Design of a Knowledge-Based System for Unsaturated Soil Properties

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ABSTRACT

The Soil-Water Characteristic Curve (SWCC) is an important soil function relating the amount of water in a soil to soil suction. Many soil properties (or functions) can be related to the water content versus suction relationship of a soil. Hydraulic conductivity, shear strength, chemical diffusivity, chemical adsorption, storage, unfrozen volumetric water content, specific heat, thermal conductivity and volume change are all functions of the soil-water characteristic curve. Considerable judgment is required to enforce the relationship between soil property functions. Experts in the field of unsaturated soil mechanics provided the rules necessary in relating different soil properties. The judgment rules can be enforced by a Knowledge-Based System (KBS) design based on observations and empirical relationships among soil property functions.

A design for a Knowledge-Based System was developed using a relational database management system (RDBMS) known as Microsoft's Access® database program. The design provides an estimate of the soil-water characteristic curve as well as a wide variety of unsaturated soil property functions from basic soil classification data. The accuracy of the design was tested using the Access® and the output of the prediction functions was verified using MathCad®. Applications of the Knowledge-based System were also illustrated to demonstrate the power and flexibility of such a system. The design should reduce both time and costs associated with obtaining the soil properties for numerical modelling.

ACKNOWLEDGMENTS

I would like to acknowledges the contribution of Natural Sciences and Engineering Research Council of Canada in providing financial support for the completion of this thesis. Without this funding, this thesis would not have been completed.

The guidance provided by my supervisor, G.W. Wilson, and my father, D.G. Fredlund, was invaluable in both research and my own personal development. In the course of two years, I came to greatly enjoy working with both men. To be successful at your work is difficult, but to be successful in the eyes of your family is a greater accomplishment that both men have also achieved. Deserving congratulations go to D.G. Fredlund who managed to get a son to "follow in his footsteps" without bribery, blackmail etc.

The assistance of Scott "Scooter" Sillers, M.Sc. candidate and Sai Vanapalli Ph.D. was greatly appreciated. Scott Sillers provided friendship and help with current research on the soil-water characteristic curve as well as providing data for 200 soils. Sai Vanapalli was an invaluable source of information when looking for references relating to any area in unsaturated soils.

I also must mention the support of my brunette beauty, Barb, who married me half way through my Master's program. Thanks, firstly, for marrying me, and secondly, thanks for bringing me meals (and DQ) to the office when I was working late, and lastly, thanks for working so hard this last year so as to make ends meet. I don't deserve you Barb!

This thesis would not be complete without giving credit to my Lord Jesus Christ who died on a cross for me 2000 years ago so I could live. Long after the words in this thesis have been

forgotten, God's Word will still be providing the basis for a strong personal relationship with Him.

> *"Two men owed money to a certain moneylender. One owed him five hundred denarii. and the other fifty. Neither of them had the money to pay him back, so he canceled the debts of both. Now which of them will love him more?"* - *Jesus*

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1. CHAPTER - Introduction

Recent years have witnessed a rapid expansion in the application of computers to the field of civil engineering. Analysis of the problems presented by geotechnical engineers require vast amounts of computer storage and speed. These computational demands have resulted in use of mainframe computers. The increased speed and performance of desktop and laptop computers has allowed development of geotechnical engineering applications on the personal computer platform. These applications allow for modelling the processes of seepage, stress analysis, slope stability, thermal analysis, volume change and contaminant transport.

The applications developed to solve geotechnical engineering problems are complex. Typically, the problems presented by geotechnical engineers involve the coupling of several highly nonlinear partial differential equations to accurately describe the physical problem. Traditional applications have provided simplified approximations to the solution by omitting coupling of the problem. This omission then allows solution to most problems in a reasonable time period. The speed of personal computers has continued to double every 18 months as shown in Figure **1-1**. This increase in computing power allows more complexity to be added to geotechnical applications. Current areas of development for applications in the field of geotechnical engineering involve coupling of processes and moving from 2-dimensional to a 3-dimensional descriptions of a given problem.

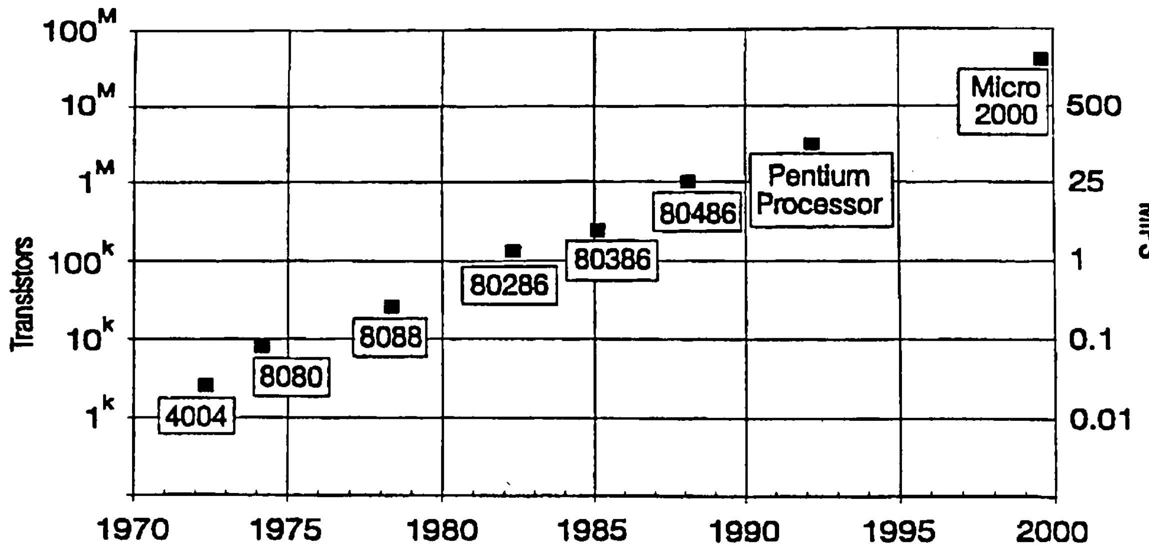


Figure 1-1 Intel microprocessors have approximately doubled in computing power every 18 months (Fredlund, 1996)

The solution to a geotechnical problem by computer typically involves the following five steps:

1. Soil testing,
2. Analysis of data,
3. Input into computer modelling package,
4. Solve computer model,
5. Viewing of output.

A description of the materials involved is the first step. Experimental testing should be done to properly determine the properties of the soil(s). Once experimental testing is performed, some analysis of the data is typically required to translate the data into a form useable by a computer model. Analysis then allows data to be input into the computer model where it can be solved. The solution is typically achieved by a solver module implementing either the finite element or finite difference technique. Solution of the model then allows the output to be viewed and examined by the geotechnical engineer.

A difficulty with completing the five steps presented was encountered during the development of this thesis. The definition of potential properties for input into the computer model is often a problem. Soil testing is expensive, time consuming, and there is usually no way to check for experimental error. The result of this is that a high percentage of geotechnical engineers do not perform proper testing. Input of geotechnical properties into computer models is typically estimated by the engineer with the most "experience". Upper and lower bounds may be set for the input properties, allowing for a range of possible outputs. This has the potential for inaccuracies in the modelling if the "experience" of the engineer is not reliable or if the engineer performing the modelling does not have enough experience.

It was also noted that current software available to geotechnical engineers does not address this problem. In general, the current applications concentrate on steps three to five of the modelling process. The applications allow for the input of the problem into the computer, provide a numerical solution, and allow a method for viewing the output. However, the output received is entirely dependent on the validity of the input. This allows for many questions to arise. For example, how does the geotechnical engineer determine what input is reasonable? Can you provide a reasonable analysis with a limited dataset or is there consistency between soil functions? During the course of this thesis it was determined that reliable output required reliable input.

There are two ways of obtaining input for modelling of soil functions. Soil data can be experimentally measured or it can be estimated from known data. Experimental data was the preferred data source but it is costly and time consuming to obtain and it does not provide a "feel" for the soil. It may also be noted that research has provided many acceptable techniques for the estimation of soil properties. In many cases these techniques have often not been applied to current modelling practice for a variety of reasons. Firstly, it is difficult to adequately search the literature to find the estimations of interest. Furthermore, once the estimations are located, how is it determined which is the most reliable technique? Estimation techniques typically involve integrations or differentiations which are difficult to duplicate. In general, the difficulties in applying advanced theory to practice have led to the omission of the most recent research in the practice of geotechnical engineering. This is particularly true for the application of unsaturated soil technology to current practice.

After considerable review, it was concluded that a system needs do be developed that provides a combination of theoretical and experimental data. This system would combine experimental data with the ability to predict soil properties where there are "holes" in the data. Furthermore, the required system should allow for prediction of missing soil data while also giving an indication of the variability of soil data.

The primary goal of this thesis is to design a Knowledge-based system that allows for the prediction of complex soil properties with ease and simplicity. For example, the knowledge-based system should be able to provide the soil functions required for numerical analysis in areas such as seepage modelling, thermal analysis, stress analysis, and contaminant transport. The Knowledge-based system should also provide a means of estimating these function on the basis of volume-mass and grainsize information together with a "feel" for the variability of data. This will allow modelling of typical, best case, and worst case conditions. The system should assist the modelling of unsaturated soil processes such that analysis may be performed at a minimal cost due to reductions in the demand for experimentally measured data. Experimental data might only be needed to confirm results or to provide additional accuracy when required.

Knowledge-based systems have been limited to large hardware platforms in the past. This is because of the large amount of computer power required to run such systems. Recent advances in the speed of hardware and the design of software for personal computers made the design of this system possible. Pentium computer systems along with newly emerging Windows database software provided a system capable of manipulating large amounts of data. Data can also be managed in a way that is easy to understand because of an intuitive Windows graphical interface.

The knowledge-based system design presented in this thesis combines the fields of knowledge-based systems with geotechnical engineering to achieve a solution to the problem as described above. Sample experimental data is used to provide a basis for the estimations of other soil properties. Models of various soil functions are fit to experimental data to allow interpretation of the data. Analytical predictions techniques are also implemented to allow the prediction of soil functions. The knowledge-base design also allows for the statistical estimation of soil properties. In summary the system design provides an estimate of soil properties and functions while also giving a "feel" for the variability of the soil properties.

1.1 Objectives of Research Program

The objectives of this research program are two fold. They are as follows:

1. To develop the conceptual framework for a Knowledge-Based System capable of predicting soil properties when the existing data is not complete; and
2. To devise methods of generating mathematical or digital representation of unsaturated property functions for use in modelling of unsaturated soil processes.

The purpose of this thesis is to provide a framework and method for solving the problem of determining the input parameters required for modelling routinely encountered in current geotechnical practice. The system design should provide a method for the statistical estimation of soil properties when data is limited. Statistical estimations will help provide an indication of the range of the data. These estimations will allow reasonable management of the high variability of soils information.

Analytical prediction techniques will be selected in the system design. A search of current literature will be performed and prediction techniques will be selected to allow estimation of soil functions for the purpose of unsaturated soil modelling. Analytical prediction techniques will be preferred over statistical estimations. As a greater range of soils can be accommodated with this approach. Unsaturated soil property functions such as the soil-water characteristic curve (SWCC), the hydraulic conductivity function, and the thermal conductivity function form the basis for numerical modelling in unsaturated soils. Research has shown that theoretical predictions of these functions may be sufficiently accurate for modelling many unsaturated soil processes (Fredlund, 1994). A primary objective of the system design is to allow for analytical predictions of unsaturated soil functions should "holes" exist in the experimental data or should the geotechnical engineer desire to obtain an indication of potential behavior of the soil.

Modelling unsaturated soil processes also requires a description, preferably a mathematical one, of a soil function from zero suction all the way to 1 000 000 kPa. One million kPa of suction corresponds to the zero water content of all soils. A continuous mathematical equation is most suitable for use in modelling practice. Current modelling practice does not provide continuous functions for the entire suction range and this can cause difficulty in modelling the behavior of unsaturated soils at very high suctions. The mathematical equations must also provide a correct theoretical interpretation for the physical processes of the soil. Fitting spline functions through experimental data may cause unrealistic "humps" and inflections that do not correctly represent physical conditions and therefore may cause numerical instability when modelling (Sillers, 1996). The goal of this work is to design a system which provides continuous and theoretically reasonable functions for modelling unsaturated soil processes.

1.2 Organization of Thesis

The information presented in this thesis is the result of combining the research areas of unsaturated soils and computer software together with knowledge system principles. Providing extensive documentation for each of these fields would fill many volumes. The emphasis of this thesis is therefore to provide an overview of each of these fields and concentrate on an explanation of the system design produced. Chapter 2 provides background information describing the development of unsaturated soil mechanics as well as a brief history of Knowledge-Based Systems. A discussion of the central importance of the soil-water characteristic curve is also included.

A primary phase in the development of a Knowledge-Based System is acquiring the knowledge on which to base the system. A description of this process can be found in Chapter 3. This chapter introduces the experts interviewed and explains how the design of the system was initiated. A search of the current literature in this area is also presented. The methodology of importing soil information into the system design is also described and a review of the impact of the Knowledge-Based System design on current geotechnical modelling software is also presented.

Chapter 4 outlines the implementation of knowledge in a system shell. The development of a Knowledge-Based System requires a shell to handle the routine manipulation of data. The shell used for implementation of the design is described in Chapter 4. An explanation is given for each soil function selected in the system design. It is explained how the knowledge is organized in the system design and how this relates to classical knowledge representations. The form of knowledge presentation in the current system is also outlined.

Chapter 5 describes the verification of the methods selected and developed to predict unsaturated soils properties. A description of the theoretical aspects of the prediction technique is given along with a comparison showing the accuracy of the prediction methods.

Chapter 6 provides a summary of the entire system design and its application to the field of unsaturated soil mechanics. Future plans and suggestions for the design of a Knowledge-Based System are presented in Chapter 7.

2. CHAPTER - Literature Review

2.1 Introduction

The emergence of unsaturated soil mechanics dates back to the 1950's. It could be argued that the theoretical basis for unsaturated soil mechanics was laid about the same time as Artificial Intelligence. Artificial Intelligence, AI, has probably been in the minds of people for hundreds of years but showed no signs of becoming reality until the 1950's when the digital computer was developed. Since the 1950's, advances have been made which have moved the field of Artificial Intelligence from a good idea to a practical solution-provider for many problems. The complexity of unsaturated soil mechanics has created a reluctance to apply new technology in practice. Advances in the field of AI allow the knowledge of an expert to be incorporated into a knowledge-based system. This allows a relative novice to apply unsaturated soils technology in practice.

Soil mechanics as an engineering science dates back to the 1930's. However, soil has been used as a foundation and construction material for as long as people have been building things. Dikes and levees made out of soil have been found in flood plains dating back to the time of ancient Egypt, Babylonia, China, and India. The middle ages show problems with the settlement of large cathedrals in Europe. Old Scandinavian buildings show timber piles used to support houses and buildings on soft clay (Holtz, 1981). Early work seems to be mostly empirical and little theoretical work was evident until the mid-1700's.

Coulomb developed the theory for earth pressures against retaining walls during the 1700's. His theory of active and passive pressures is still in use today. Also worthy of mention was during the late 1700's is the development of consistency limits was proposed by Atterberg in Sweden. Atterberg Limits are still used today as a basis for classification of soils.

Although significant advances were made in the field of soil mechanics, the theoretical basis of modern *saturated* soil mechanics was developed by an Austrian, Karl Terzaghi, in 1925.

He published the first modern book on soil entitled "Theoretical soil mechanics" which provided the basis for *effective stress* in describing the stress state of soils. Karl Terzaghi eventually moved to the United States where he taught soil mechanics at Harvard University with colleague Arthur Casagrande until his retirement in 1956. He continued as a consultant until his death at 80 years of age in 1963.

The theory of saturated soil mechanics was widely used and accepted by the engineering community for many years. The theory of saturated soil was relatively easy to understand and designs could be implemented with simple calculations. As time progressed, it was recognized that there was a fundamental problem with applying the theory of saturated soil mechanics to many applications. This problem was that most soils used in design were not saturated.

This problem was addressed at the first ISSMFE conference (International Society for Soil Mechanics and Foundation Engineering) in 1936. The conference provided a forum for the establishment of principles and equations relevant to *unsaturated* soil mechanics (Fredlund, 1993). Although relevant, the principles and equations presented at this conference were not consistent and a theory for unsaturated soil mechanics was slow to develop in subsequent years (Fredlund, 1979). Lytton (1967) did much to ensure that the understanding of unsaturated soil mechanics was established on a sound theoretical basis. Work carried out in the Ph.D. thesis of D.G. Fredlund (1973) presented a theory for unsaturated soil mechanics that was consistent with the principles put forth in continuum mechanics. This work presented parallel principles and equations that could be used to describe the behavior of unsaturated soils.

One drawback associated with the theory of unsaturated soil mechanics was that it is more complex than the theory of saturated soil mechanics. This has led to confusion as to how the properties of an unsaturated soil should be defined. Research has shown that the Soil-Water Characteristic Curve (SWCC) is the central relationship which can be used to describe the behavior of an unsaturated soil (Fredlund, 1994). Once the SWCC is known, it can be related to other properties describing the behavior of the soil. An example of this is that it has become possible to predict the permeability function for an unsaturated soil from the SWCC and the saturated permeability.

In general, methods of ensuring that soil properties are properly defined does not exist. Mitchell (1993) stated in his book regarding analysis of soils,

> *"Analyses and designs are useless if the boundary conditions and material properties are improperly defined."*

The Knowledge-Based System proposed for this thesis is intended to help address the problem of properly defining material properties. It provides an environment that facilitates the easy prediction, estimation, and confirmation of unsaturated and saturated soil properties. The system is built by combining current knowledge of the behavior of the SWCC and knowledge-based systems technology.

2.2 Soil-Water Characteristic Curve and its Relationship to Unsaturated Soil Property Functions

The soil-moisture retention curve, or SWCC for a soil is defined as the relationship between water content and suction for the soil (Williams 1982). As suction increases in a soil, water is progressively pulled out of the soil. The SWCC provides a basic distribution and geometry for a soil structure. Because of this, the SWCC has been found to relate to other soil properties such as permeability, shear strength, unfrozen water content, specific heat, thermal conductivity, storage, diffusion and adsorption. The SWCC can serve as a predictive function which describes how a soil behaves. This has a significant impact on the area of numerical modelling.

Total soil suction is made up of two components; matric suction and osmotic suction. Together these two suctions contribute to the energy potential of the pore-water. The suction component in the SWCC may be either matric suction or osmotic suction. Osmotic suction is the result of salts in the pore-fluid of the soil. Matric suction can be related to curvature of the air-water interface (i.e. contractile skin).

A typical SWCC for a silty soil is shown in Figure 2-1. This figure demonstrates a typical shape as well as the key features of SWCCs. Each SWCC will have a maximum volumetric water content at zero suction where saturated or near-saturated conditions exist. Once suction is sufficiently large to cause the largest pores to drain, a break in the SWCC is noticed. This point is referred to as the air-entry value of the soil. The soil will typically continue to desaturate at a rapid rate until a residual value is reached. The curve will then flatten somewhat until the suction reaches 1 000 000 kPa which corresponds to zero water content. The concept of zero water content at one million kPa suction is determined approximately as oven drying 24 hours at 105 °C (Wilson, 1990).

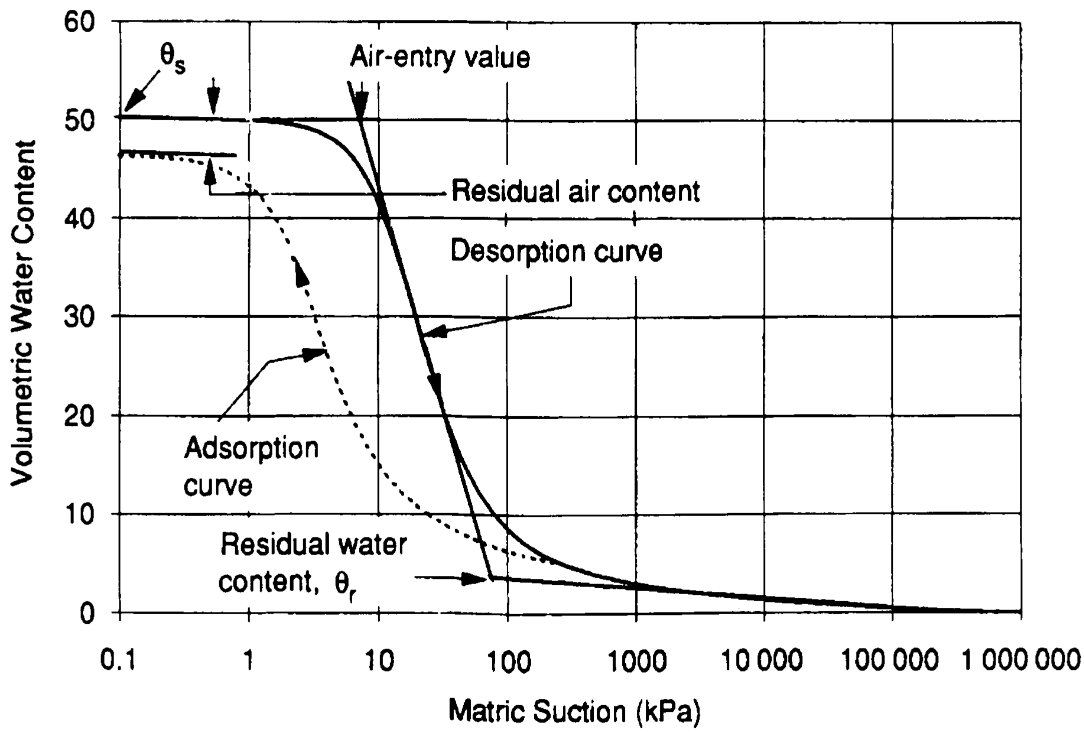


Figure 2-1 Typical soil-water characteristic curve for a silty soil (Fredlund, 1994)

This concept has been experimentally determined and supported for a variety of soils including sands, silty sands and loamy sands (Croney and Coleman, 1961). Soils containing a high clay content exhibit a slightly different shape. The air-entry value occurs at a higher suction and its break is less drastic. A soil with a high clay content will retain significant water even at high suctions. This may eliminate the flat portion of the SWCC at high suctions and yield a steady drop from the air-entry value to zero water content at 1 000 000 kPa. Examples of soil-water characteristic curves can be seen in Figure 2-2.

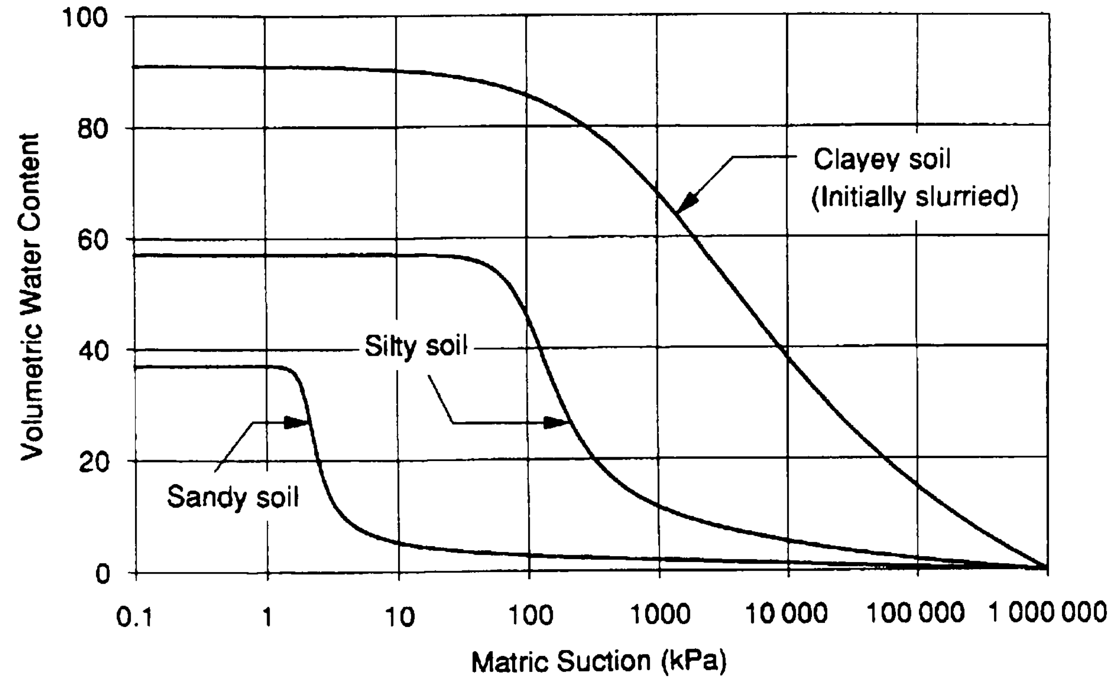


Figure 2-2 Typical soil-water characteristic curves for a sandy, silty, and clayey soil (Fredlund, 1994)

Soils also have different wetting and drying curves as shown in Figure 2-3. Soil-water characteristic curves are most commonly measured on the drying curve due to increased difficulty in measuring the wetting curve. The reason for this can be seen in Figure 2-4 which shows the capillary model for a soil. When capillary A) is drying, the suction applied only desaturates the tube to the point where suction is equal to the capillary forces. This results in the large void space remaining filled in part B). As drainage continues the void space will empty; however the value of matric suction remains almost the same. Upon rewetting the capillary tube will fill at the same value of matric suction but the large void will fill only after matric suction decreases to a much smaller value. The SWCC for the tube shown would then look like the one shown in Figure 2-4 which is a gross representation of a soil.

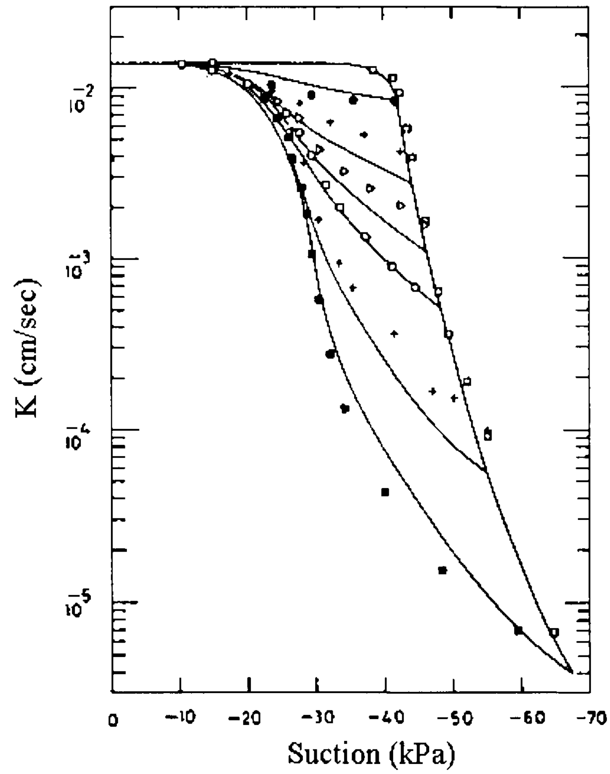


Figure 2-3 Example of hysteresis in the soil-water characteristic curve (Topp & Miller, 1966)

Also of significance is how the shape of the SWCC relates to the type of soil it represents. Clays produce a different SWCC than sands or silts. A comparison is provided in Figure 2-2 which shows a typical SWCC for a sand, a silt, and a clayey soil.

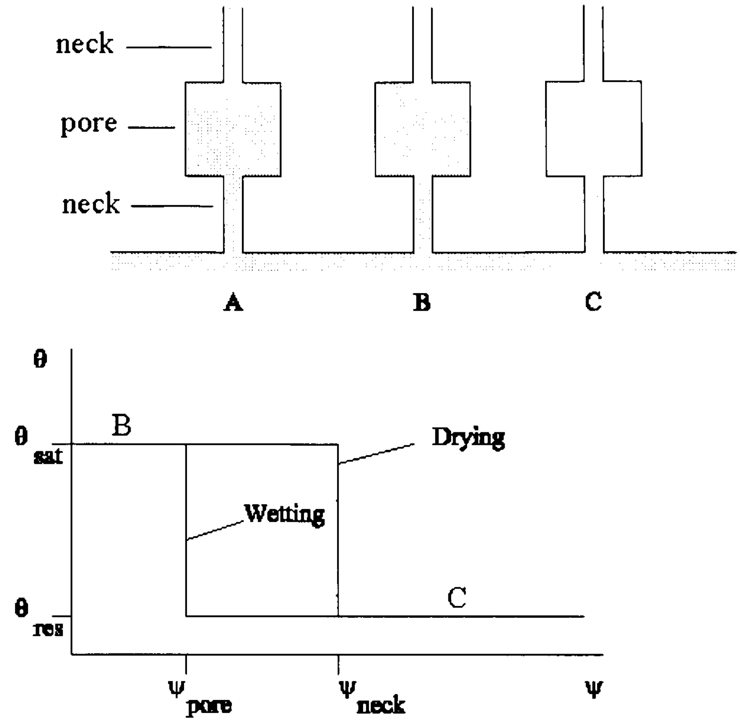


Figure 2-4 Capillary model for a soil (Sillers, 1996)

2.2.1 Historical Development

The first SWCCs were developed by Buckingham in 1907. His experimental method simulated the capillary model in that tubes were packed with soil and a suction was placed on each tube by connections to water sources. The height that water rose to in each tube was then viewed as a "capillary potential". A significant aspect of his work was the fact that the SWCC was described as continuous (Barbour, 1996).

Many of the methods used today for the measurement of the SWCC were developed in the early 1900's. The pressure plate was the method used by Richards (1928) to measure the soil-water interface. An understanding of the forces across the air-water interface began to emerge. An understanding of the meniscus of water in a soil led to explanations of such phenomenon as hysteresis in the SWCC. Soil-water characteristic curves measured by Richards can be seen in Figure 2-5.

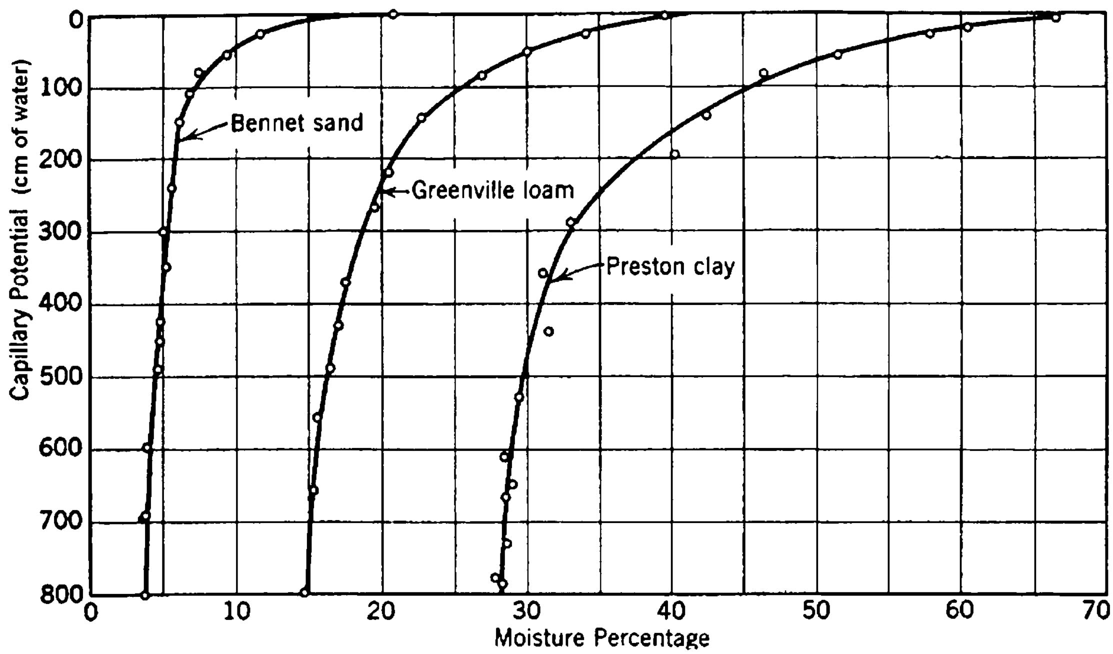


Figure 2-5 Tension-moisture curves of Richards (Baver, 1940)

Central to the SWCC was the development of the conceptual model behind the process of water leaving or entering the soil. Early formulations were based on the capillary tube model. This led to the view that the soil could be envisioned as a series of capillary tubes with different diameters. As the soil drained, the larger tubes would drain first, followed by the smaller tubes until the soil was completely desaturated. This conceptual model could not explain hysteresis in the SWCC and was therefore eventually modified.

Childs (1940) modified the capillary model of the soil to account for varying sizes of interconnected pores. This led to the discovery that the SWCC contained valuable information related to the geometry and pore-size distribution of a soil. He is noted as writing:

> *"Use of the soil moisture characteristics in this way depends on the fact that these characteristics may be interpreted as showing the pore size distribution within the soil. Thus they play a part analogous and complementary to mechanical analyses: they give the same sort of*

information about the pores as that given by mechanical analyses about the particles."

It was also realized by Childs (1940) that the pores were quite irregular in shape. An equation was developed to predict an effective pore size distribution which accounted for the irregularities in the soil pores.

Prediction techniques using the SWCC began to develop once it was proven that the SWCC provided a crucial link to the geometry of soil structure. Prediction of hydraulic conductivity was the first area addressed from the aspect of soil moisture. Methods were developed (Hazen 1911; Russo, 1980; Ahuja, 1989; Brakensiek, 1992; Rawls, 1993; Sperry, 1994; Fredlund, 1994; Durner, 1994) to allow the prediction of the saturated hydraulic conductivity as well as a hydraulic conductivity function. Many of these methods have now become accepted as standard practice in industry. Other prediction methods have also been developed which add further to the central importance of the SWCC for unsaturated soils.

2.3 Knowledge-Based Systems or Expert Systems

The aim of this section is to provide a brief history and overview of the field of artificial intelligence, AI. This will provide a context in which to view the current system. Enormous amounts of work have been carried on in this field in recent years. Confusion in terminology and classification of systems has accompanied this work. The following overview is, therefore, not a strict guideline but presents general views on the classification of systems.

Artificial Intelligence (AI) has probably been in the minds of people for hundreds of years but showed no signs of becoming reality until the 1950's when the digital computer was developed. In the years prior to, and following World War II, various groups in Europe and United States pioneered research into the area of human intelligence and formal reasoning (Parsaye, 1988). Since World War II, advances in the field of AI have led to applications such as shown in Figure 2-6. How expertise was developed historically in these areas is a larger issue. Table 2-1 presents a general summary of the significant paradigms that have led to modern systems. This table is a gross simplification but represents milestones in the field.

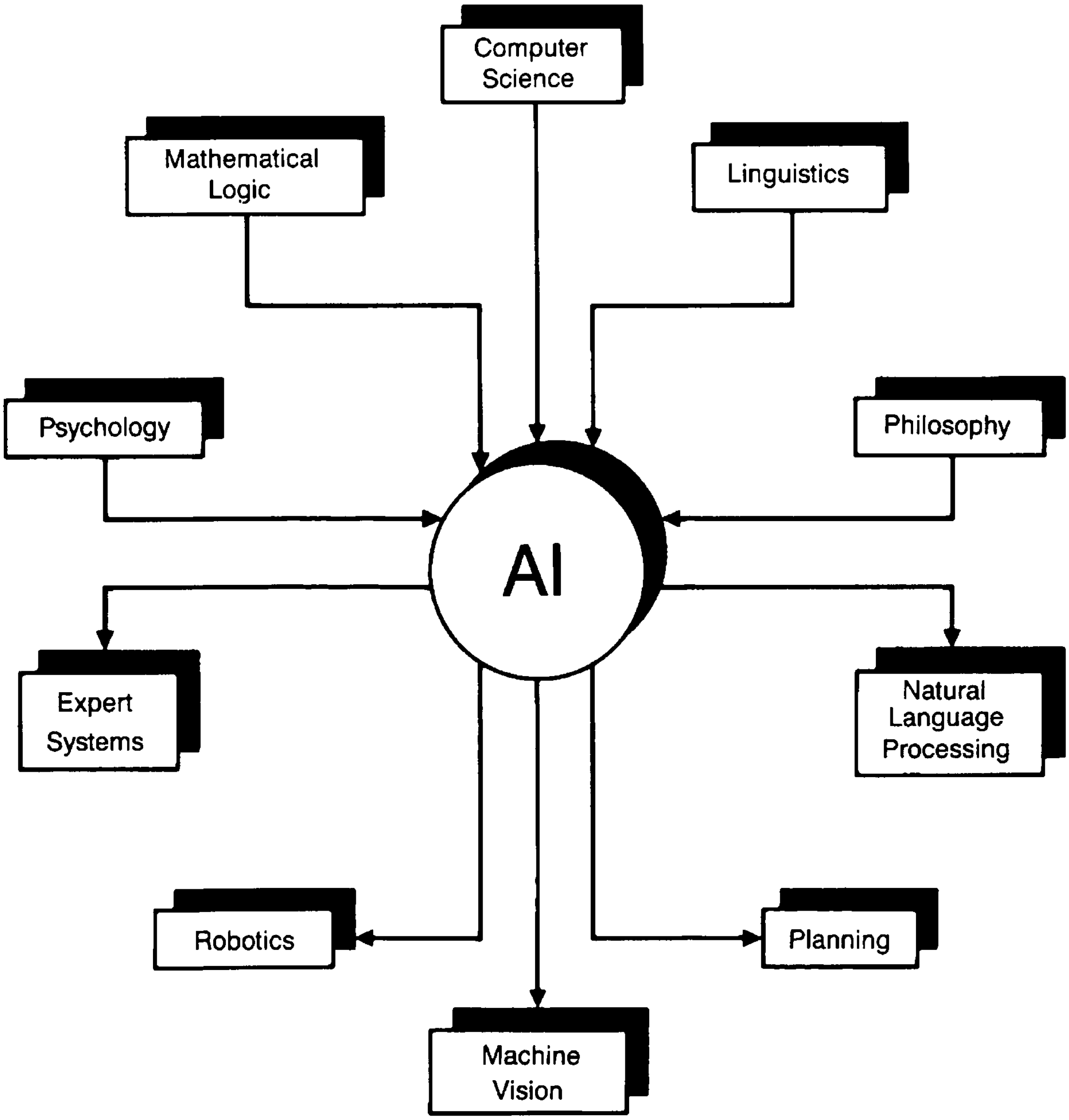


Figure 2-6 An input-output model for artificial intelligence (Parsaye, 1988)

Table 2-1 A brief history of AI (Forsyth, 1988)

	Paradigm	Researchers	System
1950s	Neural networks	Rosenblatt (Wiener, McCulloch)	Perceptron
1960s	Heuristic search	Newell & Simon (Shannon, Turing)	GPS
1970s	Knowledge engineering	Shortliffe (Minsky, Feigenbaum)	MYCIN
1980s	Machine Learning	Lenat (Samuel, McCarthy)	EURISKO

The first two columns in Table 2-1 identify the era as well as the paradigm that was developed. The next two columns show the people that worked on the project and the computer system that characterizes their work. In the researchers column, the names in brackets represent the thinkers that laid the foundation for the work to be done. Each of the paradigms are described in subsequent sections.

2.3.1 Neural Nets

Researchers of the 1950's tried to build intelligent machinery designed to mimic the human brain. This effort failed largely due to computer hardware and software that lacked sufficient power (Forsyth, 1989). Exponential increases in computer speed have led to a recent resurgence in the interest in neural nets. Modern efforts have more realistic expectations of what is possible with neural nets due to early failures.

The key computer program initially developed was called Perceptron. This was a trainable neural network that can be thought of as a crude model of the retina in the Vertebrate eye. It could be taught to recognize patterns but was shown later to be extremely limited in what it could recognize.

The system was based on the theory that a richly connected network of simulated neurons could start off knowing nothing, and by a training regime of reward and punishment could end up performing a number of tasks. Unlike statistical estimators, neural nets provide a mathematical means of estimation (Kosko, 1992). They also differ from rule-based expert systems in that they are mathematically based rather than symbolically based. They are classified as "model free" estimators. They "learn from experience" with no previous knowledge of a certain subject.

The false optimism of the 1950's soon faded simply because the results were not good enough. More recent times have seen a renewed interest in this field because of the increase in computer power. Significant shortcomings have been realized however. Neural nets can provide no explanation for their results. This often leads to questions of the soundness of the solution provided by neural nets.

An example of this is recent work performed by the US Military. Neural nets were designed to recognize hostile tanks given photographs of the battlefield. The system was optimized so as to identify occluded tanks or tanks that were partly hidden. The system was then "trained" by showing it a series of pictures and identifying hostile tanks. When taken out into the field, however, the system failed miserably. Investigation into the matter revealed that the system had failed because of a variation in the pictures used to "train" the system. All of the pictures without tanks had been taken on sunny days while the pictures taken with tanks hidden in them had been taken on cloudy days. The neural net had failed in the field because it could not recognize tanks on sunny days.

Neural nets are still considered to remain a viable solution for many problems. Research continues to present better neural nets capable of much more than the early versions.

2.3.2 Heuristic Search

Allen Newell and Herbert Simon of Carnegie-Mellon University discarded the neural net model. (Forsyth, 1989). They realized that the then current technology was not even sufficient to design a frog's nervous system. So they designed a system called GPS (General Problem Solver) which was based on the notion of a heuristic search.

Heuristic knowledge refers to general knowledge or "rules of thumb". The problem was viewed as solving a search through a set of solutions while guided by heuristic rules. The GPS program was general in the sense that it made no reference to the subject matter at hand. The geotechnical engineer could define a task environment in terms of objects and operators applicable to the objects.

GPS was limited to puzzles with a relatively small set of states and well-defined rules. Similar to most other AI systems, it could only operate on problems (e.g., Towers of Hanoi) that are, in human terms, no problem. The creators fell victim to misplaced optimism when Simon (1957) predicted that within ten years a computer would be the world chess champion. (Simon has since won the Nobel Prize, which shows that scientific reputation does not depend on perfect foresight). By attempting to prove that both minds and computers are examples of symbol-manipulating devices, they paved the way for the next advance in AI.

2.3.3 Knowledge Engineering

The criticism of AI applications was that they could not solve real-world problems. In the 1970's, Edward Feigenbaum at Stanford University led a team that set out to remedy that deficiency. It was assumed that an expert is a person that knows more and more about less and less. This allowed for a well-defined boundary of knowledge in a particular field; but before progress could continue, the team had to decide on a model of knowledge representation. The idea of neural nets was too limited and the heuristic search showed no promise of solving real-world problems. It was decided that knowledge could best be represented by storing heuristic rules in the form of IF...THEN statements.

This approach led to the development of the DENDRAL expert system and its successor MYCIN. The programs applied knowledge to the medical-diagnostic field and allowed diagnoses of bacterial infections of the blood and then prescribed a suitable therapy. Although the MYCIN program never made its way into practical use by doctors, it spawned a series of medical-diagnosis programs many of which are in use today (Forsyth, 1989).

The most significant aspect of the MYCIN program was that it presented several landmark concepts in knowledge representation.

Firstly, its knowledge was stored in the form of rules such as the following.

IF 1. the infection is primary-bacteriaemia, and

2. the site of the culture is a sterile site, and

3. the suspected portal of entry of the organism is the gastro-intestinal tract,

THEN

there is suggestive evidence (Probability=70%) that the identity of the organism is bacteroides.

Secondly, the rules were probabilistic. The benefit of probabilistic rules was that the program could arrive at conclusions even when evidence was uncertain or sketchy. The MYCIN program is significant because it was the first to apply this concept to knowledge engineering. Much research today is an extension of this system and applies probability theory, fuzzy set theory or some calculus of likelihood to a system of rules (Forsyth, 1989).

Thirdly, MYCIN was the first program that could explain the path of logic used to reach conclusions. If doctors had doubts regarding a conclusion, the program could be questioned as to the reasoning process used to reach that conclusion. Access to the reasoning was valuable because it allowed human checking of the reasoning process and allowed a certain confidence in the system.

Fourthly, the MYCIN program actually worked. There was a saying in the field of AI that "if it works, it's not AI". This was finally proved wrong by the team of Feigenbaum. A trial of the system was performed in 1979 and showed that MYCIN's performance compared favorably with that of clinicians on patients with bacteriaemia and meningitis. Ten cases were examined and the results were analyzed by eight adjudicators. The MYCIN program scored

52/80 compared to a score of 50/80 for the best physician on the Stanford faculty, and 24/80 for a medical student. In summary, the program performed as well as an expert and significantly better than a non-expert. Successors of MYCIN could then be applied to the field of medical diagnosis with a great deal of confidence.

2.3.4 Machine Learning

The 1970's laid the foundation for a host of similar rule-based systems in the 1980's. Developers soon realized that a great deal of time and effort went into determining the series of rules that make up a system. It was also recognized that the quality of the system depended largely on the quality of the rules upon which it was based.

Knowledge is hard to acquire. Many knowledge-bases contain heuristic rules that have been laboriously hand-crafted or developed from interviews with experts. The focus then shifted to machine learning in the 1980's to remedy this problem. It was reasoned that if better systems of machine learning could be developed, it would remove the bottleneck of knowledge acquisition. It was further reasoned that a knowledge system could be "trained" by allowing it access to databases containing particular information in a field. A system could then be developed that could analyze and "learn" from the data itself.

The most notable and impressive example of the 1980's was a machine learning system called EURISKO which automatically improves and extends its own body of heuristic rules. Its significant accomplishments include winning the Trillion Credit Squadron naval wargame three years in succession (despite rule-changes designed to thwart it) (Forsyth, 1989).

Another example of machine learning was the work done by Michalski (1983) and colleagues at the University of Illinois. Significant to this work is the fact that it is the first recorded instance where an expert system was used to improve human knowledge. Michalski (1983) collaborated with an expert plant pathologist to produce a system of rules used for identifying soybean diseases. This hand-crafted set of rules was then implemented in an expert system.

The system was then refined and tested against real-world cases. It was found that this system was right 72% of the time in its first-choice diagnosis.

A different approach was then taken. Several hundred example descriptions of diseased soybean plants were input into a inductive rule generator named AQ11. The rules generated from this system were then used to produce an expert system that was 97% correct in first-choice diagnosis of soybean disease.

The astounding results produced by the system led Michalski (1983) to further modify the system until it was 83% correct on *unseen* samples. At this point, the expert system approach was abandoned and Michalski taught himself the machine-generated rules and used them in his own professional practice. Significant to this case is that it is the first recorded case where a machine expert outperformed a human expert.

2.3.5 Present Day Systems Classification

Recent work has led to a renewed interest in the applications of AI. Advances in computer speed and power have allowed further, more successful work on neural nets. Languages specific to the needs of AI have also emerged such as LISP and PROLOG (Carrico, 1989). New understandings have also brought a more realistic view of Artificial Intelligence. Expert systems programs will not be called "Artificial Intelligence" for long. Instead, expert systems will be considered conventional programs with different representation techniques (Carrico, 1989).

The terminology used in the description of expert systems has also changed. The following sections provide a brief summary of terms used to describe expert systems and components that typically make up these systems.

2.3.5.1 Knowledge-based Systems and Expert Systems

Knowledge-based systems are typically made up of the components shown in Figure 2-7. Knowledge can be stored in any particular representation and is interpreted and applied through an inference engine. Typical methods for storing knowledge are Semantic Networks, Decision Tables, Decision Trees, Production Rules, Frames, and Demons. A summary of each of these representation techniques is shown in Table 2-2.

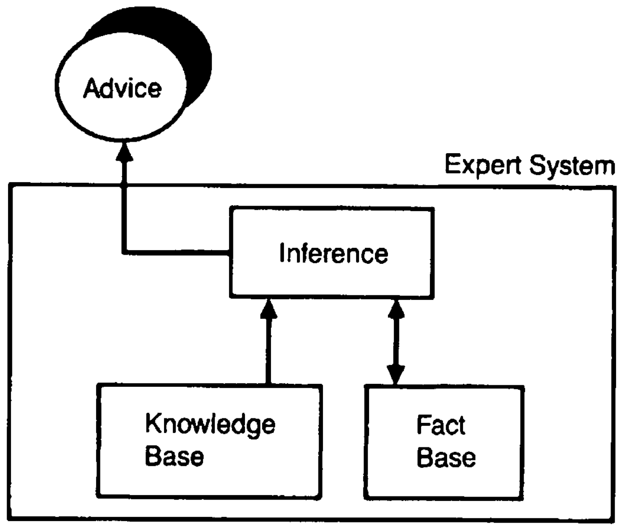


Figure 2-7 Typical component layout for an expert or knowledge-based system (Parsaye, 1988)

Expert systems have the same general form as knowledge-based systems and therefore the terms have often been used interchangeably. Expert systems have evolved into a specialized version of a knowledge-based system (KBS). They differ from a KBS in that Expert systems typically represent knowledge in the form of rules. Knowledge-based systems can also represent knowledge in the form of rules but an Expert system implies a single rule-based form of knowledge representation.

Table 2-2 Summary of representation techniques (Carrico, 1989)

Representation	Description
Semantic networks	maps of relationships utilizing nodes and links.
Decision tables	matrices of conditions that are to be considered in the description of a rule along with the actions to be taken for each set of conditions.
Decision trees	a hierarchical structure of information wherein the nodes are decision points and the branches are alternative decisions.
Production rules	knowledge representation that utilizes the cause and effect format IF (premise) THEN (conclusion) ELSE (conclusion).
Frames	representation of an object utilizing a relational table approach.
Demons	a coding technique that provides the ability to only trigger a code or a function when certain conditions have been met.

2.3.5.2 Expert Database Systems

An increasing number of applications have need of large amounts of information. Handling this information is a challenging task for programmers. This has led to standardization of data management techniques and the development of Relational DataBase Management Systems (RDBMS) whose purpose is to handle the manipulation of large amounts of information. Expert systems recently developed often have both large amounts of knowledge information as well as large databases used to train and develop the system. This has led to a combination of expert system (ES) technologies and database management technologies in the form of Expert Database Systems (EDS) (Kerschberg, 1986).

2.3.5.3 Intelligent Database Systems

Intelligent database systems (IDS) are similar to expert database systems. The typical scientific method is to gather information, analyze the data, make observations, and draw conclusions. IDS systems seek to help us make these "discoveries" automatically (Parsaye, 1990). IDS systems also seek to provide tools to allow automatic error detection, flexible query processing, intelligent user interfaces, and an intelligent database engine. As the demand for information increases, intelligent database systems provide solutions to problems.

2.3.6 Use of Expert Systems

A survey published in AI Expert magazine summarized the use of expert systems in 89 organizations that have implemented expert systems. Table 2-3 shows the area of applications design currently implemented. Hardware platforms for expert systems shows the trend towards small desktop systems (Table 2-4). Also presented in this survey was the hypothesized future direction for expert systems (Table 2-5). Users were asked to rate areas from one (little importance) to five (significant importance). To be noted is one of the directions presented in Table 2-5. The interface to a database system is considered important. The knowledge-based system subsequently presented uses such an interface.

Table 2-3 Areas of application (Philip, 1990)

Area of application	No. of organizations	% of organizations
Manufacturing	39	44
Management	26	29
Accounting	18	20
Finance	12	14
Marketing	12	14
Education	8	9
Distribution	7	8
Engineering	**5**	**6**

Table 2-4 Hardware platforms (Philip, 1990)

Hardware platform	No. of organizations	% of organizations
PC compatible	**74**	**83**
Macintosh	17	19
Microvax	8	9
Sun 386	8	9
HP 9000	5	6
DEC Workstation	4	5
Others	12	13
IBM 3090	13	15
VAX	4	5

Table 2-5 Future of expert systems (Philip, 1990)

Category	No. ranking 3 or higher	% ranking 3 or higher
Many future applications will need to interface to a DBMS	**79**	**89**
Applications provide an excellent tool for strategic information systems	75	84
Our firm will be using systems for decision support systems	68	76
There will be a significant increase in applications over the next two years in our firm	66	74
Applications reduce manpower needs	49	55
Our firm will be using systems for executive information systems	48	54
"Expert system" is an overworked term and will fail over time	20	22

An old African proverb goes as follows:

When an old man dies,
a library burns.

The goal of knowledge-based systems is to allow the transfer of information from the mind of an expert to a computer representation. There have been inventions that have transformed the world. These inventions have typically involved a physical device of great usefulness.

Knowledge-based systems offer thought tools, extensions not of muscle but of mind (Barrett, 1989) A knowledge-based system will allow the computer to mimic a human expert in helping people diagnose problems, select among alternatives and plan and manage operational systems. These systems will offer the ability to retain knowledge accumulated by experts for use by the less experienced. For geotechnical engineering, knowledge-based tools hold much promise. The knowledge-based system design presented in the following chapter allows understanding and application for the field of unsaturated soil mechanics.

3. CHAPTER - Knowledge Acquisition

The most important process in developing a Knowledge-Based System is the acquisition of knowledge. How the knowledge is obtained and where it is obtained determines the usefulness of the system (Barrett, 1989). The Knowledge-Based System described in this paper compiles information from three primary sources.

1. Experts in the field of unsaturated soil mechanics were interviewed to obtain methods and heuristics common to the field of unsaturated soils.
2. A search of current and past research was performed to determine the framework of the system. Experimental soil data was needed to test the system. A requirement for the soil data was that it contain a reasonably defined soil-water characteristic curve (SWCC).
3. Lastly, current computer modelling software in the field of unsaturated soils was reviewed to determine the most significant input properties. The information was then compiled to create a system to describe the soil 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, professors at the University of Saskatchewan, Saskatoon, Canada, provided the primary insight and guidance into the design of the system and the manner in which soil information should be represented. Research done on the physical theory related to unsaturated soils behavior by D.G. Fredlund laid the foundation for development of the system. Since the SWCC is central to the system, advice was also received from D.G. Fredlund on its 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, USDA, Agricultural Research Service, Beltsville, Maryland who provided input in assessing the most suitable 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 prediction methods used by the knowledge system are summarised in Table 3-1.

Table 3-1 Prediction methods used for Knowledge-Based Systems

	Description	Reference
1	Prediction of saturated hydraulic conductivity using an effective porosity, n_e	Ahuja, L.R., Cassel, D.K., Bruce, R.R., and Barnes, B.B., 1989, Evaluation of spatial distribution of hydraulic conductivity using effective porosity data, Soil Science Journal, Vol. 148, No. 6, pp. 404-411
2	Prediction of saturated hydraulic conductivity using D_{10}	Holtz, Robert D., Kovacs, William D., 1981, An introduction to geotechnical engineering, Prentice-Hall, Inc., Englewood Cliffs, New Jersey
3	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
4	Prediction of shear strength envelope from the SWCC	Fredlund, D.G., Xing, Anqing, Fredlund, M.D., and Barbour, S.L., 1996, The relationship of the unsaturated soil shear strength functions to the soil-water characteristic curve, Canadian Geotechnical Journal, In press
5	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
6	Prediction of thermal conductivity from the SWCC	Johansen, O., 1975, Thermal conductivity of soils, Ph.D. Thesis, (CRREL Draft Translation 637, 1977), Trondheim, Norway
7	Prediction of specific heat capacity from the SWCC	Farouki, O.T., 1986, Thermal properties of soils, Trans Tech Publications, Clausthal-Zellerfeld, Germany, pp. 112-117
8	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.
9	Prediction of coefficient of diffusion from the SWCC	Lim, P.C,. Barbour, S.L., and Fredlund, D.G., 1996, Diffusion and adsorption processes in unsaturated soils II: effect of the degree of saturation on the coefficient of diffusion, Canadian Geotechnical Journal, In press
10	Prediction of adsorption curve from SWCC	Lim, P.C., 1995, Characterization and prediction of the functional for the coefficients of diffusion and adsorption for inorganic chemicals in unsaturated soils, Ph.D. Thesis, University of Saskatchewan.

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 SWCCs were reviewed and compiled by Sillers (1996) into a database of soils. In summary, the database consists of soil information needed to test the functionality of the system design.

3.3.1 Methodology for importing soils data

Soils data was typically received in the form of long ASCII text files. A procedure was therefore developed to ensure the data was correctly imported and implemented into the Access™ database. Data integrity is of great importance and will affect the ability of the database to present reasonable calculations and correlations.

Text files were typically organized in a table-type format. Data values were separated by knowing the number of characters present in each field. This format allowed easy importing of information into Excel™ by import functions provided by the program. Manual verification of the data was then performed in Excel™ to ensure correct importing of data. Data was then imported into Access. Access also performed checks on data to determine if the field type was correct (e.g. a numeric field did not contain characters) and that the field was within the allowable range predefined for that field. An example of this was that the allowable range for porosity was greater than zero and less than 100%. If a soil contained fields outside allowable limits, the soil was regarded as erroneous and discarded.

Spot checks were then performed on the data. Soils were picked at random and checked against original text files to check for errors. If any errors were found, the current soils information was deleted and the import process was repeated.

Volume-mass calculations were then completed. Soils information obtained typically contained three volume-mass properties such as porosity, volumetric water content, and specific gravity. Using these three properties, the remaining volume-mass properties were calculated by group calculations. Once the remaining volume-mass properties were calculated, the properties were checked for reasonableness. Soils with unreasonable volume-mass properties were discarded.

3.4 Review of current computer modelling procedures

The input soil property functions required by the five computer programs listed below are used as an example to illustrate the soil functions that are most widely used in unsaturated soils modelling:

Company	Product Name	Description
Geo-Slope	SEEP/W	Modelling of unsaturated soil water flow
Geo-Slope	TEMP/W	Modelling of thermal fluxes in unsaturated soils
Geo-Slope	SIGMA/W	Modelling of stress/deformation of unsaturated soils
Geo-Slope	CTRAN/W	Modelling of contaminant processes in unsaturated soils
U. of Sask.	SoilCover	Modelling of boundary fluxes in unsaturated soils

Seepage modelling programs for unsaturated soils typically require a SWCC and a hydraulic conductivity versus matric suction curve. Either of these curves can be obtained in two ways from the knowledge system design. The curves can be theoretically predicted from a SWCC or the database can be searched for experimental data representing a similar soil.

TEMP/W performs uncoupled thermal analysis of soils and therefore requires soil property functions describing thermal conductivity and specific heat capacity. SoilCover is a fully coupled, one-dimensional finite element program to model the flux boundary conditions at the surface of unsaturated soils. As such, it requires soil property functions describing volumetric water content, hydraulic conductivity, thermal conductivity, specific heat capacity and unfrozen water content. To satisfy the needs for programs such as these, the knowledge system design is capable of providing functions representing volumetric water content versus suction (SWCC), hydraulic conductivity versus suction, thermal conductivity versus suction, volumetric specific heat versus suction, and unfrozen volumetric water content versus degrees below freezing.

The program SIGMA/W performs uncoupled modelling of stress and deformation of an unsaturated soil. A function describing the relationship between deformation of an unsaturated soil, and the stress state (i.e. suction and net normal stress) is required to properly model this phenomenon. The Knowledge-Based System design provides a method of predicting this function. For fully coupled programs modelling volume change in unsaturated soils, the system design provides soil property functions describing the change in void ratio, water content, and shear strength versus both suction and net normal stress.

CTRAN/W performs the uncoupled modelling of contaminant transport in unsaturated soils. To model contaminant transport problems, soil property functions describing the coefficient of diffusion and the coefficient of adsorption for different degrees of saturation are needed. An estimate of each of these curves can be obtained from the Knowledge-Based System design.

The Knowledge-Based System design thus provides soil property functions which can be used for coupled or uncoupled modelling in the areas of seepage, thermal analysis, contaminant transport, volume change and shear strength.

4. CHAPTER - Program Implementation

The system design was developed within the relational database shell provided by Microsoft's Access relational database management system (RDMS). The Microsoft Access® database management system version 1.1 and the Microsoft® FoxPro® database version 2. 5 for the Windows™ operating system were rated the top two multi-user databases for Windows in the July 1993 *Software Digest* Ratings Report® published by the National Software Testing Laboratories (NSTL). Microsoft Access received the highest overall score of 7.7 and Microsoft FoxPro 2.5 for Windows came in a very close second with an overall score of 7.6. The ratings are based on a scale from 0-10, with 10 being the highest. Access version 2.0 has continued in this tradition and has received even more acclaim than its predecessor version 1.1. Access 2.0 was selected for the operating shell because it handles the manipulation of large amounts of data while allowing time to be focused on the development of the knowledge system design.

The proposed design is implemented on Access® but the details of coding are not provided. Instead, the function and utility of the design is described since it is the issue of value to geotechnical engineers.

A proposed design for a main switchboard can be seen in Figure 4-1. The design will be referenced as the Knowledge-Based System (KBS) design in the following documentation.

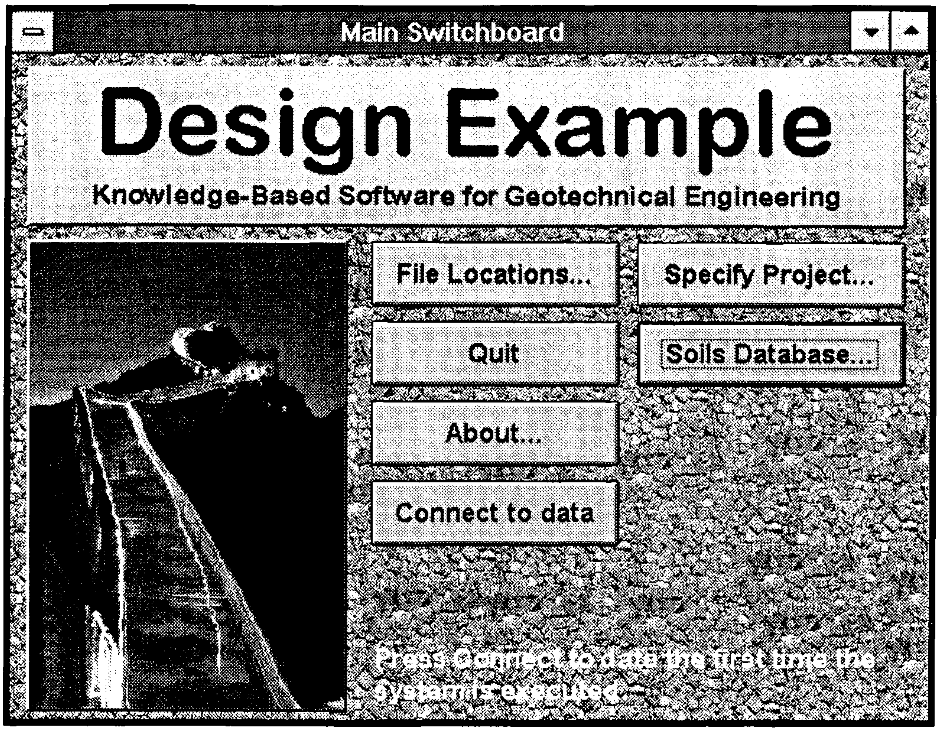


Figure 4-1 Example of the main switchboard for the Knowledge-Based System design

4.1 Form Composition

A standard method of presenting information was adopted for the KBS design. Data representation was grouped into objects representing related information called forms. These forms represented experimental data, theoretical data, predictive algorithms, curve-fitting algorithms, and general knowledge related to a certain soil property. The use of a standard grouping method will help the geotechnical engineer to access information quickly and efficiently with a minimized training time. Forms also make use of Windows 'intuitive' feel to further ease operation. Figure 4-2 shows a typical form in the KBS design. Parts of the form have been labeled to clarify future reference.

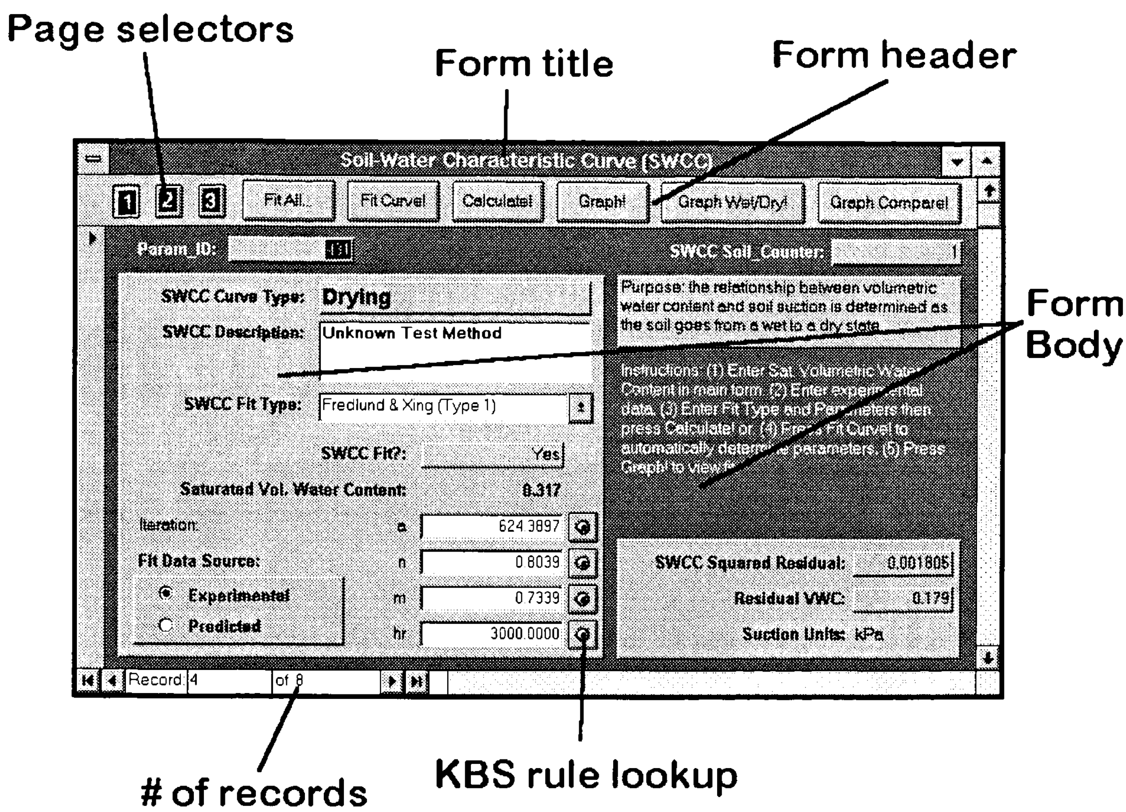


Figure 4-2 Composition of form in KBS design

The structure of the form header and form body is essential. The form header typically contains operations that can be performed on data shown in the form body. For example, the permeability form header contains options allowing access to algorithms or methods used to predict saturated and unsaturated hydraulic conductivities. Each form header contains options referencing methods unique to the type of data stored. The left side of the form header contains numbered options allowing quick access to the pages of the current form.

The form body includes all information presented between the form header and bottom scroll bar on all pages of the current form. Information is then subdivided graphically into sub-categories to aid in visual presentation. The first page of the forms generally present parameters controlling the behavior of the soil property. The second page typically displays the generated equation describing the property function and tables showing x-y points for both experimental and predicted soil functions.

4.2 Knowledge Representation

The area of Knowledge-Based Systems has blossomed over the past decade from merely an academic interest into a useful technology. Carrico (1989) describes Knowledge-Based 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)

The knowledge representation followed the knowledge acquisition phase. With a suitable amount of knowledge gathered, the structure and representation method for the knowledge system design is described. The general anatomy of a typical Knowledge-Based System can be seen in Figure 4-3. It consists of a collection of utilities and programs for the development environment and the delivery environment.

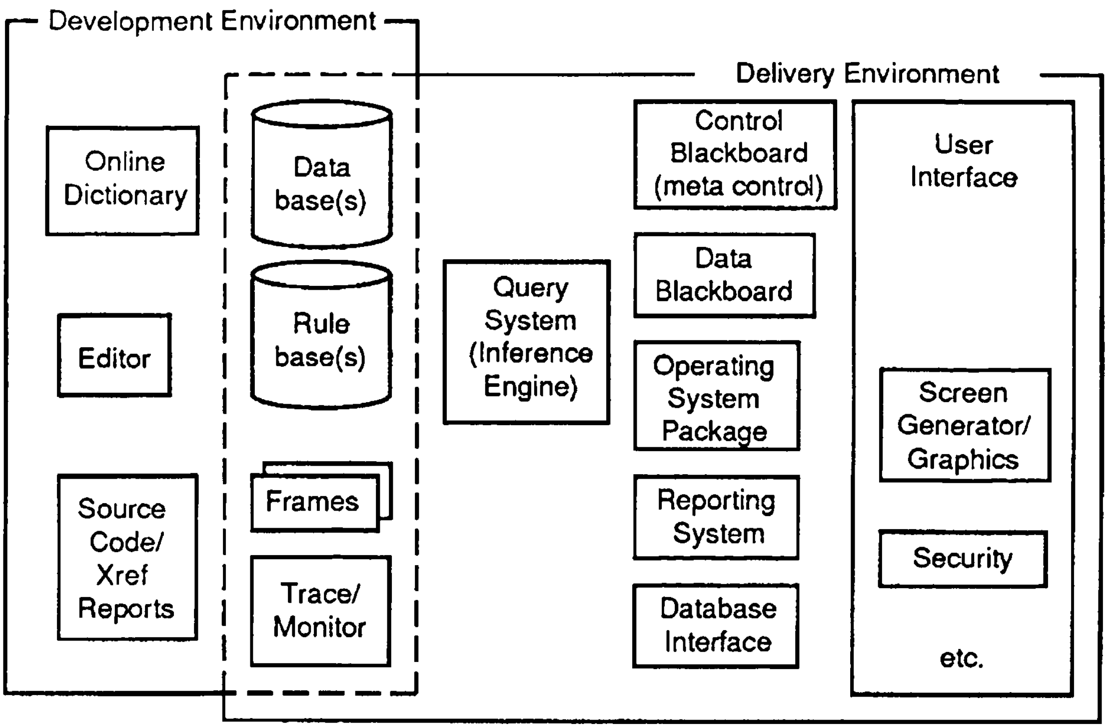


Figure 4-3 Anatomy of a knowledge-based system (Carrico, 1989)

The knowledge representation used in the current Knowledge-Based System design can be seen in Figure 4-4. The information required is represented in forms. Each form consists 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 interface which allows the information to be viewed in forms, tables, or charts. An example is the main soil information form which should contain soil texture, description, volume-mass relations, soil origin, as well as other soil properties. Another example is the permeability form which should store information related to the hydraulic conductivity of a soil as well as algorithms and rules applicable to this form. Independent of the knowledge forms is the query engine which allow for access to pertinent information. The query engine builds a query based on wizard-like forms.

