Appendix D

Capillary Barrier

D-1.0 CAPILLARY BARRIER

Capillary barriers, consisting of fine-over-coarse soil layers (Figure D-1.0-1), are another alternative cover system used in final landfill closures, especially in dry climates. Capillary barriers may be designed to take advantage of the hydraulic enhancements they offer, but at LANL they will only be used as a consequence of the inclusion of optional layers (i.e., biointrusion or gas vent layers) that result in a fine–over-coarse soil arrangement. Differences in pore size distribution between two soil layers cause infiltrated water to be retained in the upper soil layer under unsaturated flow conditions, as long as the contrast in unsaturated properties (e.g., soil-moisture characteristics and unsaturated hydraulic conductivities) of the soils in the two soil layers is sufficiently large (Dwyer 1997).

Figure D.1-1. Profile of capillary barrier

In general, the upper soil layer must consist of a soil exhibiting a significantly greater retention (matric potential) than the lower soil layer at the same water content (Figure D-1.0-2). Thus a capillary barrier effect results when a "relatively fine-grained soil" overlies a "relatively coarse-grained soil." The capillary pressure head in the fine-grained upper soil layer typically must approach a value near zero (i.e., saturated conditions) before any appreciable flow occurs into the lower coarse-grained layer (Dwyer 1997).

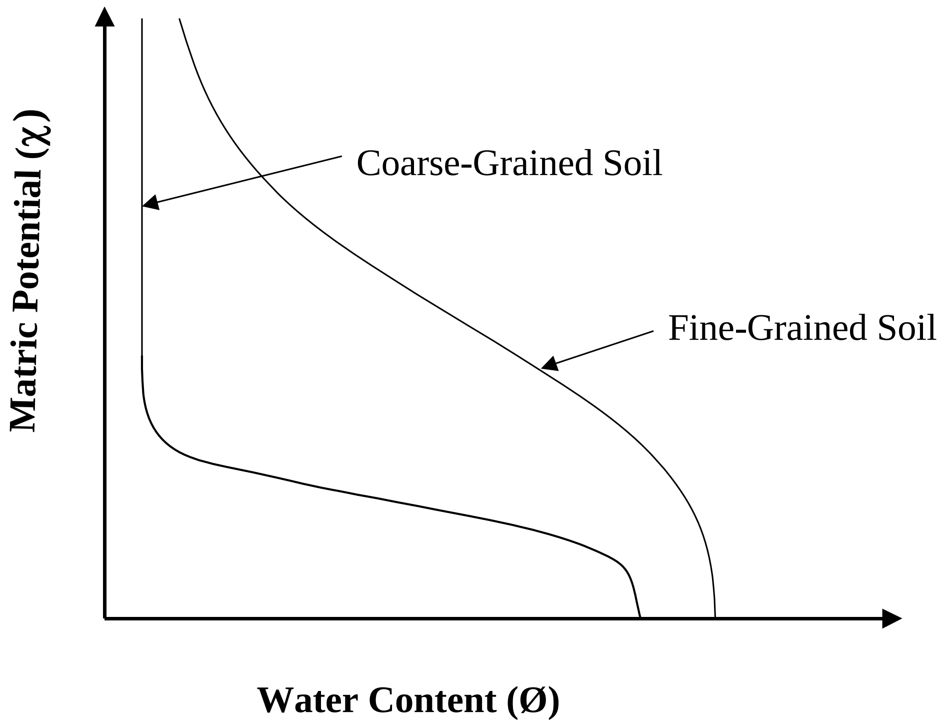

Figure D-1.0-2. Typical soil moisture characteristic curves for fine- and coarse-grained soils

The performance of a capillary barrier can be explained by considering Figure D-1.0-3. Beginning at relatively dry conditions, that is, at high suctions, the fine soil has a finite hydraulic conductivity, whereas the hydraulic conductivity of the coarse layer will be immeasurably small. With increasing water content and decreasing suction head, the hydraulic conductivity of the fine layer will increase gradually. The hydraulic conductivity of the coarse layer will remain immeasurably small until its water entry head is overcome. Under these conditions, water will not move from the fine layer into the coarse layer, but increase the water content of the fine layer. Breakthrough into the coarse layer occurs when the suction head at the contact equals the water entry head of the coarse layer. When the suction head decreases below this value, the hydraulic conductivity of the coarse layer will increase rapidly and eventually exceed that of the fine layer.

