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ESTIMATION OF UNSATURATED SOIL PROPERTIES USING A KNOWLEDGE-BASED SYSTEM

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ABSTRACT

The Soil-Water Characteristic Curve (SWCC) is an important soil function relating the water content of a soil to soil suction. Many unsaturated soil properties (or soil property functions) can be related to the water content versus suction relationship of a soil. Hydraulic conductivity, shear strength, chemical diffusivity, water storage, unfrozen volumetric water content, specific heat, and thermal conductivity are all functions of the Soil-Water Characteristic Curve. Considerable judgment is required to develop the relationship between soil property functions. The judgment rules can be enforced using a knowledge-based system based on observations and empirical relationships amongst soil property functions. A knowledge-based system was developed using a relational database management system (RDBMS) known as Microsoft's Access® database program. Access® provided a suitable environment for combining the user interface, knowledge base, database, and query system. This system provides an estimate of the Soil-Water Characteristic Curve as well as the other unsaturated property functions using basic soil classification data such as the grain-size distribution, density and specific gravity. The system allows the estimation of many complex soil properties while reducing both time and cost requirements.

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1.0 INTRODUCTION

Theory governing the behavior of unsaturated soils has been available for several years and has shown that the Soil-Water Characteristic Curve is the central relationship describing how a soil behaves as it desaturates. Research has shown that empirical relationships can be used to describe unsaturated property functions related to the Soil-Water Characteristic Curve. These empirical relationships can then be used to predict the permeability, shear strength, thermal properties, and diffusion properties as a soil desaturates. The principles related to the behavior of a soil are encoded into the knowledge-based system. The process for predicting the behavior of an unsaturated soil is then greatly simplified. General soil properties are stored in a primary knowledge form. Subsidiary properties are stored in forms which are linked to the main soil form. Knowledge was acquired by interviewing experts in the field as well as researching current publications. Soils information for the soils database was acquired from several different sources with a total of approximately 5500 soils represented in the database.

2.0 PROBLEM DEFINITION

Classical soil mechanics has emphasized specific types of soils (e.g., saturated sands, silts, and clays and dry sands). Textbooks cover the theories related to these types of soils in a completely dry or a completely saturated condition. Recently, it has been shown that attention must be given to soils that do not fall into these common categories. Many of these soils can be classified as unsaturated soils. Engineering related to unsaturated soils has typically remained empirical due to the complexity of their behavior. An unsaturated soil consists of more than two phases and therefore the natural laws governing its behavior are changed. Central to the behavior of an unsaturated soil is the relationship between water and air as the soil desaturates. This relationship is described by the Soil-Water Characteristic Curve (SWCC). Laboratory studies have shown that there is a relationship between the Soil-Water Characteristic Curve and unsaturated soil properties (Fredlund and Rahardjo, 1993b).

Properties such as hydraulic conductivity, shear strength, water storage, unfrozen water content, specific heat, thermal conductivity, and diffusion can all be related to the soil-water characteristic curve. Until recently, a method of combining unsaturated soil property functions into a single system has not existed. The knowledge system provides a way to link complex property functions together to describe the behaviour of an unsaturated soil.

2.1 The Soil-Water Characteristic Curve (SWCC)

The soil-water characteristic curve, often referred to as the moisture retention curve, is a continuous sigmoidal function representing the water storage capacity of a soil as it is subjected to an increasing soil suction. It is the relation between volumetric water content, θ, and soil suction stress state, (u_a-u_w). The soil-water characteristic curve can be used as a means of deriving and linking soil behaviors such as permeability, shear strength and volume change. It is central to the engineering behavior of an unsaturated soil. The soil-water characteristic curve provides a means of relating the fundamental soil properties to each other and controlling the state at which each engineering behavior is calculated. The stress state is important for modeling more than one aspect of soil behavior in a single analysis. The soil-water characteristic curve contains three important pieces of information; that is, pore size distribution, amount of water contained in the pores at any suction and the stress state of the soil and soil-water.

