s)^b \tag{34.12}$$

where a and b are constants obtained from curve fitting. The a and b values as well as the saturated hydraulic conductivity for one of the candidate evapotranspirative cover soils are listed in Table 34.2. The simulated water balance variables for the OII site are shown in Figure 34.12. This figure indicates that the moisture storage of the cover increases during periods of infiltration and subsequently decreases during period of evapotranspiration. The infiltration is typically higher in the early party of the year, while the evapotranspiration is higher in the late spring and summer months. Figure 34.13a shows equivalence results, as quantified by the percolation ratio (basal percolation through the ET cover divided by the basal percolation through the prescriptive cover) with time. This equivalence demonstration shown in the figure corresponds to an evapotranspirative cover system constructed using soils placed under compaction conditions defined by series T1 (Table 34.2). The percolation ratio is below 0.1 (and well below the MCPR

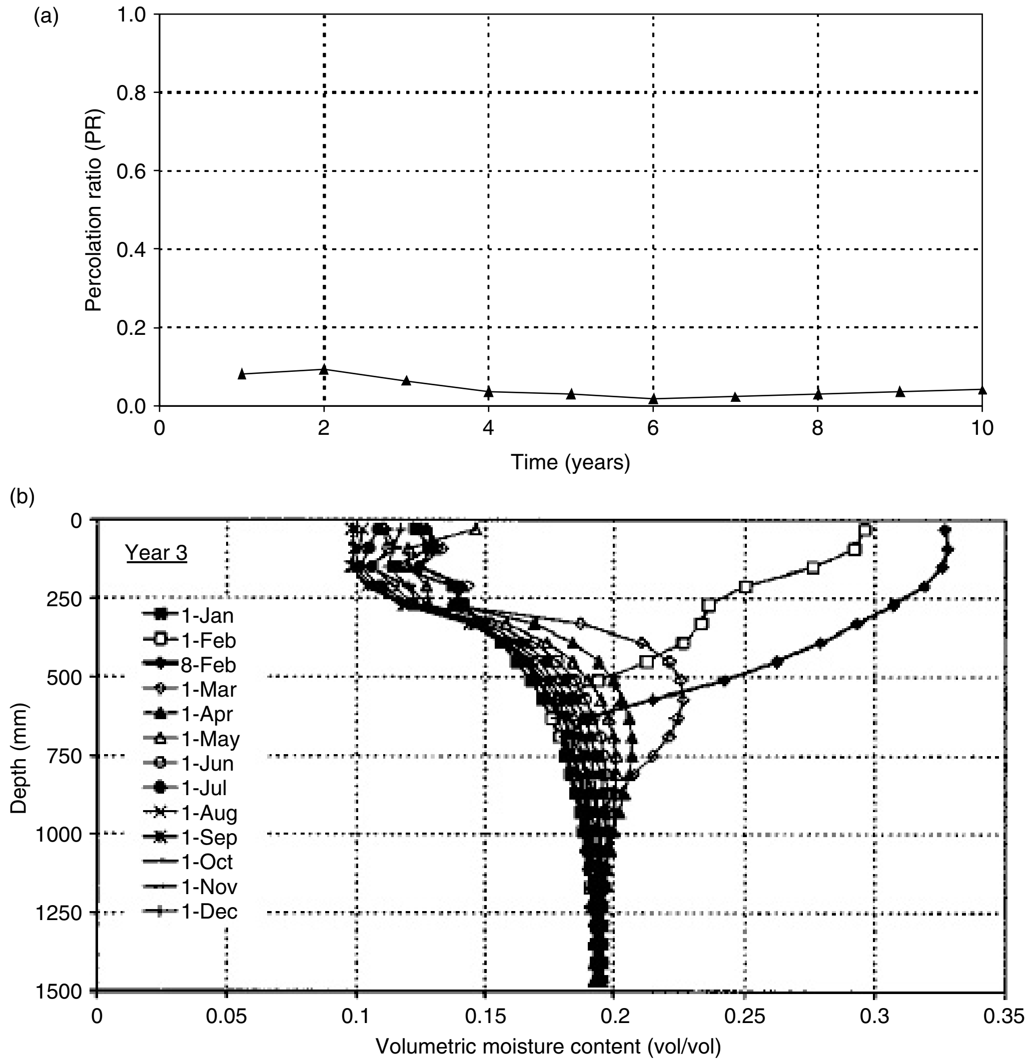

FIGURE 34.13 Performance variables for the O11 landfill evapotranspirative cover estimated using LEACHM: (a) comparative percolation ratio and (b) volumetric moisture content profiles during wettest simulation year (Zornberg et al. 2003).

