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Historical developments and milestones in unsaturated soil mechanics

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ABSTRACT: The development of soil mechanics for unsaturated soils began about two to three decades after the commencement of soil mechanics for saturated soils. The basic principles related to the understanding of unsaturated soil mechanics were formulated mainly in the 1970's. There were two series of conferences that played a dominant role in our understanding of unsaturated soils. These were the series of conferences on expansive soils from 1965 to 1992, and the series of conferences on unsaturated soil mechanics from 1993 to the present.

The development of unsaturated soil mechanics has gone through several stages as it has moved towards implementation in standard geotechnical engineering practice. These stages are traced through an analysis of research papers published at a number of engineering conferences related to unsaturated soils.

Key words: unsaturated soils, expansive soils, history, research papers, conference papers.

1 INTRODUCTION

There is a rich heritage related to the emergence of unsaturated soil mechanics. It is the intent of this paper to highlight some of the historical aspects of this subject. It will not be possible to do justice to all the research that has taken place. As a result, comments and a brief analysis will be undertaken on a limited number of documents related to the subject of unsaturated soil behavior (i.e., mainly conference proceedings). The desire is to acknowledge and pay tribute to the many excellent studies on expansive and unsaturated soils that have been performed in numerous countries of the world.

Our historical heritage can be divided into seven decades. Each of the past five decades, in particular, has identified unique steps forward towards the emergence of unsaturated soil mechanics. An attempt will be made to identify these steps through a focus on the proceedings of key conferences and the publication of several books. There are two series of conferences that have played a dominant role in communicating developments in our understanding of unsaturated soil behavior. These are the series of conferences on expansive soils from 1965 to 1992 and the series of conferences on unsaturated soils from 1993 to the present. There are also other one-time conferences that have also played an important role. An attempt has been made to analyze the contents of research papers at conferences in order to better understand the stages involved in the emergence of unsaturated soil mechanics.

In undertaking this synthesis, it is obvious that many valuable contributions will not be given proper credit. However, I trust that the synthesis will make mention of some of the key research publications and to a lesser extent, some of the many important researchers involved and the contribution that each has made. The focus is on research papers published at research conferences as opposed to those published in journals. A number of statistical indicators will be used to assist in the task.

2 HISTORICAL DEVELOPMENTS (1930'S TO 1950'S)

The first ISSMFE conference (International Society for Soil Mechanics and Foundation Engineering) in 1936 provided a forum for the establishment of principles and equations relevant to saturated soil mechanics. These principles and equations became pivotal throughout subsequent decades of research. This same conference was also a forum for numerous research papers on unsaturated soil behavior. Unfortunately, a parallel set of principles and equations did not immediately emerge for unsaturated soils. In subsequent years, a science and technology for unsaturated soils has been slow to develop. Not until the research at Imperial College in the late

1950's did the concepts for understanding unsaturated soils behavior begin to be established (Bishop, 1959). The research of Lytton (1967) in the United States did much to ensure that the understanding of unsaturated soil behavior was founded upon principles set forth in continuum mechanics.

One of the engineering problems observed in the 1930's related to unsaturated soils, involved the flow of water in the zone of negative pore-water pressure (i.e., capillary flow; Hogentogler and Barber, 1941). One of the problems that appeared to perplex civil engineers was that of the movement of water above the groundwater table. The term "capillarity" was adopted to describe the phenomenon of water flow upward from the static groundwater table. Terzaghi (1943) in his book, *Theoretical Soil Mechanics*, endorsed the concepts related to the capillary tube model. The importance of the air-water interface was emphasized with respect to its effect on soil behavior.

The historical review for the period up to the 1950's shows that most of the attention given to unsaturated soils was related to capillary flow. An attempt was made to use the capillary tube rise model to explain the observed phenomenon. Although this model was of some value, it had limitations that became increasingly obvious. In fact, attempts to heavily rely on the capillary tube rise model appear to be a significant factor in the slow development of unsaturated soil mechanics.

3 SUMMARY OF STATISTICS ON CONFERENCE PAPERS

The research literature is too extensive to review in detail. Therefore, it was decided that some of the primary publications would be selected for study and analysis. It was decided to focus primarily on the proceedings of conferences where unsaturated soils formed a significant theme of the conference. Most of the conferences were international in scope but some more regional conferences have also been selected. Mention will also be made of some of the books that have been written related to unsaturated soil behavior. A short review is provided on some of the conferences while a few statistics are simply given on other conferences. Unfortunately, space does not permit a thorough coverage of all the published information.

Table 1 provides a listing of the conference proceedings that have been reviewed. The table is divided into three sections; namely the period from the 1950's to 1964 (Table 1a), the period from 1965 to 1992 (Table 1b), the period from 1993 to the present (Table 1c). The period from 1965 to 1992 is the period when international conferences were held (approximately) every 4 years. Subsequently, this international conference series was changed to focus more broadly on unsaturated soils. This change was at the request of the TC6 subcommittee of the ISSMFE.

The chronology of the conferences related to unsaturated soil behavior is plotted on Figure 1. Also shown beside each conference is the number of research papers published on unsaturated soils. It is apparent that there has been a constantly growing interest in research related to unsaturated soils as shown in the plot of the number of research papers published during each decade (Fig. 2). The first research papers appeared in the late 1950's and have steadily increased until the present time.

3.1 *Categorization of Papers Based on the Soil Property Being Studied*

The proceedings listed in Table 1 contained more than 1000 research papers on unsaturated and expansive soils. All of the papers were analyzed with respect to three categorizations. The first categorization was with respect to the soil property being analyzed. Sub-categories were then selected that seemed to cover essentially all of the soil properties that had been researched. The sub-categories were: volume change, shear strength, soil suction measurements, classification of soils, permeability and chemical concentration properties. The category of "general" was also added since some of the papers did not fit the designated categories. It must be realized that the categorizations are approximate since it is difficult in some cases to put the research paper in only one category. The summary of the themes of the research papers is shown in Tables 2.

The cumulative number of research papers published on each of the soil properties for unsaturated soils is shown in Figure 3. A vertical line is shown between 1992 and 1993 since this is the approximate time when the scope of research was broadened to consider all aspects of unsaturated soils research. Volume change studies have formed the primary focus of research from the earliest of studies. At the same time, the volume change behavior remains the soil property about which the least is known from an engineering standpoint. Approximately 5 times as many papers have been published on volume change behavior as have been published on shear strength and permeability. And still, it is the shear strength and permeability (or hydraulic conductivity) related problems that have enjoyed the greatest success in implementation into engineering practice.

Figure 3 shows that there has been a significant increase in research related to the coefficient of permeability of unsaturated soils, in recent years. This area of research would appear to be largely driven by increased concern in the environmental and geo-environmental areas. While less research has been

Table 1. List of conference proceedings reviewed and analyzed with respect to the development of unsaturated soil mechanics

Table 1a.) Early conference proceedings (1950's to 1964) emphasizing the behavior of unsaturated soils

1959 (October)	Conference on Theoretical and Practical Treatment of Expansive Soils, University of Colorado, Boulder, CO, U.S.A.
1960 (June)	Conference on Shear Strength of Cohesive Soils, ASCE, University of Colorado, Boulder, CO, U.S.A.
1961 (March)	Conference on Pore Pressures and Suction in Soils, Butterworths, London, England.
1963 (June)	Third Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Salisbury, Rhodesia.

