Vadose Zone Modeling with VADOSE/W 2007

An Engineering Methodology

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1 Introduction

The flow of water through soil is one of the fundamental issues in geotechnical and geo-environmental engineering. In fact, if water were not present in the soil, there would not be a need for geotechnical engineering. This is a nonsensical statement: if there were no water in the soil, there would be no way to sustain an ecosystem, no humans on earth and no need for geotechnical and geo-environmental engineering. However, the statement does highlight the importance of water in working with soil and rock.

Flow quantity is often considered to be the key parameter in quantifying seepage losses from a reservoir or determining the amount of water available for domestic or industrial use. In engineering, the more important issue is the pore-water pressure. The emphasis should not be on how much water is flowing through the ground, but on the state of the pore-water pressure in the ground. The pore-water pressure, whether positive or negative, has a direct bearing on the shear strength and volume change characteristics of the soil. Research in the last few decades has shown that even the flow of moisture in the unsaturated soil near the ground surface is directly related to the soil suction (negative water pressure). So, even when flow quantities are the main interest, it is important to accurately establish the pore-water pressures.

In the past, the analyses related to groundwater have concentrated on saturated flow. As a result, flow problems were typically categorized as being confined and unconfined situations, such as confined or unconfined aquifers. Flow beneath a structure would be a confined flow problem, while flow through a homogeneous embankment would be unconfined flow. Historically speaking, unconfined flow problems were more difficult to analyze because the analysis required determining the phreatic surface. The phreatic surface was considered an upper boundary and any flow that may have existed in the capillarity zone above the phreatic line was ignored.

It is no longer acceptable to take a simplified approach and ignore unsaturated flow above the phreatic surface. Not only does it ignore an important component of moisture flow in soils, but it greatly limits the types of problems that can be analyzed. It is mandatory to deal with unsaturated flow in typical situations such as modeling infiltration of precipitation. Transient flow problems are another good example. It is nearly impossible to model a situation where a wetting front moves though an earth structure without correctly considering the unsaturated component of flow. Fortunately, it is no longer necessary to ignore the unsaturated zone. With the help of this document and the associated software, unsaturated flow can be considered in numerical modeling and the door is opened to analyzing almost any kind of seepage problem.

The term *seepage* usually refers to situations where the primary driving force is gravity controlled, such as establishing seepage losses from a reservoir, where the driving force is the total hydraulic head difference between the entrance and exit points. Another cause of water movement in soils is the existence of excess pore-water pressure due to external loading. This type of water flow is usually not referred to as seepage, but the fundamental mathematical equations describing the water movement are essentially identical. As a result, a software formulation for the analysis of seepage problems can also be used to analyze the dissipation of excess pore-water pressures resulting from changes in stress conditions. In the context of the discussions and examples in this document and in using the VADOSE/W software, the term seepage is used to describe all movement of water through soil regardless of the creation or source of the driving force or whether the flow is through saturated or unsaturated soils.

Balancing the sun's energy at the ground surface

The energy from the sun drives the physical processes that occur at the ground surface. Figure 1-1 shows a brief example of how this energy is balanced within VADOSE/W.

The sun's energy is driving the evaporation and transpiration processes. The following example describes how this energy may be distributed and accounted for in VADOSE/W.

Let us assume the sun applies an energy of 20 MJ/day/m^2 to the ground surface. This energy is the equivalent of approximately 8.15 mm/day of potential evaporated water (VADOSE/W will calculate the actual value based on climate data or the user can input this value if they have measured data).

If a combination of plants and bare ground exists at the surface, then this energy must be partitioned between the two. Assume the Leaf Area Index function for the plants indicates that there is significant but not total leaf coverage of the surface. Based on relationships discussed in subsequent pages of this manual, VADOSE/W determines that, for example, 6 mm/day of Potential Energy is intercepted by the plants and 2.15 mm/day is intercepted by the ground.

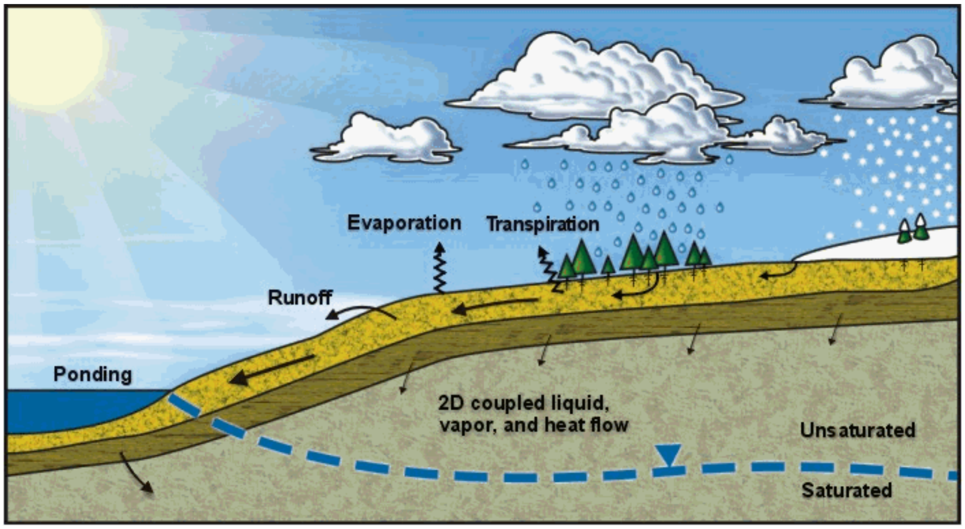

Figure 1-1 **Physical processes relating to seepage**

Now assume the ground is not fully saturated at the surface. Because it is not saturated, the ground can not give up water to the sun at the full potential rate. Based on the Penman-Wilson (1990, 1994) method, VADOSE/W determines that of the 2.15 mm/day Potential Evaporation, only 1.15 mm/day actually evaporates (AE).