of 1.0) for each year of the soil-specific, 10-year simulation. The engineered evapotranspirative cover constructed using the local soils, and placed under conditions defined by the T1 series, was then deemed to satisfy compliance with the prescriptive cover according to this demonstration. Figure 34.13b shows a prediction of the typical moisture content profiles expected for the cover. This figure indicates that the moisture fluctuations take place within the top meter of the soil cover, which reflects proper monolithic cover performance as discussed in Section 34.3.1.

34.6.3 Rocky Mountain Arsenal

Almost 200 acres of RCRA-Equivalent evapotranspirative covers have been recently designed to contain contaminated materials at the Rocky Mountain Arsenal (RMA), located near Denver, Colorado, USA. The climate in Denver is semiarid, with an average annual precipitation of 396 mm and an average pan evaporation of 1394 mm (as quantified for the 1948 to 1998 period). The wettest months of the year

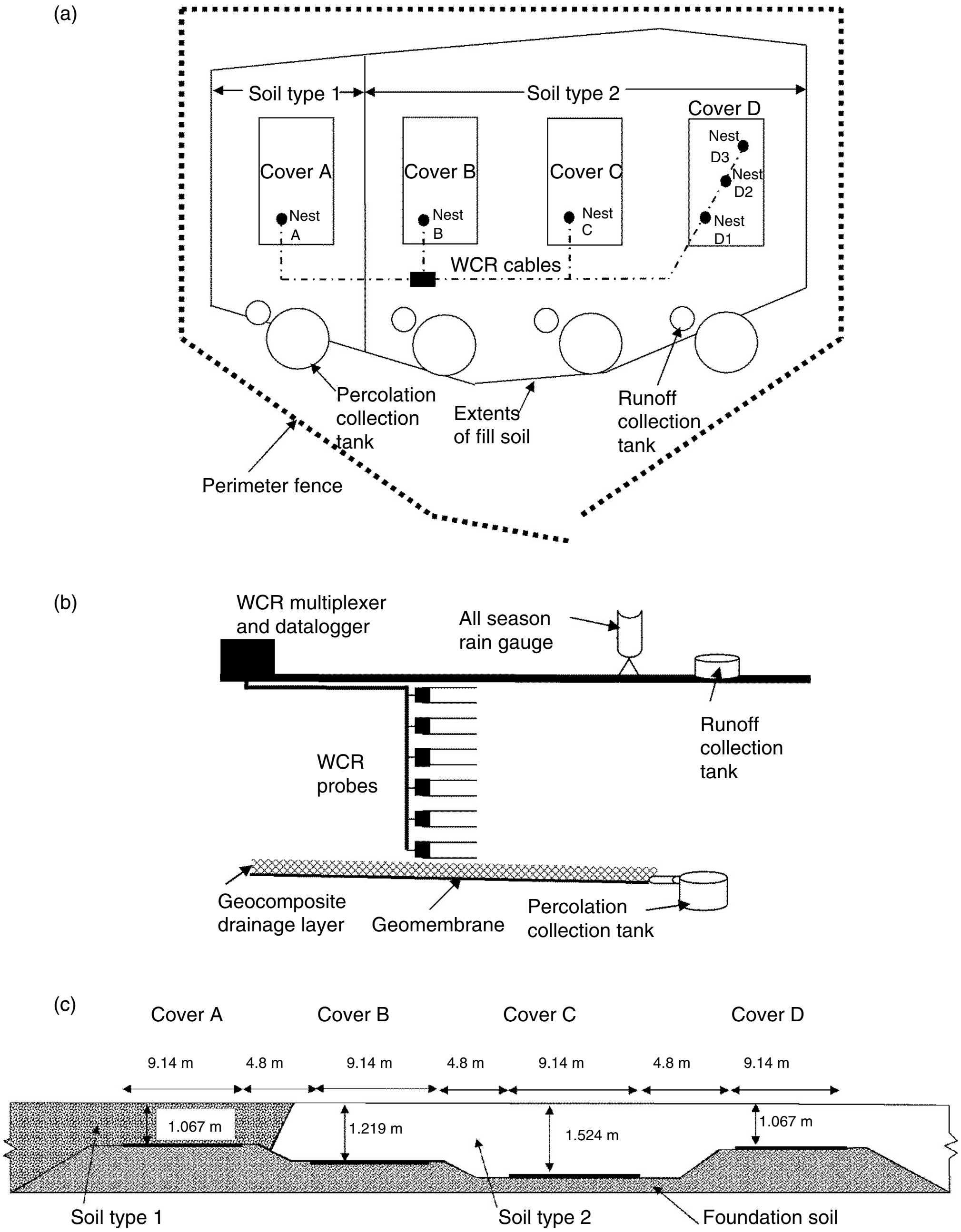

FIGURE 34.14 Layout for the monitoring program at the Rocky Mountain Arsenal: (a) plan view; (b) schematic view of instrumentation; and (c) elevation view.