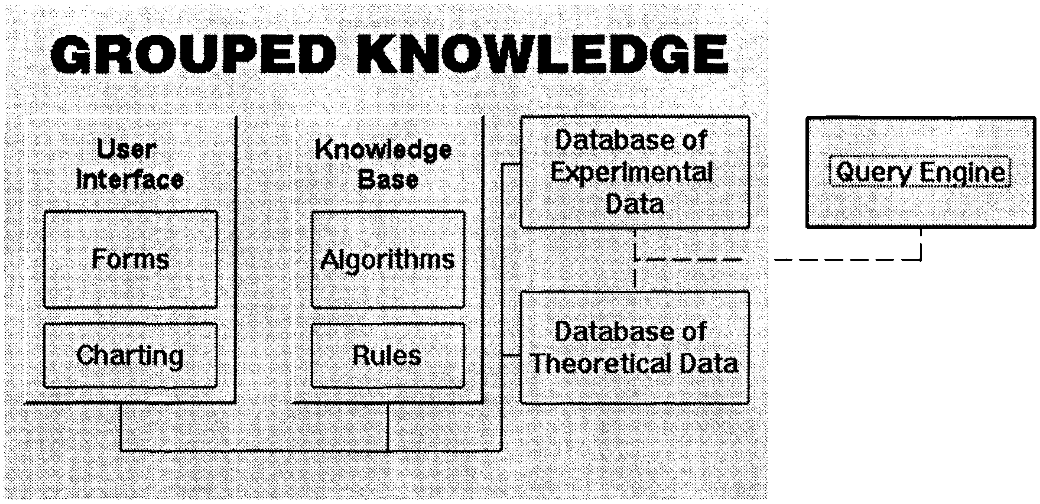


Figure 4-4 Representation of knowledge in the proposed system

The soil properties are organized into separate forms or sub-categories which are linked to the main soil information form. The manner in which this can be done is shown in Figure 4-5. While Figure 4-4 shows the theoretical structure of the Knowledge-Based System design, Figure 4-5 displays the proposed implementation of the system design in Access® which is a relational database program.

Knowledge-based systems typically contain an inference engine allowing for a decision-tree type of dialog between the system and the geotechnical engineer. The size of the unsaturated soil mechanics field and uncertainty regarding the application the system design dictated several decisions. A finite set of rules for the knowledge-base were selected in the design. This means the geotechnical engineer may only access a set of well-defined rules governing statistical estimation of soil parameters. This type of structure was selected for the sake of simplicity. The inference engine will therefore answer questions such as, "What is a good estimate of this soil parameter based on previous data?". Alternately, questions are "asked" by selecting options beside soil properties. Developing an inference engine capable of chaining and resolving ambiguity is beyond the scope of this thesis.

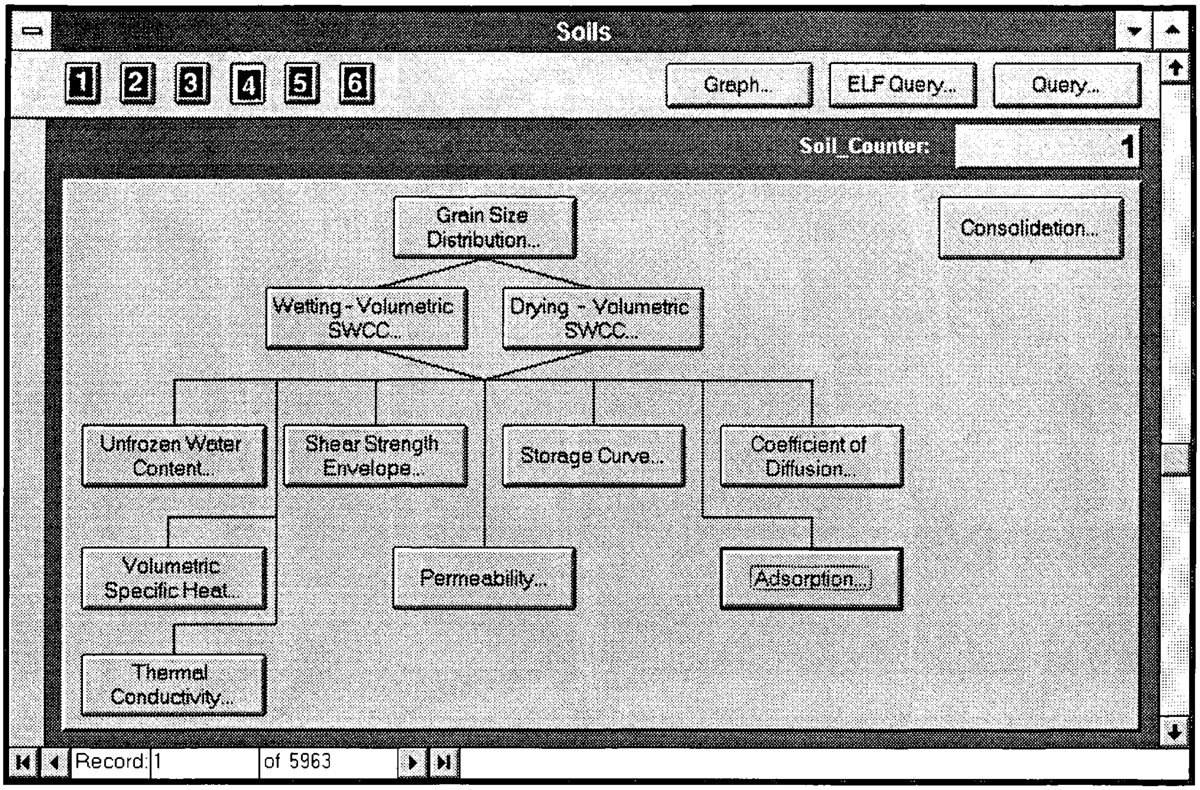


Figure 4-5 Knowledge forms included in system design

4.2.1 Knowledge-Base Volume-Mass Calculations

A fundamental component of the Knowledge-Based System design has the ability to calculate basic volume-mass properties once any three volume-mass properties are known. This is done by rearranging the equations describing the volume-mass properties of an unsaturated soil. Once any three volume-mass properties are known, the geotechnical engineer may the "lock" the properties. The Calculate option may then be selected to calculate the remaining volume-mass properties from the three locked properties. This is illustrated in Figure 4-6.

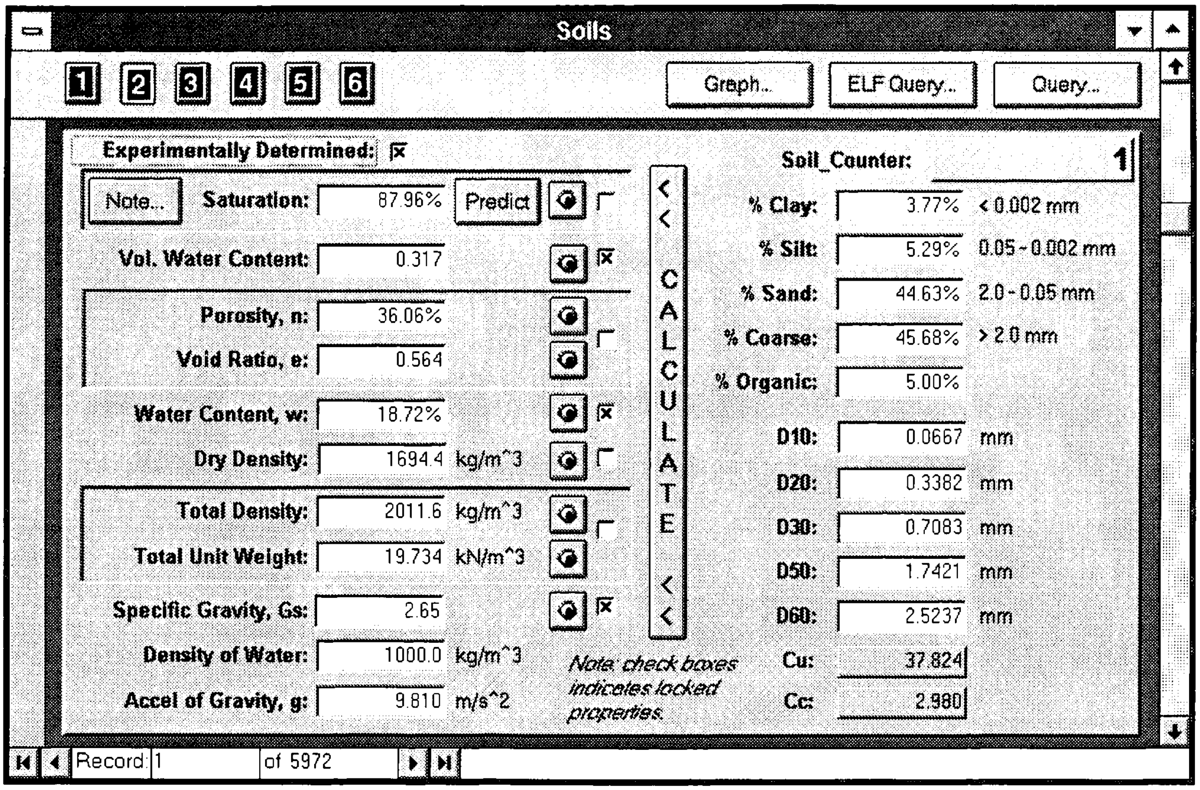


Figure 4-6 Volume-mass property page allowing calculation from three locked properties

An example of this might be as follows. A soil is obtained and the properties are as follows:

Volumetric water content, θw	0.35
Porosity, n	38%
Specific Gravity, Gs	2.63

The above properties are entered into page two of the main soil form and locked. Selecting the ***Calculate*** option yields the following properties:

Saturation:	92.11%
Void Ratio:	0.613
Porosity:	38.00%
Water Content:	21.46%
Volumetric Water Content:	0.35
Dry Density:	1630.6
Total Density:	1980.6
Total Unit Weight:	19.42969
Specific Gravity:	2.63

4.2.2 Knowledge-Base Curve Fitting

Standard database applications are of little use when representing unsaturated soil functions. Experimentally measured points along soil function curves may be stored in the database but a method of representing these data points must be developed.

Measured points on a soil function are of no use to a modelling program. The points must be interpreted as continuous in some fashion. Current modelling practice involves fitting a spline curve through experimental data points. This procedure results in unreasonable "humps" and dips in the soil function which then can lead to numerical instability in the modelling package (Sillers, 1996).

The developed knowledge-based system design uses mathematical equations to represent soil functions. These equations can be made to fit experimental data by the variation of their parameters. An example of this can be seen in [4.1] which is the equation used to fit the soil-water characteristic curve.

$$\theta = \theta_s\left(1 - \frac{\ln(1+\psi/\psi_r)}{\ln(1+1000000/\psi_r)}\right)\left[\frac{1}{\ln\left(e+(\psi/a)^n\right)}\right]^m \qquad \textbf{[4.1]}$$

where: ψ = total soil suction (kPa),

e = natural number, 2.71828...,

ψ_r = total suction (expressed in kPa) corresponding to the residual water content,

q_r,

a = a soil parameter which is related to the air entry value of the soil (kPa),

n = a soil parameter which controls the slope at the inflection point in the soil-

water characteristic curve,

m = a soil parameter which is related to the residual water content of the soil.

The parameters a, n, and m are varied according to the type of experimental data present. Varying the parameters manually would be time consuming so a least-squares algorithm was selected which fits parameters to equations.

The properties fit with an equation are grain-size, consolidation, and soil-water characteristic curve. New equations were developed to fit grain-size and consolidation data. A search of current literature by Sillers (1996) revealed 28 different equations that have been used to fit the soil-water characteristic curve. To avoid controversy, all 28 equations were implemented into the knowledge-based system design. The system design is capable, therefore, of fitting any of the 28 equations to experimental data. A listing of the different equations can be seen in Table 4-1. The equations were found to have one of three modifiers attached to the front of the equations. Equations were classed as Type 1, Type 2, or Type 3 depending on the modifier used.

Table 4-1 Summary of equations that can automatically be fit to experimental SWCC data in the Knowledge-Based System design

FIT TYPE FOR SWCC	
Fredlund & Xing (Type 1)	Fermi
van Genuchten (Type 1)	Gardner
van Genuchten, Mualem (Type 1)	van Genuchten, Burdine
van Genuchten, Burdine (Type 1)	van Genuchten, Mualem
Gardner (Type 1)	Boltzman (Type 2)
Boltzman (Type 1)	Brooks and Corey (Type 2)
Brutsaert (Type 1)	Brutsaert (Type 2)
Brooks and Corey (Type 1)	Fermi (Type 2)
Fermi (Type 1)	Gardner (Type 2)
Tani (Type 1)	Tani (Type 2)
vG, Mualem, New (Type 1)	van Genuchten, Burdine (Type 2)
Brooks and Corey	van Genuchten, Mualem (Type 2)
Brutsaert	Brooks and Corey, New (Type 1)
Boltzman	Tani

4.2.3 Knowledge-Base Prediction Algorithms

Algorithms were required to perform analytical predictions. These algorithms were developed and then linked to applicable forms by options. The development of the algorithms can be seen in Appendix B which presents the mathematical development of each prediction technique. Detailed development of each prediction technique can also be found in the sources listed in Table 3-1. Geotechnical engineers must enter the appropriate form, select the data on which to operate, and then initiate the algorithm. The implementation of the prediction algorithms can be seen in Section 4.5. Chapter 5 describes the theory and verification of the algorithms. Currently algorithms are not tied into an inference engine but are in a sense 'hard-wired' into the structure of the system design.

4.2.3.1 Methodology for Implementation of Prediction Algorithms

A search of current literature revealed that a wide variety of prediction methods have been presented. The variety of methods required a criteria to be developed. This criteria allowed certain methods to be selected for implementation into the knowledge-based system design.

The first criteria was the proposed method must have gained a certain degree of acceptance. The method must have been put into practice in the engineering field in some way. Experts in the respective fields of permeability, shear strength, thermal properties, and contaminant transport were consulted to obtain the most reliable prediction technique. It was then ensured that the prediction technique was reliable.

Secondly, prediction techniques fell into one of two categories. Predictions were either statistically based or theoretically based. Statistically based predictions of soil functions were more difficult to implement. They are also would typically limited to only one group of soils (e.g. Sands). Theoretically based predictions of soil functions showed the most reliability in predictions of varying soil types and were therefore implemented into the knowledge-based system design.

Once an analytical prediction technique was selected, its implementation involved two steps. Firstly, the theory and results of the prediction were duplicated with the help of MathCad®. Duplicating the results of the research confirmed that the theory presented was understood and implemented properly. The sensitivity of each of the input parameters could also be checked. Sample listings of the MathCad® pages used to check the theory can be seen in Appendix B. Once the results were implemented in MathCad® the next step was to implement the prediction technique in the knowledge-based system design. Algorithms were programmed in Visual Basic® to duplicate the results of MathCad®. Results of the algorithms were checked against the solutions obtained in MathCad® to ensure the accuracy of the results. The methodology presented allowed for confirmation that the prediction techniques were implemented properly.

4.2.4 Knowledge-Base Rules

Knowledge-base rules can be divided into two categories. The first category of rules are structural rules or rules which are inherent in the structure of the Knowledge-Based System (KBS) design. Structural rules may include rules of thumb (heuristics) such as reasonable ranges for certain parameters (e.g., Specific Gravity) or volume-mass relation rules such as the rules inherent on page two of the Soil form. Structural rules are 'hard-wired' into the KBS design and are designed to guide the input of data and enforce data integrity.

The second category of rules may be referred to as the Rule Base. Much research has been performed to estimate individual parameters for a soil. For example, data may be available for describing a certain soil but be missing the porosity of the soil. To estimate the missing porosity, a group of similar soils could be collected and the porosities noted. This procedure would produce a statistical distribution of similar porosities.

The KBS design mimics the aforementioned process to provide statistical estimations for soil parameters. Criteria specifying how to extract similar data from the database are stored in the Rule Base. This allows the geotechnical engineer to ask the Rule Base to estimate a certain parameter. The Rule Base then searches its rules to see if any of the rules apply. If a rule applies, the criteria is initiated and a query brings up a statistical frequency distribution of the resulting values. The geotechnical engineer then has the choice of accepting or rejecting the proposed estimation. Figure 4-7 shows the Rule Base form and its resulting estimation.

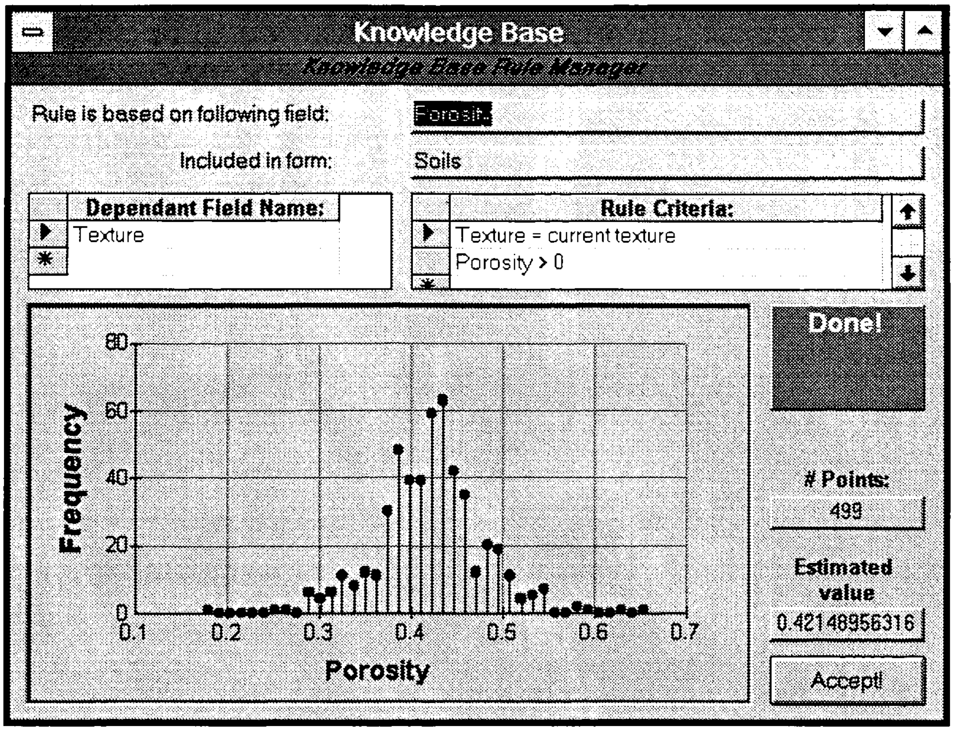


Figure 4-7 Knowledge-base Rule Manager form

The reliability of the rule base predictions is a function of the amount of data currently in the database. Predictions of basic volume-mass properties such as porosity, specific gravity, and dry density will be reasonably sound due to the large amount of available data. For parameters such as the Shear Parameter, there is less data to draw upon and therefore the resulting prediction may lack confidence. However, as data is added to the system design, the predictions will become increasingly accurate. The Rule Base therefore has a limited capacity to "learn" from its past as data is added to the system design.

4.3 General Operation of The Knowledge-Based System design

Productive use of the Knowledge-Based System design requires basic knowledge of its proposed implementation. This is not to confuse but to provide insight into the capabilities of the Knowledge-Based System design. The following sections will outline how information can be stored, how information can be viewed and manipulated, and a short description of how to travel around in the Knowledge-Based System design. Functions which deal with many soils at a time are also outlined. The Knowledge-Based System design allows for storage of many different soils and this can be quite confusing. Selectively extracting information meeting a certain criteria is often desired. This process is called Querying and will be subsequently described. Once a certain group of soils has been selected, property functions for the entire group can be placed on a single graph through the Graph Manager.

4.3.1 Information Storage

Microsoft's Access relational database program suggests that information in a system be stored in two separate files. One file will contain the data used by the system design while the other file stores all information describing an application. Hard soil data is stored in a file entitled DATA.MDB while the description of an application itself is contained in the file APPLICAT.MDB. This format allows changes to be made to an application without changing any of the data previously generated. New versions of an application can be linked to previously created datasets easily and error free.

Within the DATA.MDB file, information is stored in tables made up of columns and rows. Each column represents a piece of information stored for each entry in the table. Rows in the table are referred to as records and contain the values of all columns for a certain topic. A typical table is shown in Figure 4-8. Primary soils information such as texture, volume-mass relations, atterberg limits, source and location information is stored in a table entitled Soils. To optimize storage efficiency, each related unsaturated soil property function such as permeability, shear strength, or the SWCC has been given its own table and linked to the Soils table. This creates a table structure as outlined in Figure 4-9.

Table: Diffusion

Diffu_ID	Diffusion Soil Cou	Diffusion Descripti	Diffusion Fit Type	Diffusion Curve T
5	1	Trial of drying curve	Fredlund & Xing (Ty	
6	1	Trial of wetting curv	Fredlund & Xing (Ty	
7	350	Potassium - back c	Fredlund & Xing (Ty	
8	350	Chloride - back calc	Fredlund & Xing (Ty	
9	350	Deuterium - back ca	Fredlund & Xing (Ty	
10	351	Potassium - back c	Fredlund & Xing (Ty	
(Counter)	0			

Record: 1 of 6

Figure 4-8 Typical table showing organization of soils information

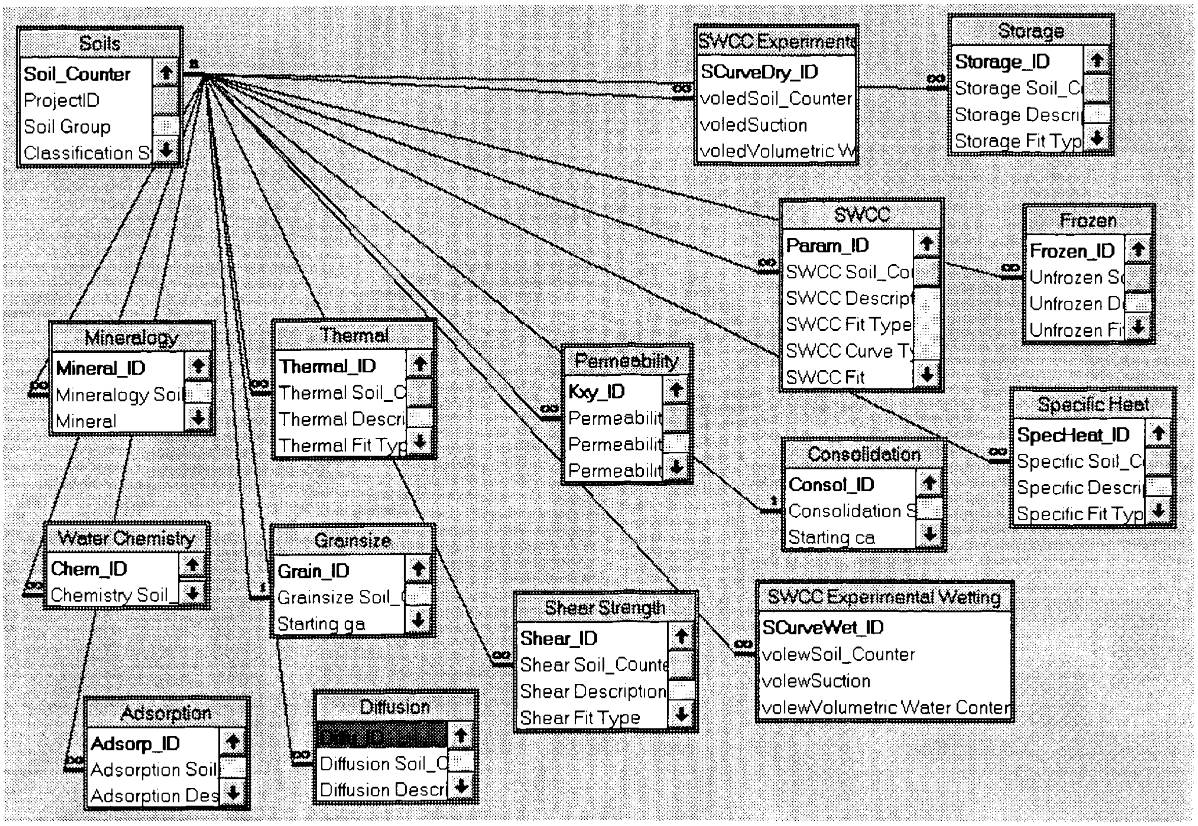


Figure 4-9 Graphical display of links between primary database tables

4.3.2 Viewing and changing of information

Information stored in the Knowledge-Based System design is viewed through forms. These forms have two different display modes entitled form and datasheet. The form view is the default view and presents information in a form-type view. Options are provided in form view to allow access to prediction algorithms, curve fit algorithms, knowledge-base lookup buttons (KBLB) and other such information. The datasheet view is organized like an EXCEL™ spreadsheet and only allows viewing of the raw data in table form. The form view is the default view and is selected when a form is first opened. Changes to the raw data are allowed in either form view or datasheet view.

4.3.3 Structure of the Knowledge-Based System design Soils Information

The structure of soils information closely follows the layout of the tables shown in Figure 4-9. A form was designed for each table to allow viewing and editing of information in the proper manner. Forms radiate out from the main Soil form and are linked together to provide all information on the current soil selected in the Soil form. Figure 4-10 shows the forms that can be accessed from the Soil form.

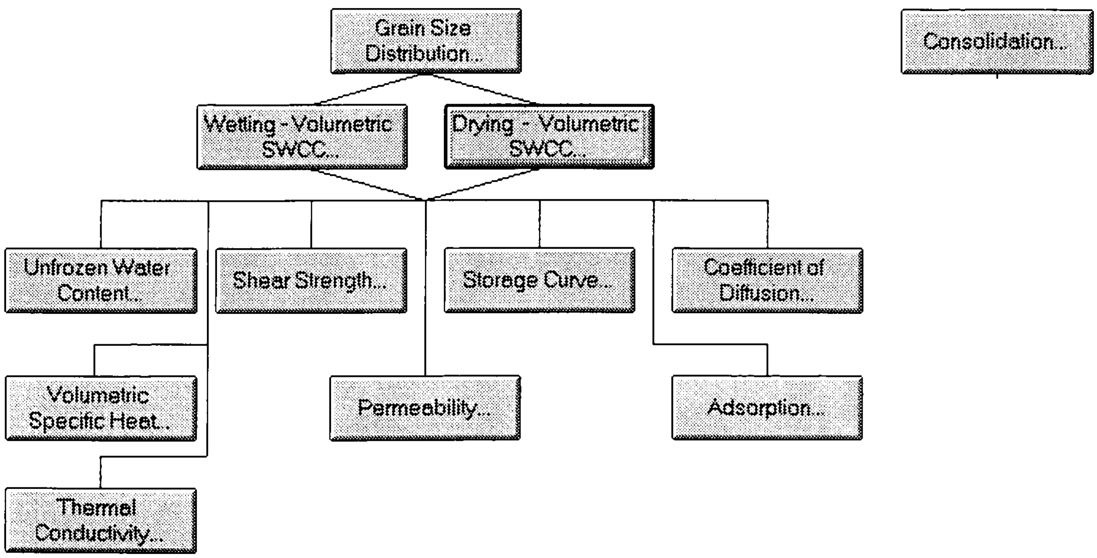


Figure 4-10 Organization of forms linked to main Soil form

Soil information stored in the database is often not complete. It is unusual for information on shear strength, permeability, adsorption and thermal conductivity to be complete for one soil.

4.3.4 Querying

Querying allows geotechnical engineers to find and display pieces of data (or collections of data of interest). The dataset sample used in the Knowledge-Based System design contains information on many soils. Dealing with this information at one time can be overwhelming. By allowing querying the database, a subset of soils can be selected for manipulation. The Knowledge-Based System design includes two methods of querying the database. The first method allows the geotechnical engineer access to the fields making up the soil information tables. Criteria and sorting order can be specified to produce a selected subset of soils. The second method provides a more general method of selecting soil information. English language questions can be typed into the computer to obtain soil information. This allows geotechnical engineers less familiar with the KBS design to access information quickly and easily.

4.3.4.1 Query Manager

The Query Manager provides access to previously stored queries as well as allowing for the creation of new queries. An example of a query manager form is displayed in Figure 4-11. Functions are provided to allow queries to be created, deleted, applied, viewed, and graphed. An old query can also be applied to a new form by selecting the query and selecting the form the query is to be applied to.

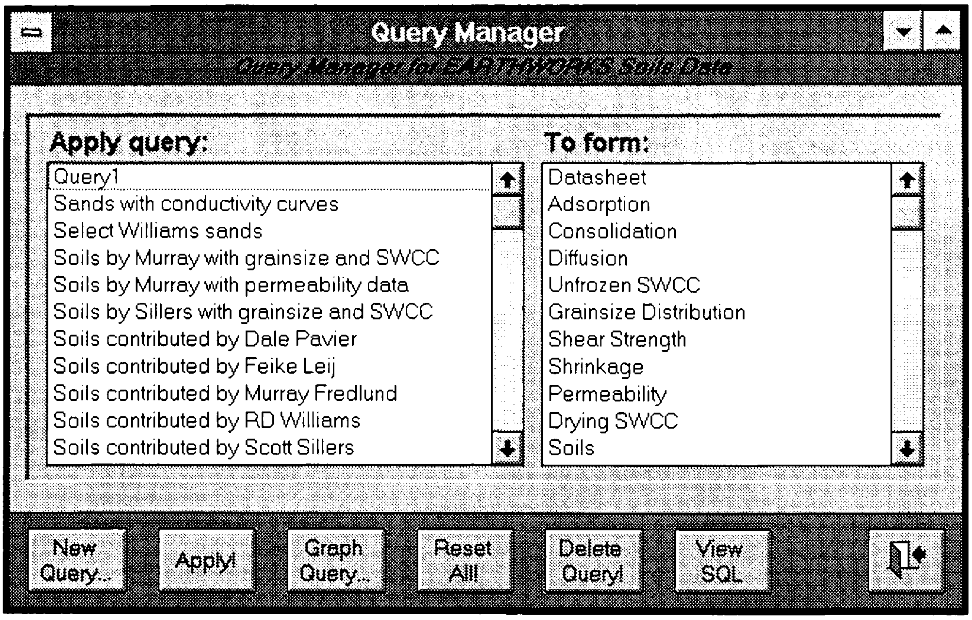


Figure 4-11 Query Manager form

4.3.4.2 Graphing two variables against each other in a query

The query manager used in the design allows two numerical fields to be plotted against each other on a graph. This feature is particularly useful for identifying correlations between various soil properties. Which two fields to be used for plotting is determined by selecting the Graph Query shown in Figure 4-11. This brings up the form shown in Figure 4-12 which allows for an x and y field to be selected. A typical plot of plastic limit versus residual volumetric water content is shown in Figure 4-13.

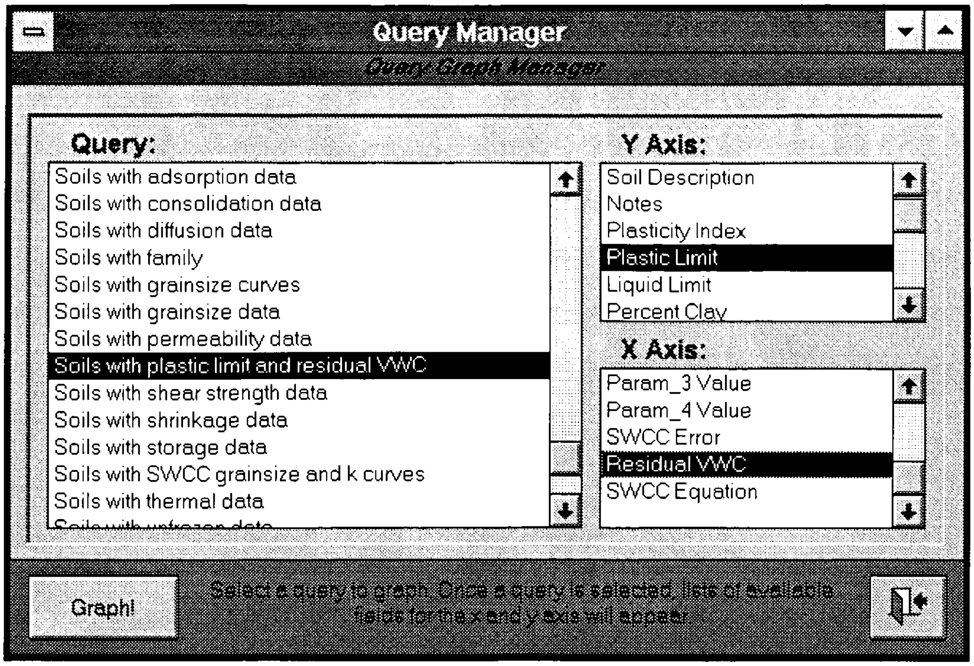


Figure 4-12 Query Graph Manager form

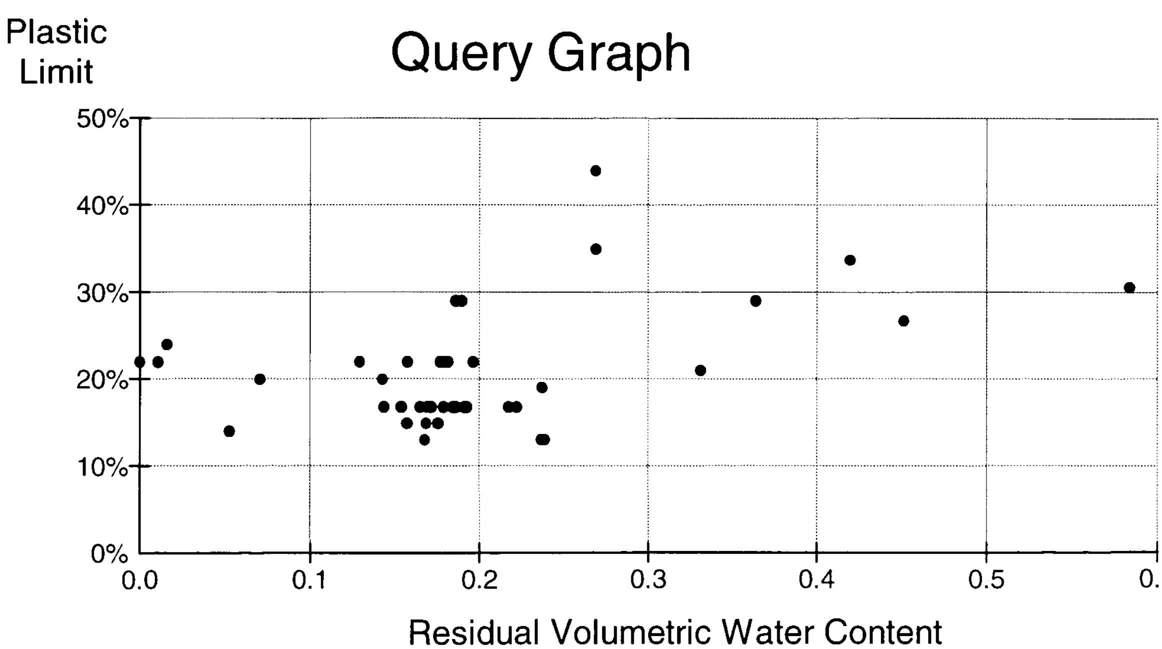


Figure 4-13 Typical plot of plastic limit vs. residual volumetric water content produced from query

4.3.5 Graphing multiple property functions

In unsaturated soil mechanics, it is often desired to plot the property functions of several different soils together on the same plot. This can be accomplished through the Graph Manager which is started by selecting the Graph option on the form header of the Soil form (Figure 4-14). Once the property curve along with the fit type, curve type, and x axis variable have been selected, the Graph option is used to begin searching for curves. The Graph Manager also displays the number of soils currently selected and the maximum number of curves that will be plotted on one graph.

The algorithm used in the KBS design to select curves operates as follows. The soils selected in the current query are sequentially searched to see if they have data points generated on the fit curve (experimental points are not plotted). Only curves with generated data points will be plotted. Searching for curves can be quite lengthy if many soils are selected. The searching process can be stopped by selecting the Stop option in the pop-up window. If the searching process is stopped, the number of property curves that have been selected so far will be plotted. Figure 4-15 shows plots where property curves have been combined onto one plot.

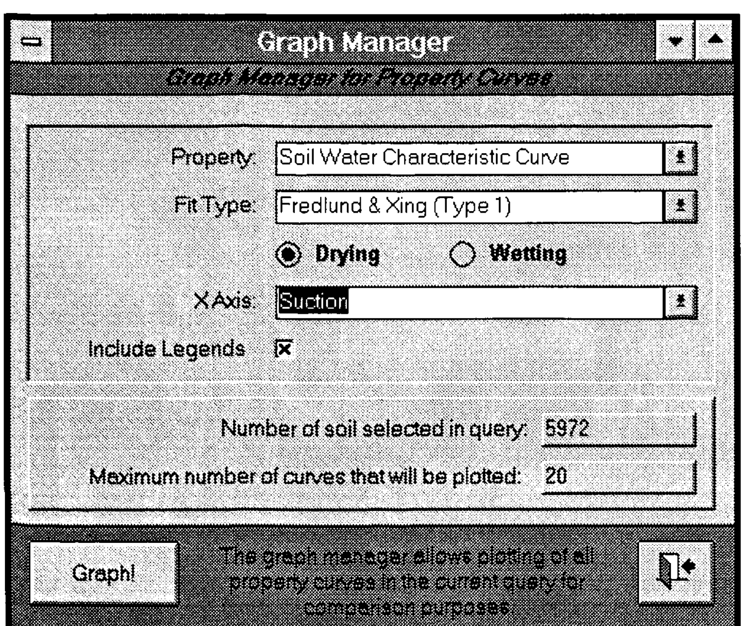


Figure 4-14 Display of the Graph Manager for Property Curves

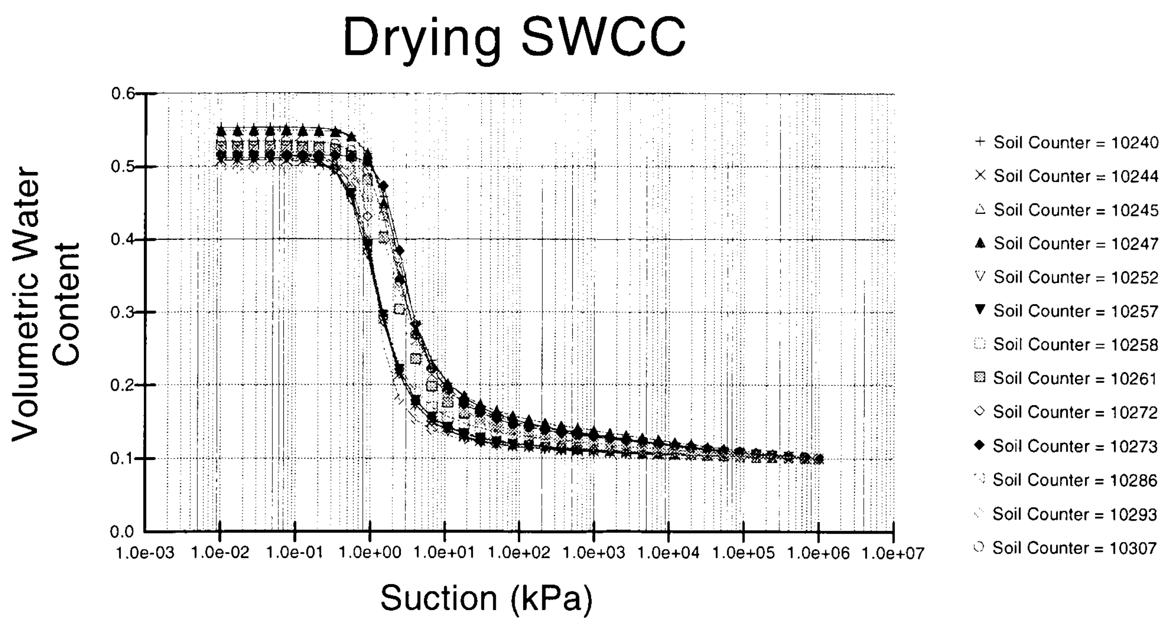


Figure 4-15 SWCC for sands from R.D. Williams data

4.4 Main Soil Information Form

The fields used in the design for classification of the soil were adopted from current USDA soil databases for the sake of familiarity. Figure 4-16 shows the main text descriptors used to classify soils. The volume-mass and grain-size properties have also been used for soil classification and are shown in Figure 4-17. Other soil properties stored include 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 .

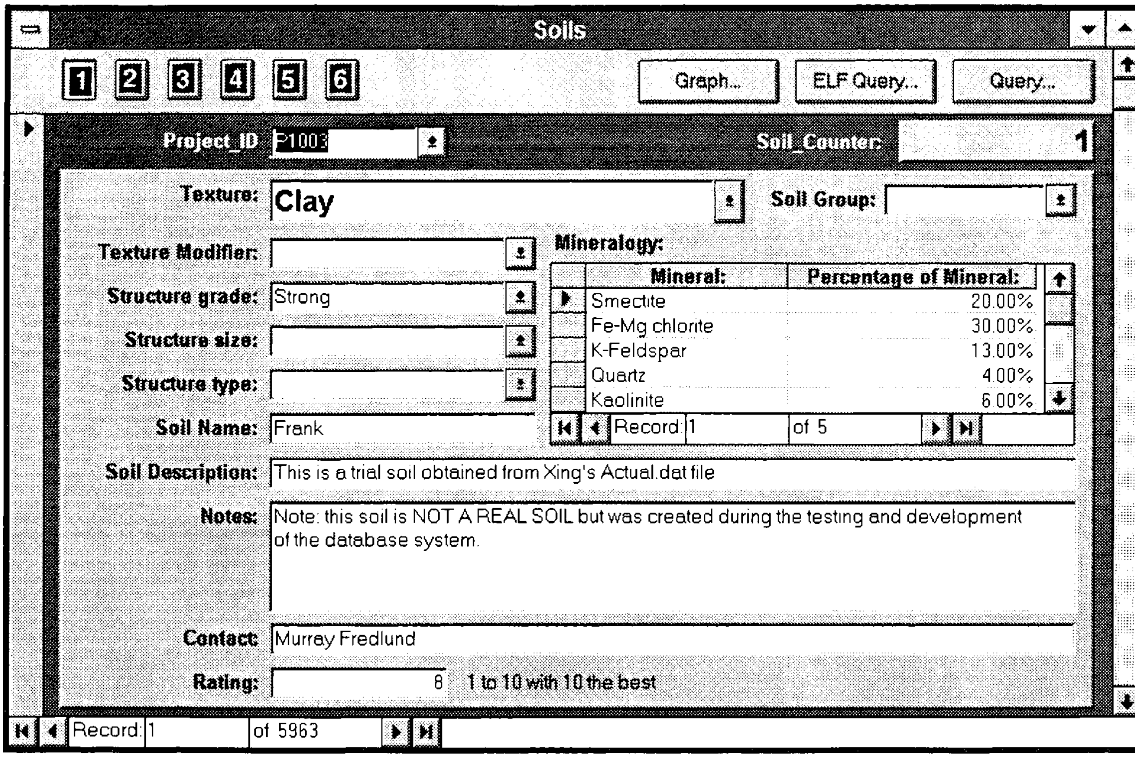


Figure 4-16 Page one of the main soil form showing classification properties

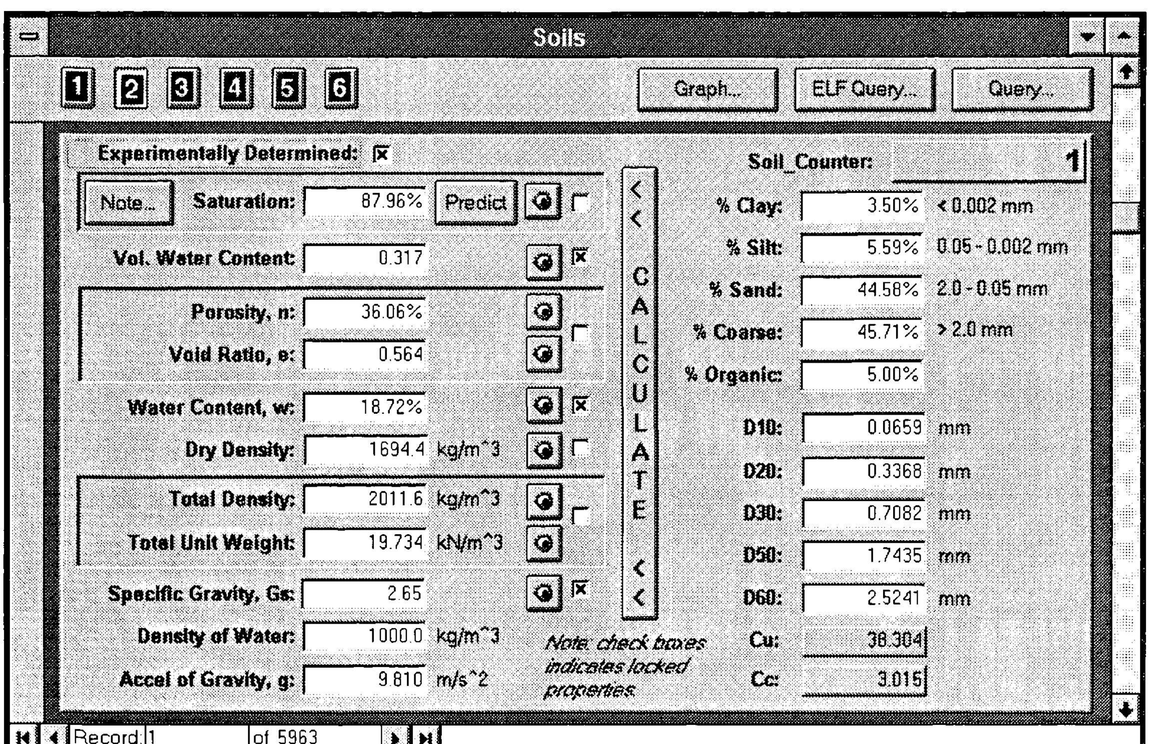


Figure 4-17 Page two of the main soil form showing volume-mass classification properties

The main soil information form also provides links to the forms describing soil properties such as SWCC, permeability, and shear strength etc. Navigating the linked forms can be accomplished by selecting page 4 of the Soil form and choosing an option as shown in Figure 4-10. A description of the forms linked to the Soil form are shown in the following sections.

4.5 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	SWCC
Storage	Permeability
Shear strength	Consolidation
Specific heat	Thermal conductivity
Unfrozen volumetric water content	Diffusion
Adsorption	

Soil properties fall into one of two categories. Properties are either fit with a curve-fitting algorithm or they are theoretically predicted. Fitting a curve to experimental data requires several elements. An equation used to fit the data is required. This equation typically has three or four unknown parameters that must be determined for each set of experimental data. The use of a linear regression curve fitting algorithm allows the parameters to be found quickly and efficiently. Once an equation is fit to data, this provides a continuous, mathematical description of how the soil property performs which can be used for further calculations. Fit soil properties include the SWCC, grain-size distribution, and consolidation curve.

Theoretically predicted soil functions use fitted curves to begin calculations. The data used as input in each individual prediction is outlined in the following sections. Instead of the equation parameters that vary in the fit curves, predicted curves have typically one or more parameters that vary to account for uncertainty in the prediction. Soil property curves that are predicted are: adsorption, diffusion, unfrozen volumetric water content, specific heat, thermal conductivity, permeability, shear strength, and storage. Details regarding the fit or prediction of the aforementioned curves can be found in the following sections.

4.5.1 Implementation of Grain-size Distribution Function

All information relevant in describing the grain-size is organized in a single form in the KBS design. This form can be reached by selecting the Grain Size Distribution option on page four of the Soil form. Figure 4-18 shows the grain-size form developed for the KBS design. Two pages are required to present the information necessary. The first page contains parameters controlling the fit of grain-size, the Smallest Particle Diameter, the error between fit data and experimental data, the error between predicted SWCC and experimental data predicted and experimental data, and counters which Access® uses to identify individual records. Page one also contains the Packing Porosity field which controls the prediction of the soil-water characteristic curve. Page two displays the equation used to fit the experimental data as well as experimental data points and generated data points on the fit curve. Figure 4-19 shows the second page of the Grain-size form.

The form header allows for a number of helpful functions and algorithms. If soil data consists of % Coarse, % Sand, % Silt, % Clay or D10, D20, D30, D50, or D60 data on page two of the main soil form, selecting the Load from property info option converts the data into experimental points on the grain-size distribution graph. Once experimental data is obtained, a linear regression algorithm is used to fit the equation to experimental data. The fit equation can then be used to generate more accurate % Coarse, % Sand, % Silt, % Clay or D10, D20, D30, D50, or D60 data by selecting Update property info. The results of the fit can be viewed by the geotechnical engineer by using the Graph option.

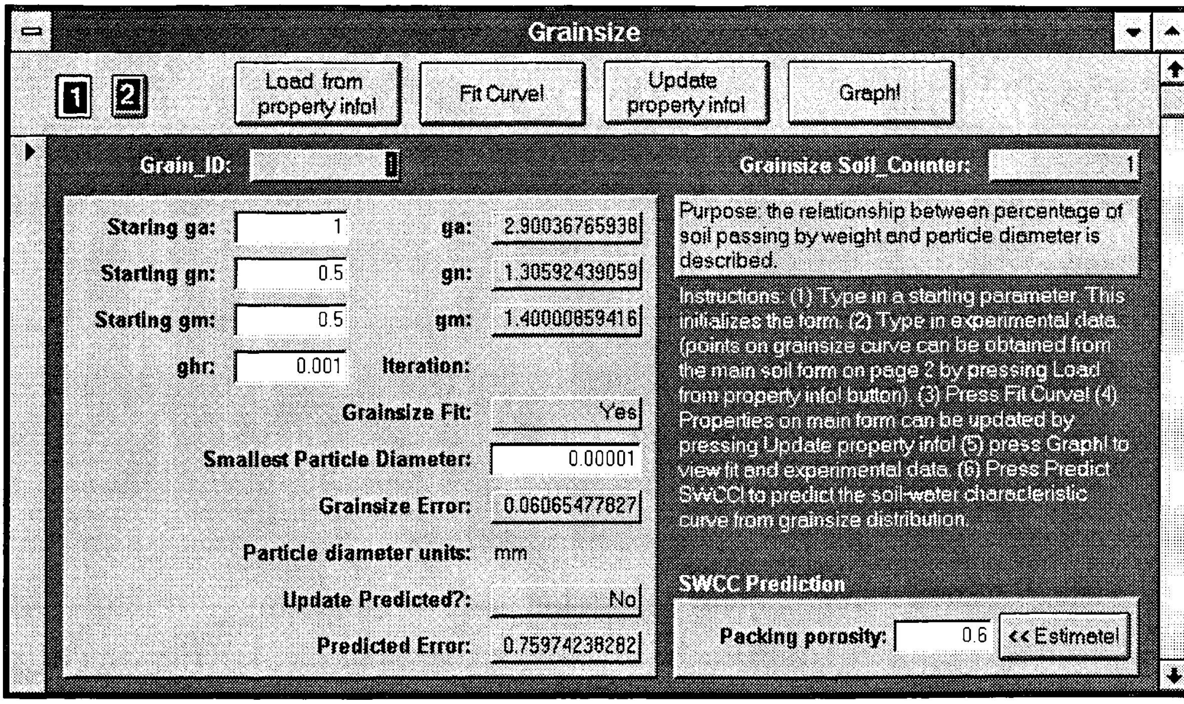


Figure 4-18 Page one of the grain-size distribution form

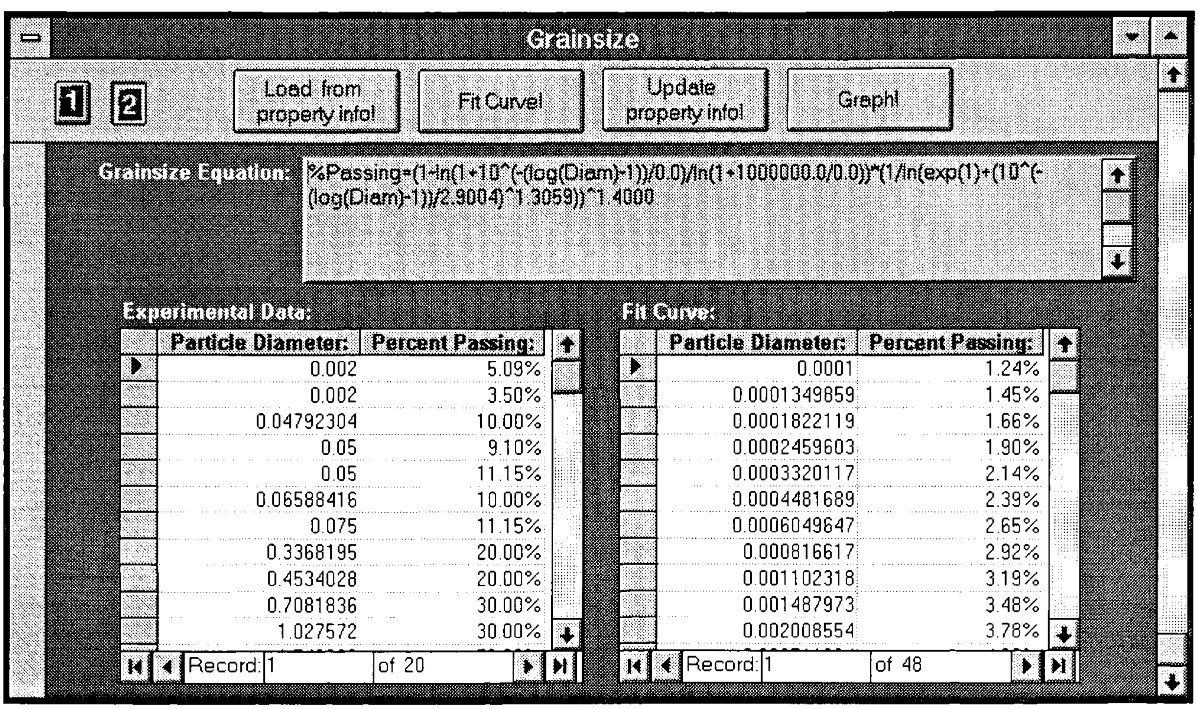


Figure 4-19 Page two of the grain-size distribution form

4.5.2 Implementation of the Soil-Water Characteristic Curve

Page one of the SWCC form can be seen in Figure 4-20. This form stores pertinent information relating to the SWCC as well as experimental and fitted points on the curve. As can be seen in Figure 4-21, once experimental data is fit with a curve, the equation describing the curve is stored in the database. A focus of the Knowledge-Based System design was to allow mathematical representation of soil property functions wherever possible. This then allows the equations to be entered into popular finite element modelling packages for modelling of unsaturated soil behavior. To provide a starting point for mathematical representation, the SWCC, grain-size distribution, and consolidation curves must be fit with a mathematical equation. A single equation was selected to fit each of grain-size and consolidation curves. For the SWCC, however, a number of different equations have been previously used. To accommodate this variability, 28 different equations are available for use in the system design. The equations were found to have one of three modifiers attached to the front of the equations. Equations were then classed as Type 1, Type 2, or Type 3 depending on the modifier used. A listing of equations can be seen in the following chapter in Table 4-1. 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 selected.

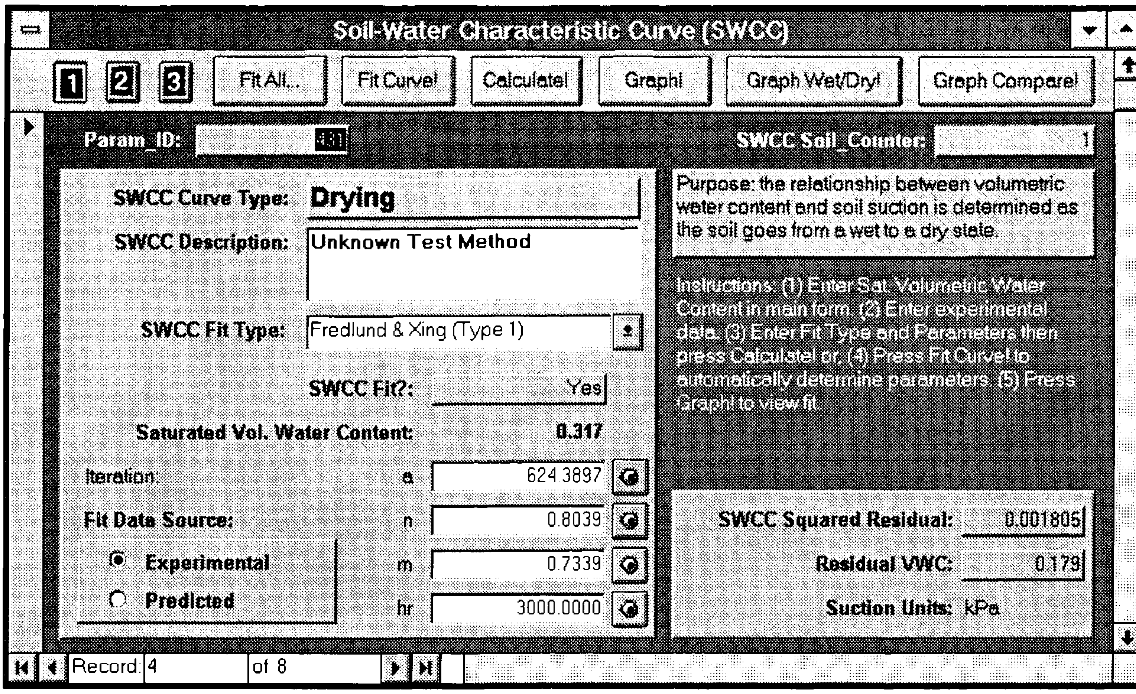


Figure 4-20 Page one of form describing SWCC information

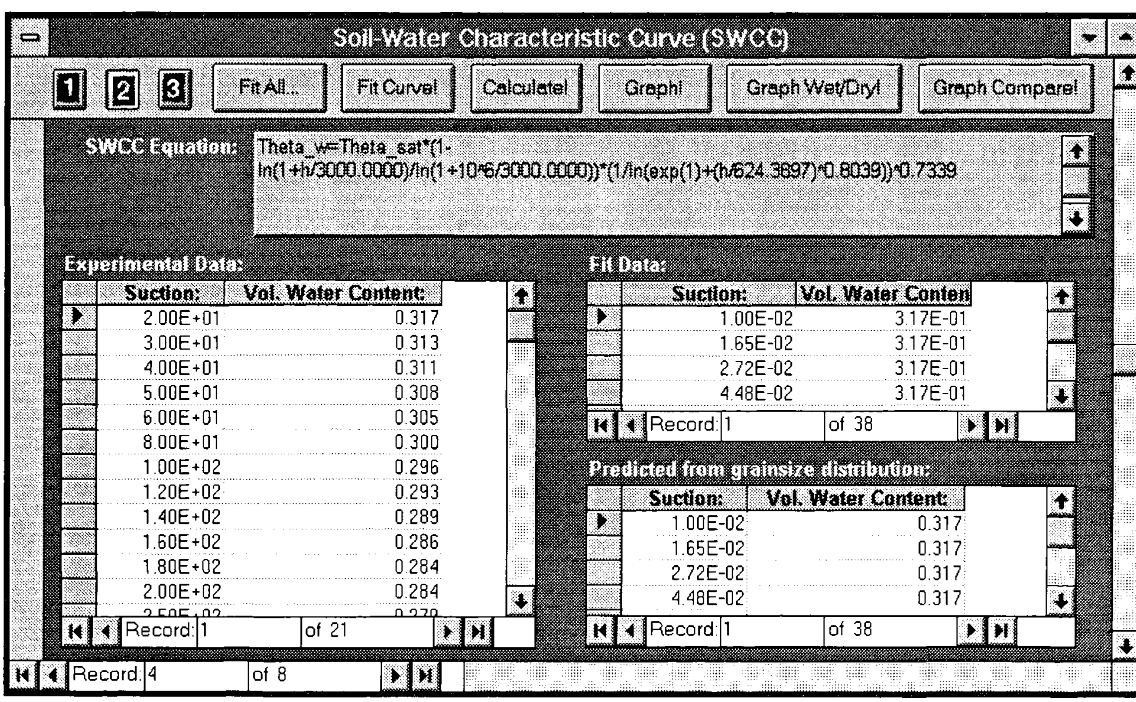


Figure 4-21 Page two of form describing SWCC information

Once an equation is fit to experimental data, the resulting equation can be used in the calculation of other soil properties.

4.5.3 Implementation of the Storage Function

All information relevant in describing the storage function is organized in a single form in the KBS design. This form can be reached by selecting the Storage option on page four of the Soil form. Figure 4-22 shows the storage form for the KBS design. Once a storage fit type has been specified, selecting the predict option generates an equation as well as points on the curve so the storage curve may be viewed.

The Query Manager contains a query which will select a subset of soils containing the desired information since not all soils in the database have storage information.

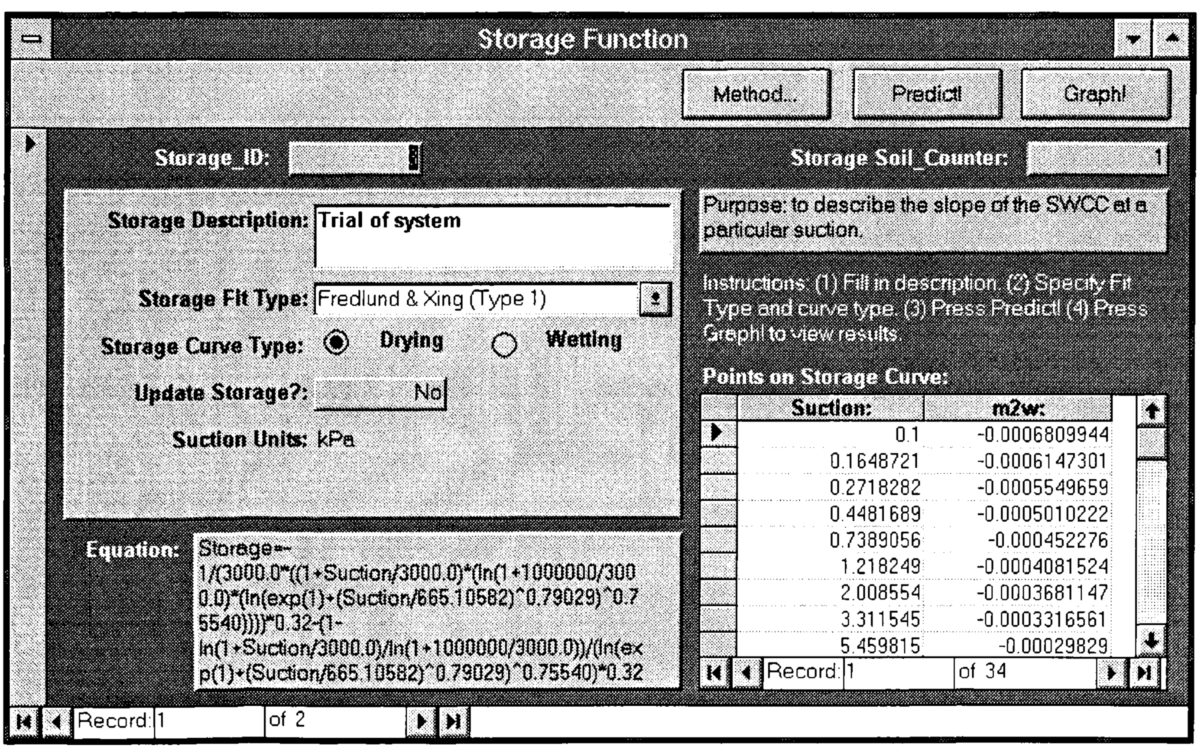


Figure 4-22 Storage form for the KBS design

4.5.4 Implementation of the Permeability Function

All information relevant in describing the hydraulic conductivity function is organized in a single form in the KBS design. This form can be reached by using the Permeability option on page four of the Soil form. Figure 4-23 shows page one of the permeability form developed for the KBS design. Two pages are required to present the information necessary. The first page contains the saturated hydraulic conductivities for directions one and two. The angle of inclination of Saturated kw1 and Saturated kw2 is defined by the Alpha Angle field. The conductivities Saturated kw1 and Saturated kw2 are always at a right angle to each other. The Permeability Description field allows for a short description of the current record while the Permeability Fit Type and Permeability Curve Type fields describe the SWCC to use in the prediction method. It must be noted that parameters for a SWCC must first be generated before a hydraulic conductivity curve can be predicted.

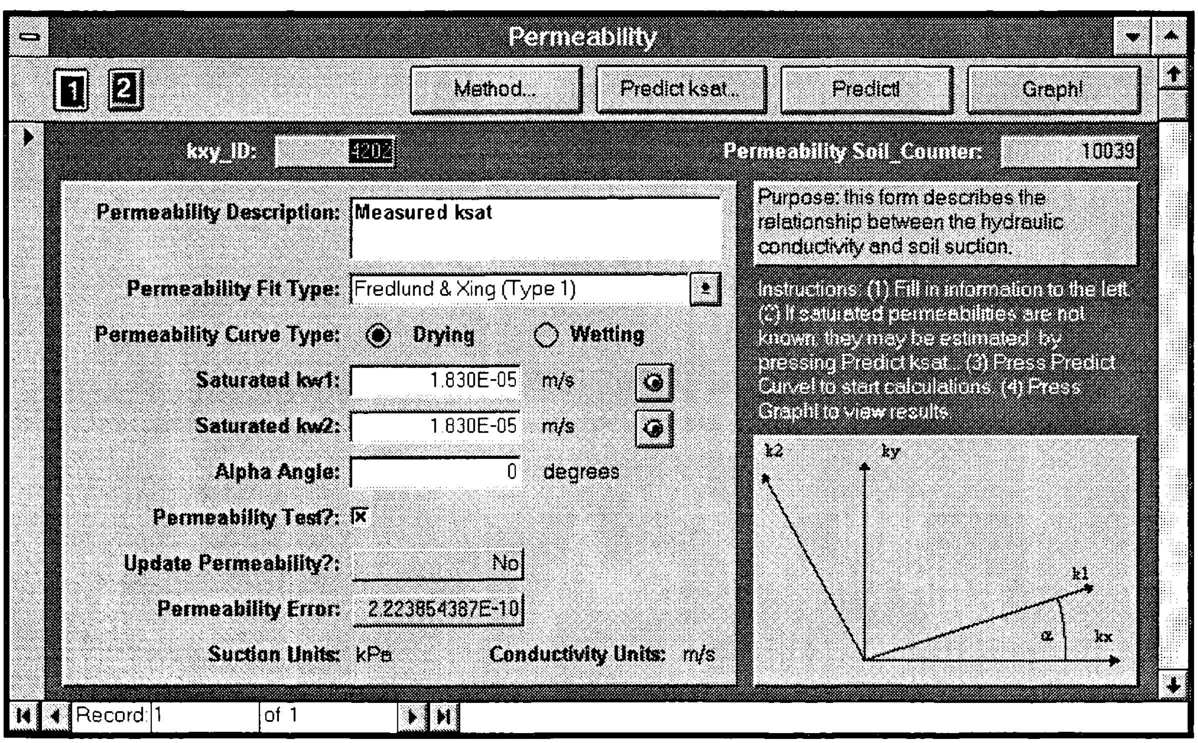


Figure 4-23 Page one of the permeability form

Page two of the permeability form shown in Figure 4-24, contains points generated on the permeability curves in each of the two directions as well as experimental points for comparison purposes. Once the form information has been specified, the prediction algorithm is initiated. The form header also allows graphing of the generated points once the prediction algorithm is completed.

