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# USE OF A KNOWLEDGE-BASED GEOTECHNICAL SYSTEM IN THE DESIGN, CONSTRUCTION AND MANAGEMENT OF PIPELINES

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## ABSTRACT

The design, construction and management of pipelines poses a series of unique geotechnical problems. The problems are unique primarily because of i.) the geometric character of a pipeline and ii.) the fact that the pipelines are commonly placed near to the ground surface, within the unsaturated portion of the soil profile. The geometric character of the pipeline is linear, resulting in an enormous area for which geotechnical information must be assembled. Unsaturated soil properties functions must be measured or predicted in order to model the soil-structure interaction behavior of the pipeline.

The availability of increased computational capabilities has provided several powerful options for addressing both of the above problems. Solutions arise from the application of database technologies and knowledge-based systems to various aspects of pipeline design, construction and management.

The proposed paper describes the application of the new computer based technologies. In particular, emphasis is placed on the use of a knowledge-based system in the assessment of suitable unsaturated soil properties. An understanding of the soil-water characteristic curve provides the key information required for the prediction of all unsaturated soil property functions. Thousands of soil-water characteristic curves tests (along with grain size distribution curves) have been performed by agriculture based disciplines such as agronomists from many countries of the world. This test data can be imported into a knowledge-based system and forms the basis for the approximation of the soil properties required in the analysis of pipelines. The proposed paper will describe the functionality and application of such a knowledge-based system.

## INTRODUCTION

There are many aspects related to the design, construction and management of a pipeline where geotechnical type analyses could prove to be of great benefit. The geometric character of a pipeline is such that it does not lend itself to a conventional geotechnical investigation and associated analyses. Therefore, it is important that engineers pursue new technologies and procedures to address problems associated with pipelines. In fact, it could be said that it is necessary that the entire geotechnical engineering approach must go through a complete paradigm shift in order to be of practical value.

There are many aspects of engineering design, construction and management of a pipeline that could be studied. All engineering related aspects will not be addressed in this paper. Rather, reference will be made to a few aspects that would appear to be worthy of study primarily because of recent advances in instrumentation technology, unsaturated soil theories and computing capabilities. Some unique aspects related to a pipeline engineering are as follows:

## GEOMETRIC CHARACTER OF THE PROJECT

The lineal nature of a pipeline produces an area of large extent that must be investigated and studied. Therefore, the type and nature of the site investigations must be altered from that of a site investigation done for a specific site (e.g., for a building). The collection of data, the storing of data and the analyzing of data, are all subjects unique to the character of a pipeline.

i) Site Specific Subsurface Investigations

The geotechnical engineer is most often commissioned to perform a subsurface investigation at a specific site. The site may range in area from being 1000 $m^2$ to 100,000 $m^2$ and the subsurface exploration may proceed as follows. A number of borings, (e.g., 3 to 100), are advanced through the strata of relevance for the engineering structure under consideration. Undisturbed tube samples may be taken at $1\frac{1}{2}$ *m* intervals and disturbed water content samples may be taken every $\frac{1}{3}$ *m*. SPT tests and samples may also be taken ever $1\frac{1}{2}m$.

The soil samples are taken to the laboratory for detailed description, classification tests, water content determinations and physical property tests. The undisturbed soil samples may be tested for physical properties such as the coefficient of permeability, shear strength and volume change properties, depending upon the nature of the project at hand. The results of the testing program can then be applied to analyses for seepage, stability and volume change, according to the need at hand.

The above description illustrates the character of a typical specific site investigation. It is typical to classical soil mechanics, but may not be representative of the type of investigation carried out for the design, construction and management of a pipeline.

ii) Lineal Infrastructure Site Investigation

A soil investigation for a pipeline will be quite different than that performed for a specific site. The engineer will generally have much less detailed soils information available for use as part of design.

The lineal character of a pipeline means that the engineer is concerned with a strip of land a few 100 m wide extending over a length of 1 km to 100's of km. The overall land area is greatly increased and the amount of soil information available to the design engineer, is generally decreased. It becomes necessary to place greater reliance on other sources of geotechnical information and other means to estimate suitable soil parameters. The available data may be more general in nature. In fact, the total amount of information, while being more qualitative and subjective, may be very large. New techniques and procedures should be pursued to make the most effective use of the available information.