2.2 Methods of obtaining the soil-water characteristic curve

There are several methods available in the knowledge-based system for obtaining a soil-water characteristic curve for a particular soil. The method used is strongly influenced by the application for which the soil-water characteristic curve will be used and the desired accuracy. The most accurate way to determine a soil-water characteristic curve is through laboratory experimentation. Because of the high cost of laboratory equipment and the time required to run this test, alternate methods are desirable. The knowledge-based system provides three alternative methods of determining a soil-water characteristic curve as shown below:

1. The database of 5500 soils can be searched for a soil with similar properties.
2. The knowledge-based system can be requested to suggest reasonable fitting parameters based on the current soil properties.
3. A theoretical method was developed and implemented into the system to predict the soil-water characteristic curve from volume-mass properties and a grain-size distribution.

2.3 Prediction of unsaturated soil properties based on the soil-water characteristic curve

Laboratory studies have shown that there is a relationship between the Soil-Water Characteristic Curve and unsaturated soil properties (Fredlund and Rahardjo, 1993b). A literature review was performed to determine the best prediction methods currently available. These prediction methods were then implemented into the knowledge-based system.

3.0 KNOWLEDGE ACQUISITION

The most important process in a knowledge-based system is knowledge acquisition. How the knowledge is obtained and where it is obtained determines the usefulness of the system. The knowledge-based system described in this paper compiles information from three primary sources. Experts in the field of unsaturated soils were interviewed to obtain methods and heuristics common to the field of unsaturated soils. A search of current and past research was performed to determine the framework of the system. Experimental soil data containing, at the minimum, a Soil-Water Characteristic Curve was required for the database system. Lastly, current computer modeling software in the field of unsaturated soils was reviewed to determine what input properties were most significant. The information was then compiled to create a system to describe the property functions for unsaturated soils.

3.1 Interviewing Experts

Much knowledge in the field of unsaturated soils can only be found by probing the minds of people currently involved in research. Documentation of the newer techniques is not extensive making it necessary to rely on the experience of current experts. D.G. Fredlund and G.W Wilson provided insight and guidance into the design of the system and the way soil information should be represented. Research done in the physical theory of the bahavior of unsaturated soils, by D.G. Fredlund, laid the foundation for development of the system. Since the soil-water characteristic curve is central to the system, advice was also received from D.G. Fredlund on its mathematical representation and implementation. Knowledge regarding the implementation of thermal properties of soils was contributed by G.W. Wilson with colleague S.L. Barbour providing insight into how unsaturated soils behave in the area of contaminant transport. Mention must also be given to Walter Rawls from the USDA who provided input in determining the methods to use in the prediction of saturated hydraulic conductivity. Advice from the aforementioned experts provided the foundation for the design of the system as well as the heuristic rules used in the field of unsaturated soils.

3.2 Search of current literature

An extensive literature review was performed to determine the best prediction methods to use in the knowledge system. The source for the prediction methods used by the knowledge system are summarised in Table 1.

Table 1 Summary of prediction methods used in Knowledge-Based System

Description	Reference
Prediction of SWCC from grain-size curve	Fredlund, Murray D., Fredlund, D.G., Wilson, G.W., (1996), Prediction of the Soil-Water Characteristic Curve from Grain-Size Distribution and Volume-Mass Properties, 3rd Brazilian Symposium on Unsaturated Soils, Rio de Janeiro, Brazil.
Prediction of coefficient of diffusion from the SWCC	Lim P.C. S.L. Barbour and D.G. Fredlund, (1996), Diffusion and Adsorption Processes in Unsaturated Soils II: Effect of The Degree of Saturation on the Coefficient of Diffusion, Canadian Geotechnical Journal
Prediction of unfrozen volumetric water content from the SWCC	Black, P.B. and Tice, A.R., (1989), Comparison of soil freezing curve and soil water curve data for Windsor Sandy Loam., Water Resources Research, Vol. 25, No. 10., pp. 2205-2210.

