1

CANADIAN THESES ON MICROFICHE

I.S.B.N.

THESES CANADIENNES SUR MICROFICHE

National Library of Canada
Collections Development Branch

Canadian Theses on
Microfiche Service

Ottawa, Canada
K1A 0N4

Bibliothèque nationale du Canada
Direction du développement des collections

Service des thèses canadiennes
sur microfiche

NOTICE

The quality of this microfiche is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us a poor photocopy.

Previously copyrighted materials (journal articles, published tests, etc.) are not filmed.

Reproduction in full or in part of this film is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30. Please read the authorization forms which accompany this thesis.

**THIS DISSERTATION
HAS BEEN MICROFILMED
EXACTLY AS RECEIVED**

AVIS

La qualité de cette microfiche dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de mauvaise qualité.

Les documents qui font déjà l'objet d'un droit d'auteur (articles de revue, examens publiés, etc.) ne sont pas microfilmés.

La reproduction, même partielle, de ce microfilm est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30. Veuillez prendre connaissance des formules d'autorisation qui accompagnent cette thèse.

**LA THÈSE A ÉTÉ
MICROFILMÉE TELLE QUE
NOUS L'AVONS REÇUE**

National Library
of Canada

Bibliothèque nationale
du Canada

CANADIAN THESES
ON MICROFICHE

THÈSES CANADIENNES
SUR MICROFICHE

59919

NAME OF AUTHOR/NOM DE L'AUTEUR Paul Joseph Conlon

TITLE OF THESIS/TITRE DE LA THÈSE The Influence Of Geochemical Variables

On Selected Engineering And Electrical

Properties Of Re-Sedimented Leda Clay

UNIVERSITY/UNIVERSITÉ Carleton University

DEGREE FOR WHICH THESIS WAS PRESENTED/
GRADE POUR LEQUEL CETTE THÈSE FUT PRÉSENTÉE Ph.D.

YEAR THIS DEGREE CONFERRED/ANNÉE D'OBTENTION DE CE DEGRÉ 1983

NAME OF SUPERVISOR/NOM DU DIRECTEUR DE THÈSE J. Kenneth Torrance

Permission is hereby granted to the NATIONAL LIBRARY OF
CANADA to microfilm this thesis and to lend or sell copies
of the film.

The author reserves other publication rights, and neither the
thesis nor extensive extracts from it may be printed or other-
wise reproduced without the author's written permission.

*L'autorisation est, par la présente, accordée à la BIBLIOTHÈQUE
NATIONALE DU CANADA de microfilmer cette thèse
de prêter ou de vendre des exemplaires du film.*

*L'auteur se réserve les autres droits de publication; ni
thèse ni de longs extraits de celle-ci ne doivent être imprimés
ou autrement reproduits sans l'autorisation écrite de l'auteur.*

DATED/DATE May 16, 1983

SIGNED/SIGNÉ

Paul J. Conlon

PERMANENT ADDRESS/RÉSIDENCE FIXE

P.O. Box 489 - 9 Edward St.

Manotick, Ontario K0A 2N0, Canada

THE INFLUENCE OF GEOCHEMICAL VARIABLES
ON SELECTED ENGINEERING AND ELECTRICAL
PROPERTIES OF RE-SEDIMENTED LEDA CLAY

by

© Paul Joseph Conlon

A thesis submitted to
The Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for
the degree of
DOCTOR OF PHILOSOPHY
in
CIVIL ENGINEERING

Faculty of Engineering
Carleton University
Ottawa, Ontario
March 19, 1983

The undersigned hereby recommend to the Faculty of
Graduate Studies and Research acceptance of the thesis,

submitted by

PAUL JOSEPH CONLON

in partial fulfilment of the requirements for
the degree of Doctor of Philosophy

A.P.S. Selvadurai

.....
Chairman, Department of Civil Engineering
Professor A.P.S. Selvadurai

J. Kenneth Torrance

.....
Thesis Supervisor
Professor J.K. Torrance

R.J. Mitchell

.....
External Examiner
Professor R.J. Mitchell, Queen's University

ABSTRACT

Leda Clay is a general name applied to the post-glacial marine sediments of the St. Lawrence and Ottawa River Valleys. Like its Scandinavian counterparts, Leda Clay is a sensitive, landslide-prone soil which has been responsible for considerable loss of human life and property.

Studies of naturally occurring deposits of Leda Clay are made difficult by the variability of this material, both vertically within a single borehole and geographically as well. For this reason, the present study was undertaken with a controlled suite of laboratory samples. These were generated by re-sedimenting, re-consolidating and leaching Leda Clay under conditions similar to those prevailing when the sediment originally accumulated. Specially designed equipment and procedures achieved their intended purpose, but some chemical changes do appear to have occurred, apparently as a result of the oxidizing conditions prevailing in the laboratory.

The reconstituted samples were subjected to extensive testing using an integrated program which allowed many tests to be performed on each relatively small sample. Tests included determination of the particle-size distribution, the water content, the Atterberg limits, the oxidation-reduction potential, the pH, the cation-exchange capacity and the coefficient of permeability. The concentrations of pore-water cations and adsorbed cations were also determined. A special procedure was devised to measure the diffusion coefficient of the samples. These tests indicated that the samples were similar in most respects to naturally occurring material. One exception has been alluded to above: the oxidizing conditions of the

laboratory are thought to have caused weathering of the samples. This is inferred from the liquid limits of the laboratory samples, which were observed to be higher than that of the naturally occurring material used for the experiment. It was also noted that certain edge effects resulted from the sedimentation of the clay in the cylindrical apparatus.

A specially designed vane apparatus and procedures were developed to determine the deformability characteristics and shear strength of the samples. It was possible to measure very small elastic deformations in both undisturbed and remolded material. In the case of the undisturbed soil, the elastic response was found to be principally related to the degree of consolidation and the degree of flocculation. The elastic recovery of some remolded soils was as high as 100%.

The undisturbed and remolded shear strengths determined by the vane were generally found to be higher than those obtained with a conventional fall-cone device. A definite relationship was found to exist between the two sets of values and an equation has been developed to express this. The remolded shear strength increased with increasing salinity of the pore water. The sensitivity of the samples was found to be related to the percent of monovalent cations in the pore water. The greatest sensitivity was exhibited by samples to which colloidal SiO_2 had been added.

A system was designed and built to measure the induced-polarization (IP) response and other electrical properties of the samples. The impedance and the steady-state voltage were found to be related to the pore-water salinity. Not all samples exhibited an IP response. The time-dependent rise in voltage exhibited by samples having an IP response was also found to be related to the pore-water salinity. The IP response of these clay samples was comparable to mineralized rock containing 2% to 8% disseminated sulphides.