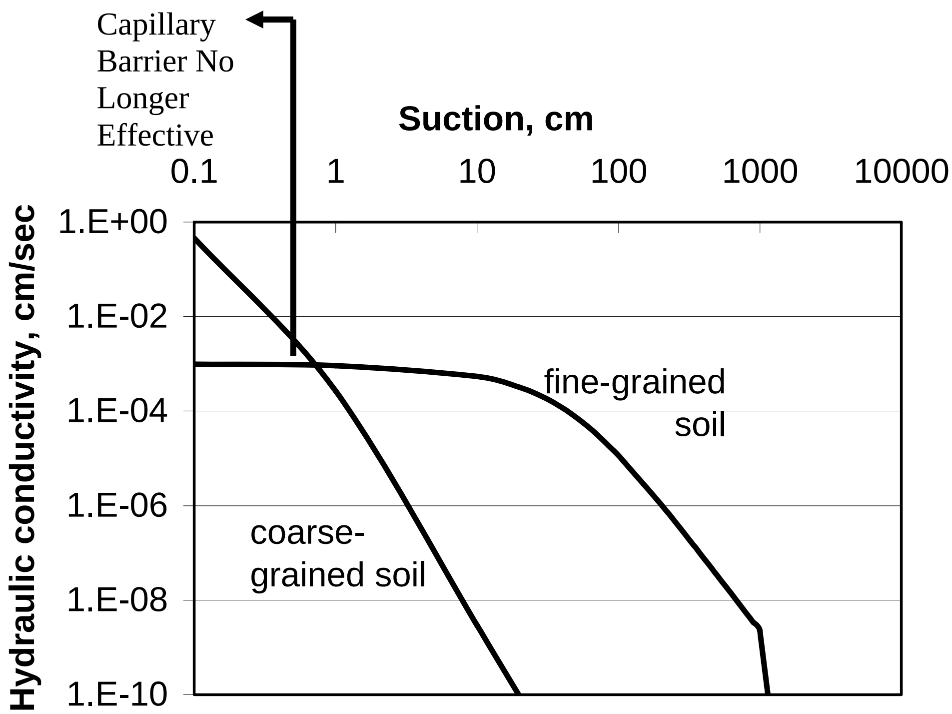

Figure D-1.0-3. Suction vs. hydraulic conductivity for fine- and coarse-grained soil

Soil-water is removed from a non-sloped capillary barrier system only by ET, or by percolation (breakthrough) into the underlying coarse layer. If the water storage capacity of the fine-textured soil layer is sufficient to store the expected infiltration at a particular site, then non-sloping capillary barriers can prevent vertical water movement (breakthrough) into the underlying waste.

The lateral movement of water in a sloped capillary barrier system shall be considered. Lateral diversion is essentially gravity-driven unsaturated drainage within the fine layer. Because the water content in the fine layer is usually greatest near its interface with the underlying coarse-textured soil layer, and the hydraulic conductivity of an unsaturated soil increases with water content, lateral diversion is concentrated near this interface. Laterally diverted water will result in increasing water content in the downdip direction. The diversion length is the distance which water is diverted along the fine/coarse interface before there is appreciable breakthrough into the coarse layer (Figure D-1.0-4).