Prediction of specific heat capacity from the SWCC	Farouki O.T., (1986), Thermal Properties of Soils, Trans Tech Publications, Clausthal-Zellerfeld, Germany, 112-117
Prediction of thermal conductivity from the SWCC	Johansen, O., (1975), Thermal Conductivity of Soils, Ph.D. Theses, (CRREL Draft Translation 637, 1977), Trondheim, Norway
Prediction of quartz content	Tarnawski, Vlodek R., and Bernhard Wagner, (1993), Thermal and hydraulic properties of soils, Saint Mary's University, Division of Engineering, Halifax, Nova Scotia
Prediction of shear strength envelope from the SWCC	Fredlund D.G., Anqing Xing, M.D. Fredlund and S.L. Barbour, (1996), The Relationship of the Unsaturated Soil Shear Strength Functions to the Soil-Water Characteristic Curve, Canadian Geotechnical Journal
Prediction of unsaturated hydraulic conductivity function from the SWCC	Fredlund, D.G., Xing, A. and Huang, S., (1994), Predicting the permeability function for unsaturated soil using the Soil-Water Characteristic Curve, Canadian Geotechnical Journal, Vol. 31, No. 3., pp. 533-546.
Prediction of saturated hydraulic conductivity using D_{10}	Holtz, Robert D., William D. Kovacs, (1981), An introduction to geotechnical engineering, Prentice-Hall, Inc., Englewood Cliffs, New Jersey
Prediction of saturated hydraulic conductivity using an effective porosity, n_e	Ahuja L.R. D.K. Cassel, R.R. Bruce, and B.B. Barnes, (1989), Evaluation of Spacial Distribution of Hydraulic Conductivity Using Effective Porosity Data, Soil Science Journal, Vol. 148, No. 6, 404-411

3.3 Acquisition of existing databases

Existing experimental data was needed to test the design of the Knowledge-based System. Once a sample database of soil information was acquired, statistical calculations were performed to check the validity of theoretical predictions as well as to provide an estimation of the reasonableness of current soil properties. The design allows for soil data to be continually added to the system but the original data was collected from one main source. Hundreds of research publications containing soil-water characteristic curves were reviewed and compiled by Sillers (1996) into a database of soils. The database contains the soil information needed to test the functionality of the system design.

3.4 Review of current computer modeling procedures

The knowledge-based system provides property functions to allow for coupled or uncoupled modeling in the areas of seepage, thermal, and contaminant transport. Data can be output from the program in tables, in equation form, or as a series of data points along a curve. The system adheres to Windows standards of data transfer and is therefore compatible with any modeling package which conforms to these standards and makes use of soil functions.

4.0 KNOWLEDGE REPRESENTATION

The area of knowledge-based systems has blossomed over the past decade from merely an academic interest into a useful technology. Carrico describes knowledge systems as follows.

> *Knowledge systems are software systems that have structured knowledge about a field of expertise. They are able to solve some problems within their domain by using knowledge derived from experts in the field. (Carrico, 1989)*

Development of the methods for knowledge representation followed the knowledge acquisition phase. Information was represented in forms. Each form consisted of a database of experimental data, a database of theoretical data, a knowledge base consisting of rules and algorithms applicable to the current form, and the user interface which allowed the information to be viewed in forms, tables, or charts. Independent of the knowledge forms is a query engine which allow for access to pertinent information.

The soil properties are organized into separate forms or subcategories which are linked to the main soil information form. The manner in which this is done is shown in Figure 1.