The Query Manager contains a query which will select a subset of soils containing the desired information since not all soils in the database have permeability information.

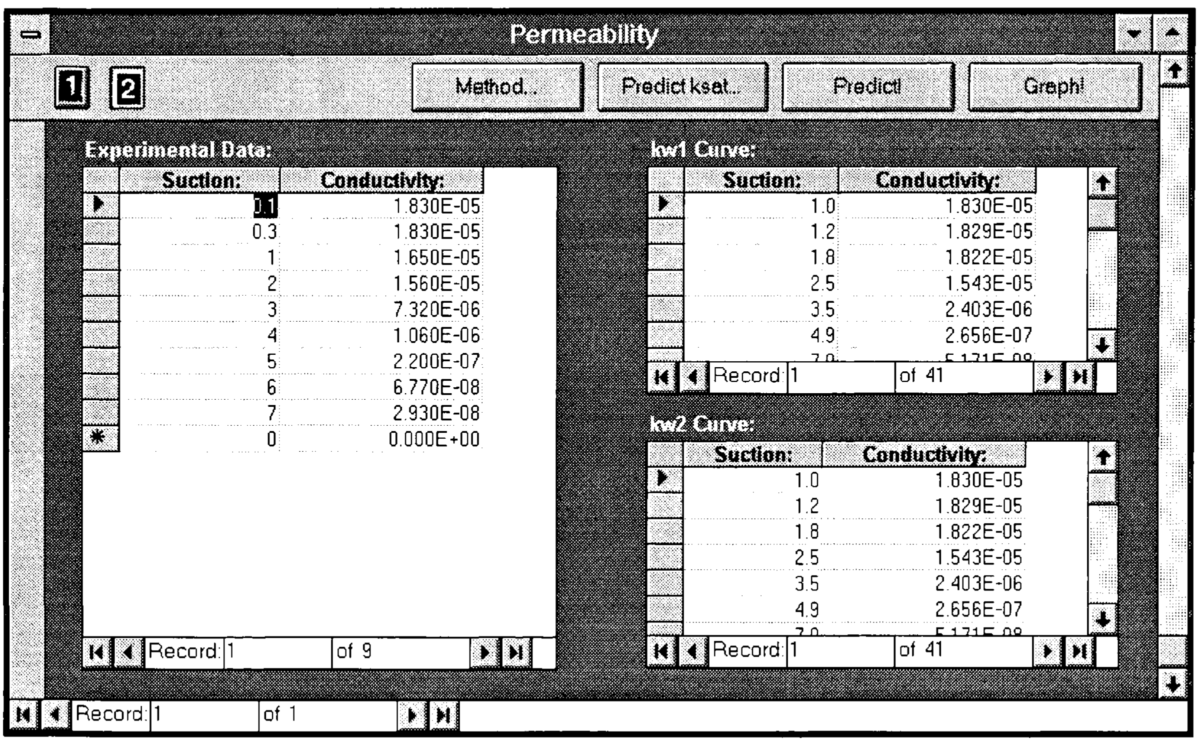


Figure 4-24 Page two of permeability form

4.5.5 Implementation of the Shear Strength Function

All information relevant in describing the shear strength function is organized in a single form in the KBS design. This form can be reached by selecting the Shear Strength option on page four of the Soil form. Figure 4-25 shows page one of the shear strength forms for the KBS design. Two pages are required to present the information necessary. The first page contains the effective angle of internal friction and the effective cohesion parameters. These two parameters along with the SWCC are needed for the prediction of the shear strength envelope. A shear parameter is also provided to vary the prediction. The shear parameter controls the degree to which the water phase affects the shear strength of the soil. A shear parameter of 1.0 takes full account of the water phase while higher values discount the contribution of suction and water to shear strength.

Page two of the shear strength form (shown in Figure 4-26) contains plotting information, the equation of the shear strength envelope, experimental points, and points predicted by the algorithm. Information on page two must be entered after page one has been completed. The plotting information does not change the generated equation but changes how points are generated. 2-dimensional or 3-dimensional plots may be selected and linear or logarithmic scales can be used on the 2-dimensional plot. Once plotting information has been specified, the prediction algorithm is initiated. The form header also allows graphing of the generated points once the prediction algorithm is completed.

As stated previously, the Query Manager contains a query which will select a subset of soils containing the desired information since not all soils in the database have shear strength information.

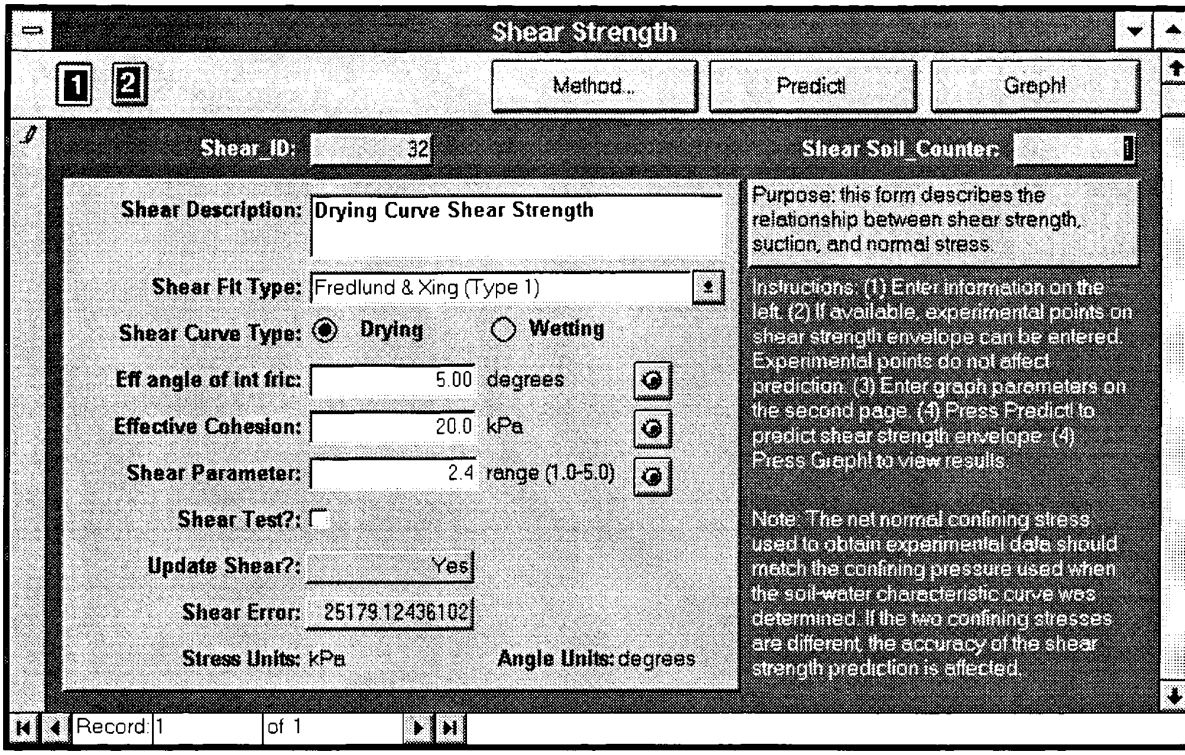


Figure 4-25 Page one of shear strength form

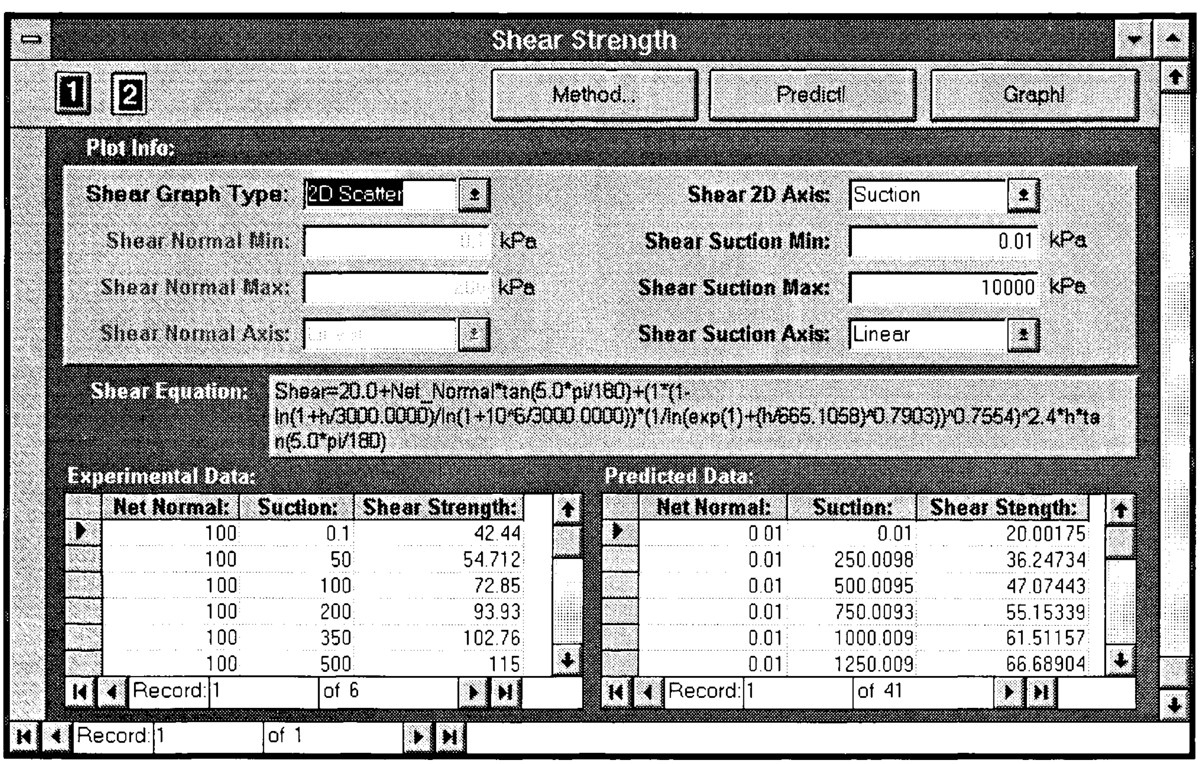


Figure 4-26 View showing page two of shear strength form

4.5.6 Implementation of Compression Function

All information relevant in describing the consolidation function is organized in a single form in the KBS design. This form can be reached by selecting the Consolidation option on page four of the Soil form. Figure 4-27 and Figure 4-28 show the consolidation form for the KBS design. Two pages are required to present the necessary information. The first page contains parameters controlling the fit of the equation, the error between fit and experimental data, maximum void ratio, and counters which Access® uses to identify individual records. Page two displays the equation used to fit the experimental data as well as experimental data points and generated data points on the fit curve.

The form header allows for fitting of the consolidation equation to experimental data as well as graphing both experimental and fit data. When the Fit Curve option is selected, the curve fitting algorithm is initiated and begins trying to optimize the equation parameters beginning with the starting guesses. Once a suitable fit is found and the error is minimized, an equation is generated describing the fit curve. Points are also generated along the fit curve to allow viewing of the data. The points generated on the fit curve are not used in any further calculations but are merely to allow viewing of the fit curve.

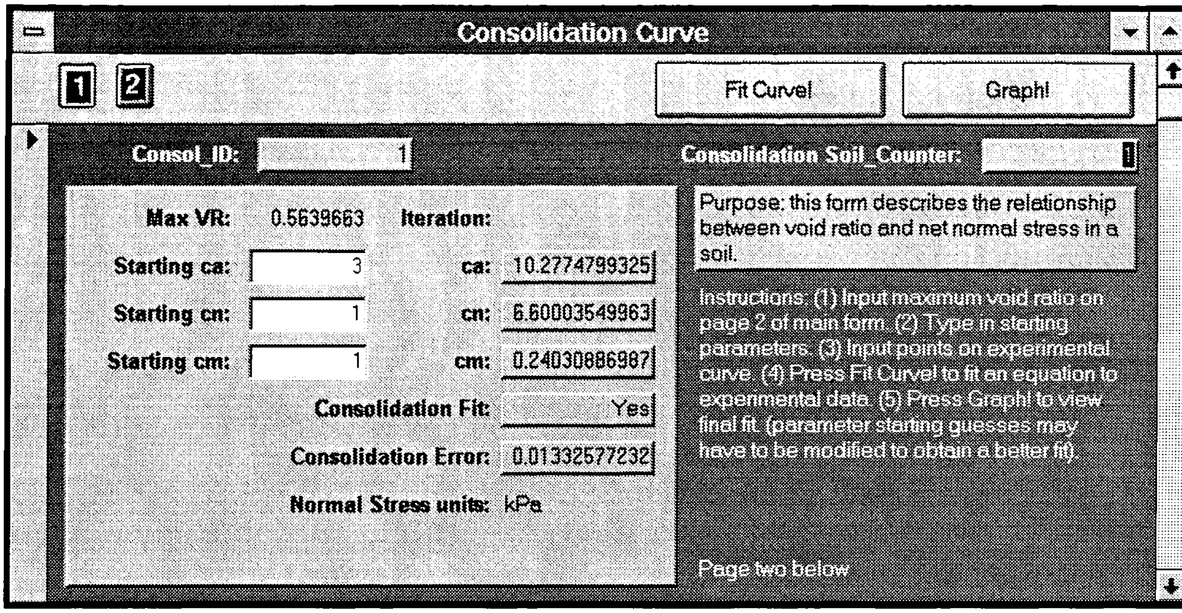


Figure 4-27 Organization of page 1 of interface for consolidation form

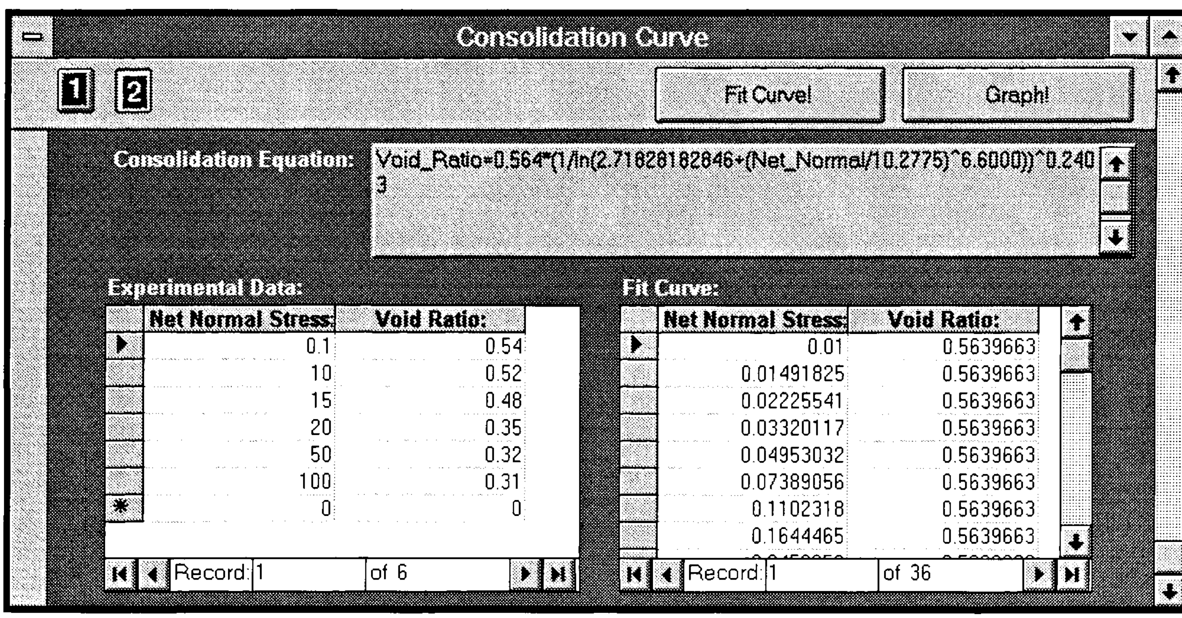


Figure 4-28 Organization of page 2 of interface in consolidation form

4.5.7 Implementation of the Specific Heat Function

All information relevant in describing the specific heat function is organized in a single form in the KBS design. This form can be reached by using the Specific Heat option on page four of the Soil form. Figure 4-29 shows the specific heat form for the KBS design. Two pages are required to present the information necessary. The first page contains parameters controlling the type of SWCC equation to use, dry density, specific heat of soil particles, and counters which Access® uses to identify individual records. Page two displays the equation used to fit the experimental data as well as generated data points on the fit curve.

The form header allows for estimating the specific heat of the soil particles as well as predicting and graphing the generated curve. Selecting the Predict SH of Soil option brings up a table of typical specific heats of soil particles. Estimation of the current soil property can be obtained from this table. Choosing the Predict option will then initiate the prediction algorithm which will generate an equation describing how volumetric specific heat varies with suction as well as generating points on the curve for viewing purposes.

The Query Manager contains a query which will select a subset of soils containing the desired information since not all soils in the database have specific heat information.

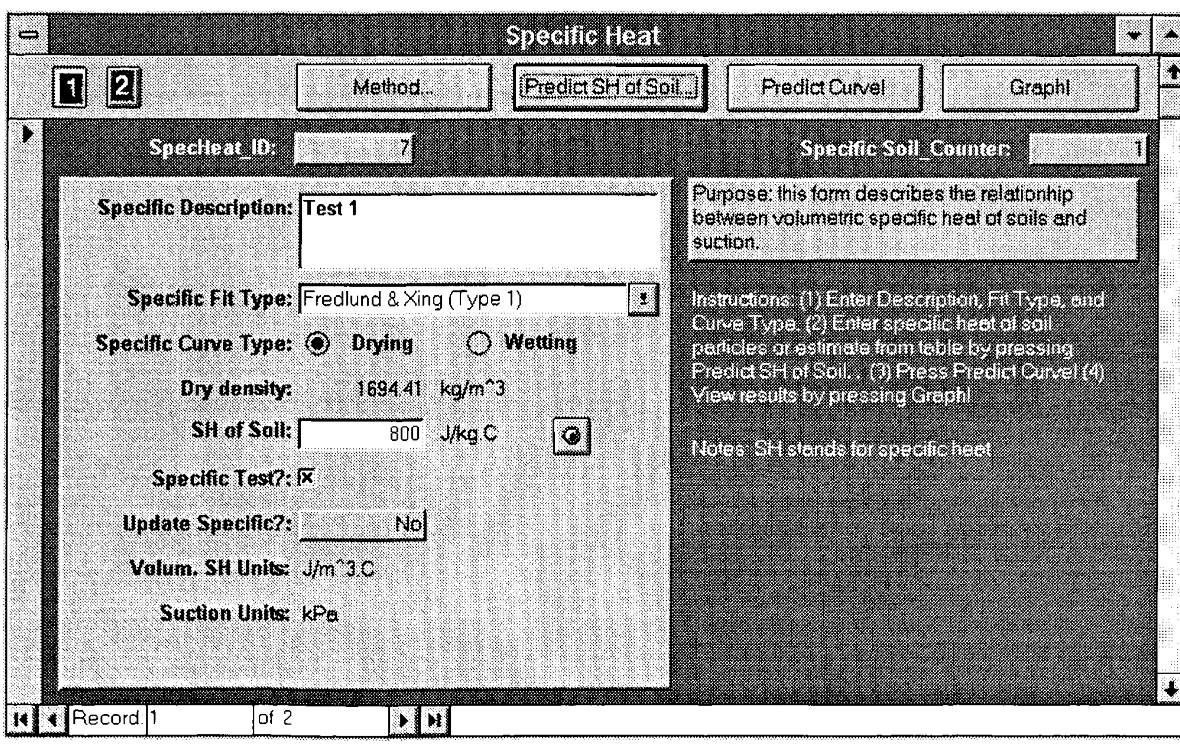


Figure 4-29 Page one of the volumetric specific heat form

4.5.8 Implementation of the Thermal Conductivity Function

All information relevant in describing the thermal conductivity function is organized in a single form in the KBS design. This form can be reached by selecting the Thermal Conductivity option on page four of the Soil form. Figure 4-31 and Figure 4-32 shows the thermal conductivity form for the KBS design. Two pages are required to present the information necessary. The first page contains parameters controlling the fit of the equation, the error between fit and experimental data, dry density, porosity, soil state, soil gradation, quartz content, and counters which Access® uses to identify individual records. Page two displays the equation used to fit the experimental data as well as experimental data points and generated data points on the fit curve.

The form header allows for predicting the quartz content of the soil, predicting the thermal conductivity curve, and graphing the experimental and predicted results. The Predict Quartz Content option allows the quartz content of the soil to be estimated from the grain-size distribution. For the prediction to be successful, a grain-size curve for the current soil must have been entered. The quartz content of the soil is predicted based on a graph of average quartz content for each particle size shown in Figure 4-30. This graph was obtained from the users manual of the software package entitled "The HyProS" developed by Vlodek R. Tarnawski and Bernhard Wagner (1991).

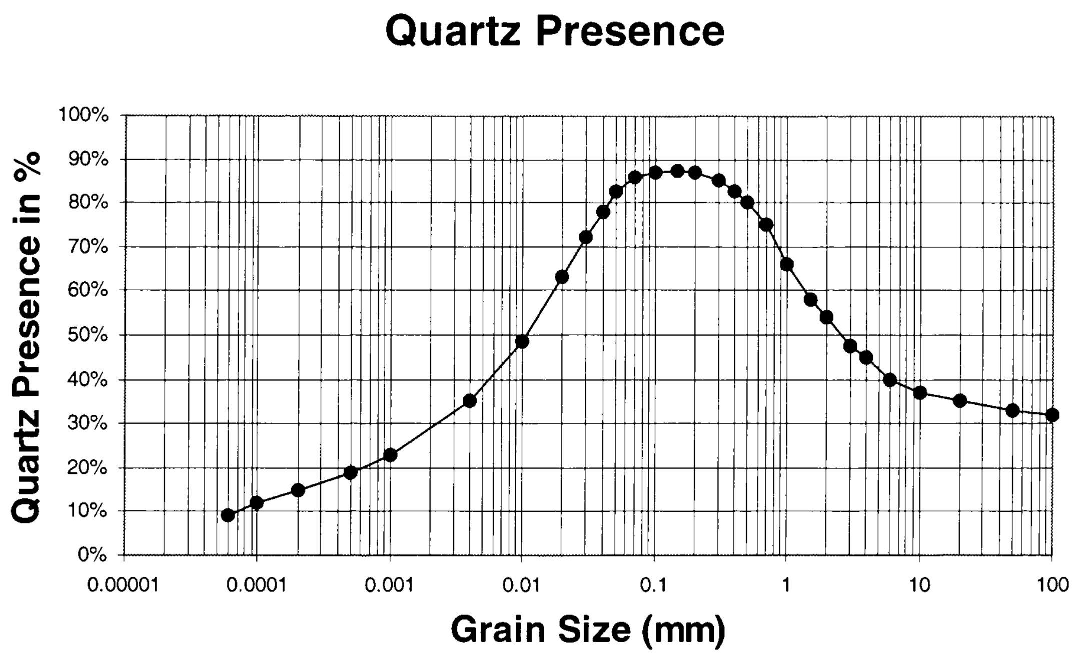


Figure 4-30 Quartz approximate occurrence in basic soil separates (Tarnawski, 1993)

When the Predict option is initiated, the prediction algorithm is initiated and generates a predicted curve of thermal conductivity versus suction. Points are also generated along the fit curve to allow viewing of the data. The points generated on the predicted curve are not used in any further calculations but are merely to allow viewing of the predicted curve.

Since not all soils in the database have thermal conductivity information, the Query Manager contains a query which will select a subset of soils containing the desired information.

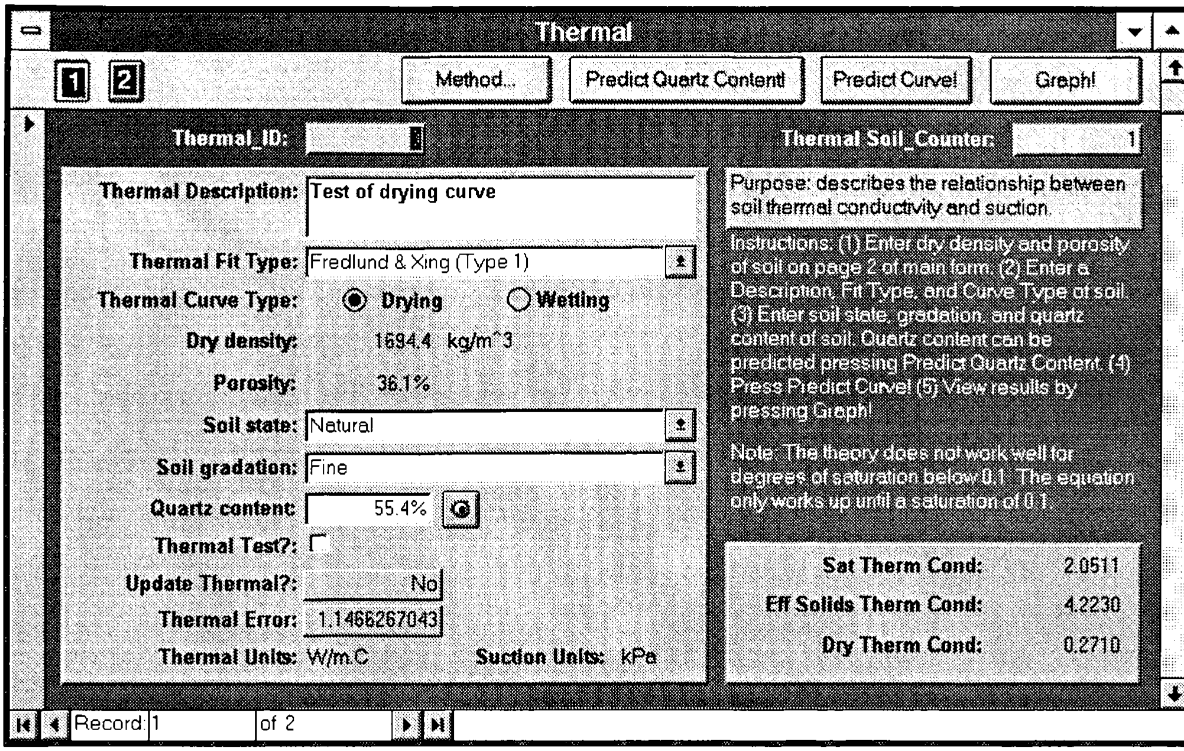


Figure 4-31 Page one of the thermal conductivity form

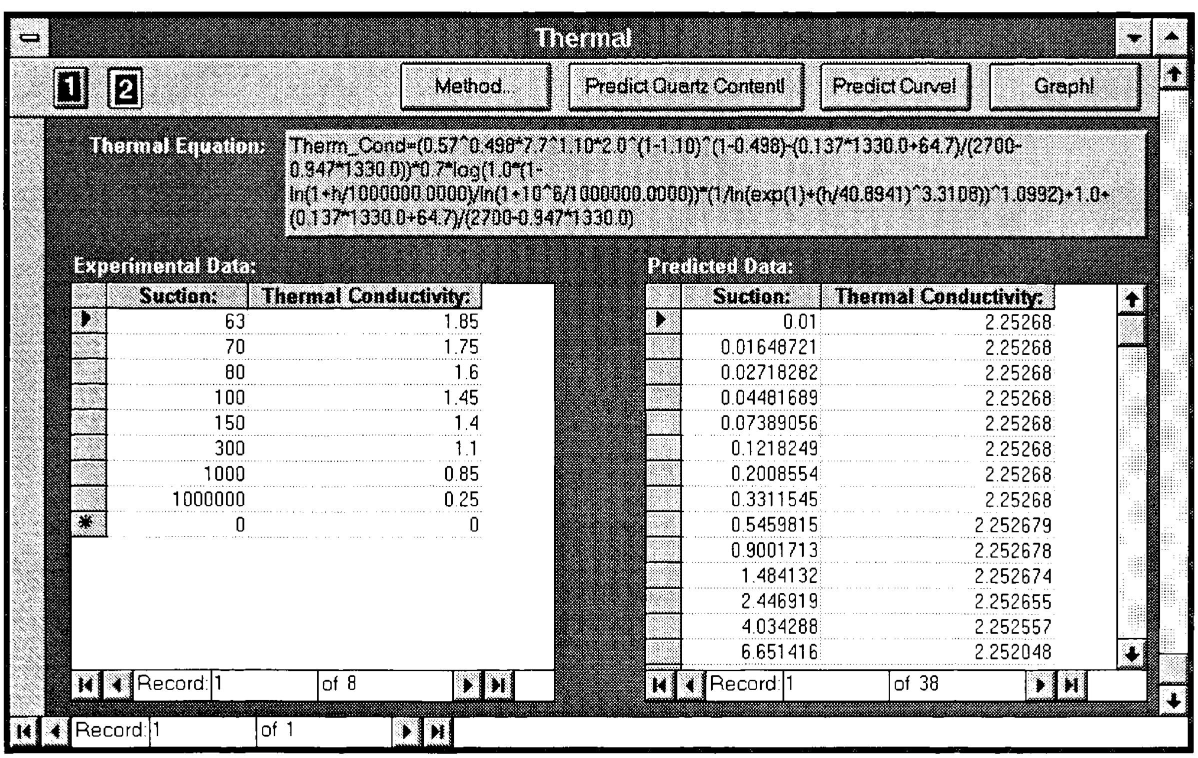


Figure 4-32 Page two of the thermal conductivity form

4.5.9 Implementation of the Unfrozen Water Content Function

All information relevant in describing the unfrozen water content function is organized in a single form in the KBS design. This form can be reached by choosing the Unfrozen Water Content option on page four of the Soil form as shown in Figure 4-5. Figure 4-33 shows the unfrozen water content form for the KBS design. Two pages are required to present the information necessary. The first page contains parameters controlling the prediction of unfrozen water content, the Unfrozen Parameter, and the error between predicted and experimental data, and counters which Access® uses to identify individual records. Page two displays the equation used to fit the experimental data as well as experimental data points and generated data points on the fit curve. Figure 4-34 shows the second page of the unfrozen water content form.

The form header allows for displaying the prediction method, predicting the unfrozen volumetric water content curve, and graphing the experimental and predicted results.

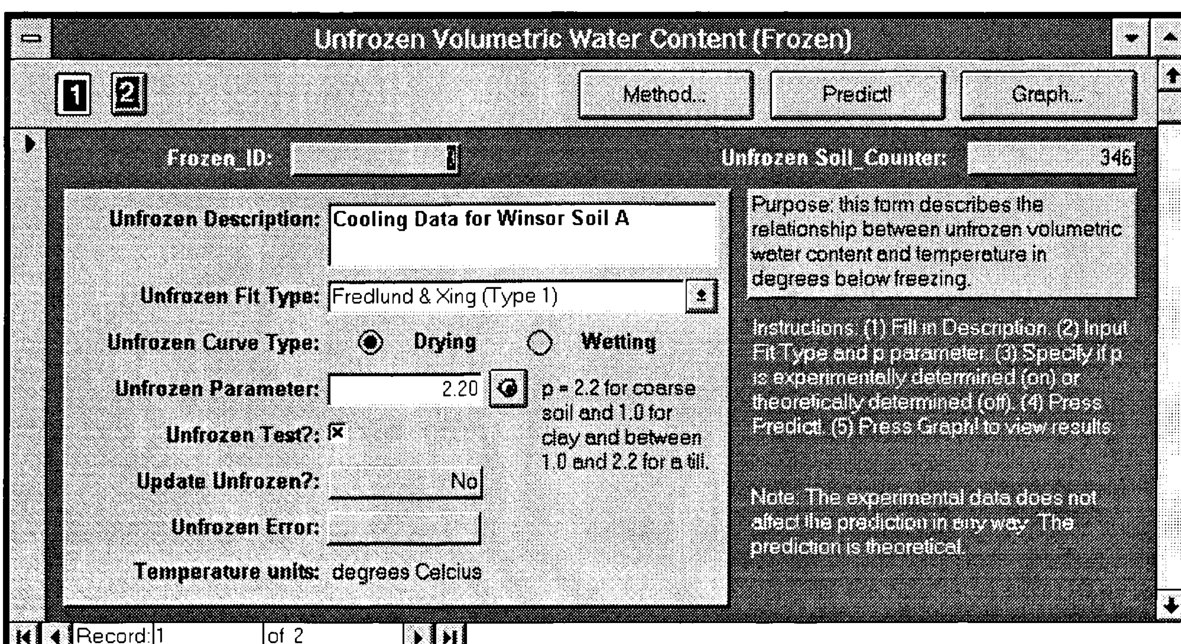


Figure 4-33 Page one of the unfrozen volumetric water content form

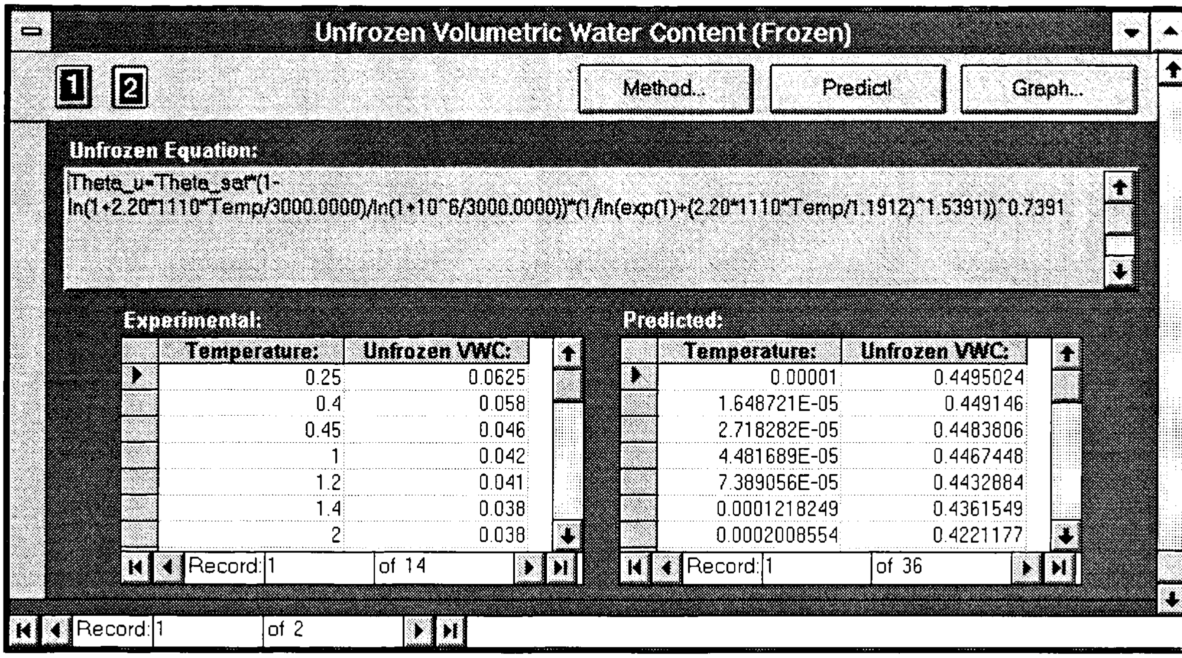


Figure 4-34 Page two of the unfrozen volumetric water content form

4.5.10 Implementation of Diffusion Properties

Information regarding the diffusion properties was stored in a form linked to the Soil form. The diffusion properties can be reached by selecting the Diffusion option on page four of the Soil form (shown in Figure 4-5). Page one of the diffusion form is shown in Figure 4-35 while page two is displayed in Figure 4-36. The data required to predict the diffusion function is listed on page one. The fit type and curve type parameters specify what fit of the SWCC to use in the prediction.

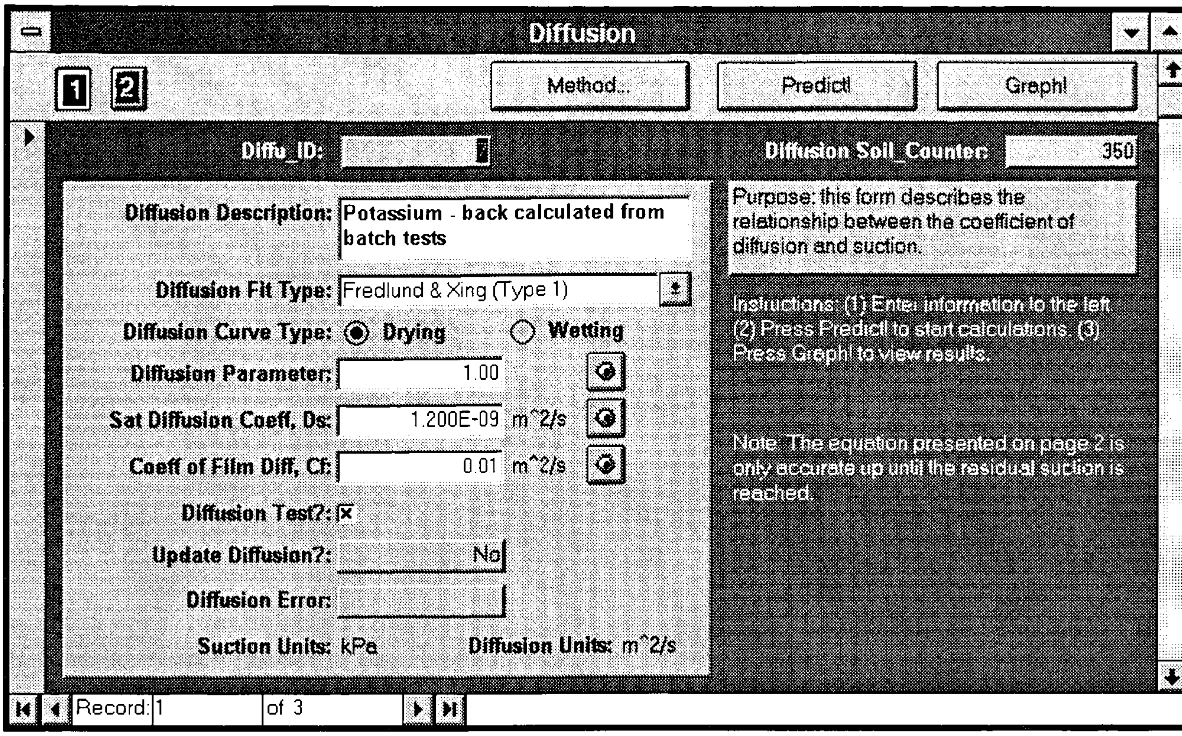


Figure 4-35 Page one of the diffusion form

The prediction algorithm requires input of a soil-water characteristic curve, a Diffusion Parameter, a Sat. Diffusion Coeff, Ds, and a Coeff of Film Diff, Cf. Once more soils have been added to the system design, the Rule Base can provide a statistical estimation of these three properties. Once the proper parameters have been entered, selecting the Predict option on the form header will initiate the prediction algorithm. The prediction algorithm will generate an equation describing effective diffusion as well as generating points at regular intervals along a curve of effective diffusion versus suction. The generated points are generated strictly for the purpose of viewing a graph of the properties. As such, only a certain number of points can be generated to keep storage to a minimum. Additional points can be generated by cutting and pasting the equation into a spreadsheet such as Excel™ and generating effective diffusion for any corresponding suction. Selecting the Graph option will generate a graph of both predicted and experimental results for viewing purposes.

Soils with diffusion information can be selected by entering the Query Manager and selecting the appropriate query.

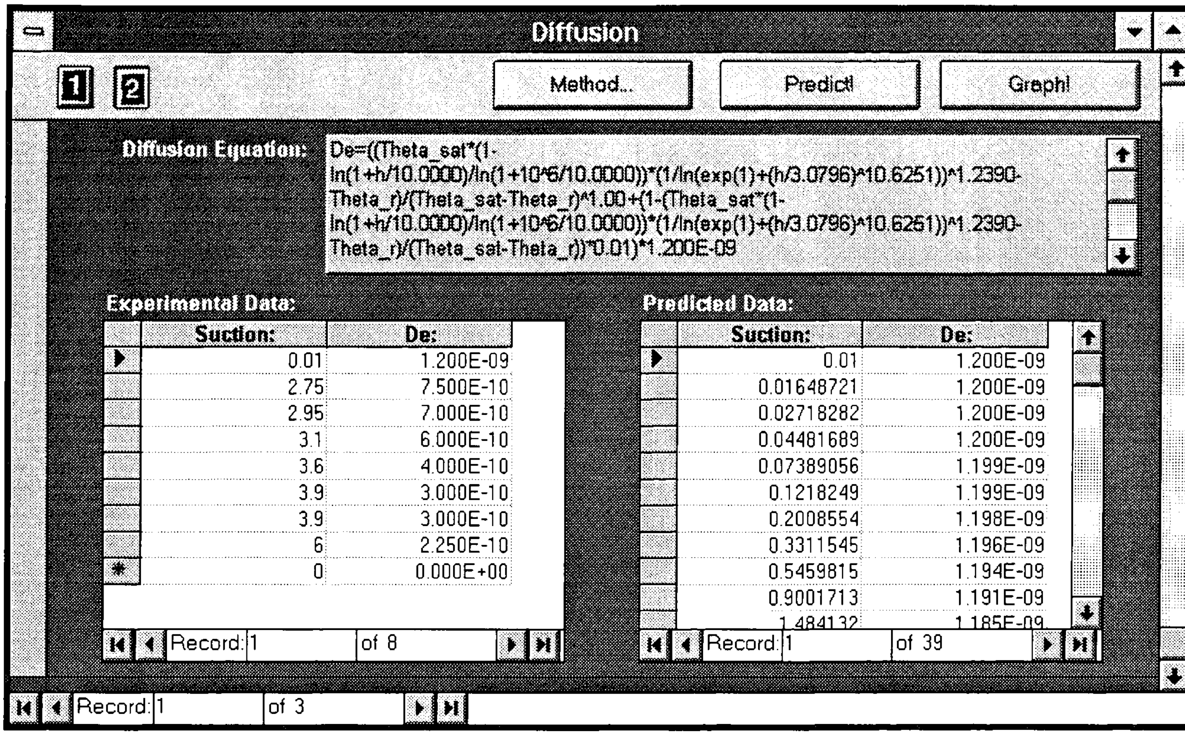


Figure 4-36 Page two of the diffusion form

4.5.11 Implementation of the Adsorption Function

Information regarding the adsorption properties is stored in a form linked to the soil form. The adsorption properties form can be reached by selecting the Adsorption option on page four of the Soil form (shown in Figure 4-5). Page one of the adsorption form is shown in Figure 4-37 while page two is displayed in Figure 4-38. The data required to predict the adsorption function are listed on page one. The fit type and curve type parameters specify what fit of the SWCC to use in the prediction. Parameters for a fit type must be available for the prediction to proceed.

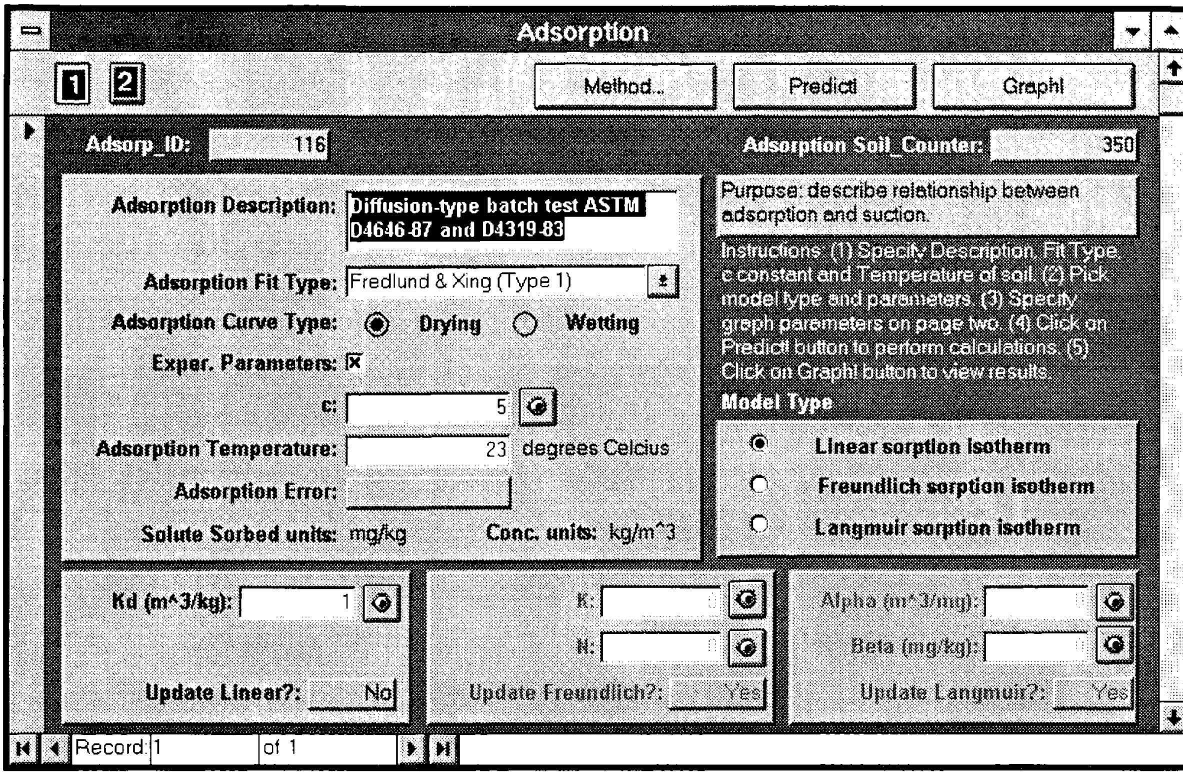


Figure 4-37 Page one of the adsorption form

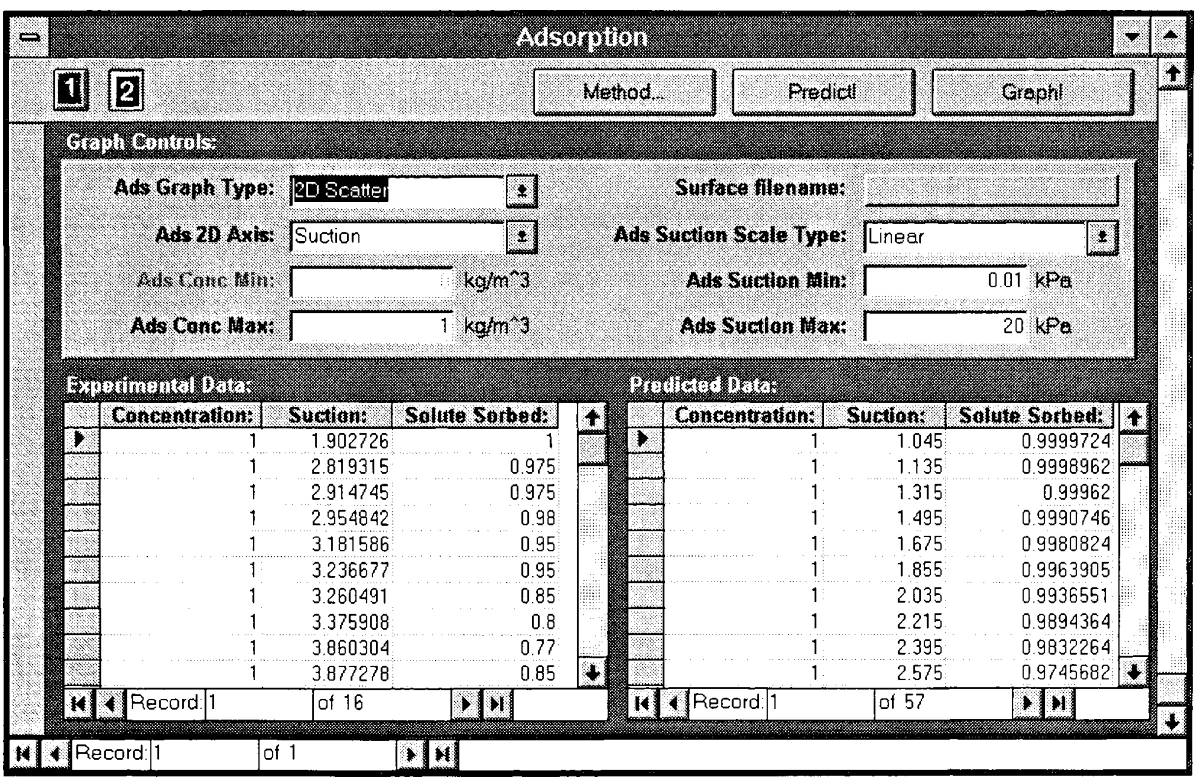


Figure 4-38 Page two of the adsorption form

The 'c' parameter allows for uncertainty in how the SWCC affects the adsorption prediction. The method of prediction used by the Knowledge-Based System design can be viewed by selecting the Method option on the form header. Three prediction models are included in the adsorption form: Linear, Langmuir, and Freundlich. The theory behind these three models can be found in Table 5-4.

Graph parameters must be specified to indicate how points are generated for the graph. 2-dimensional or 3-dimensional, logarithmic or linear plots are allowed to properly view the performance of the function. The implementation of the adsorption function involved prediction of solute sorbed as a function of both concentration and suction, therefore 3-dimensional plots are provided to properly view the function. Once the graph parameters are specified, the geotechnical engineer can initiate the prediction algorithm by choosing the Predict option on the form header. The resulting graph can be viewed by selecting the Graph option.

4.6 Summary

The implementation of the proposed design combined ease-of-use with the flexibility and power needed to provide adequate solutions. Access proved adequate to handle the design in three ways. First of all the Access database system provides an easy-to-use developer interface. This allowed development of the design of a system in a reasonable time period. Time could be focused on the design of the system rather than the implementation details. Secondly Access is also a professional database which allows for the necessary flexibility and speed. Points stored along theoretical fit or predicted curves amounted to large amounts of data. Access provided the means to handle the data with reasonable speed.

Thirdly, Access provided a powerful graphical user interface (GUI) which allowed the design to be implemented in such a way as to be understood. Pictures or text can be attached to buttons to allow an intuitive feel of the system design. The design of the system allows a geotechnical engineer to be guided in a logical way through the system.

A method of verifying the system design was described once the system design was implemented in Access. The purpose of the verification was to ensure that prediction techniques produced the same results as when published in original research. Chapter 5 describes the process used for verification. Also presented is the theory and the data used for verification of the prediction techniques.

5. CHAPTER - Program Verification

Chapter 5 presents the theory and verification of each of the soil properties. A short development of the theory associated with each soil property is presented. A rigorous theoretical development is not presented at this time. A complete theoretical development of each prediction technique can be found in the papers referenced in Table 3-1. Enough theory is presented to indicate understanding of the original development.

Soil properties can be either fit with an equation or predicted by analytical methods. Soil grain-size, consolidation, and soil-water characteristic curve (SWCC) functions are fit with equations. Equations were developed by the author to fit the grain-size and consolidation soil properties. The equations used are presented in the following sections along with verification of the equations performance. A least-squared regression technique was used to determine the parameters of an equation. The verification of grain-size, consolidation, and SWCC present the results of fitting equations to various experimental data.

The soil properties hydraulic conductivity, storage, shear strength, specific heat, unfrozen water content, thermal conductivity, diffusion and adsorption can be analytically predicted. The theory of the analytical prediction is presented in the following sections. Verification of the analytical predictions involved two steps.

Firstly, the theory and results of the prediction were duplicated with the help of MathCad®. Duplicating the results of the research confirmed that the theory presented was understood and implemented properly. The sensitivity of each of the input parameters could also be checked. Sample listings of the MathCad® pages used to check the theory can be seen in Appendix B. Once the results were implemented in MathCad® the next step was to implement the prediction technique in the knowledge-based system design. Algorithms were programmed in Visual Basic® to duplicate the results of MathCad®. Results of the algorithms were checked against the solutions obtained in MathCad® to ensure the accuracy of the results. The methodology presented allowed for confirmation that the prediction techniques were implemented properly.

5.1 The Grain-size Distribution Function

During development of the Knowledge-Based System design, it was decided that provision must be made for the storage of grain-size information. If grain-size information were to be stored, a method of mathematically representing each grain-size curve had to be found. The benefits of this would be two-fold. A grain-size curve fit with a mathematical equation would then allow further computations to be performed on the curve. It was theorized that prediction of the soil-water characteristic curve would be possible if the grain-size distribution could be fit with an equation.

The second benefit of mathematically representing each grain-size curve was that it would provide coefficients of indices by which grain-size curves may be classified. This then allows the luxury of searching the database for soils with grain-size curves in a certain band. This technique has proven invaluable in performing sensitivity analysis on soil parameters.

5.1.1 Theory of the Grain-size Distribution Function

Previous research carried out to fit the grain-size curves was reviewed (Wagner, 1994). Work done by Wagner presented several lognormal distributions capable of fitting the grain-size curve. Providing a meaningful representation of the grain-size data for all extremes proved difficult for a lognormal distribution. A similarity between the grain-size distribution and the soil-water characteristic curve. A different approach was taken for the KBS design. The Fredlund & Xing (1994) equation which has previously been used to fit SWCC data, provided a flexible and continuous equation that could be fit by the nonlinear regression using three parameters. This equation was modified to allow fitting of grain-size curves. The modified equation [5.1] allowed for a continuous fit and proper definition of the extremes of the curve.

$$P_p(d) = \frac{1}{\ln\left[\exp(1) + \left(\frac{ga}{d}\right)^{gn}\right]^{gm}} \left[1 - \left[\frac{\ln\left(1 + \frac{d_r}{d}\right)}{\ln\left(1 + \frac{d_r}{d_m}\right)}\right]^7\right] \qquad [5.1]$$

where:

$P_p(d)$	=	percent passing at any particular grain-size, d
ga	=	fitting parameter corresponding to initial break of equation,
gn	=	fitting parameter corresponding to maximum slope of equation,
gm	=	fitting parameter corresponding to curvature of equation,
d	=	particle diameter (mm),
d_r	=	residual particle diameter (mm),
d_m	=	minimum particle diameter (mm)

5.1.2 Verification of Grain-size Distribution Function

The equation used to fit the grain-size distribution worked well. As can be seen from Figure 5-1, experimental data can be fit with a minimal amount of error. A minimum particle size restriction was implemented in the equation. This allowed the smallest particle diameter in the current soil to be specified. The equation performed in a similar manner to the original Fredlund & Xing (1994) equation. The ga parameter corresponded to an initial break in the equation. The gn parameter corresponded to the slope of the equation and the gm parameter gave an indication of the curvature of the equation. A minimum particle diameter variable was introduced into the formulation. This was considered important due to the influence of clay-sized particles on the performance of the soil. A summary of the parameters used to fit the grain-size distributions can be found in Table 5-1.

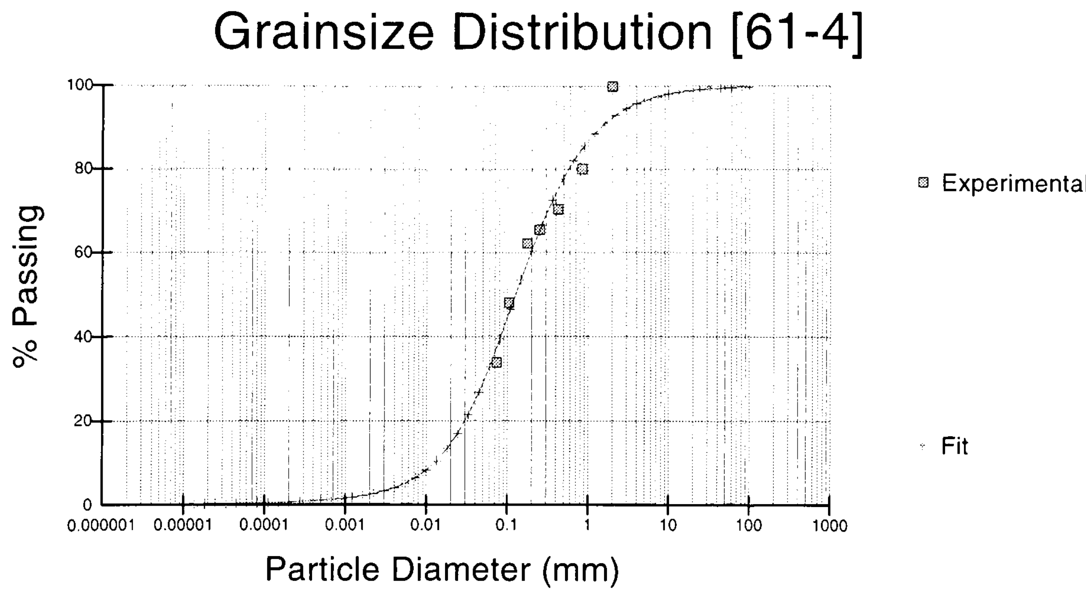


Figure 5-1 Grain-size distribution fit for a Loam (Soil_Counter = 61)

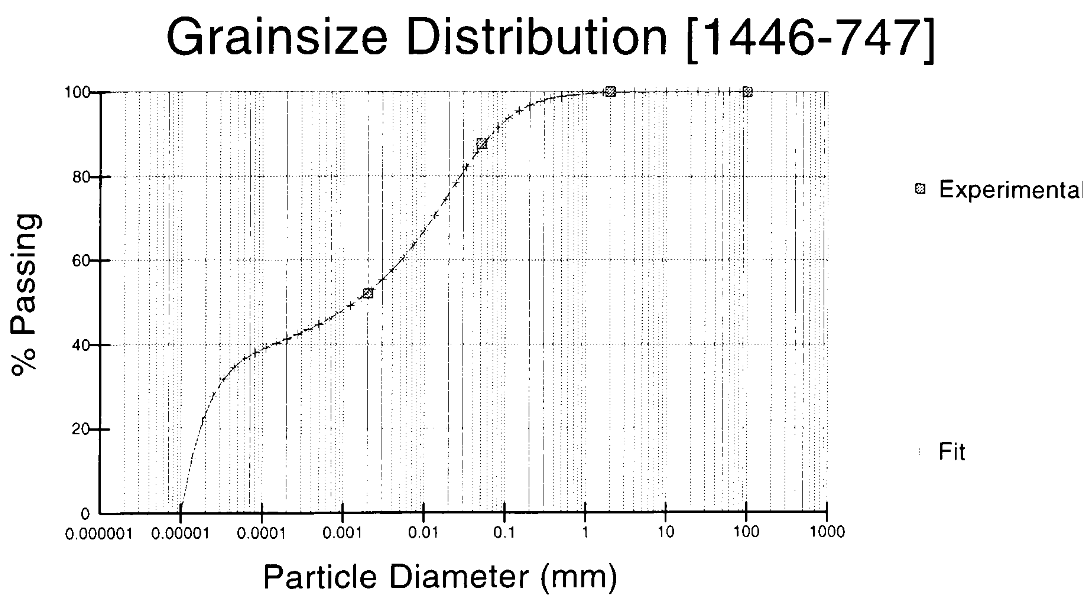


Figure 5-2 Grain-size distribution fit for a clay

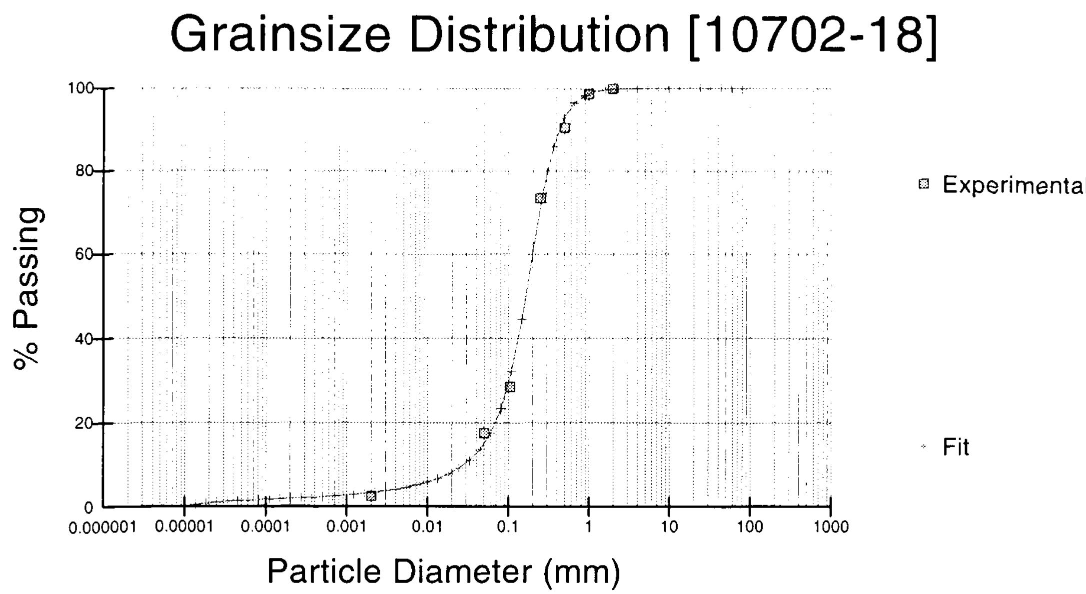


Figure 5-3 Grain-size distribution fit for a loamy sand

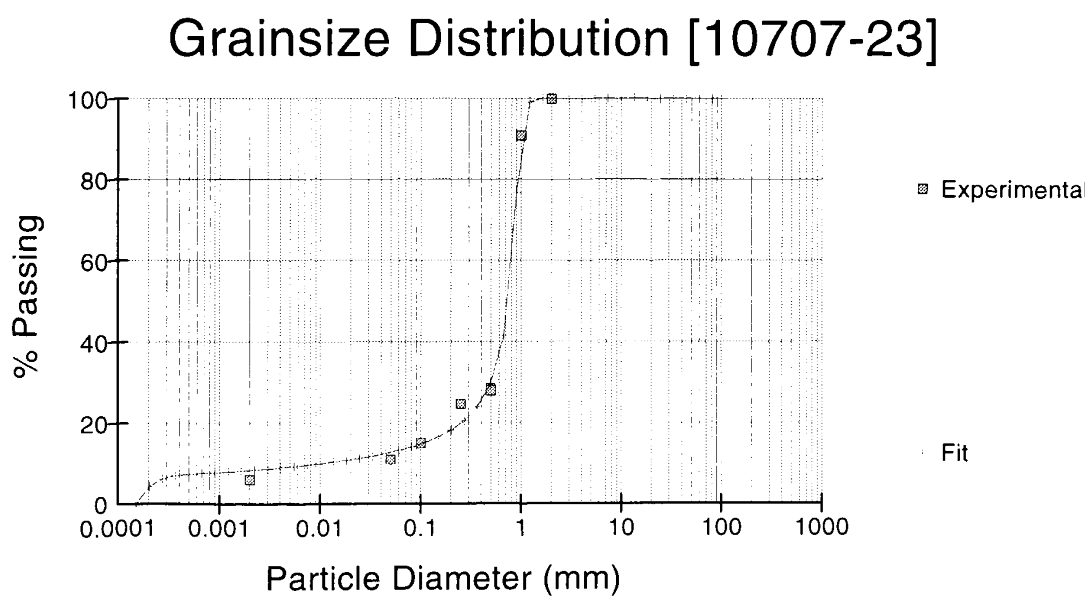


Figure 5-4 Grain-size distribution for a sand

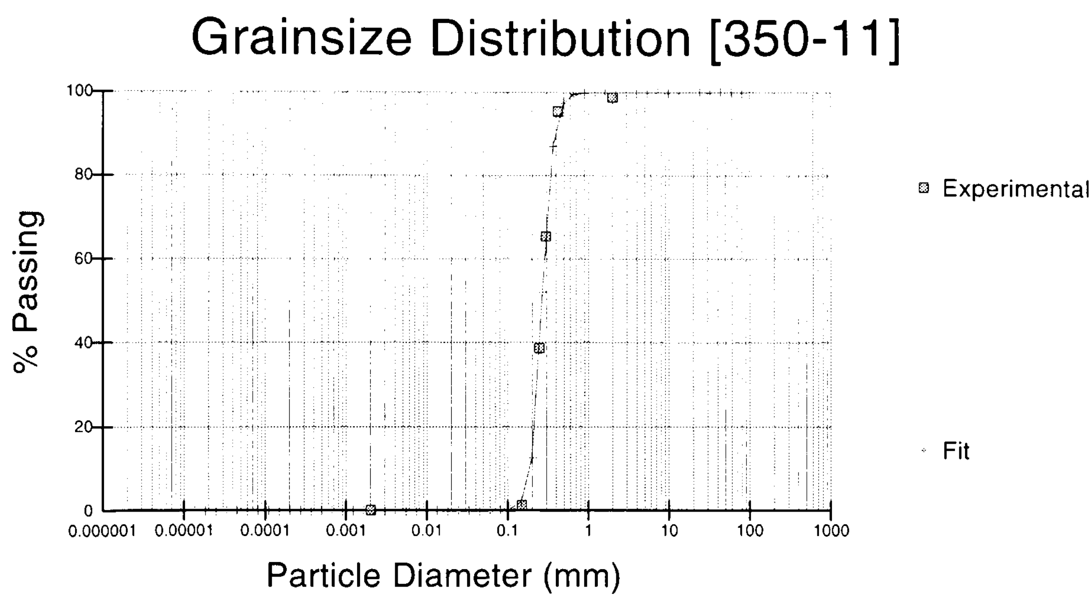


Figure 5-5 Grain-size distribution for a sand (Soil_Counter = 350)

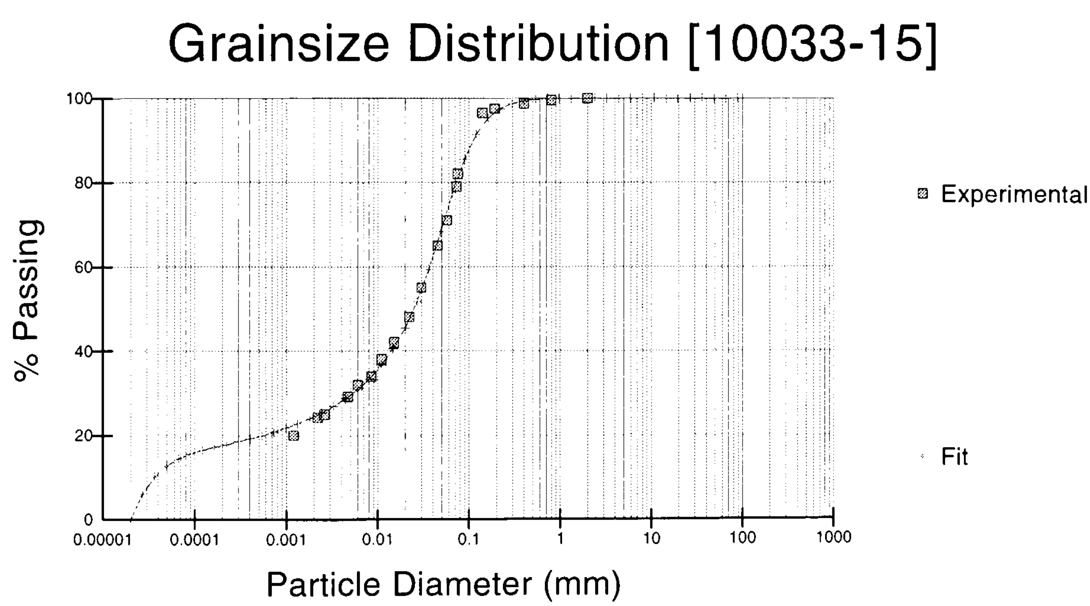


Figure 5-6 Grain-size distribution for clay #10033

Table 5-1 **Summary of parameters used to fit grain-size distribution data**

Soil_Counter	ga	gn	gm	Smallest particle size	ghr	Squared error
61	98.22	0.872	2.95	.00001	.001	.0142
1446	176.8	1.219	0.458	.00001	.001	.0000645
10702	41.90	2.55	1.36	.00001	.001	.00246
10707	10.45	13.00	0.566	.00015	.001	.00359
350	40.20	5.71	3.42	.00001	.001	.000748
10035	157.24	0.716	1.30	.00001	.001	.0145

5.2 The Soil-Water Characteristic Curve (SWCC)

Classical soil mechanics has emphasized specific types of soils (e.g., saturated sands, silts, and clays and dry sands). Textbooks cover 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 common categories. A large portion of these soils can be classified as unsaturated soils. Unsaturated soils have typically been avoided 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 as 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).

It is of use to describe the shape of the SWCC with an equation. Approximately twenty-eight different equations have been proposed that describe the SWCC. Rather than debate the pro's and con's of each equation, all twenty-eight equations where implemented into the Knowledge-Based System design. Table 4-1 lists the equations that the Knowledge-Based System design utilises curve fitting. The System design is capable of fitting any or all of the equations to experimental data. The only limitation for the equations used is that one of the five equations shown below must be used if the SWCC is to be used in the prediction of the other soil properties described in the subsequent sections.

Fredlund & Xing (Type 1)

Van Genuchten (Type 1)

Van Genuchten & Mualem (Type 1)

Van Genuchten & Burdine (Type 1)

Gardners (Type 1)

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

5.2.1 Theory of the Soil-Water Characteristic Curve

A description of the development and theory of the soil-water characteristic curve can be found in Section 2.2.