The desktop computer has also provided a tool whereby advantage can be taken of new technologies. Much of the information presented later suggests ways in which use can be made of the desktop computer and information technology.

Many man-made structures such as pipelines have been designed and built by civil engineers throughout history and into the present geotechnical era (i.e., since the 1930's). Classical soil mechanics procedures were developed primarily to accommodate site specific investigations. The geotechnical engineer needs to ascertain what new site investigation tools can be applied to a pipeline (e.g., data collection tools, geo-statistical tools and computational techniques).

## AVAILABILITY OF COMPUTATIONAL CAPABILITIES

The digital computer has revolutionized the manner in which the geotechnical engineer carries out geotechnical studies. Some of the ways in which the digital computer has impacted the practice of geotechnical engineering were described by Fredlund (1996).

Some of the areas of computer application are as follows:

i) Geometric Mapping – There are several sources of geometric information that can provide input to the design engineer. The surface topographic information can originate from surveys or topographic maps. The surface geology may originate from traversing the site, from aerial photography, surficial geology maps or pedological maps. All relevant information can be stored in a usable form, in a database, and subsequently extracted for the preparation of plans.

The storage of data and information with respect to x- and y-coordinates (and also z-coordinates) has become known as Geographical Information Systems or GIS. In essence, GIS is a large database that contains information that can be "operated upon" (i.e., Operations Research) to provide information for analysis and decision-making in engineering. GIS can be applied to virtually every area of civil engineering, as well as other engineering areas. Probably the greatest impact of GIS has been in the transportation field (provided the military applications are ignored).

GIS can be combined with the satellite system to give rise to Global Positioning Systems (i.e., GPS). These systems are extremely powerful for surveying, but also have relevance in geotechnical engineering. Virtually every phase of a pipeline project can be impacted by GIS and GPS.

ii) Geo-statistical Extrapolations – Krige (1966) introduced what is commonly referred to as the kriging method, for the geo-statistical analysis of randomly collected data. The technique allows a limited amount of data to be extrapolated and interpolated as a meaningful response in natural phenomena. The technique was originally used for the prediction of the quantity of ore in an ore body.

The kriging method has now become a part of the larger field of geo-statistical methods taught at universities in most engineering geology programs. The success of the technique centers on the use of spline type, interpolating functions (Matheron, 1981). The technique can be used to generate mesh surfaces referred to as "nets" for any variable in two-dimensional space (Fig. 1). The variable in the third dimension may be the: i) elevation of the ground surface, ii) elevation of the interface between any two soil types, or iii) any soil property.

The kriging technique can be used to predict a reasonable value for a variable at a particular point, if the value is known at a number of other points. The variable could be a chemical concentration or any soil property.

The topography along the pipeline route or any other variable associated with the design of the pipeline, can be estimated using the kriging method. As such, it becomes an extremely valuable engineering tool made available because of the increased computational power available to the engineer. For example it is a valuable tool for establishing the geometry for a slope stability analysis or a saturated-unsaturated seepage analysis.

iii) Discretization for Geotechnical Numerical Modelling – With the aid of a microcomputer, it is now possible to select a cross-section through the geometry (e.g., a canal), and have the regions of the continuum discretized into finite elements within a fraction of a second. The problems related to numbering elements and nodes, when performing a finite element analysis have essentially become non-existent. All of this has been made available as a result of combined developments in computer hardware and software. These developments provide the engineer with an entirely new approach to addressing problems and recommending solutions.

iv) Using the Computer in Problem Solving – The geotechnical engineer can re-create the geometry and soil conditions related to essentially any problem, in the computer, within a matter of minutes. It is then possible to consider a wide range of "What if and thereby arrive at reasonable engineering judgements. For example, it is possible for the engineer to study: a) "What if..." the geometry of the pipeline excavation were changed slightly; how much would the stability of the slope change?, b) "What if..." the coefficient of permeability was one order of magnitude greater; what would the changes in infiltration and possible loss of stability?, or c) "What if..." the angle of internal friction were 5 degrees lower; what would be the change in the factor of safety?