Table 1b.) Some of the conference proceedings (1965 to 1992) devoted primarily to the engineering behavior of expansive soils

1965 (September)	Engineering Effects of Moisture Changes in Soils, First International Research and Engineering Conference on Expansive Clay Soils, College Station, TX, U.S.A.
1965	Moisture Equilibria and Moisture Changes in Soils Beneath Covered Areas (A Symposium in Print) Butterworths, Australia, G, D. Aitchison, Editor.
1966 (July)	Symposium on Permeability and Capillarity of Soils, a Symposium presented at 69th Annual Meeting of ASTM, Atlantis City, NJ, U.S.A.
1969 (June)	Second International Research and Engineering Conference on Expansive Clay Soils, College Station, TX, U.S.A.
1971	Proceedings of the Fifth Regional Conference for Africa, Soil Mechanics and Foundation Engineering, Luanda, Angola.
1973 (August)	Proceedings of the Third International Conference on Expansive Soils, Haifa, Israel.
1980 (June)	Proceedings of the Fourth International Conference on Expansive Soils, Denver, CO, U.S.A.
1984 (May)	Proceedings of the Fifth International Conference on Expansive Soils, Adelaide, Australia.
1985 (February)	First International Conference on Geomechanics in Tropical Lateritic and Saprolitic Soils, TropicaLS '85, Brasilia, Brazil.
1987 (December)	Proceedings of the Sixth International Conference on Expansive Soils, New Delhi, India.
1988 (August)	Proceedings of the International Conference on Engineering Problems of Regional Soils, Beijing, China.
1992 (August)	Proceedings of the Seventh International Conference on Expansive Soils, Dallas, TX, U.S.A.

Table 1c.) Conference proceedings emphasizing the behavior of unsaturated soils from 1992 to the Present

1993 (July)	ASCE Geotechnical Special Publication, Unsaturated Soils Session, Geotechnical Special Publication, No. 39.
1994 (April)	Proceedings of the Second Brazilian Symposium on Unsaturated Soils, Recife, PE, Brazil
1995 (September)	Proceedings of the First International Conference on Unsaturated Soils, Paris, France.
1997 (April)	NSAT '97 Solos Não Saturados, Proceedings of the third Brazilian Symposium on Unsaturated Soils, Rio de Janeiro, Brazil.
1997 (July)	ASCE Geo-Logan Conference, Unsaturated Soil Engineering Practice, Geotechnical Special Publication, No. 68, Logan, Utah, U.S.A.
1998 (August)	Proceedings of the Second International Conference on Unsaturated Soils, Beijing, China.
2000 (May)	Asia 2000 Conference on Unsaturated Soils, Singapore.
2000 (August)	ASCE Geo-Denver Unsaturated Soils Specialty Session, Denver, CO, U.S.A.

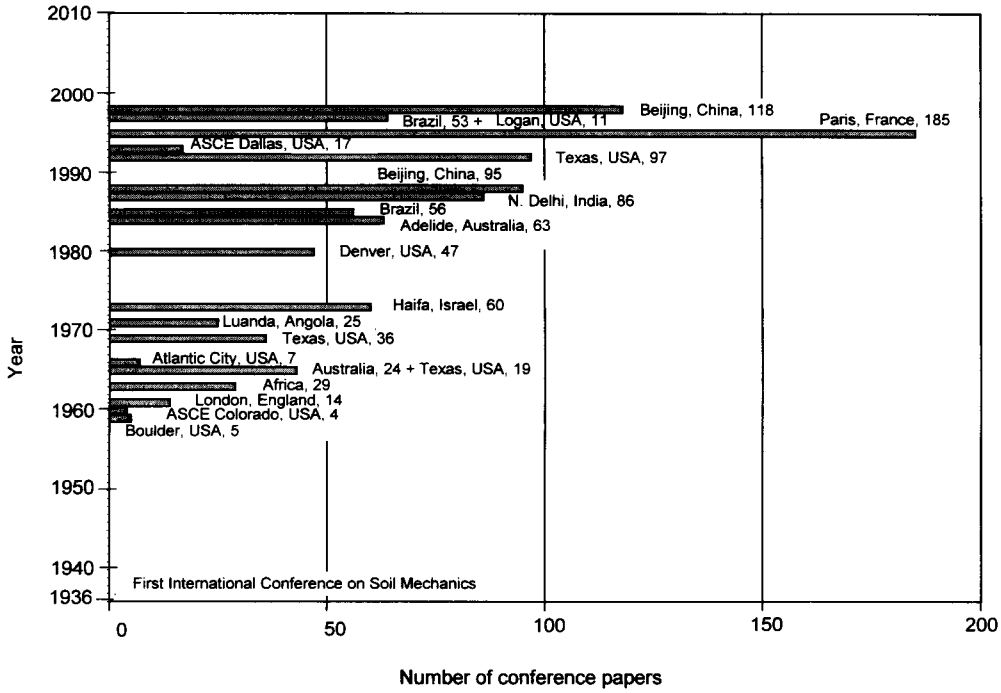


Figure 1. Chronology of the main conference with a theme related to unsaturated soil behavior.

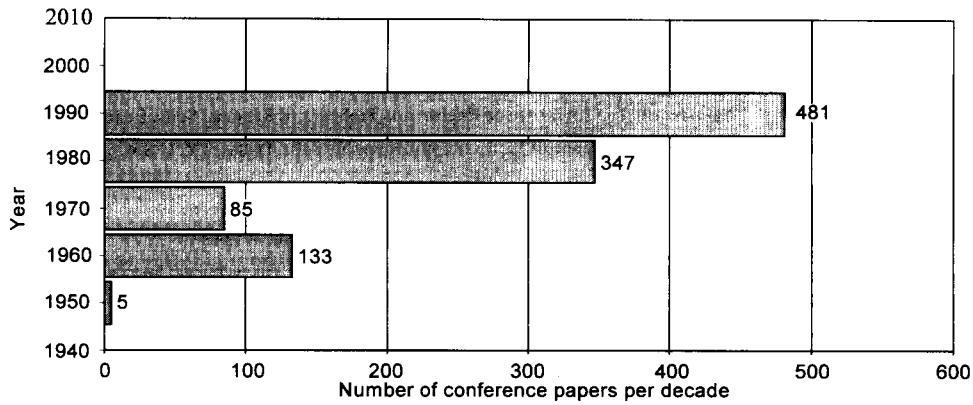


Figure 2. Number of research papers per decade published at the main conferences that had unsaturated soils themes.

undertaken on the shear strength of unsaturated soils, their behavior appears to have been easier to quantify. Research into the adsorption, diffusion and dispersion behavior of chemicals in unsaturated soils does not appear to have been extensive. However, probably the selection of research conferences is not the most appropriate for these topics.

The graph would also appear to indicate that although engineers have attempt to relate the behavior of unsaturated soils to soil suction, there has not been extensive research devoted to the measurement of soil suction. Fundamental studies on soil suction may have often been left to the soil science and soil physics disciplines. It would seem that more attention should be given to the measurement of soil suction and its components.