(April to October) are also the months with the highest pan evaporation, which is appropriate for an evapotranspirative cover.

The Record of Decision (ROD) for the site requires a compliance demonstration to show equivalence of the alternative design with a prescriptive cover before construction of the final evapotranspirative covers. The design and compliance of the covers at the RMA site is governed by a quantitative percolation criterion. A MQPV threshold of 1.3 mm/year was selected at this site, which was based on eight years of leachate data collected from two landfill covers built to RCRA Subtitle C standards in Hamburg, Germany, according

TABLE 34.3 Hydraulic and Geotechnical Properties for Rocky Mountain Arsenal Cover Soils

Cover	Soil cover thickness (mm)	USCS classification (ASTM D2487)	Average % passing #200 sieve (% fines)	Atterberg limits		Saturated hydraulic conductivity (m/s)	van Genuchten model parameters				Relative compaction[a] (%)
				Average PL (%)	Average LL (%)		α (kPa^{-1})	N	θ_r	θ_s	
A	1143	SC	43.4	9	24.4	1.60E-05	0.6118	1.39	0.03	0.482	72.9
B	1270	CL	60.2	12.8	27.6	4.70E-06	0.3386	1.335	0.025	0.470	72.8
C	1676	CL	59.2	11.7	26.7	4.70E-06	0.3386	1.335	0.025	0.470	72.8
D	1168	CL	61.5	12	26.8	4.70E-06	0.3386	1.335	0.025	0.470	72.8

[a] In relation to standard Proctor test (ASTM 698).