The microcomputer has become an integral part of solving problems in geotechnical engineering. It can safely be stated that the entire approach to problem solving in geotechnical engineering has been strongly influenced and even controlled by the microcomputer. It can be said that we are in the age of "instant questions" and we want

The impact of the digital computer has only been surficially addressed in what has been written, but it is obvious that engineers are continuously seeking more and more ways in which to apply the microcomputer to respective problems.

## BEHAVIOUR OF NEAR-GROUND SURFACE SOILS

Soils near to the ground surface are generally unsaturated and their pore-water pressures are negative (Fig. 2). These soils are often considered to be problematic soils and as such have been treated in an empirical manner. However, recent developments in unsaturated soil theories and their application, have led to new possibilities for solving geotechnical problems (Fredlund, 1995).

The properties associated with unsaturated soils can be estimated, to a large extent, through a knowledge of the soil-water characteristic curve (Fredlund, et al., 1997). These curves have been measured on thousands of soils from many countries of the world. As such, the results form a large database that can be analyzed using "operational research techniques". The developed computer software with query ability, analytical ability and decision-making ability are known as knowledge-based systems. The procedures being developed are extremely powerful and are significantly impacting the application of unsaturated soils theories in engineering practice.

## QUANTIFICATION OF FLUX BOUNDARY CONDITIONS

The ground surface interacts with the climatic environment and as such becomes a moisture flux boundary. Classical soil mechanics never paid much attention to the quantification of moisture flux boundary conditions. However, recent developments in the environmental and geo-environmental areas have illustrated that it is necessary to have this information as input when solving geotechnical problems.

Climatic conditions, for any region of the earth's surface, can be are summarized in the form of large databases. In fact, this has already been done for many areas of the earth's surface. The theory for the prediction of the evaporative flux is known and the technology is now available to utilize this information to compute suitable design quantities for precipitation and "actual" evapotranspiration. The prediction of "actual" evapotranspiration was a difficult problem to solve, but it is now possible to solve the coupled heat and mass transport problem on a microcomputer. The computation of "actual" evapotranspiration has proven to be extremely important in obtaining practical solutions to geo-environmental, mine waste problems. These problems commonly involve the computation of quantities of contaminant that will be released to the environment, upon "closure" of a mining operation.

The quantification of the moisture flux boundary conditions for near-ground-surface infrastructures appears to be equally as important in solving geotechnical problems, as the quantification of unsaturated soil properties. The determination of moisture flux conditions is also important to the testing of various scenarios related to the design and performance of a pipeline system.

## CONSTRUCTION CONTROL AND MONITORING TECHNIQUES

The engineer must have at his disposal techniques that can be used to control the performance of the contractor and ensure the adequacy of the engineering design. The measurement of positive pore-water pressures, through the use of piezometers, is often used for this purpose in *saturated* soils. There is a similar need, or requirement, when dealing with unsaturated soils. However, the *in situ* measurement of highly negative pore-water pressures has proven to be a challenge to geotechnical engineers.

There have been several new technological developments related to devices that can measure highly negative pore-water pressures. The direct measurement of high suctions has been successfully carried out at Imperial College (Ridley, 1993) and at the University of Saskatchewan (Guan, 1996). It has been found that by prestressing the water in the measuring system, to several thousand kPa in a tensiometer, the device can measure negative pore-water pressures up to 1000 kPa. Further research on these devices is still required, but the physics and principles of operation have been proven successful.

Thermal conductivity matric suction sensors have also been proven successful for the indirect measurement of matric suctions. Much of the research on these devices has been undertaken at the Railway Academy of Sciences (Beijing, China) and at the University of Saskatchewan (Saskatoon, Canada) (Fig. 3). Recent devices have been shown to have durable ceramics and durable electronics to measure suctions up to 500 kPa, over extended periods of time. The devices can readily be connected to a data acquisition system for field monitoring.

The filter paper technique to measure soil suction is simple and inexpensive. Even so, the method must be standardized and the technique should undergo further research to ensure consistency in the measured data.

## NEED FOR A PARADIGM SHIFT

A paradigm shift occurs when a significantly different way is discovered for solving a specific problem or providing a specific service. The advent of microcomputers set the stage for a major paradigm shift within geotechnical engineering (Fredlund, 1997). The paradigm shift has been significant within classical, saturated soil mechanics, but holds potential for being even more dramatic within unsaturated soil mechanics. One of the unique features of unsaturated soil mechanics is the manner in which essentially all analyses become highly nonlinear. Solutions to highly nonlinear analyses (e.g., unsaturated seepage analyses) were not practical or even feasible prior to the advent of the modern computer.