5.2.2 Verification of the Soil-Water Characteristic Curve

Experimental data was collected to indicate the shape of the SWCC for a variety of soils. A model of the experimental data was required for two reasons. Firstly, experimental data along a SWCC cannot be utilized in a finite element package. Input into a modelling package requires that a method of representing the experimental data be developed. The method of representation must be continuous and must exhibit reasonable emulation of the physical world. Mathematical equations were determined to provide the best representation of the SWCC. Twenty eight different equations have been previously utilized to fit the SWCC. Each equation could be made to fit experimental data by varying two or three parameters. The same curve-fitting algorithm used to fit the grain-size and consolidation curves was utilized to fit equations to the SWCC. This allowed experimental data to be represented by two or three parameters. Soils could then be grouped in the database according to their parameters.

The second reason a model of experimental data was needed was to allow calculations based on the SWCC. Once the SWCC was fit with a mathematical equation, the fit curve could be used in subsequent calculations as a basis for analytical predictions.

The Fredlund & Xing (1994) equation seemed to provide the best fit for the majority of cases (Sillers, 1996). Examples of experimental data represented by the Fredlund & Xing equation for various soil types can be seen in Figure 5-7, Figure 5-8, and Figure 5-8. Table 5-2 shows the parameters used to fit equations to data. It provides a continuous function that describes the SWCC from a small suction to a suction of 1 x 10^6 kPa which is useful in the modelling process. There is, however, no single equation that will account for all possible variations in the SWCC. An example of this is a bimodal SWCC. None of the current 28 equations in the system have the ability to represent this behavior. The system design does, however, provide the geotechnical engineer with 28 different options in fitting the SWCC. The geotechnical engineer is then free to pick the method best suited to the problem at hand. Figure 5-10 shows a plot of several different equations fit to the same experimental data. A summary of the performance of each equation is considered outside the scope of this thesis. A detailed description of the performance of each equation can be found in work done by Sillers (1996).

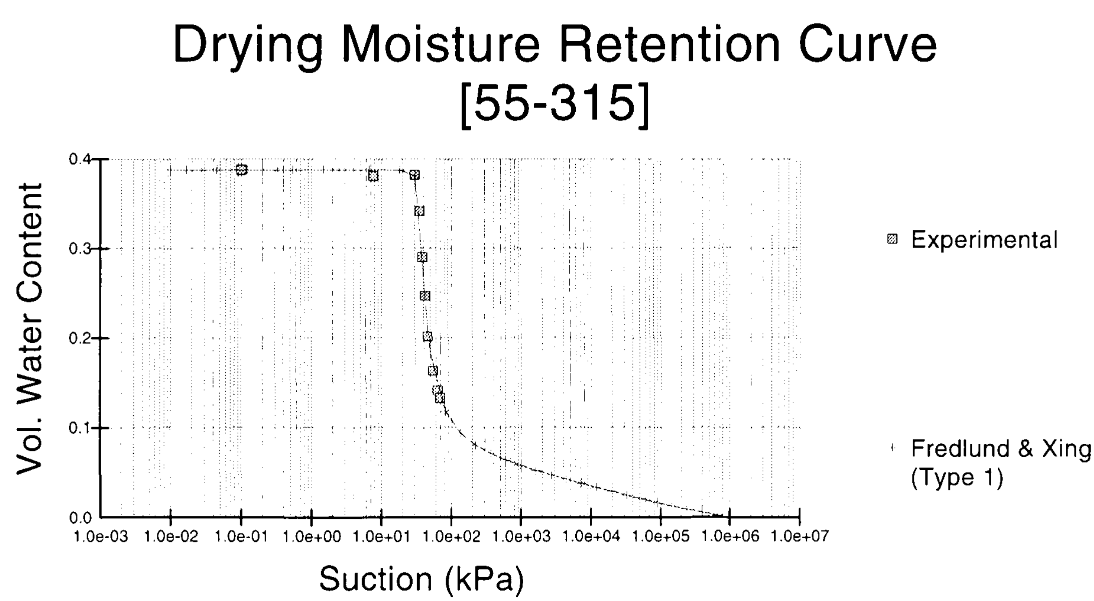


Figure 5-7 Example fit of sand with Fredlund & Xing (1994) equation

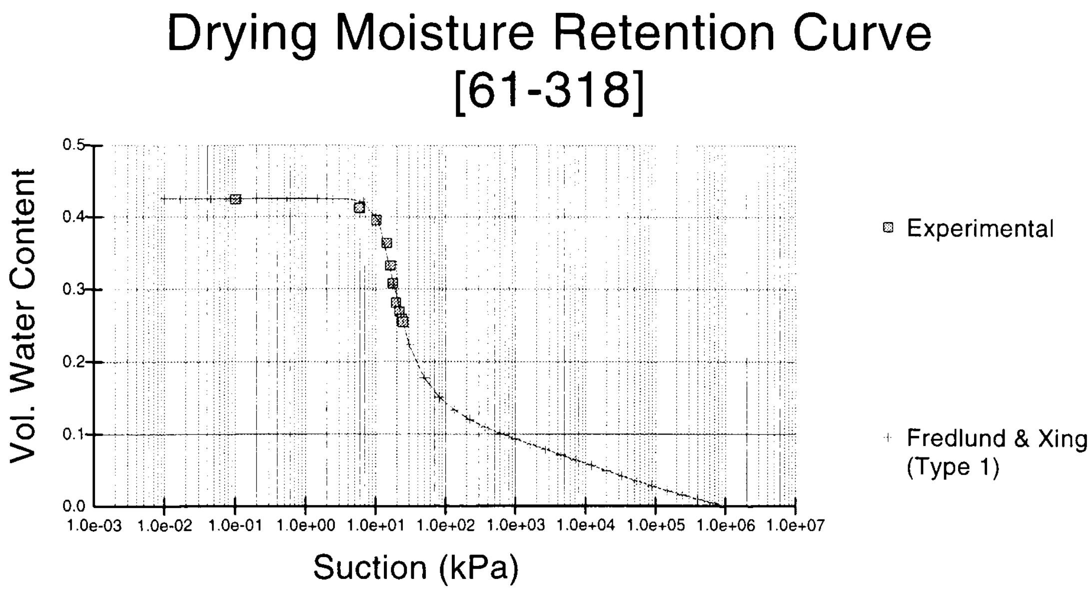


Figure 5-8 Example fit of sandy loam with Fredlund & Xing (1994) equation

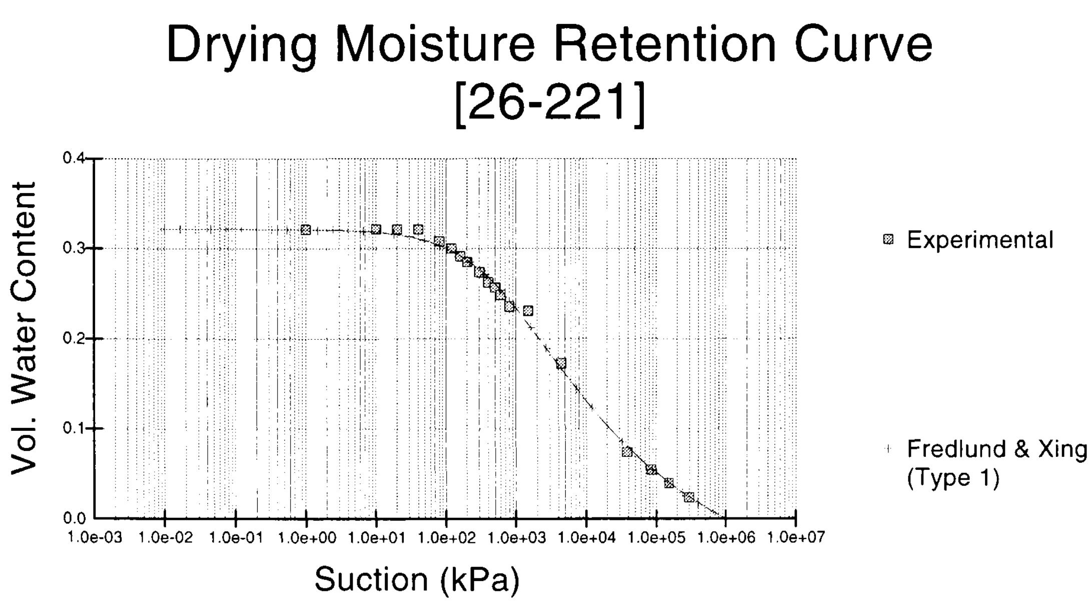


Figure 5-9 Example fit of loam with Fredlund & Xing (1994) equation

Table 5-2 Parameters used in Fredlund & Xing (1994) equation to fit curves presented above

Soil_Counter	a	n	m	hr	Squared error
55	35.28	14.11	.481	3000	.000772
61	13.02	4.25	.502	3000	.00228
26	406.24	0.815	.594	3000	.006074

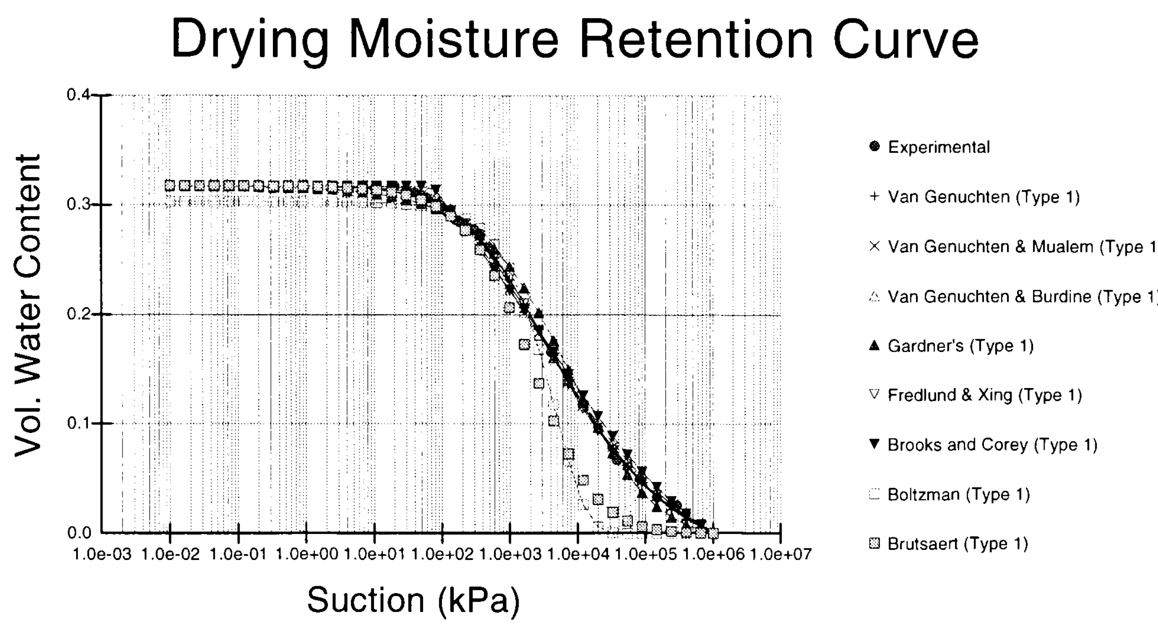


Figure 5-10 Comparison of several SWCC equations fit to the same experimental data

5.3 The Storage Function

The storage curve shows the change in volumetric water content versus suction. This function is useful in modelling seepage through unsaturated soils as it indicates the rate of change in the water storage of a soil at a given suction.

5.3.1 Theory of the Storage Function

In mathematical terms, the storage curve is the derivative or slope of the SWCC equation. The KBS design is able to determine the derivative of the five continuous SWCC equations presented in section 5.2. The five primary SWCC equations and their derivatives can be found in Appendix B.

An example of this is the Fredlund & Xing (1994) equation:

$$\theta_w(\psi) := \left[1 - \frac{\ln\left(1 + \frac{\psi}{\psi_r}\right)}{\ln\left(1 + \frac{1000000}{\psi_r}\right)}\right] \cdot \left[\frac{1}{\left[\ln\left[\exp(1) + \left(\frac{\psi}{a}\right)^n\right]\right]^m}\right] \cdot \theta_s$$

which, when input into MathCad allows the following derivative function to be produced:

$$\theta'(x) := \frac{-1}{\left[\psi_r \cdot \left[\left(1 + \frac{x}{\psi_r}\right) \cdot \left[\ln\left(1 + \frac{1000000}{\psi_r}\right) \cdot \left[\ln\left[\exp(1) + \left(\frac{x}{a}\right)^n\right]\right]^m\right]\right]\right]} \cdot \theta_s - \frac{\left[1 - \frac{\ln\left(1 + \frac{x}{\psi_r}\right)}{\ln\left(1 + \frac{1000000}{\psi_r}\right)}\right]}{\left[\ln\left[\exp(1) + \left(\frac{x}{a}\right)^n\right]\right]^m} \cdot \theta_s \cdot m \cdot \left(\frac{x}{a}\right)^n \cdot \frac{n}{\left[x \cdot \left[\left[\exp(1) + \left(\frac{x}{a}\right)^n\right] \cdot \ln\left[\exp(1) + \left(\frac{x}{a}\right)^n\right]\right]\right]}$$

5.3.2 Verification of the Storage Function

Derivatives of the five continuous SWCC equations presented in section 5.2 were obtained though MathCad. The derivatives were implemented into the Knowledge-Based System design. This allowed the storage curve to be calculated from the soil-water characteristic curve. Verification of the derivatives of the five equations can be examined in the results presented in Appendix B. An example of a SWCC and the resulting storage curve are shown in Figure 5-11 and Figure 5-12. The slope of the SWCC is referred to as m^2w.

The storage function is used extensively in seepage modelling. The derivative of the SWCC function provides a mathematically exact representation of the change in storage of the soil. Fitting the SWCC with a spline can produce errors in the storage function. Unrealistic "humps" in the SWCC can result in unrealistic inflections in the storage curve.

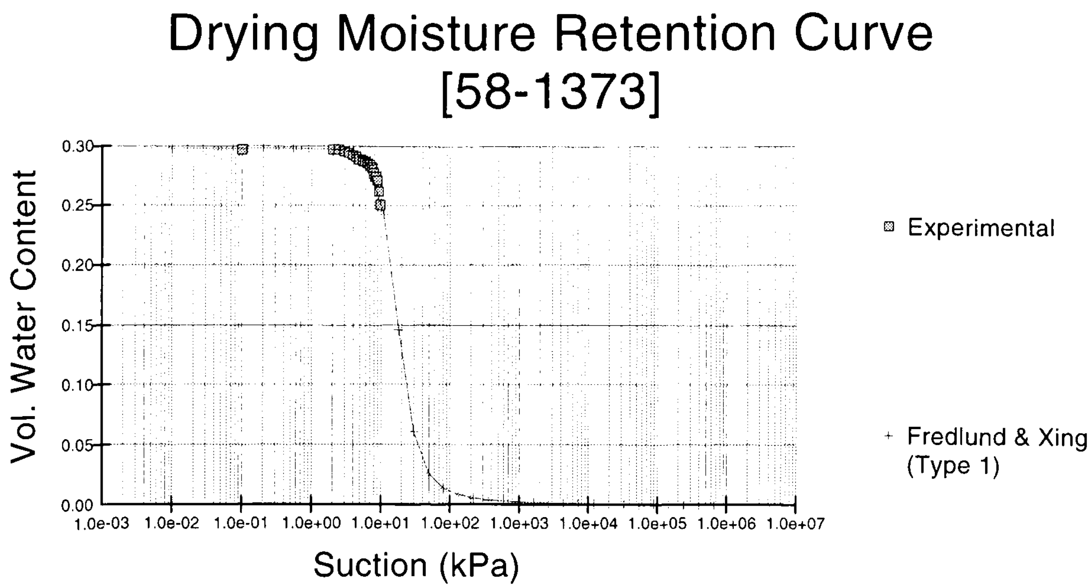


Figure 5-11 Soil-water characteristic curve for a sand (Soil_Counter=58)

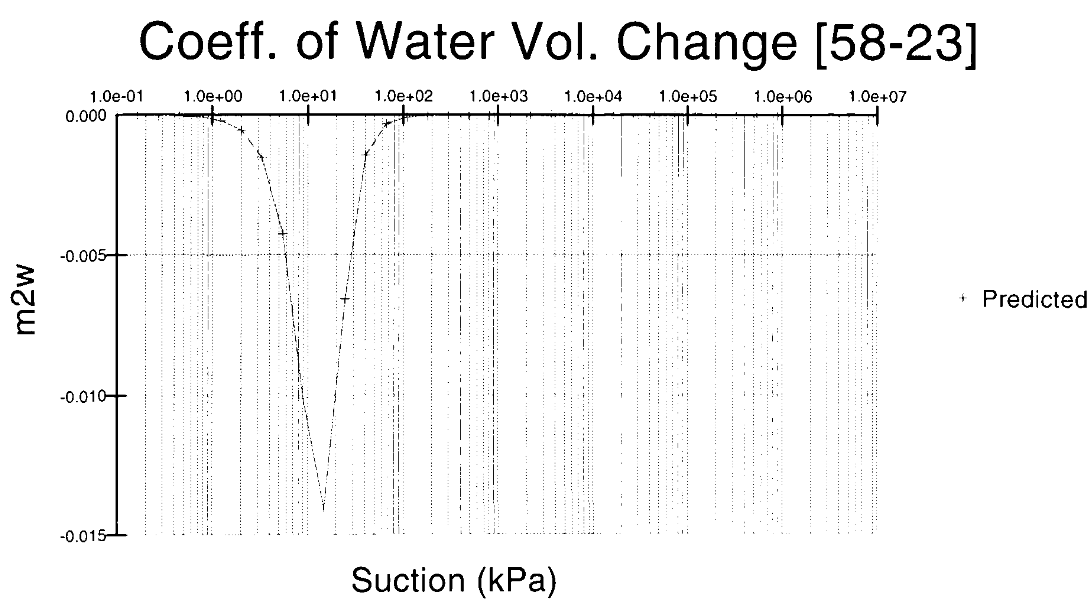


Figure 5-12 Storage curve for a sand (Soil #58)

5.4 The Permeability Function

> *"There is no engineering soil property that can vary more widely than that of the coefficient of permeability"* (Fredlund, 1994).

The difference in permeability between a clay and a gravel can be greater than 10 orders of magnitude. Accurate prediction of this parameter is a major obstacle in analyzing seepage through soil.

Knowing the hydraulic conductivity of a soil is vital for field management of resources and maintenance of environmental quality. Much effort has been expended to develop computer models capable of analyzing the seepage through soil. The problem is further complicated by the fact that the seepage rate through soil varies according to the level of saturation of the soil. The determination of soil hydraulic properties is also time consuming and expensive. Many measurements must be made at all levels of saturation to provide confidence in the accuracy. It is, therefore, of value to utilize simplified theoretical methods of predicting the hydraulic conductivity of soils.

Models which predict the hydraulic conductivity of soils can be divided into three categories. The model either will predict (1) the saturated hydraulic conductivity of a soil (Ahuja, 1989; Russo, 1980; Brakensiek, 1992; Rawls, 1993; Sperry, 1994), or, (2) the curve describing the variation of hydraulic conductivity as a soil desaturates (Fredlund, 1994), or, (3) both the saturated hydraulic conductivity and the curve showing the variation of hydraulic conductivity as a soil desaturates (i.e. Durner, 1994). For the KBS design, the problem was divided into two parts: the estimation of saturated hydraulic conductivity and the estimation of the hydraulic conductivity curve as the soil desaturates. Two separate methods were provided by the KBS design for estimating saturated hydraulic conductivity. These methods are based on work done by A. Hazen (1911) and Ahuja (1989).

Once the saturated hydraulic conductivity of a soil is measured or estimated, the hydraulic conductivity of a soil has been shown to be a relatively unique function of the water content (Fredlund, Xing, and Huang, 1994). The function appears to be unique as long as the volume change of the soil structure is negligible or reversible. An computational method was developed for the KBS design which allows the full hydraulic conductivity function to be estimated from a saturated hydraulic conductivity and a SWCC.

5.4.1 Theory of the Permeability Function

The following sections present a development of the theory used in the prediction algorithms. There are numerous methods which have been presented for the prediction of saturated hydraulic conductivity. The following methods were selected for their simplicity and their popularity in engineering practice.

5.4.1.1 Hazen's Equation for Saturated Hydraulic Conductivity

An empirical equation was proposed by Hazen in 1911. It was developed for use with *clean* sands (with less than 5% passing the No. 200 sieve) and with D_{10} sizes between 0.1 and 3.0 mm. Hazen's equation is shown in [5.2]. The C constant was found to vary between 0.004 and 0.012 with an average of 0.01. This will produce hydraulic conductivities in m/s when D_{10} is in mm. The equation is valid for $k \geq 10^{-5}$ m/s

$$k = CD_{10}^{2} \qquad [5.2]$$

5.4.1.2 Kozeny - Carman Equation for Saturated Hydraulic Conductivity

The Kozeny-Carman equation is presented L.R. Ahuja (1989). This equation allows the prediction of saturated hydraulic conductivity based on effective pore size. The equation is shown in [5.3]. B is a constant that for most soils has been found to be 1058. In the paper presented by Ahuja, the equation is verified against soils in the Cecil, Lakeland, Norfolk, and Wagram series (Williams, 1993). The Cecil, Lakeland, and Norfolk series have been entered into the KBS design and can be isolated by querying for the respective series names. The prediction is based on an effective porosity, n_e, which is defined as the total porosity minus the volumetric water content corresponding to a suction of 33 kPa.

$$k_s = Bn_e^4 \qquad [5.3]$$
$$n_e = n - \theta_w$$

where:

k_s = saturated permeability (m/s), and

B = constant equal to 0.002939, and

n = porosity of the soil, and

θ_w = volumetric water content when a suction of 33 kPa is applied to the soil.

5.4.1.3 Predicting the Unsaturated Hydraulic Conductivity Function

Burdine (1953) developed a model for predicting the relative hydraulic conductivity of a soil. This model was based on equation [5.4].

$$k_r(\theta) = \frac{k(\theta)}{k_s} = \Theta^q \left(\frac{\int_{\theta_r}^{\theta} \frac{d\theta}{\psi^2(\theta)}}{\int_{\theta_r}^{\theta_s} \frac{d\theta}{\psi^2(\theta)}} \right)^2 \qquad [5.4]$$

where:

k_r = relative hydraulic conductivity of the soil, and

ψ = soil suction, and

Θ = normalized soil-water characteristic curve, and

θ = volumetric water content, and

k_s = saturated hydraulic conductivity, and

θ_r = residual volumetric water content, and

θ_s = saturated volumetric water content.

Fredlund & Xing (1994) extended the work of Burdine and produced the equation shown in [5.5]. This equation is capable of predicting the hydraulic conductivity of an unsaturated soil given the SWCC and the saturated hydraulic conductivity.

$$k_r(\psi) = \frac{\int_{\psi}^{\psi_r} \frac{\theta(y) - \theta(\psi)}{y^2} \theta'(y) dy}{\int_{\psi_{aev}}^{\psi_r} \frac{\theta(y) - \theta_s}{y^2} \theta'(y) dy} \qquad [5.5]$$

where:

y	= variable of integration, and
ψ_r	= suction at which residual water content occurs, and
ψ_{aev}	= suction at the air entry value, and
θ'	= derivative of the soil-water characteristic curve function.

The method proposed by Fredlund & Xing (1994) is implemented into the Knowledge-Based System design. The system design develops the algorithm using the soil-water characteristic curve and the saturated hydraulic conductivity to predict the permeability of a soil at all levels of suction.

5.4.2 Verification of the Permeability Function

A statistically sound group of soils was obtained from which to test the theoretical predictions provided by the Knowledge-Based System design. The statistical estimations provided by the Knowledge-Based System design allowed for a "feel" of the accuracy of theoretical predictions. Estimations could be divided into two categories; the estimations of saturated hydraulic conductivities, and the estimation of the unsaturated hydraulic conductivity function.

The estimation of saturated hydraulic conductivity proved the most difficult. Variations of saturated hydraulic conductivity values of more than four orders of magnitude were found within till and clay soil categories. This variation was countered within the Knowledge-Based System design by providing three different methods of estimating saturated hydraulic conductivity. Two proven theoretical methods, Hazen's (1911) equation and the Kozeny-Carman (Ahuja, 1989) equation were provided as two common prediction tools. The accuracy of each of these equations is described by the publishing authors and therefore will not be covered here.

An estimation of the sensitivity of a parameter is often needed in geotechnical engineering. The Knowledge-Based System design therefore provides a means by which a statistical distribution is generated for the desired parameter. Figure 5-13, Figure 5-14, and Figure 5-15 show the statistical distributions produced for the soil categories of sand, silt loam and clay.

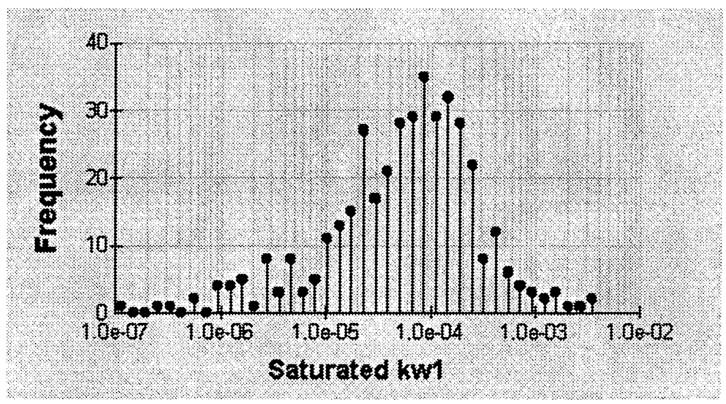


Figure 5-13 Statistical distribution produced by Rule Base of saturated hydraulic conductivities for sands. Conductivities are in m/s.

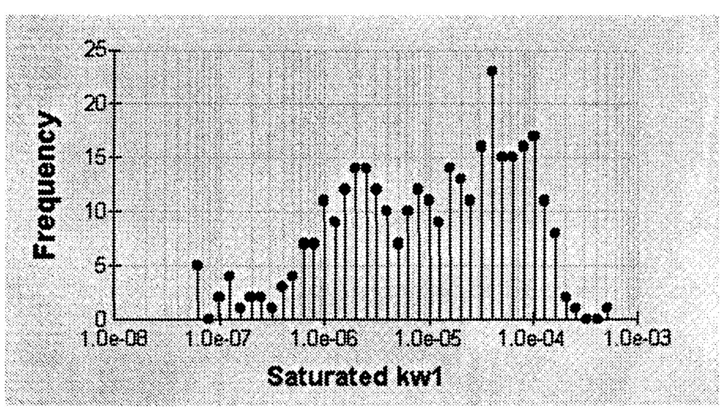


Figure 5-14 Statistical distribution produced by Rule Base for saturated hydraulic conductivity of silt loam. Conductivities are in m/s.

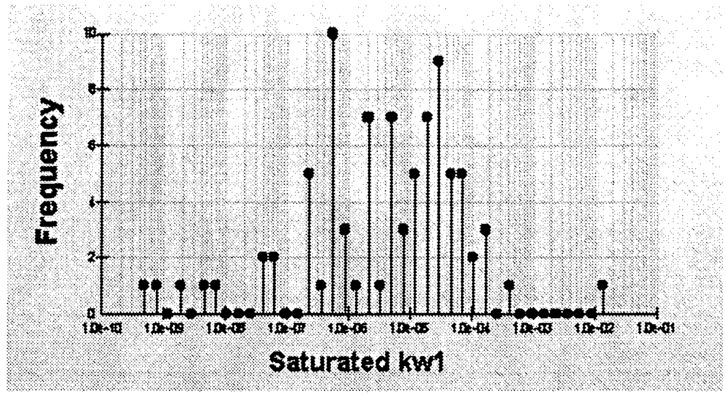


Figure 5-15 Statistical distribution produced by Rule Base for saturated hydraulic conductivity of clay. Conductivities are in m/s.

Once the saturated hydraulic conductivity is known, Fredlund & Xing's (1994) equation was used to generate a function of hydraulic conductivity versus suction. From work published by Fredlund and Xing, and from soils tested in the database, the method provides an accurate means of predicting the conductivity function. A typical comparison between predicted and experimental data is shown in Figure 5-16, Figure 5-17, and Figure 5-18. It has been shown that, since the prediction technique is based on the soil-water characteristic curve, an accurate description of the soil-water characteristic curve is imperative (Fredlund, 1994).

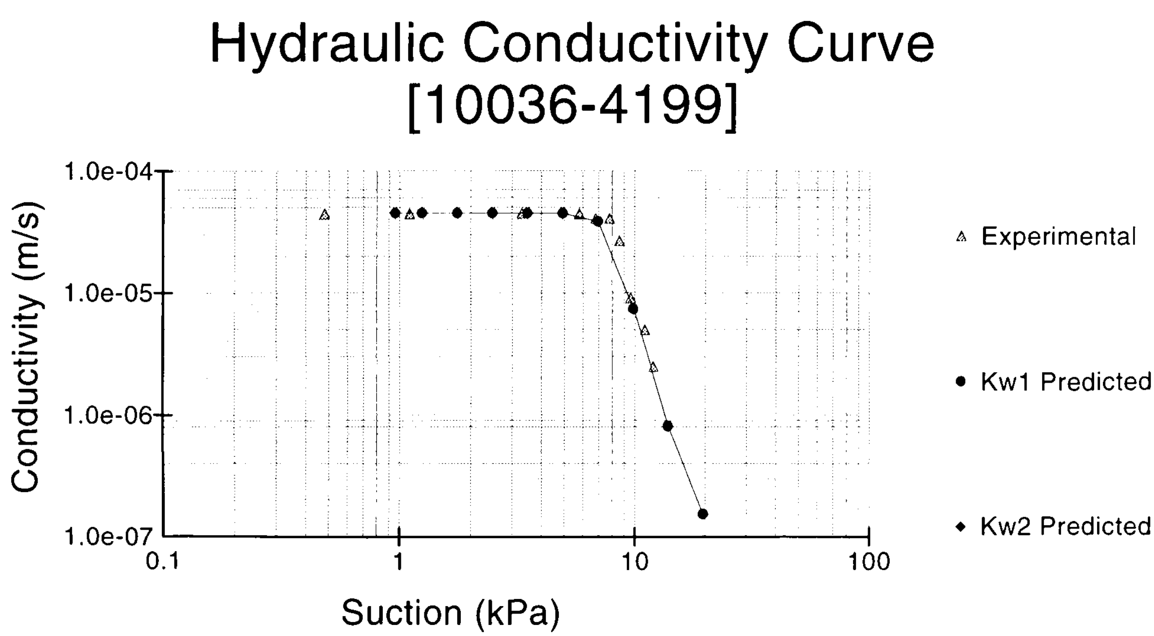


Figure 5-16 Comparison between predicted and experimental data for a Touchlet Silt Loam

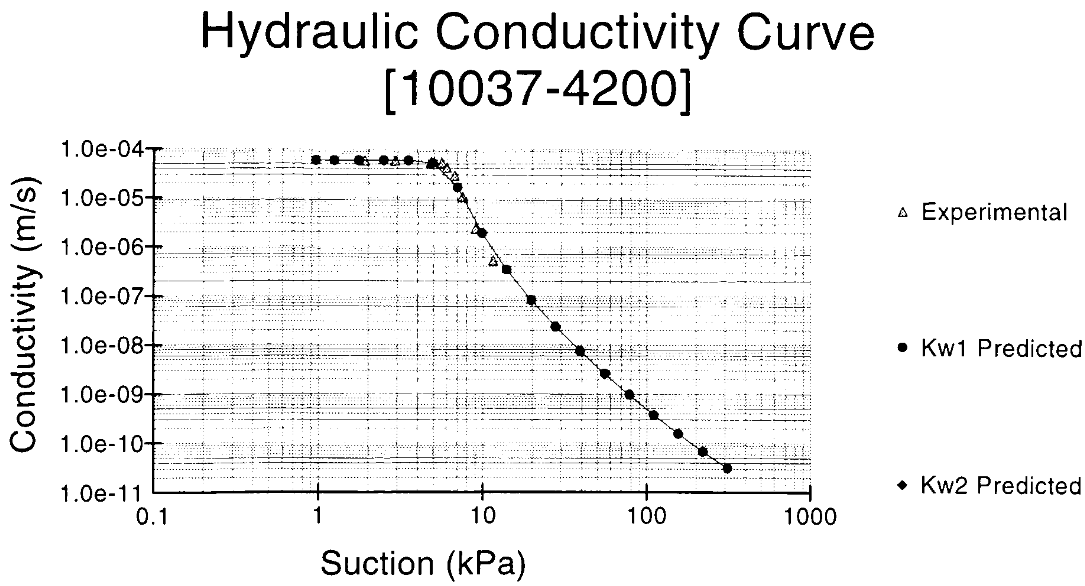


Figure 5-17 Comparison between experimental and predicted data for a Columbia Sandy Loam

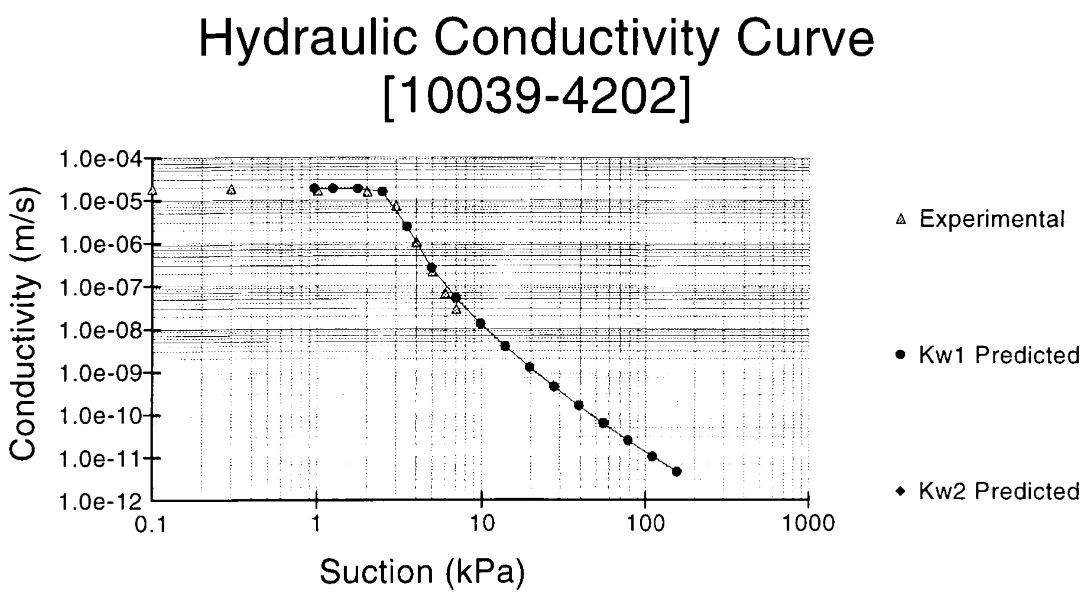


Figure 5-18 Comparison between experimental and predicted conductivity for a sand

5.5 The Shear Strength Function

A theoretical framework for unsaturated soil mechanics has been firmly established over the past couple of decades. The constitutive equations for volume change, shear strength and flow for unsaturated soil have become generally accepted in geotechnical engineering (Fredlund and Rahardjo, 1993a). The measurement of soil parameters for the unsaturated soil constitutive models, however, remains a demanding laboratory process. For most practical problems, it has been found that approximate soil properties are adequate for most analyses (Fredlund, 1995). Hence, empirical procedures to estimate unsaturated soil functions are adequate.

Laboratory studies have shown that there is a relationship between the SWCC and the unsaturated soil properties (Fredlund and Rahardjo, 1993b). Several models have been proposed to empirically predict the permeability function for an unsaturated soil from the soil-water characteristic curve by using the saturated coefficient of permeability as the starting value (Fredlund et al, 1994). The KBS design provides engineers with a means of estimating the shear strength function for an unsaturated soil from the soil-water characteristic curve by using the saturated shear strength parameters as the starting values. The theory was developed from work done by the author along with D.G. Fredlund, A. Xing, and S.L. Barbour.

5.5.1 Theory of the Shear Strength Function

The contribution of matric suction to the shear strength of an unsaturated soil can be assumed to be proportional to the product of matric suction, $(u_a - u_w)$, and the normalized area of water, a_w, at a particular stress state (Fredlund et al, 1995). That is,

$$\tau = a_w (u_a - u_w) \tan \phi' \qquad \textbf{[5.6]}$$

where: $a_w = A_{dw} / A_{tw}$

A_{dw} = area of water corresponding to any degree of saturation.

A_{tw} = total area of water at saturation

The normalized area of water, a_w, decreases as the matric suction increases. The chain rule of differentiation on Eq. [5.6] shows that there is two components of shear strength change associated with a change in matric suction.

$$d\tau = \tan\phi'\left[a_w\, d(u_a - u_w) + (u_a - u_w)da_w\right] \qquad \textbf{[5.7]}$$

The normalized area of water in the soil, a_w, may be assumed to be proportional to the normalized volumetric water content at a particular suction value by applying Green's theorem, (Fung, 1977) [i.e., $\Theta(u_a - u_w)$ which is equal to $\theta(u_a - u_w) / \theta_s$]. The normalized area of water can be defined by the following equation,

$$a_w = [\Theta(u_a - u_w)]^\kappa \qquad \textbf{[5.8]}$$

where: $\Theta(u_a - u_w)$ = normalized volumetric water content as a function of matric suction, and

κ = a soil parameter dependent upon the soil type.

Then, substituting [5.8] into $d\tau = \tan\phi'\left[a_w\, d(u_a - u_w) + (u_a - u_w)da_w\right]$

[5.7] gives

$$d\tau = \tan\phi'\left\{[\Theta(u_a - u_w)]^\kappa + \kappa(u_a - u_w)[\Theta(u_a - u_w)]^{\kappa-1} d\Theta(u_a - u_w)\right\} d(u_a - u_w)$$

Integrating the above equation yields,

$$\tau(u_a - u_w) = C + \tan\phi' \int_0^{u_a - u_w} \left\{[\Theta(u_a - u_w)]^\kappa + \kappa(u_a - u_w)[\Theta(u_a - u_w)]^{\kappa-1} d\Theta(u_a - u_w)\right\} d(u_a - u_w) \qquad \textbf{[5.9]}$$

where: C = constant of integration.

The constant of integration, C, in Eq. [5.9] is the shear strength of the soil at zero suction (i.e., the saturated shear strength). Therefore,

$$C = \tau(0) = c' + (\sigma_n - u_w)\tan\phi' \qquad \textbf{[5.10]}$$

where: $u_w = u_a$ (i.e., at saturation)

c' = effective cohesion,

ϕ' = effective angle of internal friction.

Substituting [5.10] into [5.9] gives the following shear strength expression as a function of matric suction and the effective angle of internal friction, ϕ',

$$\tau(u_a - u_w) = c' + (\sigma_n - u_a)\tan\phi' +$$
$$\tan\phi' \int_0^{u_a - u_w} \left\{ \left[\Theta(u_a - u_w)\right]^{\kappa} + \kappa(u_a - u_w)\left[\Theta(u_a - u_w)\right]^{\kappa - 1} d\Theta(u_a - u_w) \right\} d(u_a - u_w) \qquad \textbf{[5.11]}$$

where : $\Theta(u_a - u_w) = \theta(u_a - u_w)/\theta_s$, and

$\theta(u_a - u_w)$ = the volumetric water content at any suction.

Equation [5.11] can be used to predict the shear strength function of an unsaturated soil using the soil-water characteristic curve and the *saturated* shear strength parameters.

Equation [5.11] can be written in a different form as follows.

$$\tau = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\left[\Theta(u_a - u_w)\right]^{\kappa}\tan\phi' \qquad \textbf{[5.12]}$$

This equation is found by substituting equation [5.8] into equation [5.6]. Equation [5.12] will produce the same shear strength curve as equation [5.11].The simple form of equation [5.12] now allows for the easy substitution of a normalized soil-water characteristic curve. The other advantage of equation [5.12] is that the difficult integration shown in equation [5.11] is avoided. This allows equation [5.12] to work well with a number of soil-water characteristic equations.

5.5.2 Verification of the Shear Strength Function

The shear strength prediction worked well for a number of different soils. Twenty-five different soils were used to verify the prediction algorithm. The shear parameter accounted for uncertainty in the predictions. Not enough soils were obtained, however, to allow the shear parameter to be estimated by the Rule Base with great certainty. Once more soils are collected, the Rule Base will provide accurate estimation of the shear parameter for different soil types. The Rule Base uses predefined criteria to check previous predictions of shear strength. If the search finds similar soils used in the past, the data is used to provide a reference for future predictions.

Typical plots generated by the shear strength form can be seen in Figure 5-19, Figure 5-20, and Figure 5-21. A more complete description of the shear strength prediction can be found in the paper "The Relationship of the Unsaturated Soil Shear Strength Function to the Soil-Water Characteristic Curve" by Fredlund et al (1996).

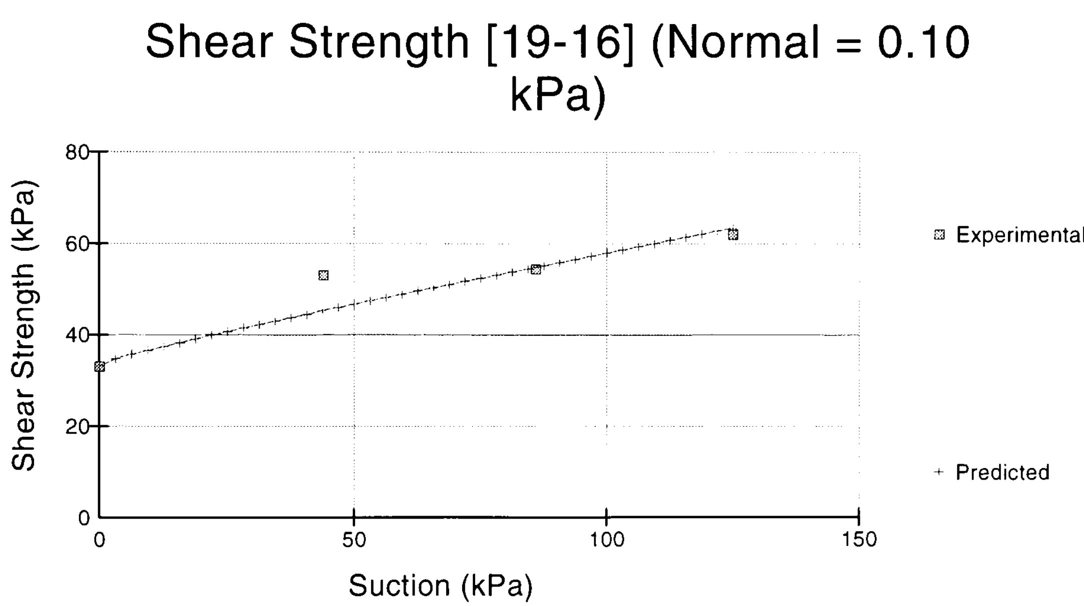


Figure 5-19 Shear strength prediction for a sandy clay loam (Soil_counter=19)

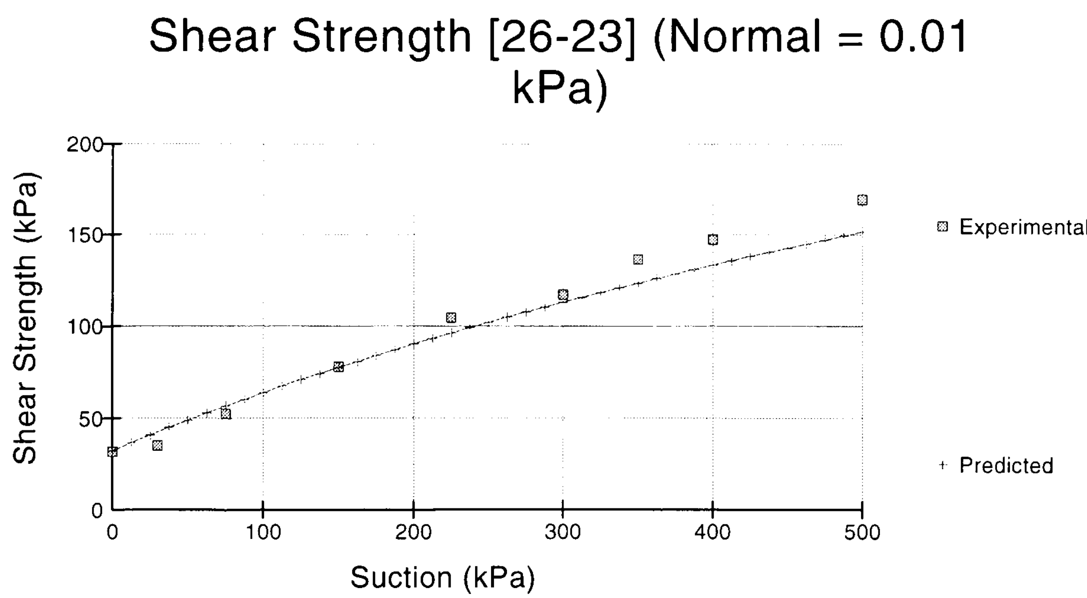


Figure 5-20 Shear strength prediction for a loam (Soil_Counter=26)

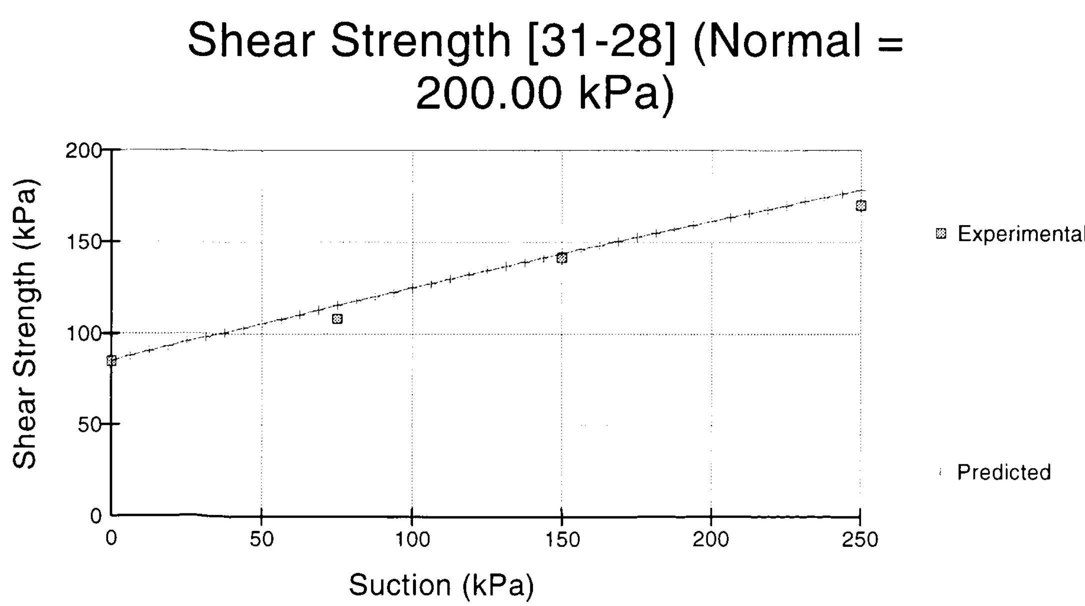


Figure 5-21 Shear strength prediction for a loam (Soil_Counter=31)

5.6 The Consolidation (or Compression) Curve

The consolidation form provides information on how the void ratio of a soil varies with a change in net normal stress. This relationship is typically determined in the laboratory with a consolidation test. The consolidation curve, like the SWCC, forms the basis for volume change relations in a soil. The KBS design, therefore, does not allow theoretical prediction of this curve but provides a method whereby the relationship may be estimated. This can be accomplished by searching the database for similar soils. Once a group of similar soils has been selected, the consolidation plots can be combined on one plot to observe the amount of divergence in the soils. A small amount of variance between plotted functions will indicate that parameters for the consolidation curve may be safely estimated. To allow the consolidation curve to be used as the basis for theoretical calculations, the experimental data must be fit with an equation. A modified Fredlund & Xing (1994) equation along with a fitting algorithm was used to fit experimental consolidation data. This provided a good method of empirically describing the consolidation process.

Estimation of the consolidation function provides valuable data for consolidation modelling. Terzaghi's equation uses the consolidation function as its central relationship. Recent work publishing the results of several consolidation predictions all required the input of a consolidation function (Townsend, 1990). General volume change formulations for both uncoupled and coupled, saturated and unsaturated soils will make use of a consolidation function in some form. The consolidation equation will become important in the future as more work is done in the area of coupled consolidation of unsaturated porous media (Dakshanamurthy, 1984)

5.6.1 Theory of Compression

When clays undergo loading their compression is controlled by the rate at which water is squeezed out of the pores because of their relatively low permeability. This process is called *consolidation*. Because of the universality of this problem, a solution for this has received much attention.

The first step to solving a problem is to identify the processes. In the case for consolidation of a saturated soil, an understanding of the physics occurring must be obtained. For a saturated soil, if we assume that a representative elementary volume (REV) is made up of soil and water, then any changes in volume can be attributed to addition or loss of water. This is assuming that the soil particles themselves do not change volume. What causes a soil element to change volume? Going back to basic soil mechanics it can be shown that a change in volume is tied to a change in effective stress of the soil. The relationship can be described by a graph similar to the one presented in Figure 5-22. This allows calculation of the current volume at any particular stress level given effective overburden and preconsolidation pressure.

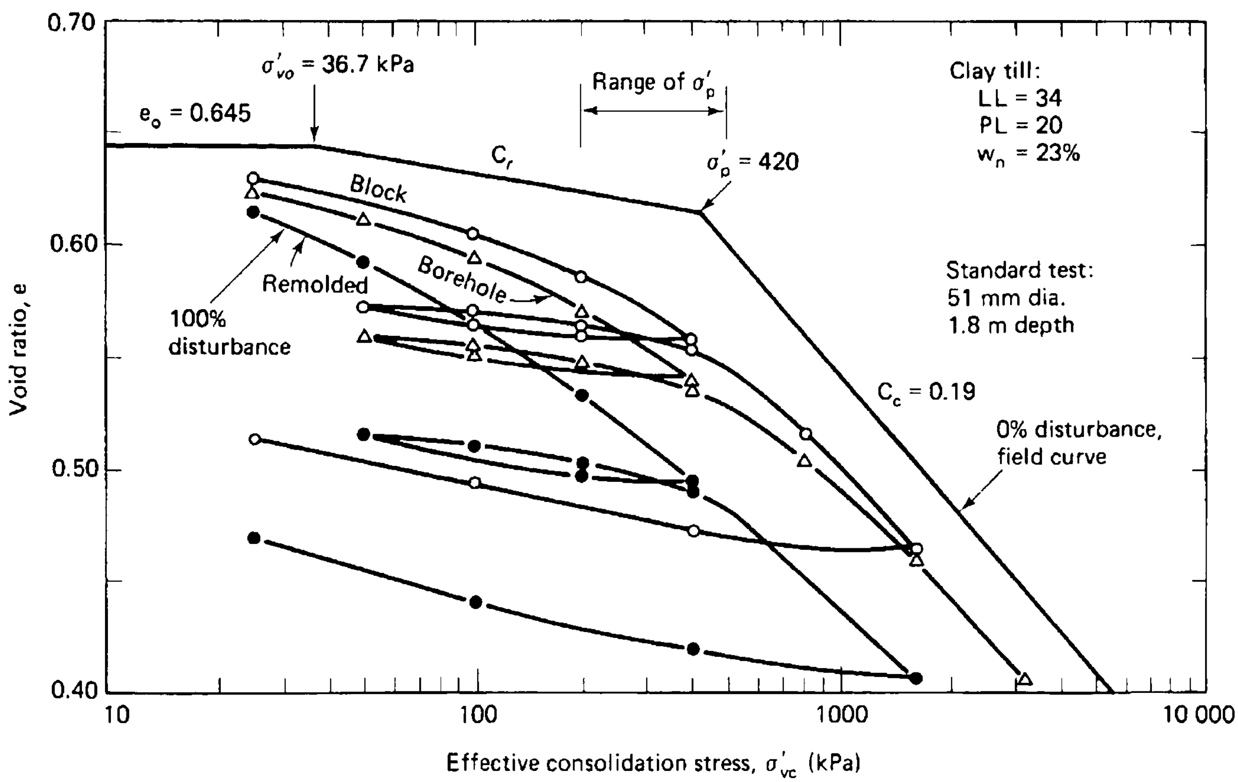


Figure 5-22 Typical curve showing relationship between void ratio and effective stress (Holtz & Kovacs, 1981)

In actual soils, when a pressure is applied to a soil, it does not change volume instantaneously. Pore-water pressures initially take all the extra load applied and then slowly dissipate to allow the soil structure to take the load. During this dissipation, the soil decreases in volume until the stress state in Figure 5-22 is obtained. This process of volume change and the time it takes is referred to as consolidation.

In 1924 Terzaghi developed a partial differential equation describing the process of consolidation in a saturated soil (Cryer, 1962). This equation is shown below.

$$\frac{\partial u_w}{\partial t} = c_v \frac{\partial^2 u_w}{\partial y^2}$$

where $c_v = \dfrac{k}{m_v \gamma_w}$

Terzaghi's equation has been used extensively in predicting consolidation processes in soils. The equation requires only two input parameters; saturated hydraulic conductivity, and m_v. The coefficient of volume change, m_v, can be related to the slope of the consolidation curve, a_v, through the equation:

$$m_v = \frac{a_v}{1 + e_o}$$

The relationship between void ratio and net normal stress is therefore significant in the consolidation process of saturated soils. It has been shown that the consolidation curve forms the basis for constitutive relations describing the behavior of an unsaturated soil (Fredlund, 1993). This is illustrated in Figure 5-23.

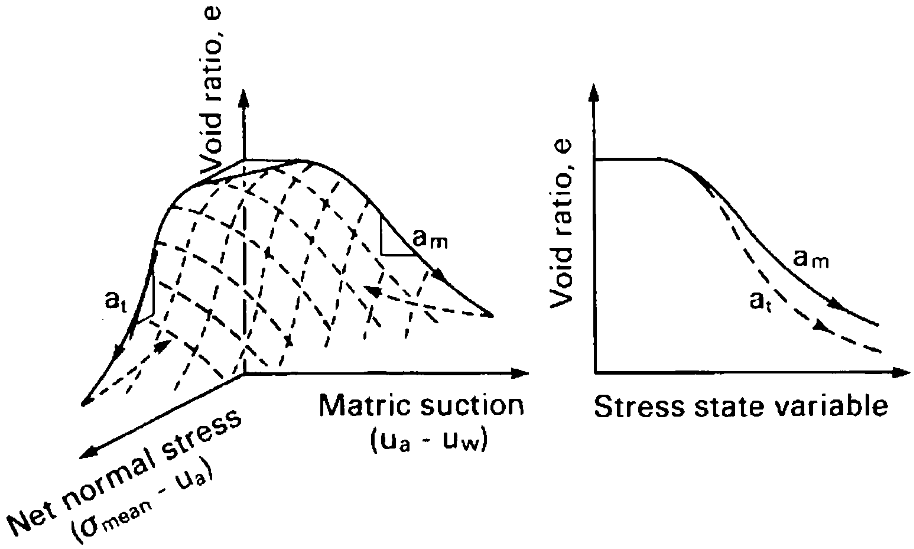


Figure 5-23 Constitutive surfaces for an unsaturated soil expressed using soil mechanics terminology (Fredlund, 1993)

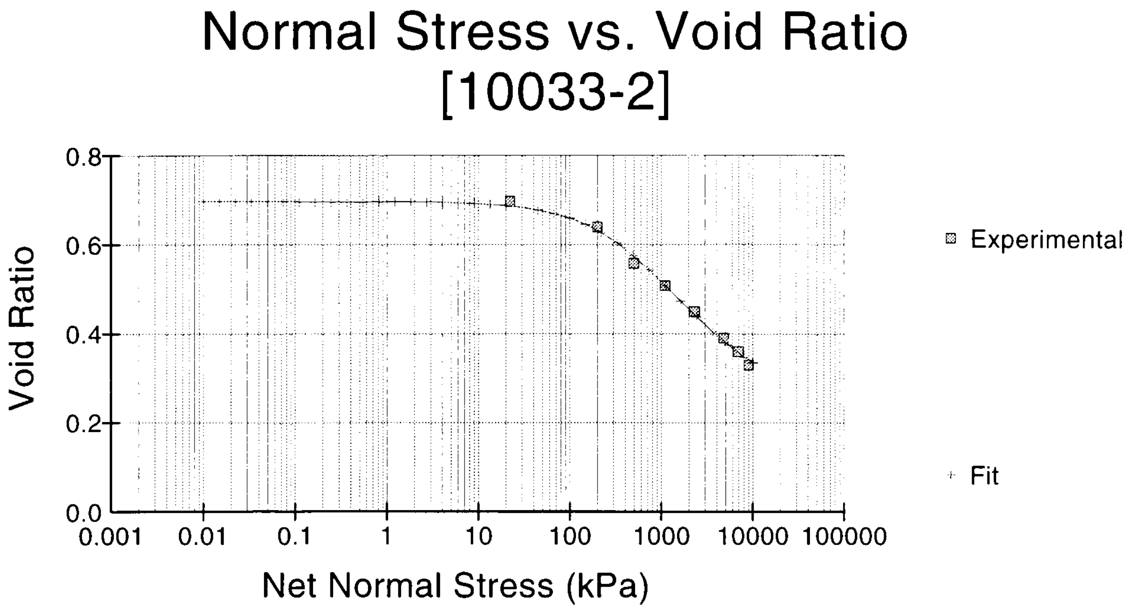
The shape of consolidation curves was noted to be similar to the shape of the SWCC. Since the SWCC can be fit quite well with the Fredlund & Xing (1994) equation, it was assumed that a similar equation could be developed to fit consolidation data. A modified Fredlund & Xing (1994) equation was developed in this research which appears to fit consolidation data quite successfully. The equation developed by the author is shown below.

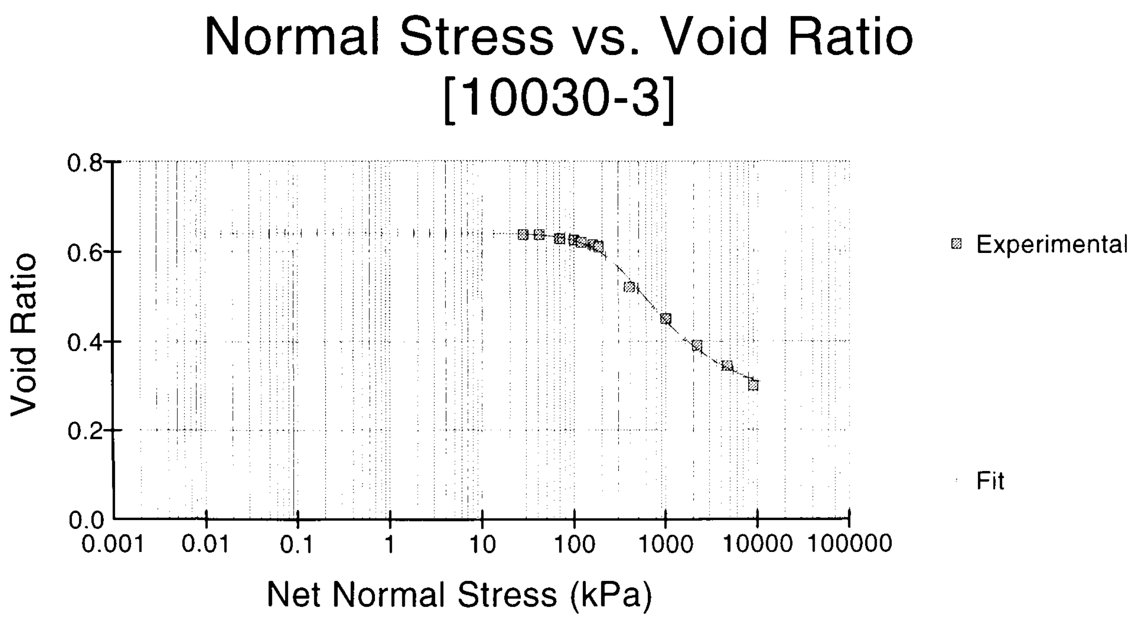
$$e(\sigma_n) = e_o \left[\frac{1}{\ln\left(\exp(1) + \left(\frac{\sigma_n}{a} \right)^n \right)} \right]^m$$

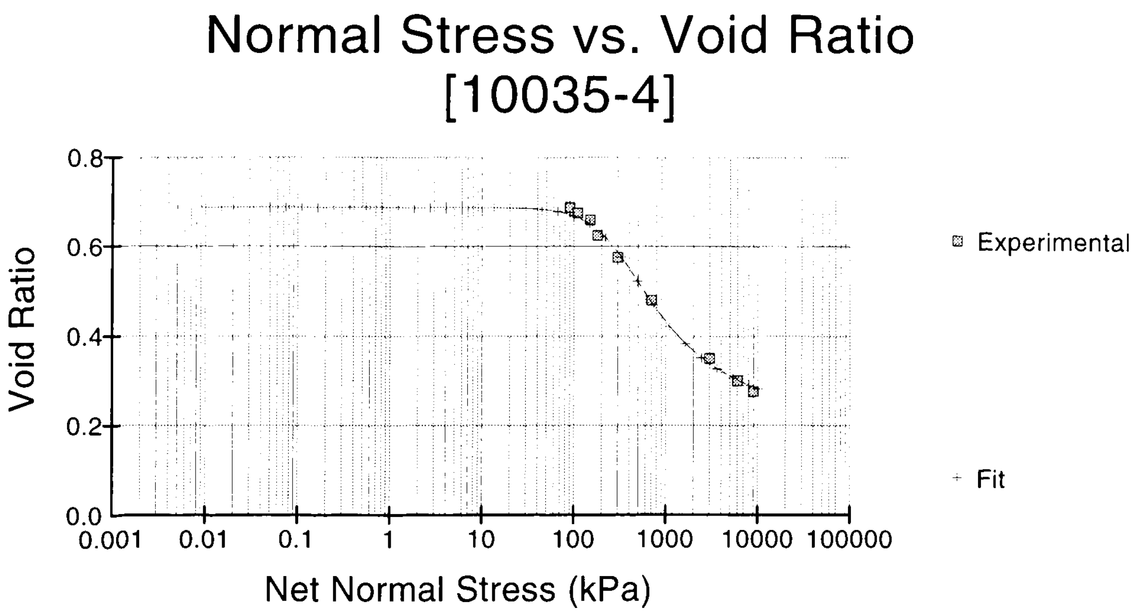
The modified Fredlund and Xing (1994) equation contains three unknown parameters (a, n, and m) which must be found by a linear regression algorithm. The parameters a, n, and m were found to perform in a manner similar to the Fredlund & Xing (1994) equation. The 'a' parameter corresponded to the initial break in the equation while the 'n' parameter corresponded to the maximum slope of the equation. The 'm' parameter gave an indication of the curvature of the equation.

5.6.2 Verification of the Compression Function

Fitting the modified Fredlund & Xing (1994) equation to experimental data produced good results. An equation was obtained which mathematically described the consolidation function for soils. Graphs showing some consolidation curves for soils are shown below. Parameters used to fit the consolidation equation to experimental data can be found in Table 5-3.







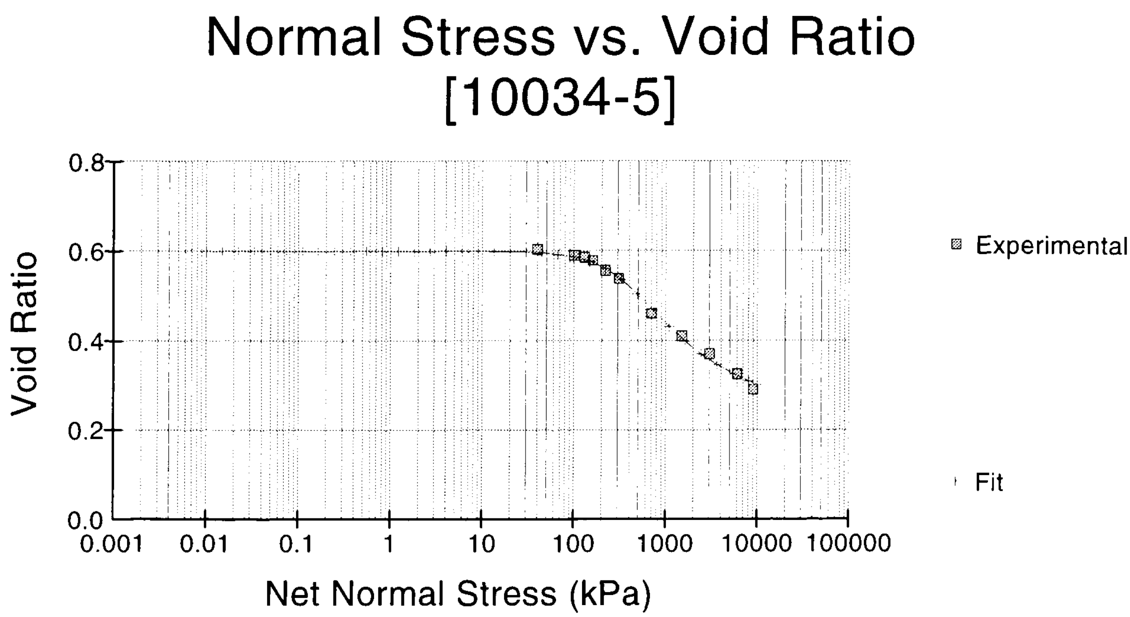


Figure 5-24 Plots showing the fit of the modified Fredlund & Xing (1994) equation to consolidation data

Table 5-3 Summary of the parameters used to fit the consolidation experimental data

Soil_Counter	ca	cn	cm	Squared error
10033	452.3	0.929	.664	.00135
10030	270.7	1.71	.399	.00200
10035	254.7	1.85	.466	.00223
10034	327.2	1.55	.412	.00206

5.7 The Specific Heat Function

Modelling thermal changes in soil requires knowledge of the specific heat of a soil. Unfortunately, specific heat is not constant for an unsaturated soil but varies according to the level of saturation. Typically, only saturated or dry specific heat capacities are used. A method was selected that combined SWCC information with the mass specific heat of the soil solids to predict the volumetric specific heat capacity of the soil for all levels of saturation. The method was incorporated into the KBS design.

5.7.1 Theory of the Specific Heat Function

The volumetric specific heat capacity was calculated using the following expression (Newman, 1995):

$$vsh = \gamma_d(c_s + 4.184\ \theta_w)$$

where:

vsh = the volumetric specific heat (J/m^3 C),

γ_d = the dry density of the soil (kg/m^3),

c_s = the mass specific heat of the soil solids (J/g C),

θ_w = the volumetric water content of the soil.

5.7.2 Implementation of the Specific Heat Function

No data was found to confirm the prediction of specific heat. A typical curve produced by the specific heat function can be seen in Figure 5-25.

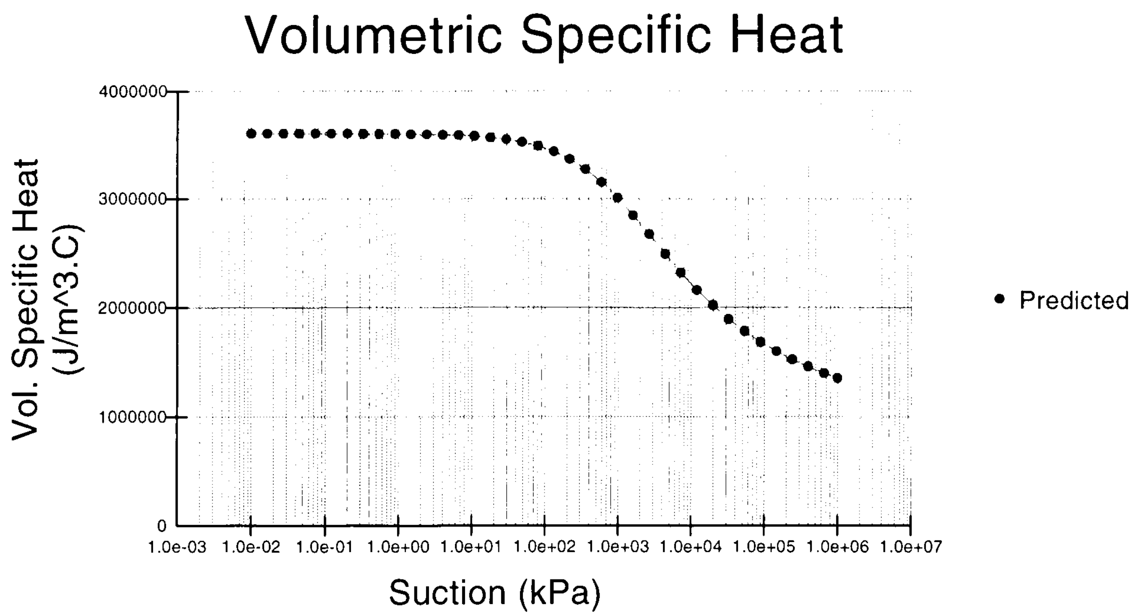


Figure 5-25 Typical plot of volumetric specific heat versus soil suction

5.8 The Thermal Conductivity Function

Estimation of the thermal conductivity of a soil is necessary for predicting heat flow. Experimental measurement of this property can often be difficult to obtain. In addition, water contents of soil often vary significantly and change the thermal conductivity of the soil. The Knowledge-Based System design attempts to provide a continuous function describing the thermal conductivity at all levels of saturation. Johansen (1975) developed a method of predicting thermal conductivity. The method required the input of soil state, soil gradation, quartz content, and a SWCC. The method then provides a continuous equation describing how thermal conductivity varies according to suction.