The results of this research indicate that profitable areas for future research include more detailed investigations of: the elastic properties of undisturbed and remolded soils; the induced-polarization response and other electrical properties of soils; and the diffusion rates of ions in soils.

PREFACE

This thesis has had a longer than normal gestation period, one which was marked by as many frustrations as triumphs. I am convinced that it would never have been successfully completed without the help of many people and it is with great pleasure that I take this opportunity to publicly express my gratitude to them.

A special thanks must first go to Ken Torrance who has not only been my Professor and Supervisor, but a real friend and colleague as well. I have not worked with a more able scientist. The Geography Department provided the necessary laboratory facilities and members of the staff supported and encouraged my research. Laurent Boyle and Alan Pendlington were the two very capable technicians who fabricated much of the equipment, attended to a myriad of details and offered valuable advice on many occasions.

I am indebted to Patrick Selvadurai who supported and encouraged the use of the vane apparatus to measure the strength and deformation characteristics of my soil samples and who guided my progress within the Department of Civil Engineering. I also appreciated the interest and encouragement of other members of the department.

The Geological Survey of Canada supported the research on the electrical response of my soil samples. I am particularly grateful to Peter Annan (now of A-Cubed, Inc.) and Les Davis (now of Earthteck, Inc.) for their assistance with this aspect of my research. My association with them was a very intellectually stimulating and memorable experience.

The final stages of experimentation could not have been completed without the help of Hugh McKinnon and Maria Pirnat. They were eager and cheerful helpers whose work was of the highest quality. Norman Miles, of Agriculture Canada, was kind enough to do the X-ray diffraction analysis of my soil material.

I am also grateful to Beverley McMillan for the fine job of typing which is evident in the pages that follow. The Atomic Energy Control Board was kind enough to allow the use of its facilities for the reproduction of the thesis. My colleagues at work were also especially understanding with respect to the distraction the thesis became during its final months of preparation.

To the many others who have helped in one way or another, I offer my heartfelt thanks.

My final acknowledgement is unquestionably the most important. This thesis has consumed a disproportionate share of my time and energy and my wife and children have had to settle for less of my attention than they deserved. In spite of this, they have encouraged and supported my efforts and have assisted with many of the details. I therefore happily dedicate this thesis to them.

TABLE OF CONTENTS

ABSTRACT	ii
PREFACE	v
TABLE OF CONTENTS	vii
LIST OF FIGURES	xiii
LIST OF TABLES	xvii
CHAPTER	
1 INTRODUCTION	1
1.1 Post-Glacial Marine Clays	1
1.1.1 Leda Clay	2
1.1.2 Mineralogy of Leda Clay	2
1.1.3 Geotechnical Properties of Leda Clay	3
1.2 Experimental Program	5
1.2.1 Conceptual Framework for Research	5
1.2.2 Research Objectives and Approach	7
1.2.3 Soil System Properties Measured	8
1.2.3.1 Mechanical Properties	8
1.2.3.2 Electrical Properties	8
1.2.3.3 Chemical and Hydraulic Properties	9
1.2.4 Controlling Variables Examined	9
2 SEDIMENTATION -- EQUIPMENT AND PROCEDURE	13
2.1 Objective	13
2.2 Sedimentation Apparatus	15
2.2.1 Design Objectives	15
2.2.2 Description of Sedimentation Apparatus	15
2.2.3 Assembly of Apparatus and Laboratory Set-Up	16
2.3 Chemistry of Sedimentary Environment	19
2.4 Soil Material	22
2.4.1 Source	22
2.4.2 Initial Soil Preparation and Storage	22
2.4.3 Preparation of Soil Material for Experiment	23
2.4.3.1 Dispersion	23
2.4.3.2 Soil Aliquots	24
2.4.4 Adjustment of Particle-Size Distribution	26

2.4.5	Addition of SiO ₂ to Soil Material	26
2.5	Addition of Soil	27
2.6	Consolidation During Sedimentation	30
3	CONSOLIDATION -- EQUIPMENT AND PROCEDURE	31
3.1	General Considerations	31
3.2	Second Phase of Consolidation	32
3.3	Third Phase of Consolidation	35
3.4	Fourth Phase of Consolidation	40
4	LEACHING -- EQUIPMENT AND PROCEDURE	43
4.1	Preliminary Considerations	43
4.2	Leaching Apparatus	45
4.3	Leaching Solutions	47
5	MEASUREMENT OF SHEAR MODULUS -- EQUIPMENT AND PROCEDURE	48
5.1	Nature of Test	48
5.2	Vane Apparatus	49
5.2.1	Application of Torque	49
5.2.1.1	Vane and Shaft Assembly	49
5.2.1.2	Loading of Sample	53
5.2.2	Measurement of Rotation	55
5.3	Test Procedure	56
5.3.1	Preparation of Sample	56
5.3.2	Insertion of Vane into Soil	58
5.3.3	Cyclic Loading and Unloading	58
5.3.4	Loading to Failure	59
5.3.5	Remolded Shear Strength	59
5.4	Potential for Comparison of Results with Triaxial Test.	61
6	MEASUREMENT OF LOW-FREQUENCY ELECTRICAL PROPERTIES -- EQUIPMENT AND PROCEDURE	63
6.1	Fundamental Considerations and Objectives	63
6.2	General Considerations Governing Design of the System..	65
6.2.1	Wave Form	65
6.2.2	Electrodes	66
6.2.3	Receiver	66
6.3	Layout of the System	67
6.3.1	System Block Diagram	67
6.3.2	System Ground Connections	67
6.4	Excitation System	69
6.4.1	External Timing Device	69
6.4.1.1	Precision Timing Device	69
6.4.1.2	Square Wave Oscillator	70
6.4.2	Transmitter	71
6.4.2.1	Switch Network	73
6.4.2.2	Signal Conditioning	73
6.4.2.3	Switch Logic	76