The microcomputer of today affects every aspect of geotechnical engineering from keeping record of the accounting, to solving analytical models to field monitoring, and to the preparation of the final report. The modelling of soil behavior is now largely conducted using finite element numerical models. The discretization of a selected cross-section through a soil mass can be quickly carried out and a series of parametric studies can be performed.

Even before cross-section(s) is selected for study, geo-statistical techniques can be applied to obtain the overall topography and stratigraphy of the region under consideration. One of the latest developments is to make use of a knowledge-based system for the assessment of reasonable saturated and unsaturated soil properties and the estimation of suitable boundary, moisture flux boundary conditions. All aspects of a knowledge-based system are once again heavily dependent upon the microcomputer. And so, the computer has revolutionized the manner in which geotechnical engineering is practiced. This has truly been a significant paradigm shift.

## THE SOIL-WATER CHARACTERISTIC CURVE

The assessment of unsaturated soil properties can generally be accomplished as an indirect computation based on the soil-water characteristic curve. The soil-water characteristic curve defines the relationship between the amount of water in the soil (i.e., volumetric water content or degree of saturation) and the suction applied to the soil (Fig. 4). A knowledge of the saturated soil parameters and the soil-water characteristic curve provide a means of computing unsaturated soil property functions. The unsaturated soil property functions can be computed for permeability, water storage, shear strength and volume change.

The indirect computation of unsaturated soil property functions is becoming acceptable practice in geotechnical engineering because: i) the cost of directly measuring unsaturated soil property functions in the laboratory is prohibitive in most cases, and ii) only an approximation of the unsaturated soil property functions are required when solving most geotechnical problems. The indirect approach was first proposed to compute the coefficient of permeability function when solving flow through unsaturated soils. Similar indirect procedures are now quite well established for the shear strength function for unsaturated soils.

In all of the above cases, it is the soil-water characteristic curve that is essential in the computation of the unsaturated soil property functions. The soil-water characteristic curve can either be measured in the laboratory or can be estimated from the classification properties of the soil. The grain-size distribution can be used as the classification property of greatest value for sands, silts and mixtures thereof. Procedures have been proposed for the estimation of the soil-water characteristic curve from the grain-size distribution curve (Fig. 5) (Fredlund et al., 1997).

Soil-water characteristic curves have been measured on thousands of soils from many countries of the world. These measurements have mainly been conducted in the soil science, agronomy and agricultural disciplines. As a result, there is an enormous amount of data that can be placed within a database. Operational research techniques can be applied to querying the database and subsequent analyses can be performed. The end result is a powerful knowledge-based system for computing unsaturated soil property functions.

## KNOWLEDGE-BASED SYSTEMS FOR UNSATURATED SOIL PROPERTY FUNCTIONS

Search and query techniques can be applied to large arrays of data in order to find data on soils with a similar classification or by testing for the similarity in their grain-size distribution curves. The soil-water characteristic curves can be extracted and studied by the engineer. An average or best-fit soil-water characteristic curve can be selected to represent the soil under consideration.

In the case of coefficient of permeability functions, there have also been a considerable number of direct measurements made in the laboratory. This information can also be stored in the database and used for verification of the theoretical estimates (Fredlundet al., 1998)

Both the operation of the knowledge-based system and related analytical procedures require the use of a microcomputer. These systems of operation are new to the geotechnical profession, but appear to rapidly becoming entrenched as acceptable procedures.

The design and construction of a pipeline provides an excellent opportunity to study the application of new, computationally intensive procedures. The measurement of soil-water characteristic curves could also provide new, additional data for a database. Further research will still be required to study all the ways in which the computer and knowledge-based systems can be used in geotechnical engineering practice.

## IMPLEMENTATION OF THEORY IN DESIGN

Most of the theory related to unsaturated soil behavior is now well established. Even so, there is another large independent step involved in moving the science to the implementation stage. In other words, it can be difficult for the engineer "to see" the procedure required for the implementation of the science. As a result, it is necessary for research to be done to determine the best procedures for the implementation of a science such as the unsaturated soil theories into geotechnical engineering practice.