5.8.1 Theory of the Thermal Conductivity Function

The method developed by Johansen (1975) was selected for its accuracy and ease of use. It gives best results for degrees of saturation above 0.1. Below a saturation of 0.1, the function was linearly approximated. The method shown below enables the thermal conductivity to be calculated for various cases. The main equation used by Johansen (1975) is:

$$\lambda = (\lambda_{sat} - \lambda_{dry})\lambda_e + \lambda_{dry}$$

where:

λ_{sat} = the saturated thermal conductivity (W/m°C)

= $0.57^n \lambda_s^{(1-n)}$ for the unfrozen case,

n = the porosity of the soil,

λ_s = the effective solids thermal conductivity (W/m°C)

= $7.7^q \, 2.0^{1-q}$ if $q > 0.20$,

= $7.7^q \, 3.0^{1-q}$ if $q < 0.20$,

q = the quartz content as a fraction of total solids content,

λ_{dry} = the thermal conductivity of the soil matrix in the dry state (W/m°C)

= $\dfrac{0.137\gamma_d + 64.7}{2700 - 0.947\gamma_d}$ if the soil is in a natural state,

= $0.39 \, n^{-2.2}$ if the soil is crushed,

γ_d = the dry density of the soil (kg/m^3)

λ_e = the Kersten number,

= $0.7 \log S_r + 1.0$ for a coarse, unfrozen soil,

= $\log S_r + 1.0$ for a fine, unfrozen soil,

S_r = the degree of saturation.

5.8.2 Verification of the Thermal Conductivity Function

The prediction algorithm was tested against experimental data collected by Greg Newman (1995). The predicted results matched reasonably well and can be viewed in Figure 5-26. The quartz content of the soil seemed to be quite sensitive. Some adjusting of the quartz content was needed to match experimental results.

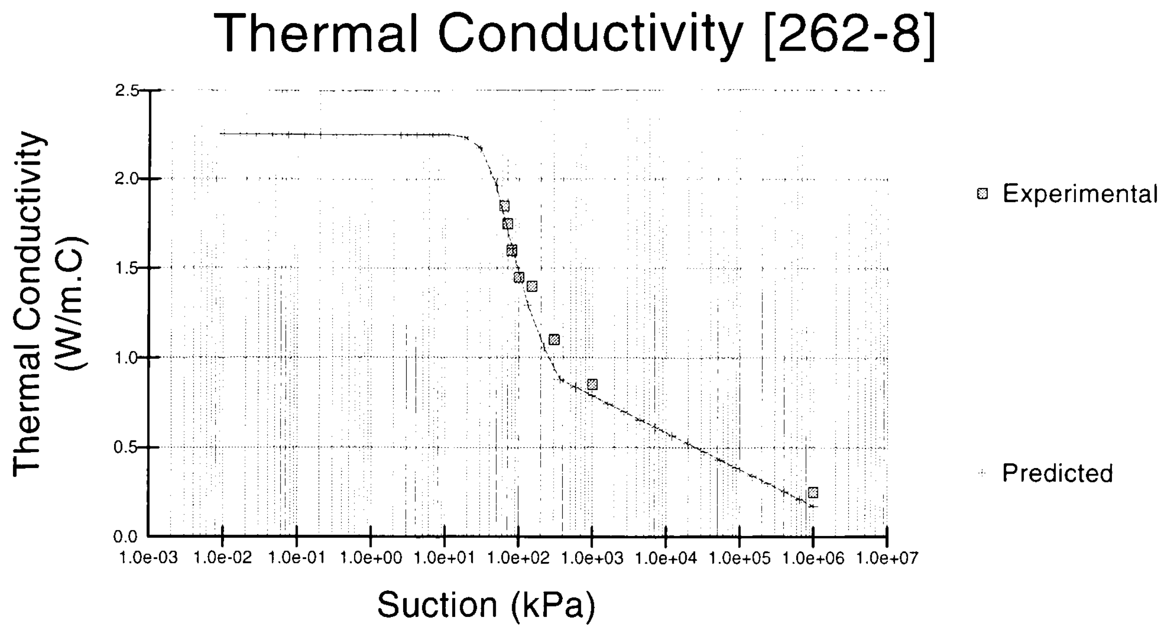


Figure 5-26 Plot of experimental and predicted results for a silica flour (Soil #262)

5.9 The Unfrozen Volumetric Water Content Function

Modelling of processes in frozen soils is becoming common. This has resulted in a demand for the relationship between unfrozen volumetric water content and temperature. Such a relationship has typically been measured in the laboratory using such equipment as pulsed nuclear magnetic resonance (PNMR). Because of the prohibitive cost of such equipment, methods have been developed for the prediction of these soil functions, hereafter referred to as soil freezing characteristic curves. It has been shown that SWCCs can be used to predict unfrozen water content of those same soils as a function of temperature and pore pressure (Miller, 1973). This has led to a formulation allowing the soil freezing characteristic curve to be predicted from the soil-water characteristic curve (Black, 1989). The Knowledge-Based System design has selected this technology to allow prediction of soil freezing curves.

5.9.1 Theory of the Frozen Water Content Function

The theoretical basis for the relation between the soil-water characteristic curve and the soil freezing characteristic curve was developed by Miller (1965), and Koopmans and Miller

(1966). An overview of the theory is presented in the following section. A complete development of the theory is provided by Black (1989).

The matric suction of the soil without the presence of ice is expressed as

$$\psi_{aw} = u_a - u_w$$

where u represents suction and the subscripts a and w represent air and water respectively. Likewise, the state of water in an air-free soil containing both ice and water can be expressed as

$$\psi_{iw} = u_i - u_w$$

where u_i is the ice pressure.

It was hypothesized by Miller (1965) that if the same states of soil moisture content and distribution are achieved by a freezing and thawing process as in a drying and wetting process, then the two states should be similar and interchangeable if the soil is either colloidal (pure clay) or colloid-free (coarse soils such as sands and gravels). This resulted in a relationship relating ψ_{aw}, and ψ_{iw}.

$$\psi_{aw} = C_f \cdot \psi_{iw}$$

where C_f is a correction factor. It was hypothesized that for a purely colloidal soil (such as a pure clay), the two stress state variables should be directly related. This produced a correction factor, C_f, of 1.0 for a pure clay. Koopmans and Miller (1966) experimentally proved this theory. They found that for a purely colloidal soil, the soil-water characteristic curve could be related directly to the soil freezing curve. Experimentation also proved that soils dominated by capillary space such as coarse sands and gravels required a correction factor of 2.2. Experimentation has not been performed to validate the correction factor for other soil types.

Once the above relationship is combined with the Clasius-Clapeyron equation, the following relationship is provided.

$$\psi_{aw} = C_f\,(-1110)\,t$$

where:

ψ_{aw}	=	the suction in the air-water interface [kPa]
t	=	temperature in degrees Celsius below zero

This conversion between temperature and suction is then substituted into the equation of the soil-water characteristic curve to produce an equation describing the relationship between unfrozen volumetric water content and temperature. Correction factors of 1.0 and 2.2 are used for pure clays and coarse soils respectively.

5.9.2 Verification of the Unfrozen Water Content Function

Proper testing of the prediction method was achieved by comparing prediction results to those obtained by Black (1989). Six Windsor sandy loams were obtained from Black as well as one soil from Newman (1996). A comparison between experimental results and predicted results is shown in Figure 5-27 for the Windsor sandy loams. The prediction of unfrozen water content was relatively the same for all Windsor sandy loams so the results of only one prediction are displayed. The prediction results of unfrozen water content for the silica flour obtained from Newman (1996) are shown in Figure 5-28.

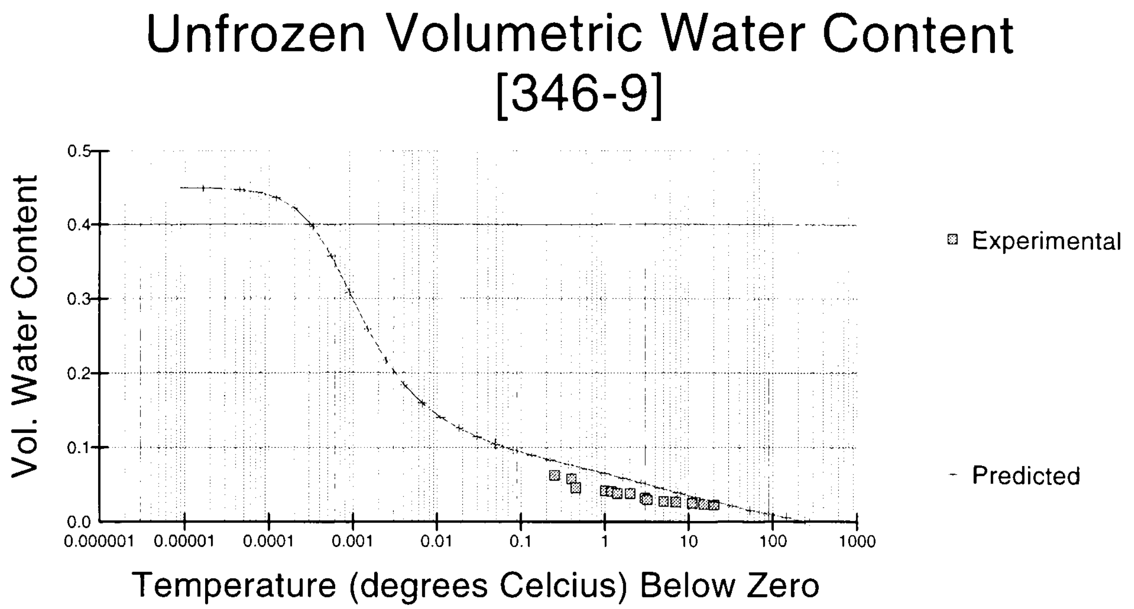


Figure 5-27 Comparison between experimental and predicted data for Windsor sandy loam horizon A

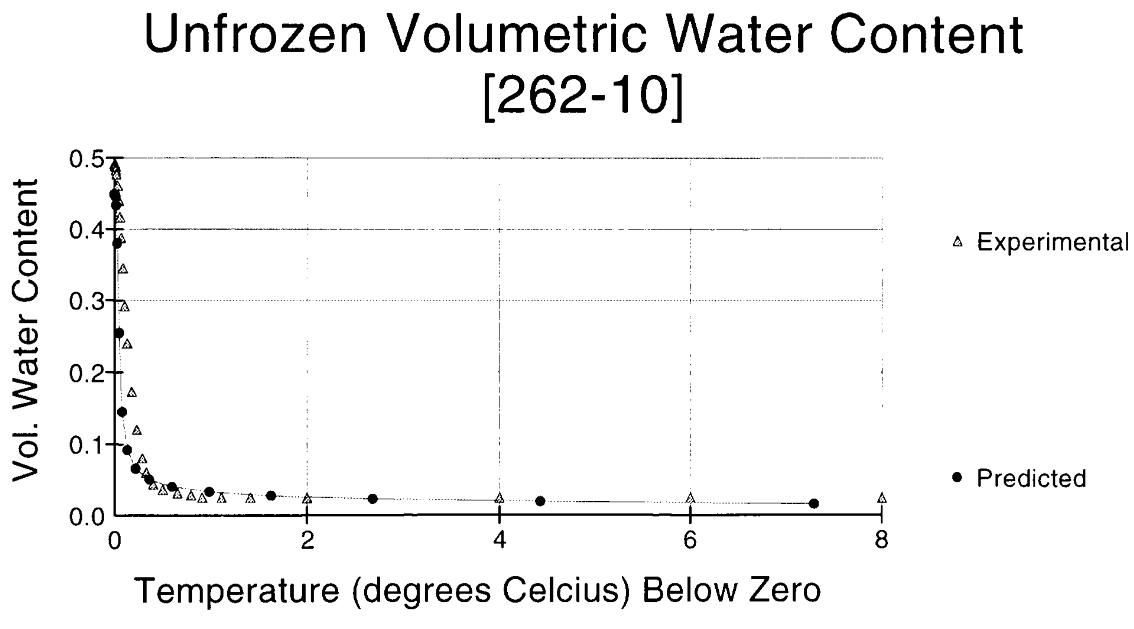


Figure 5-28 Comparison between experimental and predicted data for a Silt Flour

The differences between experimental and predicted results for the Windsor sandy loam can be attributed to the fit of the soil-water characteristic curve. Black (1989) fit the soil-water characteristic curves with a Brooks and Corey (1966) equation while the results presented here are the result of applying the Fredlund & Xing (1994) equation to fit experimental SWCC data.

A shortcoming of the data obtained from Black (1989) is that the experimental data for the soil-water characteristic curve does not overlap with the experimental data for the soil freezing characteristic curve. More data is needed for a complete comparison. As more data is added to the Knowledge-Based System design, it will also allow for accurate estimation of the Unfrozen Parameter by the Rule Base. An accurate assessment of how this parameter varies could not be obtained.

5.10 The Diffusion Function

Studies have shown that diffusion can be a dominant mechanism governing the movement of contaminants in fine-grained soils due to the low hydraulic conductivity associated with these soils (Lim, 1996). Low hydraulic conductivity can result in diffusion becoming a significant transport mechanism. Diffusion coefficients are readily available for most chemicals assuming diffusion in distilled water. Complications have arisen when applying these diffusion coefficients to soils. They arise because the degree of saturation of a soil typically changes over time. As the degree of saturation decreases, a reduction in the coefficient of diffusion has been noted (Lim, 1996). The Knowledge-Based System design has therefore selected a method of predicting the variation in the coefficient of diffusion for a soil as it desaturates.

5.10.1 Theory of Diffusion Function

The theory behind the prediction of diffusion was developed by Lim (1996) at the University of Saskatchewan. The theory has two parameters to account for variation. The Diffusion Parameter, p controls the effect of the soil-water characteristic curve on diffusion. The Coefficient of Film Diffusion, C_f, controls the diffusion in small films of water around soil particles. C_f is typically 0.0 for sands, 0.1 for silts, and 0.2 for clays. Taking the preceding into account, the following equation is produced which estimates an effective diffusion as the soil desaturates.

$$D_e(\psi) = D_s\left[\Theta(\psi)^p + (1 - \Theta(\psi))\ C_f\right]$$

where:

De	=	effective coefficient of diffusion, and
Ds	=	saturated coefficient of diffusion,
Θ	=	normalized soil-water characteristic curve or degree of saturation curve,
p	=	parameter accounting for influence of the soil-water characteristic curve,
ψ	=	suction level.

5.10.2 Verification of the Diffusion Function

Two soils were available with experimental data to test the diffusion prediction. The first was a Beaver Creek Sand with a porosity of 38.2%. The second soil was a light brown, clean, processed silt produced from a natural silt. The comparison between experimental and predicted results can be seen in Figure 5-29 and Figure 5-30. The results show good correlation for the prediction method. The most highly sensitive values were found to be the Diffusion Parameter in the diffusion form and the residual suction specified in the SWCC form. The formulation of the diffusion prediction produces a constant value after residual suction. The Diffusion Parameter had to be adjusted to allow a close prediction. More soils added to the Knowledge-Based System design will allow the Rule Base to estimate the Diffusion Parameter quickly and efficiently.

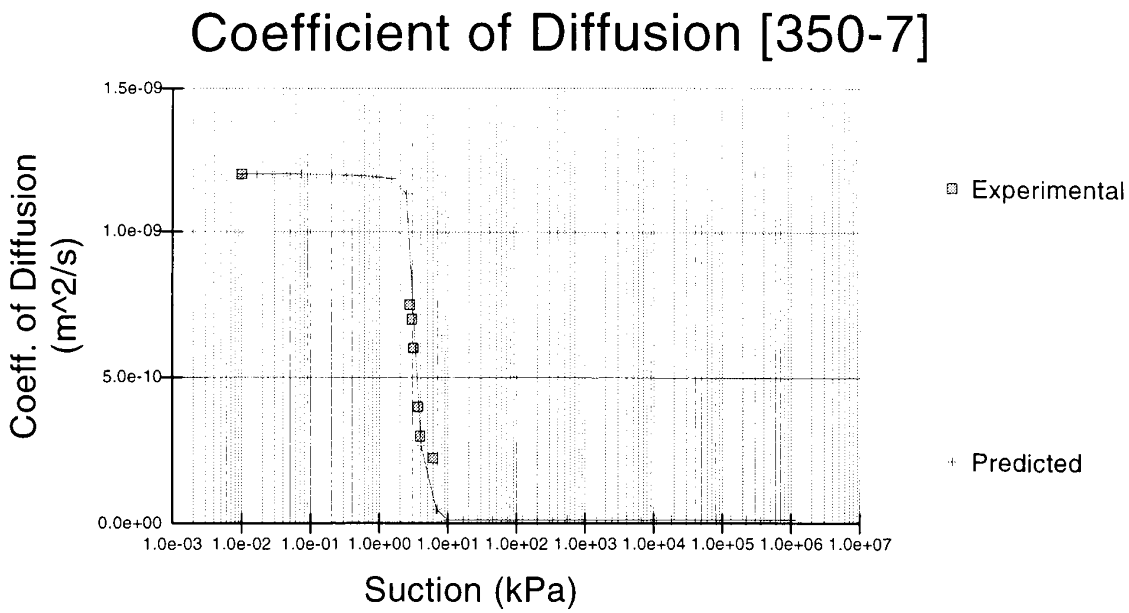


Figure 5-29 Comparison of predicted and experimental diffusions for Beaver Creek Sand

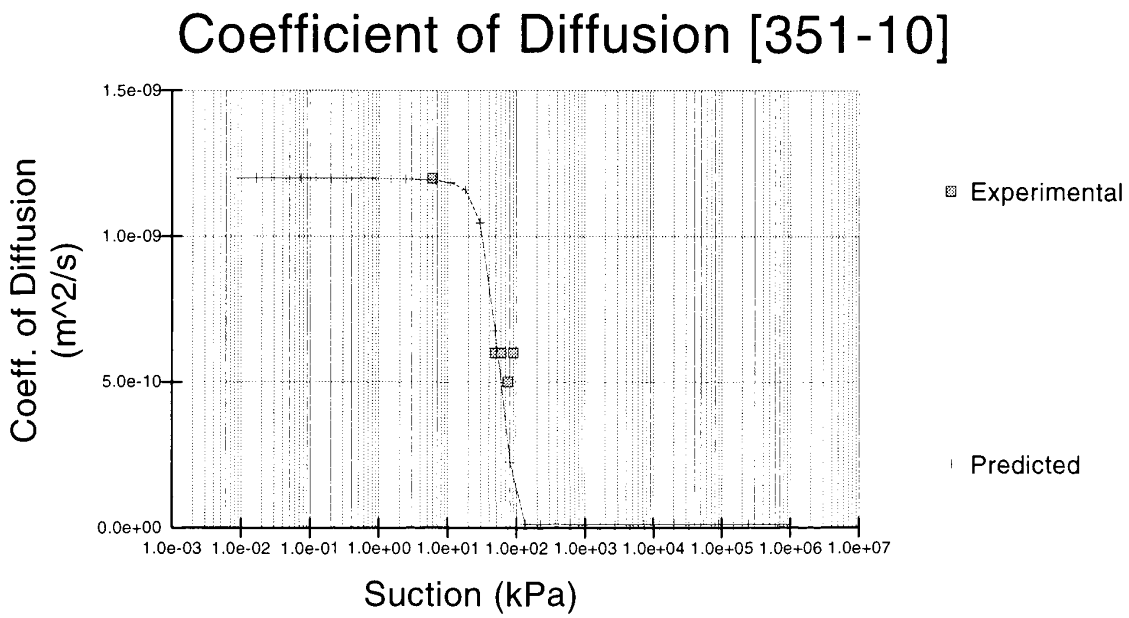


Figure 5-30 Comparison of predicted and experimentally measured diffusion for Processed Silt

5.11 *The Adsorption Function*

Geoenvironmental engineering has recently directed attention to the adsorptive qualities of soils. There is use for engineered soils that can be used as barriers to inhibit the flow of contaminants into the natural hydrogeologic environment (Lim, 1996). Adsorption provides a method by which the movement of contaminants may be attenuated.

Two processes work to move contaminants through the soil. *Advection* is the process by which dissolved solids are carried along with the flowing groundwater (Fetter, 1993). *Hydrodynamic dispersion* or *diffusion* moves contaminant by turbulent water flow and/or molecular diffusion. Counteracting the moving processes are attenuation processes which remove dissolved solute from the groundwater. Solute can be sorbed onto the surfaces of soil particles, sorbed by organic carbon which might be present, undergo chemical precipitation, be subjected to abiotic and biodegradation, and participate in oxidation-reduction reactions. Radioactive compounds can also decay. As a result of these processes, some solutes will move more slowly through the soil than the ground water that is transporting them.

Separating each attenuation process is not always necessary. A mathematical description can be used to describe the overall effect of the various processes. The process of describing the relationship between contaminant in solution and the solid phase is called *partitioning*. The capacity of a solid to remove a solute is a function of the concentration of the solute and the degree of saturation of the soil. This process can be described by an *equilibrium sorption isotherm* (Fetter, 1993). Recent research has also shown that sorption varies depending on the degree of saturation of a soil. A method of predicting how degree of saturation will affect sorption was also developed (Lim, 1996). The Knowledge-Based System design has implemented this technology to allow the prediction of a three-dimensional surface describing how soil sorption varies in relation to solute concentration and degree of saturation.

5.11.1 Theory of the Adsorption Function

Three common model descriptions are presented in describing the relationship between the amount of a solute sorbed onto solid, C*, and the concentration of the solute, C. The three models are termed Linear, Freunlich, and Langmuir. The equations used in each model are listed in Table 5-4.

Table 5-4 Adsorption isotherm models

Model	Equation
Linear	$C^* = K_d\,C$
Freundlich	$C^* = K\,C^N$
Langmuir	$C^* = \frac{\alpha\beta C}{1 + \alpha C}$

Work measuring the adsorption in soils has typically assumed that adsorption of the entire soil mass is effective regardless of the degree of saturation. Bear (1979) made this assumption in describing the adsorption process in soils. Bear later postulated that the adsorption process in soils should be a function of the degree of saturation as shown below:

$$C^* = S\,K_d\,C$$

Lim (1995) measured the relationship between actual adsorption and potential adsorption for various soils and developed a theoretical model for adsorption in unsaturated soils taking into account varying degrees of saturation. Development of the theory is as follows.

Adsorptive activity of a soil particle can be described by the following equation:

$$Q_d = 1/(d)^c$$

where:

Q_d = adsorption activity of a soil particle, and

c = a constant which comprises the effect of surface reactivity, and

d = the diameter of the soil particle (mm).

The preceding equation expresses adsorptive activity in terms of particle size. Actual adsorption is also controlled by the accessibility of the contaminant to adsorption sites. As a soil desaturates, the number of available adsorption sites decreases, causing a decrease in the adsorption potential. In order to relate the loss of adsorption to the effect of desaturation, there is a need to define the adsorption activity in terms of the pore-size (Lim, 1996). Correlations have shown that pore-size can be related to grain-size so pore-size can be substituted for grain-size. The equation describing the activity of a soil particle based on pore-size can be written as:

$$A_d = 1/(d_{pi})^c$$

where:

A_d = apparent adsorption activity of a soil particle associated with the *i*th pore, and

d_{pi} = diameter if the *i*th pore.

Pore diameters can then be calculated using the capillary model (Childs, 1969) as follows:

$$d_p = 4T_s/(u_a - u_w)$$

where:

Ts = surface tension of water (F L^{-1}), and

$(u_a - u_w)$ = soil suction (F L^{-2}).

The adsorption of a soil must also account for the distribution of adsorption sites. The distribution of the adsorption sites can be assumed to follow the same distribution as the pore-size distribution (Lim, 1996). The SWCC then provides an estimation of the distribution of pores. Adsorption can then be calculated as the integration of potential adsorption sites divided by pore diameter.

$$A_{total} = \int_0^{\psi_r} \frac{dS}{(d_p)^c}$$

where:

A_{total}	=	total potential adsorption sites in a given volume of soil, and
dS	=	derivative of the saturation function,
c	=	a constant which comprises the effect of surface reactivity,
ψ_r	=	residual suction or suction at which water phase is discontinuous.

As the soil desaturates, the loss of potential adsorption sites can be written as,

$$A_{inactive} = \int_0^{\psi} \frac{dS}{(d_p)^c}$$

where:

$A_{inactive}$ = inactive adsorption sites or the fraction of soil particles from the continuous diffusion pathways, and

ψ = current suction.

The loss of adsorption sites as suction increases is then normalized to generate the following β factor.

$$\beta(S) = 1 - \left(\frac{A_{inactive} = \int_0^{\psi} \frac{dS}{(d_p)^c}}{A_{total} = \int_0^{\psi_r} \frac{dS}{(d_p)^c}} \right)$$

The β factor is then combined with either the Linear, Freundlich, or Langmuir model to predict how adsorption varies with changes in concentration and changes in suction.

5.11.2 Verification of the Adsorption Function

Two soils were available with experimental data to test the adsorption prediction. The first was a Beaver Creek Sand with a porosity of 38.2%. The second soil was a light brown, clean, processed silt produced from a natural silt. The comparison between experimental and predicted results can be seen in Figure 5-31 and Figure 5-32. The results show good correlation for the prediction method. The most highly sensitive values were found to be the ***c*** parameter in the adsorption form and the residual suction specified in the SWCC form. The formulation of the adsorption prediction produces zero adsorption after residual suction. The ***c*** parameter had to be adjusted to allow a close prediction. As more soils are added to the Knowledge-Based System design, the Rule Base will allow the ***c*** parameter to be estimated quickly and efficiently.

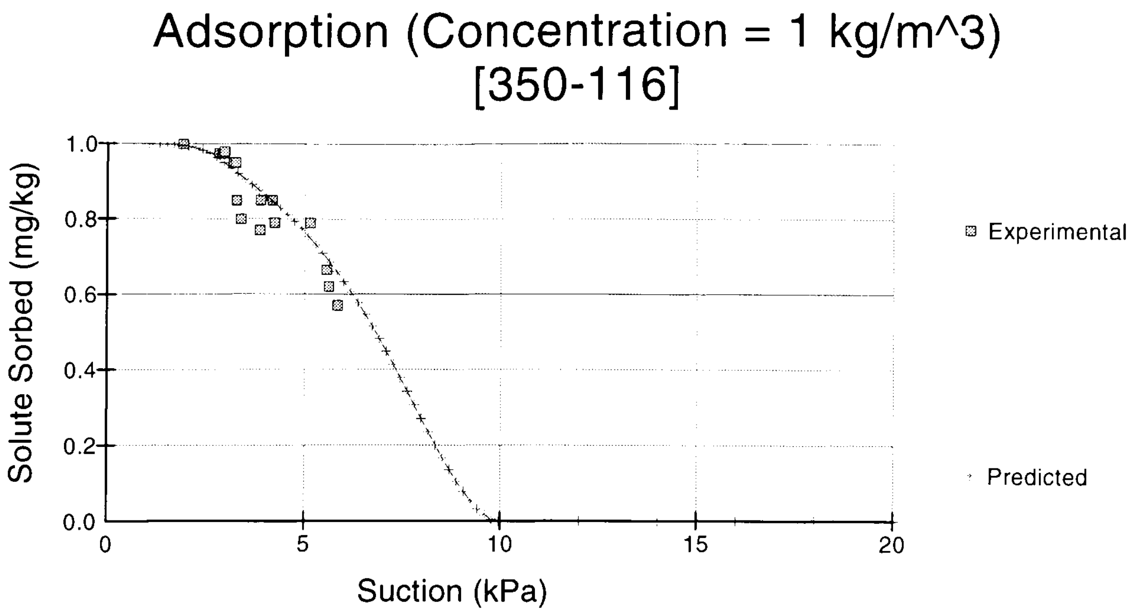


Figure 5-31 Comparison between experimental and predicted results for Beaver Creek Sand

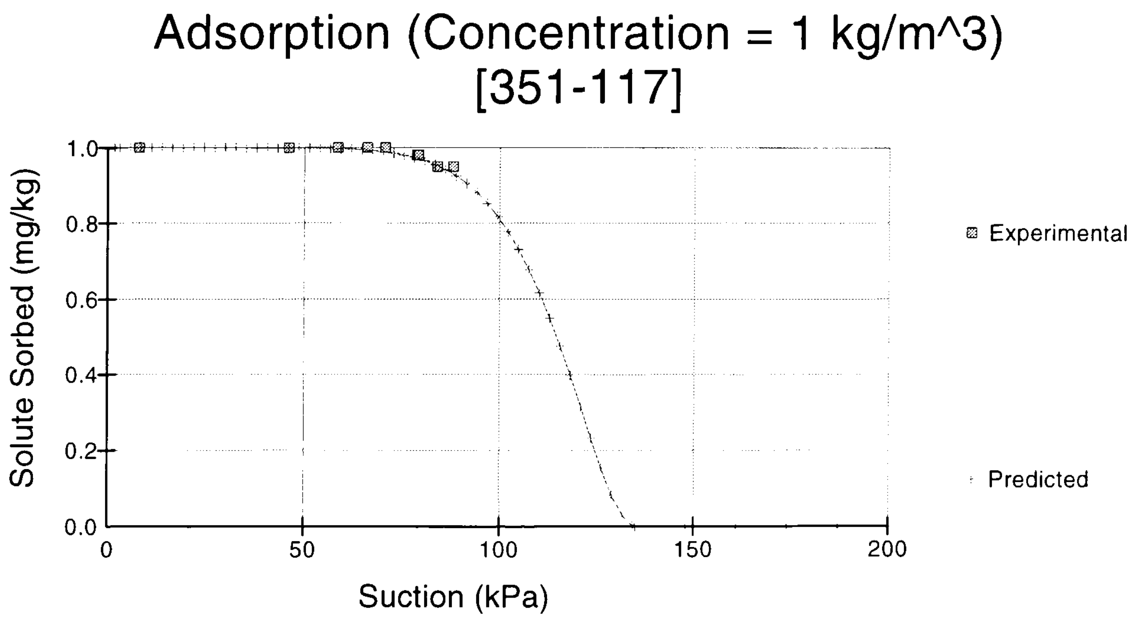


Figure 5-32 Comparison between experimental and predicted results for a Processed Silt

5.12 Example Application 1 - OK TEDI Mine

An example of how this technology may be applied is as follows. Recent work was performed on the OK TEDI Mine site in Papua, New Guinea. Soil information on several soils in the form of basic volume-mass properties and a grain-size distribution was known as shown in Figure 5-33. From this data, it was necessary to determine a reasonable SWCC. To solve this problem, the soil information was input into the Knowledge-Based System design. The grain-size form then allowed for a direct theoretical prediction of the soil-water characteristic curve as shown in Figure 5-34.

To check if this curve was reasonable, the soils database was queried for all soils with a similar grain-size curve. Similar soils were selected by specifying a range of variation for the parameters used to fit the grain-size curve. Figure 5-35 was produced which showed the similar grain-size curves that had been selected. The corresponding soil-water characteristic curves for these grain-size curves were then plotted and are shown in Figure 5-36. This allowed for verification of the original prediction of the soil-water characteristic curve as well as providing a sensitivity analysis as to how much variation was possible. The SWCC and conductivity function were then used to develop a conceptual design for a soil cover system for the mine tailings.

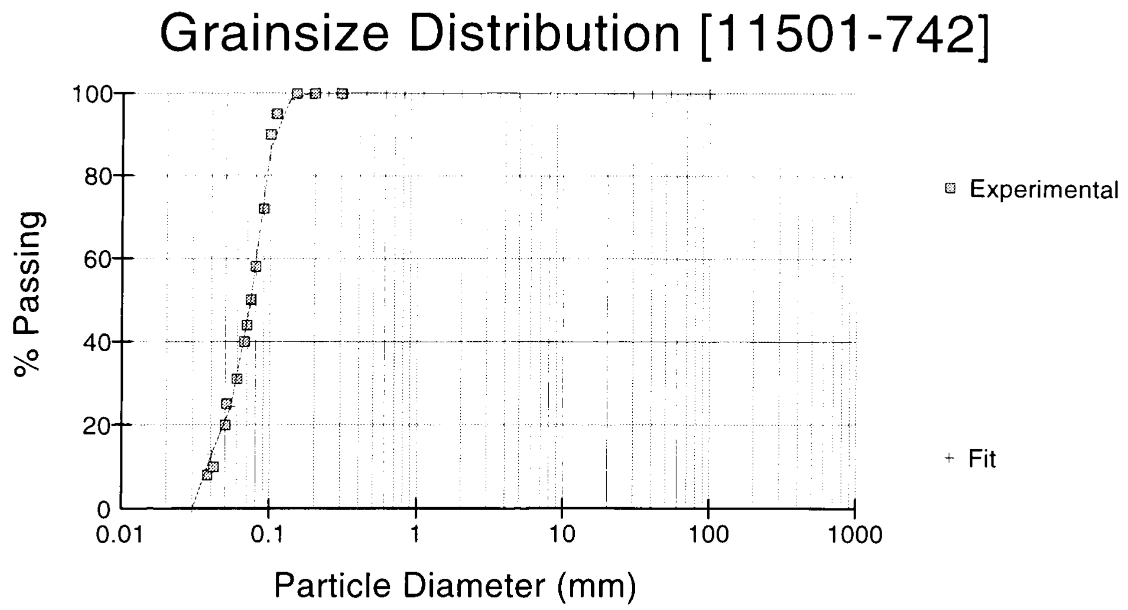


Figure 5-33 Grain-size distribution of Fine Sand

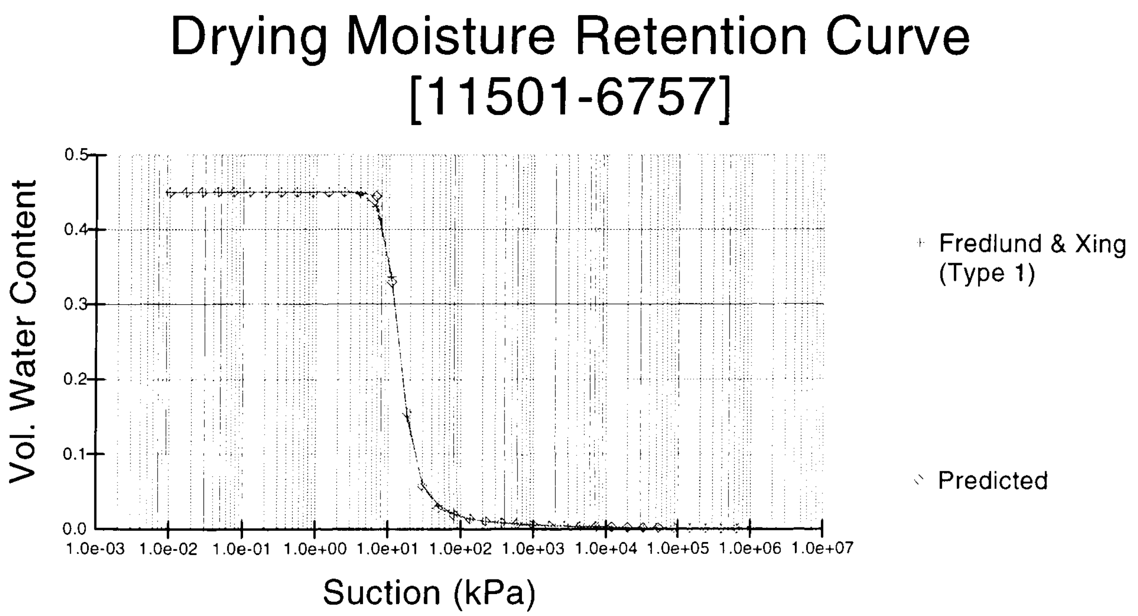


Figure 5-34 Predicted soil-water characteristic curve of Fine Sand

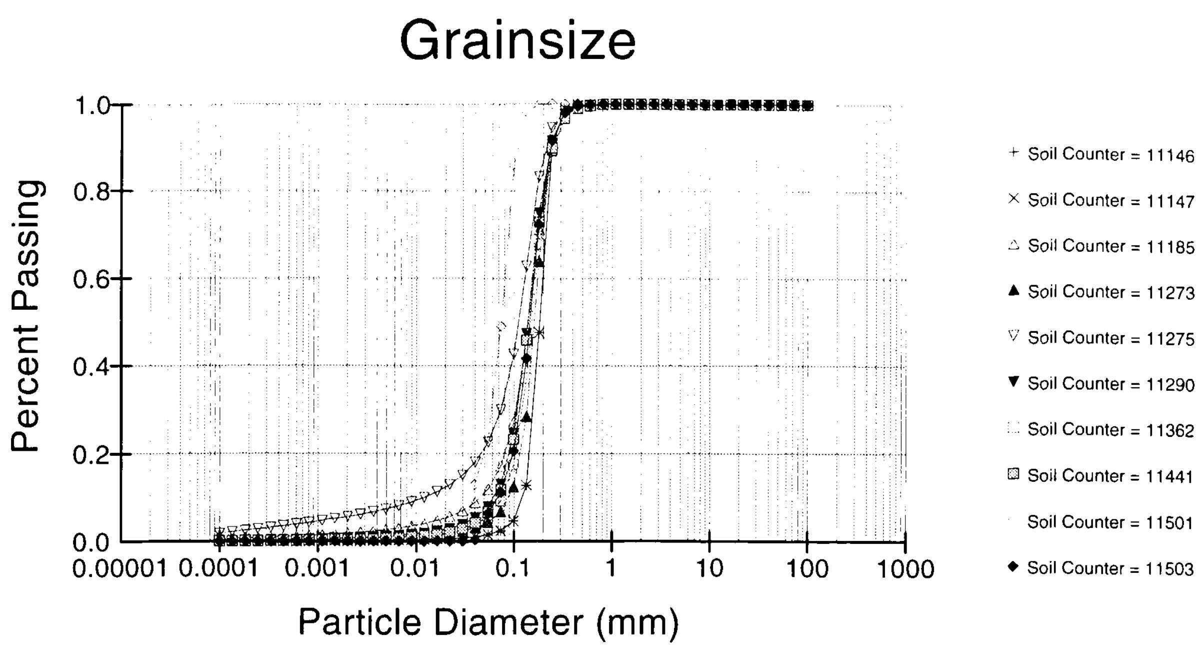


Figure 5-35 Similar grain-size curves selected by query

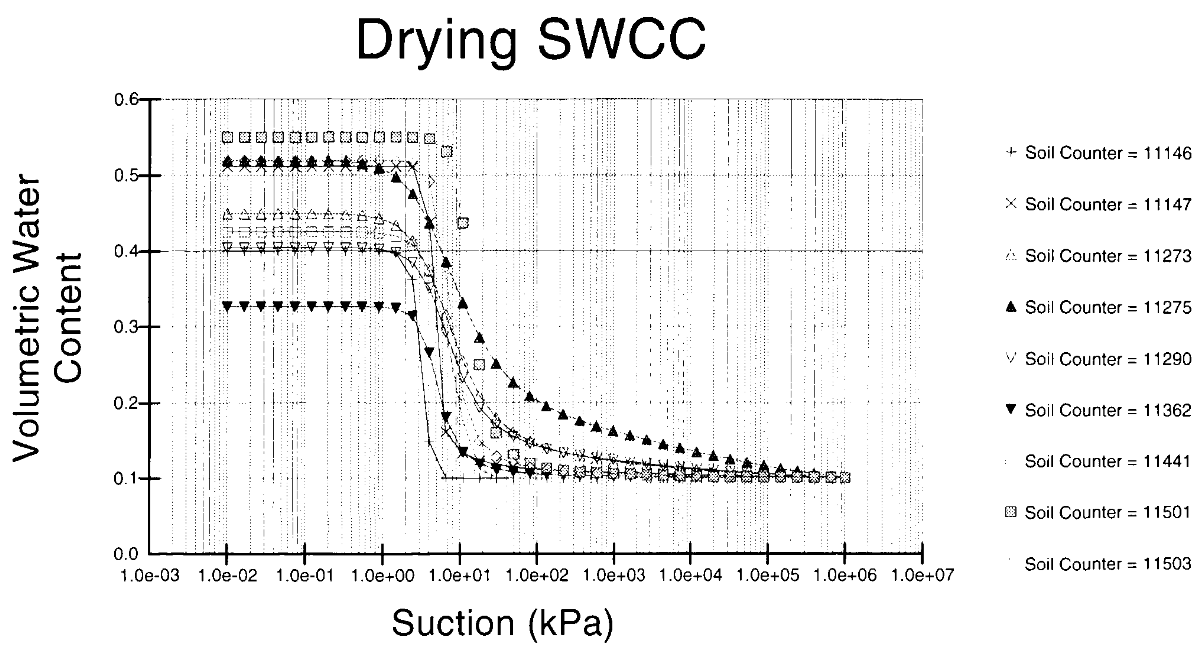


Figure 5-36 Soil-water characteristic curves matching grain-size curves

5.13 Example Application 2 - Knowledge base learning

The amount of data in the database influences the ability of the knowledge-base to predict soil properties. The knowledge-base will look to previous soils for direction in estimating the current soil parameter. The criteria used to search for previous soils is shown in the Rule Manager form. Typically, the knowledge-base system design will look for previously defined soils with non-zero values of the current parameter in the same textural class as the present soil.

An example of this in the current database is the estimation of saturated hydraulic conductivity. Certain textural classifications are well represented in the sample database. Other classifications are not as well represented. Estimating the saturated hydraulic conductivity for a Silt will produce an estimation as shown in Figure 5-37. It can be seen that the estimate of saturated hydraulic conductivity produced by the Rule Manager is somewhat unsure. Therefore the geotechnical engineer would not be sure of what a reasonable variation in the parameter might be. Alternately, a comparable estimation of the saturated hydraulic conductivity for Sands is shown in Figure 5-38. Due to a larger number of soils in the database, the Rule Manager can estimate saturated hydraulic conductivity and provide an indication of the variability of the data. The system design has therefore "learned" the probability distribution of this soil parameter.

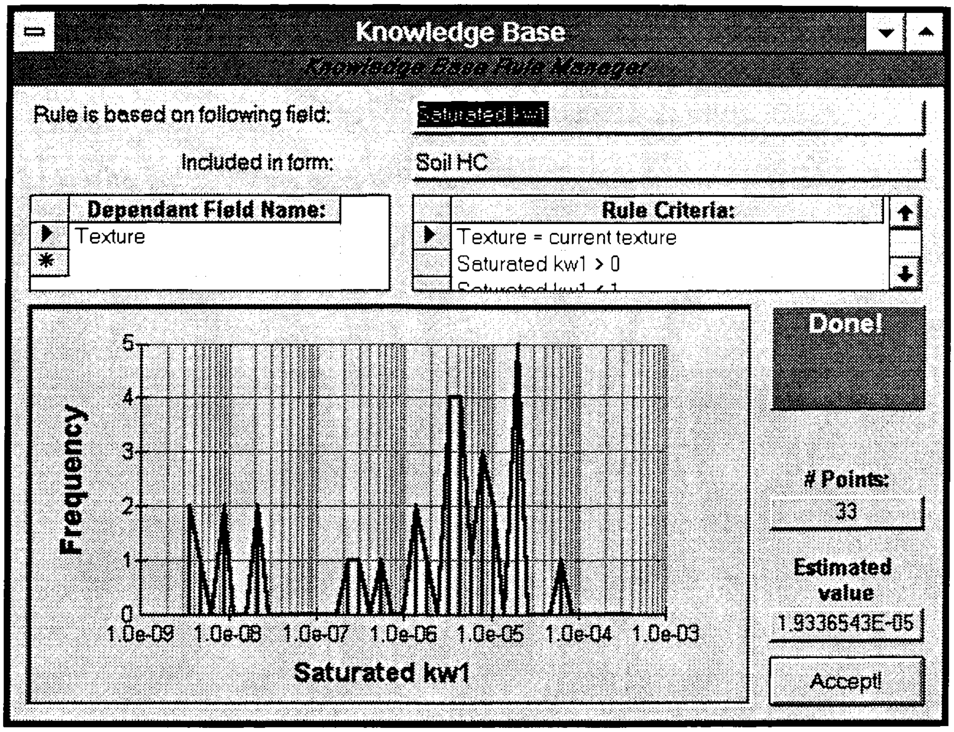


Figure 5-37 Estimation of saturated hydraulic conductivity for a Silt

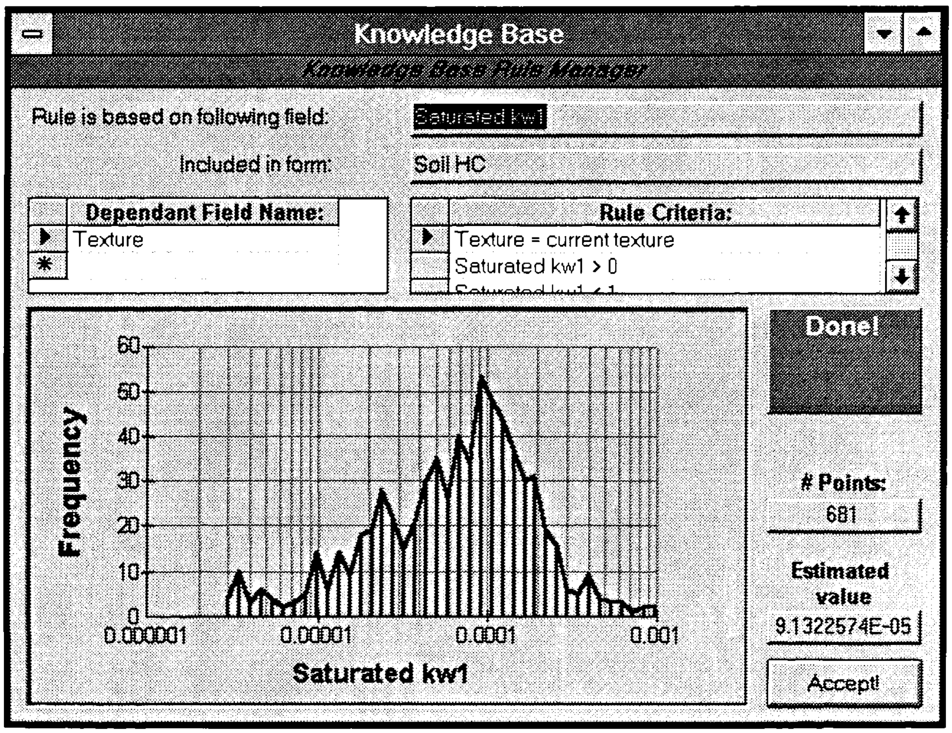


Figure 5-38 Estimation of the saturated hydraulic conductivity for a sand

5.14 Example Application 3 - Estimation of soil-water characteristic curve

It is often desired to estimate the soil-water characteristic curve (SWCC) of a certain textural soil classification. The Knowledge-Based System design allows for such a prediction. The prediction is accomplished by teaching the system design what reasonable parameters are for an equation used to fit the soil-water characteristic curve. All soil-water characteristic curves in the current system design were fit with the Fredlund & Xing (1994) equation. The system design then had sufficient data to draw upon for the estimation of the SWCC parameters. The estimations of the parameters by the Rule Base are shown in Figure 5-39, Figure 5-40 and Figure 5-41. An estimate of each curve parameter was taken as the mode of the distribution. The estimated parameters were then input into the KBS and a SWCC was generated. The resulting SWCC is then shown in Figure 5-42. The parameters for a Silty Clay were also estimated by the Rule Base and the resulting SWCC is shown in Figure 5-43.

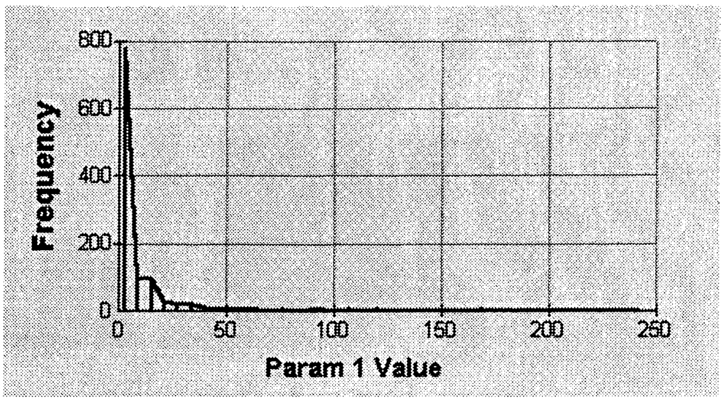


Figure 5-39 Distribution of 'a' parameter for a sand

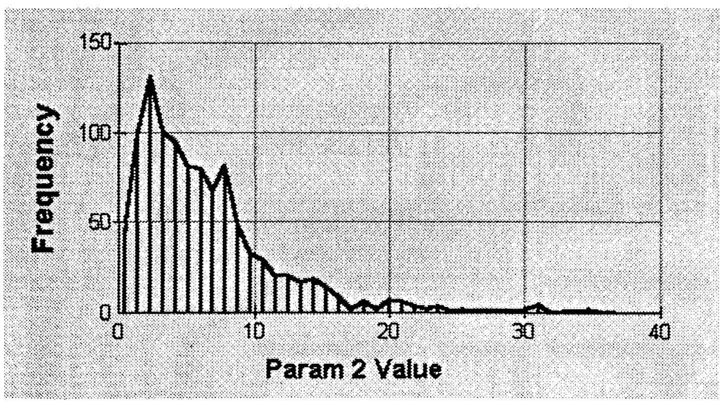


Figure 5-40 Distribution of 'n' parameter for a sand

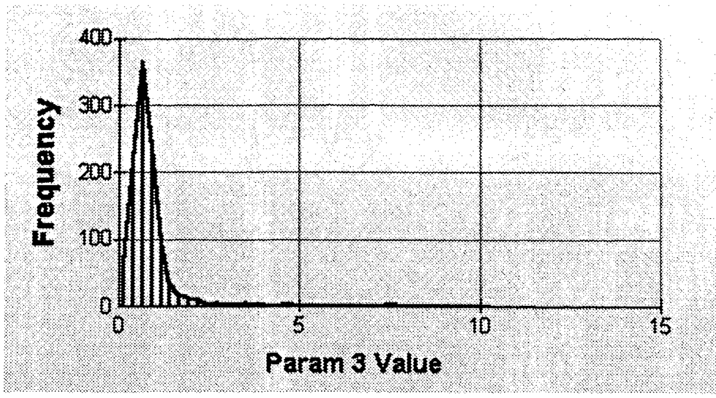


Figure 5-41 Distribution of 'm' parameter for a sand

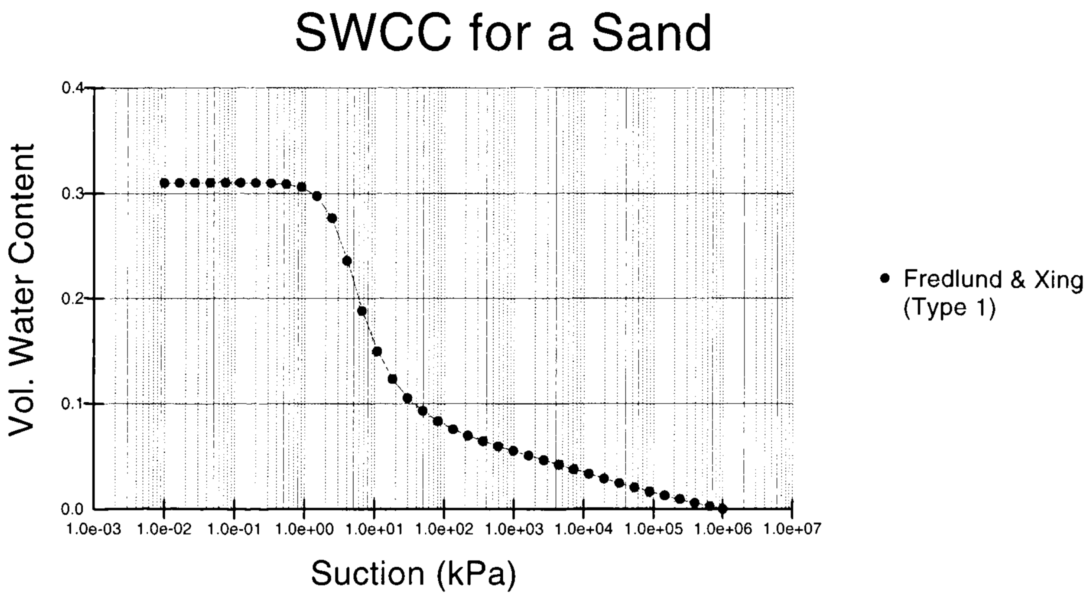


Figure 5-42 Resulting soil-water characteristic curve using Rule Base estimates of curve parameters for a sand

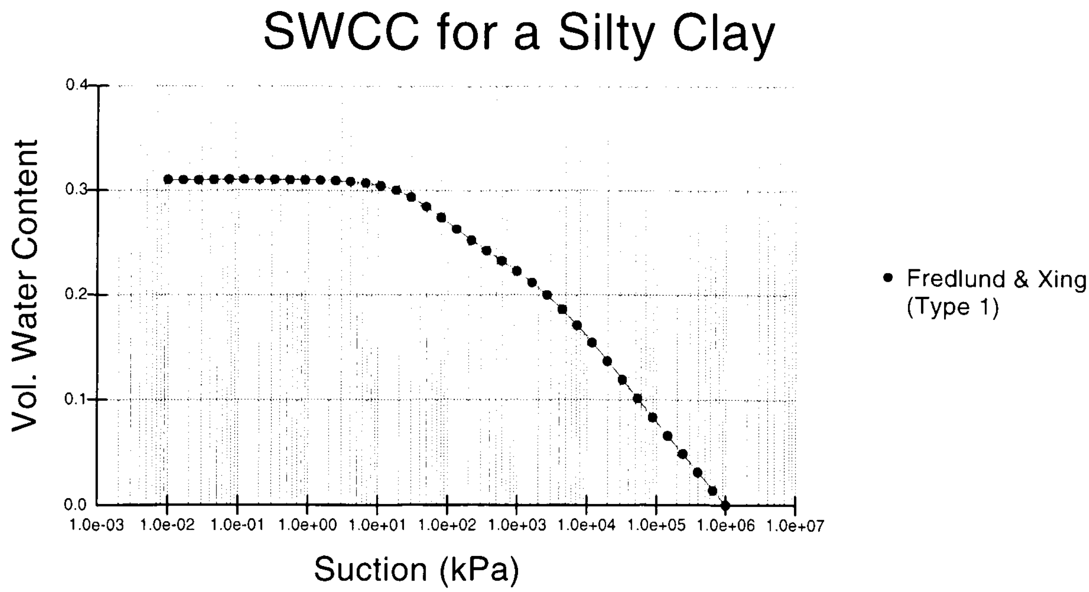


Figure 5-43 Resulting soil-water characteristic curve using Rule Base estimations of curve parameters for a silty clay

5.15 Example Application 4 - Estimation of hydraulic conductivity function

Estimation of the hydraulic conductivity function is commonly performed for unsaturated soils modelling. The following example shows how a hydraulic conductivity function may be estimated. Comparison is also made to experimentally measured results. A sand was used for the comparison. The measured soil-water characteristic curve can be seen in Figure 5-44. Saturated hydraulic conductivity was then estimated once a fit of the soil-water characteristic curve was established. The Cozeny-Carmen equation estimated a saturated conductivity of 7.367×10^{-5} m/s which compared to an experimentally measured saturated conductivity of 1.83×10^{-5} m/s. The complete distribution of saturated conductivity for sands can be seen in Figure 5-38. The complete hydraulic conductivity curve was then predicted from the measured saturated conductivity and is presented in Figure 5-45. The results can be seen to match closely to experimental data.

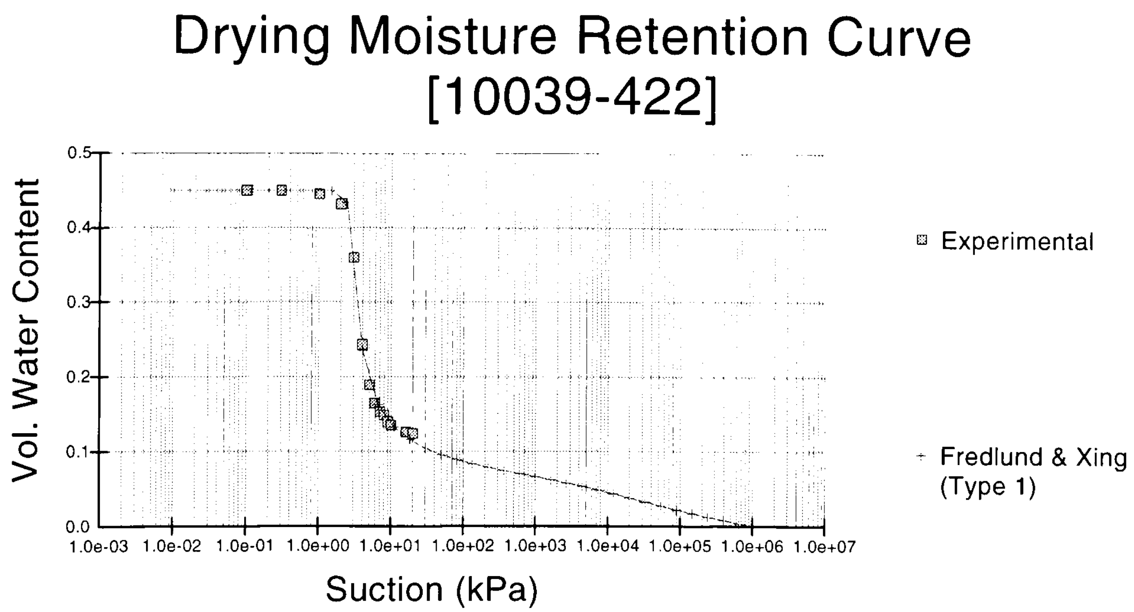


Figure 5-44 Soil-water characteristic curve for Superstition Sand (Soil_Counter=10039)

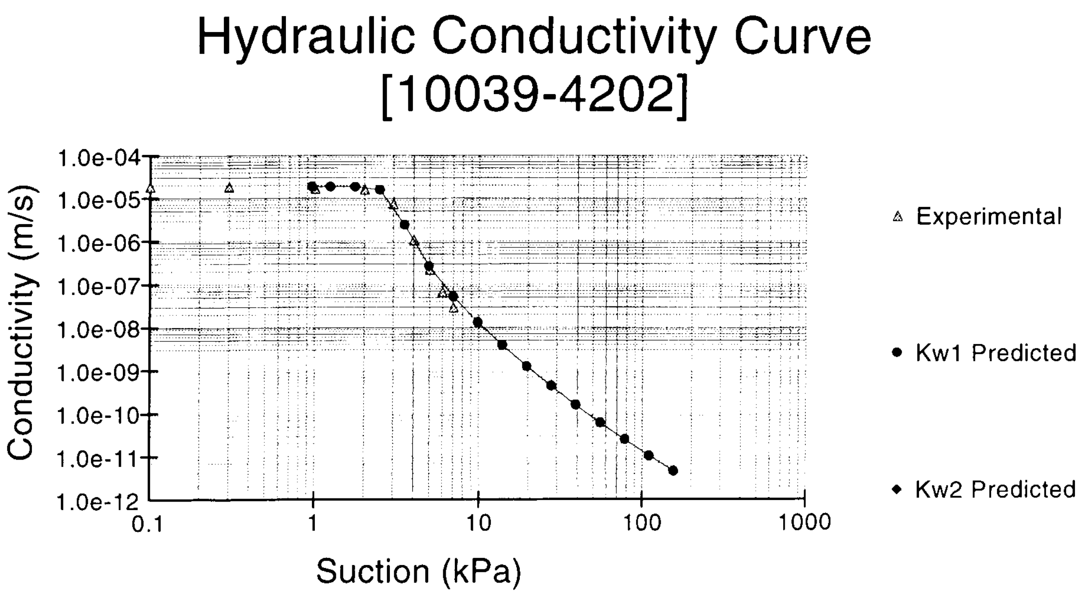


Figure 5-45 Comparison between experimentally measured and predicted conductivity curves for Superstition Sand (Soil_Counter=10039)

5.16 Example Application 5 - Querying for a group of soil-water characteristic curves

The query function allows for great flexibility in the selection of soils. Any number of soils can be selected by specifying a simple of complex criteria. Groups of curves can be selected and displayed for an estimation of the variability of soils information. This is another method of obtaining a reasonable estimate of a particular soil function. The following query selects a group of soil-water characteristic curves based on the query presented below. The curves selected by the query can be seen in Figure 5-46.

Texture:	Sandy Loam
θ_s:	between 0.36 and 0.42
Saturation:	greater than 90%
ρ_d:	between 1550 and 1630 kg/m^3

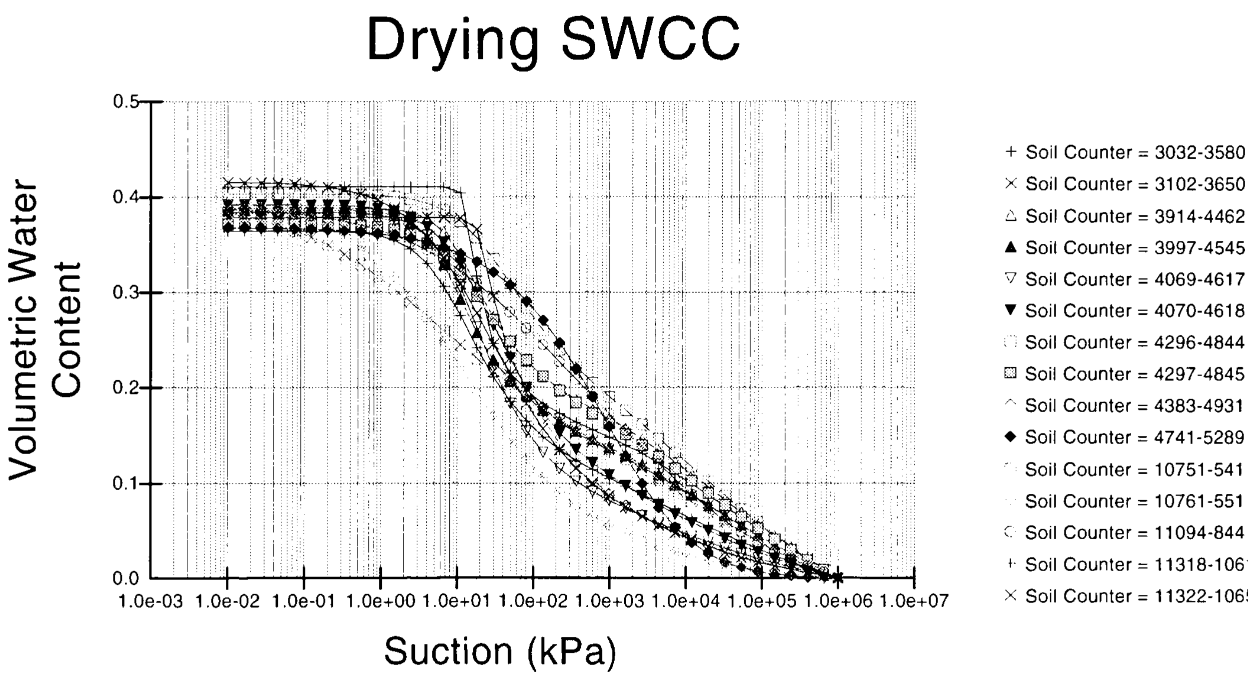


Figure 5-46 Soil-water characteristic curves selected by the query process

6. CHAPTER - Summary and Conclusions

The increased speed and performance of desktop and laptop computers has allowed development of geotechnical engineering applications on the personal computer platform. These applications allow for modelling the processes of seepage, stress analysis, slope stability, thermal analysis, volume change, and contaminant transport. The computer applications are very complex due to the highly nonlinear behavior of unsaturated soils. While much effort has been focused on modelling of unsaturated soils problems, little effort has been directed to ensure that soil properties used for input are correct.

Recent developments in computer modelling have shifted the focus towards three dimensional modelling and coupled solutions. The solution to coupled models requires several related soil functions.

The definition of potential properties for input into the computer model is a problem. Soil testing is expensive, time consuming, and there is usually no way to check for experimental error. The result of this is that a high percentage of geotechnical engineers do not perform proper testing. Input of geotechnical properties into computer models is typically estimated by the engineer with the most "experience". Upper and lower bounds may be set for the input properties, allowing for a range of possible outputs. This has the potential for inaccuracies in the modelling if the "experience" of the engineer is not reliable or if the engineer performing the modelling does not have enough experience.

It was also noted that current software available to geotechnical engineers does not address this problem. Current applications allow for the input of the problem into the computer, provide a numerical solution, and allow a method for viewing the output. However, the output received is entirely dependent on the validity of the input.

There are two ways of obtaining input for modelling of soil functions. Soil data can be experimentally measured or it can be estimated from known data. Experimental data was the preferred data source but it is costly and time consuming to obtain and it does not provide a "feel" for the soil. It may also be noted that research has provided many acceptable techniques for the estimation of soil properties. In general, however, the difficulties in applying advanced theory to practice have led to the omission of the most recent research in the practice of geotechnical engineering. This is particularly true for the application of unsaturated soil technology to current practice.

After considerable review, it was concluded that a system needs do be developed that provides a combination of theoretical and experimental data. This system would combine experimental data with the ability to predict soil properties where there are "holes" in the data. Furthermore, the required system should allow for prediction of missing soil data while also giving an indication of the variability of soil data.

The knowledge-based system design presented in this thesis combines the fields of knowledge-based systems with geotechnical engineering to achieve a solution to the problem as described above. Sample experimental data is used to provide a basis for the estimations of other soil properties. Models of various soil functions are fit to experimental data to allow interpretation of the data. Analytical predictions techniques are also implemented to allow the prediction of soil functions. The knowledge-base design also allows for the statistical estimation of soil properties. In summary the system design provides an estimate of soil properties and functions while also giving a "feel" for the variability of the soil properties.

The most important process in developing a Knowledge-Based System is the acquisition of knowledge. How the knowledge is obtained and where it is obtained determines the usefulness of the system (Barrett, 1989). The Knowledge-Based System described in this paper compiles information from three primary sources.

1. Experts in the field of unsaturated soil mechanics were interviewed to obtain methods and heuristics common to the field of unsaturated soils.

2. A search of current and past research was performed to determine the framework of the system. Experimental soil data was needed to test the system. A requirement for the soil data was that it contain a reasonably defined soil-water characteristic curve (SWCC).
3. Lastly, current computer modelling software in the field of unsaturated soils was reviewed to determine the most significant input properties. The information was then compiled to create a system to describe the soil property functions for unsaturated soils.

Once knowledge was acquired, focus shifted to the design of the system. The system design was developed within the relational database shell provided by Microsoft's Access relational database management system (RDMS). Access 2.0 was selected for the operating shell because it handles the manipulation of large amounts of data while allowing time to be focused on the development of the knowledge system design. Data was represented in tables linked together by Access. Information was grouped according to different soil functions. The data in separate tables was viewed through forms which were designed in the Access system. The forms provided a graphical user interface by which the data could be viewed.

Each form consists 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 interface which allowed the information to be viewed in forms, tables, or charts. The soil properties were organized into separate forms or sub-categories and linked to the main soil information form.

Knowledge was represented by four different methods. Firstly, a method of determining volume-mass properties of a soil based on any three properties was developed. This allowed complete volume-mass properties to be developed for each soil.

Secondly, curve-fitting provided a way of using a mathematical model to represent experimental soil functions. This allowed soil functions to be grouped according to curve parameters. This also allowed a mathematical representation of a soil curve to be developed. The mathematical representation then allowed further calculations based on the mathematical model. The representation could also be exported to a modelling package to provide a continuous input function. Digital representation of curves was also accounted for viewing purposes and to allow export to other applications.

Thirdly, algorithms were required to perform analytical predictions. These algorithms were developed and then linked to applicable forms by options. The development of the algorithms can be seen in Appendix B which presents the mathematical development of each prediction technique. Detailed development of each prediction technique can also be found in the sources listed in Table 3-1.

