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UNSATURATED DRAINAGE LAYERS FOR DIVERSION OF INFILTRATING WATER

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ABSTRACT: An approach for draining water from unsaturated soil is presented that utilizes a sloping system of a fine sand overlying a coarser sand or gravel. In this configuration, referred to as an unsaturated drainage layer, the sand laterally drains water that accumulates above the capillary break provided by the coarse material. Drainage capacity is maximized when the sand layer has sufficient moisture to be relatively conductive, yet remains unsaturated so as to prevent failure of the capillary break. Results from field tests indicate substantial downward infiltrating water can be laterally diverted with an unsaturated drainage layer. Numerical simulations are presented that illustrate the potential effectiveness of unsaturated drainage layers to divert sufficient infiltrating water and prevent the development of positive pore water pressures.

INTRODUCTION

Drainage of water from soils is typically considered as a saturated flow process, however, there are a number of applications where it would be beneficial if water could be diverted out of the system while the soil pore water pressures remain negative. For example, capillary barriers are being evaluated as components of surface cover systems to limit infiltration into underlying wastes. The capillary break afforded by these fine-over-coarse soil systems functions as a barrier to downward water flow as long as the fine layer does not approach saturation. Consequently, if water infiltrating into the fine layer could be laterally drained before the soil becomes saturated, the barrier's integrity would be preserved. Another application for unsaturated soil drainage is in areas where stability is of concern. It may be desirable to promote unsaturated soil drainage to eliminate, or at least reduce, positive pore water pressures and associated failures. Design procedures for problems of this type, such as embankments and retaining walls, often include provisions for drainage but not until the soil has become saturated. Stability may be enhanced if drainage would maintain only negative water pressures in the soil, or if the location of saturated soil conditions is minimized. In this paper a method to drain substantial amounts of water under unsaturated conditions is described.

Lateral water movement (drainage) in unsaturated soils can occur when downward moving water encounters dipping layers of different properties as described by Miyazaki (1988). This process is enhanced if the overlying soil is finer than the underlying soil and a capillary break is formed. In this case water will accumulate near the fine-coarse interface, and because hydraulic conductivity of an unsaturated soil increases with water content, lateral drainage will be concentrated in this region. For the common case where the infiltrating water is horizontally distributed across the fine layer and is not a point source, the soil moisture content will increase in the down-dip direction due to the lateral diversion of the downward moving water at the interface. A distance termed the drainage or diversion length is commonly used to describe the length along the fine-coarse interface that water is diverted before the soil moisture content increases to the point where appreciable

breakthrough into the underlying soil occurs as shown in Fig. 1(a).

A simple scheme to promote unsaturated soil drainage is to incorporate a sloped coarse-grained layer within a soil profile to create a capillary break and promote lateral drainage in the overlying soil [Fig. 1(a)]. The effectiveness of this approach will depend on the unsaturated transport properties of the overlying soil, the contrast between the fine- and coarse-grained layers, and the infiltration rate. In general, the lateral diversion lengths of these fine-over-coarse systems are relatively short [less than 10 m, e.g., Nyhan et al., (1990)] when typical near-surface soils such as loams and silts are used as the fine layer. The relatively low hydraulic conductivities of these soils limits the amount of water that can be transported under unsaturated conditions, and thus limits lateral drainage capabilities.

The unsaturated drainage of soils can be increased substantially by placing an intermediate layer such as a fine-grained sand between the overlying soil and the underlying coarse material [Fig. 1(b)]. The combined intermediate and coarse material form what will be referred to as an unsaturated drainage layer. The intermediate material should be conductive enough to laterally divert or drain downward moving water, yet remain unsaturated so as to preserve the capillary break with the underlying coarse material. In this paper the functional performance of an unsaturated drainage layer is explained, and experimental evidence of its effectiveness is provided. Results from numerical simulations are given to suggest the potential of this drainage concept.