6.4.3	Constant Current Source	77
6.4.3.1	Bilateral Current Source	79
6.4.3.2	Control Voltage Circuit	80
6.4.3.3	Control Resistance Circuit	81
6.4.3.4	Current Source Switches	81
6.5	Sample and Electrodes	82
6.6	Receiver and Self-Potential Buckout Circuit	84
6.6.1	Receiver Amplifiers	87
6.6.2	Receiver Switches	89
6.6.3	Self-Potential Buckout Circuit	89
6.6.4	Calibration of Receiver Gain	90
6.7	Data Acquisition, Storage and Processing	93
7	AUXILIARY TESTS AND MEASUREMENTS	94
7.1	Coefficient of Permeability	94
7.2	Water Content	95
7.3	Particle-Size Distribution	96
7.4	Pore-Water Chemistry	98
7.4.1	Initial Estimate of Leaching Effectiveness....	98
7.4.1.1	Equilibration Technique	98
7.4.1.2	Diffusion Technique	99
7.4.2	Pore-Water Extraction	100
7.4.3	Dilution of Pore-Water Sample	101
7.4.4	Measurement of Cation Concentrations in Pore Water	101
7.5	Shear Strength	102
7.6	Atterberg Limits	103
7.7	Miscellaneous Chemical Tests	105
7.7.1	Sample Eh and pH	105
7.7.2	Cation-Exchange Capacity	105
7.7.3	Ammonium-Acetate-Extractable Cations (Exchangeable Bases)	105
7.8	Procedure for Sample Testing	107
8	RESULTS, CONCLUSIONS AND FUTURE DIRECTIONS	109
8.1	Framework for Presentation of Results	109
8.2	Preparation of Samples	111
8.2.1	Sedimentation	111
8.2.1.1	Particle-Size Distribution	111
8.2.1.2	Particle Mineralogy	116
8.2.1.3	Chemistry of Sedimentary Environment	117
8.2.1.4	Suspended-Sediment Concentration	117
8.2.1.5	Sediment-Water Interface	118
8.2.1.6	Flocculation	119
8.2.1.7	Cyclic Banding	121

8.2.2	Consolidation	122
8.2.3	Leaching	123
8.2.4	Possibility of Weathering or Similar Chemical Changes	126
8.3	Chemical Properties of the Soil Systems	129
8.3.1	Redox Potential and pH	129
8.3.2	Cation-Exchange Capacity and Ammonium-Acetate- Extractable Cations (Exchangeable Bases)	132
8.3.3	Diffusion Coefficient	135
8.4	Hydraulic Properties of the Soil Systems	137
8.5	Mechanical Properties of the Soil Systems	138
8.5.1	Nature of Information Obtained	138
8.5.2	Graphical Analysis	138
8.5.3	Elastic Parameters	138
8.5.4	Elastic Recovery	145
8.5.5	Shear Strength and Sensitivity	149
8.5.6	Equipment Modifications	159
8.6	Electrical Properties of the Soil Systems	160
8.6.1	Nature of Information Obtained	160
8.6.2	Conceptual Model of Processes	160
8.6.3	Parameters Examined	165
8.6.4	Observed Trends and Relationships	168
8.7	General Conclusions and Directions for Future Research	177
8.7.1	Objectives Achieved	177
8.7.1.1	Sample Preparation	177
8.7.1.2	Development of Soil-Property- Measurement Equipment and Testing Procedures	177A
8.7.1.3	Experimental Observations	177A
8.7.2	Future Research	178
8.7.2.1	Controlling Variables	178
8.7.2.2	Determination of Poisson's Ratio	179
8.7.2.3	Shear Strength Determinations With the Vane and The Fall Cone	180
8.7.2.4	Full Penetration of the Vane	180
8.7.2.5	Extended Analysis of the Electrical- Property Data	180
8.7.2.6	Field Application of Induced Polarization to Soils	180
8.7.2.7	Correlation of IP Response With Electrokinetic Potential	181
8.7.2.8	Examining the IP Response of Soils as an Aid to Mineral Exploration	182
8.7.2.9	Diffusion in Soils	182

APPENDIX A	A SUMMARY OF DIFFUSE DOUBLE-LAYER THEORY WITH APPLICATION TO CLAY-WATER-ELECTROLYTE SYSTEMS	184
A.1	Introduction	184
A.1.1	Technology	184
A.1.2	A Sigmoidal Solution	185
A.1.3	Particle Charge	186
A.1.4	Soil Structure	187
A.1.5	Clay-Water-Electrolyte System	187
A.2	Processes by Which Particles Acquire Charge	188
A.2.1	Usual Process Due to Surface Effect	188
A.2.2	Factors Which Control the Nature and Magnitude of Charge	189
A.2.3	The Origin of Charge on Clay Minerals	191
A.3	Description of the Diffuse Double Layer	193
A.3.1	Ion Distribution Adjacent to a Charged Particle	193
A.3.2	Mathematical Description of the Diffuse Double Layer	195
A.3.3	Examination of Assumptions Invoked in Analysis	199
A.3.4	The Stern Layer	201
A.4	The Effect of Concentration and Valence Changes on the Diffuse Double Layer	203
A.4.1	Thickness of the Diffuse Double Layer	203
A.4.2	Increase of Valence or Concentration	204
A.4.3	Surface of Constant Charge vs. Surface of Constant Potential	206
A.5	Stability and Flocculation	210
A.5.1	Competing Forces	210
A.5.2	Net Interactive Force	211
A.5.3	Application to Clay-Water-Electrolyte System ...	213
A.5.4	Implications With Respect to Leda Clay	215
APPENDIX B	SUMMARY OF RELEVANT THEORY AND CALCULATIONS PERTAINING TO THE MEASUREMENT OF THE SHEAR MODULUS OF A SOIL BY MEANS OF A CIRCULAR VANE	218
B.1	Theoretical Basis for Apparatus and Experiment of Chapter 5	218
B.1.1	Underlying Assumptions	218
B.1.2	Resulting Equations	219
B.2	Computational Relationships Pertaining to the Apparatus Described in Chapter 5	221
B.2.1	Angular Relationships Existing in the Telescope/Mirror System	221
B.2.2	Considerations Pertaining to the Load Added by Means of the Floating Weight	223
B.2.2.1	Correction for Movement of the Water Bath	223
B.2.2.2	Initial Load When the Weight is Floating Vertically in the Bath	223
B.2.2.3	Correction for Surface Tension	224

B.2.2.4	Error in Weight Applied Resulting from Rotation of Shaft	225
B.2.2.5	Error Due to Bubbles Attached to Weight	225
B.2.3	Miscellaneous Errors	225
B.2.3.1	Error Due to Twist in Vane Shaft	225
B.2.3.2	Error Due to Friction in Shaft and Pulley Bearings	226
B.3	Determination of Deformability and Strength Characteristics from Experimental Data	227
B.3.1	Evaluation of the Modulus of Elasticity	227
B.3.2	Determination of the Shear Strength	228
APPENDIX C	A COMPENDIUM OF INFORMATION PERTAINING TO THE MEASUREMENT OF THE LOW-FREQUENCY ELECTRICAL PROPERTIES OF A SOIL BY MEANS OF AN INDUCED POLARIZATION TECHNIQUE	229
C.1	Introduction	229
C.1.1	Electrical Phenomena Associated With a Clay-Water-Electrolyte System	229
C.1.2	The Electrokinetic Potential of Leda Clay	230
C.1.2.1	Previous Study	230
C.1.2.2	Present Study	231
C.2	The Phenomenon of Induced Polarization or Overvoltage	232
C.2.1	The Observed IP Effect	232
C.2.1.1	Transient Decay Voltage	232
C.2.1.2	Frequency Dependence	232
C.2.1.3	Equivalence of Time and Frequency Responses	234
C.2.2	The Causes of IP or Overvoltage	236
C.2.2.1	Electrode Polarization	236
C.2.2.2	Membrane Polarization and Ion Sieving	237
C.2.2.3	Electrokinetic Polarization	239
C.2.2.4	Miscellaneous	240
APPENDIX D	SUMMARY OF ANALYTICAL BASIS FOR DIFFUSION EXPERIMENT ..	241
D.1	General Equations	241
D.1.1	Fick's Laws of Diffusion	241
D.1.2	Heat Transfer Analogues	241
D.1.3	Corresponding Parameters	243
D.2	Specific Solutions	244
D.2.1	Transient Heat Conduction in a Plane of Infinite Extent	244
D.2.2	Diffusion Analogue	245
D.3	Practical Considerations	246
D.3.1	Limiting Assumptions	246
D.3.2	Factors Influencing the Diffusion Rate in Soils	246
D.3.3	Composite Diffusion Coefficient	247
REFERENCES		248