Fourthly, knowledge-base rules were developed to allow statistical estimation of soil parameters. These rules may be referred to as the Rule Base. The Rule Base provides statistical estimations for soil parameters. Criteria specifying how to extract similar data from the database are stored in the Rule Base. This allows the geotechnical engineer to ask the Rule Base to estimate a certain parameter. The reliability of the rule base predictions is a function of the amount of data currently in the database. However, as data is added to the system design, the predictions will become increasingly accurate. The Rule Base therefore has a limited capacity to "learn" from its past as data is added to the system design.

The final design consisted of a main soil information form with 11 soil property tables linked to the main soil form. Grain-size, consolidation, and SWCC were represented with fit equations while the remaining soil functions were estimated with prediction methods.

The equation presented to fit the grain-size distribution performed well. Reasonable fits were obtained with the majority of soils. The grain-size equation allows specification of minimum particle size which was considered important for future analysis due to the influence of clay-size particle on engineering behavior. Fitting an equation to the grain-size distribution also allowed for soils to be grouped by equation parameters. The database could then be searched for soils with grain-size distributions in a certain 'band'.

The SWCC was also represented with equations. Approximately twenty-eight different equations have been proposed that describe the SWCC. All twenty-eight equations where implemented into the Knowledge-Based System design. This allows the geotechnical engineer great flexibility in applying an equation to model the behaviour of the SWCC. Properties such as hydraulic conductivity, shear strength, storage, unfrozen water content, specific heat, thermal conductivity, diffusion and adsorption can all be related to the SWCC. The knowledge system design provides a way to link complex property functions together to describe the behaviour of an unsaturated soil. The curve-fitting routine works to fit any of the equations to data. Difficulty was encountered in knowing when to stop the optimisation process. The curve-fit routine can therefore be stopped at any point to allow for early termination of the optimisation process.

The storage function is the derivative of the SWCC equation. The KBS can generate an equation describing the storage of a soil for five different fits of the SWCC.

The KBS allows estimation of the permeability function. Separate estimations are provided for saturated permeability and the permeability function. Saturated permeability can be estimated by Hazen's equation, the Cozeny-Carmen equation, or estimated statistically. The permeability function is estimated by the Fredlund & Xing (1994) method. Results were compared against experimental data for three soils and found to be satisfactory. The extreme variation of saturated permeability does not allow for high accuracy in its estimation. The Rule Base does, however, allow statistical confidence intervals to be established.

The KBS design provides engineers with a means of estimating the shear strength function for an unsaturated soil from the SWCC by using the saturated shear strength parameters as the starting values. Experimental results matched well with predicted results. The accuracy of the prediction was sensitive to the Shear Parameter and a description of how the Shear Parameter varies has yet to be discovered. A greater volume of experimental data will allow greater confidence in estimating the Shear Parameter.

An equation was developed by the author to fit the consolidation curve. As with the grain-size equation, this equation will allow quantization of soils by their consolidation curve parameters. The fit will also allow the consolidation curve to be used as the basis for theoretical calculations in the future. The existing equation fit all soils data with a low residual error. There was ambiguity in defining the minimum void ratio at high compressions that should be addressed in future work. The current equation does not allow a minimum void ratio to be specified. A greater sample of soils will allow more thorough checking of the performance of the equation.

Specific heat of a soil changes as a soil desaturates. A method of predicting the specific heat from the SWCC information and the mass specific heat of the soil was incorporated into the design. This will aid in thermal analysis of unsaturated soils.

The prediction algorithm for thermal conductivity was tested against experimental data collected by Greg Newman (1995). The predicted results matched reasonably well. The quartz content of the soil seemed to be quite sensitive. Some adjusting of the quartz content was needed to match experimental results.

Proper testing of the unfrozen volumetric water content prediction method was achieved by comparing prediction results to those obtained by Black (1989). Six Windsor sandy loams were obtained from Black as well as one soil from Newman (1996). The prediction of unfrozen water content was relatively the same for all Windsor sandy loams. The prediction results of unfrozen water content for the silica flour obtained from Newman (1996) showed good accuracy.

The differences between experimental and predicted results for the Windsor sandy loam can be attributed to the fit of the soil-water characteristic curve. Black (1989) fit the soil-water characteristic curves with a Brooks and Corey (1966) equation while the results presented here are the result of applying the Fredlund & Xing (1994) equation to fit experimental SWCC data.

Performance of the prediction algorithms for diffusion and adsorption was good. An estimation of the accuracy of the predictions for different soil types was not obtained due to a lack of experimental data. Only two soils were obtained to verify the accuracy of the predictions. A greater representation of experimental data is needed to allow a 'feel' of the prediction's performance for various soil types.

The Knowledge-Based System design manipulates 11 separate property forms and allows prediction of 8 different soil property functions. The Knowledge-Based System design then allows for the estimation of unsaturated soil properties when experimental data is limited or too costly to obtain. Mathematical and digital representation of the functions is generated by the KBS to allow interface with current modelling software. The unsaturated property functions can be used in other applications such as finite element modelling to give an estimate of engineering design limits.

6.1 Concluding Remarks

The current system design allows for expansion in a number of ways. The most pressing interest appears to be to combine the soil system design with a modelling system so that unsaturated soil processes can be more accurately studied. The system design provides excellent input functions to perform modelling in a number of areas.

Another area of development may be the further development of property functions. Functions are currently defined in terms of suction. Describing property functions in terms of net normal stress may be a possible area of development. This would allow a 3-dimensional surface to be developed which would describe the behavior of the soil.

Additional data needs to be input into the system. This would allow confidence in estimation of less common soil parameters. Significant data is present for analysis of volume-mass, grain-size, SWCC, and permeability data. More data should be collected for areas such as unfrozen volumetric water content, specific heat, thermoconductivity, shear strength, diffusion and adsorption. This would improve the confidence of the system when making predictions.

Further development could be performed on the knowledge base. A comprehensive way of applying knowledge encoded into the system design is needed. Assigning probabilities to rules in the database is another consideration. Currently, the system design does not account for incomplete or uncertain answers. Complete knowledge representation would correct this problem.

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APPENDIX A

SOIL DATA

TABLE OF CONTENTS

Soils

07-Sep-96

1. Soil_Counter: 61

ProjectID:	SP1003
Soil Group:	
Texture:	Sandy Loam
Texture Modifier:	
Structure Grade:	
Structure Size:	
Structure Type:	
Soil Name:	Castor Loam
Soil Description:	69-STA-V-LOAM
Notes:	Sieve Analysis >0.841(19.9%)
Plasticity Index:	0
Plastic Limit:	
Liquid Limit:	0
Percent Clay:	2.46%
Percent Silt:	26.55%
Percent Sand:	63.41%
Percent Coarse:	7.48%
Percent Organic:	
D10:	0.0126771
D20:	3.006407E-02
D30:	5.253718E-02
D50:	0.127152
D60:	0.195915028452873
Cu:	15.45424
Cc:	1.111337
Experimentally Determined:	Yes
Saturation:	90.00%
Void Ratio:	0.895
Porosity:	47.22%
Water Content:	30.39%
Volumetric Water Content:	0.425
Dry Density:	1398.611
Total Density:	1823.611
Total Unit Weight:	17.88963
Specific Gravity:	2.65
Locked S:	No
Locked VWC:	Yes
Locked VR:	Yes
Locked WC:	No
Locked DD:	No
Locked TD:	No
Locked SG:	Yes
Accel of Gravity:	9.81
Density of Water:	1000
CEC:	
pH:	
Electrolyte Level:	
SAR:	
ESP:	
EC:	
Free Fe and Al Oxide:	
Family:	
Soil Series:	
Year Sampled:	
Land Use:	
Drainage:	
Slope:	
Number of Horizons:	
Horizon Number:	

Horizon Code:	
Horizon Depth Upper:	
Horizon Depth Lower:	
Depth to Groundwater:	
Author:	Staple, W. J.
Paper Name:	Comparison of Computed and Measured Moisture Redistri
Year Published:	1969
Publisher:	
Journal Name:	Soil Science Society of America Proceedings
Volume:	33
Page Numbers:	840-847
Contact:	Scott Sillers
Rating:	8
Country:	
Province:	
Region:	
Site:	

Grainsize

07-Sep-96

Grain_ID:	4
Grainsize Soil_Counter:	61
Starting ga:	500
Starting gn:	1
Starting gm:	1
ghr:	0.001
ga:	98.2248700411705
gn:	0.871519116598653
gm:	2.95126149969445
Grainsize Fit:	Yes
Smallest Particle Size:	0.00001
Grainsize Equation:	%Passing=(1-ln(1+10^(-(log(Diam)-1))/1.00e-0 3)/ln(1+1000000.0/1.00e-03))*(1/ln(exp(1)+(1
Grainsize Error:	1.42960094960904E-02
Packing Porosity:	0.6
Update Predicted:	No
Predicted Error:	8.8217018853823E-03

Particle Diameter:	Percent Passing:
0.074	33.80%
0.105	48.00%
0.177	62.30%
0.25	65.50%
0.42	70.50%
0.841	80.10%
2	100.00%

Particle Diameter:	Percent Passing:
0.00001	0.00%
1.349859E-05	0.09%
1.822119E-05	0.16%
2.459603E-05	0.22%
3.320117E-05	0.28%
4.481689E-05	0.33%
6.049647E-05	0.39%
8.16617E-05	0.45%
1.102318E-04	0.51%
1.487973E-04	0.59%
2.008554E-04	0.67%
2.711264E-04	0.78%
3.659823E-04	0.90%
4.940245E-04	1.06%

6.668633E-04	1.25%
9.001713E-04	1.48%
1.215104E-03	1.78%
1.640219E-03	2.16%
2.214064E-03	2.63%
2.988674E-03	3.25%
4.034288E-03	4.05%
5.445719E-03	5.08%
7.350952E-03	6.43%
9.922747E-03	8.19%
1.339431E-02	10.46%
1.808042E-02	13.36%
2.440602E-02	17.00%
3.294468E-02	21.45%
4.447067E-02	26.73%
6.002912E-02	32.78%
8.103084E-02	39.43%
0.1093802	46.44%
0.1476478	53.52%
0.1993037	60.39%
0.2690319	66.81%
0.363155	72.60%
0.490208	77.67%
0.6617116	82.01%
0.8932172	85.64%
1.205717	88.62%
1.627548	91.04%
2.19696	92.98%
2.965585	94.52%
4.003122	95.73%
5.403649	96.69%
7.294164	97.43%
9.846091	98.01%
13.29083	98.46%
17.94075	98.81%
24.21748	99.09%
32.69017	99.29%
44.12712	99.46%
59.56538	99.58%
80.40485	99.68%
100	99.73%

Soils

07-Sep-96

2. Soil_Counter: 1446

ProjectID: SP1015
Soil Group: 14
Texture: Clay
Texture Modifier:
Structure Grade: Weak
Structure Size: Fine (or thin)
Structure Type: Granular
Soil Name:
Soil Description:
Notes: This soil was used to estimate a soft, highly plastic clay in Papua New Guinea for a tailings pond in lowe
Plasticity Index: 0
Plastic Limit: 0
Liquid Limit: 0

Percent Clay:	52.28%
Percent Silt:	34.70%
Percent Sand:	12.80%
Percent Coarse:	0.22%
Percent Organic:	4.50%
D10:	1.251091E-05
D20:	1.704719E-05
D30:	2.869186E-05
D50:	1.39715E-03
D60:	5.18817454576492E-03
Cu:	414.6921
Cc:	1.268277E-02
Experimentally Determined:	Yes
Saturation:	91.87%
Void Ratio:	1.500
Porosity:	60.00%
Water Content:	52.50%
Volumetric Water Content:	0.5512
Dry Density:	1050
Total Density:	1601.2
Total Unit Weight:	15.70777
Specific Gravity:	2.625
Locked S:	No
Locked VWC:	Yes
Locked VR:	Yes
Locked WC:	No
Locked DD:	Yes
Locked TD:	No
Locked SG:	No
Accel of Gravity:	9.81
Density of Water:	1000
CEC:	0
pH:	0
Electrolyte Level:	0
SAR:	0
ESP:	0
EC:	0
Free Fe and Al Oxide:	0
Family:	
Soil Series:	BEAMONT
Year Sampled:	1957
Land Use:	Cropland, General
Drainage:	
Slope:	0.50%
Number of Horizons:	2
Horizon Number:	1
Horizon Code:	AP
Horizon Depth Upper:	0
Horizon Depth Lower:	0.2
Depth to Groundwater:	0
Author:	Lund, Z.F. and L.L. Lofton
Paper Name:	Physical Characteristics of Some Representative Louis
Year Published:	1960
Publisher:	U.S. Department of Agriculture, Washington, DC
Journal Name:	Agricultural Research Service
Volume:	ARS 41-33
Page Numbers:	pp.83
Contact:	Walter Rawls
Rating:	6
Country:	United States
Province:	Louisiana
Region:	Jefferson Davis
Site:	

Grainsize

07-Sep-96

Grain_ID:	747
Grainsize Soil_Counter:	1446
Starting ga:	10
Starting gn:	1
Starting gm:	1
ghr:	0.001
ga:	176.797329562122
gn:	1.21900099401544
gm:	0.45808415976726
Grainsize Fit:	Yes
Smallest Particle Size:	0.00001
Grainsize Equation:	%Passing=(1-ln(1+10^(-(log(Diam)-1))/1.00e-03)/ln(1+1000000.0/1.00e-03))*(1/ln(exp(1)+(1
Grainsize Error:	6.45319918707886E-05
Packing Porosity:	0.5
Update Predicted:	No
Predicted Error:	4.61303413512565E-03

Particle Diameter:	Percent Passing:
0.002	52.00%
0.05	87.70%
2	100.00%
100	100.00%

Particle Diameter:	Percent Passing:
0.00001	0.00%
1.349859E-05	12.85%
1.822119E-05	21.70%
2.459603E-05	27.72%
3.320117E-05	31.78%
4.481689E-05	34.56%
6.049647E-05	36.51%
8.16617E-05	37.97%
1.102318E-04	39.16%
1.487973E-04	40.24%
2.008554E-04	41.28%
2.711264E-04	42.36%
3.659823E-04	43.51%
4.940245E-04	44.74%
6.668633E-04	46.09%
9.001713E-04	47.56%
1.215104E-03	49.19%
1.640219E-03	50.99%
2.214064E-03	52.98%
2.988674E-03	55.21%
4.034288E-03	57.70%
5.445719E-03	60.47%
7.350952E-03	63.54%
9.922747E-03	66.92%
1.339431E-02	70.56%
1.808042E-02	74.40%
2.440602E-02	78.31%
3.294468E-02	82.13%
4.447067E-02	85.69%
6.002912E-02	88.86%
8.103084E-02	91.54%
0.1093802	93.71%
0.1476478	95.40%
0.1993037	96.69%
0.2690319	97.64%

0.363155	98.33%
0.490208	98.83%
0.6617116	99.18%
0.8932172	99.43%
1.205717	99.60%
1.627548	99.72%
2.19696	99.81%
2.965585	99.87%
4.003122	99.91%
5.403649	99.94%
7.294164	99.95%
9.846091	99.97%
13.29083	99.98%
17.94075	99.98%
24.21748	99.99%
32.69017	99.99%
44.12712	99.99%
59.56538	100.00%
80.40485	100.00%
100	100.00%

Soils

07-Sep-96

3. Soil_Counter: 10702

ProjectID:	SP1020
Soil Group:	200
Texture:	loamy sand
Texture Modifier:	
Structure Grade:	
Structure Size:	Massive
Structure Type:	Single Grain
Soil Name:	
Soil Description:	undisturbed
Notes:	PSD was determined with dry sieving, particle densit y by pycnometer method.
Plasticity Index:	0
Plastic Limit:	0
Liquid Limit:	0
Percent Clay:	3.35%
Percent Silt:	11.68%
Percent Sand:	84.75%
Percent Coarse:	0.22%
Percent Organic:	0.00%
D10:	2.829953E-02
D20:	0.0690883
D30:	0.1026534
D50:	0.164796
D60:	0.199797242879868
Cu:	7.06009
Cc:	1.863709
Experimentally Determined:	Yes
Saturation:	86.61%
Void Ratio:	0.786
Porosity:	44.00%
Water Content:	25.58%
Volumetric Water Content:	0.3811
Dry Density:	1489.6
Total Density:	1870.7
Total Unit Weight:	18.35157
Specific Gravity:	2.66

Locked S:	No
Locked VWC:	Yes
Locked VR:	Yes
Locked WC:	No
Locked DD:	No
Locked TD:	No
Locked SG:	Yes
Accel of Gravity:	9.81
Density of Water:	1000
CEC:	
pH:	
Electrolyte Level:	
SAR:	
ESP:	
EC:	
Free Fe and Al Oxide:	
Family:	loamy, siliceous, thermic Grossarenic Paleudult
Soil Series:	Troup
Year Sampled:	1979
Land Use:	
Drainage:	
Slope:	0.00%
Number of Horizons:	0
Horizon Number:	0
Horizon Code:	A22
Horizon Depth Upper:	0.58
Horizon Depth Lower:	0.92
Depth to Groundwater:	500
Author:	
Paper Name:	
Year Published:	0
Publisher:	
Journal Name:	Dane et al., South. Coop. Ser. Bull. 262, Ala. Agric
Volume:	
Page Numbers:	
Contact:	J.H. Dane, Dept. of Agronomy and Soils, Auburn Univ.
Rating:	
Country:	USA
Province:	AL
Region:	Union Springs
Site:	West plot

Grainsize

07-Sep-96

Grain_ID:	18
Grainsize Soil_Counter:	10702
Starting ga:	10
Starting gn:	1
Starting gm:	1
ghr:	0.001
ga:	41.8966166847766
gn:	2.55310864608444
gm:	1.35713590101748
Grainsize Fit:	Yes
Smallest Particle Size:	0.00001
Grainsize Equation:	%Passing=(1-ln(1+10^(-(log(Diam)-1))/1.00e-0 3)/ln(1+1000000.0/1.00e-03))*(1/ln(exp(1)+(1
Grainsize Error:	2.45905652322968E-03
Packing Porosity:	0.44
Update Predicted:	No
Predicted Error:	3.65103637272436E-03

Particle Diameter:	Percent Passing:
0.002	2.50%
0.05	17.50%
0.106	28.50%
0.25	73.40%
0.5	90.50%
1	98.60%
2	100.00%

Particle Diameter:	Percent Passing:
0.00001	0.00%
1.349859E-05	0.47%
1.822119E-05	0.82%
2.459603E-05	1.07%
3.320117E-05	1.26%
4.481689E-05	1.41%
6.049647E-05	1.53%
8.16617E-05	1.64%
1.102318E-04	1.75%
1.487973E-04	1.85%
2.008554E-04	1.96%
2.711264E-04	2.09%
3.659823E-04	2.22%
4.940245E-04	2.37%
6.668633E-04	2.53%
9.001713E-04	2.72%
1.215104E-03	2.93%
1.640219E-03	3.17%
2.214064E-03	3.45%
2.988674E-03	3.78%
4.034288E-03	4.16%
5.445719E-03	4.61%
7.350952E-03	5.16%
9.922747E-03	5.83%
1.339431E-02	6.67%
1.808042E-02	7.74%
2.440602E-02	9.14%
3.294468E-02	11.04%
4.447067E-02	13.70%
6.002912E-02	17.57%
8.103084E-02	23.39%
0.1093802	32.15%
0.1476478	44.61%
0.1993037	59.87%
0.2690319	74.70%
0.363155	85.88%
0.490208	92.76%
0.6617116	96.47%
0.8932172	98.32%
1.205717	99.21%
1.627548	99.63%
2.19696	99.83%
2.965585	99.92%
4.003122	99.96%
5.403649	99.98%
7.294164	99.99%
9.846091	100.00%
13.29083	100.00%
17.94075	100.00%
24.21748	100.00%
32.69017	100.00%
44.12712	100.00%
59.56538	100.00%

80.40485	100.00%
100	100.00%

Soils

07-Sep-96

4. Soil_Counter: 10707

ProjectID:	SP1020
Soil Group:	200
Texture:	Sand
Texture Modifier:	
Structure Grade:	Weak
Structure Size:	Medium
Structure Type:	Granular
Soil Name:	
Soil Description:	undisturbed
Notes:	Soil texture by pipette method. NA
Plasticity Index:	0
Plastic Limit:	0
Liquid Limit:	0
Percent Clay:	8.37%
Percent Silt:	4.33%
Percent Sand:	87.29%
Percent Coarse:	0.00%
Percent Organic:	0.00%
D10:	1.055051E-02
D20:	0.2547677
D30:	0.5013363
D50:	0.741338
D60:	0.807796001434326
Cu:	76.56467
Cc:	29.49059
Experimentally Determined:	No
Saturation:	89.85%
Void Ratio:	0.672
Porosity:	40.18%
Water Content:	22.85%
Volumetric Water Content:	0.361
Dry Density:	1580
Total Density:	1941
Total Unit Weight:	19.04121
Specific Gravity:	2.641125
Locked S:	No
Locked VWC:	Yes
Locked VR:	No
Locked WC:	No
Locked DD:	Yes
Locked TD:	No
Locked SG:	Yes
Accel of Gravity:	9.81
Density of Water:	1000
CEC:	
pH:	
Electrolyte Level:	
SAR:	
ESP:	
EC:	
Free Fe and Al Oxide:	
Family:	NA
Soil Series:	Lakeland
Year Sampled:	

Land Use:	
Drainage:	
Slope:	0.00%
Number of Horizons:	0
Horizon Number:	0
Horizon Code:	C1
Horizon Depth Upper:	0.23
Horizon Depth Lower:	0.41
Depth to Groundwater:	
Author:	
Paper Name:	
Year Published:	0
Publisher:	
Journal Name:	Dane et al., South. Coop. Ser. Bull. 262, Ala. Agric
Volume:	
Page Numbers:	
Contact:	V.L. Quisenberry, Dept. Agronomy and Soils, Clemson
Rating:	
Country:	USA
Province:	SC
Region:	Blackville
Site:	Plot 1, Edisto Station, Clemson Univ.

Grainsize

07-Sep-96

Grain_ID:	23
Grainsize Soil_Counter:	10707
Starting ga:	10
Starting gn:	1
Starting gm:	1
ghr:	0.001
ga:	10.447886082051
gn:	13.0031099027265
gm:	0.565603682202142
Grainsize Fit:	Yes
Smallest Particle Size:	0.00015
Grainsize Equation:	%Passing=(1-ln(1+10^(-(log(Diam)-1))/1.00e-0 3)/ln(1+66666.7/1.00e-03))*(1/ln(exp(1)+(10^
Grainsize Error:	3.59025531061762E-03
Packing Porosity:	0.53
Update Predicted:	No
Predicted Error:	7.66114545743555E-03

Particle Diameter:	Percent Passing:
0.002	6.00%
0.05	11.00%
0.1	15.00%
0.25	24.70%
0.5	28.00%
1	90.80%
2	100.00%

Particle Diameter:	Percent Passing:
0.00015	0.00%
2.024788E-04	4.26%
2.733178E-04	6.14%
3.689405E-04	6.97%
4.980176E-04	7.36%
6.722534E-04	7.61%
9.074472E-04	7.81%
1.224926E-03	8.02%
1.653477E-03	8.23%

2.23196E-03	8.46%
3.012831E-03	8.70%
4.066896E-03	8.97%
5.489735E-03	9.26%
7.410367E-03	9.58%
1.000295E-02	9.93%
1.350257E-02	10.32%
1.822656E-02	10.76%
2.460329E-02	11.25%
3.321096E-02	11.81%
4.483011E-02	12.45%
6.051432E-02	13.20%
8.168579E-02	14.08%
0.1102643	15.16%
0.1488412	16.49%
0.2009146	18.22%
0.2712064	20.55%
0.3660903	23.97%
0.4941702	29.62%
0.66706	41.58%
0.9004369	76.78%
1.215463	99.09%
1.640703	99.98%
2.214717	100.00%
2.989556	100.00%
4.035478	100.00%
5.447326	100.00%
7.35312	100.00%
9.925674	100.00%
13.39826	100.00%
18.08576	100.00%
24.41322	100.00%
32.9544	100.00%
44.48379	100.00%
60.04683	100.00%
81.05474	100.00%
100	100.00%

Soils

07-Sep-96

5. Soil_Counter: 350

ProjectID: SP1012
Soil Group:
Texture: Sand
Texture Modifier:
Structure Grade: Weak
Structure Size: Fine to medium
Structure Type: Granular
Soil Name: Beaver Creek Sand
Soil Description: Olive brown, oxidized, uniform sand
Notes: Used to test the prediction of Adsorption and Diffusi on. Soil obtained from a natural aeolin sand deposit

Plasticity Index:	0
Plastic Limit:	0
Liquid Limit:	0
Percent Clay:	0.00%
Percent Silt:	0.05%
Percent Sand:	99.95%
Percent Coarse:	0.00%

Percent Organic:	0.00%
D10:	0.1917282
D20:	0.2157306
D30:	0.2336219
D50:	0.2658199
D60:	0.283346176147461
Cu:	1.477853
Cc:	1.004671
Experimentally Determined:	Yes
Saturation:	99.80%
Void Ratio:	0.618
Porosity:	38.20%
Water Content:	23.10%
Volumetric Water Content:	0.381236
Dry Density:	1650.06
Total Density:	2031.296
Total Unit Weight:	19.92702
Specific Gravity:	2.67
Locked S:	No
Locked VWC:	Yes
Locked VR:	Yes
Locked WC:	No
Locked DD:	No
Locked TD:	No
Locked SG:	Yes
Accel of Gravity:	9.81
Density of Water:	1000
CEC:	1.3
pH:	0
Electrolyte Level:	0
SAR:	0
ESP:	0
EC:	0
Free Fe and Al Oxide:	0
Family:	
Soil Series:	
Year Sampled:	1995
Land Use:	Cropland - General
Drainage:	Somewhat poorly drainedd
Slope:	
Number of Horizons:	0
Horizon Number:	0
Horizon Code:	
Horizon Depth Upper:	0
Horizon Depth Lower:	0
Depth to Groundwater:	0
Author:	P.C. Lim, S.L. Barbour, and D.G. Fredlund
Paper Name:	Diffusion and Adsorption Processes in Unsaturated Soi
Year Published:	1996
Publisher:	
Journal Name:	Canadian Geotechnical Journal
Volume:	
Page Numbers:	
Contact:	Murray Fredlund
Rating:	10
Country:	Canada
Province:	Saskatchewan
Region:	Beaver Creek
Site:	

Grainsize

07-Sep-96

Grain_ID:	11
Grainsize Soil_Counter:	350

Starting ga:	10
Starting gn:	1
Starting gm:	1
ghr:	0.001
ga:	40.197608654804
gn:	5.71082842915596
gm:	3.41518275519511
Grainsize Fit:	Yes
Smallest Particle Size:	0.00001
Grainsize Equation:	%Passing=(1-ln(1+10^(-(log(Diam)-1))/1.00e-0 3)/ln(1+1000000.0/1.00e-03))*(1/ln(exp(1)+(1
Grainsize Error:	7.47667106377968E-04
Packing Porosity:	0.75
Update Predicted:	No
Predicted Error:	5.86643474344697E-02

Particle Diameter:	Percent Passing:
0.002	0.11%
0.149	1.30%
0.246	38.60%
0.297	65.40%
0.417	95.40%
2	98.90%

Particle Diameter:	Percent Passing:
0.00001	0.00%
1.349859E-05	0.00%
1.822119E-05	0.00%
2.459603E-05	0.00%
3.320117E-05	0.00%
4.481689E-05	0.00%
6.049647E-05	0.00%
8.16617E-05	0.00%
1.102318E-04	0.00%
1.487973E-04	0.00%
2.008554E-04	0.00%
2.711264E-04	0.00%
3.659823E-04	0.00%
4.940245E-04	0.00%
6.668633E-04	0.00%
9.001713E-04	0.00%
1.215104E-03	0.00%
1.640219E-03	0.00%
2.214064E-03	0.00%
2.988674E-03	0.00%
4.034288E-03	0.00%
5.445719E-03	0.00%
7.350952E-03	0.00%
9.922747E-03	0.00%
1.339431E-02	0.01%
1.808042E-02	0.01%
2.440602E-02	0.01%
3.294468E-02	0.02%
4.447067E-02	0.04%
6.002912E-02	0.08%
8.103084E-02	0.18%
0.1093802	0.50%
0.1476478	2.08%
0.1993037	12.58%
0.2690319	51.97%
0.363155	87.02%
0.490208	97.44%
0.6617116	99.53%

0.8932172	99.92%
1.205717	99.98%
1.627548	100.00%
2.19696	100.00%
2.965585	100.00%
4.003122	100.00%
5.403649	100.00%
7.294164	100.00%
9.846091	100.00%
13.29083	100.00%
17.94075	100.00%
24.21748	100.00%
32.69017	100.00%
44.12712	100.00%
59.56538	100.00%
80.40485	100.00%
100	100.00%

Soils

07-Sep-96

6. Soil_Counter: 10035

ProjectID: SP1013
Soil Group:
Texture: Inorganic clay low plastic
Texture Modifier:
Structure Grade:
Structure Size: Fine to medium
Structure Type:
Soil Name: Glacial Till
Soil Description: Glacial Till from the Indian Head area of Saskatchewa
Notes: Soil from David Ho's Ph.D. thesis. Used to test volum
e change predictions

Plasticity Index:	0.202
Plastic Limit:	0.13
Liquid Limit:	0.332
Percent Clay:	27.59%
Percent Silt:	44.67%
Percent Sand:	25.61%
Percent Coarse:	2.01%
Percent Organic:	0.00%
D10:	3.637714E-05
D20:	5.982512E-04
D30:	2.677538E-03
D50:	1.539528E-02
D60:	3.10394801199436E-02
Cu:	853.2689
Cc:	6.349338
Experimentally Determined:	Yes
Saturation:	63.00%
Void Ratio:	0.688
Porosity:	40.76%
Water Content:	15.68%
Volumetric Water Content:	0.2567773
Dry Density:	1637.441
Total Density:	1894.218
Total Unit Weight:	18.58228
Specific Gravity:	2.764
Locked S:	No
Locked VWC:	Yes
Locked VR:	Yes

Locked WC:	No
Locked DD:	No
Locked TD:	No
Locked SG:	Yes
Accel of Gravity:	9.81
Density of Water:	1000
CEC:	0
pH:	7.9
Electrolyte Level:	0
SAR:	1800
ESP:	0
EC:	0
Free Fe and Al Oxide:	0
Family:	
Soil Series:	
Year Sampled:	1986
Land Use:	
Drainage:	
Slope:	0.00%
Number of Horizons:	0
Horizon Number:	0
Horizon Code:	
Horizon Depth Upper:	0
Horizon Depth Lower:	0
Depth to Groundwater:	0
Author:	David Y.F. Ho
Paper Name:	The Relationships Between the Volumetric Deformation
Year Published:	1988
Publisher:	University of Saskatchewan
Journal Name:	Ph.D Thesis
Volume:	
Page Numbers:	
Contact:	Murray Fredlund
Rating:	9
Country:	Canada
Province:	Saskatchewan
Region:	Pilot Butte
Site:	

Grainsize

07-Sep-96

Grain_ID:	14
Grainsize Soil_Counter:	10035
Starting ga:	10
Starting gn:	1
Starting gm:	1
ghr:	0.001
ga:	157.23949451334
gn:	0.716321814845513
gm:	1.30439678477716
Grainsize Fit:	Yes
Smallest Particle Size:	0.00001
Grainsize Equation:	%Passing=(1-ln(1+10^(-(log(Diam)-1))/1.00e-03)/ln(1+1000000.0/1.00e-03))*(1/ln(exp(1)+(1
Grainsize Error:	1.44912668528851E-02
Packing Porosity:	0.6
Update Predicted:	No
Predicted Error:	8.37409447992061E-04

Particle Diameter:	Percent Passing:
0.00092	15.00%
0.0013	25.00%
0.0022	30.00%
0.003	33.00%
0.0055	39.00%
0.0075	44.00%
0.01	45.00%
0.015	50.00%
0.0205	55.00%
0.028	58.00%
0.04	62.00%
0.068	66.00%
0.075	71.00%
0.14	79.00%
0.19	82.00%
0.4	92.00%
0.8	96.50%
2	100.00%

Particle Diameter:	Percent Passing:
0.00001	0.00%
1.349859E-05	3.54%
1.822119E-05	6.16%
2.459603E-05	8.12%
3.320117E-05	9.61%
4.481689E-05	10.80%
6.049647E-05	11.81%
8.16617E-05	12.73%
1.102318E-04	13.62%
1.487973E-04	14.54%
2.008554E-04	15.52%
2.711264E-04	16.59%
3.659823E-04	17.77%
4.940245E-04	19.08%
6.668633E-04	20.55%
9.001713E-04	22.19%
1.215104E-03	24.04%
1.640219E-03	26.10%
2.214064E-03	28.40%
2.988674E-03	30.98%
4.034288E-03	33.83%
5.445719E-03	36.98%
7.350952E-03	40.42%
9.922747E-03	44.13%
1.339431E-02	48.09%
1.808042E-02	52.25%
2.440602E-02	56.53%
3.294468E-02	60.86%
4.447067E-02	65.15%
6.002912E-02	69.31%
8.103084E-02	73.25%
0.1093802	76.93%
0.1476478	80.29%
0.1993037	83.30%
0.2690319	85.95%
0.363155	88.27%
0.490208	90.26%
0.6617116	91.95%
0.8932172	93.38%
1.205717	94.57%
1.627548	95.56%

2.19696	96.38%
2.965585	97.05%
4.003122	97.61%
5.403649	98.06%
7.294164	98.43%
9.846091	98.73%
13.29083	98.97%
17.94075	99.17%
24.21748	99.33%
32.69017	99.46%
44.12712	99.56%
59.56538	99.64%
80.40485	99.71%
100	99.75%

Consolidation

07-Sep-96

Consol_ID:	4
Consolidation Soil_Counter:	10035
Starting ca:	10
Starting cn:	1
Starting cm:	1
ca:	254.743562785728
cn:	1.85417465418499
cm:	0.465969091725691
Consolidation Fit:	Yes
Consolidation Equation:	Void_Ratio=0.688*(1/ln(2.71828182846+(Net_Normal/254.7436)^1.8542))^0.4660
Consolidation Error:	2.22882687470884E-03

1

Net Normal	Void Ratio:
90	0.688
110	0.675
150	0.66
180	0.625
300	0.575
700	0.48
3000	0.35
6000	0.3
9000	0.275

Net Normal	Void Ratio:
0.01	0.688
1.491825E-02	0.688
2.225541E-02	0.688
3.320117E-02	0.688
4.953032E-02	0.688
7.389056E-02	0.688
0.1102318	0.688
0.1644465	0.6879999
0.2453253	0.6879997
0.3659824	0.6879994
0.5459815	0.6879987
0.8145087	0.6879972
1.215104	0.6879942

1.812722	0.6879877
2.704264	0.6879742
4.034288	0.6879459
6.01845	0.6878864
8.978473	0.6877616
13.39431	0.6875
19.98196	0.6869525
29.80958	0.6858104
44.47067	0.6834452
66.34244	0.6786172
98.97129	0.6690454
147.6478	0.6510999
220.2647	0.6206152
328.5963	0.5761107
490.208	0.522397
731.3044	0.4685205
1090.978	0.4212724
1627.548	0.3826309
2428.016	0.3516895
3622.175	0.3267877
5403.649	0.3064302
8061.297	0.2894822
10000	0.2814671

Soils

07-Sep-96

7. Soil_Counter: 58

ProjectID:	SP1003
Soil Group:	
Texture:	Sand
Texture Modifier:	
Structure Grade:	
Structure Size:	
Structure Type:	
Soil Name:	Del Monte California Sand
Soil Description:	79-NAR-V-SAND
Notes:	

Plasticity Index:	0
Plastic Limit:	
Liquid Limit:	0
Percent Clay:	0.00%
Percent Silt:	0.00%
Percent Sand:	100.00%
Percent Coarse:	0.00%
Percent Organic:	
D10:	
D20:	
D30:	
D50:	
D60:	
Cu:	
Cc:	
Experimentally Determined:	Yes
Saturation:	100.00%
Void Ratio:	0.425
Porosity:	29.80%
Water Content:	16.02%

Volumetric Water Content:	0.298
Dry Density:	1860.3
Total Density:	2158.3
Total Unit Weight:	21.17292
Specific Gravity:	2.65
Locked S:	No
Locked VWC:	No
Locked VR:	No
Locked WC:	No
Locked DD:	No
Locked TD:	No
Locked SG:	No
Accel of Gravity:	9.81
Density of Water:	1000
CEC:	
pH:	
Electrolyte Level:	
SAR:	
ESP:	
EC:	
Free Fe and Al Oxide:	
Family:	
Soil Series:	
Year Sampled:	
Land Use:	
Drainage:	
Slope:	
Number of Horizons:	
Horizon Number:	
Horizon Code:	
Horizon Depth Upper:	
Horizon Depth Lower:	
Depth to Groundwater:	
Author:	Narasimhan, T. N.
Paper Name:	The Significance of the Storage Parameter in Saturate
Year Published:	1979
Publisher:	
Journal Name:	water Resources Research
Volume:	15
Page Numbers:	569-575
Contact:	Scott Sillers
Rating:	8
Country:	U. S. A.
Province:	California
Region:	Del Monte
Site:	

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SWCC

07-Sep-96

Param_ID:	1373
SWCC Soil_Counter:	58
SWCC Description:	Drying curve
SWCC Fit Type:	Fredlund & Xing (Type 1)
SWCC Curve Type:	0
SWCC Fit:	Yes
Fit Data Source:	0
Param_1 Name:	a
Param_2 Name:	n
Param_3 Name:	m
Param_4 Name:	hr
Param_1 Value:	15.5809083953831
Param_2 Value:	3.12256687961726
Param_3 Value:	1.88041008311128
Param_4 Value:	3000

Drainage:	
Slope:	0.00%
Number of Horizons:	0
Horizon Number:	0
Horizon Code:	
Horizon Depth Upper:	0
Horizon Depth Lower:	0
Depth to Groundwater:	0
Author:	Brooks, R.H., and Corey, A.T.
Paper Name:	Hydraulic Properties of porous medium
Year Published:	1964
Publisher:	Colorado State University (Ft. Collins)
Journal Name:	
Volume:	
Page Numbers:	
Contact:	Murray Fredlund
Rating:	8
Country:	
Province:	
Region:	
Site:	

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SWCC

07-Sep-96

Param_ID:	419
SWCC Soil_Counter:	10036
SWCC Description:	Unknown Test Method
SWCC Fit Type:	Fredlund & Xing (Type 1)
SWCC Curve Type:	0
SWCC Fit:	Yes
Fit Data Source:	0
Param_1 Name:	a
Param_2 Name:	n
Param_3 Name:	m
Param_4 Name:	hr
Param_1 Value:	7.94423507750422
Param_2 Value:	10.4067441371818
Param_3 Value:	0.453755644664971
Param_4 Value:	3000
SWCC Error:	2.31134379619878E-03
Residual VWC:	5.831716E-02
SWCC Equation:	Theta_w=Theta_sat*(1-ln(1+h/3000.0000)/ln(1+10^6/3000.0000))*(1/ln(exp(1)+(h/7.9442)^10.4067))^0.4538

1

Suction:	Vol. Water Content:
6.50E-01	0.430
1.40E+00	0.421
3.80E+00	0.426
6.00E+00	0.417
7.00E+00	0.413
8.00E+00	0.378
9.00E+00	0.327
1.00E+01	0.280
1.10E+01	0.236
1.30E+01	0.202
1.50E+01	0.185

1.80E+01	0.172
2.00E+01	0.159
2.20E+01	0.142
2.80E+01	0.133
3.00E+01	0.125

Suction:	Vol. Water
1.00E-02	4.30E-01
1.65E-02	4.30E-01
2.72E-02	4.30E-01
4.48E-02	4.30E-01
7.39E-02	4.30E-01
1.22E-01	4.30E-01
2.01E-01	4.30E-01
3.31E-01	4.30E-01
5.46E-01	4.30E-01
9.00E-01	4.30E-01
1.48E+00	4.30E-01
2.45E+00	4.30E-01
4.03E+00	4.30E-01
6.65E+00	4.19E-01
1.10E+01	2.45E-01
1.81E+01	1.62E-01
2.98E+01	1.31E-01
4.91E+01	1.13E-01
8.10E+01	1.01E-01
1.34E+02	9.21E-02
2.20E+02	8.51E-02
3.63E+02	7.92E-02
5.99E+02	7.41E-02
9.87E+02	6.92E-02
1.63E+03	6.44E-02
2.68E+03	5.94E-02
4.42E+03	5.43E-02
7.29E+03	4.90E-02
1.20E+04	4.35E-02
1.98E+04	3.80E-02
3.27E+04	3.26E-02
5.39E+04	2.73E-02
8.89E+04	2.22E-02
1.47E+05	1.73E-02
2.42E+05	1.25E-02
3.98E+05	7.95E-03
6.57E+05	3.56E-03
1.00E+06	7.90E-21

Permeability

07-Sep-96

Kxy_ID:		4199
Permeability Soil_Counter:		10036
Permeability Description:	Estimated ksat	
Permeability Fit Type:	Fredlund & Xing (Type 1)	
Permeability Curve Type:		0
Saturated kw1:		4.50549794904695E-05
Saturated kw2:		4.50549794904695E-05
Alpha Angle:		0
Permeability Test:		No
Update Permeability:		No
Permeability Error:		2.05927828182726E-09

1

Suction:	Conductivity:
0.48	4.460E-05
1.1	4.460E-05
3.3	4.500E-05
5.8	4.460E-05
6.8	4.050E-05
7.8	4.050E-05
8.6	2.660E-05
9.6	9.010E-06
11	4.950E-06
12	2.480E-06

Suction:	Conductivity:
1.0	4.504E-05
1.2	4.504E-05
1.8	4.504E-05
2.5	4.503E-05
3.5	4.501E-05
4.9	4.478E-05
7.0	3.825E-05
9.9	7.337E-06
13.9	8.077E-07
19.7	1.535E-07
27.8	3.855E-08
39.2	1.131E-08
55.4	3.685E-09
78.3	1.299E-09
110.6	4.894E-10
156.2	1.957E-10
220.7	8.288E-11
311.7	3.705E-11
440.3	1.741E-11
621.9	8.537E-12
878.5	4.329E-12
1240.9	2.244E-12
1752.9	1.175E-12
2476.0	6.156E-13
3497.5	3.199E-13
4940.3	1.641E-13
6978.3	8.290E-14
9857.1	4.125E-14
13923.6	2.025E-14
19667.5	9.825E-15
27781.1	4.722E-15
39241.8	2.250E-15
55430.4	1.064E-15
78297.5	4.982E-16
110598.0	2.299E-16
156223.6	1.036E-16
220671.4	4.462E-17
311706.3	1.768E-17
440296.2	5.896E-18
621934.2	1.271E-18
878504.3	2.141E-20

Soils

07-Sep-96

9. Soil_Counter: 19

ProjectID:	SP1002
Soil Group:	
Texture:	Sandy Clay Loam
Texture Modifier:	
Structure Grade:	Weak
Structure Size:	
Structure Type:	
Soil Name:	
Soil Description:	Agricultural top soil
Notes:	Soil from Bankole Adams. Used to test shear strength prediction. Good prediction
Plasticity Index:	0
Plastic Limit:	0
Liquid Limit:	0
Percent Clay:	0.00%
Percent Silt:	0.00%
Percent Sand:	0.00%
Percent Coarse:	0.00%
Percent Organic:	
D10:	0
D20:	0
D30:	0
D50:	0
D60:	0
Cu:	0
Cc:	0
Experimentally Determined:	Yes
Saturation:	100.00%
Void Ratio:	1.530
Porosity:	60.48%
Water Content:	
Volumetric Water Content:	0.604818
Dry Density:	
Total Density:	
Total Unit Weight:	
Specific Gravity:	0
Locked S:	No
Locked VWC:	No
Locked VR:	No
Locked WC:	No
Locked DD:	No
Locked TD:	No
Locked SG:	No
Accel of Gravity:	9.81
Density of Water:	1000
CEC:	
pH:	
Electrolyte Level:	
SAR:	
ESP:	
EC:	
Free Fe and Al Oxide:	
Family:	
Soil Series:	
Year Sampled:	
Land Use:	
Drainage:	
Slope:	
Number of Horizons:	
Horizon Number:	

Horizon Code:
Horizon Depth Upper:
Horizon Depth Lower:
Depth to Groundwater:
Author:
Paper Name:
Year Published:
Publisher:
Journal Name:
Volume:
Page Numbers:
Contact: Murray Fredlund
Rating: 8
Country:
Province:
Region:
Site:

1

SWCC

07-Sep-96

Param_ID: 383
SWCC Soil_Counter: 19
SWCC Description: Unknown Test Method
SWCC Fit Type: Fredlund & Xing (Type 1)
SWCC Curve Type: 0
SWCC Fit: Yes
Fit Data Source: 0
Param_1 Name: a
Param_2 Name: n
Param_3 Name: m
Param_4 Name: hr
Param_1 Value: 1.34095797073563
Param_2 Value: 2.21563872033604
Param_3 Value: 0.483106764659308
Param_4 Value: 3000
SWCC Error: 8.15024826969769E-03
Residual VWC: 0.1351877
SWCC Equation: Theta_w=Theta_sat*(1-ln(1+h/3000.0000)/ln(1+10^6/3000.0000))*(1/ln(exp(1)+(h/1.3410)^2.2156))^0.4831

1

Suction:	Vol. Water Content:
1.00E-01	0.605
7.00E-01	0.589
2.07E+00	0.464
2.07E+00	0.471
1.17E+01	0.320
2.76E+01	0.242
2.96E+01	0.234
5.00E+01	0.203
5.00E+01	0.205
5.00E+01	0.206
7.50E+01	0.200
7.50E+01	0.201
1.00E+02	0.202
1.50E+02	0.188

2.00E+02	0.188
2.00E+02	0.194
3.00E+02	0.176
3.00E+02	0.179
3.00E+02	0.187
3.00E+02	0.179
3.00E+02	0.178
4.00E+02	0.173
4.00E+02	0.178
4.00E+02	0.168
5.00E+02	0.166
1.00E+03	0.164
1.00E+03	0.165
1.50E+03	0.161
1.50E+03	0.160

Suction:	Vol. Water
1.00E-02	6.05E-01
1.65E-02	6.05E-01
2.72E-02	6.05E-01
4.48E-02	6.05E-01
7.39E-02	6.05E-01
1.22E-01	6.04E-01
2.01E-01	6.03E-01
3.31E-01	6.00E-01
5.46E-01	5.91E-01
9.00E-01	5.67E-01
1.48E+00	5.18E-01
2.45E+00	4.47E-01
4.03E+00	3.77E-01
6.65E+00	3.25E-01
1.10E+01	2.87E-01
1.81E+01	2.59E-01
2.98E+01	2.38E-01
4.91E+01	2.21E-01
8.10E+01	2.07E-01
1.34E+02	1.96E-01
2.20E+02	1.85E-01
3.63E+02	1.76E-01
5.99E+02	1.67E-01
9.87E+02	1.57E-01
1.63E+03	1.48E-01
2.68E+03	1.38E-01
4.42E+03	1.27E-01
7.29E+03	1.15E-01
1.20E+04	1.02E-01
1.98E+04	8.99E-02
3.27E+04	7.73E-02
5.39E+04	6.50E-02
8.89E+04	5.29E-02
1.47E+05	4.13E-02
2.42E+05	3.00E-02
3.98E+05	1.91E-02
6.57E+05	8.57E-03
1.00E+06	1.90E-20

Shear Strength

07-Sep-96

Shear_ID: 16

Shear Soil_Counter: 19

Shear Description:	Drying Curve Shear Strength
Shear Fit Type:	Fredlund & Xing (Type 1)
Shear Curve Type:	0
Effective angle of internal	36.5
Effective Cohesion:	33
Shear Parameter:	1
Shear Test:	Yes
Update Shear:	Yes
Shear Error:	
Shear Equation:	Shear=33.0+Net_Normal*tan(36.5*pi/180)+(1*(1-ln(1+h/300.0000)/ln(1+10^6/300.0000))*(1/ln(exp(1)+(h/5.6100)
Shear Graph Type:	2D Scatter
Shear 2D Axis:	Suction
Shear Suction Min:	0.1
Shear Suction Max:	125
Shear Suction Type:	Linear
Shear Normal Min:	0.1
Shear Normal Max:	100
Shear Normal Type:	Linear

1

Net Normal:	Suction:	Shear Strength:
0.1	0.1	33
0.1	44	53
0.1	86	54.5
0.1	125	62

Net Normal:	Suction:	Shear Stength:
0.1	0.1	33.14796
0.1	3.2225	34.69015
0.1	6.345	35.64113
0.1	9.4675	36.52781
0.1	12.59	37.38303
0.1	15.7125	38.21613
0.1	18.835	39.03215
0.1	21.9575	39.83434
0.1	25.08	40.62497
0.1	28.2025	41.4057
0.1	31.325	42.17782
0.1	34.4475	42.94233
0.1	37.57	43.70002
0.1	40.6925	44.45156
0.1	43.815	45.1975
0.1	46.9375	45.93831
0.1	50.06	46.67438
0.1	53.1825	47.40605
0.1	56.305	48.13362
0.1	59.4275	48.85735
0.1	62.55	49.57748
0.1	65.6725	50.29421
0.1	68.795	51.00773
0.1	71.9175	51.7182
0.1	75.04	52.42577
0.1	78.1625	53.13058
0.1	81.285	53.83274
0.1	84.4075	54.53239
0.1	87.53	55.22962
0.1	90.6525	55.92452
0.1	93.775	56.6172

0.1	96.8975	57.30771
0.1	100.02	57.99615
0.1	103.1425	58.68259
0.1	106.265	59.36709
0.1	109.3875	60.04972
0.1	112.51	60.73053
0.1	115.6325	61.40957
0.1	118.755	62.08691
0.1	121.8775	62.76258
0.1	125	63.43663

Soils

07-Sep-96

10. Soil_Counter: 26

ProjectID: SP1002
Soil Group:
Texture: Loam
Texture Modifier:
Structure Grade:
Structure Size:
Structure Type:
Soil Name: Indian Head Till
Soil Description: Optimum water content
Notes: Soil from Sai Vanapalli, 100 kPa loading. Used to tes
t shear strength prediction. Good prediction. Used in

Plasticity Index:	0
Plastic Limit:	0
Liquid Limit:	0
Percent Clay:	0.00%
Percent Silt:	0.00%
Percent Sand:	0.00%
Percent Coarse:	0.00%
Percent Organic:	
D10:	0
D20:	0
D30:	0
D50:	0
D60:	0
Cu:	0
Cc:	0
Experimentally Determined:	Yes
Saturation:	100.00%
Void Ratio:	0.474
Porosity:	32.15%
Water Content:	
Volumetric Water Content:	0.321468
Dry Density:	
Total Density:	
Total Unit Weight:	
Specific Gravity:	0
Locked S:	No
Locked VWC:	No
Locked VR:	No
Locked WC:	No
Locked DD:	No
Locked TD:	No
Locked SG:	No
Accel of Gravity:	9.81
Density of Water:	1000
CEC:	
pH:	

Electrolyte Level:	
SAR:	
ESP:	
EC:	
Free Fe and Al Oxide:	
Family:	
Soil Series:	
Year Sampled:	
Land Use:	
Drainage:	
Slope:	
Number of Horizons:	
Horizon Number:	
Horizon Code:	
Horizon Depth Upper:	
Horizon Depth Lower:	
Depth to Groundwater:	
Author:	
Paper Name:	
Year Published:	
Publisher:	
Journal Name:	
Volume:	
Page Numbers:	
Contact:	Murray Fredlund
Rating:	8
Country:	
Province:	
Region:	
Site:	

1

SWCC

07-Sep-96

Param_ID:	221
SWCC Soil_Counter:	26
SWCC Description:	Unknown Test Method
SWCC Fit Type:	Fredlund & Xing (Type 1)
SWCC Curve Type:	0
SWCC Fit:	Yes
Fit Data Source:	0
Param_1 Name:	a
Param_2 Name:	n
Param_3 Name:	m
Param_4 Name:	hr
Param_1 Value:	406.23656574839
Param_2 Value:	0.814763623370742
Param_3 Value:	0.594340488336802
Param_4 Value:	3000
SWCC Error:	6.07408973072935E-03
Residual VWC:	0.184459
SWCC Equation:	Theta_w=Theta_sat*(1-ln(1+h/3000.0000)/ln(1+10^6/3000.0000))*(1/ln(exp(1)+(h/406.2366)^0.8148))^0.5943

1

Suction:	Vol. Water Content:
1.00E+00	0.321
1.00E+01	0.321

2.00E+01	0.321
4.00E+01	0.321
8.00E+01	0.308
1.20E+02	0.300
1.60E+02	0.291
2.00E+02	0.285
3.00E+02	0.274
4.00E+02	0.262
5.00E+02	0.257
6.00E+02	0.248
8.00E+02	0.236
1.50E+03	0.231
4.40E+03	0.173
3.80E+04	0.074
8.56E+04	0.055
1.52E+05	0.039
2.98E+05	0.024

Suction:	Vol. Water
1.00E-02	3.21E-01
1.65E-02	3.21E-01
2.72E-02	3.21E-01
4.48E-02	3.21E-01
7.39E-02	3.21E-01
1.22E-01	3.21E-01
2.01E-01	3.21E-01
3.31E-01	3.21E-01
5.46E-01	3.21E-01
9.00E-01	3.21E-01
1.48E+00	3.21E-01
2.45E+00	3.20E-01
4.03E+00	3.20E-01
6.65E+00	3.19E-01
1.10E+01	3.18E-01
1.81E+01	3.16E-01
2.98E+01	3.13E-01
4.91E+01	3.09E-01
8.10E+01	3.03E-01
1.34E+02	2.95E-01
2.20E+02	2.85E-01
3.63E+02	2.71E-01
5.99E+02	2.54E-01
9.87E+02	2.34E-01
1.63E+03	2.13E-01
2.68E+03	1.90E-01
4.42E+03	1.67E-01
7.29E+03	1.44E-01
1.20E+04	1.23E-01
1.98E+04	1.03E-01
3.27E+04	8.55E-02
5.39E+04	6.93E-02
8.89E+04	5.46E-02
1.47E+05	4.13E-02
2.42E+05	2.92E-02
3.98E+05	1.82E-02
6.57E+05	7.97E-03
1.00E+06	1.74E-20

Net Normal:	Suction:	Shear Strength:
100	0.1	31.8
100	30	35
100	75	52.36
100	150	77.812

100	225	104.452
100	300	117.2
100	350	136.544
100	400	147.2
100	500	169.6

Shear Strength

07-Sep-96

Shear_ID:	23
Shear Soil_Counter:	26
Shear Description:	Drying Curve Shear Strength
Shear Fit Type:	Fredlund & Xing (Type 1)
Shear Curve Type:	0
Effective angle of internal	20
Effective Cohesion:	32
Shear Parameter:	2
Shear Test:	No
Update Shear:	Yes
Shear Error:	863.954584447399
Shear Equation:	Shear=32.0+Net_Normal*tan(20.0*pi/180)+(1*(1-ln(1+h/3 000.0000)/ln(1+10^6/3000.0000))*(1/ln(exp(1)+(h/406.2
Shear Graph Type:	2D Scatter
Shear 2D Axis:	Suction
Shear Suction Min:	0.1
Shear Suction Max:	500
Shear Suction Type:	Linear
Shear Normal Min:	0.1
Shear Normal Max:	200
Shear Normal Type:	Linear

1

Net Normal:	Suction:	Shear Stength:
0.01	0.1	32.04002
0.01	12.5975	36.46794
0.01	25.095	40.72278
0.01	37.5925	44.83738
0.01	50.09	48.82928
0.01	62.5875	52.71086
0.01	75.085	56.49169
0.01	87.5825	60.17957
0.01	100.08	63.78104
0.01	112.5775	67.30177
0.01	125.075	70.74664
0.01	137.5725	74.12001
0.01	150.07	77.42578
0.01	162.5675	80.66744
0.01	175.065	83.84815
0.01	187.5625	86.97082
0.01	200.06	90.03808
0.01	212.5575	93.05237
0.01	225.055	96.01594
0.01	237.5525	98.93088
0.01	250.05	101.7991
0.01	262.5475	104.6225
0.01	275.045	107.4026
0.01	287.5425	110.1411

0.01	300.04	112.8395
0.01	312.5375	115.4991
0.01	325.035	118.1213
0.01	337.5325	120.7074
0.01	350.03	123.2583
0.01	362.5275	125.7754
0.01	375.025	128.2596
0.01	387.5225	130.712
0.01	400.02	133.1334
0.01	412.5175	135.5248
0.01	425.015	137.8871
0.01	437.5125	140.2211
0.01	450.01	142.5274
0.01	462.5075	144.807
0.01	475.005	147.0605
0.01	487.5025	149.2885
0.01	500	151.4918

Soils

07-Sep-96

11. Soil_Counter: 31

ProjectID: SP1002
Soil Group:
Texture: Loam
Texture Modifier:
Structure Grade:
Structure Size:
Structure Type:
Soil Name: Indian Head Till
Soil Description: Wet of optimum
Notes: Soil from Sai Vanapalli, 200 kPa loading. Used to tes
t shear strength prediction. Very good prediction.
Plasticity Index: 0
Plastic Limit: 0
Liquid Limit: 0
Percent Clay: 0.00%
Percent Silt: 0.00%
Percent Sand: 0.00%
Percent Coarse: 0.00%
Percent Organic:
D10: 0
D20: 0
D30: 0
D50: 0
D60: 0
Cu: 0
Cc: 0
Experimentally Determined: Yes
Saturation: 100.00%
Void Ratio: 0.372
Porosity: 27.11%
Water Content:
Volumetric Water Content: 0.271137
Dry Density:
Total Density:
Total Unit Weight:
Specific Gravity: 0
Locked S: No
Locked VWC: No
Locked VR: No

Locked WC:	No
Locked DD:	No
Locked TD:	No
Locked SG:	No
Accel of Gravity:	9.81
Density of Water:	1000
CEC:	
pH:	
Electrolyte Level:	
SAR:	
ESP:	
EC:	
Free Fe and Al Oxide:	
Family:	
Soil Series:	
Year Sampled:	
Land Use:	
Drainage:	
Slope:	
Number of Horizons:	
Horizon Number:	
Horizon Code:	
Horizon Depth Upper:	
Horizon Depth Lower:	
Depth to Groundwater:	
Author:	
Paper Name:	
Year Published:	
Publisher:	
Journal Name:	
Volume:	
Page Numbers:	
Contact:	Murray Fredlund
Rating:	8
Country:	
Province:	
Region:	
Site:	

1

SWCC

07-Sep-96

Param_ID:	227
SWCC Soil_Counter:	31
SWCC Description:	Unknown Test Method
SWCC Fit Type:	Fredlund & Xing (Type 1)
SWCC Curve Type:	0
SWCC Fit:	Yes
Fit Data Source:	0
Param_1 Name:	a
Param_2 Name:	n
Param_3 Name:	m
Param_4 Name:	hr
Param_1 Value:	238.738867879685
Param_2 Value:	1.1266823510201
Param_3 Value:	0.400920183435032
Param_4 Value:	3000
SWCC Error:	8.07824116065159E-03
Residual VWC:	0.1537794
SWCC Equation:	Theta_w=Theta_sat*(1-ln(1+h/3000.0000)/ln(1+10^6/3000.0000))*(1/ln(exp(1)+(h/238.7389)^1.1267))^0.4009

1

Suction:	Vol. Water Content:
1.00E+00	0.271
1.50E+01	0.271
1.00E+02	0.257
2.00E+02	0.248
4.00E+02	0.233
6.00E+02	0.200
8.00E+02	0.190
1.50E+03	0.193
4.40E+03	0.143
3.80E+04	0.069
8.56E+04	0.051
1.52E+05	0.040
2.98E+05	0.025

Suction:	Vol. Water
1.00E-02	2.71E-01
1.65E-02	2.71E-01
2.72E-02	2.71E-01
4.48E-02	2.71E-01
7.39E-02	2.71E-01
1.22E-01	2.71E-01
2.01E-01	2.71E-01
3.31E-01	2.71E-01
5.46E-01	2.71E-01
9.00E-01	2.71E-01
1.48E+00	2.71E-01
2.45E+00	2.71E-01
4.03E+00	2.71E-01
6.65E+00	2.70E-01
1.10E+01	2.70E-01
1.81E+01	2.69E-01
2.98E+01	2.67E-01
4.91E+01	2.64E-01
8.10E+01	2.59E-01
1.34E+02	2.52E-01
2.20E+02	2.42E-01
3.63E+02	2.28E-01
5.99E+02	2.12E-01
9.87E+02	1.94E-01
1.63E+03	1.76E-01
2.68E+03	1.58E-01
4.42E+03	1.40E-01
7.29E+03	1.24E-01
1.20E+04	1.08E-01
1.98E+04	9.26E-02
3.27E+04	7.83E-02
5.39E+04	6.48E-02
8.89E+04	5.21E-02
1.47E+05	4.02E-02
2.42E+05	2.89E-02
3.98E+05	1.82E-02
6.57E+05	8.13E-03
1.00E+06	1.80E-20

Shear Strength

07-Sep-96

Shear_ID:		28
Shear Soil_Counter:		31
Shear Description:	Drying Curve Shear Strength	
Shear Fit Type:	Fredlund & Xing (Type 1)	
Shear Curve Type:		0
Effective angle of internal		23
Effective Cohesion:		0
Shear Parameter:		1
Shear Test:		No
Update Shear:		Yes
Shear Error:		
Shear Equation:	Shear=0.0+Net_Normal*tan(23.0*pi/180)+(1*(1-ln(1+h/30 0.0000)/ln(1+10^6/300.0000))*(1/ln(exp(1)+(h/5.6100)^	
Shear Graph Type:	2D Scatter	
Shear 2D Axis:	Suction	
Shear Suction Min:		0.1
Shear Suction Max:		250
Shear Suction Type:	Linear	
Shear Normal Min:		0.1
Shear Normal Max:		200
Shear Normal Type:	Linear	

1

Net Normal:	Suction:	Shear Strength:
200	0.1	84.88
200	75	108.36
200	150	141.58
200	250	170.1

Net Normal:	Suction:	Shear Stength:
200	0.1	84.93733
200	6.3475	87.5816
200	12.595	90.20898
200	18.8425	92.81844
200	25.09	95.40959
200	31.3375	97.98233
200	37.585	100.5367
200	43.8325	103.0728
200	50.08	105.5908
200	56.3275	108.091
200	62.575	110.5737
200	68.8225	113.039
200	75.07	115.4873
200	81.3175	117.9189
200	87.565	120.3341
200	93.8125	122.7332
200	100.06	125.1165
200	106.3075	127.4844
200	112.555	129.8371
200	118.8025	132.1749
200	125.05	134.4982
200	131.2975	136.8072
200	137.545	139.1022
200	143.7925	141.3836
200	150.04	143.6515
200	156.2875	145.9063
200	162.535	148.1483

200	168.7825	150.3776
200	175.03	152.5946
200	181.2775	154.7995
200	187.525	156.9925
200	193.7725	159.1739
200	200.02	161.344
200	206.2675	163.5029
200	212.515	165.6508
200	218.7625	167.788
200	225.01	169.9147
200	231.2575	172.0311
200	237.505	174.1373
200	243.7525	176.2336
200	250	178.3202

Soils

07-Sep-96

12. Soil_Counter: 10033

ProjectID:	SP1013
Soil Group:	
Texture:	Inorganic clay low plastic
Texture Modifier:	
Structure Grade:	
Structure Size:	Fine to medium
Structure Type:	
Soil Name:	Uniform Silt
Soil Description:	Uniform silt from the Pilot Butte area of Saskatchewa
Notes:	Soil from David Ho's Ph.D. thesis. Used to test volum e change predictions
Plasticity Index:	0.118
Plastic Limit:	0.149
Liquid Limit:	0.267
Percent Clay:	24.46%
Percent Silt:	56.64%
Percent Sand:	18.89%
Percent Coarse:	0.00%
Percent Organic:	0.00%
D10:	2.08528E-05
D20:	5.388281E-04
D30:	5.347895E-03
D50:	0.0249209
D60:	3.70031967759132E-02
Cu:	1774.495
Cc:	37.06483
Experimentally Determined:	Yes
Saturation:	61.00%
Void Ratio:	0.696
Porosity:	41.05%
Water Content:	15.62%
Volumetric Water Content:	0.250415
Dry Density:	1602.806
Total Density:	1853.221
Total Unit Weight:	18.1801
Specific Gravity:	2.719
Locked S:	No
Locked VWC:	Yes
Locked VR:	Yes
Locked WC:	No
Locked DD:	No
Locked TD:	No

Locked SG:	Yes
Accel of Gravity:	9.81
Density of Water:	1000
CEC:	0
pH:	7.5
Electrolyte Level:	0
SAR:	1600
ESP:	0
EC:	0
Free Fe and Al Oxide:	0
Family:	
Soil Series:	
Year Sampled:	1986
Land Use:	
Drainage:	
Slope:	0.00%
Number of Horizons:	0
Horizon Number:	0
Horizon Code:	
Horizon Depth Upper:	0
Horizon Depth Lower:	0
Depth to Groundwater:	0
Author:	David Y.F. Ho
Paper Name:	The Relationships Between the Volumetric Deformation
Year Published:	1988
Publisher:	University of Saskatchewan
Journal Name:	Ph.D Thesis
Volume:	
Page Numbers:	
Contact:	Murray Fredlund
Rating:	9
Country:	Canada
Province:	Saskatchewan
Region:	Pilot Butte
Site:	

1

Consolidation

07-Sep-96

Consol_ID:	2
Consolidation Soil_Counter:	10033
Starting ca:	10
Starting cn:	1
Starting cm:	1
ca:	452.342391634681
cn:	0.929850368735599
cm:	0.66368574820699
Consolidation Fit:	Yes
Consolidation Equation:	Void_Ratio=0.696*(1/ln(2.71828182846+(Net_Normal/452.3424)^0.9299))^0.6637
Consolidation Error:	1.35306677742892E-03

1

Net Normal	Void Ratio:
22	0.697
200	0.64
500	0.558
1100	0.508
2300	0.45

4800	0.39
6900	0.36
9000	0.33

Net Normal	Void Ratio:
0.01	0.696392
1.491825E-02	0.6963884
2.225541E-02	0.6963832
3.320117E-02	0.6963757
4.953032E-02	0.6963647
7.389056E-02	0.6963488
0.1102318	0.6963257
0.1644465	0.6962923
0.2453253	0.6962438
0.3659824	0.6961734
0.5459815	0.6960715
0.8145087	0.6959237
1.215104	0.6957095
1.812722	0.6953993
2.704264	0.6949503
4.034288	0.6943011
6.01845	0.6933638
8.978473	0.6920131
13.39431	0.6900726
19.98196	0.6872963
29.80958	0.6833482
44.47067	0.6777812
66.34244	0.670024
98.97129	0.6593903
147.6478	0.6451317
220.2647	0.6265572
328.5963	0.6032285
490.208	0.5751905
731.3044	0.5431389
1090.978	0.5084009
1627.548	0.4726793
2428.016	0.4376615
3622.175	0.4046758
5403.649	0.374535
8061.297	0.3475647
10000	0.3343479

Soils

07-Sep-96

13. Soil_Counter: 10030

ProjectID: SP1013
Soil Group:
Texture: Inorganic clay low plastic
Texture Modifier:
Structure Grade:
Structure Size: Fine to medium
Structure Type:
Soil Name: Uniform Silt
Soil Description: Uniform silt from the Pilot Butte area of Saskatchewa
Notes: Soil from David Ho's Ph.D. thesis. Used to test volum
e change predictions
Plasticity Index: 0.118
Plastic Limit: 0.149

Liquid Limit:	0.267
Percent Clay:	24.46%
Percent Silt:	56.64%
Percent Sand:	18.89%
Percent Coarse:	0.00%
Percent Organic:	0.00%
D10:	2.08528E-05
D20:	5.388281E-04
D30:	5.347895E-03
D50:	0.0249209
D60:	3.70031967759132E-02
Cu:	1774.495
Cc:	37.06483
Experimentally Determined:	Yes
Saturation:	81.50%
Void Ratio:	0.640
Porosity:	39.02%
Water Content:	19.18%
Volumetric Water Content:	0.3180185
Dry Density:	1658.028
Total Density:	1976.046
Total Unit Weight:	19.38502
Specific Gravity:	2.719
Locked S:	No
Locked VWC:	Yes
Locked VR:	Yes
Locked WC:	No
Locked DD:	No
Locked TD:	No
Locked SG:	Yes
Accel of Gravity:	9.81
Density of Water:	1000
CEC:	0
pH:	7.5
Electrolyte Level:	0
SAR:	1600
ESP:	0
EC:	0
Free Fe and Al Oxide:	0
Family:	
Soil Series:	
Year Sampled:	1986
Land Use:	
Drainage:	
Slope:	0.00%
Number of Horizons:	0
Horizon Number:	0
Horizon Code:	
Horizon Depth Upper:	0
Horizon Depth Lower:	0
Depth to Groundwater:	0
Author:	David Y.F. Ho
Paper Name:	The Relationships Between the Volumetric Deformation
Year Published:	1988
Publisher:	University of Saskatchewan
Journal Name:	Ph.D Thesis
Volume:	
Page Numbers:	
Contact:	Murray Fredlund
Rating:	9
Country:	Canada
Province:	Saskatchewan
Region:	Pilot Butte
Site:	