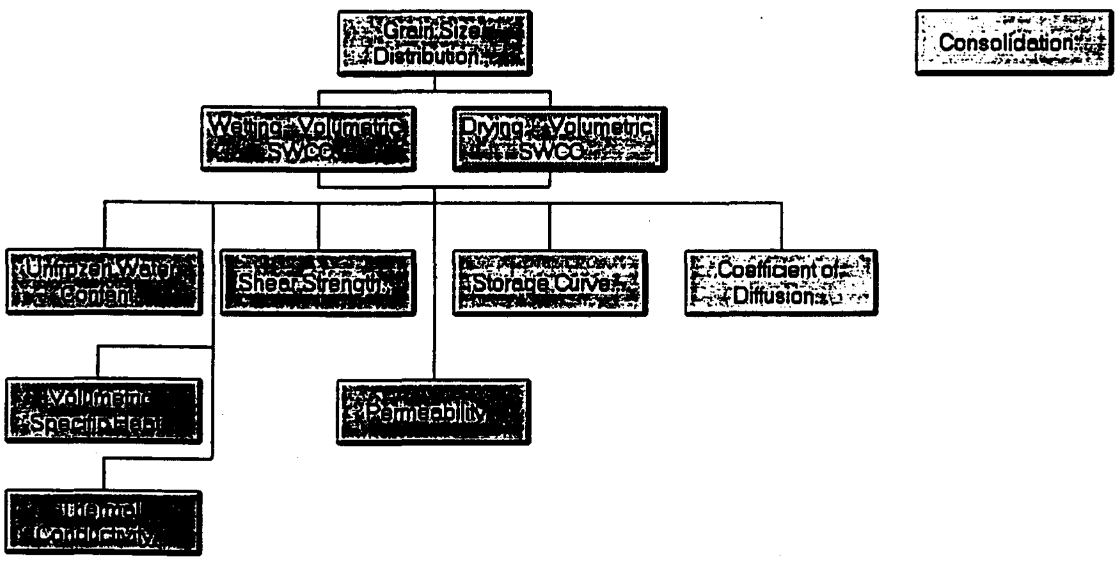

Figure 1 Knowledge forms included in the system

5.0 KNOWLEDGE SYSTEM SHELL

Once the structure of the KBS was determined, a shell or programming environment was needed to build the system. The relational database shell provided by Microsoft's Access® relational database management system (RDMS) was selected as an environment. The database system handled the manipulation of large amounts of data while allowing time to be focused on the coding of the knowledge system.

5.1 Main Soil Information Form

The fields used for classification of the soil were adopted from current USDA soil databases for the sake of familiarity. Figure 2 shows the main text descriptors used in the classification of soils. Page two of the form stores important volume-mass and grain-size properties often used for classification. Other soil properties that are stored are Atterberg limits, water chemistry, soil origin properties, publication information, and the geographical location of the soil (Country, State, County, Site). Soil origin fields store information such as horizon depth, horizon type, family, and soil series.