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1.1	Conceptual framework for experimental program.	6
2.1	Schematic diagram of sedimentation cylinder.	17
2.2	Assembled sedimentation cylinder.	17
3.1	Schematic diagram of load-application assembly.	36
3.2	Sedimentation cylinder with load-application assembly inserted.	36
3.3	Application of load by means of prepared cannisters of lead shot.	38
3.4	Use of loading rack to apply loads to samples.	41
4.1	Leaching of soil by passing solution through porous stones.	44
5.1	Vane apparatus for application of torque to a soil sample, consisting of a vane, a mirror, a moveable platform beneath the vane for carrying the sample and a moveable platform for carrying the water bath.	50
5.2	Telescope/scale apparatus for measuring soil deformation.	51
5.3	Vane and shaft assembly.	52
5.4	Application of load by floating weight.	54
5.5	Application of load by addition of discrete weights.	54
5.6	Schematic diagram of device to support soil sample during vane test and to subsequently extrude soil for other testing.	57
5.7	Method of inserting vane into soil by driving sample upwards.	57
6.1	Square wave with 50% duty cycle.	66
6.2	System layout.	68
6.3	System ground connections.	68
6.4	Functional diagram of precision timing device.	70
6.5	Negative-clipping circuit.	71
6.6	Functional diagram of transmitter.	72
6.7	Circuit diagram of transmitter.	72
6.8	Pulse trains for transmitter switches.	74

<u>Figure</u>		<u>Page</u>
6.9	Development of pulse trains within transmitter.	74
6.10	Functional diagram of constant current source.	78
6.11	Circuit diagram of constant current source.	78
6.12	Sample and electrode assembly.	82
6.13	Functional diagram of receiver.	84
6.14	Circuit diagram of receiver amplifiers.	85
6.15	Circuit diagram of receiver switches.	86
6.16	Self-potential buckout circuit.	91
6.17	Circuit for calibration of receiver gain.	91
8.1	Vertical cross-section through water-sediment interface along axis of sedimentation cylinder.	118
8.1A	Illustration of cyclic banding in Sample 16.	121A
8.2	Idealized torque/twist curves to illustrate the general nature of the information obtained for undisturbed and remolded samples.	139
8.3	Torque/twist curves for Sample 18, undisturbed and remolded.	140
8.4	Reloading curves (segment B) for Sample 18, undisturbed and remolded, showing the initial tangents to the curves.	141
8.5	Torque/twist relationship for Sample 11, remolded, showing complete recovery of strain.	148
8.6	Relationship between values of shear strength obtained by fall cone and by circular vane.	153
8.7	Remolded shear strength versus liquidity index for experimental samples	155
8.8	Sensitivity versus liquidity index for experimental samples.	156
8.9	Relationship between sensitivity and percent monovalent cations (based on concentrations expressed as meq./l.) for Leda Clay with low pore-water salinity (< 2 g./l. expressed as NaCl). Circled points are from Penner (1965); others are from this experiment.	158
8.10	Typical diagrams of voltage versus time and impedance versus frequency for a sample showing no induced-polarization response.	161
8.11	Typical diagrams of voltage versus time and impedance versus frequency for a sample showing an induced-polarization response.	162
8.12	Diagram of voltage versus time to illustrate parameters examined.	167
8.13	Relationship between the alternating current impedance and the salinity of the pore water, expressed in milliequivalents. The pore-water salinity bears a similar relationship to the direct current impedance, the steady-state voltage and both the charging and decay ramps.	171

<u>Figure</u>		<u>Page</u>
8.14	Relationship between the charging tangent and the pore-water salinity, expressed as milli-equivalents. A similar relationship exists between the pore-water salinity and the decay tangent.	173
8.15	Typical decay curve and an exponential function with a time constant equal to the characteristic time of the decay curve and having the same voltage range (0 to V_d) as the decay curve.	175
A.1	Decay of the potential with distance in the diffuse double layer adjacent to a charged plane.	195
A.2	Counter-ion distribution in the diffuse double layer adjacent to a negatively charged plane.	198
A.3	Decay of the potential with distance according to Stern's theory.	202
A.4	Effect of - (a) concentration of monovalent-monovalent electrolyte and (b) counter-ion valency at a constant equivalent concentration of 0.001N - on the decay of potential in a diffuse double layer adjacent to a charged plane (the origin on the distance axis must be placed according to the value of the surface potential).	205
A.5	Decay of the potential in the diffuse double layer adjacent to a charged plane at two different concentrations of the counter-ions in the bulk solution when the plane is: (a) a surface of constant potential, and (b) a surface of constant charge.	207
A.6	Counter-ion distribution in the diffuse double layer adjacent to a negatively charged plane at two different concentrations of the counter-ions in the bulk solution, when the plane is: (a) a surface of constant potential, and (b) a surface of constant charge.	208
A.7	(a) - Repulsive and attractive energy as a function of particle separation at three different concentrations of the counter-ions in the bulk solution. (b), (c), (d) - Net interaction energy (dashed curve) as a function of the particle separation when the concentration of counter-ions in the bulk solution is: (b) low, (c) intermediate and (d) high.	212

Figure

Page

- B.1 When the line of sight of the telescope intersects the axis about which the mirror rotates, $\phi = 2\theta$. 222
- B.2 When the line of sight of the telescope does not intersect the axis about which the mirror rotates, $\phi = (2\theta - \alpha)$. 222
- B.3 Estimation of the modulus of elasticity from either the secant or initial tangent to the reloading curve. 228
- C.1 Voltage decay with time upon interruption of current. 233
- C.2 A charging curve followed by a discharge or decay curve. 233
- C.3 IP frequency-method waveforms, showing a controlled, constant inducing current, I , at frequencies f_1 and f_2 being detected as two different voltages, where the smaller voltage results from the higher frequency. 235
- C.4 An IP charge and decay curve, using a long-period square wave. The logarithmic decay curve displays decay voltages at geometrically spaced times, t_1 , t_2 and t_3 . The charge curve is the inverse of the voltage decay with geometrically spaced frequencies, f_1 , f_2 and f_3 . 235
- C.5 Depiction of ions in a pore space forming an ion concentration barrier which creates membrane polarization. (a) - Pore path before application of an electrical potential. (b) - Pore path after application of a direct-current driving force. 238