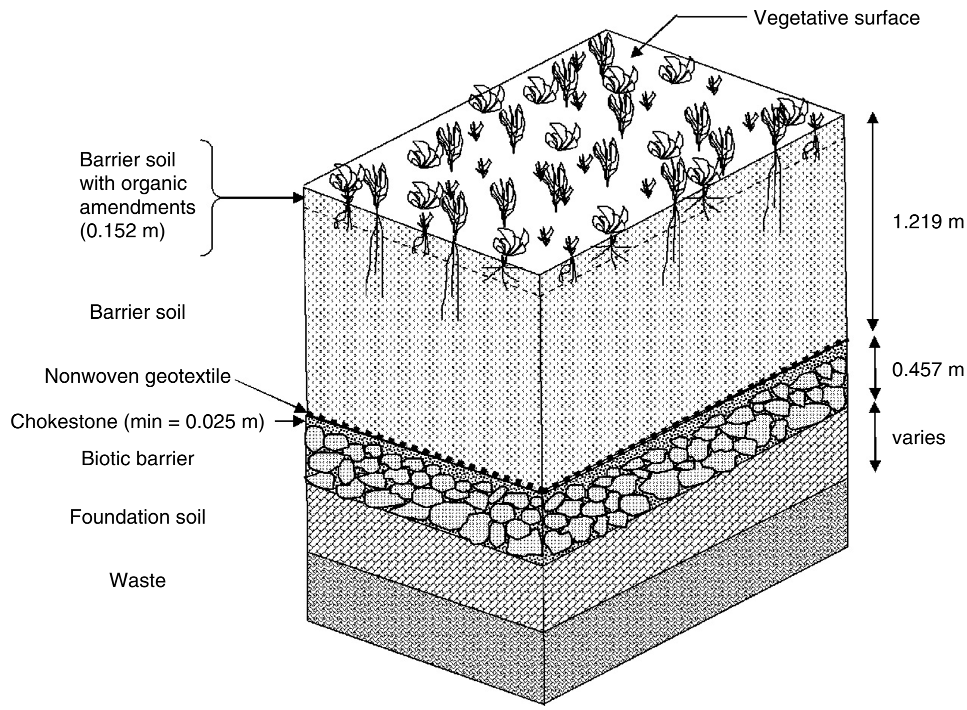

FIGURE 34.15 Final cover design at the Rocky Mountain Arsenal

to analyses described by Melchior (1997). This type of criterion was selected for its simplicity, as it sets a benchmark to be used in post-closure monitoring to demonstrate compliance, and is representative of the basal percolation for resistive covers.

The compliance demonstration at the Rocky Mountain Arsenal involved a field demonstration, which was complemented by comparative numerical analyses and a field demonstration (Kiel et al., 2002). Four evapotranspirative test covers were constructed on a rolling plain at the site in the summer of 1998. A plan view of the four test covers, referred to as covers A, B, C, and D, is shown in Figure 34.14a. The test covers were constructed using site-specific clays of low plasticity (CL), compacted atop large pan lysimeters (9.1 m by 15.2 m) placed on a 3% grade to allow gravity drainage to a collection tank. The geotechnical and hydraulic properties of the cover soils are summarized in Table 34.3. Figure 34.14b shows a schematic view of the monitoring layout used in the test covers. The instrumentation program involved monitoring of the basal percolation, precipitation, soil volumetric moisture content profile, and overland runoff in the four test covers. Basal percolation was collected in a gravity lysimeter, which consists of a geocomposite underlain by geomembrane. The lysimeters were constructed without sidewalls. Rain and snow were monitored using an all-season rain gauge. Surface water was collected in polyethylene geomembrane swales constructed around the cover perimeters. WCR probes were used to measure volumetric moisture content. Specifically, the covers were instrumented with nests of eight WCR probes. This included six WCR probes placed in a vertical nests of WCR probes and spaced evenly with depth. In addition, redundant WCR probes were placed at the same depth as the top and the bottom probes, approximately 1 foot aside from the vertical profile of WCR probes. Cover D was instrumented using three vertical profiles. Figure 34.14c shows an elevation view of the covers, indicating the depth of each cover. The covers are separated from each other by 2.4 m-wide buffer zones, and the entire area is vegetated with local grasses and shrubs.

The four test covers at the RMA were constructed to verify that the moisture flux through site-specific soils under local weather conditions remains below the MQPV of 1.3 mm/year (Kiel et al., 2002). The test plots at the Rocky Mountain Arsenal satisfied the quantitative percolation criterion over the period 1998 to 2003 of operation. That is, all four of the covers showed a yearly basal percolation rate below the MQPV despite having complemented the natural precipitation with irrigation. Although Cover D showed surface depression, possibly due to the installation of moisture probes or burrowing animals, the collected basal percolation over this cover was still below the MQPV percolation threshold.

The monitoring results of the field demonstration program were used to develop the final cover design. As shown in Figure 34.15, the final cover design is a capillary barrier with a 1.067 m barrier layer, similar to that used in covers A and D. An additional 0.152 m of topsoil is used for vegetation. The specifications for the final cover soil are based on those for soil type I used in cover A. The final design includes a nonwoven geotextile over a chokestone layer (coarse gravel) to form a capillary break at the bottom interface of the barrier soil. The geotextile also helps prevent barrier soil particles from migrating into the chokestone layer. The chokestone is underlain by a biotic barrier consisting of crushed concrete from a demolition site. The biotic barrier is design to prevent plants and burrowing animals from reaching the waste. The final cover will be instrumented with gravity lysimeters placed within the final cover to measure basal percolation and WCR probes to measure moisture profiles within the barrier soil.

Glossary

Anisotropic barrier Evapotranspirative cover with a system of barrier and drainage layers placed on a slope so that water is removed from the cover by lateral drainage.

Basal percolation Water that passes through a cover system into the underlying waste.

Biota barrier Layer of gravel or crushed concrete beneath the cover used to prevent entry of plants or animals into the waste.