The need for new engineering procedures must be presented on the basis of increased reliability, increased efficiency, increased safety (i.e., lower risk), and improved cost effectiveness. The new procedures must be presented from the standpoint that "answers to questions" can be more quickly obtained and as a result, the engineer is assisted in making decisions.

## THROUGH CONSTRUCTION TO VERIFICATION

There is a need to "observe" the behavior of any infrastructure construction in order to provide feedback to the designer. Only through *in situ* monitoring and feedback can confidence be firmly established in the design procedures.

The role of case histories plays an important part of the practice of geotechnical engineering. Many conferences are held annually where geotechnical engineers report on the investigative and design procedures that have been used, and the subsequent performance of the structure. These case histories are necessary for saturated soils situations, and the same is now true for unsaturated soils situations. It is the limited amount of case histories related to unsaturated soil conditions that result in a lack of confidence in applying the theories of unsaturated soil behavior.

There is sometimes a reluctance to have engineers installing instrumentation and making measurements during and following construction. The common complaint is that the instrumentation interferes with the progress of the project. But it is up to the geotechnical engineer to promote the importance of the monitoring aspect of science. There are benefits that can be accrued for the immediate project and there are also benefits for futures projects in other places.

The importance of monitoring should be sold on the basis of "building confidence and procedures" on the present project as well as on future projects. A competitive edge is provided

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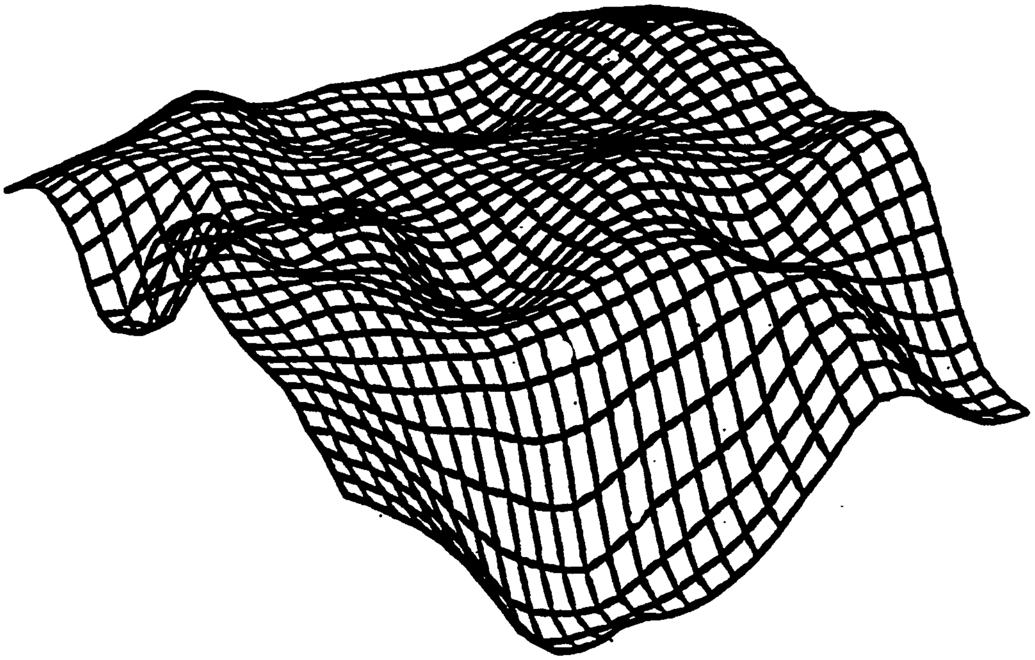

Figure 1. An example of a "net" generated as a result of using the Kriging method