Consolidation

07-Sep-96

Consol_ID:	3
Consolidation Soil_Counter:	10030
Starting ca:	10
Starting cn:	1
Starting cm:	1
ca:	270.746326480983
cn:	1.71386003305365
cm:	0.399074752826378
Consolidation Fit:	Yes
Consolidation Equation:	Void_Ratio=0.640*(1/ln(2.71828182846+(Net_Normal/270.7463)^1.7139))^0.3991
Consolidation Error:	2.00027943326825E-03

1

Net Normal	Void Ratio:
28	0.637
42	0.637
70	0.628
100	0.625
120	0.62
160	0.615
185	0.61
400	0.52
1000	0.45
2200	0.39
4700	0.345
9000	0.3

Net Normal	Void Ratio:
0.01	0.6399
1.491825E-02	0.6399
2.225541E-02	0.6399
3.320117E-02	0.6399
4.953032E-02	0.6399
7.389056E-02	0.6399
0.1102318	0.6398999
0.1644465	0.6398997
0.2453253	0.6398994
0.3659824	0.6398989
0.5459815	0.6398978
0.8145087	0.6398956
1.215104	0.6398911
1.812722	0.6398824
2.704264	0.639865
4.034288	0.6398305
6.01845	0.6397622
8.978473	0.6396266
13.39431	0.6393579
19.98196	0.6388267
29.80958	0.6377802
44.47067	0.6357332
66.34244	0.631785
98.97129	0.624369
147.6478	0.6110961
220.2647	0.5892066

328.5963	0.5572966
490.208	0.5175499
731.3044	0.4754404
1090.978	0.4362754
1627.548	0.4026515
2428.016	0.3747832
3622.175	0.3518334
5403.649	0.332783
8061.297	0.3167544
10000	0.309126

Soils

07-Sep-96

14. Soil_Counter: 10034

ProjectID:	SP1013
Soil Group:	
Texture:	Inorganic clay low plastic
Texture Modifier:	
Structure Grade:	
Structure Size:	Fine to medium
Structure Type:	
Soil Name:	Glacial Till
Soil Description:	Glacial Till from the Indian Head area of Saskatchewa
Notes:	Soil from David Ho's Ph.D. thesis. Used to test volum e change predictions
Plasticity Index:	0.202
Plastic Limit:	0.13
Liquid Limit:	0.332
Percent Clay:	27.59%
Percent Silt:	44.67%
Percent Sand:	25.61%
Percent Coarse:	2.01%
Percent Organic:	0.00%
D10:	3.637714E-05
D20:	5.982512E-04
D30:	2.677538E-03
D50:	1.539528E-02
D60:	3.10394801199436E-02
Cu:	853.2689
Cc:	6.349338
Experimentally Determined:	Yes
Saturation:	87.00%
Void Ratio:	0.599
Porosity:	37.45%
Water Content:	18.84%
Volumetric Water Content:	0.3258078
Dry Density:	1728.905
Total Density:	2054.712
Total Unit Weight:	20.15673
Specific Gravity:	2.764
Locked S:	No
Locked VWC:	Yes
Locked VR:	Yes
Locked WC:	No
Locked DD:	No
Locked TD:	No
Locked SG:	Yes
Accel of Gravity:	9.81
Density of Water:	1000
CEC:	0
pH:	7.9

Electrolyte Level:	0
SAR:	1800
ESP:	0
EC:	0
Free Fe and Al Oxide:	0
Family:	
Soil Series:	
Year Sampled:	1986
Land Use:	
Drainage:	
Slope:	0.00%
Number of Horizons:	0
Horizon Number:	0
Horizon Code:	
Horizon Depth Upper:	0
Horizon Depth Lower:	0
Depth to Groundwater:	0
Author:	David Y.F. Ho
Paper Name:	The Relationships Between the Volumetric Deformation
Year Published:	1988
Publisher:	University of Saskatchewan
Journal Name:	Ph.D Thesis
Volume:	
Page Numbers:	
Contact:	Murray Fredlund
Rating:	9
Country:	Canada
Province:	Saskatchewan
Region:	Pilot Butte
Site:	

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Soils

07-Sep-96

2

Consolidation

07-Sep-96

Consol_ID:	5
Consolidation Soil_Counter:	10034
Starting ca:	10
Starting cn:	1
Starting cm:	1
ca:	327.188030630595
cn:	1.55403266366863
cm:	0.411541128266478
Consolidation Fit:	Yes
Consolidation Equation:	Void_Ratio=0.599*(1/ln(2.71828182846+(Net_Normal/327.1880)^1.5540))^0.4115
Consolidation Error:	2.05867044085834E-03

1

Net Normal	Void Ratio:
40	0.603
100	0.59
130	0.585
160	0.578
220	0.555
310	0.537
700	0.46
1500	0.41
3000	0.37
6000	0.325
9000	0.29

Net Normal	Void Ratio:
0.01	0.5987
1.491825E-02	0.5987
2.225541E-02	0.5986999
3.320117E-02	0.5986999
4.953032E-02	0.5986999
7.389056E-02	0.5986998
0.1102318	0.5986996
0.1644465	0.5986993
0.2453253	0.5986987
0.3659824	0.5986977
0.5459815	0.5986956
0.8145087	0.5986918
1.215104	0.5986848
1.812722	0.5986717
2.704264	0.5986474
4.034288	0.5986022
6.01845	0.598518
8.978473	0.5983613

13.39431	0.5980702
19.98196	0.5975305
29.80958	0.5965332
44.47067	0.5947019
66.34244	0.5913787
98.97129	0.5854723
147.6478	0.5753491
220.2647	0.5590027
328.5963	0.5348822
490.208	0.5033256
731.3044	0.4673071
1090.978	0.4311133
1627.548	0.3980739
2428.016	0.3695945
3622.175	0.3456564
5403.649	0.3256267
8061.297	0.3087609
10000	0.3007501

Soils

07-Sep-96

15. Soil_Counter: 346

ProjectID: SP1005
Soil Group:
Texture: Sandy loam
Texture Modifier:
Structure Grade:
Structure Size:
Structure Type:
Soil Name: Windsor Soil
Soil Description: Horizon A
Notes: Used to test prediction of frozen volumetric water co
ntent. Note - data might fit better using Brooks and

Plasticity Index:	0
Plastic Limit:	0
Liquid Limit:	0
Percent Clay:	0.00%
Percent Silt:	0.00%
Percent Sand:	0.00%
Percent Coarse:	0.00%
Percent Organic:	0.00%
D10:	0
D20:	0
D30:	0
D50:	0
D60:	0
Cu:	0
Cc:	0
Experimentally Determined:	Yes
Saturation:	94.30%
Void Ratio:	0.912
Porosity:	47.70%
Water Content:	32.70%
Volumetric Water Content:	0.449811
Dry Density:	1375.49
Total Density:	1825.301
Total Unit Weight:	17.9062
Specific Gravity:	2.63
Locked S:	No
Locked VWC:	No

Locked VR:	Yes
Locked WC:	No
Locked DD:	No
Locked TD:	No
Locked SG:	Yes
Accel of Gravity:	9.81
Density of Water:	1000
CEC:	0
pH:	0
Electrolyte Level:	0
SAR:	0
ESP:	0
EC:	0
Free Fe and Al Oxide:	0
Family:	
Soil Series:	
Year Sampled:	
Land Use:	
Drainage:	
Slope:	
Number of Horizons:	3
Horizon Number:	1
Horizon Code:	A
Horizon Depth Upper:	0
Horizon Depth Lower:	0
Depth to Groundwater:	0
Author:	Patric B. Black and Allen R. Tice
Paper Name:	Comparison of Soil Freezing Curve and Soil Water Curv
Year Published:	1989
Publisher:	American Geophysical Union
Journal Name:	Water Resources Research
Volume:	Vol. 25, No. 10
Page Numbers:	2205-2210
Contact:	Murray Fredlund
Rating:	6
Country:	
Province:	
Region:	
Site:	

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SWCC

07-Sep-96

Param_ID:	378
SWCC Soil_Counter:	346
SWCC Description:	Unknown Test Method
SWCC Fit Type:	Fredlund & Xing (Type 1)
SWCC Curve Type:	0
SWCC Fit:	Yes
Fit Data Source:	0
Param_1 Name:	a
Param_2 Name:	n
Param_3 Name:	m
Param_4 Name:	hr
Param_1 Value:	1.19070544874846
Param_2 Value:	1.53836808606046
Param_3 Value:	0.739202757285729
Param_4 Value:	3000
SWCC Error:	1.03163179453125E-02
Residual VWC:	6.292986E-02
SWCC Equation:	Theta_w=Theta_sat*(1-ln(1+h/3000.0000)/ln(1+10^6/3000 .0000))*(1/ln(exp(1)+(h/1.1907)^1.5384))^0.7392

Suction:	Vol. Water Content:
1.50E+00	0.335
2.00E+00	0.330
7.00E+00	0.225
8.00E+00	0.200
9.00E+00	0.180
1.30E+01	0.135
3.00E+01	0.145
4.00E+01	0.136
7.00E+01	0.120
9.00E+01	0.110

Suction:	Vol. Water
1.00E-02	4.50E-01
1.65E-02	4.50E-01
2.72E-02	4.49E-01
4.48E-02	4.49E-01
7.39E-02	4.48E-01
1.22E-01	4.46E-01
2.01E-01	4.42E-01
3.31E-01	4.34E-01
5.46E-01	4.18E-01
9.00E-01	3.90E-01
1.48E+00	3.48E-01
2.45E+00	2.98E-01
4.03E+00	2.49E-01
6.65E+00	2.09E-01
1.10E+01	1.78E-01
1.81E+01	1.55E-01
2.98E+01	1.37E-01
4.91E+01	1.23E-01
8.10E+01	1.12E-01
1.34E+02	1.03E-01
2.20E+02	9.53E-02
3.63E+02	8.84E-02
5.99E+02	8.21E-02
9.87E+02	7.61E-02
1.63E+03	7.02E-02
2.68E+03	6.43E-02
4.42E+03	5.82E-02
7.29E+03	5.20E-02
1.20E+04	4.58E-02
1.98E+04	3.96E-02
3.27E+04	3.37E-02
5.39E+04	2.80E-02
8.89E+04	2.25E-02
1.47E+05	1.74E-02
2.42E+05	1.25E-02
3.98E+05	7.87E-03
6.57E+05	3.50E-03
1.00E+06	7.71E-21

Frozen

07-Sep-96

Frozen_ID:	9
Unfrozen Soil_Counter:	346
Unfrozen Description:	Cooling Data for Winsor Soil A
Unfrozen Fit Type:	Fredlund & Xing (Type 1)
Unfrozen Curve Type:	0
Unfrozen Equation:	Theta_u=Theta_sat*(1-ln(1+2.20*1110*Temp/3000.0000)/ln(1+10^6/3000.0000))*(1/ln(exp(1)+(2.20*1110*Temp/1.1
Unfrozen Parameter:	2.2
Unfrozen Test:	Yes
Update Unfrozen:	No
Unfrozen Error:	

1

Temperature:	Unfrozen VWC:
0.25	0.0625
0.4	0.058
0.45	0.046
1	0.042
1.2	0.041
1.4	0.038
2	0.038
3	0.032
3.2	0.03
5	0.028
7	0.027
11	0.025
15	0.024
20	0.023

Temperature:	Unfrozen VWC:
0.00001	0.4495024
1.648721E-05	0.449146
2.718282E-05	0.4483806
4.481689E-05	0.4467448
7.389056E-05	0.4432884
1.218249E-04	0.4361549
2.008554E-04	0.4221177
3.311545E-04	0.3968679
5.459815E-04	0.3577716
9.001713E-04	0.3085456
1.484132E-03	0.2588335
2.446919E-03	0.2165849
4.034288E-03	0.1838861
6.651416E-03	0.1592742
1.096633E-02	0.1405859
1.808042E-02	0.1260542
2.980958E-02	0.1144326
4.914769E-02	0.1048657
8.103084E-02	0.0967519
0.1335973	8.964464E-02
0.2202647	8.318844E-02
0.363155	0.0770847
0.5987414	7.108408E-02
0.9871577	0.0650029
1.627548	5.874969E-02
2.683373	5.233549E-02
4.424134	4.584975E-02
7.294164	3.941279E-02
12.02604	3.313337E-02

19.82759	0.0270878
32.69017	0.0213184
53.89698	1.584095E-02
88.86111	1.065387E-02
146.5072	5.745566E-03
241.5495	1.099476E-03
273	0

Soils

07-Sep-96

16. Soil_Counter: 262

ProjectID:	SP1005
Soil Group:	
Texture:	Silt Loam
Texture Modifier:	
Structure Grade:	
Structure Size:	
Structure Type:	
Soil Name:	Silica Flour
Soil Description:	Could be considered an extremely fine sand
Notes:	Soil obtained from Greg Neuman to test the unfrozen w ater content prediction. This soil is also used to te
Plasticity Index:	0
Plastic Limit:	0
Liquid Limit:	0
Percent Clay:	11.30%
Percent Silt:	75.80%
Percent Sand:	12.90%
Percent Coarse:	0.00%
Percent Organic:	
D10:	1.392474E-03
D20:	6.894153E-03
D30:	1.225773E-02
D50:	2.174295E-02
D60:	2.67241857945919E-02
Cu:	19.19187
Cc:	4.03765
Experimentally Determined:	Yes
Saturation:	90.00%
Void Ratio:	0.992
Porosity:	49.81%
Water Content:	33.71%
Volumetric Water Content:	0.4483019
Dry Density:	1330
Total Density:	1778.302
Total Unit Weight:	17.44514
Specific Gravity:	2.65
Locked S:	No
Locked VWC:	Yes
Locked VR:	No
Locked WC:	No
Locked DD:	Yes
Locked TD:	No
Locked SG:	Yes
Accel of Gravity:	9.81
Density of Water:	1000
CEC:	
pH:	
Electrolyte Level:	
SAR:	
ESP:	

EC:
Free Fe and Al Oxide:
Family:
Soil Series:
Year Sampled:
Land Use:
Drainage:
Slope:
Number of Horizons:
Horizon Number:
Horizon Code:
Horizon Depth Upper:
Horizon Depth Lower:
Depth to Groundwater:
Author:
Paper Name:
Year Published:
Publisher:
Journal Name:
Volume:
Page Numbers:
Contact: Murray Fredlund
Rating: 8
Country:
Province:
Region:
Site:

1

SWCC

07-Sep-96

Param_ID: 394
SWCC Soil_Counter: 262
SWCC Description: Unknown Test Method
SWCC Fit Type: Fredlund & Xing (Type 1)
SWCC Curve Type: 0
SWCC Fit: Yes
Fit Data Source: 0
Param_1 Name: a
Param_2 Name: n
Param_3 Name: m
Param_4 Name: hr
Param_1 Value: 40.3321634979627
Param_2 Value: 3.45416089317753
Param_3 Value: 1.04721512672019
Param_4 Value: 3000
SWCC Error: 3.61735174834079E-03
Residual VWC: 2.335107E-02
SWCC Equation: Theta_w=Theta_sat*(1-ln(1+h/3000.0000)/ln(1+10^6/3000.0000))*(1/ln(exp(1)+(h/40.3322)^3.4542))^1.0472

1

Suction:	Vol. Water Content:
1.00E+00	0.448
4.60E+00	0.444
1.00E+01	0.437
2.00E+01	0.421
3.50E+01	0.366
4.08E+01	0.334

5.01E+01	0.281
6.15E+01	0.227
7.56E+01	0.177
9.76E+01	0.130
1.26E+02	0.099
1.72E+02	0.075
2.34E+02	0.061
3.35E+02	0.051
4.32E+02	0.046
6.19E+02	0.040
9.33E+02	0.036
1.15E+03	0.034
1.41E+03	0.032
1.73E+03	0.031
2.23E+03	0.030
3.20E+03	0.028
4.82E+03	0.025
8.05E+03	0.022
1.04E+04	0.021
1.65E+04	0.019
2.90E+04	0.016
4.60E+04	0.013
8.10E+04	0.011
1.58E+05	0.008
2.92E+05	0.005
5.13E+05	0.003

Suction:	Vol. Water
1.00E-02	4.48E-01
1.65E-02	4.48E-01
2.72E-02	4.48E-01
4.48E-02	4.48E-01
7.39E-02	4.48E-01
1.22E-01	4.48E-01
2.01E-01	4.48E-01
3.31E-01	4.48E-01
5.46E-01	4.48E-01
9.00E-01	4.48E-01
1.48E+00	4.48E-01
2.45E+00	4.48E-01
4.03E+00	4.48E-01
6.65E+00	4.48E-01
1.10E+01	4.46E-01
1.81E+01	4.37E-01
2.98E+01	3.97E-01
4.91E+01	2.83E-01
8.10E+01	1.62E-01
1.34E+02	9.95E-02
2.20E+02	6.94E-02
3.63E+02	5.26E-02
5.99E+02	4.19E-02
9.87E+02	3.45E-02
1.63E+03	2.88E-02
2.68E+03	2.43E-02
4.42E+03	2.04E-02
7.29E+03	1.72E-02
1.20E+04	1.43E-02
1.98E+04	1.18E-02
3.27E+04	9.59E-03
5.39E+04	7.65E-03
8.89E+04	5.94E-03
1.47E+05	4.43E-03
2.42E+05	3.09E-03

3.98E+05	1.89E-03
6.57E+05	8.18E-04
1.00E+06	1.76E-21

Frozen

07-Sep-96

Frozen_ID:	10
Unfrozen Soil_Counter:	262
Unfrozen Description:	Test of curve prediction
Unfrozen Fit Type:	Fredlund & Xing (Type 1)
Unfrozen Curve Type:	0
Unfrozen Equation:	Theta_u=Theta_sat*(1-ln(1+1.00*1110*Temp/3000.0000)/ln(1+10^6/3000.0000))*(1/ln(exp(1)+(1.00*1110*Temp/40.
Unfrozen Parameter:	1
Unfrozen Test:	Yes
Update Unfrozen:	No
Unfrozen Error:	

1

Temperature:	Unfrozen VWC:
0.001	0.492
0.003	0.491
0.005	0.489
0.008	0.488
0.013	0.483
0.02	0.477
0.031	0.461
0.045	0.44
0.057	0.417
0.07	0.388
0.086	0.345
0.105	0.292
0.132	0.24
0.178	0.173
0.23	0.12
0.29	0.08
0.33	0.06
0.4	0.043
0.501	0.036
0.653	0.031
0.794	0.028
0.91	0.025
1.11	0.025
1.41	0.025
2	0.024
4	0.024
6	0.024
8	0.024
10	0.024

Temperature:	Unfrozen VWC:
0.00001	0.4483015
1.648721E-05	0.4483013
2.718282E-05	0.4483009
4.481689E-05	0.4483003
7.389056E-05	0.4482992

1.218249E-04	0.4482975
2.008554E-04	0.4482947
3.311545E-04	0.44829
5.459815E-04	0.4482822
9.001713E-04	0.4482691
1.484132E-03	0.4482459
2.446919E-03	0.4481987
4.034288E-03	0.4480702
6.651416E-03	0.4475747
1.096633E-02	0.4451805
1.808042E-02	0.4329196
2.980958E-02	0.3793275
4.914769E-02	0.2538296
8.103084E-02	0.1446265
0.1335973	9.124587E-02
0.2202647	6.488699E-02
0.363155	4.972129E-02
0.5987414	3.980993E-02
0.9871577	3.267888E-02
1.627548	2.714714E-02
2.683373	2.259949E-02
4.424134	1.870828E-02
7.294164	1.530369E-02
12.02604	1.229858E-02
19.82759	9.642228E-03
32.69017	7.296063E-03
53.89698	5.224545E-03
88.86111	3.393536E-03
146.5072	1.771144E-03
241.5495	3.286485E-04
273	0

Soils

07-Sep-96

17. Soil_Counter: 350

ProjectID:	SP1012
Soil Group:	
Texture:	Sand
Texture Modifier:	
Structure Grade:	Weak
Structure Size:	Fine to medium
Structure Type:	Granular
Soil Name:	Beaver Creek Sand
Soil Description:	Olive brown, oxidized, uniform sand
Notes:	Used to test the prediction of Adsorption and Diffusi on. Soil obtained from a natural aeolin sand deposit
Plasticity Index:	0
Plastic Limit:	0
Liquid Limit:	0
Percent Clay:	0.00%
Percent Silt:	0.05%
Percent Sand:	99.95%
Percent Coarse:	0.00%
Percent Organic:	0.00%
D10:	0.1917282
D20:	0.2157306
D30:	0.2336219
D50:	0.2658199
D60:	0.283346176147461

Cu:	1.477853
Cc:	1.004671
Experimentally Determined:	Yes
Saturation:	99.80%
Void Ratio:	0.618
Porosity:	38.20%
Water Content:	23.10%
Volumetric Water Content:	0.381236
Dry Density:	1650.06
Total Density:	2031.296
Total Unit Weight:	19.92702
Specific Gravity:	2.67
Locked S:	No
Locked VWC:	Yes
Locked VR:	Yes
Locked WC:	No
Locked DD:	No
Locked TD:	No
Locked SG:	Yes
Accel of Gravity:	9.81
Density of Water:	1000
CEC:	1.3
pH:	0
Electrolyte Level:	0
SAR:	0
ESP:	0
EC:	0
Free Fe and Al Oxide:	0
Family:	
Soil Series:	
Year Sampled:	1995
Land Use:	Cropland - General
Drainage:	Somewhat poorly drainedd
Slope:	
Number of Horizons:	0
Horizon Number:	0
Horizon Code:	
Horizon Depth Upper:	0
Horizon Depth Lower:	0
Depth to Groundwater:	0
Author:	P.C. Lim, S.L. Barbour, and D.G. Fredlund
Paper Name:	Diffusion and Adsorption Processes in Unsaturated Soi
Year Published:	1996
Publisher:	
Journal Name:	Canadian Geotechnical Journal
Volume:	
Page Numbers:	
Contact:	Murray Fredlund
Rating:	10
Country:	Canada
Province:	Saskatchewan
Region:	Beaver Creek
Site:	

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SWCC

07-Sep-96

Param_ID:	423
SWCC Soil_Counter:	350
SWCC Description:	Unknown Test Method
SWCC Fit Type:	Fredlund & Xing (Type 1)
SWCC Curve Type:	0
SWCC Fit:	Yes
Fit Data Source:	0

Param_1 Name: a
Param_2 Name: n
Param_3 Name: m
Param_4 Name: hr
Param_1 Value: 2.86887037926505
Param_2 Value: 12.7819284316143
Param_3 Value: 1.14361911934861
Param_4 Value: 10
SWCC Error: 4.21051684899894E-02
Residual VWC: 1.508008E-02
SWCC Equation: Theta_w=Theta_sat*(1-ln(1+h/10.0000)/ln(1+10^6/10.0000))*(1/ln(exp(1)+(h/2.8689)^12.7819))^1.1436

1

Suction:	Vol. Water Content:
1.00E-02	0.381
2.75E+00	0.294
2.75E+00	0.303
2.75E+00	0.320
2.75E+00	0.299
2.95E+00	0.273
2.95E+00	0.238
2.95E+00	0.227
3.10E+00	0.214
3.10E+00	0.192
3.10E+00	0.220
3.60E+00	0.109
3.60E+00	0.121
3.60E+00	0.112
3.90E+00	0.033
3.90E+00	0.042
3.90E+00	0.081
3.90E+00	0.078
3.90E+00	0.083
3.90E+00	0.080
6.00E+00	0.046
6.00E+00	0.038
6.00E+00	0.039

Suction:	Vol. Water
1.00E-02	3.81E-01
1.65E-02	3.81E-01
2.72E-02	3.81E-01
4.48E-02	3.81E-01
7.39E-02	3.81E-01
1.22E-01	3.81E-01
2.01E-01	3.81E-01
3.31E-01	3.80E-01
5.46E-01	3.79E-01
9.00E-01	3.78E-01
1.48E+00	3.77E-01
2.45E+00	3.55E-01
4.03E+00	6.81E-02
6.65E+00	2.41E-02
1.10E+01	1.38E-02
1.81E+01	9.37E-03
2.98E+01	6.88E-03
4.91E+01	5.30E-03
8.10E+01	4.21E-03

1.34E+02	3.41E-03
2.20E+02	2.81E-03
3.63E+02	2.34E-03
5.99E+02	1.96E-03
9.87E+02	1.65E-03
1.63E+03	1.39E-03
2.68E+03	1.18E-03
4.42E+03	9.96E-04
7.29E+03	8.39E-04
1.20E+04	7.02E-04
1.98E+04	5.83E-04
3.27E+04	4.77E-04
5.39E+04	3.84E-04
8.89E+04	3.01E-04
1.47E+05	2.26E-04
2.42E+05	1.59E-04
3.98E+05	9.80E-05
6.57E+05	4.27E-05
1.00E+06	6.10E-23

Diffusion

07-Sep-96

Diffu_ID: 7
Diffusion Soil_Counter: 350
Diffusion Description: Potassium - back calculated from batch tests
Diffusion Fit Type: Fredlund & Xing (Type 1)
Diffusion Curve Type: 0
Diffusion Parameter: 1
Cf: 0.01
Ds: 1.200E-09
Diffusion Test: Yes
Update Diffusion: No
Diffusion Error:
Diffusion Equation: De=((Theta_sat*(1-ln(1+h/10.0000)/ln(1+10^6/10.0000))
*(1/ln(exp(1)+(h/3.0796)^10.6251))^1.2390-Theta_r)/(T

1

Suction:	De:
0.01	1.200E-09
2.75	7.500E-10
2.95	7.000E-10
3.1	6.000E-10
3.6	4.000E-10
3.9	3.000E-10
3.9	3.000E-10
6	2.250E-10

Suction:	De:
0.01	1.200E-09
0.01648721	1.200E-09
0.02718282	1.200E-09
0.04481689	1.200E-09
0.07389056	1.199E-09
0.1218249	1.199E-09
0.2008554	1.198E-09
0.3311545	1.196E-09

0.5459815	1.194E-09
0.9001713	1.191E-09
1.484132	1.185E-09
2.446919	1.131E-09
4.034288	2.678E-10
6.651416	4.870E-11
10	1.200E-11
16.48721	1.200E-11
27.18282	1.200E-11
44.81689	1.200E-11
73.89056	1.200E-11
121.8249	1.200E-11
200.8554	1.200E-11
331.1545	1.200E-11
545.9815	1.200E-11
900.1713	1.200E-11
1484.132	1.200E-11
2446.919	1.200E-11
4034.288	1.200E-11
6651.417	1.200E-11
10966.33	1.200E-11
18080.42	1.200E-11
29809.58	1.200E-11
49147.69	1.200E-11
81030.84	1.200E-11
133597.3	1.200E-11
220264.7	1.200E-11
363155	1.200E-11
598741.4	1.200E-11
987157.7	1.200E-11
1000000	1.200E-11

Adsorption

07-Sep-96

Adsorp_ID:		116
Adsorption Soil_Counter:		350
Adsorption Description:	Diffusion-type batch test ASTM D4646-87 and D4319-83	
Model Type:		1
Adsorption Test:		Yes
Kd:		1
K:		0
N:		0
Alpha:		0
Beta:		0
Adsorption Fit Type:	Fredlund & Xing (Type 1)	
Adsorption Curve Type:		0
c:		5
Adsorption Temperature:		23
Adsorption Error:		
Update linear:		No
Update Freundlich:		Yes
Update Langmuir:		Yes
Ads Graph Type:	2D Scatter	
Ads 2D Axis:	Suction	
Ads Conc Min:		0
Ads Conc Max:		1
Ads Suction Min:		0.01
Ads Suction Max:		20
Ads Suction Type:	Linear	
Surface filename:		

1

Concentration:	Suction:	Solute Sorbed:
1	1.902726	1
1	2.819315	0.975
1	2.914745	0.975
1	2.954842	0.98
1	3.181586	0.95
1	3.236677	0.95
1	3.260491	0.85
1	3.375908	0.8
1	3.860304	0.77
1	3.877278	0.85
1	4.169392	0.85
1	4.22476	0.79
1	5.134801	0.79
1	5.557728	0.665
1	5.613866	0.62
1	5.8374	0.57

Concentration:	Suction:	Solute Sorbed:
1	1.045	0.9999724
1	1.135	0.9998962
1	1.315	0.99962
1	1.495	0.9990746
1	1.675	0.9980824
1	1.855	0.9963905
1	2.035	0.9936551
1	2.215	0.9894364
1	2.395	0.9832264
1	2.575	0.9745682
1	2.755	0.9633204
1	2.934999	0.9499477
1	3.114999	0.9354206
1	3.294999	0.9206197
1	3.474999	0.9059223
1	3.654999	0.8912956
1	3.834999	0.8765407
1	4.014998	0.8614342
1	4.194999	0.845777
1	4.374999	0.8294021
1	4.554999	0.8121712
1	4.735	0.7939695
1	4.915	0.7747016
1	5.095	0.7542892
1	5.275001	0.7326689
1	5.455001	0.7097921
1	5.635001	0.6856244
1	5.815001	0.6601464
1	5.995002	0.6333542
1	6.175002	0.6052606
1	6.355002	0.5758962
1	6.535003	0.5453106
1	6.715003	0.5135742
1	6.895003	0.4807799
1	7.075004	0.4470443
1	7.255004	0.4125102
1	7.435004	0.3773484
1	7.615005	0.3417594

1	7.795005	0.3059761
1	7.975005	0.2702654
1	8.155005	0.2349308
1	8.335006	0.2003151
1	8.515006	0.166802
1	8.695006	0.1348197
1	8.875007	0.1048426
1	9.055007	7.739441E-02
1	9.235007	5.305091E-02
1	9.415008	3.244267E-02
1	9.595008	1.625805E-02
1	9.775008	5.246123E-03
1	9.955009	2.19759E-04
1	10	0
1	12	0
1	14	0
1	16	0
1	18	0
1	20	0

Soils

07-Sep-96

18. Soil_Counter: 351

ProjectID: SP1012
Soil Group:
Texture: Silt
Texture Modifier:
Structure Grade: Weak to moderate
Structure Size: Fine (or thin)
Structure Type: Granular
Soil Name: Processed Silt
Soil Description: Light brown, clean, uniform, coarse to medium silt wh
Notes: Used to test the predictions of adsorption and diffus
ion

Plasticity Index:	0
Plastic Limit:	0
Liquid Limit:	0
Percent Clay:	6.80%
Percent Silt:	93.00%
Percent Sand:	0.20%
Percent Coarse:	0.00%
Percent Organic:	0.00%
D10:	0
D20:	0
D30:	0
D50:	0
D60:	0
Cu:	0
Cc:	0
Experimentally Determined:	Yes
Saturation:	99.90%
Void Ratio:	0.543
Porosity:	35.20%
Water Content:	20.32%
Volumetric Water Content:	0.351648
Dry Density:	1730.16
Total Density:	2081.808
Total Unit Weight:	20.42254
Specific Gravity:	2.67
Locked S:	No

Locked VWC:	No
Locked VR:	Yes
Locked WC:	No
Locked DD:	No
Locked TD:	No
Locked SG:	Yes
Accel of Gravity:	9.81
Density of Water:	1000
CEC:	3.2
pH:	0
Electrolyte Level:	0
SAR:	0
ESP:	0
EC:	0
Free Fe and Al Oxide:	0
Family:	
Soil Series:	
Year Sampled:	1995
Land Use:	Cropland - General
Drainage:	Somewhat poorly drainedd
Slope:	
Number of Horizons:	0
Horizon Number:	0
Horizon Code:	
Horizon Depth Upper:	0
Horizon Depth Lower:	0
Depth to Groundwater:	0
Author:	P.C. Lim, S.L. Barbour, and D.G. Fredlund
Paper Name:	Diffusion and Adsorption Processes in Unsaturated Soi
Year Published:	1996
Publisher:	
Journal Name:	Canadian Geotechnical Journal
Volume:	
Page Numbers:	
Contact:	Murray Fredlund
Rating:	9
Country:	Canada
Province:	Saskatchewan
Region:	Beaver Creek
Site:	

1

Suction:	Vol. Water Content:
6.00E+00	0.349
3.50E+01	0.344
4.50E+01	0.334
5.00E+01	0.233
5.00E+01	0.173
6.00E+01	0.143
6.00E+01	0.132
7.50E+01	0.108
7.50E+01	0.109
9.00E+01	0.091
9.00E+01	0.099

SWCC

07-Sep-96

Param_ID:	424
SWCC Soil_Counter:	351
SWCC Description:	Unknown Test Method
SWCC Fit Type:	Fredlund & Xing (Type 1)
SWCC Curve Type:	0
SWCC Fit:	Yes

Fit Data Source:		0
Param_1 Name:	a	
Param_2 Name:	n	
Param_3 Name:	m	
Param_4 Name:	hr	
Param_1 Value:		46.234176573555
Param_2 Value:		56.2716863123184
Param_3 Value:		0.340386218509043
Param_4 Value:		135
SWCC Error:		1.51827097249962E-02
Residual VWC:		8.034268E-02
SWCC Equation:	Theta_w=Theta_sat*(1-ln(1+h/135.0000)/ln(1+10^6/135.0000))*(1/ln(exp(1)+(h/46.2342)^56.2717))^0.3404	

1

Suction:	Vol. Water
1.00E-02	3.52E-01
1.65E-02	3.52E-01
2.72E-02	3.52E-01
4.48E-02	3.52E-01
7.39E-02	3.52E-01
1.22E-01	3.52E-01
2.01E-01	3.52E-01
3.31E-01	3.52E-01
5.46E-01	3.51E-01
9.00E-01	3.51E-01
1.48E+00	3.51E-01
2.45E+00	3.51E-01
4.03E+00	3.50E-01
6.65E+00	3.50E-01
1.10E+01	3.49E-01
1.81E+01	3.47E-01
2.98E+01	3.44E-01
4.91E+01	2.21E-01
8.10E+01	1.03E-01
1.34E+02	8.07E-02
2.20E+02	6.83E-02
3.63E+02	5.95E-02
5.99E+02	5.25E-02
9.87E+02	4.65E-02
1.63E+03	4.12E-02
2.68E+03	3.65E-02
4.42E+03	3.22E-02
7.29E+03	2.83E-02
1.20E+04	2.46E-02
1.98E+04	2.12E-02
3.27E+04	1.80E-02
5.39E+04	1.50E-02
8.89E+04	1.22E-02
1.47E+05	9.44E-03
2.42E+05	6.85E-03
3.98E+05	4.35E-03
6.57E+05	1.95E-03
1.00E+06	0.00E+00

Diffusion

07-Sep-96

Diffu_ID:		10
Diffusion Soil_Counter:		351
Diffusion Description:	Potassium - back calculated from batch test results	
Diffusion Fit Type:	Fredlund & Xing (Type 1)	
Diffusion Curve Type:		0
Diffusion Parameter:		1
Cf:		0.01
Ds:		1.200E-09
Diffusion Test:		Yes
Update Diffusion:		No
Diffusion Error:		
Diffusion Equation:	De=((Theta_sat*(1-ln(1+h/135.0000)/ln(1+10^6/135.0000))*(1/ln(exp(1)+(h/45.9207)^3.6586))^1.3468-Theta_r)/	

1

Suction:	De:
6	1.200E-09
50	6.000E-10
60	6.000E-10
75	5.000E-10
90	6.000E-10

Suction:	De:
0.01	1.200E-09
0.01648721	1.200E-09
0.02718282	1.200E-09
0.04481689	1.200E-09
0.07389056	1.200E-09
0.1218249	1.200E-09
0.2008554	1.200E-09
0.3311545	1.200E-09
0.5459815	1.199E-09
0.9001713	1.199E-09
1.484132	1.198E-09
2.446919	1.197E-09
4.034288	1.195E-09
6.651416	1.192E-09
10.96633	1.184E-09
18.08042	1.159E-09
29.80958	1.046E-09
49.14769	6.756E-10
81.03084	2.247E-10
133.5973	1.457E-11
135	1.200E-11
222.5774	1.200E-11
366.968	1.200E-11
605.028	1.200E-11
997.5226	1.200E-11
1644.637	1.200E-11
2711.547	1.200E-11
4470.586	1.200E-11
7370.75	1.200E-11
12152.31	1.200E-11
20035.78	1.200E-11
33033.41	1.200E-11
54462.89	1.200E-11
89794.12	1.200E-11
148045.5	1.200E-11

244085.7	1.200E-11
402429.3	1.200E-11
663493.8	1.200E-11
1000000	1.200E-11

Adsorption

07-Sep-96

Adsorp_ID:		117
Adsorption Soil_Counter:		351
Adsorption Description:	Diffusion-type batch test ASTM D4646-87 and D4319-83	
Model Type:		1
Adsorption Test:		Yes
Kd:		1
K:		0
N:		0
Alpha:		0
Beta:		0
Adsorption Fit Type:	Fredlund & Xing (Type 1)	
Adsorption Curve Type:		0
c:		10
Adsorption Temperature:		23
Adsorption Error:		
Update linear:		No
Update Freundlich:		Yes
Update Langmuir:		Yes
Ads Graph Type:	2D Scatter	
Ads 2D Axis:	Suction	
Ads Conc Min:		0
Ads Conc Max:		1
Ads Suction Min:		0.01
Ads Suction Max:		200
Ads Suction Type:	Linear	
Surface filename:		

1

Concentration:	Suction:	Solute Sorbed:
1	7.9478	1
1	46.01083	1
1	58.50219	1
1	66.10594	1
1	70.56918	1
1	78.7613	0.98
1	79.10481	0.98
1	83.991	0.95
1	88.051	0.95

Concentration:	Suction:	Solute Sorbed:
1	1.67	1
1	3.01	1
1	5.690001	1
1	8.370001	1
1	11.05	1
1	13.73	1
1	16.41	1
1	19.09	0.9999999
1	21.77	0.9999998

1	24.45	0.9999994
1	27.13	0.9999982
1	29.81	0.9999948
1	32.49	0.9999866
1	35.17	0.9999682
1	37.85	0.9999288
1	40.53	0.9998491
1	43.21	0.9996957
1	45.89	0.9994181
1	48.57	0.9990351
1	51.25	0.9986124
1	53.93	0.9980913
1	56.61	0.9974065
1	59.29	0.9964874
1	61.97001	0.9952486
1	64.65	0.9935828
1	67.32999	0.9913571
1	70.00999	0.9884069
1	72.68998	0.9845316
1	75.36997	0.9794897
1	78.04996	0.972994
1	80.72996	0.9647079
1	83.40995	0.9542432
1	86.08994	0.9411583
1	88.76994	0.9249605
1	91.44993	0.9051106
1	94.12992	0.8810323
1	96.80991	0.8521275
1	99.48991	0.8177987
1	102.1699	0.7774807
1	104.8499	0.7306834
1	107.5299	0.6770489
1	110.2099	0.6164243
1	112.8899	0.5489553
1	115.5699	0.4752028
1	118.2499	0.3962882
1	120.9298	0.3140703
1	123.6098	0.2313615
1	126.2898	0.1521877
1	128.9698	8.209945E-02
1	131.6498	2.854211E-02
1	134.3298	1.293018E-03
1	135	0
1	148	0
1	161	0
1	174	0
1	187	0
1	200	0

Soils

07-Sep-96

19. Soil_Counter: 11501

ProjectID: PM6762
Soil Group: 0
Texture: Loamy Sand
Texture Modifier:
Structure Grade: Weak adherent
Structure Size: Fine to medium

Structure Type:	
Soil Name:	Dredged river sand
Soil Description:	Fine Silty sand Estimation at OK Tedi
Notes:	This contains the grainsize of the finest silty sand of all the grainsize curves on fig. 11.4 of the Waste
Plasticity Index:	0
Plastic Limit:	0
Liquid Limit:	0
Percent Clay:	0.00%
Percent Silt:	20.34%
Percent Sand:	79.66%
Percent Coarse:	0.00%
Percent Organic:	0.00%
D10:	3.716958E-02
D20:	0.0495682
D30:	6.020341E-02
D50:	7.420597E-02
D60:	8.00321772694588E-02
Cu:	2.153164
Cc:	1.2184
Experimentally Determined:	No
Saturation:	98.90%
Void Ratio:	0.833
Porosity:	45.46%
Water Content:	31.13%
Volumetric Water Content:	0.4495667
Dry Density:	1444.047
Total Density:	1893.613
Total Unit Weight:	18.57635
Specific Gravity:	2.647538
Locked S:	Yes
Locked VWC:	No
Locked VR:	Yes
Locked WC:	No
Locked DD:	No
Locked TD:	No
Locked SG:	Yes
Accel of Gravity:	9.81
Density of Water:	1000
CEC:	0
pH:	0
Electrolyte Level:	0
SAR:	0
ESP:	0
EC:	0
Free Fe and Al Oxide:	0
Family:	
Soil Series:	
Year Sampled:	0
Land Use:	Landfill
Drainage:	
Slope:	0.00%
Number of Horizons:	0
Horizon Number:	0
Horizon Code:	
Horizon Depth Upper:	0
Horizon Depth Lower:	0
Depth to Groundwater:	0
Author:	
Paper Name:	
Year Published:	0
Publisher:	
Journal Name:	
Volume:	
Page Numbers:	
Contact:	Murray Fredlund
Rating:	3

Country: Papua New Guinea
Province: Lower OK
Region: Tedi
Site:

1

SWCC

07-Sep-96

Param_ID:	6757
SWCC Soil_Counter:	11501
SWCC Description:	Predicted from grainsize
SWCC Fit Type:	Fredlund & Xing (Type 1)
SWCC Curve Type:	0
SWCC Fit:	Yes
Fit Data Source:	1
Param_1 Name:	a
Param_2 Name:	n
Param_3 Name:	m
Param_4 Name:	hr
Param_1 Value:	12.1978673917526
Param_2 Value:	4.19773517046375
Param_3 Value:	1.50679790007221
Param_4 Value:	3000
SWCC Error:	0
Residual VWC:	3.488997E-03
SWCC Equation:	Theta_w=Theta_sat*(1-ln(1+h/3000.0000)/ln(1+10^6/3000.0000))*(1/ln(exp(1)+(h/12.1979)^4.1977))^1.5068

1

Suction:	Vol. Water
1.00E-02	4.50E-01
1.65E-02	4.50E-01
2.72E-02	4.50E-01
4.48E-02	4.50E-01
7.39E-02	4.50E-01
1.22E-01	4.50E-01
2.01E-01	4.50E-01
3.31E-01	4.50E-01
5.46E-01	4.50E-01
9.00E-01	4.50E-01
1.48E+00	4.49E-01
2.45E+00	4.49E-01
4.03E+00	4.47E-01
6.65E+00	4.31E-01
1.10E+01	3.37E-01
1.81E+01	1.50E-01
2.98E+01	5.97E-02
4.91E+01	3.12E-02
8.10E+01	1.97E-02
1.34E+02	1.38E-02
2.20E+02	1.03E-02
3.63E+02	8.05E-03
5.99E+02	6.47E-03
9.87E+02	5.29E-03
1.63E+03	4.38E-03
2.68E+03	3.64E-03
4.42E+03	3.02E-03

7.29E+03	2.49E-03
1.20E+04	2.04E-03
1.98E+04	1.65E-03
3.27E+04	1.32E-03
5.39E+04	1.04E-03
8.89E+04	7.91E-04
1.47E+05	5.80E-04
2.42E+05	3.98E-04
3.98E+05	2.40E-04
6.57E+05	1.02E-04
1.00E+06	2.18E-22

Permeability

07-Sep-96

Kxy_ID:		4792
Permeability Soil_Counter:		11501
Permeability Description:	Estimation of permeability curve	
Permeability Fit Type:	Fredlund & Xing (Type 1)	
Permeability Curve Type:		0
Saturated kw1:		1.33565744704711E-05
Saturated kw2:		0.00001336
Alpha Angle:		0
Permeability Test:		No
Update Permeability:		No
Permeability Error:		0

1

Suction:	Conductivity:
1.0	1.335E-05
1.2	1.335E-05
1.8	1.334E-05
2.5	1.331E-05
3.5	1.319E-05
4.9	1.270E-05
7.0	1.101E-05
9.9	6.751E-06
13.9	1.866E-06
19.7	2.270E-07
27.8	2.437E-08
39.2	3.379E-09
55.4	6.041E-10
78.3	1.301E-10
110.6	3.204E-11
156.2	8.725E-12
220.7	2.572E-12
311.7	8.095E-13
440.3	2.694E-13
621.9	9.413E-14
878.5	3.429E-14
1240.9	1.293E-14
1752.9	5.016E-15
2476.0	1.985E-15
3497.5	7.958E-16
4940.3	3.215E-16
6978.3	1.303E-16
9857.1	5.290E-17

13923.6	2.147E-17
19667.5	8.715E-18
27781.1	3.538E-18
39241.8	1.436E-18
55430.4	5.831E-19
78297.5	2.362E-19
110598.0	9.506E-20
156223.6	3.767E-20
220671.4	1.442E-20
311706.3	5.136E-21
440296.2	1.557E-21
621934.2	3.088E-22
878504.3	4.835E-24

Soils

07-Sep-96

20. Soil_Counter: 10039

ProjectID: SP1004
Soil Group:
Texture: Sand
Texture Modifier:
Structure Grade:
Structure Size:
Structure Type:
Soil Name: Superstition Sand
Soil Description: Soil used to test prediction of hydraulic conductivit
Notes: Measured data comes from Richards 1952

Plasticity Index:	0
Plastic Limit:	0
Liquid Limit:	0
Percent Clay:	0.00%
Percent Silt:	0.00%
Percent Sand:	0.00%
Percent Coarse:	0.00%
Percent Organic:	0.00%
D10:	0
D20:	0
D30:	0
D50:	0
D60:	0
Cu:	0
Cc:	0
Experimentally Determined:	Yes
Saturation:	90.00%
Void Ratio:	1.000
Porosity:	50.00%
Water Content:	33.96%
Volumetric Water Content:	0.45
Dry Density:	1325
Total Density:	1775
Total Unit Weight:	17.41275
Specific Gravity:	2.65
Locked S:	No
Locked VWC:	No
Locked VR:	No
Locked WC:	No
Locked DD:	No
Locked TD:	No

Locked SG:	No
Accel of Gravity:	9.81
Density of Water:	1000
CEC:	0
pH:	0
Electrolyte Level:	0
SAR:	0
ESP:	0
EC:	0
Free Fe and Al Oxide:	0
Family:	
Soil Series:	
Year Sampled:	0
Land Use:	
Drainage:	
Slope:	0.00%
Number of Horizons:	0
Horizon Number:	0
Horizon Code:	
Horizon Depth Upper:	0
Horizon Depth Lower:	0
Depth to Groundwater:	0
Author:	Richards, L.A.
Paper Name:	Water conducting and retaining properties of soils in
Year Published:	1952
Publisher:	
Journal Name:	In Proceedings of an Internationa Symposium on Desert
Volume:	
Page Numbers:	523-546
Contact:	Murray Fredlund
Rating:	8
Country:	
Province:	
Region:	
Site:	

1

SWCC

07-Sep-96

Param_ID:	422
SWCC Soil_Counter:	10039
SWCC Description:	Unknown Test Method
SWCC Fit Type:	Fredlund & Xing (Type 1)
SWCC Curve Type:	0
SWCC Fit:	Yes
Fit Data Source:	0
Param_1 Name:	a
Param_2 Name:	n
Param_3 Name:	m
Param_4 Name:	hr
Param_1 Value:	2.76432848480327
Param_2 Value:	11.3663254776301
Param_3 Value:	0.443215781981737
Param_4 Value:	3000
SWCC Error:	2.87191207728074E-03
Residual VWC:	5.700589E-02
SWCC Equation:	Theta_w=Theta_sat*(1-ln(1+h/3000.0000)/ln(1+10^6/3000.0000))*(1/ln(exp(1)+(h/2.7643)^11.3663))^0.4432

1

Suction:	Vol. Water Content:
1.00E-01	0.450
3.00E-01	0.450
1.00E+00	0.445
2.00E+00	0.432
3.00E+00	0.360
4.00E+00	0.243
5.00E+00	0.189
6.00E+00	0.164
7.00E+00	0.153
8.00E+00	0.148
9.00E+00	0.140
1.00E+01	0.135
1.60E+01	0.126
2.00E+01	0.124

Suction:	Vol. Water
1.00E-02	4.50E-01
1.65E-02	4.50E-01
2.72E-02	4.50E-01
4.48E-02	4.50E-01
7.39E-02	4.50E-01
1.22E-01	4.50E-01
2.01E-01	4.50E-01
3.31E-01	4.50E-01
5.46E-01	4.50E-01
9.00E-01	4.50E-01
1.48E+00	4.50E-01
2.45E+00	4.33E-01
4.03E+00	2.35E-01
6.65E+00	1.62E-01
1.10E+01	1.33E-01
1.81E+01	1.16E-01
2.98E+01	1.04E-01
4.91E+01	9.56E-02
8.10E+01	8.89E-02
1.34E+02	8.34E-02
2.20E+02	7.87E-02
3.63E+02	7.44E-02
5.99E+02	7.04E-02
9.87E+02	6.65E-02
1.63E+03	6.24E-02
2.68E+03	5.80E-02
4.42E+03	5.33E-02
7.29E+03	4.84E-02
1.20E+04	4.32E-02
1.98E+04	3.79E-02
3.27E+04	3.26E-02
5.39E+04	2.74E-02
8.89E+04	2.23E-02
1.47E+05	1.74E-02
2.42E+05	1.27E-02
3.98E+05	8.07E-03
6.57E+05	3.62E-03
1.00E+06	8.05E-21

Permeability

07-Sep-96

Kxy_ID: 4202

Permeability Soil_Counter:	10039
Permeability Description:	Measured ksat
Permeability Fit Type:	Fredlund & Xing (Type 1)
Permeabillty Curve Type:	0
Saturated kw1:	0.0000183
Saturated kw2:	0.0000183
Alpha Angle:	0
Permeability Test:	Yes
Update Permeability:	No
Permeability Error:	2.22385438677148E-10

1

Suction:	Conductivity:
0.1	1.830E-05
0.3	1.830E-05
1	1.650E-05
2	1.560E-05
3	7.320E-06
4	1.060E-06
5	2.200E-07
6	6.770E-08
7	2.930E-08

Suction:	Conductivity:
1.0	1.830E-05
1.2	1.829E-05
1.8	1.822E-05
2.5	1.543E-05
3.5	2.403E-06
4.9	2.656E-07
7.0	5.171E-08
9.9	1.311E-08
13.9	3.852E-09
19.7	1.246E-09
27.8	4.320E-10
39.2	1.584E-10
55.4	6.101E-11
78.3	2.459E-11
110.6	1.036E-11
156.2	4.574E-12
220.7	2.115E-12
311.7	1.023E-12
440.3	5.163E-13
621.9	2.697E-13
878.5	1.444E-13
1240.9	7.845E-14
1752.9	4.273E-14
2476.0	2.313E-14
3497.5	1.235E-14
4940.3	6.482E-15
6978.3	3.339E-15
9857.1	1.689E-15
13923.6	8.412E-16
19667.5	4.133E-16
27781.1	2.009E-16
39241.8	9.672E-17
55430.4	4.615E-17
78297.5	2.179E-17
110598.0	1.013E-17

156223.6	4.592E-18
220671.4	1.990E-18
311706.3	7.926E-19
440296.2	2.654E-19
621934.2	5.745E-20
878504.3	9.704E-22

APPENDIX B

MATHCAD RESULTS

TABLE OF CONTENTS

1. Development of Storage Functions

Summary of Storage Functions for Different Curve Types

$a := 656.48$

$i := .01, .02 .. 13.8$

$n := .793$

$\psi(i) := \exp(i) - 1$

$m := .7509$

$\theta_s := 0.32$

$\psi_r := 3000$

Fredlund and Xing cf #2

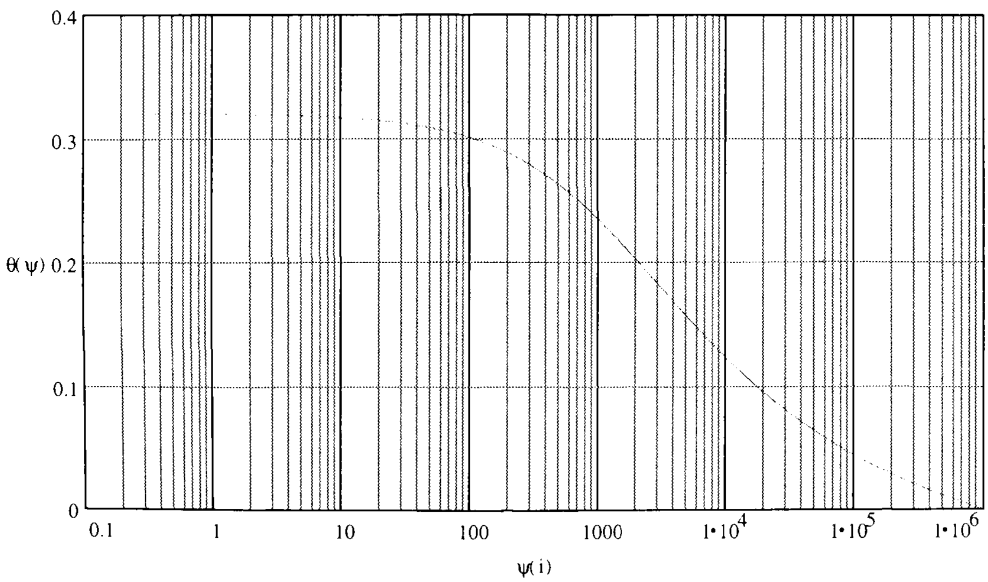
$$\theta_w(\psi) := \left[1 - \frac{\ln\left(1 + \frac{\psi}{\psi_r}\right)}{\ln\left(1 + \frac{1000000}{\psi_r}\right)}\right] \cdot \left[\frac{1}{\ln\left[\exp(1) + \left(\frac{\psi}{a}\right)^n\right]^m}\right] \cdot \theta_s$$

equation typed in - used for differentiatio

$$\theta(\psi) := \left[1 - \frac{\ln\left(1 + \frac{\psi(i)}{\psi_r}\right)}{\ln\left(1 + \frac{1000000}{\psi_r}\right)}\right] \cdot \left[\frac{1}{\ln\left[\exp(1) + \left(\frac{\psi(i)}{a}\right)^n\right]^m}\right] \cdot \theta_s$$

equation used for plotting

Plot of Fredlund & Xing equation

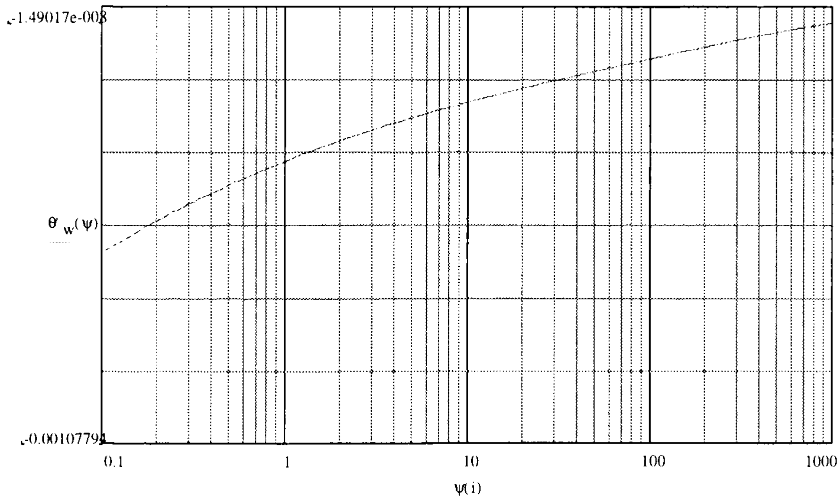


Now differentiate Fredlund and Xing equation

$$\theta'_w(\psi) = \frac{-1}{\left[\psi_r \cdot \left[\left(1+\frac{\psi(i)}{\psi_r}\right)\cdot\left[\ln\left(1+\frac{1000000}{\psi_r}\right)\cdot\left[\ln\left[\exp(1)+\left(\frac{\psi(i)}{a}\right)^n\right]^m\right]\right]\right]\right]}\cdot\theta_s - \frac{\left[1-\frac{\ln\left(1+\frac{\psi(i)}{\psi_r}\right)}{\ln\left(1+\frac{1000000}{\psi_r}\right)}\right]}{\left[\ln\left[\exp(1)+\left(\frac{\psi(i)}{a}\right)^n\right]\right]^m}\cdot\theta_s\cdot m\cdot\left(\frac{\psi(i)}{a}\right)^n\cdot\frac{n}{\left[\psi(i)\cdot\left[\left[\exp(1)+\left(\frac{\psi(i)}{a}\right)^n\right]\cdot\ln\left[\exp(1)+\left(\frac{\psi(i)}{a}\right)^n\right]\right]\right]}$$

$$\theta(x) = \frac{-1}{\left[\psi_r \cdot \left[\left(1+\frac{x}{\psi_r}\right)\cdot\left[\ln\left(1+\frac{1000000}{\psi_r}\right)\cdot\left[\ln\left[\exp(1)+\left(\frac{x}{a}\right)^n\right]^m\right]\right]\right]\right]}\cdot\theta_s - \frac{\left[1-\frac{\ln\left(1+\frac{x}{\psi_r}\right)}{\ln\left(1+\frac{1000000}{\psi_r}\right)}\right]}{\left[\ln\left[\exp(1)+\left(\frac{x}{a}\right)^n\right]\right]^m}\cdot\theta_s\cdot m\cdot\left(\frac{x}{a}\right)^n\cdot\frac{n}{\left[x\cdot\left[\left[\exp(1)+\left(\frac{x}{a}\right)^n\right]\cdot\ln\left[\exp(1)+\left(\frac{x}{a}\right)^n\right]\right]\right]}$$

Plot of differentiated equation



$\theta(.1) = -6.764\cdot10^{-4}$

$\theta(1000) = -4.41\cdot10^{-5}$

Gardner's Equation to Fit the Soil-Water Characteristic Curve

$a := .0064$

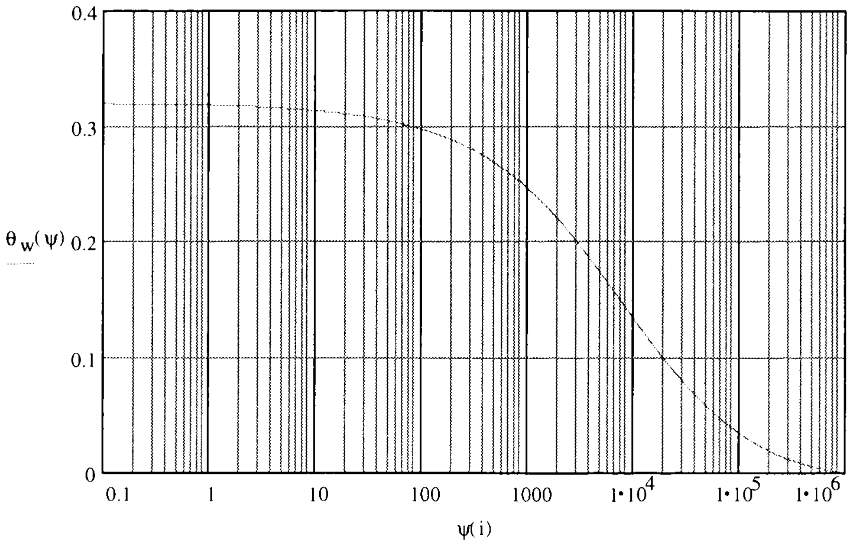
$n := 0.5227$

$\theta_s := 0.32$

$\psi_r := 3000$

$$\theta_w(\psi) := \left[1 - \frac{\ln\left(1 + \frac{\psi(i)}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)}\right] \cdot \left[\frac{\theta_s}{\left(1 + a\cdot\psi(i)^n\right)}\right]$$

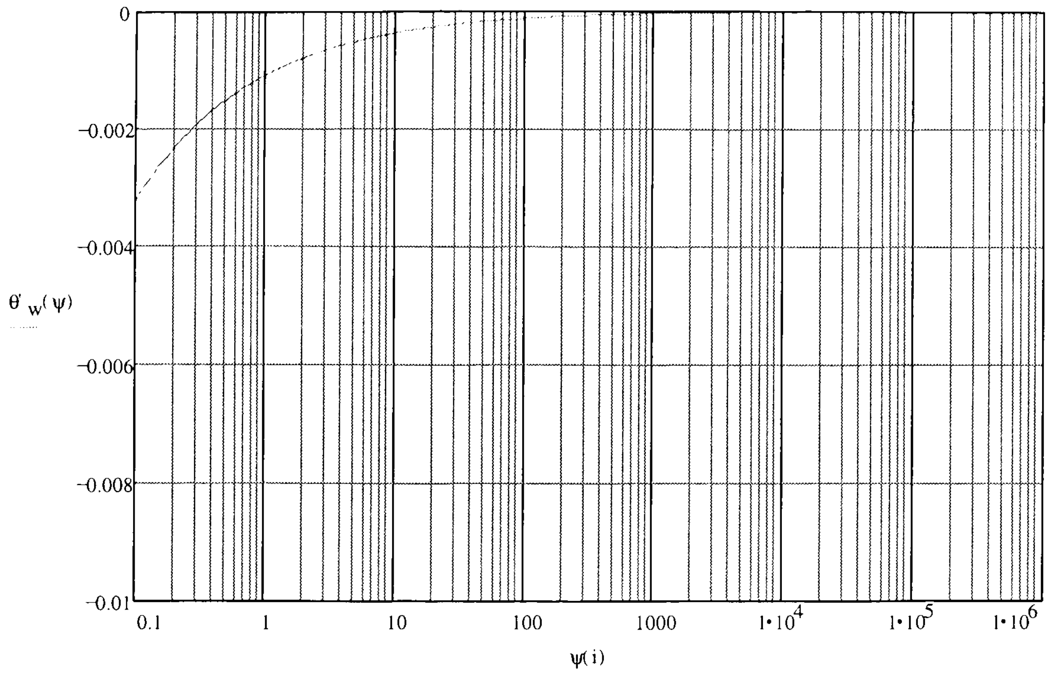
Plot of Gardner's equation



Differentiate Gardner's equation

$$\theta'_w(\psi) := \frac{-1}{\left[\psi_r\cdot\left[\left(1 + \frac{\psi(i)}{\psi_r}\right)\cdot\ln\left(1 + \frac{1000000}{\psi_r}\right)\right]\right]}\cdot\frac{\theta_s}{\left(1 + a\cdot\psi(i)^n\right)} - \left[1 - \frac{\ln\left(1 + \frac{\psi(i)}{\psi_r}\right)}{\ln\left(1 + \frac{1000000}{\psi_r}\right)}\right]\cdot\frac{\theta_s}{\left(1 + a\cdot\psi(i)^n\right)^2}\cdot a\cdot\psi(i)^n\cdot\frac{n}{\psi(i)}$$

Plot of differentiated Gardner's equation



Van Genuchten and Assumption No. 1

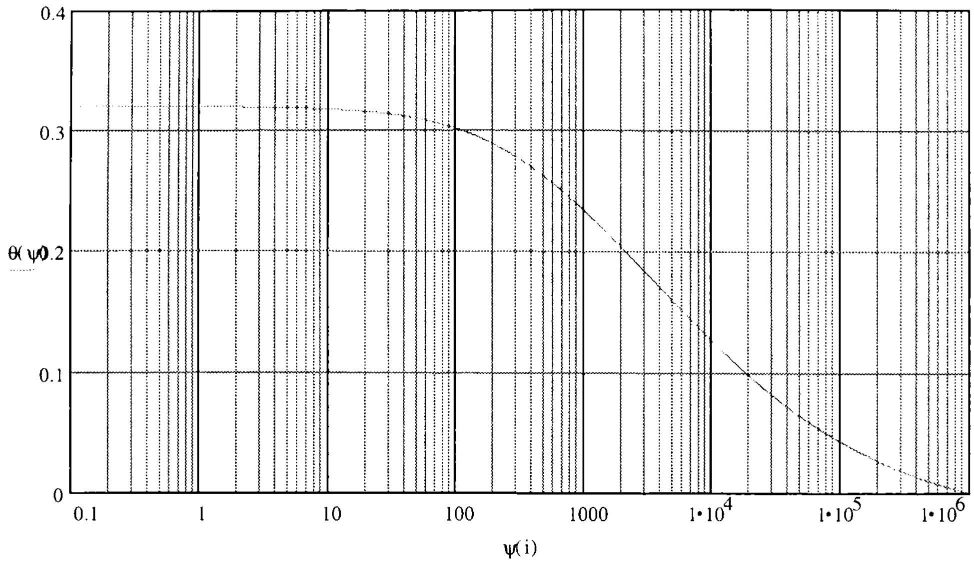
$a := 0.0028$

$n := .9188$

$m := .2067$

$$\theta(\psi) := \left[1 - \frac{\ln\left(1 + \frac{\psi(i)}{\psi_r}\right)}{\ln\left(1 + \frac{1000000}{\psi_r}\right)}\right] \cdot \left[\frac{1}{\left[1 + (a \cdot \psi(i))^n\right]^m}\right] \cdot \theta_s$$

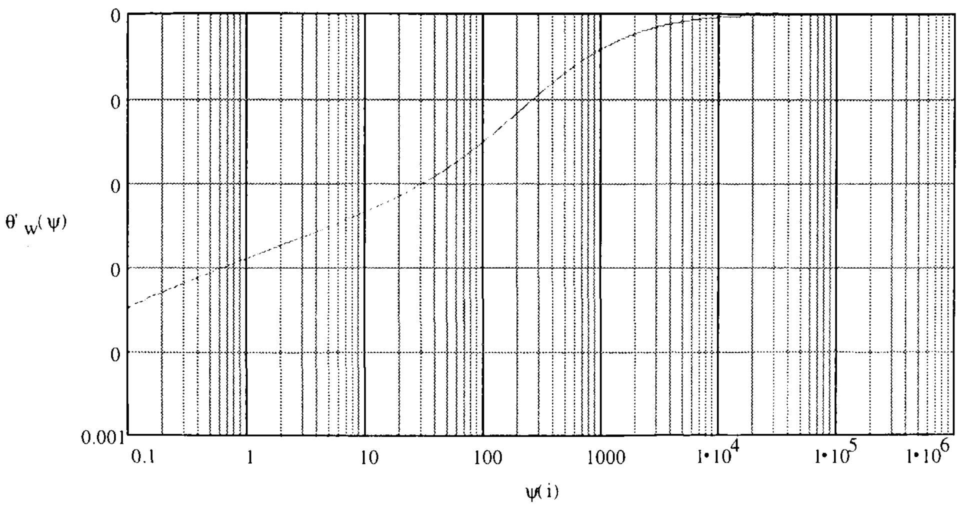
Plot of Van Genuchten's equation



Now differentiate Van Genuchten's equation

$$\theta'_w(\psi) := \frac{-1}{\left[\psi_r \cdot \left[\left(1+\frac{\psi(i)}{\psi_r}\right)\cdot\left[\ln\left(1+\frac{1000000}{\psi_r}\right)\cdot\left[\left[1+(a\cdot\psi(i))^n\right]^m\right]\right]\right]\right]}\cdot\theta_s - \frac{\left[1-\frac{\ln\left(1+\frac{\psi(i)}{\psi_r}\right)}{\ln\left(1+\frac{1000000}{\psi_r}\right)}\right]}{\left[\left[1+(a\cdot\psi(i))^n\right]^m\right]}\cdot\theta_s\cdot m\cdot(a\cdot\psi(i))^n\cdot\frac{n}{\left[\psi(i)\cdot\left[1+(a\cdot\psi(i))^n\right]\right]}$$

Plot of differentiated Van Genuchten's equation



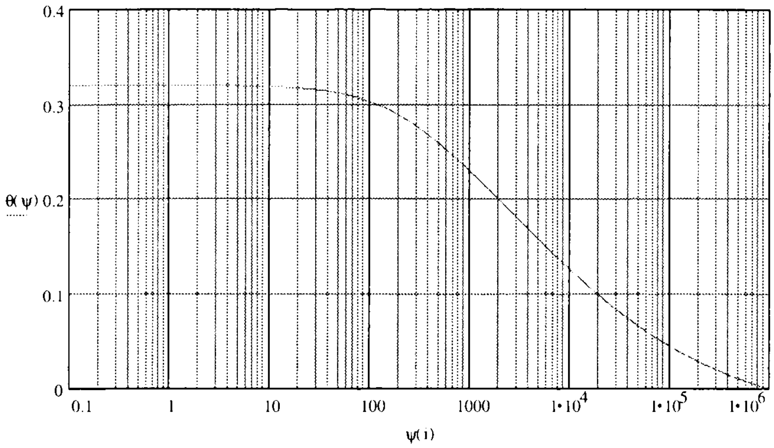
Van Genuchten's Equation with Mualem's Assumption

a = .0048

n = 1.1662

$$\theta(\psi) := \left[1 - \frac{\ln\left(1 + \frac{\psi(i)}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)}\right] \cdot \left[\frac{\theta_s}{\left[1 + (a \cdot \psi(i))^n\right]^{\left(1 - \frac{1}{n}\right)}}\right]$$