Capillary break cover Evapotranspirative cover that exploits the increased moisture storage arising from placing a fine-grained soil over a coarse-grained soil.

Degree of saturation Ratio of the volumetric moisture content and the porosity.

Evapotranspirative cover systems Class of alternative landfill cover systems that functions by storing water from precipitation until it may be removed by evapotranspiration.

Field capacity Moisture content at which water will drain from a soil by gravity.

Geocomposite Drainage material consisting of a geonet with high transmissivity sandwiched between two nonwoven geotextile filters.

Geomembrane Low permeability geosynthetic used in hydraulic barriers.

HDU Heat dissipation unit, a device used to measure soil suction.

Lysimeter Device used to measure the basal percolation through a saturated soil layer.

MCPR Maximum comparative percolation ratio, a percolation criterion relying on comparison of the performance of an evapotranspirative cover and a prescriptive cover.

Monolithic cover Evapotranspirative cover with a single layer of soil acting as a hydraulic barrier and vegetation substrate.

MPQV Maximum percolation quantitative value, a percolation criterion relying on comparison of the performance of an evapotranspirative cover with a selected basal percolation value.

Prescriptive cover Landfill cover prescribed by government regulations that limits percolation by maximizing overland runoff.

Richards' equation Governing equation for water flow through unsaturated porous media.

Suction Difference between the pore air pressure and pore water pressure.

TDR Time domain reflectometry, a device used to infer the soil volumetric moisture content.

Volumetric moisture content Volume of water in a soil divided by the total volume of the soil.

Porosity Ratio of the volume of voids and the total volume.

WCR Water content reflectometer, a device used to measure volumetric moisture content in the field based on TDR technology.

References

Albright, W.H. and Benson, C.H. (2002). *Alternative Cover Assessment Program 2002 Annual Report.* US EPA Publication No. 41182. 48 p.

Albright, W.H., Gee, G.W., Wilson, G.V., and Fayer, M. (2002). *Alternative Cover Assessment Program Phase 1 Report.* US EPA Publication 41183. 203 p.

Albright, W.H., Benson, C.H., Gee, G.W., Roesler, A.C., Abichou, T., Apiwantragoon, P., Lyles, B.F., and Rock, S.A. (2004). "Field water balance of landfill final covers." *Journal of Environmental Quality.* 33, 2317–2332.

Anderson, J.E., Nowak, R.S., Ratzlaff, T.D., and Markham, O.D. (1993). "Managing soil moisture on waste burial sites in arid regions." *Journal of Environmental Quality.* 22, 62–69.

Benson, C. and Gribb, M. (1997). "Measuring unsaturated hydraulic conductivity in the laboratory and field." In *Unsaturated Soil Engineering Practice.* Houston, S. and Wray, W. (eds). ASCE. Reston, VA. 113–168.

Benson, C., Abichou, T., Wang, X., Gee, G., and Albright, W. (1999). *Test section installation instructions — Alternative Cover Assessment Program.* Environmental Geotechnics Report 99-3, Department of Civil & Environmental Engineering, University of Wisconsin-Madison.

Benson, C., Abichou, T., Albright, W., Gee, G., and Roesler, A. (2001). "Field evaluation of alternative earthen final covers." *International Journal of Phytoremediation.* 3, 1–21.

Brooks, R.H. and Corey, A.T. (1964). "Hydraulic properties of porous medium." Colorado State University (Fort Collins). Hydrology Paper No. 3. March.

Burdine, N.T. (1953). "Relative permeability calculations from pore-size distribution data." *Petroleum Transactions of the American Institute of Mining and Metallurgical Engineering.* 198, 71–77.

Bussiere, B., Aubertin, M., and Chapuis, R. (2003). "The behavior of inclined covers used as oxygen barriers." *Canadian Geotechnical Journal.* 40, 512–535.

Cabral, A.R., Planchet, L., Marinho, F.A., and Lefebvre, G. (2004). "Determination of the soil water characteristic curve of compressible materials: Case study of de-inking residues." *ASTM Geotechnical Testing Journal.* 27(2): 154–162.

Campbell, G. (1974). "A simple method for determining unsaturated conductivity from moisture retention data." *Soil Science.* 117(6): 311–314.