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1.1	Summary of the intended modes or values of the controlling variables for the 22 samples.	10
2.1	Major ion composition of seawater.	20
2.2	Chemical compounds for artificial seawater mixture.	20
4.1	Examples of leaching solutions.	47
8.1	Summary of the intended modes or values of the controlling variables for the 22 samples.	112
8.2	Particle-size distributions.	113
8.3	Monitoring of the chemistry of the sedimentary environment.	113
8.4	Void ratio, water content and Atterberg limits.	114
8.5	Efficiency of leaching.	124
8.6	Pore-water cations.	125
8.7	Oxidation-reduction potential and pH	130
8.8	Cation-exchange capacity and ammonium-acetate- extractable cations (exchangeable bases).	133
8.9	"Composite" diffusion coefficient and coefficient of permeability.	136
8.10	Elastic parameters	142
8.11	Elastic recovery.	146
8.12	Shear strength and sensitivity.	150
8.13	Electrical measurements.	169

CHAPTER 1

INTRODUCTION

1.1 Post-Glacial Marine Clays

Deposits of post-glacial marine clays which have been raised above sea level are found at various locations throughout the world in areas which have experienced late-Pleistocene glaciation. The most extensive of these deposits occur in eastern Canada and Scandinavia.

These clays are notable for their high sensitivity and their susceptibility to landslides of large proportions. As a consequence, they are the subject of keen interest and in particular, the clays of eastern Canada and Scandinavia have been studied intensively.

The landslide activity associated with these clays has resulted in considerable loss of human life and extensive property damage. The interested reader is referred to LaRoche et al. (1970), Tavenas et al. (1971), and Eden and Mitchell (1973) who present summary accounts of the destruction experienced in eastern Canada and an introduction to the literature dealing with reports of this nature.

The sensitive, landslide-prone clays of eastern Canada and Scandinavia were deposited under marine or brackish conditions in areas which were inundated by the sea immediately following retreat of the continental glaciers. These areas have been subsequently raised above sea level by isostatic rebound. In the intervening time since their elevation above sea level, these clays have undergone significant changes

as a result of the subaerial conditions (Torrance, 1975a, 1975b, 1979).

1.1.1 Leda Clay

Leda Clay is the name which is generally applied to a range of clay soils deposited during a marine transgression which submerged the St. Lawrence and Ottawa River valleys from approximately 12,500 to 10,000 years BP. There is also evidence to suggest that some of these soils in the Ottawa area were deposited under fresh-water conditions as the land gradually rose above sea level. A detailed introduction to the history of the Champlain Sea and the variability of the Leda Clay deposits is given by Gadd (1975).

1.1.2 Mineralogy of Leda Clay

The mineralogy of Leda Clay has received considerable attention because of its implications with respect to the behaviour of this material (Brydon and Patry, 1961; Soderman and Quigley, 1965; Gillott, 1971; Bentley and Smalley, 1978a; Yong et al., 1979). The mineralogy is complex, with significant variations occurring vertically within a single borehole as well as geographically throughout the area of the deposit. There appears to be general agreement that the principal layered silicates present in the clay fraction of this soil are illite and chlorite. Montmorillonite and other swelling clay minerals are either absent or present only in very small amounts. In addition, there are large amounts of finely divided, glacially ground rock flour consisting of quartz, feldspar, amphibole and other primary rock minerals. Amorphous material is also known to be present in the clay fraction.

Considerable disagreement exists with respect to the relative proportions of the various constituents comprising the clay fraction.

Brydon and Patry (1961), Soderman and Quigley (1965) and Gillott (1971) consider the layered silicates to be the predominate mineral group with primary rock minerals forming a significant but subordinate portion of the clay fraction. Bentley and Smalley (1978a) contend that the reverse is the case. There is also considerable discussion pertaining to the role and significance of the amorphous material (Bentley and Smalley, 1978b; Yong et al., 1979).

1.1.3 Geotechnical Properties of Leda Clay

Because of the potential hazard this soil presents, the geotechnical properties of Leda Clay have been extensively examined. The results have been summarized in two excellent review papers, one by Crawford (1968) and another by Quigley (1980).

The most notable geotechnical property of Leda Clay, namely its sensitivity, has already been alluded to above. Sensitivity is the pronounced reduction in undrained shear strength upon remolding of a soil. A quantitative expression of this phenomenon is the ratio of the undrained, undisturbed shear strength to the undrained, remolded shear strength. Leda Clay can have sensitivity values in excess of 300 (Penner, 1965; Crawford, 1968).

High sensitivity reflects the fact that the undisturbed soil has a water content in excess of its liquid limit. In extreme cases, upon remolding, the clay liquifies and flows. A clay of this nature is known as a quick clay. This characteristic can result in retrogressive flow slides. Landslides of this nature commonly begin as simple rotational slides. In an insensitive clay, the material involved in the rotational slide acts as a buttress at the toe of the slope to prevent further sliding. However, in a clay of high sensitivity, the slide debris may liquify and flow away, leaving the slope unsupported at its base and essentially as unstable as before. New slides can then occur around the circumference

of the initial slide and the scar enlarges (Bjerrum, 1955). The whole process can escalate very rapidly to a slide of major proportions. When a slide of this nature occurs in a developed area, the cost in human life and property can be very high, as was noted, above.

Carson (1977) questions the use of Bjerrum's model to explain the Canadian experience and proposes instead another model which is based upon a retrogressive spreading of the clay mass. However, Eden (1978) points out that Bjerrum's model is consistent with eyewitness accounts of several major Canadian flow slides. Examples can be cited which support each model but the relative number of landslides of each kind and the circumstances which favour one or the other mechanism remain unknown.

There is a lively debate continuing with respect to the causes of sensitivity. Various possibilities are presented by Mitchell (1976) within a general framework and research specific to the sensitivity of Leda Clay is summarized by Quigley (1980). Torrance (1983) has attempted to reconcile the disparate points of view with a general model which incorporates features of each.