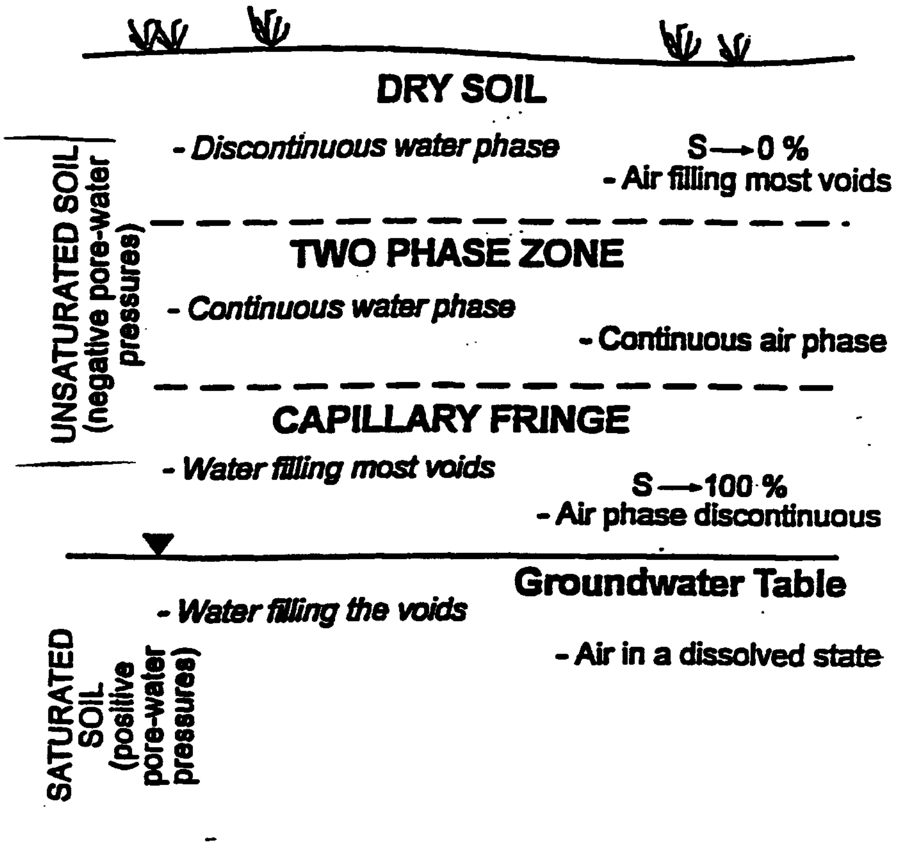

Figure 2. Zones of unsaturation for soils above the water table

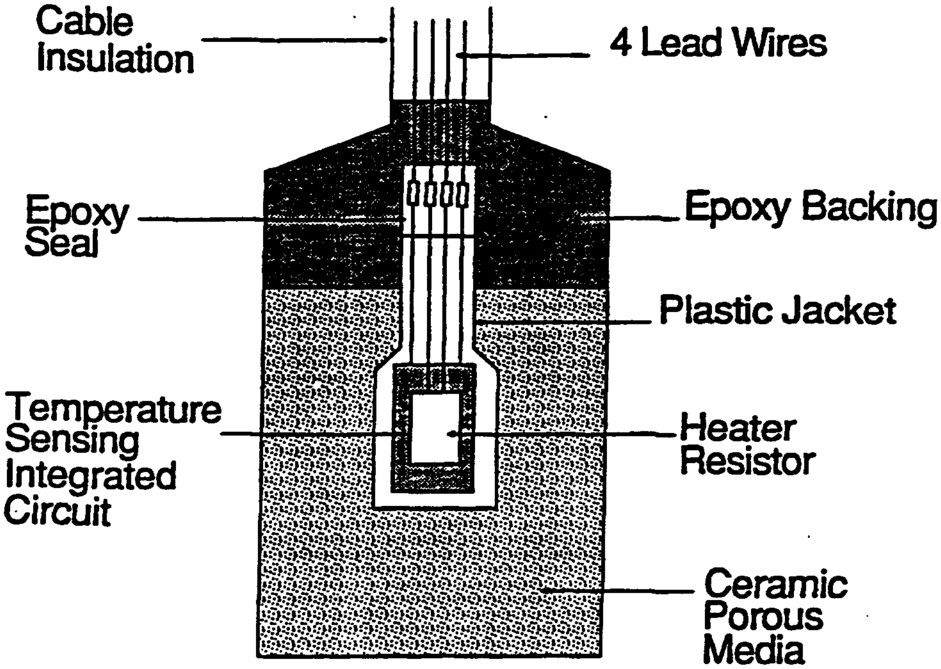

Figure 3. Section of the thermal conductivity, matric suction sensor

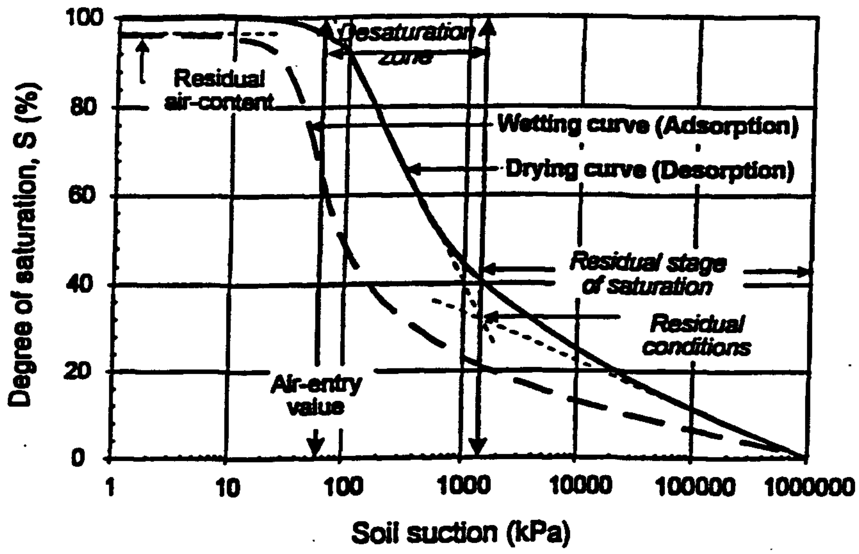