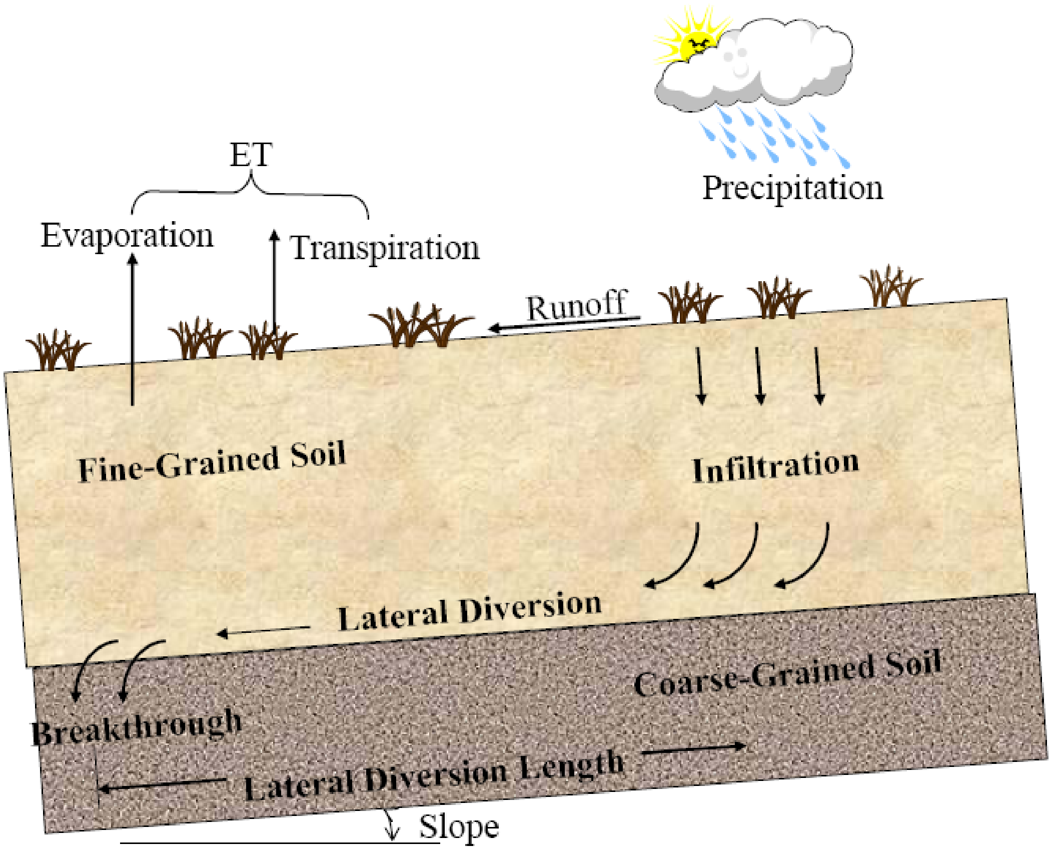

Figure D-1.0-4. Sloped capillary barrier

Advantages of incorporating a capillary barrier in a cover system include:

1. The fine-textured soil layer of a capillary barrier system will store more water than a comparable layer without the capillary break (i.e., a free-draining layer). Compared to a simple soil cover, the additional storage capacity will either serve to reduce overall percolation, or reduce the total thickness requirements of the overlying cover soil to yield the same degree of percolation inhibition.

2. The additional water stored within a capillary barrier system will tend to encourage the establishment and development of the surface vegetation. The increased vegetation cover, in turn, will remove more soil-water due to greater ET. Furthermore, plants serve an important function in reducing surface erosion.

3. In addition to providing the capillary break, the coarse layer of the capillary barrier system can serve as a biointrusion barrier and/or gas collection layer.

Disadvantages of incorporating a capillary barrier system into a landfill cover system include:

1. Significant desiccation cracking in the fine-textured soil layer can be detrimental to a capillary barrier system. Every reasonable effort shall be made to avoid desiccation cracking (e.g., compacting the soil “dry of optimum” rather than ”wet of optimum”; use soils that are less susceptible to desiccation cracking, such as sandy silts or silty sands rather than clay).

2. A capillary barrier system may not be effective in wetter climates or where appropriate soil materials are not readily available.

3. Slope can be an advantage in laterally diverting water but, in turn, can be a huge disadvantage if the diversion length of the cover system is inadequate, thereby resulting in significant breakthrough. If a capillary barrier system is sloped, the two-dimensional (lateral and vertical) effects of soil-water movement must be taken into account.

4. Differential settlement can introduce significant discontinuities in the fine-over-coarse soil layer interface, thus rendering the capillary barrier system less effective. This is especially true for sloped capillary barrier systems.

5. Costs are generally higher for a capillary barrier than an ET cover (Dwyer 1998).

6. Construction can be more difficult to build a capillary barrier than an ET cover (Dwyer 2000).

Figures D-1.0-5 and D-1.0-6 show pictures of capillary barrier cover systems. Figure D-1.0-5 is a capillary barrier over a hazardous waste site that is a Superfund closure in Farmington, New Mexico. Figure D-1.0-6 is a capillary barrier cover system at RMA in Denver, Colorado.