1.2 Experimental Program

1.2.1 Conceptual Framework for Research

The clay fraction is often the controlling or predominate factor governing the behaviour of fine-grained soils (Mitchell, 1976). The characteristic properties of the clay fraction are due in large measure to the fact that surface forces acting on the very small particles comprising the clay fraction predominate over the body forces. The nature and origin of these surface forces and some important implications arising from their existence are summarized in Appendix "A". For the present discussion, it is sufficient to note that these forces are largely a function of the composition and configuration of the ion clouds in the electrolyte surrounding the particles.

Recognition of the above led Lambe (1958) to propose that a proper definition of the structure of fine-grained soils must include not only the size, shape and arrangement of the constituent particles but the nature and magnitude of the inter-particle forces as well. Mitchell (1976) has taken the broader approach of defining a clay-water-electrolyte system. The two models are completely compatible and differ only in the relative emphasis given to the macroscopic and microscopic aspects respectively.

The conceptual framework presented in Figure 1.1 has been conceived with these distinctions in mind. Each controlling variable can assume a range of either values or index characteristics and any credible combination of these will define a possible soil system and the state of that system. Each soil system will have certain bulk properties which reflect the particular combination of controlling variables.

Figure 1.1: Conceptual framework for experimental program.

When viewed from this perspective, one possible approach to the study of soil behaviour is to examine the effect that changes in certain controlling variables have on the system properties, both with respect to their nature and magnitude. The experimental program upon which this thesis is based was developed and undertaken within this context.

1.2.2 Research Objectives and Approach

The objectives of this research were twofold:

- (a) to develop simple geotechnical and electrical measurements and procedures to index certain system properties; and,
- (b) to examine the relative impact of certain controlling variables upon selected properties of a soil system.

Leda Clay was the soil system chosen for study but efforts to understand the behaviour of Leda Clay have been hampered by the lack of uniformity of this material. There is usually a considerable variation in the nature and properties of Leda Clay. It is impossible with natural, undisturbed material to find samples which differ only in a single variable. The many factors influencing behaviour are so tightly intertwined that they cannot be studied separately.

For this reason, a suite of controlled laboratory samples, in which each controlling variable could be treated independently, was used. Natural material from one site was dispersed in deionized water and then artificially sedimented and consolidated using equipment specially designed and built for this project. This equipment and the procedures used are described in Chapters 2, 3 and 4.

1.2.3 Soil System Properties Measured

1.2.3.1. Mechanical Properties

The mechanical properties of particular interest were:

- (a) the elastic response; and,
- (b) the shear strength and sensitivity.

The elastic response was measured using a vane apparatus which was designed and built for this project. A description of the apparatus and its use is presented in Chapter 5. The theory upon which the measurements were based was developed by Selvadurai (1979). A summary of this theory and other relevant considerations are presented in Appendix "B".

The shear strength of both the undisturbed and remolded samples was determined with the vane and also with the fall-cone (Hansbo, 1957). This allowed a comparison of results obtained by the two methods.

1.2.3.2 Electrical Properties

Because the mineral grains comprising the solid phase of a soil system are essentially dielectric, the transfer of an electric current through a soil is accomplished by means of ion movements in the pore-water electrolyte. The mobility of these ions is partly determined by their relationship to the particles of the solid phase as explained in Appendix "A".

It seems reasonable to assume that some information regarding the interaction between the particles and electrolyte can be inferred from the electrical response of the bulk sample. For this reason, an attempt was made to assess the low-frequency electrical response of the suite of

controlled soil samples generated in this experiment.

The technique chosen was induced polarization. A summary of information pertaining to the phenomenon of induced polarization and its possible causes is presented in Appendix "C". A description of the equipment which was designed and built for this purpose can be found in Chapter 6.

1.2.3.3 Chemical and Hydraulic Properties

The only hydraulic property measured was the permeability. Chemical properties which were examined include the Eh, pH, cation-exchange capacity, exchangeable bases and diffusion coefficient.

An outline of the methods and procedures used for these measurements is presented in Chapter 7.

1.2.4 Controlling Variables Examined

During the course of this experiment 22 soil samples were prepared and tested. All of the controlling variables shown in Figure 1.1 with the exception of temperature and the water/gas ratio were examined to some extent. Table 1.1 presents an overview of the whole experiment with a listing of the controlling variables pertaining to each of the 22 samples. Although most of the controlling variables received some measure of attention, a few deserve a more detailed explanation because they formed the principal basis upon which the samples were grouped into "runs" or phases of the experiment.

The first 8 samples were initially identical in every respect. However, each was leached to a different degree in order to examine the effect of changes in the pore-water chemistry of sediments which had

Table 1.1: Summary of the intended modes or values of the controlling variables for the 22 samples.

Sam. No.	Temp. (°C)	Orig. Part. Mater. or Compos.	Part.- Size Distrib. (Silt/Clay)	^a Chen. of Sed. Envir. (g./l.)	^b Susp. Sed. Conc. (g./l.)	Present (Final) Stress (kPa.)	Stress Hist. (Consol.) (kPa.)	^c Present (Final) Pore-Mtr. Chem. (g./l.)	Cement.	Weather.	Mtr./Gas Ratio In Pores
1	20	Normal	40/60	26	5	24.3	57.6	0	None	d ^a Possible-A	Sat.
2	20	Normal	40/60	26	5	24.3	57.6	0	None	d ^a Possible-B	Sat.
3	20	Normal	40/60	26	5	24.3	57.6	0.5	None	None	Sat.
4	20	Normal	40/60	26	5	24.3	57.6	1	None	None	Sat.
5	20	Normal	40/60	26	5	24.3	57.6	2	None	None	Sat.
6	20	Normal	40/60	26	5	24.3	57.6	4	None	None	Sat.
7	20	Normal	40/60	26	5	24.3	57.6	10	None	None	Sat.
8	20	Normal	40/60	26	5	24.3	57.6	0	None	None	Sat.
9	20	Normal	40/60	26	15	18.2	18.2	0	None	None	Sat.
10	20	Normal	40/60	26	7	18.2	18.2	0	None	None	Sat.
11	20	Normal	40/60	26	3	18.2	18.2	0	None	None	Sat.
12	20	Normal	40/60	26	1	18.2	18.2	0	None	None	Sat.
13	20	Normal	40/60	8	5	18.2	18.2	0	None	None	Sat.
14	20	Normal	40/60	4	5	18.2	18.2	0	None	None	Sat.
15	20	Normal	40/60	2	5	18.2	18.2	0	None	None	Sat.
16	20	Normal	40/60	0	5	18.2	18.2	0	None	None	Sat.
17	20	Normal	75/25	26	5	18.2	18.2	0	None	None	Sat.
18	20	Normal	40/60	26	5	18.2	18.2	0	None	None	Sat.
19	20	Normal	40/60	26	5	18.2	18.2	1	None	None	Sat.
20	20	Normal	10/90	26	5	18.2	18.2	0	None	None	Sat.
21	20	SiO ₂ Add.	40/60	26	5	18.2	18.2	1	None	None	Sat.
22	20	SiO ₂ Add.	40/60	26	5	18.2	18.2	0	None	None	Sat.