Figure 4 shows the soil property area distribution for all the papers published to-date. Here, volume

Table 2. Summary of statistics on the research papers presented at selected conferences

	Soil property							
Year	Volume change	Shear strength	Permeability	Soil suction	Classification	Chemical	General	Total
1959 Boulder	5	0	0	0	0	0	0	5
1960 ASCE Colorado	0	4	0	0	0	0	0	4
1961London	4	0	7	3	0	0	0	14
1963 Africa	16	5	3	2	3	0	0	29
1965 Texas	16	2	1	0	0	0	0	19
1965 Australia	5	0	9	6	4	0	0	24
1966 Atlantic City	0	0	7	0	0	0	0	7
1969 Texas	30	2	3	0	0	0	1	36
1971 Angola	17	5	0	0	3	0	0	25
1973 Haifa	43	1	5	5	4	2	0	60
1980 Denver	35	3	2	2	5	0	0	47
1984 Adelaid	51	2	0	3	7	0	0	63
1985 Brazil	23	7	5	1	15	3	2	56
1987 N. Delhi, India	72	5	0	1	7	0	1	86
1988 Beijing	62	19	4	1	3	5	1	95
1992 Texas	81	5	2	4	0	4	1	97
1993 ASCE Dallas	11	0	3	2	0	0	1	17
1995 Paris	82	21	49	18	3	5	7	185
1997 Brazil	17	12	8	4	9	2	1	53
1997 Logan	5	1	4	0	0	0	1	11
1998 Beijing	59	17	20	14	2	5	1	118
Total	634	111	132	66	65	26	17	1051

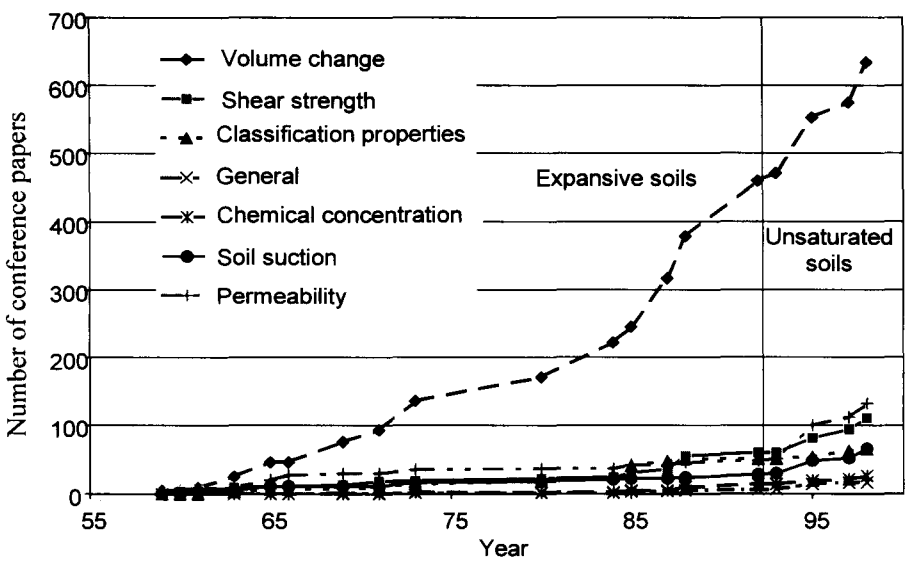


Figure 3. The cummulative number of paper published related to each soil property

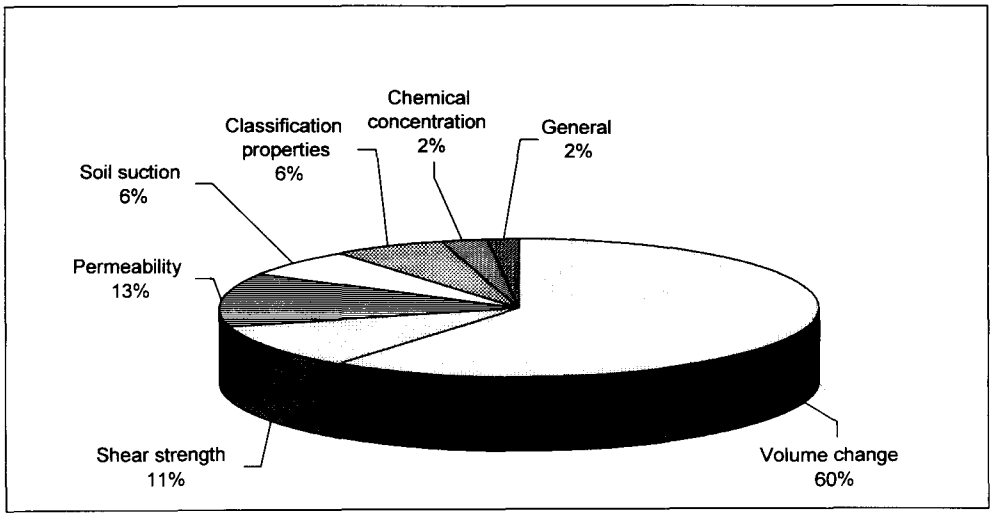


Figure 4. Percentage of research papers published relative to the various soil property categories (total of 1051 papers).

change studies account for 60% of the research while shear strength and permeability account for 11% and 13%, respectively. However, when the research papers are subdivided for the periods before and after 1992, the percentages are somewhat different. Volume change studies accounted for 77% of the papers before 1992 and have subsequently accounted for only 45% of the papers. On the other hand, shear strength papers accounted for only 5% of the papers prior to 1992 and presently account for 13%. Likewise, the number of publication related permeability has risen from 5% to 22% for similar time periods. The analysis of specific conferences show the same trends.

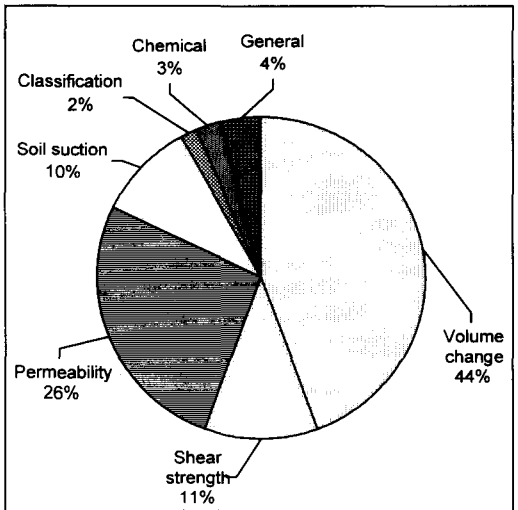
The analysis of the First and Second International Conferences on Unsaturated Soils are shown in Figure 5, indicating about 50% of the papers were on volume change. Figure 6 shows that the early international conferences on expansive soils were almost exclusively devoted to volume change studies. The Second International Conference on Expansive Soils had 83% of the papers on volume change but this reduced to72% by the Third International Conference on Expansive Soils. These results show a general increase in research in all aspects related to unsaturated soils behavior.

3.2 *Categorization Based on Type of Research Being Undertaken*

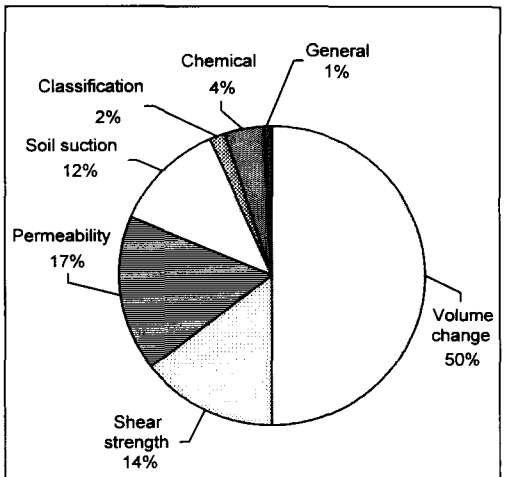
The second categorization of the research papers was based upon the type of research being undertaken; namely, whether the study was of an experimental or theoretical nature and whether the study was in the laboratory or the field. The four subcategories were theory, laboratory experiments, field measurement and the application of formulations and theory to engineering problems. It is realized that all categories are not necessarily mutually exclusive and in some cases it was necessary to select the dominant aspect of the study. The results of the research paper analysis for categorization 2 and 3 are presented in Table 3. The analysis of categorization 3 will be discussed later.