Figure D-1.0-5. Capillary barrier under construction on Superfund site, Farmington, NM

Figure D-1.0-6. Capillary barrier over contaminated site at RMA, Denver, Colorado

D-2.0 DESIGN CONSIDERATIONS FOR A CAPILLARY BARRIER

Design considerations for the fine-textured soil layer of the capillary barrier system include all of those listed for the ET cover system. In general, the capillary barrier enhances the water storage capacity of the fine-textured soil layer. Consequently, this layer will not need to be as thick as that in an ET cover system. In fact, the fine-textured soil layer must be thick enough to store infiltrating water, yet thin enough so that all of the stored water can later be removed via ET. Thus the design considerations for a capillary barrier involve determining the proper fine-textured soil layer thickness and slope gradient to minimize the percolation of water through this layer. In general, layer thickness and slope gradient requirements depend on climatological information for the specific site (e.g., precipitation, temperature, and humidity) and the characteristics of the soils used in the cover (e.g., water storage capacity, hydraulic conductivity, and texture). Other factors that shall be taken into consideration include such things as slope stability, vegetation characteristics, and desiccation (Dwyer 1997).

D-2.1 Selection of Soils

D-2.1.1 Fine Soil Layer

The soil used for the fine layer or cover layer will often be the near-surface soil (topsoil) stockpiled during clearing and preparation of the site, or material taken from a nearby borrow pit. Important considerations in the design and performance of the cover layer are its ability to serve as a rooting medium, the soil-water storage capacity, as well as the cover's lateral diversion capacity (when designing a sloped capillary barrier system).

Rooting medium – Plants generally play an essential role in the stability and performance of a cover system. Beyond the logistical and economic constraints of importing a non-local soil, the use of soils similar to those of the surroundings has merit from the consideration of its function as a rooting medium for native plants. Each site has a characteristic climax plant community (that is, the species and density of plants that are best suited for the particular climate, soil, and topography). It is probable that regardless of the initial condition of a plot of ground (from bare to vegetated), the climax community will eventually be established. Thus using local soil should result in more predictable vegetation, consistent with vegetation that has evolved naturally for that location. While it is possible to amend a soil to improve its characteristics as a rooting medium, any additional processing or amendments will increase costs.

Water storage capacity – The water storage capacity of the cover layer soils depends upon the physical characteristics of the soil and the presence of the underlying capillary break. The water storage capacity of a capillary barrier can be estimated from the soil moisture characteristic curve of its fine soil layer to indicate the additional storage capacity as a result of the underlying capillary break (Stormont and Morris 1998). The texture of this overlying fine soil is important in determining the additional water storage capacity. The water storage capacity of a capillary barrier was measured in a field-scale (14 m^2 surface area) water balance experiment (Stormont 1996). In this test, a 900-mm-thick silty sand was placed over a uniform gravel to form a capillary barrier. The water content in the fine layer was measured as water was added at a constant rate of about 10 mm/day. Breakthrough into the coarse layer was detected by collecting water that drained from the coarse layer. The water content in the fine layer at breakthrough was about 40% by volume near the interface. The total amount of water stored in the capillary barrier at breakthrough was estimated by integrating the measured water content over the thickness of the fine layer. Expressed as a normalized quantity with respect to area (volume of water divided by surface area), the capillary barrier stored 285 mm of water at breakthrough. The storage capacity of the capillary barrier can be compared to that estimated for a simple monolithic soil cover. Without the capillary break, water will drain approximately to a characteristic water content of a soil termed its field capacity or drained upper limit. The field capacity for the same soil (silty sand) is estimated at 20%. By integrating this water content over the same 900-mm thickness, the silty sand in a simple soil cover configuration would be expected to store about 180 mm of water before it drained. Thus an additional 105 mm of water storage was gained by the capillary break for the same cover soil thickness. Alternatively, a simple soil cover would need to be about 1425 mm thick to store the same amount of water as 900 mm of the same soil in a capillary barrier configuration.