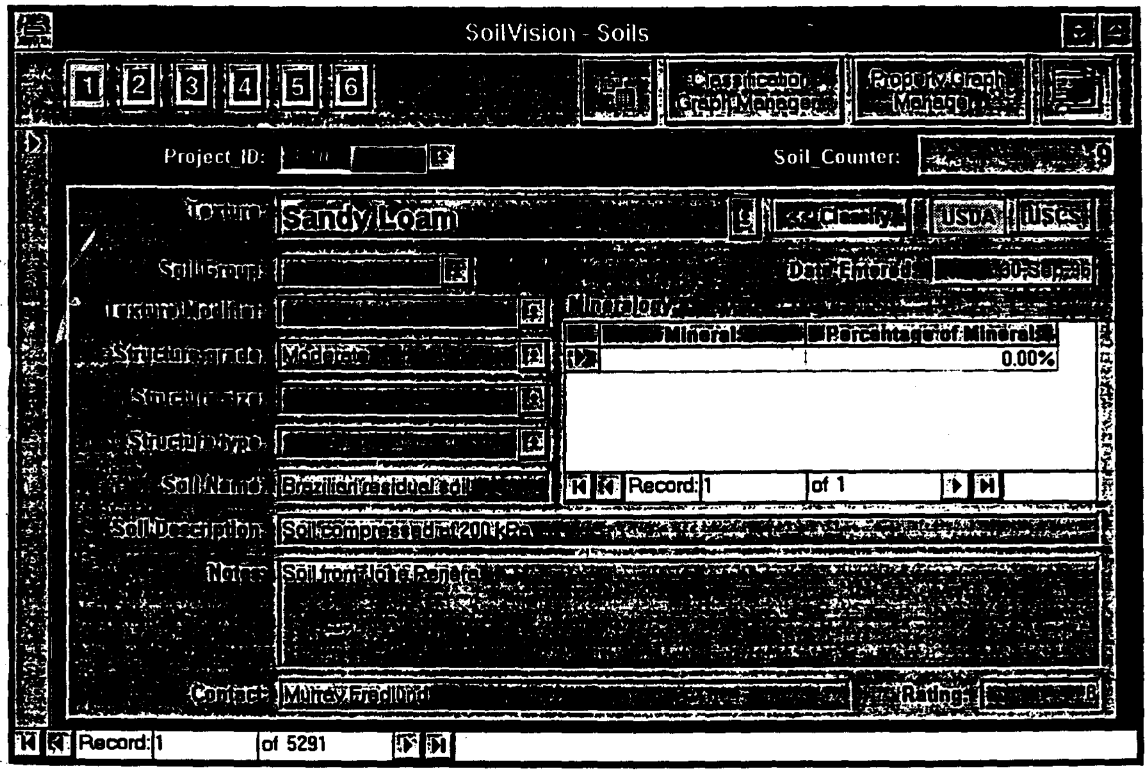

Figure 2 Page one of the main soil form showing the classification properties

The main soil information form also provides links to the forms describing soil properties such as soil-water characteristic curve, coefficient of permeability, shear strength, etc. Forms linked to the main soil form are described in the following sections. For the sake of brevity, not all the forms linked to the main soil form are shown.

5.2 Other Forms Linked to Main Form

Complimentary to data stored in the main soil form is information stored in other forms which are linked to the main form. Information was organized in forms for storage efficiency reasons as well as to provide a good conceptual view of the different soil properties. The properties or forms linked to the main soil form are listed below:

Grain-size distribution	Soil-water characteristic curve
Water Storage	Coefficient of permeability
Compression	Shear strength
Diffusion	Specific heat
Unfrozen water content	Thermal conductivity

The linked design of the system provides an efficient and logical presentation of data. This form stores pertinent information relating to the soil-water characteristic curve as well as experimental and fitted points on the curve. A focus of the knowledge-based system was to allow mathematical representation of soil property functions wherever possible. This then allows the equations to be entered into popular finite element modeling packages for modeling of unsaturated soil behavior. To provide a starting point for mathematical representation, the soil-water characteristic curve, grain-size distribution, and compression curves must be fit with a mathematical equation. A single equation was selected to fit each of the grain-size and compression curves. For the soil-water characteristic curve, however, a number of different equations have been previously used. To accommodate this variability, six different equations are available for use in the system. For each equation, a routine allowing the equation to be fit to experimental data must be provided. Therefore, a number of curve fitting algorithms were implemented. Once an equation is best-fit to experimental data, the resulting equation can be used in the predictions of other soil functions. An example of these predictions can be seen in Figure 3.