Chandler, D.G., Seyfried, M., Murdock, M., and McNamara, J.P. (2004). "Field calibration of water content reflectometer." *Soil Science Society American Journal.* 68: 1501–1507.

Conca, J. and Wright, J. (1992). "Diffusion and flow in gravel, soil, and whole rock." *Applied Hydrogeology.* 1, 5–24.

Dell'Avanzi, E., Zornberg, J.G., and Cabral, A.R. (2004). "Suction profiles and scale factors for unsaturated flow under increased gravitational field." *Soils and Foundations.* 44, 1–11.

Dwyer, S.F. (1998). "Alternative landfill covers pass the test." *Civil Engineering.* ASCE. 68(9): 50–52.

Dwyer, S.F. (2003). *Water balance and computer simulations of landfill covers.* Doctoral thesis. The University of New Mexico. Albuquerque.

Fayer, M. and Jones, T.L. (1990). "UNSAT-H version 2.0: Unsaturated soil water and heat flow model." PNL-679, Pacific Northwest Laboratory, Richland, Washington.

Flint, A.L., Campbell, G.S., Ellet, K.M., and Calissendorff, C. (2002). "Calibration and temperature correction of heat dissipation matric potential densors." *Soil Science Society of America Journal.* 66, 1439–1445.

Forbes, P.L. (1994). "Simple and accurate methods for converting centrifuge data into drainage and imbibition capillary pressure curves." *The Log Analyst.* 35, 31–53.

Fredlund, D.G. and Xing, A. (1994). "Equations for the soil-water characteristic curve." *Canadian Geotechnical Journal.* 31, 521–532.

Gardner, R.A. (1937). "The method of measuring the capillary pressures in small core samples." *Soil Science.* 43, 277–283.

GeoSlope International Ltd. (2004). *Vadose/W Technical Overview.* Calgary, Canada.

Hassler, G.L. and Brunner, E. (1945). "Measurements of capillary pressure in small core samples." *Transactions of AIME.* 160, 114–123.

Hillel, D. (1998). *Environmental Soil Physics.* Academic Press. San Diego, CA.

Hutson, J.L. and Wagenet, R.J. (1992). "Leaching Estimation and Chemistry Model, LEACHM." New York State College of Agriculture and Life Sciences, Cornell University.

Kampf, M. and Holfelder, T. (1999). "Designing capillary barriers." *Seventh International Waste Management and Landfill Symposium.* CISA. Environmental Sanitary Engineering Centre, Sardinia. pp. 381–388.

Khire, M.V., Meerdink, J.S., Benson, C.H., and Bosscher, P.J. (1995). "Unsaturated hydraulic conductivity and water balance predictions for earthen landfill final covers." *Soil Suction Applications in Geotechnical Engineering Practice*, Geotechnical Special Publication No. 48. ASCE, 38–57.

Khire, M.V., Benson, C.H., and Bosscher, P.J. (1999). "Field data from a capillary barrier and model predictions with UNSAT-H." *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, 125, 518–527.

Khire, M., Benson, C., and Bosscher, P. (2000). "Capillary Barriers in Semi-Arid and Arid Climates: Design Variables and the Water Balance." *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, Vol. 126, No. 8, pp. 695–708.

Kiel, R.E., Chadwick, D.G., Lowrey, J., Mackey, C.V., and Greer, L.M. (2002). "Design of evapotranspirative (ET) covers at the Rocky Mountain Arsenal." *Proceedings: SWANA 6th Annual Landfill Symposium.*

Kim, K.C. and Benson, C.H. (2002), *Moisture Content Calibrations for Final Cover Soils*, University of Wisconsin-Madison Geotech. Eng. Report 02-12, Madison, WI, 122 p.

Klute, A. (1986). Water Retention: Laboratory Methods. *Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods* SSSA. Madison, WI. 635–662.

Kool, J.B. and Parker, J.C. (1987). "Development and evaluation of closed-form expression for hysteretic soil hydraulic properties." *Water Resources Research*, 23, 105–114.

Lu, N. and Likos, W.J. (2005). *Unsaturated Soil Mechanics.* Wiley. New York. 584 p.

McCartney, J.S. and Zornberg, J.G. (2002). "Design and performance criteria for evapotranspirative cover systems." *Fourth International Congress on Environmental Geotechnics.* Rio de Janeiro, Brazil.