Assuming in addition, that the ground beneath the surface is not fully saturated, the plant moisture limiting function, which deals with wilting pore pressures among other things, is used by the program to determine that the plant roots can only transpire 3 mm/day of the potential 6 mm/day intercepted by the leaves on surface.

So, we have 8.15 mm/day of potential evaporative energy (PE) being demanded at the ground surface and only 1.15 mm/day actually evaporates (AE). The plants were able to transpirate 3mm/day (AT). The question that remains is; what happened to the other 4 mm/day?

Since we must balance the energy, we can not ignore this 4 mm/day. It is the extra 4 mm/day of previously unaccounted energy that results in heating of the ground surface.

VADOSE/W accounts for all of these physical processes based on first principle physics. The user is not required to make any assumptions about how the energy is partitioned or applied.

Actual evaporation

The key to geotechnical modeling of the vadose zone is the ability to accurately predict the surface boundary condition. The most significant variable to quantify is the magnitude of surface infiltration and actual evaporation, or in modeling terms, the surface unit flux boundary. VADOSE/W determines this value by coupling the moisture and heat stress states at the ground surface with climate conditions present above the ground surface. Vapor flow in the soil is mandatory and is included in VADOSE/W.

It is not acceptable to have actual evaporation (AE) computed as a function of drying time or soil water content. Actual evaporation must be computed as a function of soil surface negative water pressure; a stress state variable. VADOSE/W is currently the only numerical 2D model capable of calculating AE based on first principle physical relationships, not empirical AE formulations that are developed for unique soil types, soil moisture conditions, or climate parameters.

Typical applications

Typical applications for VADOSE/W include:

- designing single or multi layered soil covers over mine waste and municipal landfill disposal sites;
- obtaining climate controlled soil pore pressures on natural slopes or man made covered slopes for use in stability analysis;
- determining infiltration and evaporation and plant transpiration from agricultural irrigation projects etc.
- VADOSE/W can be used wherever accurate surface boundary conditions are required.

1.1 Overview of this book

Modeling the flow of water through soil with a numerical solution can be very complex. Natural soil deposits are generally highly heterogeneous and non-isotropic. In addition, boundary conditions often change with time and cannot always be defined with certainty at the beginning of an analysis; in fact, the correct boundary condition can sometimes be part of the solution. Furthermore, when a soil becomes unsaturated, the coefficient of permeability or hydraulic conductivity becomes a function of the negative pore-water pressure in the soil. The pore-water pressure is the primary unknown and needs to be determined, so iterative numerical techniques are required to match the computed pore-water pressure and the material property, which makes the solution highly non-linear. These complexities make it necessary to use some form of numerical analysis to analyze seepage problems for all, but the simplest cases. A common approach is to use finite element formulations and VADOSE/W, the subject of this book, is an example of a numerical software tool.

While part of this document is about using VADOSE/W to do seepage analyses, it is also about general numerical modeling techniques. Numerical modeling, like most things in life, is a skill that needs to be acquired. It is nearly impossible to pick up a tool like VADOSE/W and immediately become an effective modeler. Effective numerical modeling requires some careful thought and planning, and it requires a good understanding of the underlying fundamental physical concepts. Aspects such as discretization of a finite element mesh and applying boundary conditions to the problem are not entirely intuitive at first. Time and practice are required to become comfortable with these aspects of numerical modeling.

A large portion of this book focuses on the general guidelines of how to conduct effective numerical modeling. Chapter 2, Numerical Modeling: What, Why and How, is devoted exclusively to discussions on this topic. The general principles discussed apply to all numerical modeling situations, but are used in the context of seepage analyses in this document.

Broadly speaking, there are three main parts to a finite element analysis. The first is discretization: dividing the domain into small areas called elements. The second part is specifying and assigning material properties. The third is specifying and applying boundary conditions. Separate chapters have been devoted to each of these three key components within this document.

Part of the Analysis Settings chapter is dedicated to using VADOSE/W in a one dimensional mode. There are unique model settings that will help with the numerical solution when the mesh is a one dimensional column. There are also a few key concepts to understand regarding runoff and lateral flow that have significance in this 1D mode.

Saturated and unsaturated seepage numerical modeling is a highly non-linear problem that requires iterative techniques to obtain solutions. Numerical convergence is consequently a key issue. Also, the temporal integration scheme, which is required for a transient analysis, is affected by time step size relative to element size and material properties. These and other numerical considerations are discussed the chapter called Numerical Issues.

One chapter is dedicated to presenting and discussing illustrative examples.

A full chapter is dedicated to theoretical issues associated with climate-ground coupling and the finite element solution of the partial differential flow equation for saturated and unsaturated heat and water flow in soils. Additional finite element numerical details regarding interpolating functions and infinite elements are given in Appendix A.

The chapter entitled “Modeling Tips and Tricks” should be consulted to see if there are simple techniques that can be used to improve your general modelling method or to help gain confidence and develop a deeper understanding of finite element methods, VADOSE/W conventions or data results. It also contains a checklist of key vadose zone modeling issues that you can print out and use to check that you are on the right path to solving a successful model.

In general, this book is not a HOW TO USE VADOSE/W manual. This is a book about how to model. It is a book about how to engineer seepage problems using a powerful calculator; VADOSE/W. Details of how to use various program commands and features are given in the on line help inside the software.