Figure 7 shows a cumulative plot of the types of research studies being undertaken with time on unsaturated soils. Once again, an arbitrary dividing line is places between 1992 and 1993, denoting a change to a broader scope in unsaturated soils research. Throughout the period of research, the majority of studies were performed in the laboratory. On the other hand, the field measurements were the least common. The distributions shown are to be expected since certain types of research require greater research dollars to conduct. An analysis of all of the types of research studies undertaken is shown in Figure 8. The results indicate that about 20% of the studies were theoretical in nature while 25% of the studies were directed towards the application of the theory to practical problems. About 42% of the studies involved experimental measurements in the laboratory while 12% of the studies involved field measurements.

If the analysis separates the papers before and after 1992, it can be seen that there has been an increase in theoretical and laboratory studies. Theoretical studies accounted for 18% of the papers prior to 1992 and 24% of the papers after 1992. Laboratory studies accounted for 35% of the papers prior to 1992 and 50% of the papers after 1992. The field and application papers show a decrease during recent years. It would appear that the broadening of

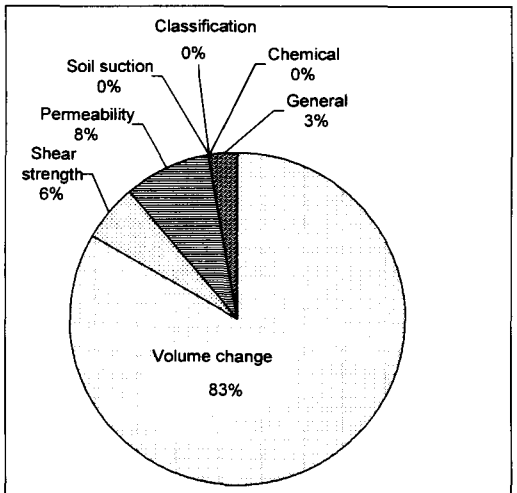


a.) First International Conference on Unsaturated Soils, 1995, Paris, France.

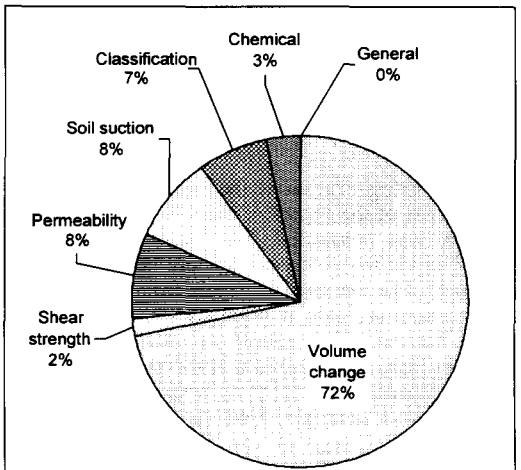


b.) Second International Conference on Unsaturated Soils, 1998, Beijing, China

Figure 5. Percentage of research papers published relative to the various soil property categories, a.) First International Conference on Unsaturated Soils, 1995, Paris, France, and b.) Second International Conference on Unsaturated Soils, 1998, Beijing, China



a.) Second Conference on Expansive Soils 1969, Texas, USA



b.) Third Conference on Expansive Soils 1973, Haifa, Israel

Figure 6. Percentage of research papers published relative to the soil property categories, a.) Second Conference on Expansive Soils, 1969, Texas, USA, and b.) Third Conference on Expansive Soils, 1973, Haifa, Israel

the scope to embrace all types of unsaturated soils research resulted in a rejuvenation of theoretical and laboratory studies. Figure 9 shows the distributions for the Texas conference (1969) and the Paris conference (1995), illustrating the changes in emphasis with time. While these changes may be good, it also reveals that additional research is required in order to ensure that the research becomes implemented into engineering practice.

Table 3. Summary of statistics on the research papers presented at selected conferences

	Type of research study					Region of the world						
Year	Theory	Lab	Field	Application	General	Africa	Asia	Australia	Europe	Middle East	North America	South America
1959 Boulder	2	0	0	3	0	0	0	0	0	0	5	0
1960 ASCE Colorado	0	4	0	0	0	0	0	0	4	0	0	0
1961 London	5	5	2	2	0	1	1	0	12	0	0	0
1963 Africa	2	9	5	12	1	28	0	1	0	0	0	0
1965 Texas	3	5	4	7	0	1	1	4	1	0	12	0
1965 Australia	2	7	6	9	0	8	2	8	4	2	0	0
1966 Atlantic City	0	4	2	1	0	1	0	1	0	0	5	0
1969 Texas	7	14	2	13	0	3	7	2	4	6	13	1
1971 Angola	5	9	1	10	0	14	1	0	5	0	3	2
1973 Haifa	14	25	3	15	3	7	8	14	7	12	12	0
1980 Denver	10	14	5	18	0	5	4	4	7	4	21	2
1984 Adelaide	10	16	22	15	0	7	5	16	7	7	21	0
1985 Brazil	4	29	7	15	1	5	9	3	9	4	3	23
1987 N. Delhi, India	18	33	6	29	0	5	44	1	15	7	13	1
1988 Beijing	16	45	9	24	1	2	74	1	10	2	5	1
1992 Texas	17	32	17	30	1	9	21	5	15	6	37	4
1993 ASCE Dallas	4	8	0	4	1	0	0	1	4	1	10	1
1995 Paris	43	93	12	34	3	6	35	18	64	14	28	20
1997 Brazil	13	25	9	6	0	0	0	1	0	0	8	44
1997 Logan	2	5	1	2	1	0	1	0	1	0	9	0
1998 Beijing	29	59	14	15	1	7	40	5	30	2	25	9
Total	206	441	127	264	13	109	253	85	199	67	230	108

3.3 *Categorization Based on the Part of the World the Research is Being Conducted (Global Distribution)*

The third categorization of the research papers was on the basis of the region of the world in which the research was conducted. The regions were sub-categorized in terms of the the major land regions of the world. The numbers of papers from each region can be found in Table 3. It would appear that every region has problems related to unsaturated soils. However, it is also realized that the population base and the financial resources to address unsaturated and expansive soils problems, is not the same in every region.

The cumulative number of research papers published from each of the regions is shown in Figure 10. There are a number of observations that can be made from this graph. It can be observed that there has been a steady and gradual increase in research on unsaturated soils on all of the regions with time. Two regions have shown a dramatic increase in unsaturated soils research during the past two decades. For example, research in the mid-1980's dramatically increased in Asia. Later, in the early 1990's, there was a significant increase in research in South America (primarily in Brazil) in the area of unsaturated soils. However it should be noted that the research papers from the Brazil, 1992 conference were not included in the study because only 2 papers were in English. In both of these cases, it would appear to be the broadening of the scope of unsaturated soils that precipitated studies on slope stability and other areas. The regions of Africa and the Middle East certainly have arid conditions and a need for unsaturated soil mechanics. There has been a slow but gradual increase in studies in these areas. At the same time, it must remembered that much of the early research on expansive soils was undertaken in South Africa and in Israel. The First International Conference on Expansive Soils came about as a result discussions between Professor Buchanan in United States and Dr. Aitchison in Australia. In fact, many regions of the world participated in the series of conferences on expansive soils.