NOTES: (a) - Ionic suite similar to that of seawater; expressed as grams of salt per liter of solution.

(b) - Expressed as grams of soil solids per liter of suspension.

(c) - Intended final salinity, expressed as grams per liter of NaCl.

(d) - Samples leached to low salinity and allowed to stand for extended periods of time (A < B), raising possibility of weathering.

accumulated in a saline environment. It was anticipated that this would result in measurable differences in several system properties. The effect on the sensitivity was of particular interest. Although the importance of low pore-water salinity to the development of high sensitivity in Leda Clay is now generally recognized (Quigley, 1980), such was not always the case (Penner, 1965; Crawford, 1968).

Because of the important influence that the pore-water electrolyte has on the interparticle forces (see Appendix "A"), it was also anticipated that the effects of leaching would be reflected in the elastic response of the samples. A reduction in pore-water salinity would also make weathering possible (Torrance, 1975a).

There appears to be general agreement that an open, randomly oriented, flocculated particle arrangement is an important factor contributing to high sensitivity (Torrance, 1975b, 1983), because it results in a high water content which can be maintained in spite of other changes taking place in the soil. For reasons which are explained in Appendix "A", a saline sedimentary environment and a high concentration of suspended sediment will each promote this kind of particle arrangement. These two variables were examined in the second group of 8 samples.

A flocculated structure will have a bearing upon other mechanical properties besides sensitivity. For example, Mitchell (1976) reports that a flocculated structure is more rigid than one which is not. This will have a direct influence on the elastic response of the soil system.

The electrical properties should also be influenced by the nature of the particle arrangement because the ion movements necessary for charge transfer should be facilitated by an open, flocculated structure.

The effect of changes in the particle-size distribution and the particle mineralogy were examined in the third group consisting of 6 samples. Recent theories regarding the causes of sensitivity in Leda Clay have included the suggestion that finely-ground clay-sized primary rock minerals play an important role (Smalley, 1971; Cabrera and Smalley, 1973; Bentley and Smalley, 1978a, 1978b). Colloidal SiO_2 was added to 2 of the samples as a preliminary assessment of these proposals. The change in the mineralogy could also be expected to have an effect on the elastic response and electrical properties of the soil.

Another 2 samples were prepared with altered particle-size distributions in order to assess the effect of these changes on the sensitivity and other mechanical properties as well as the electrical, chemical and hydraulic properties of the soil.

The results of the experiment are presented in Chapter 8.

CHAPTER 2

SEDIMENTATION -- EQUIPMENT AND PROCEDURE

2.1 Objective

Sedimentation is the first and perhaps the most important step in the production of samples that are consistent within groups or which vary in a predictable fashion. A suite of controlled laboratory samples which are to be as nearly identical as possible to natural specimens of Leda Clay must be sedimented under conditions which closely simulate those found in the Champlain Sea.

The marine transgression known as the Champlain Sea brought seawater deep into the heart of North America. All along its northern flank, melting glaciers were discharging large volumes of fresh water into this sea (Gadd, 1975) and as a result, the Champlain Sea was an estuarine environment with an average salinity which was thought to be on the order of 26 grams of salt per litre of water (Torrance, 1975a). This situation appears consistent with information obtained for Norwegian soils of the same origin (Torrance, 1975b).

The glacial meltwater entering the Champlain Sea carried large volumes of sediment. In rivers which are currently fed by glacial meltwater, suspended sediment concentrations of 5 grams per litre are not uncommon (Fahnestock, 1963). Sediment input to the Champlain Sea probably also exhibited diurnal and seasonal variations.

It was the objective of the sedimentation phase to duplicate as nearly as possible these natural conditions. The temperature of

sedimentation was ignored and two other aspects could not be duplicated: the timeframe in the laboratory was compressed in comparison to the natural situation and the settling distance for the sediment in the laboratory was but a small fraction of that in the Champlain Sea. However, with reference to this second point, it was noted that for those conditions in which the material readily flocculated, the floccules quickly reached a characteristic and reasonably uniform size that did not appreciably change as the sediment fell through the water column.

2.2 Sedimentation Apparatus

2.2.1 Design Objectives

The challenge was to design an apparatus in which the samples would be able to proceed through sedimentation, consolidation, leaching and finally testing with as little disturbance as possible.

Sedimentation in a standard sedimentation cylinder or apparatus with similar dimensions seemed desirable. Years of experience has established that these cylinders provide sufficient supernatant liquid to ensure proper flocculation and sedimentation although deficiencies such as the effect of the cylinder wall on the sedimentation process are recognized. Unlike the standard sedimentation cylinders, which are made of glass, the material of the apparatus had to be machinable in order to provide the close tolerances necessary for subsequent phases such as consolidation.

It was important to ensure that the chemical and physical characteristics of the soil material were not altered inadvertently. As a consequence, the apparatus and all the vessels, mixing tools and laboratory equipment which came into contact with the soil had to be made of inert plastics or silica glass. Any parts of the equipment that would abrade or could not meet these specifications for other reasons had to be made of materials which were chemically compatible with the soil in order not to introduce elements into the soil which were not there naturally.

2.2.2 Description of Sedimentation Apparatus

The sedimentation cylinder was made entirely of plexiglass except for a porous stone which was carborundum. Although virtually inert, the chemical makeup of carborundum is such that, if it were to dissolve, no

ions would be added to the system which were not already present due to alteration of clays and other silicates.

As shown in Figure 2.1, there are three principal parts to the sedimentation cylinder: a base plate, a centre section and a top section. The base plate contains a porous carborundum stone, the function of which will be described in a later chapter. After a membrane filter was placed over the porous stone to prevent clay particles from clogging the pores, the base plate was bolted to the centre section. A small amount of silicone stopcock grease was applied to the joint to provide a waterproof seal. The top section fit snugly over this central section and was bolted to it. Stopcock grease was also used at this connection.

The finished assembly, shown in Figure 2.2, resembled a standard sedimentation cylinder. It was 53 cm. in height with an internal diameter of about 5 cm. and a wall thickness of 0.7 cm. The internal diameter of the centre section was machined to close tolerances in order to accommodate a loading plate during the consolidation phase.

This design provided great flexibility, allowing a sample to proceed through the sedimentation phase, the consolidation phase and the leaching phase to final testing without being removed from the centre section.

2.2.3 Assembly of Apparatus and Laboratory Set-Up

A total of 8 top sections and 16 centre sections and base plates were constructed. Up to 8 samples could be in the sedimentation phase at any time. The duplicate set of centre sections and base plates allowed the sedimentation of another set of samples to begin as soon as the preceding set was transferred to final consolidation and the top sections became available.