McCartney, J.S. and Zornberg, J.G. (2005a). "The Centrifuge Permeameter for Unsaturated Soils (CPUS)." *Proceedings of the International Symposium on Advanced Experimental Unsaturated Soil Mechanics, Experus 2005.* Trento, Italy, June 27–29, A.A. Balkema, pp. 299–304.

McCartney, J.S., Kuhn, J.A., and Zornberg J.G. (2005b). "Geosynthetic drainage layers in contact with unsaturated soils." *16th ISSMGE Conference: Geotechnical Engineering in Harmony with the Global Environment.* 12–16 September 2005. Osaka, Japan.

Meerdink, J.S., Benson, C.H., and Khire, M.V. (1996). "Unsaturated hydraulic conductivity of two compacted barrier soils." *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, 122, 565–576.

Melchior, S. (1997). "In-situ studies of the performance of landfill caps (Compacted clay liners, geomembranes, geosynthetic clay liner, capillary barriers)." *Land Contamination and Reclamation.* 5, 209–216.

Meyer, P.D. and Gee, G.W. (1999). "Flux-based estimation of field capacity." *Journal of Geotechnical and Geoenvironmental Engineering.* 125, 595–599.

Monteith, J.L. (1965) "Evaporation and environment." *Symposia of the Society for Experimental Biology.*

Morris, C.E. and Stormont, J.C. (1997). "Capillary barriers and Subtitle D covers: Estimating equivalency." *Journal of Environmental Engineering, ASCE*, 123, 3–10.

Nachabe, M.H. (1998). "Refining the definition of field capacity in the literature." *Journal of Irrigation and Drainage Engineering.* 124, 230–232.

Nichol, C., Smith, L., and Beckie, R. (2003). "Long-term measurement of matric suction using thermal conductivity sensors." *Can. Geotech. J.* 40: 587–597.

Nimmo, J.R., Rubin, J., and Hammermeister, D.P. (1987). "Unsaturated flow in a centrifugal field: Measurement of hydraulic conductivity and testing of Darcy's law." *Water Resources Research.* 23, 124–134.

O'Kane, M., Wilson, G.W., and Barbour, S.L. (1998). "Instrumentation and monitoring of an engineered soil cover system for mine waste rock." *Canadian Journal of Geotechnical Engineering.* 35, 828–846.

Olson, R.E. and Langfelder, L.J. (1965). "Pore water pressures in unsaturated soils." *Journal of the Soil Mechanical and Foundation Division* ASCE, 91, 127–151.

Parent, S.E. and Cabral, A.R. (2004). Procedure for the design of inclined covers with capillary barrier effect. *Proc. 57th Canadian Geotechnical Conference*, Québec, October, 24–28.

Ridley, A.M. and Burland, J.B. (1995). "A pore pressure probe for the in-situ measurement of soil suction". *Proceedings of Conference on Advances in Site Investigation Practice.* I.C.E.:London.

Scanlon, B.R. and Milly, P.C.D. (1994). "Water and heat fluxes in desert soils 2. Numerical simulations." *Water Resources Research.* 30, 721–733.

Schroeder, P.R., Dozier, T.S., Zappi, P.A., McEnroe, B.M., Sjostrom, J.W., and Peyton, R.L. (1994). "The Hydrologic Evaluation of Landfill Performance (HELP) Model: Engineering documentation for Version 3, EPA/600/R-94/168b." US EPA Risk Reduction Engineering Laboratory, Cincinnati, OH.

Shackelford, C.D., Chang, C.-K., and Chiu, T.-F. (1994). "The capillary barrier effect in unsaturated flow through soil barriers." *1st ICEG Conference.* Edmonton, CA, pp. 789–793.

Siddiqui, S.I., Drnevich, V.I., and Deschamps, R.J. (2000). "Time domain reflectometry development for use in geotechnical engineering," *Geotechnical Testing Journal.* 23, 9–20.

Simunek, J., Sejna, M., and van Genuchten, M. 1998. *HYDRUS-1D: Code for Simulating the One-Dimensional of Water, Heat, and Multiple Solutes in Variably Saturated Porous Media.* Version 2.02. International Groundwater Modeling Center. Colorado School of Mines. Golden, CO.