Figure 11 shows the percentage distribution for all the research papers published from the various regions of the world. If the research papers are divided between those published before and after 1992, it can be observed that certain regions of the world have had a renewed interest in the subject. North America accounted for 30% of the papers prior to 1992 and 21% subsequent to 1992. The distribution of papers by region, published at the First and Second International Conferences on Unsaturated Soils is shown on Figure 12. The three largest contributors are Asia, Europe, and North America. It is important not to read too much into the regional

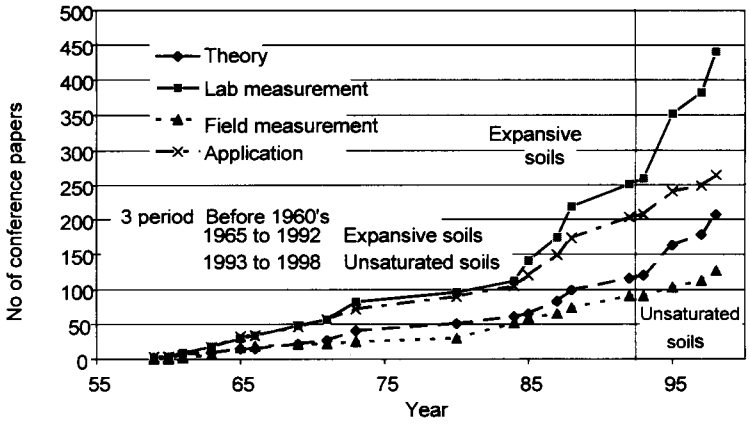


Figure 7. Number of papers in each year presented in various types of research study.

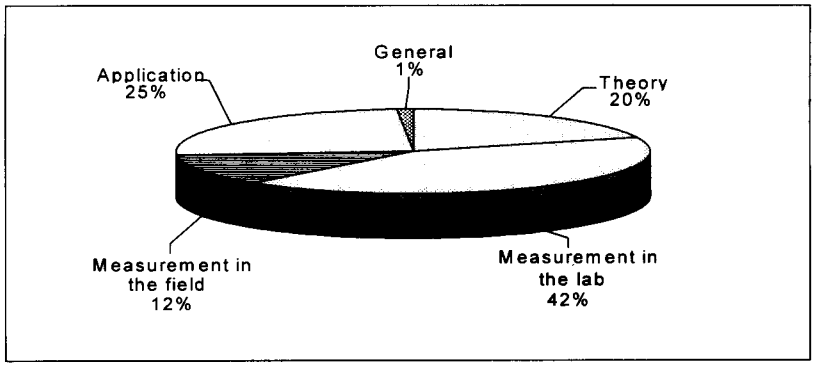


Figure 8. Percentage of papers presented in various types of research study (total of 1051).

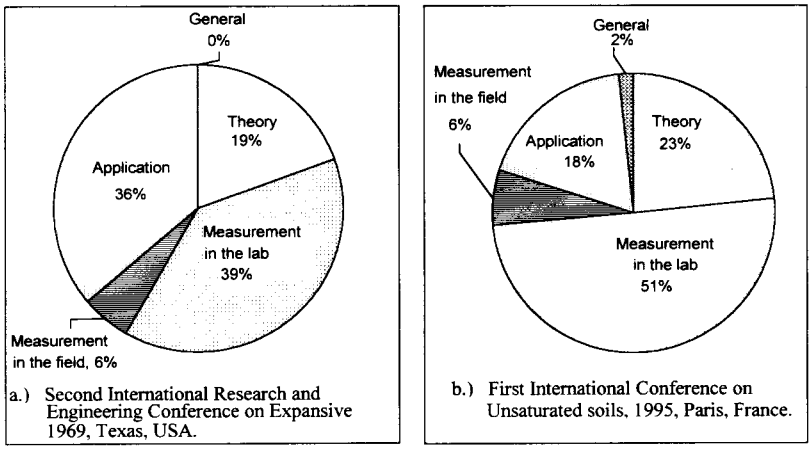


Figure 9. Percentage of papers presented in various aspects of soil property in the a.) Second International Research and Engineering Conference on Expansive Clay Soils, 1969, Texas, USA, and b.) First International Conference on Unsaturated Soils, 1995, Paris, France.

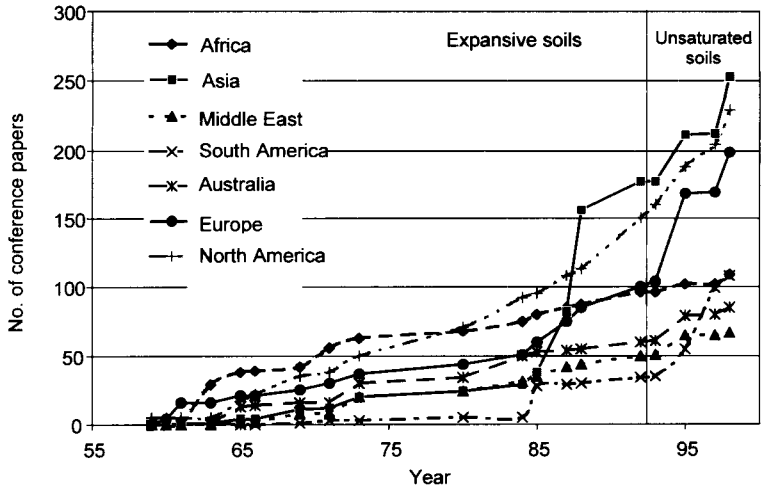


Figure 10 The cummulative number of paper published from various areas of the world.

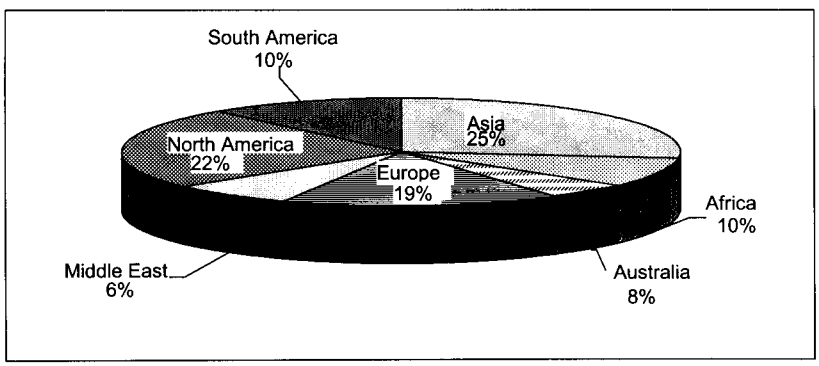


Figure 11. Percentage of research paper published from various areas of the world (total of 1051 papers)