The type of soil used for the fine or cover soil layer affects the water storage capacity of a capillary barrier. A finer-grained soil is expected to store more water than a more coarse-grained soil in a comparable configuration. The difficulty with soil selection is that one is normally governed by available local soils. Desiccation cracking in the fine layer of a Capillary barrier system would be detrimental and shall be avoided. Silty sands or sandy silts, although their water-holding capacity may be less than a clay and consequently require a thicker overlying fine soil layer, will be less vulnerable to desiccation cracking. Compacting the fine layer "dry of optimum" rather than "wet of optimum," as recommended with resistive clay barriers, should also help minimize the chance for desiccation cracking as well as having a lower initial moisture content, thus increasing its initial excess water storage capacity.

Lateral diversion – The lateral diversion capacity of the fine layer is dependent in large part on the hydraulic conductivity of the fine layer. In general, the hydraulic conductivity of clays, silts, and loams is too low to permit appreciable lateral diversion. Field tests of capillary barriers with homogeneous fine layers indicate the effective diversion lengths are less than 10 m (Nyhan et al. 1990b), Hakonson et al. 1994, Stormont 1995, Stormont 1996). These short diversion lengths are a consequence of the relatively low hydraulic conductivity of the fine-grained soils compared to the infiltration rate during stressful periods when the soil is relatively wet (e.g., spring snowmelt). Thus soils that are often preferred as a rooting medium and for their water storage capacity (e.g., loams and silts) may not be conductive enough to substantially divert soil-water laterally.

Utilizing “transport layers” or “unsaturated drainage layers” within the fine layer (Stormont 1995) can increase the diversion capacity of capillary barriers. Transport layers are one or more relatively conductive layer(s) that drain water laterally within the cover’s fine soil layer while remaining unsaturated. Because soil-water tends to accumulate near the fine/coarse interface and unsaturated hydraulic conductivity increases with water content, a transport layer near the interface is most effective in laterally diverting water. Lateral diversion can be designed into a capillary barrier by means of a relatively thin (e.g., <300-mm) transport layer placed at the fine/coarse interface. The transport layer shall be relatively fine-grained, uniform sand that possesses as great a hydraulic conductivity as possible under low to moderate values of suction head. The lateral diversion afforded by a transport layer will complement the water storage function of the overlying soil, expanding the conditions and climate for which a capillary barrier could be effective.

D-2.1.2 Coarse Soil Layer

The coarse layer soil could range from coarse sand to cobbles. The primary function of the coarse layer is to form a capillary break, but it may also serve as a biointrusion barrier or a gas collection layer.

Capillary break – The movement of water from the overlying layer into the underlying layer is controlled by the water entry suction of the underlying layer. The water entry suction is the suction associated with the movement of water into the smallest pores that form a continuous network. Water will not move from an initially dry medium at suctions larger than the water entry suction of the underlying layer. Minimizing the water entry suction gradient delays the movement of water from the overlying fine layer into the coarse layer, permitting more water to be stored in the fine layer near the interface. The water entry head can be roughly approximated by the height of capillary rise within a soil (Hillel and Baker 1988). Thus the water entry head is expected to be small for a uniform coarse-grained soil and increase as the amount of fines in the soil increases.

D-2.2 Stability of the Fine-Over-Coarse Soil Layers

In general, the effectiveness of a capillary break is increased with an increased contrast in texture or particle-size distribution of the fine and coarse materials (Stormont 1997). There is concern, however, that fine soil particles will move into the pores of the coarse soil, degrading the interface and reducing the effectiveness of the capillary break. The conventional approach for evaluating the stability of the fine-over-coarse system is to ensure the soils satisfy soil retention or filtering criteria. Although a large number of criteria have been developed, most are similar in that they are based on some measure of the particle-size distributions of the fine and coarse soils. The following criterion is widely used:

$$\frac{D_{15}}{d_{85}} \leq 5$$ **Equation D-1**

where:

D_{15} = particle size of the coarse soil for which 15% of the particles are finer,

d_{85} = particle size of the fine soil for which 85% of the particles are finer.

From conventional criteria, interface stability is favored by soils having similar particle-size distributions, apparently in conflict with maximizing the effectiveness of a capillary break. Conventional criteria, however, have been developed using high hydraulic gradients for applications such as dams. In contrast, capillary barriers would only rarely, if ever, experience positive pore pressures, and the associated hydraulic gradients would be small. Furthermore, capillary barriers will be subjected to cycles of wetting and drying in response to climatic conditions. Thus interface stability shall be considered under dry conditions, as well as under relatively small positive water pressures.