UNSATURATED DRAINAGE LAYER

The hydraulic conductivity as a function of negative pore water pressure head is given in Fig. 2 for soils consistent with

FIG. 1. Lateral Drainage in Unsaturated Soils Due to: (a) Simple Capillary Break; (b) Inclusion of Intermediate Material to Form Unsaturated Drainage Layer

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FIG. 2. Hydraulic Conductivity versus Negative Pore Water Pressure Head for Soil, Sand, and Gravel; Hydraulic Conductivities Were Calculated from Measured Moisture Characteristic Curves and Saturated Hydraulic Conductivities (Stormont 1995)

the soil profile shown in Fig. 1(b). Assume that the system is in equilibrium under initially dry conditions, that is, with high negative pore water pressure heads. As water infiltrates into the fine soil, its negative pore water pressure head will decrease. When the negative pore water pressure head at the soil-sand interface has decreased to about 300 mm, the hydraulic conductivity of the sand is greater than that of the soil and can accommodate as much water as the soil can provide. Because the sand is underlain by the gravel, it will retain all of the infiltrating water until the negative pore water pressure head decreases to about 10 mm (the water entry head of the gravel) when breakthrough into the gravel will occur. Though the sand is in a relatively conductive state it is still unsaturated (over the range 300 to 10 mm of negative pore water pressure for the system described in Fig. 2), and can effectively drain water by gravity if the layer is sloped.

Fig. 2 suggests that the unsaturated drainage layer should possess as large a hydraulic conductivity as possible under low to moderate values of negative pore water pressure head when compared to the overlying soil. The unsaturated drainage layer is especially effective in removing moisture when the corresponding negative pore water pressure head is in the region between points A and B in Fig. 2. This region is bounded approximately by the intersections of the unsaturated drainage layer hydraulic conductivity function with the hydraulic conductivity functions for the overlying soil and the underlying coarse material.

CAPACITY OF UNSATURATED DRAINAGE LAYERS

Experiments Illustrating Capacity of Unsaturated Drainage Layers

Experimental evidence of the effectiveness of unsaturated drainage layers is provided from a series of water balance tests conducted on 7-m long fine-over-coarse systems (capillary barriers) sloped at 5% and 10%. These tests investigated many aspects of capillary barrier performance, including unsaturated water movement within various capillary barrier designs. Only a brief summary of the experiments and results that illustrate

the unsaturated drainage layer concept are presented here. A complete description of the tests and results are given elsewhere (Stormont 1995, 1996). The barriers consisted of a 900-mm thick fine layer over a 250-mm thick coarse gravel layer. For each grade two designs were constructed. One barrier consisted of a homogeneous fine layer comprised only of a silty sand. The fine layer of the other barrier consisted of alternating 100-mm thick layers of a fine-grained, uniform sand and 200-mm thick layers of silty sand. The first layer on top of the gravel was sand, followed by the silty sand, and so on. Only the bottom sand layer was underlain by a coarse material, and thus can be considered an unsaturated drainage layer as defined here. To stress the barriers, water was added to the top of each profile at a constant rate of 5 mm/day and 10 mm/day for the barriers on 5% and 10% grade, respectively. Measurements were made of water storage and lateral diversion in the fine layer, and breakthrough into the coarse layer.

In both tests the homogeneous capillary barrier failed with infiltrating moisture flowing into the underlying coarse soil, whereas this moisture was completely diverted laterally in the layered barriers and no breakthrough occurred. The layered barriers also contained less water than the homogeneous barriers at the conclusion of the tests, indicating that the drainage layer not only prevented system failure but also aided in reducing the overall fine soil moisture content during the test period. In addition the tests identified the bottom sand layer as the principal location where water was laterally diverted, with the upper sand layers diverting only small amounts of water.