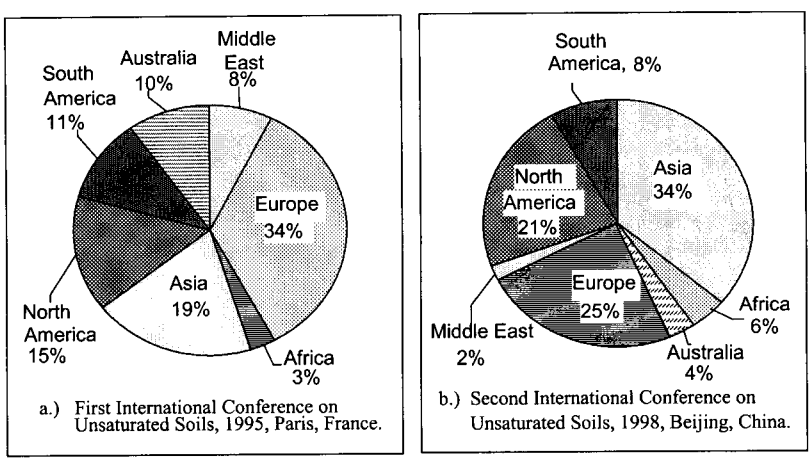


Figure 12 Percentage of research papers presented from various areas of the world in the a.) First International Conference on Unsaturated Soils, 1995, Paris, France, and b.) Second International Conference on Unsaturated Soils, 1998, Beijing, China.

analysis because there are many factors involved in the research paper distributions. For example, the commitment to unsaturated soils research may be very high in a particular area but the population or financial base may be low.

It is interesting that about 570 conference papers (i.e., 19 papers per year) were published up to 1991 and 481 papers (i.e., 69 papers per year) were published from 1992 to the present time. The figures show that there has been significant increase in research into the behavior of unsaturated soils.

3.4 *Books Published on Unsaturated Soil Behavior and Analysis*

There have been several books published that focus on the problems related to expansive and unsaturated soils. A list of books available is shown in Table 4. Three of the books deal specifically with expansive soils. The book published by Kassiff et al in 1969 contains extensive information on engineering in expansive soils areas. It is the authors impression that this book is an example of a valuable document that has not been given sufficient attention. Below is a short review of the contents of the book.

3.5 *Short Review of Pavements on Expansive Clays by G. Kassiff, M. Livneh and G. Wiseman (1969)*

Textbooks serve an important role in the development of unsaturated soil mechanics since they synthesize the "thinking" of many researchers into a somewhat a "cohesive" context. The text, "Pavements on Expansive Clays" focuses on expansive soils and pavements and appears to be the first book of its kind. The book does not address unsaturated soils in general but the experimental and experiential information presented is of great value as theories for unsaturated soil mechanics were later formalized. The authors had three objectives in mind when writing the book; namely:

1. To put forward those aspects of research into the behavior of unsaturated, expansive clays that are pertinent to the design of pavements.
2. To provide general background information that will enable the engineer with a basic knowledge of soil mechanics to follow the advances that are likely to be made in the coming years in the treatment of expansive clay subgrades.
3. To indicate design and construction recommendations that were believed to lead to successful pavement design on expansive clay subgrades.

The synthesis of material was undertaken primarily with the needs of the country of Israel in mind. However, research literature has been brought together in a logically organized manner from many countries of the world. The engineering basis for the subject is empirical and experimental.

The chapter on the *Methods of Classification and Identification of Swelling Clays* presents various procedures that have been used to identify expansive soils. The field measurements of pavement performance behavior are of great value. The final chapter uses the information on expansive soils in outlining pavement design methods. The treatment of expansive soils in pavement design is thorough and valuable for practicing geotechnical and transportation engineers. This book was written in 1969, and shows that the engineering difficulties associated with expansive were being systematically analyzed by a group of engineers in Israel. The initial intent was to produce a similar book devoted to structures on expansive clays. It is unfortunate that the second book was never completed.

4.0 UNSATURATED SOILS RESEARCH FROM THE LATE 1950'S TO THE 1960'S

Research into the volume change and shear strength of unsaturated soils commenced with new impetus in the late 1950's. Some of the researchers were Black and Croney (1957), Bishop et al., (1960), Aitchison (1967), and Williams (1957). The research resulted in the proposal of several so-called single-valued effective stress equations for unsaturated soils. During the next decade, reservations were expressed regarding the use of a single-valued effective stress equation. There was subsequently a slow change towards the acceptance of the use of two independent stress state variables (Coleman, 1962; Matyas and Radhakrishna, 1968; Fredlund and Morgenstern, 1977).

The first national conference on expansive soils was held in South Africa in 1957. Two years later, in 1959, a symposium on expansive soils was held at the Colorado School of Mines in Golden, Colorado. The proceedings from this symposium clearly described the nature of expansive soils problems and set the stage for an international series of conferences. A short review of the 1959 symposium held in Colorado is presented later.

A conference was held in London, England in 1960 where the focus was primarily of the measurement of negative pore-water pressure and its application in engineering practice. The proceedings provided a summary of valuable research information and a short review of this conference is later presented. The ASCE in United States held a Research Conference on Shear Strength of Cohesive Soils at the University of Colorado in Boulder, CO, in 1960. Much of the proceedings was devoted to better understanding the shear strength of saturated soils. However, there were a couple of important, and often referenced papers published in the proceedings. Once again, a short review of this conference is given below.

Table 4. List of Books Published Related to the Behavior of Unsaturated Soils

1969	Pavements on Expansive Clays by G. Kassif, M. Livneh, and G. Wiseman, Jerusalem Academic press, Jerusalem, Israel.
1975	Foundations on Expansive Soils, Development in Geotechnical Engineering Vol. 12 by F. H. Chen, Elsevier Scientific Publishing Co., New York, N. Y.
1992	Expansive Soils Problems and Practice in Foundation and Pavement Engineering by John D. Nelson, Debora J Miller, John Wiley & Sons, Inc., New York, N. Y.
1993	Soil Mechanics for Unsaturated Soils by D. G. Fredlund, and H. Rahardjo, John Wiley & Sons, New York, N.Y.
1999	The Emergence of Unsaturated Soil Mechanics-Fredlund Volume by A.W. Clifton, G.W. Wilson and S. L. Barbour. National Research Council of Canada, Ottawa, Canada.

4.1 *Short Review of Proceedings of the Colorado School of Mines conference on "Theoretical and Practical Treatment of Expansive Soils", October 1959.*

The first soil mechanics conference organized by the Colorado School of Mines in U.S.A., was on the timely topic of "expansive soils". There were only 5 papers presented in 1 day to the conference; however, the conference proved to be of wide interest, drawing a good attendance. The presenters to the conference were selected so as to treat the topic with recognized experience and accomplishment.

Professor Means from Oklahoma State University, presented the first paper entitled "Building on Expansive Soils". He drew upon his extensive experience with the expansive soils problem in mid-west U.S.A. The paper clearly describes the interaction between climatic conditions and the expansive soils problem. There are numerous well-described examples given that illustrate the types of damage common to expanding clays. These are followed with a section on "methods of preventing damage". Material in this paper was later be incorporated into a soil mechanics book (i.e., Physical Properties of Soils by Means and Parcher) that dedicated a significant portion to engineering with expansive soils.

Professors Lambe and Whitman presented a paper on "The Role of Effective Stress in the Behavior of Expansive Soils"; a paper that has been often referenced. An attempt was made to direct engineers to think in terms of changes in effective stress. In other words, volume increases in the soil occur because of a decrease in effective stress. In the discussion following the paper, Dr. Hilf encouraged the search of the soil science literature "which provide a theory for negative pore-water pressures in unsaturated soils".