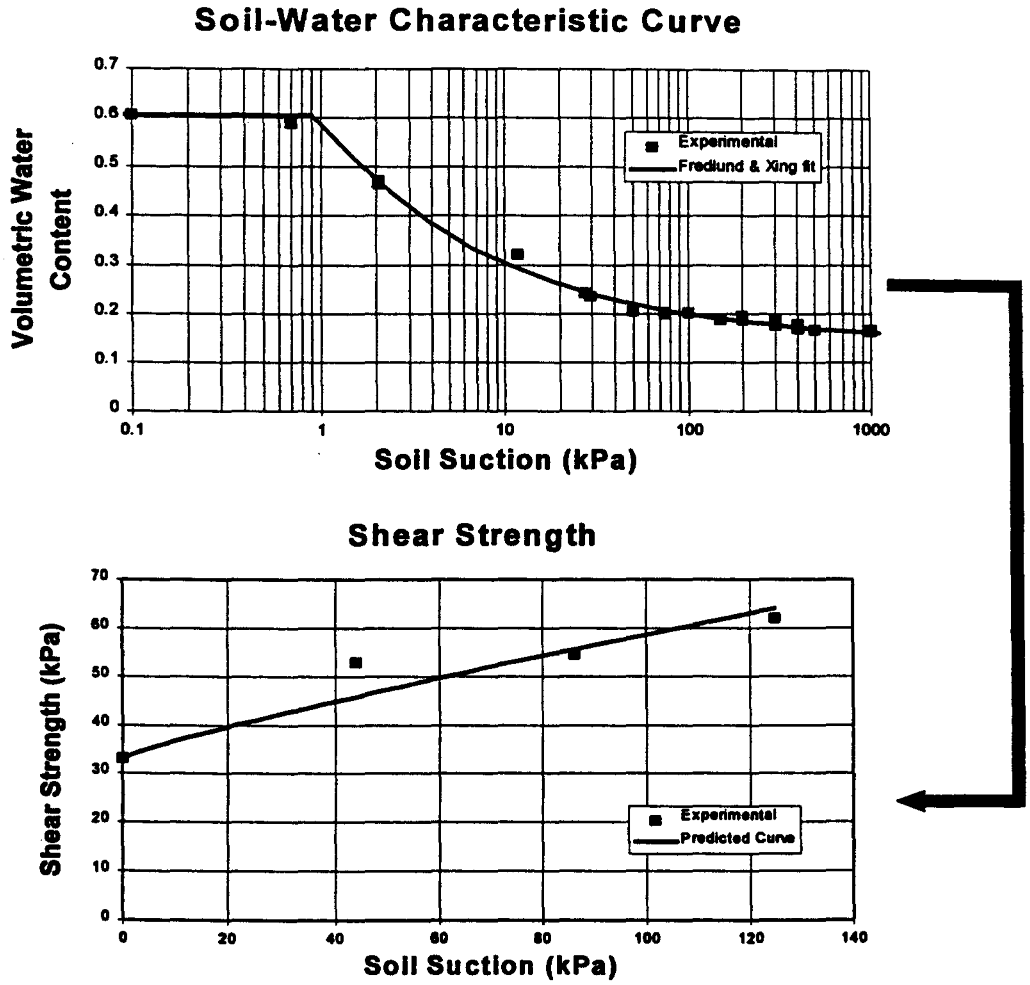

Figure 3 Plot of soil-water characteristic curve and predicted shear strength envelope for a Sandy Clay Loam

6.0 SUMMARY

Theory governing the behavior of unsaturated soils has been available for several years and has shown that the Soil-Water Characteristic Curve is the central relationship describing how a soil behaves as it desaturates. Research has shown that empirical relationships can be used to describe property functions related to the Soil-Water Characteristic Curve. These empirical relationships can then be used to predict how the coefficient of permeability, shear strength, thermal properties, and diffusion coefficient will behave as a soil desaturates. The complexity of unsaturated soil physics requires a knowledge-based system to provide tools for describing unsaturated soil behavior.

The database system handled the manipulation of large amounts of data while allowing time to be focused on the coding of the knowledge system. Information was stored in forms consisting of a main soil form with links established to alternate soil property forms. The knowledge-based system can handle eleven separate property forms and allows prediction of eight different soil property functions. The system then allows for the estimation of unsaturated soil properties when experimental data is limited or too costly to obtain. The unsaturated property functions can be used in finite element modeling among other applications to give an estimate of engineering design limits.

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