Sisson, J.B., Gee, G., Hubbell, J.M., Bratton, W.L., Ritter, J.C., Ward, A.L., and Caldwell, A.C. (2002). "Advances in tensiometry for long-term monitoring of soil water pressures." *Vadose Zone Hydrology.* 1, 310–315.

Stormont, J. (1995). "The effect of constant anisotropy on capillary barrier performance." *Water Resources Res.* 32, 783–785.

Stormont, J.C. and Anderson, C.E. (1999). "Capillary barrier effect from underlying coarser soil layer." *Journal of Geotechnical and Geoenvironmental Engineering.* 125, 641–648.

Stormont, J.C. and Morris, C.E. (2000). "Characterization of unsaturated nonwoven geotextiles." In *Advances in Unsaturated Geotechnics: Proceedings of Sessions of Geo-Denver 2000.* Chang, N.-Y., Houston, S.L., and Shackelford, C.D. (eds) August 5–8, 2000. Denver, Colorado. pp. 153–164.

Suwansuwat, S. and Benson C.H. (1999). "Cell size for water content-dielectric constant calibrations for time domain reflectometry." *Geotechnical Testing Journal.* 22, 3–12.

Tarantino, A. and Mongiovì, L. (2003). "Calibration of tensiometer for direct measurement of matric suction." *Géotechnique.* 53, 137–141.

Topp, G., Davis, J., and Annan, A. (1980). "Electromagnetic determination of soil water content: Measurement in coaxial transmission lines." *Water Resources Research.* 16, 574–582.

Topp, G.C. and Miller, E.E. (1966). "Hysteretic moisture characteristics and hydraulic conductivities for glass-bead media." *Soil Science Society of American Proceedings.* 30, 156–162.

van Genuchten, M. (1980). "A closed-form equation for predicting the hydraulic conductivity of unsaturated soils." *SSSA.* 44, 892–898.

Wang, X. and Benson, C.H. (2004). "Leak-free pressure plate extractor for the soil water characteristic curve." *Geotechnical Testing Journal.* 27, 1–10.

Watson, K.K. (1996). "An instantaneous profile method for determining the hydraulic conductivity of unsaturated porous materials." *Water Resour. Res.*, 2, 709–715.

Waugh, W.J., Petersen, K.L., Link, S.O., Bjornstad, B.N., and Gee, G.W. (1994). "Natural analogs of the long term performance of engineered covers." *In situ Remediation: Scientific Basis for Current and Future Technologies*, Gee, G.W. and Wing, N.R. (eds), Battelle Press, Richland Washington. pp. 379–409.

Williams, J.R., Jones, C.A., and Dyke, P.T. (1984). "The EPIC model and its application." *Proceeding of ICRISAT-IBSNAT-SYSS Symposium on Minimum Data Sets for Agrotechnology Transfer*. March 1993.

Zornberg, J.G. and McCartney, J.S. (2003). *Analysis of monitoring data from the evapotranspirative test covers at the Rocky Mountain Arsenal.* Geotechnical Research Report, US Environmental Protection Agency, Region 8, December 2003, 227 p.

Zornberg, J.G., Jernigan, B.L., Sanglerat, T.R., and Cooley, B.H. (1999). "Retention of free liquids in landfills undergoing vertical expansion." *Journal of Geotechnical and Geoenvironmental Engineering.* ASCE, 125, 583–594.

Zornberg, J.G., LaFountain, L., and Caldwell, J.C. (2003). "Analysis and design of evapotranspirative cover for hazardous waste landfill." *Journal of Geotechnical and Geoenvironmental Engineering.* ASCE. 129, 427–438.

Further Information

Further information on the hydraulic properties of unsaturated soils may be found in Lu and Likos (2005). Descriptions of common techniques used to determine the SWRC can be found in Wang and Benson (2004) and the proceedings of *Experus* (2005). Descriptions of common techniques used to determine the K-function can be found in Benson and Gribb (1997). The ACAP Phase 1 report provides a comparative analysis of available numerical models for evapotranspirative cover performance evaluation, while the 2002 ACAP Annual Report provides a summary of field monitoring programs for evapotranspirative covers. An overview of current research topics in monitoring and analysis of evapotranspirative covers can be found in ASCE Geotechnical Special Publication 142 "Waste Containment and Remediation," held at GeoFrontiers 2005 in Austin, TX.