Measurements of vertical movement in expansive soils were presented by Professor Dawson, along with a suggested method of rating climatic conditions. Holtz presented information on the properties of expansive soils and the problems often encountered in practice. The main soils discussed are the clay shales encountered in Colorado and throughout the mid-west part of U.S.A. The plots of the percent swell, and the swelling pressure, under various density and water content conditions have been often referenced.

C. McDowell reported on the relevance of laboratory tests in the design of pavements and structures on expansive soils. A graph of the relationship between volumetric swell and load was developed. It was noticed that all soils produced curves of similar shape and it was suggested that "families" of curves could be produced. These curves defined the general character of results that could be anticipated from oedometer tests and provided a means of dealing with soils that extended over a wide region such as is encountered in the design of a highway.

In the discussions following the paper presentations, Prof. Dawson suggested that more attention should be given to the measurement of negative pore-water pressures. The discussions made reference to extensive research underway on expansive soils in England and South Africa. The double oedometer tests performed in South Africa by Jenning and Knight (1957) was suggested as a testing procedure to be considered.

In the closing remarks, Walker stated, "These are expansive soils, but they are much more expensive when you have to treat them after the fact, than before the fact." It was pointed out that each of the main presenters had close to 30 years experience with problems associated with expansive soils and there is reason for optimism. For a 1-day conference, these proceedings provided a wealth of material that has been often referenced.

4.2 *Short Review of Pore Pressure and Suction in Soils, Conference held in March 1960 and the Proceedings were published in 1961*

The conference, attended by over 160 people from 6 countries, was held in March, 1960 and the proceedings were published in 1961. In total, 17 papers were presented for discussion along with an opening address by Prof. Skempton on "Effective Stress in Soils, Concrete and Rocks". The conference focused on fundamental theories and behavior, with all but 3 papers dealing with unsaturated soils. The

conference was also an attempt to synthesize efforts of the Institution of Civil Engineers in the international field.

The conference was most appropriately titled since the emphasis was on the measurement of negative pore-water pressures and soil suction. It had become obvious that matric suction (i.e., $u_a - u_w$ where u_a = pore-air pressure and u_w = pore-water pressure) was the primary stress variable to which unsaturated soil behavior must be related. There was a reinforcement of Bishop's (1959) effective stress equation where the soil property χ, was primarily related to the degree of saturation of the soil. Other similar forms for an effective stress equation for unsaturated soils were presented by Aitchison (Australia), Jennings (South Africa) and, Croney and Coleman (England). There was considerable discussion on the meaning of soil suction and the form that a single-valued equation should take but there was no question regarding the importance of soil suction in describing soil behavior.

A key set of experimental data was presented by Croney and Coleman. The data is the first complete soil-water characteristic curve published in geotechnical engineering. Later, it would become more common to interchange the variables on the abscissa and ordinate. The data for a heavy clay, also presents a shrinkage curve and the soil suction versus water content plot for a continuously disturbed soil. The data provides clear evidence of a soil suction value of 1,000,000 kPa at zero water content.

The proceedings of the Pore Pressure and Suction in Soils conference should be read by every student of unsaturated soil behavior. The laboratory and field test results have much to teach us about the importance of careful and meticulous data collection. Experimental testing information on high air entry disks continue to form the basis for most laboratory research on unsaturated soils.

4.3 *Short Review of ASCE, Research Conference on Shear Strength of Cohesive Soils, University of Colorado, Boulder, CO, June, 1960*

The purpose of the ASCE conference was to assemble, summarize and discuss present knowledge of factors governing the shear strength of cohesive soils. A portion of the conference was devoted to the shear strength of compacted cohesive soils. Approximately 400 engineers from 18 countries attended the conference. While the scope was narrow, the impact of the conference was substantial.

The reviewers of the research papers noted that there was controversy and uncertainty regarding negative pore-water pressures, and whether it was necessary to measure pore-air pressure. In general, Bishop's equation was endorsed but engineers were cautioned about assuming that χ is a given soil property dependent only on degree of saturation.

Seed and Hirschfeld (1960) noted that the shear strength of compacted, cohesive soils is a "subject that has probably undergone a more rapid development in the past ten years than any other aspect of strength". These early insights into the shear strength of compacted soils are likely the reason why shear strength became the first area to be developed in unsaturated soil mechanics. There was much discussion on the measurement of negative pore-water pressures that were felt to be inherently difficult to measure. At the same time, the papers by Bishop and Bjerrum (1960) (i.e., The Relevance of the Triaxial Test to the Solution of Stability Problems) and by Bishop, Alpan, Blight and Donald (1960) (i.e., Factors Controlling the Strength of Partly Saturated Cohesive Soils) provided a wealth of information on the laboratory testing of unsaturated soils. The "ingenious techniques and the use of very fine ceramic disks instead of the conventional coarse porous stones" opened the way for measuring very negative pore-water pressures.

The ASCE Boulder Conference of 1960 has gone down in history as an important conference on shear strength and this is equally true for unsaturated soils. Shear strength was addressed from a fundamental and classical soil mechanics standpoint. The "ground work" had been laid but it would take almost two more decades before the next significant steps forward would be taken in further understanding the shear strength of unsaturated soils.

5 UNSATURATED SOILS RESEARCH (PRIMARILY EXPANSIVE SOILS RESEARCH) FROM THE 1965 TO THE 1992

The First International Conference on Expansive Soils was held at Texas A & M University in 1965. Also delivered to the conference was a Symposium-in-Print edited by Dr. G. Aitchison of Australia. The proceedings of the conference, along with the Symposium-in-Print formed an informative, complimentary combination that would set the stage for subsequent conferences on expansive soils. The Symposium-in-Print started with a review of the theory related to soils with negative pore-water pressures, as viewed from the Soil Science and Soil Physics disciplines. This information has proved to be of value in forming an understanding of the differences between the way soil behavior was viewed in the earth sciences and in geotechnical engineering. With time, it has been found to be necessary to modify some of the theories of soil behavior to better fit the geotechnical engineering profession. The international series of conferences on expansive soils took place, approximately every four years over the period from 1965 to 1992 (Table. 1).

The series of conferences did much to bring attention to the lack of understanding associated with

soils with negative pore-water pressures and in particular, expansive soils. Each of the conferences provided ample examples of buildings and other engineered structures that had cracked due to expansive soils. While these pictures and case histories were important, they did not appear to produce the development of a consistent theoretical framework for understanding the general behavior of unsaturated soils.

It is observed in the analysis of the papers presented to the conferences that the high percentage of research papers were devoted to volume change problems. In particular there was considerable emphasis on the formulation of mathematical models for the prediction of heave. These models were one-dimensional in character and were formulated to follow either the suction change stress path or the total stress change path. Even though many of the problems were two-dimensional in character, the models to predict heave remained one-dimensional. In general, there seemed to be a lack in fully understanding the theory associated with volume change behavior. Even with the largest number of research papers having been presented on the volume change problem, it would still appear that even today, it is the volume change behavior that still requires the most research. It can quite clearly be stated that the volume change problem is the most difficult aspect of unsaturated soil behavior to fully understand and use in geotechnical engineering practice.

There were several other conferences during the period from 1965 to 1992 that provided further understanding of the expansive soils problem as well as extending the scope of problems to include problems related to residual soils, collapsing soils, compacted soils and soils in arid regions. The conference on tropical Lateritic and Saprolitic soils in Brasilia in 1985, brought attention to the engineering problems unique to residual soils. However, there was a common aspect that placed the behavior of residual soils into the same category as expansive soils; namely, the pore-water pressures were negative.