Figure 4. Definition of variables associated with the soil-water characteristic curve

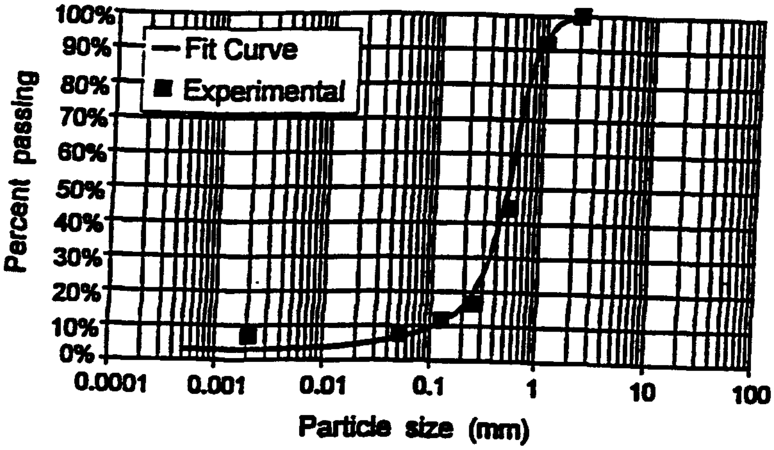

**Figure 5.a. Grain-size distribution curve fit for sand**

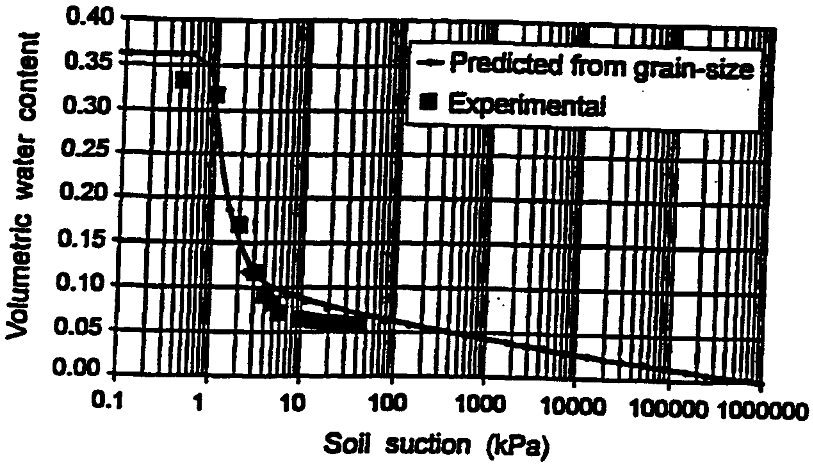

**Figure 5. A soil-water characteristic curve computed from a grain size distribution curve**