Numerical Simulations of Unsaturated Drainage Layer Capacity

Field tests are invaluable, but are expensive, time-consuming, and applicable principally to the site-specific configuration and climatic conditions. A modeling approach developed by Morris and Stormont (1997a) that accounts for near-surface, climate-dependent processes as well as transient, unsaturated flow was used to extend this concept to different climatic conditions and configurations. This numerical approach has been demonstrated to satisfactorily simulate unsaturated water movement associated with capillary barriers, including reasonably reproducing the previously described field tests (Morris and Stormont 1997b). Complete description of the numerical procedures are given in Morris and Stormont (1997a).

To illustrate the behavior of an unsaturated drainage layer, simulations were made of water movement through a 2.3-m thick soil profile, consisting of a 0.3-m thick drainage layer sloped at 5% sandwiched between two 1-m thick layers of a silty sand. The modeled geometry as shown in Fig. 3 could represent a portion of a fill behind a retaining wall or within an embankment, or other situations where positive pore water pressures may be of concern. For the drainage layer we considered four possibilities: (1) soil (i.e., no drainage layer); (2) a sand layer, which represents a conventional drainage layer suitable for positive pressures; (3) a gravel layer, which forms a capillary break with the overlying silty sand; and (4) a gravel layer with an overlying sand layer, which constitutes an unsaturated drainage layer. At the base of the silty sand is a silt layer with a lower saturated hydraulic conductivity ($<10^{-6}$ mm/s).

Simulations were conducted for a three-year duration using daily varying climatic conditions representative of San Francisco, Calif. During the second year, the 100-yr annual precipitation (812 mm) was imposed. The precipitation for the first and third years was 469 and 327 mm, respectively. An evaporative zone depth of 500 mm and potential ET associated with a fair stand of grass was assumed. The soil, sand, and

Composition of Drainage Layer			
Case	Soil	Sand	Gravel
No Drainage Layer	✓		
Conventional Drainage Layer		✓	
Capillary Break			✓
Unsaturated Drainage Layer		✓	✓

FIG. 3. Model Used in Numerical Simulations of Various Drainage Layers

FIG. 4. Pore Water Pressures that Develop Beneath Drainage Layers Comprised of Unsaturated Drainage Layer (○), a Capillary Break (—), Sand (×), and Soil (●)

gravel properties are those for the materials represented in Fig. 2.

Results from these simulations are given in Fig. 4 as pore water pressure (in mm) as a function of time at the 2.3 m depth (point A in Fig. 3). The seasonal variation associated with San Francisco's wet winters and dry summers is reflected in the predicted pore water pressures for all of the configurations except that of the unsaturated drainage layer. Positive pore water pressures develop in years 2 and 3 for the configurations that use soil and sand as the drainage layer, and in year 2 for the gravel drainage layer (capillary barrier). A conventional drain (i.e., a sand layer) at point A may dissipate large pore water pressures, but the soil would still reach saturation and perhaps experience related deleterious effects. The unsaturated drainage layer, in contrast, diverts all downward infiltrating water laterally and nearly constant negative pore water pressures are maintained in the underlying soil.

CONCLUSIONS

An unsaturated drainage layer, defined as a sloped system of a relatively conductive sand layer overlying a coarse layer that forms a capillary break, can be an effective means to prevent or minimize positive pore water pressures from developing in soils in response to infiltration. The sand layer laterally drains water that has accumulated above the capillary break. Drainage capacity is maximized when the sand layer has sufficient moisture to be relatively conductive yet remains unsaturated so as to prevent failure of the capillary break. Field tests have demonstrated the capacity of unsaturated drainage layers comprised of a fine-grained, uniform sand layer overlying a gravel layer to effectively intercept and laterally divert infiltrating water. Simulations of infiltration into a soil profile subjected to a three year duration of daily varying climatic conditions representative of San Francisco, Calif., were conducted as an illustrative example. The unsaturated drainage layer was effective at diverting the infiltrating water, and in preventing positive pore water pressures (saturation) from developing beneath the drainage layer. Future efforts will be directed toward investigation of specific applications of unsaturated drainage layers.

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