A conference on regional problematic soils was held in Beijing in 1988. The proceedings contained considerable information on the behavior of collapsible soils as well as compacted, residual and expansive soils. In fact, four of the five main problematic soils discussed at the conference were soils with negative pore-water pressures.

6 UNSATURATED SOILS RESEARCH FROM 1993 TO THE PRESENT

In the early 1990's, there was general concensus that the scope of the expansive soils conferences should be expanded to more accurately reflect problems encountered in geotechnical engineering practice. Under the leadership of the President of the ISSMFE, Dr. Morgenstern, it was moved that the TC6 subcommittee on expansive soils should be renamed to the sub-committee on unsaturated soils. This change in emphasis was reflected in the cross-section of research papers submitted to the 7th International Conference on Expansive Soils held in Dallas, Texas in 1992.

The change in name from expansive soil to unsaturated soils rekindled an interest in seeing a soil mechanics developed for unsaturated soils that was parallel in context to that enjoyed within saturated soil mechanics. The First International Conference on Unsaturated Soils was held in Paris, France in 1995. The interest in the broader scope of topics in unsaturated soils was obvious from the response to the call for papers. The conference drew a record number of participants from all over the world. Similarly, the Second International Conference on Unsaturated Soils in Beijing, China in 1998 attracted widespread interest. The Third International Conference on Unsaturated Soils is presently being planned for Brazil in 2002.

In addition to the series of international conferences, a number of national conferences have been organized. Table 1 lists other unsaturated soils conferences that have been organized, such as those in the United States and Brazil. There presently appears to be considerable interest in the general area of unsaturated soils behavior. It appears that there are new opportunities on the horizon for the implementation of unsaturated soils theories in standard geotechnical engineering practice.

It is of value to review the steps that are required in moving from a science that is studied in the laboratory to its implementation in engineering practice. Such a review will provide an understanding of what has been accomplished to-date and what aspects still require further research.

7 STAGES IN MOVING TOWARDS THE IMPLEMENTATION OF UNSATURATED SOIL MECHANICS

The progress in developing a science basis for unsaturated soil mechanics can be viewed in terms of a series of stages leading towards implementation. The stages leading towards implementation are listed in Figure 13 (Fredlund, 1999). Research studies over the past 6 decades has been directed at all stages leading towards an appropriate technology for implementation.

7.1 *The State Variable Stage*

The state variable stage is the most basic and fundamental level at which a science for unsaturated soil behavior can be initiated. The most important state variables for an unsaturated soil are the stress

state variables; namely the net normal stress, [$(\sigma-u_a)$ where σ = total stress and u_a = pore-air pressure], and the matric suction, [(u_a-u_w) where u_w = pore-water pressure)]. These state variables have become widely accepted and illustrate the need to separate the effects of total stress and pore-water pressure when the pore-water pressures are negative. There is also a smooth transition between the saturated and unsaturated states. The matrix form of the stress tensors for an unsaturated soil are shown in Equation (1).

$$\begin{bmatrix} (\sigma_x - u_a) & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & (\sigma_y - u_a) & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & (\sigma_z - u_a) \end{bmatrix} \quad (1a)$$

$$\begin{bmatrix} (u_a - u_w) & 0 & 0 \\ 0 & (u_a - u_w) & 0 \\ 0 & 0 & (u_a - u_w) \end{bmatrix} \quad (1b)$$

7.2 *The Constitutive Stage*

The constitutive stage becomes the point at which empirical, semi-empirical and possibly theoretical relationships between state variables are proposed and verified. The verification of proposed constitutive relations must be conducted for a wide range of soils in order to ensure uniqueness, and subsequently confidence on the part of the practicing engineer. Extensive research studies on constitutive relationships for unsaturated soils were made in the 1970's but earlier and later developments have also contributed to our understanding of unsaturated soil behavior.

7.3 *The Formulation Stage*

The formulation stage involves combining the constitutive behavior of a material with the conservation laws of physics applied to an elemental volume. The result is generally a partial differential equation that describes a designated process for an element of the continuum.

7.4 *The Solution Stage*

The solution stage involves solving specific examples representative of a class of problems. At the solution stage, the partial differential equations are converted to a numerical solution that becomes known as a software package.

7.5 *The Design Stage*

The is a gradual increase in engineering confidence as research progresses from the formulation stage, to the solution stage and on to the design stage. The design stage focuses on the primary unknowns that must be quantified from a practical engineering standpoint. The design stage generally involves a quantification of geometric and soil property variables that become part of an engineering design. The computer has an important role in the design of earth systems (Fredlund, 1996) and has changed the way in which geotechnical designs are conducted and design generally takes the form of a parametric type study.

7.6 *The Verification and Monitoring Stage*

There is need to "observe" the behavior of any infrastructure during construction and subsequent to construction in order to provide feedback to the designer. Only through field monitoring and feedback can confidence be firmly established in the design procedures. The "observational method" as defined by Peck (1969) goes even beyond the verification of design and is considered to be a part of the design process.

7.7 *The Implementation Stage*

The implementation stage may not be realized in engineering practice even when the theoretical formulations and related design procedures have been fully studied and verified. Implementation is the final stage in bringing an engineering science into routine engineering practice. Other factors that need to be addressed at the implementation level are: i.) the cost of undertaking any special site investigations, soil testing and engineering analyses, ii.) the human resistance to change, and iii.) the political, regulatory and litigation factors that may be involved.

The slowness in the implementation of unsaturated soil mechanics appears to be related to the cost of soil testing for the quantification of soil properties. The old soil mechanics paradigm involving the direct measurement of soil properties becomes extremely costly when measuring unsaturated soil property functions. However, there are a number of other procedures that provide a new paradigm for evaluating unsaturated soil property functions. New procedures have been proposed, and are necessary for the assessment of unsaturated soil property functions (Fredlund, 1999).

The field of unsaturated soil mechanics has developed through a series of stages and today engineers are faced with the challenge of implementing a new science as part of geotechnical engineering. This may prove to be the greatest challenge; one on which further research is still required. At the same time it is the challenge that can open the door to unique technological applications and financial rewards.

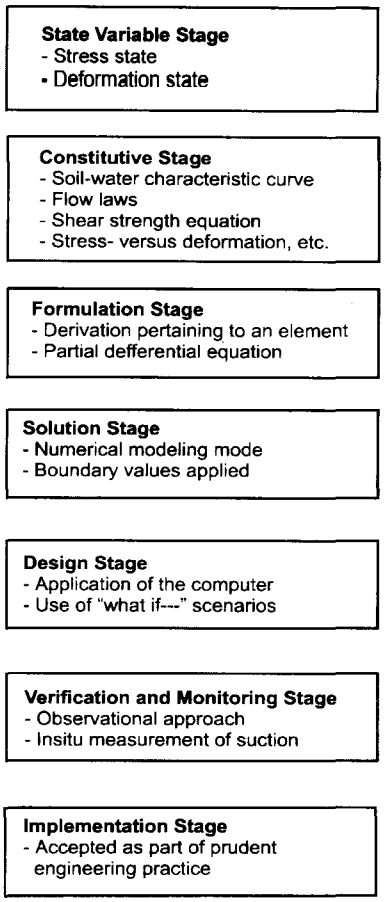


Figure 13. Primary stages leading towards the successful implementation of unsaturated soil mechanics.

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