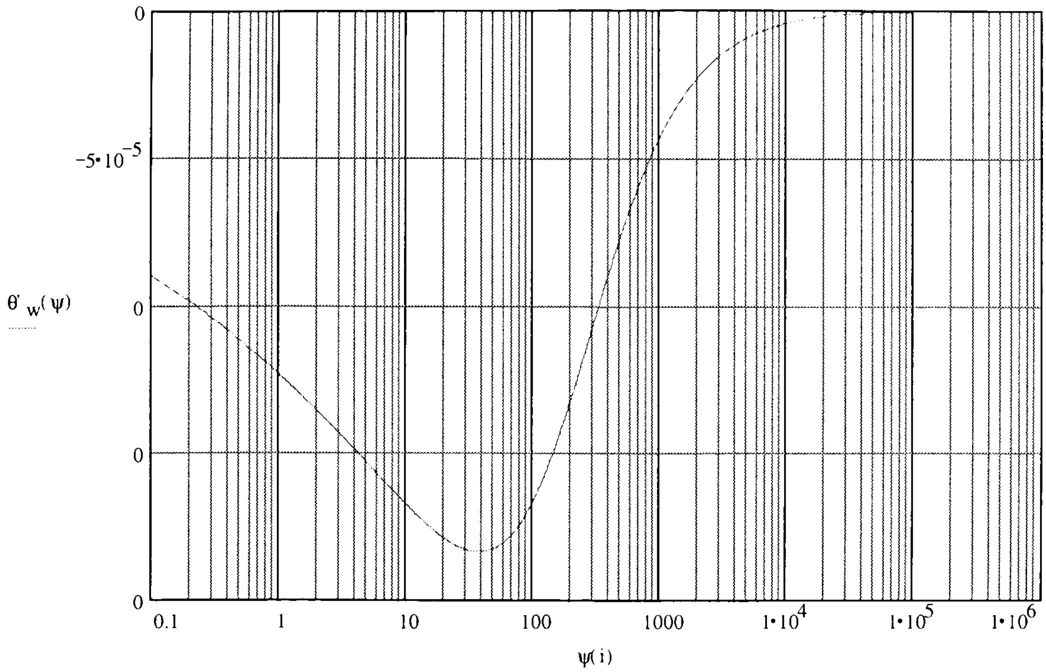
Plot of Mualem's equation



Differentiate Mualem's equation

$$\theta'_w(\psi) := \frac{-1}{\left[\psi_r \cdot \left[\left(1 + \frac{\psi(i)}{\psi_r}\right) \cdot \ln\left(1 + \frac{1000000}{\psi_r}\right)\right]\right]} \cdot \frac{\theta_s}{\left[\left[1 + (a \cdot \psi(i))^n\right]^{\left(1 - \frac{1}{n}\right)}\right]} - \left[1 - \frac{\ln\left(1 + \frac{\psi(i)}{\psi_r}\right)}{\ln\left(1 + \frac{1000000}{\psi_r}\right)}\right] \cdot \frac{\theta_s}{\left[\left[1 + (a \cdot \psi(i))^n\right]^{\left(1 - \frac{1}{n}\right)}\right]} \cdot \left(1 - \frac{1}{n}\right) \cdot (a \cdot \psi(i))^n \cdot \frac{n}{\left[\psi(i) \cdot \left[1 + (a \cdot \psi(i))^n\right]\right]}$$

Plot the differentiated Mualem's equation



Van Genuchten's Equation with Berdine's Assumption

$a := 0.0089$

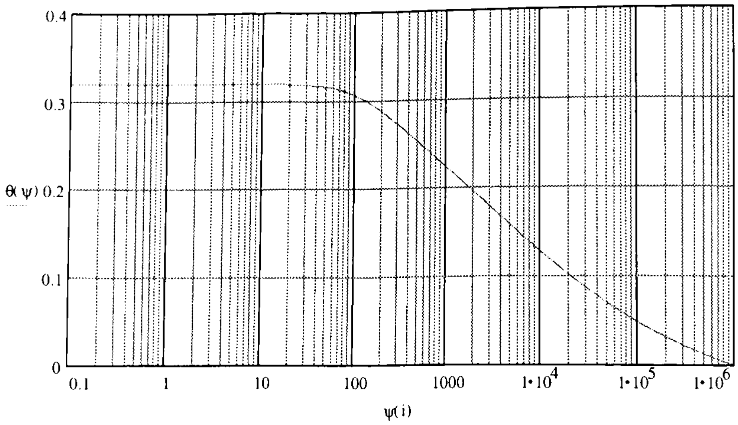
$n := 2.139$

$\theta_s := 0.32$

$\psi_r := 3000$

$$\theta(\psi) := \left[1 - \frac{\ln\left(1 + \frac{\psi(i)}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)}\right] \cdot \left[\frac{\theta_s}{\left[1 + (a\cdot\psi(i))^n\right]^{\left(1 - \frac{2}{n}\right)}}\right]$$

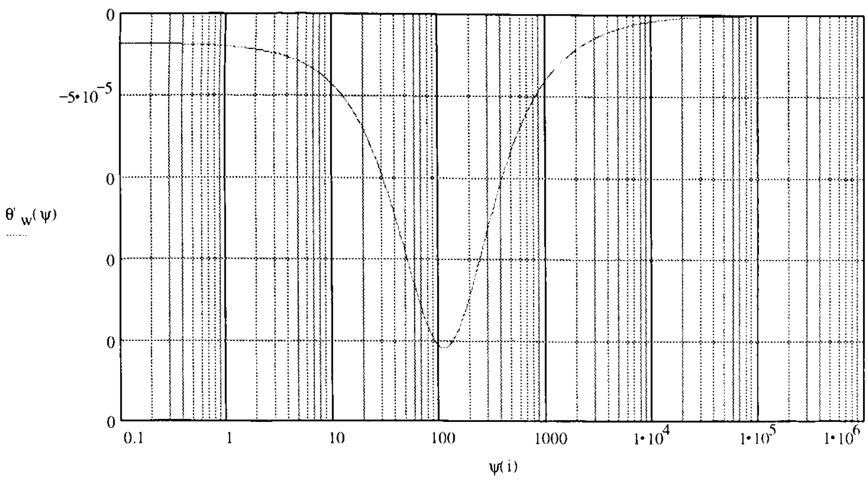
Plot of Berdine's equation



Differentiate Berdine's equation

$$\theta'_w(\psi) := \frac{-1}{\left[\psi_r\cdot\left[\left(1+\frac{\psi(i)}{\psi_r}\right)\cdot\ln\left(1+\frac{1000000}{\psi_r}\right)\right]\right]}\cdot\frac{\theta_s}{\left[\left[1+(a\cdot\psi(i))^n\right]^{\left(1-\frac{2}{n}\right)}\right]} - \left[1-\frac{\ln\left(1+\frac{\psi(i)}{\psi_r}\right)}{\ln\left(1+\frac{1000000}{\psi_r}\right)}\right]\cdot\frac{\theta_s}{\left[\left[1+(a\cdot\psi(i))^n\right]^{\left(1-\frac{2}{n}\right)}\right]}\cdot\left(1-\frac{2}{n}\right)\cdot(a\cdot\psi(i))^n\cdot\frac{n}{\left[\psi(i)\cdot\left[1+(a\cdot\psi(i))^n\right]\right]}$$

Plot differentiated Berdine's equation



2. Development of Hydraulic Conductivity Prediction

Development of Prediction of Hydraulic Conductivity from SWCC

$a := 8.34$

$n := 9.90$

$m := .44$

Give values to variables

$\theta_s := 0.43$

$hr := 30$

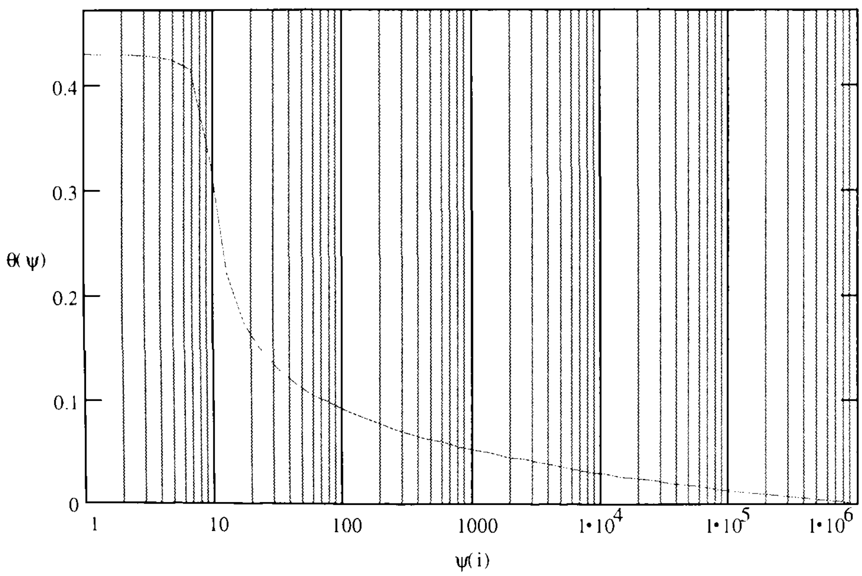
$i := .01, .3 .. 13.8$

$\psi(i) := \exp(i) - 1$

Define SWCC

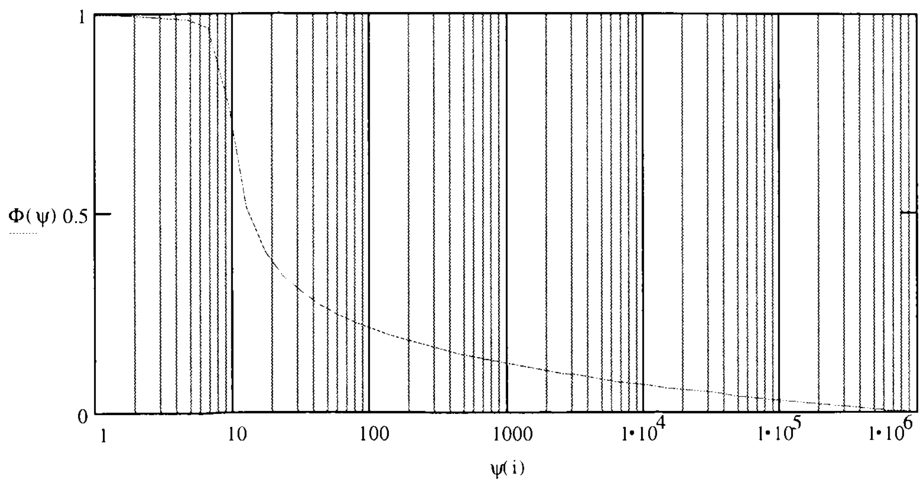
$$\theta(\psi) := \theta_s \cdot \left[1 - \frac{\ln\left(1 + \frac{\psi(i)}{hr}\right)}{\ln\left(1 + \frac{10^6}{hr}\right)} \right] \cdot \left[\frac{1}{\ln\left[\exp(1) + \left(\frac{\psi(i)}{a}\right)^n\right]} \right]^m$$

Show plot of SWCC using current variables



$$\Phi(\psi) = \left[1 - \frac{\ln\left(1 + \frac{\psi(i)}{hr}\right)}{\ln\left(1 + \frac{10^6}{hr}\right)}\right] \cdot \left[\frac{1}{\ln\left[e + \left(\frac{\psi(i)}{a}\right)^n\right]}\right]^m$$

Normalize SWCC



$\psi_r := hr$ $\qquad \psi_r = 30$

$\psi_{aev} := a$ $\qquad \psi_{aev} = 8.34$

The following equations were typed into MathCad. MathCad then performed the integrations.

Equation developed from Fredlund & Xing's paper - kro represents a wrong method

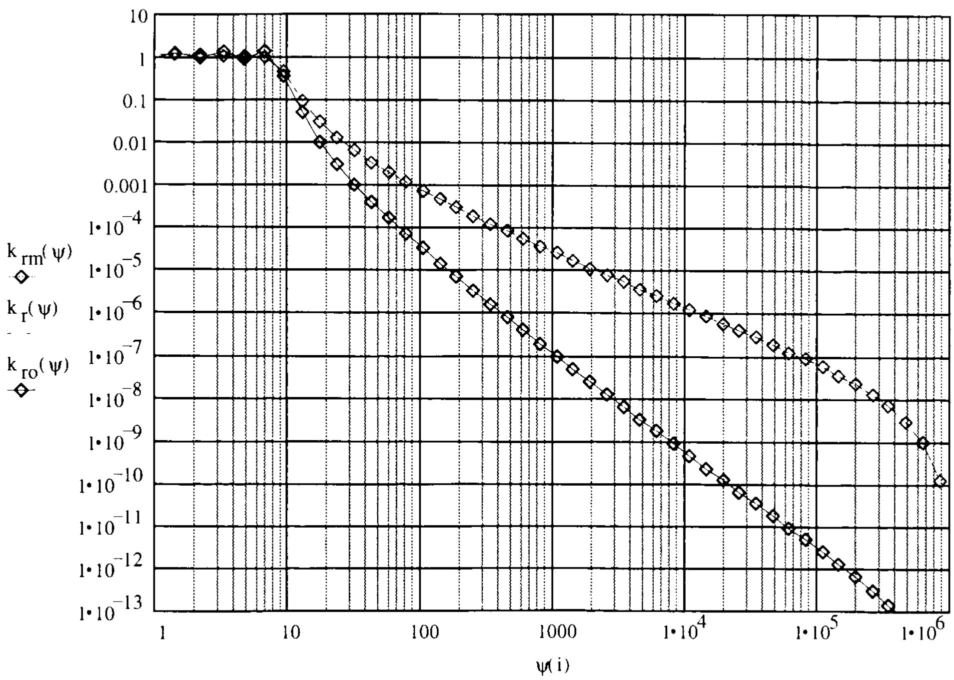
$$k_{ro}(\psi) = \frac{\displaystyle\int_{\ln(\psi(i))}^{\ln(1000000)} \frac{\theta_s\left[1-\frac{\ln\left(1+\frac{e^y}{\psi_r}\right)}{\ln\left(1+\frac{10^6}{\psi_r}\right)}\right]\left[\frac{1}{\ln\left[e+\left(\frac{e^y}{a}\right)^n\right]}\right]^m-\theta_s\left[1-\frac{\ln\left(1+\frac{\psi(i)}{\psi_r}\right)}{\ln\left(1+\frac{10^6}{\psi_r}\right)}\right]\left[\frac{1}{\ln\left[e+\left(\frac{\psi(i)}{a}\right)^n\right]}\right]^m}{e^y}\left[\frac{-\theta_s}{\psi_r\left[\left(1+\frac{\exp(y)}{\psi_r}\right)\cdot\ln\left(1+\frac{1000000}{\psi_r}\right)\right]}\left[\frac{1}{\ln\left[e+\left(\frac{\exp(y)}{a}\right)^n\right]}\right]^m-\theta_s\left[1-\frac{\ln\left(1+\frac{\exp(y)}{\psi_r}\right)}{\ln\left(1+\frac{1000000}{\psi_r}\right)}\right]\left[\frac{1}{\ln\left[e+\left(\frac{\exp(y)}{a}\right)^n\right]}\right]^m\cdot\frac{m}{\ln\left[e+\left(\frac{\exp(y)}{a}\right)^n\right]}\cdot\left(\frac{\exp(y)}{a}\right)^n\cdot\frac{n}{\exp(y)\left[e+\left(\frac{\exp(y)}{a}\right)^n\right]}\right]dy}{\displaystyle\int_{\ln(\psi_{aev})}^{\ln(1000000)} \frac{\theta_s\left[1-\frac{\ln\left(1+\frac{e^y}{\psi_r}\right)}{\ln\left(1+\frac{10^6}{\psi_r}\right)}\right]\left[\frac{1}{\ln\left[e+\left(\frac{e^y}{a}\right)^n\right]}\right]^m-\theta_s}{e^y}\left[\frac{-\theta_s}{\psi_r\left[\left(1+\frac{\exp(y)}{\psi_r}\right)\cdot\ln\left(1+\frac{1000000}{\psi_r}\right)\right]}\left[\frac{1}{\ln\left[e+\left(\frac{\exp(y)}{a}\right)^n\right]}\right]^m-\theta_s\left[1-\frac{\ln\left(1+\frac{\exp(y)}{\psi_r}\right)}{\ln\left(1+\frac{1000000}{\psi_r}\right)}\right]\left[\frac{1}{\ln\left[e+\left(\frac{\exp(y)}{a}\right)^n\right]}\right]^m\cdot\frac{m}{\ln\left[e+\left(\frac{\exp(y)}{a}\right)^n\right]}\cdot\left(\frac{\exp(y)}{a}\right)^n\cdot\frac{n}{\exp(y)\left[e+\left(\frac{\exp(y)}{a}\right)^n\right]}\right]dy}$$

Equations kr and krm are good implementations of the Fredlund & Xing Method

$$k_{rm}(\psi) = \frac{\displaystyle\int_{\ln(\psi(i))}^{\ln(1000000)} \frac{\theta_s\left[1-\frac{\ln\left(1+\frac{e^x}{hr}\right)}{\ln\left(1+\frac{10^6}{hr}\right)}\right]\left[\frac{1}{\ln\left[e+\left(\frac{e^x}{a}\right)^n\right]}\right]^m-\theta_s\left[1-\frac{\ln\left(1+\frac{\psi(i)}{hr}\right)}{\ln\left(1+\frac{10^6}{hr}\right)}\right]\left[\frac{1}{\ln\left[e+\left(\frac{\psi(i)}{a}\right)^n\right]}\right]^m}{e^x}\left[-\theta_s\frac{\exp(x)}{hr\left[\left(1+\frac{\exp(x)}{hr}\right)\cdot\ln\left(1+\frac{1000000}{hr}\right)\right]}\left[\frac{1}{\ln\left[e+\left(\frac{\exp(x)}{a}\right)^n\right]}\right]^m-\theta_s\left[1-\frac{\ln\left(1+\frac{\exp(x)}{hr}\right)}{\ln\left(1+\frac{1000000}{hr}\right)}\right]\left[\frac{1}{\ln\left[e+\left(\frac{\exp(x)}{a}\right)^n\right]}\right]^m\cdot\frac{m}{\ln\left[e+\left(\frac{\exp(x)}{a}\right)^n\right]}\cdot\left(\frac{\exp(x)}{a}\right)^n\cdot\frac{n}{\left[e+\left(\frac{\exp(x)}{a}\right)^n\right]}\right]dx}{\displaystyle\int_{\ln(\psi_{aev})}^{\ln(1000000)} \frac{\theta_s\left[1-\frac{\ln\left(1+\frac{e^x}{hr}\right)}{\ln\left(1+\frac{10^6}{hr}\right)}\right]\left[\frac{1}{\ln\left[e+\left(\frac{e^x}{a}\right)^n\right]}\right]^m-\theta_s}{e^x}\left[-\theta_s\frac{\exp(x)}{hr\left[\left(1+\frac{\exp(x)}{hr}\right)\cdot\ln\left(1+\frac{1000000}{hr}\right)\right]}\left[\frac{1}{\ln\left[e+\left(\frac{\exp(x)}{a}\right)^n\right]}\right]^m-\theta_s\left[1-\frac{\ln\left(1+\frac{\exp(x)}{hr}\right)}{\ln\left(1+\frac{1000000}{hr}\right)}\right]\left[\frac{1}{\ln\left[e+\left(\frac{\exp(x)}{a}\right)^n\right]}\right]^m\cdot\frac{m}{\ln\left[e+\left(\frac{\exp(x)}{a}\right)^n\right]}\cdot\left(\frac{\exp(x)}{a}\right)^n\cdot\frac{n}{\left[e+\left(\frac{\exp(x)}{a}\right)^n\right]}\right]dx}$$

$$k_r(\psi) = \frac{\displaystyle\int_{\ln(\psi(i))}^{\ln(1000000)} \frac{\theta_s\left[1-\frac{\ln\left(1+\frac{\exp(p)}{hr}\right)}{\ln\left(1+\frac{10^6}{hr}\right)}\right]\left[\frac{1}{\ln\left[\exp(1)+\left(\frac{\exp(p)}{a}\right)^n\right]}\right]^m-\theta_s\left[1-\frac{\ln\left(1+\frac{\psi(i)}{hr}\right)}{\ln\left(1+\frac{10^6}{hr}\right)}\right]\left[\frac{1}{\ln\left[\exp(1)+\left(\frac{\psi(i)}{a}\right)^n\right]}\right]^m}{\exp(p)}\left[\theta_s\frac{\exp(p)}{hr\left[\left(1+\frac{\exp(p)}{hr}\right)\cdot\ln\left(1+\frac{1000000}{hr}\right)\right]}\left[\frac{1}{\ln\left[\exp(1)+\left(\frac{\exp(p)}{a}\right)^n\right]}\right]^m-\theta_s\left[1-\frac{\ln\left(1+\frac{\exp(p)}{hr}\right)}{\ln\left(1+\frac{1000000}{hr}\right)}\right]\left[\frac{1}{\ln\left[\exp(1)+\left(\frac{\exp(p)}{a}\right)^n\right]}\right]^m\cdot\frac{m}{\ln\left[\exp(1)+\left(\frac{\exp(p)}{a}\right)^n\right]}\cdot\left(\frac{\exp(p)}{a}\right)^n\cdot\frac{n}{\left[\exp(1)+\left(\frac{\exp(p)}{a}\right)^n\right]}\right]dp}{\displaystyle\int_{\ln(\psi)}^{\ln(1000000)} \frac{\theta_s\left[1-\frac{\ln\left(1+\frac{\exp(p)}{hr}\right)}{\ln\left(1+\frac{10^6}{hr}\right)}\right]\left[\frac{1}{\ln\left[\exp(1)+\left(\frac{\exp(p)}{a}\right)^n\right]}\right]^m-\theta_s}{\exp(p)}\left[\theta_s\frac{\exp(p)}{hr\left[\left(1+\frac{\exp(p)}{hr}\right)\cdot\ln\left(1+\frac{1000000}{hr}\right)\right]}\left[\frac{1}{\ln\left[\exp(1)+\left(\frac{\exp(p)}{a}\right)^n\right]}\right]^m-\theta_s\left[1-\frac{\ln\left(1+\frac{\exp(p)}{hr}\right)}{\ln\left(1+\frac{1000000}{hr}\right)}\right]\left[\frac{1}{\ln\left[\exp(1)+\left(\frac{\exp(p)}{a}\right)^n\right]}\right]^m\cdot\frac{m}{\ln\left[\exp(1)+\left(\frac{\exp(p)}{a}\right)^n\right]}\cdot\left(\frac{\exp(p)}{a}\right)^n\cdot\frac{n}{\exp(1)+\left(\frac{\exp(p)}{a}\right)^n}\right]dp}$$

Plot of equations - kro is wrong and krm and kr are right



This shows the differenc
between adding the
exponent and
differentiating or
differentiating and then
adding the exponent.

3. Development of Consolidation Equation

Development of proper equation for Consolidation Curve

$j := .1, .2 .. 13.8$

$a := 656.48$

$n := .793$

Give value to starting parameters

$m := .7509$

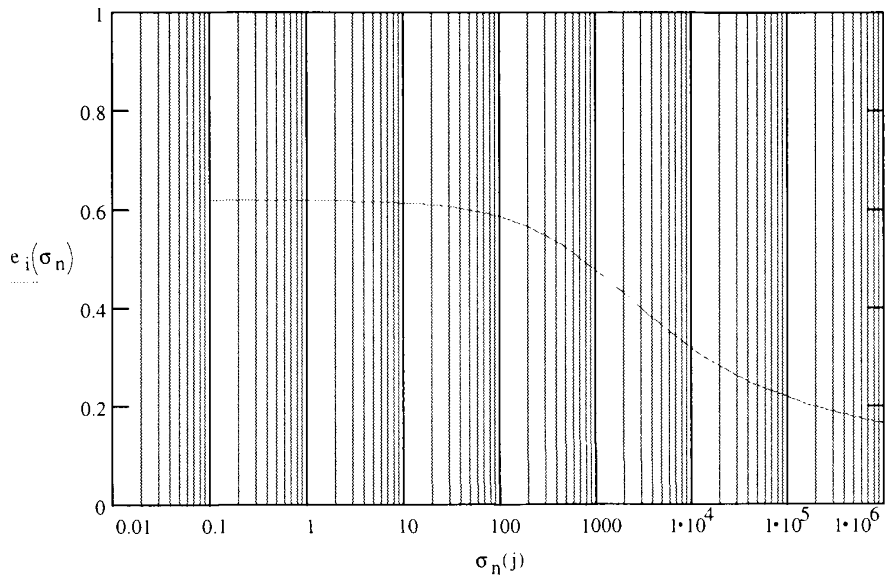
$\sigma_n(j) := \exp(j) - 1$

$e_o := 0.62$

This is the consolidation equation modified from Fredlund & Xing equation

$$e_i(\sigma_n) := e_o \cdot \left[\frac{1}{\ln\left[e + \left(\frac{\sigma_n(j)}{a} \right)^n \right]} \right]^m$$

This is a plot of the equation



Differentiate the equation with respect to a, n, and m parameters

$$\sigma_{nn} = 1$$

$$Void\_Ratio = e_o \cdot \left[\frac{1}{\ln\left[e + \left(\frac{\sigma_{nn}}{a} \right)^n \right]} \right]^m$$

$$Void\_Ratio = e_o \cdot \left[\frac{1}{\ln\left[e + \left(\frac{\sigma_{nn}}{a} \right)^n \right]} \right]^m \cdot \ln\left[\frac{1}{\ln\left[e + \left(\frac{\sigma_{nn}}{a} \right)^n \right]} \right]$$ dm

$$Void\_Ratio = -e_o \cdot \left[\frac{1}{\ln\left[e + \left(\frac{\sigma_{nn}}{a} \right)^n \right]} \right]^m \cdot \frac{m}{\ln\left[e + \left(\frac{\sigma_{nn}}{a} \right)^n \right]} \cdot \left(\frac{\sigma_{nn}}{a} \right)^n \cdot \frac{\ln\left(\frac{\sigma_{nn}}{a} \right)}{\left[e + \left(\frac{\sigma_{nn}}{a} \right)^n \right]}$$ dn

$$Void\_Ratio = e_o \cdot \left[\frac{1}{\ln\left[e + \left(\frac{\sigma_{nn}}{a} \right)^n \right]} \right]^m \cdot \frac{m}{\ln\left[e + \left(\frac{\sigma_{nn}}{a} \right)^n \right]} \cdot \left(\frac{\sigma_{nn}}{a} \right)^n \cdot \frac{n}{\left[a \cdot \left[e + \left(\frac{\sigma_{nn}}{a} \right)^n \right] \right]}$$ da

4. Development of Shear Strength Equation

SHEAR STRENGTH PREDICTION

$a := 482.67$

$i := .01, .1 .. 6.5$

Wet of optimum at 25 kPa loading

$n := 0.881$

$\psi(i) := \exp(i) - 1$

$m := 0.717$

define parameters

$\theta_s := 0.353$

$\psi_{th} := 3000$

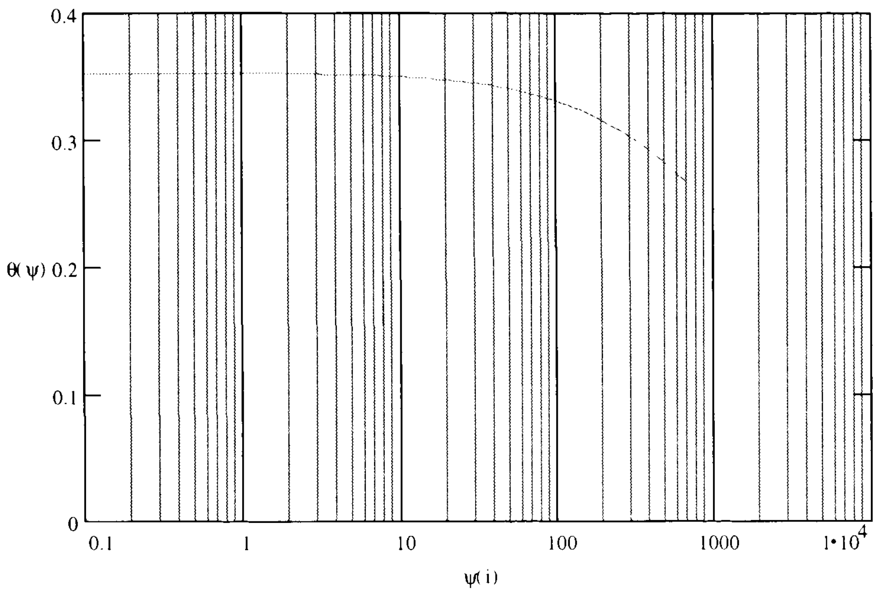
$\psi_r := 3000$

$$\theta(\psi) := \theta_s \cdot \left[1 - \frac{\ln\left(1 + \frac{\psi(i)}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)}\right] \cdot \left[\frac{1}{\ln\left[e + \left(\frac{\psi(i)}{a}\right)^n\right]}\right]^m$$

Input Fredlund & Xing equation

$$\theta_w(h) := \theta_s \cdot \left[1 - \frac{\ln\left(1 + \frac{h}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)}\right] \cdot \left[\frac{1}{\ln\left[e + \left(\frac{h}{a}\right)^n\right]}\right]^m$$

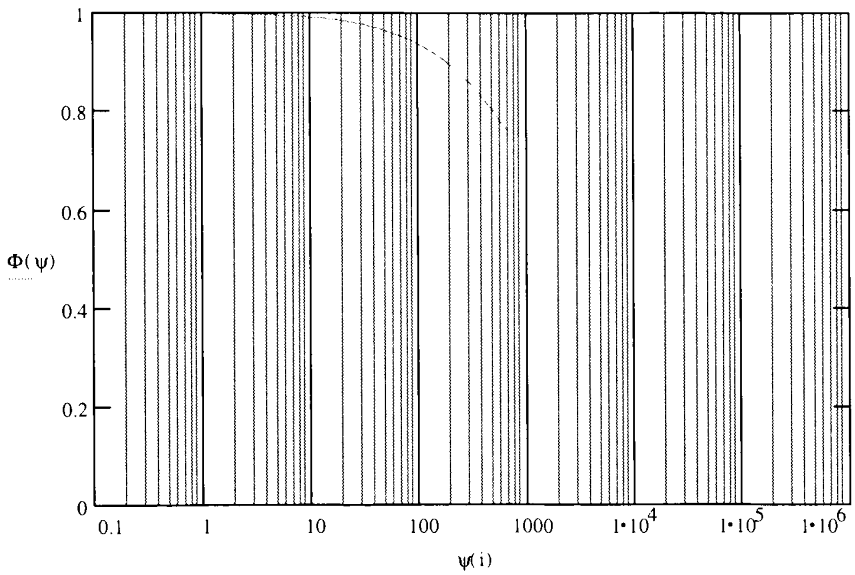
Plot Fredlund & Xing equatior



$$\Phi(\psi) = \left[1 - \frac{\ln\left(1 + \frac{\psi(i)}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)}\right] \cdot \left[\frac{1}{\ln\left[e + \left(\frac{\psi(i)}{a}\right)^n\right]}\right]^m$$

Normalize Fredlund & Xing equatioı

Plot normalized equation



$\phi' := 23 \cdot \frac{3.14159}{180}$ $\qquad p := 2.4$

define saturated shear strength parameters

$c' := 0$

$\sigma := 25$

$\tau_e(\psi) := \Phi(\psi)^p \cdot \psi(i) \cdot \tan(\phi') + c' + \sigma \cdot \tan(\phi')$ (this is the proposed equation)

$\tau_{exp}(\psi) := \left(5 \cdot 10^{-7} \cdot \psi(i)^3 - 0.0007 \cdot \psi(i)^2\right) + 0.3686 \cdot \psi(i) + 86.026$ (rough approx. of exper. data)

$\theta_r := \theta_w(\Psi_r) \qquad \theta_{th} := \theta_w(\Psi_{th})$

$\kappa := 1 \qquad \theta_r = 0.186 \qquad \theta_{th} = 0.186$

$$\Omega(\psi) := \frac{\theta(\psi) - \theta_{th}}{\theta_s - \theta_{th}}$$

$\tau_z(\psi) := c' + \sigma \cdot \tan(\phi') + \tan(\phi') \cdot \psi(i) \cdot \Omega(\psi)^\kappa$ Alternate equation

$$\tau_{s2}(\Psi_j) := c' + \sigma \cdot \tan(\phi') + \tan(\phi') \cdot \int_0^{\psi(i)} \left[\frac{\theta_s \cdot \left[1 - \frac{\ln\left(1 + \frac{x}{\Psi_r}\right)}{\ln\left(1 + \frac{10^6}{\Psi_r}\right)}\right] \cdot \left[\frac{1}{\ln\left[e + \left(\frac{x}{a}\right)^n\right]}\right]^m - \theta_r}{\theta_s - \theta_r} \right]^\kappa dx$$

Alternate equatior

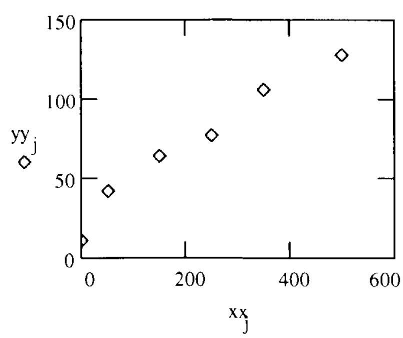
$NN := 6 \qquad j := 0..NN - 1$

$xx_j := \mathrm{READ}(shrw25x)$

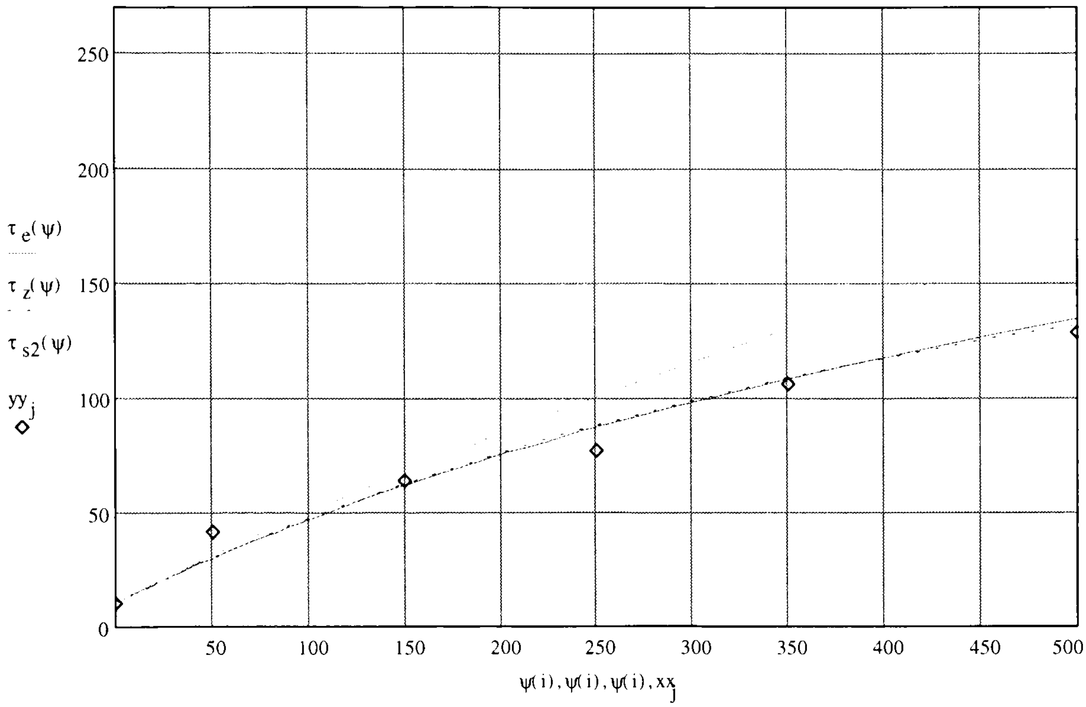
$yy_j := \mathrm{READ}(shrw25y)$

Read in experimental data for comparison

xx_j	yy_j
0	10.61
50	41.81
150	63.7
250	77.02
350	106
500	127.8



Final plot comparing experimental data to various predictions



5. Development of Frozen Volumetric Water Content

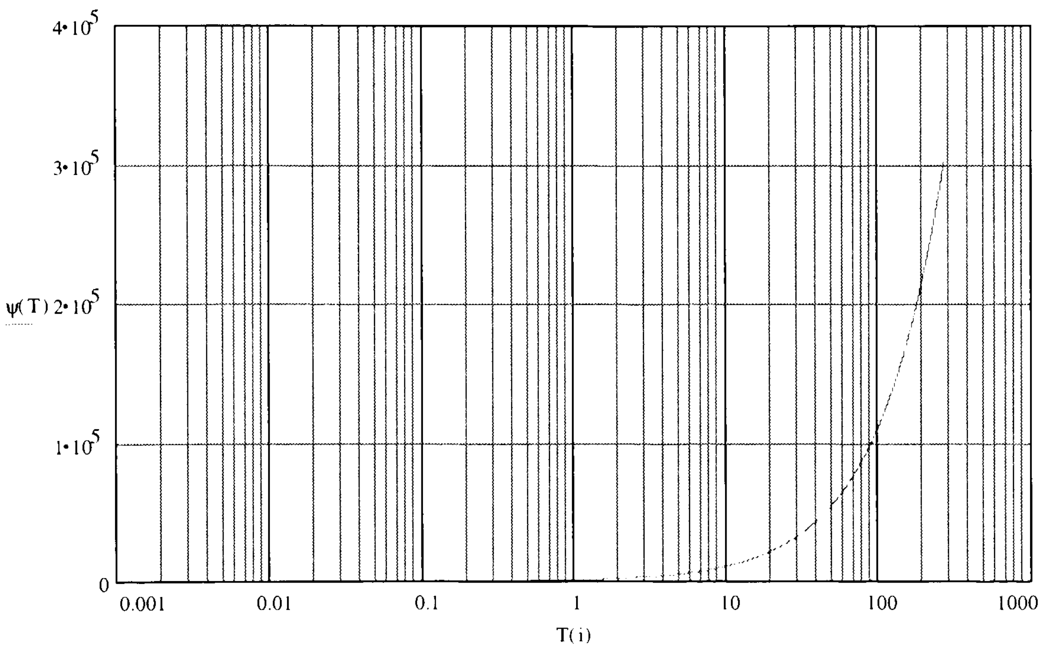
Development of Equations for Frozen Hydraulic Conductivity

$i := .001, .002 .. 5.6131$ where T = soil temperature

$T(i) := \exp(i) - 1$

$p := 1.0$ define parameters

$\psi(T) := p \cdot 1110 \cdot T(i)$



$a := 40.83$

$n := 3.34$

$m := 1.09$ define parameters

$\theta_s := 0.5$

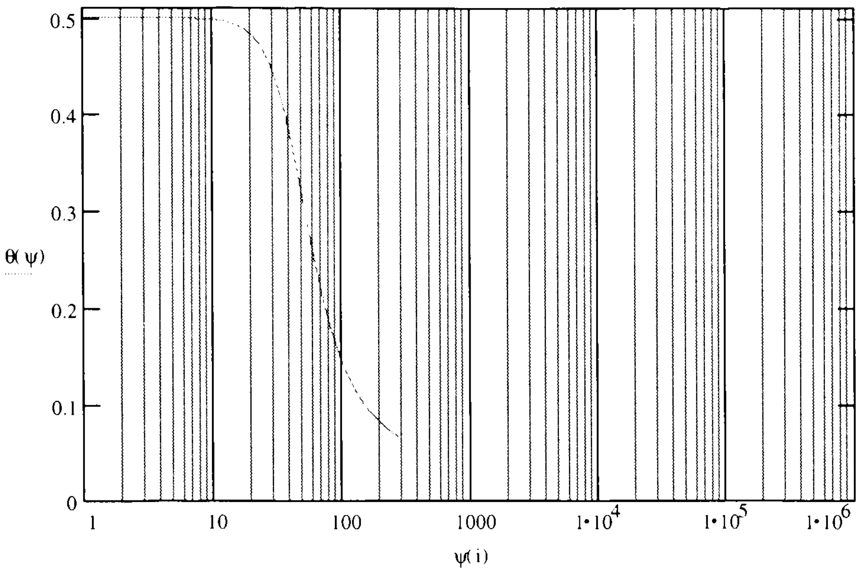
$hr := 100000$

$\psi(i) := \exp(i) - 1$

$$\theta(\psi) := \theta_s \cdot \left[1 - \frac{\ln\left(1 + \frac{\psi(i)}{hr}\right)}{\ln\left(1 + \frac{10^6}{hr}\right)} \right] \cdot \left[\frac{1}{\ln\left[e + \left(\frac{\psi(i)}{a}\right)^n \right]} \right]^m$$

Input Fredlund & Xing equation

Plot Fredlund & Xing equation

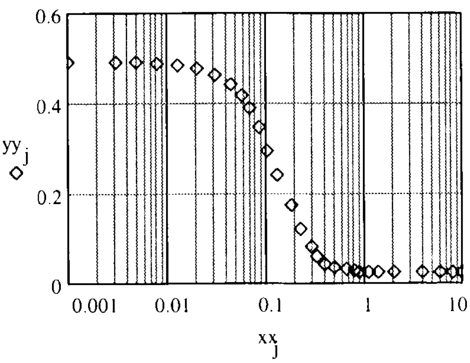


$NN := 29 \quad j := 0..NN-1$

Read in experimental data from Newman

$xx_j := READ(thermx)$

$yy_j := READ(thermy)$



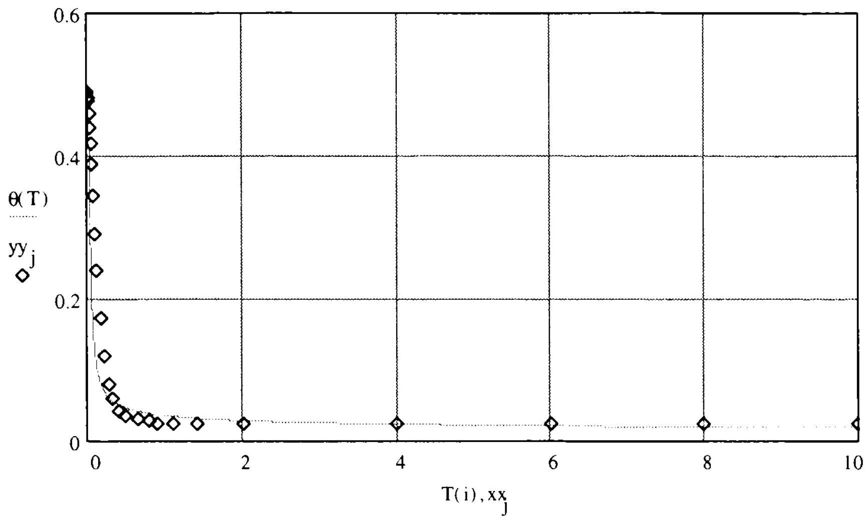
Plot of experimental data

$p := 1$ p=2.2 for coarse soils and p=1.0 for pure clay

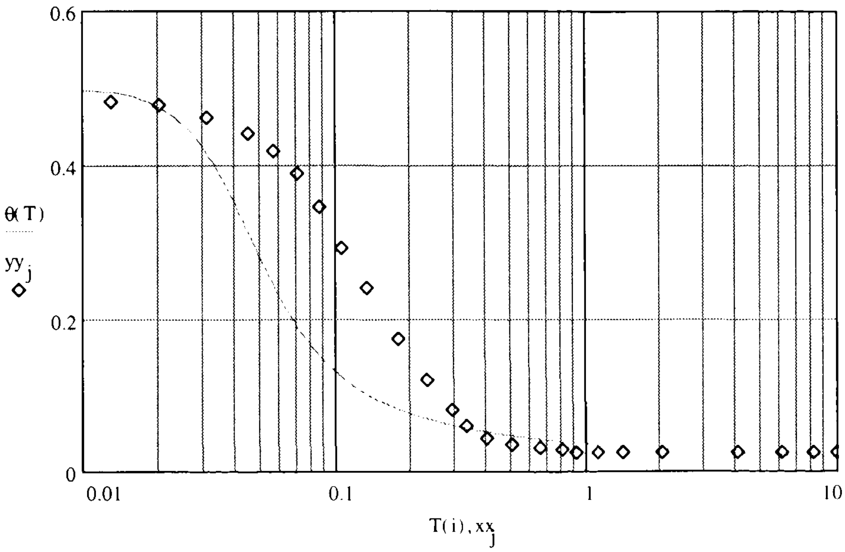
Equation used to predict unfrozen water content

$$\theta(T) := \theta_s \cdot \left[1 - \frac{\ln\left(1 + \frac{p \cdot 1110 \cdot T(i)}{hr}\right)}{\ln\left(1 + \frac{p \cdot 1110 \cdot 273}{hr}\right)} \right] \cdot \left[\frac{1}{\ln\left[e + \left(\frac{p \cdot 1110 \cdot T(i)}{a}\right)^n\right]} \right]^m$$

Plot comparing predicted to measured results



Same plot as above on a log scale



6. Development of Diffusion Equation

Development of Function for Effective Diffusion

$a := 18.48$

$i := .01, .1 .. 13.8$

$n := 1.66$

$\psi(i) := \exp(i)$

$m := 0.48$

define parameters

$\theta_s := 0.37$

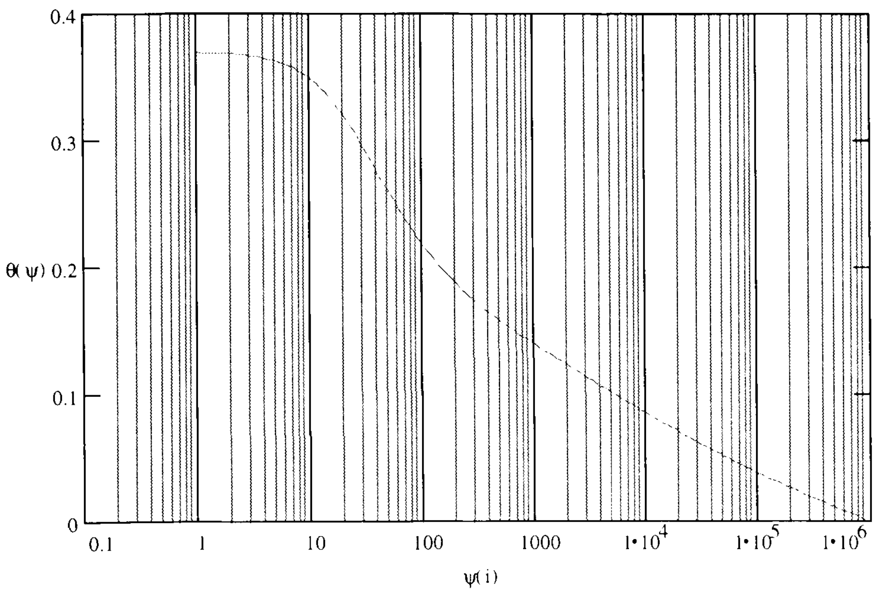
$\psi_r := 2000$

$$\theta(\psi) := \theta_s \cdot \left[1 - \frac{\ln\left(1 + \frac{\psi(i)}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)}\right] \cdot \left[\frac{1}{\ln\left[e + \left(\frac{\psi(i)}{a}\right)^n\right]}\right]^m$$

Introduce Fredlund & Xing SWCC equation

$$\theta_w(h) := \theta_s \cdot \left[1 - \frac{\ln\left(1 + \frac{h}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)}\right] \cdot \left[\frac{1}{\ln\left[e + \left(\frac{h}{a}\right)^n\right]}\right]^m$$

Plot Fredlund & Xing SWCC equatior



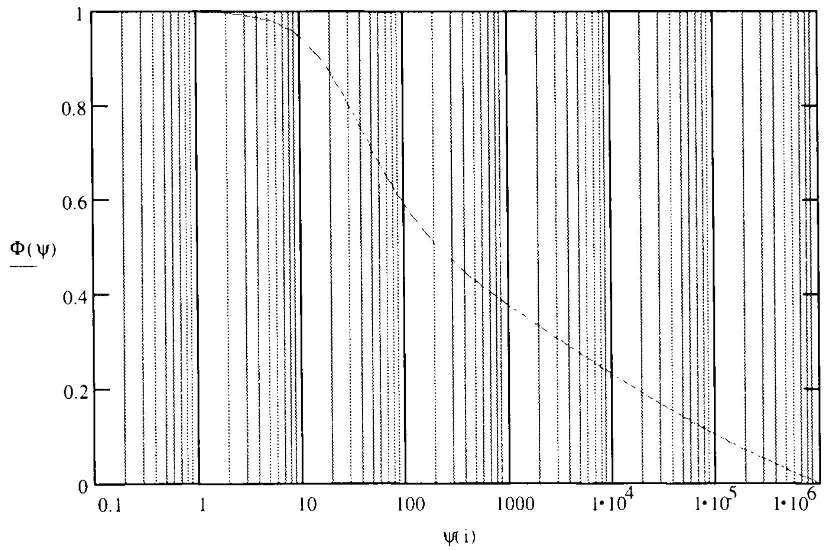
Normalize Fredlund & Xing SWCC equation

$$\Phi(\psi) = \left[1 - \frac{\ln\left(1 + \frac{\psi(i)}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)}\right] \cdot \left[\frac{1}{\ln\left[e + \left(\frac{\psi(i)}{a}\right)^n\right]}\right]^m$$

Take the derivative of the Fredlund & Xing equation

$$\Phi'(\psi) = \frac{-1}{\left[\psi_r \cdot \left[\left(1 + \frac{\psi}{\psi_r}\right) \cdot \ln\left(1 + \frac{1000000}{\psi_r}\right)\right]\right]} \cdot \left[\frac{1}{\ln\left[e + \left(\frac{\psi}{a}\right)^n\right]}\right]^m - \left[1 - \frac{\ln\left(1 + \frac{\psi}{\psi_r}\right)}{\ln\left(1 + \frac{1000000}{\psi_r}\right)}\right] \cdot \left[\frac{1}{\ln\left[e + \left(\frac{\psi}{a}\right)^n\right]}\right]^m \cdot \frac{m}{\ln\left[e + \left(\frac{\psi}{a}\right)^n\right]} \cdot \left(\frac{\psi}{a}\right)^n \cdot \frac{n}{\left[\psi \cdot \left[e + \left(\frac{\psi}{a}\right)^n\right]\right]}$$

Plot the normalized equation



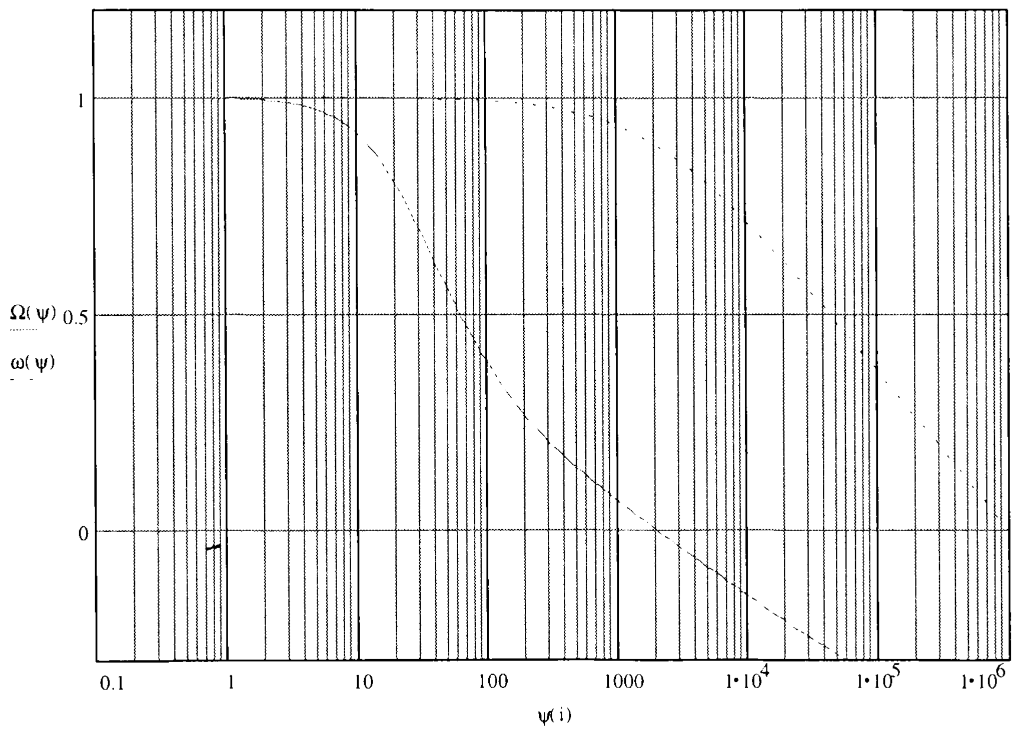
$\theta_r = \theta_w(\psi_r)$

Definition of active part of SWCC

This definition is used

$$\Omega(\psi) = \frac{\theta(\psi) - \theta_r}{\theta_s - \theta_r}$$

$$\omega(\psi) = 1 - \frac{\ln\left(\frac{\psi(i)}{\psi_r} + 1\right)}{\ln\left(\frac{1000000}{\psi_r} + 1\right)}$$



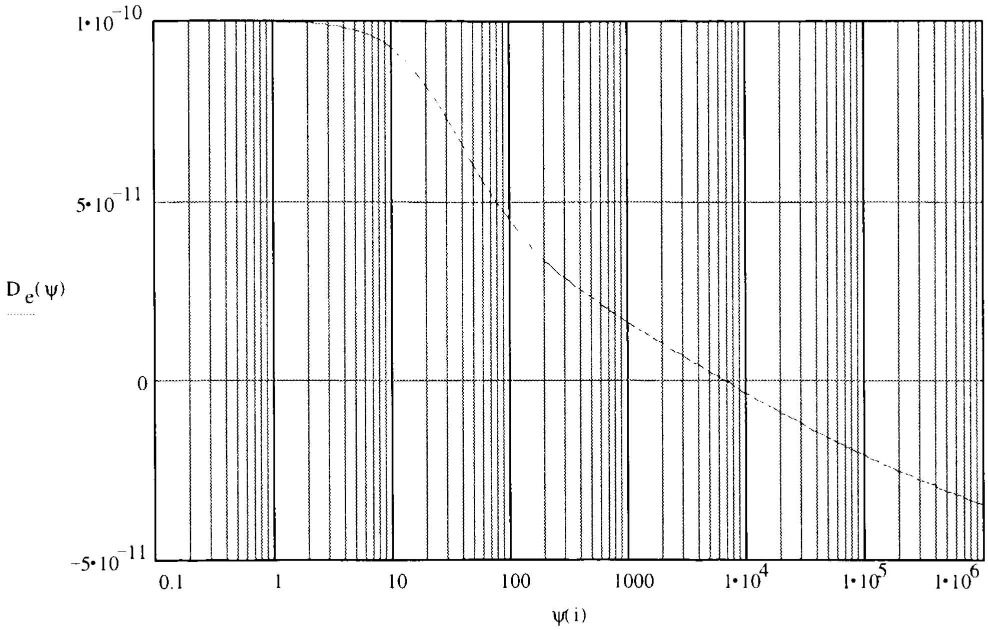
$D_s = 1 \cdot 10^{-10}$ m^2/s

$p = 1$

$C_f = .1$ film diff. 0 for sands and 0.1 or 0.2 for silts and clays

$D_e(\psi) = \left[\Omega(\psi)^p + (1 - \Omega(\psi)) \cdot C_f\right] \cdot D_s$ This is the final equation

Plot of final prediction



7. Development of Adsorption Prediction

Development of Function for Adsorption

$a := 5.61$

$i := .01, .3 .. 13.8$

$n := 2.24$

$\psi(i) := \exp(i) - 1$

Based on soil #2 in the database for testinç

$m := .4$

define parameters

$\theta_s := 0.249$

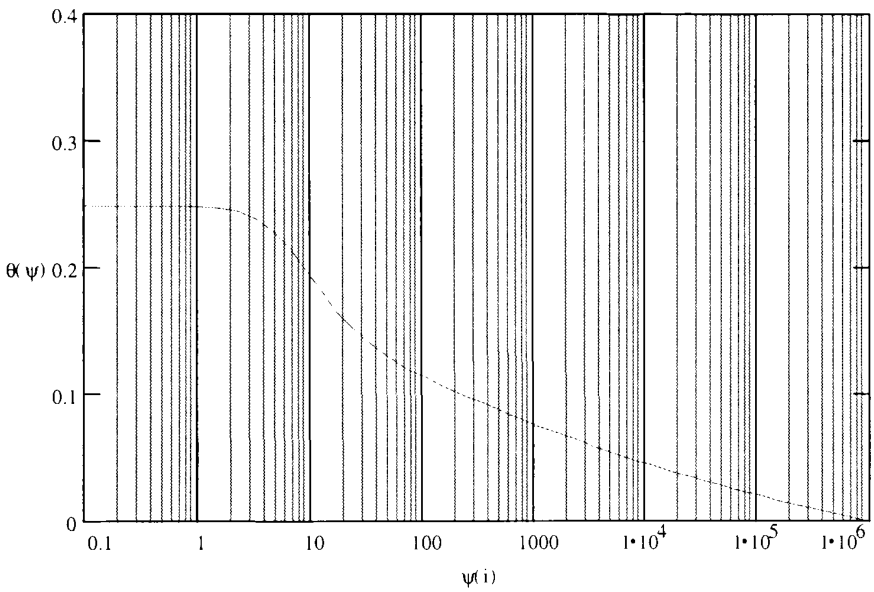
$\psi_r := 300$

$$\theta(\psi) := \theta_s \cdot \left[1 - \frac{\ln\left(1 + \frac{\psi(i)}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)}\right] \cdot \left[\frac{1}{\ln\left[e + \left(\frac{\psi(i)}{a}\right)^n\right]}\right]^m$$

Introduce Fredlund & Xing equation

$$\theta_w(h) := \theta_s \cdot \left[1 - \frac{\ln\left(1 + \frac{h}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)}\right] \cdot \left[\frac{1}{\ln\left[e + \left(\frac{h}{a}\right)^n\right]}\right]^m$$

Plot Fredlund & Xing SWCC equatior



Normalize curve

$$\Phi(\psi) := \left[1 - \frac{\ln\left(1 + \frac{\psi(i)}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)}\right] \cdot \left[\frac{1}{\ln\left[e + \left(\frac{\psi(i)}{a}\right)^n\right]}\right]^m$$

$$\theta_r := \theta_w(\psi_r)$$

$$\theta_r = 0.095$$

$T := 20$ Degrees Celcius set temperature

$T_s(T) := -0.1683 \cdot T + 76.11$ $T_s(T) = 72.744$ input surface tension of water equation

$$d_i(\psi) := \frac{T_s(T)}{\psi}$$ Relate surface tension and suction to pore diameter

$c := 1$

$$A_t := \int_0^{\psi_r} \frac{\dfrac{\left[1 - \frac{\ln\left(1 + \frac{x}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)}\right] \cdot \left[\frac{1}{\ln\left[e + \left(\frac{x}{a}\right)^n\right]}\right]^m \cdot \theta_s - \theta_r}{\theta_s - \theta_r}}{\left(\frac{-0.1683 \cdot T + 76.11}{x}\right)^c} \, dx$$

Top part of Lim's formulation

$$A_t = 35.278$$

$$A_{in}(\psi) := \int_0^{\psi(i)} \frac{\dfrac{\left[1 - \frac{\ln\left(1 + \frac{x}{\psi_r}\right)}{\ln\left(1 + \frac{10^6}{\psi_r}\right)}\right] \cdot \left[\frac{1}{\ln\left[e + \left(\frac{x}{a}\right)^n\right]}\right]^m \cdot \theta_s - \theta_r}{\theta_s - \theta_r}}{\left(\frac{-0.1683 \cdot T + 76.11}{x}\right)^c} \, dx$$

Bottom part of Lim's formulatio

Correction to top part of Lim's formulation

$$B_t = \int_0^{\psi_r} \frac{\dfrac{-1}{\psi_r \cdot \left[\left(1 + \dfrac{x}{\psi_r}\right) \cdot \ln\left(1 + \dfrac{1000000}{\psi_r}\right)\right]} \cdot \left[\dfrac{1}{\ln\left[e + \left(\dfrac{x}{a}\right)^n\right]}\right]^m - \left[1 - \dfrac{\ln\left(1 + \dfrac{x}{\psi_r}\right)}{\ln\left(1 + \dfrac{1000000}{\psi_r}\right)}\right] \cdot \left[\dfrac{1}{\ln\left[e + \left(\dfrac{x}{a}\right)^n\right]}\right]^m \cdot \dfrac{m}{\ln\left[e + \left(\dfrac{x}{a}\right)^n\right]} \cdot \left(\dfrac{x}{a}\right)^n \cdot \dfrac{n}{x \cdot \left[e + \left(\dfrac{x}{a}\right)^n\right]}}{\left(\dfrac{-0.1683 \cdot T + 76.11}{x}\right)^c} \, dx$$

$B_t = 0.326$

Correction to bottom part of Lim's formulation

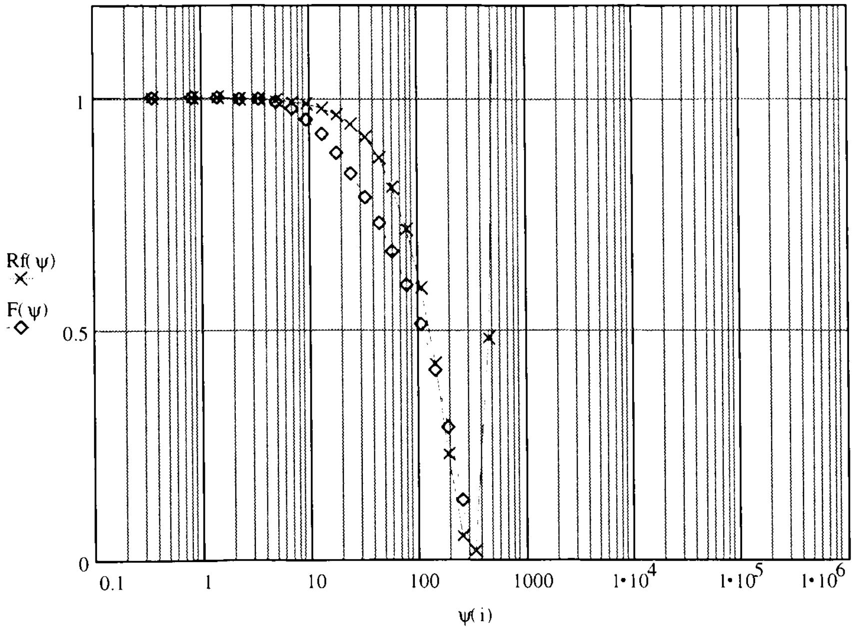
$$B_{in}(\psi) = \int_0^{\psi(i)} \frac{\dfrac{-1}{\psi_r \cdot \left[\left(1 + \dfrac{x}{\psi_r}\right) \cdot \ln\left(1 + \dfrac{1000000}{\psi_r}\right)\right]} \cdot \left[\dfrac{1}{\ln\left[e + \left(\dfrac{x}{a}\right)^n\right]}\right]^m - \left[1 - \dfrac{\ln\left(1 + \dfrac{x}{\psi_r}\right)}{\ln\left(1 + \dfrac{1000000}{\psi_r}\right)}\right] \cdot \left[\dfrac{1}{\ln\left[e + \left(\dfrac{x}{a}\right)^n\right]}\right]^m \cdot \dfrac{m}{\ln\left[e + \left(\dfrac{x}{a}\right)^n\right]} \cdot \left(\dfrac{x}{a}\right)^n \cdot \dfrac{n}{x \cdot \left[e + \left(\dfrac{x}{a}\right)^n\right]}}{\left(\dfrac{-0.1683 \cdot T + 76.11}{x}\right)^c} \, dx$$

$$F(\psi) = 1 - \frac{B_{in}(\psi)}{B_t}$$

Final equation that produces a scaling factor that simulates the soil drying

$$Rf(\psi) = 1 - \frac{A_{in}(\psi)}{A_t}$$ Original formulation

Comparison of final formulation (F is the formulation used)



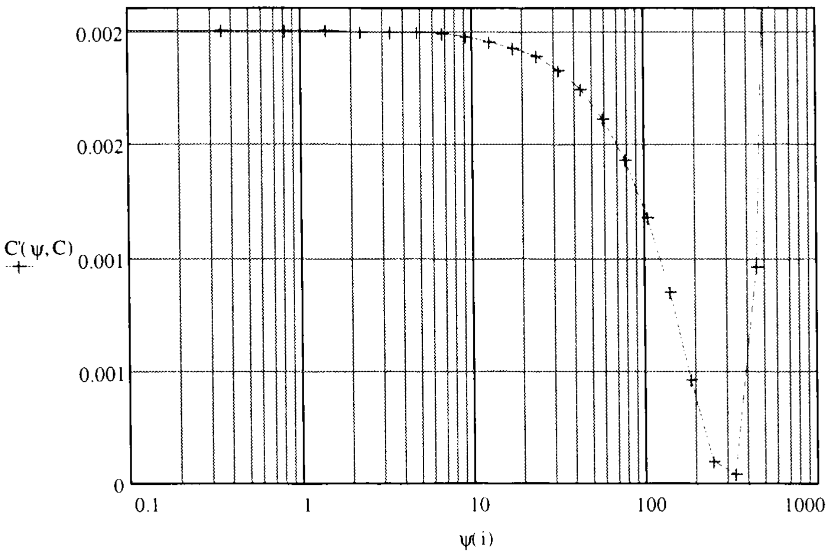
Linear Sorption Isotherm

$Kd = 2$

$C = 1 \cdot 10^{-3}$

$C'(\psi, C) = Rf(\psi) \cdot Kd \cdot C$

Plot using Linear isotherm



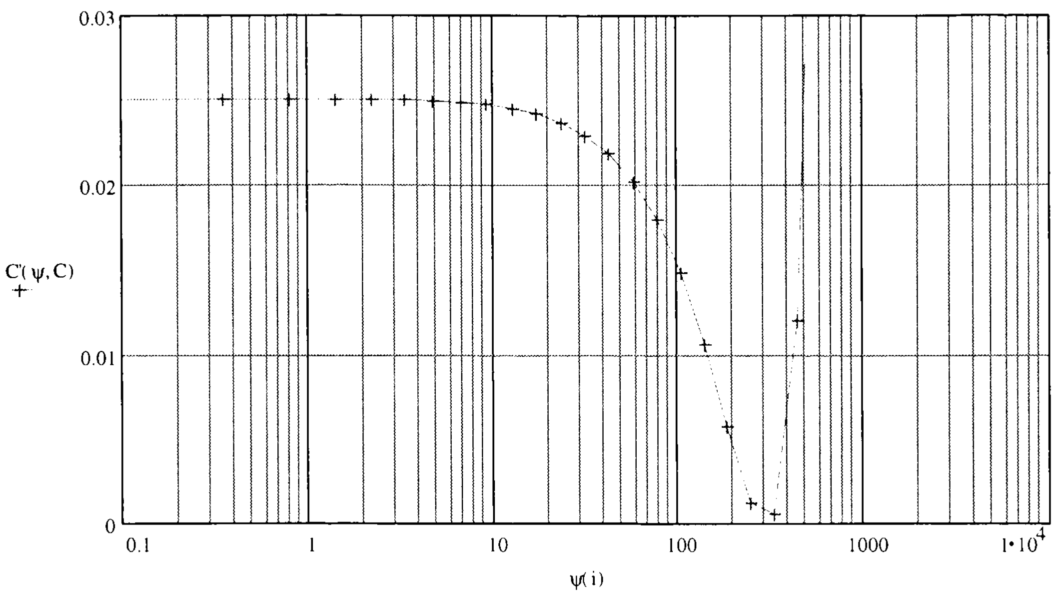
Freundlich Sorption Isotherm

$N = 1.1$

$K = 50$

$C'(\psi, C) = K \cdot Rf(\psi) \cdot C^{N}$

Plot using Freundlich isotherm



Langmuir sorption isotherm

$\alpha = 4.8$

$\beta = 4$

$$C'(\psi, C) = \frac{\alpha \cdot \beta \cdot C \cdot Rf(\psi)}{1 + \alpha \cdot C}$$

Plot using Langmuir isotherm