Figure 2.1: Schematic diagram of sedimentation cylinder.

Figure 2.2: Assembled sedimentation cylinder.

Assembly of each apparatus began by placing the porous stone in water and applying a vacuum until the water boiled in order to remove air from the pores of the stone. The de-aired stone was then placed in the base plate and covered with a membrane filter and the three parts of the apparatus were bolted together as described earlier.

The sedimentation cylinders were individually clamped to large wooden platforms in order to minimize the possibility of tipping or other disturbance and then filled with solutions of appropriate salinity and ionic composition to provide the desired sedimentary environment.

The sedimentation phase of the experiment was conducted in a darkroom in order to reduce the likelihood of algal growth in the settling medium.

2.3 Chemistry of Sedimentary Environment

Leda Clay is primarily of marine origin and in order to study this material, it was necessary that some of the sedimentation take place in water that had the approximate chemical composition and salinity of the seawater or the near-marine water which constituted the Champlain Sea. There are several possible problems with using natural seawater for this kind of experiment. Among these, biological contamination is probably the most important. For example, it would have been impossible to control the growth of algae during the experiments and the influence of organic debris on the system would have been an unpredictable factor. For this reason, an artificial mixture was developed based on the ionic make-up of average seawater. Only the most obscure ions were neglected.

The major ions present in average seawater are listed in Table 2.1. As can be seen, the total salt content is 35.141 grams per litre.

Table 2.2 lists a series of common chemical compounds which, when mixed in appropriate amounts, can give the desired ionic composition. If these salts are dissolved in the amounts shown in Table 2.2 and the resulting solution brought to a volume of one litre, its salinity would be 35.085 grams per litre. This compares very favourably with the salinity of natural seawater noted above.

It was noted earlier that the salinity of the Champlain Sea throughout most of its existence was approximately 26 grams per litre. For this reason it was decided that the working solution would be prepared with a salinity of 52 grams per litre. If the solution containing the salts in Table 2.2 is brought to a volume of 675 millilitres instead of 1 litre, the resulting salinity is 52 grams per litre.

Table 2.1: Major ion composition of seawater.

(from McAllister and Corcoran, 1969: Table 1-3)

Chemical Form In Ocean	Parts Per Thousand
Cl^-	19.353
Na^+	10.760
SO_4^{2-}	2.712
Mg^{+2}	1.294
Ca^{+2}	0.413
K^+	0.387
HCO_3^-	0.142
Br^-	0.067
Sr^{+2}	0.008
H_3BO_3	0.004
F^-	0.001
	<u>35.141</u>

Table 2.2: Chemical compounds for artificial seawater mixture.

Chemical Compound	Amount (g./l.)
$\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$	1.514
NaHCO_3	0.195
KCl	0.738
$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	6.958
$\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$	5.082
NaCl	27.199
NaBr	0.032

In practice, each compound was dissolved individually to obtain 7 standard solutions of known concentrations. An appropriate volume (usually 50 or 100 millilitres) of each standard solution was transferred to a graduated cylinder and water added to the mixture to yield 675 millilitres of 52-gram-per-litre working solution.

This working solution was then diluted to give solutions of 26 grams per litre, 8 grams per litre, 4 grams per litre, et cetera, as required by the conditions of the particular experiment.

2.4 Soil Material

2.4.1 Source

In 1971, a large landslide occurred along the South Nation River near Ottawa. This landslide has been described by Eden, Fletcher and Mitchell (1971). In May of 1977, some of the original slide material was remobilized and a second landslide took place immediately adjacent to the river, partially blocking the course of the river. The material used in this experiment was taken from three locations along the river where unweathered Leda Clay had been exposed by the May, 1977 landslide. The sampling sites appeared to be along the flanks of large blocks which had been thrust up by the latest movement. The original sedimentary layering was visible.

The natural water contents of the three samples were between 40% and 47% and their liquid limits ranged from 34% to 38%.

2.4.2 Initial Soil Preparation and Storage

Each soil sample was brought to the laboratory, placed in a large rectangular plastic basin and thoroughly remolded and homogenized using a hand-held electric mixer. Deionized water was added to facilitate the process and the final water contents ranged from 62% to 64%.

The homogenized soil was transferred to a series of glass canning jars which were equipped with polypropylene lids. Before capping each jar, about 1 centimetre of deionized water was placed on top of the soil to act as an additional barrier to the free transfer of oxygen to the soil. In so doing, the jars were effectively filled to the brim when capped,

although a small amount of air did remain in each jar.

After capping, a tight-fitting polyethylene bag was pressed down over the top of each jar, air pockets were squeezed out of the bag, masking tape was used to cover the bag and contour it to the lid and top of the jar, and finally, the top of each jar, to a point below the glass-polyethylene contact, was dipped in molten wax. The sealed jars were stored under conditions of controlled temperature (7°C) and high humidity until needed. By these precautions, the likelihood of change in the soil material during storage due to drying, oxidation or other chemical alteration was minimized.

For the series of jars holding one of the three soil samples, the assumption was made that the soil material in each jar was identical to that in any other jar. Soil material from the three samples was initially mixed in the same proportions for each experiment. Therefore, on the basis of the above assumption, if no changes occurred in the soil material during storage, all experiments began with similar soil material unless it was subsequently altered as part of the experimental design.

2.4.3 Preparation of Soil Material for Experiment

2.4.3.1 Dispersion

Thorough dispersion of the soil material was desired immediately before its use in any experiment. The use of chemical dispersants was incompatible with the intent of the experiment so, as a consequence, the soil was dispersed in deionized water by means of vigorous shaking in 2.5-litre Winchester flasks. Only about 2 litres of soil suspension was put into each flask in order to leave room for vigorous agitation of the mix.

The experimental procedure required that the suspension which would be added to the sedimentation cylinders have a suspended-sediment concentration of 50 grams per litre. Therefore, enough of the bulk sample from the glass canning jars to yield approximately 100 grams of suspended soil particles was washed into each Winchester flask with 1.5 litres of deionized water. Then the flasks were shaken for twenty-four hours on a reciprocating shaker to disperse the soil.

Each mixture was then passed through a number 200 (74 microns) sieve made of stainless steel mesh in a plexiglass frame to remove all particles greater than silt size as these could jam the consolidation apparatus. The particles resting on the sieve were collected, dried and weighed.

From the information on the water content of the bulk sample and the weight of material retained on the sieve, the amount of deionized water required to bring the suspended-sediment concentration to 50 grams per litre was calculated. After the necessary water was added, the flasks were again shaken for a prolonged period to ensure the complete dispersion of the soil.

2.4.3.2 Soil Aliquots

When dispersion of the soil had been completed, the Winchester flasks were emptied into a large glass vat. A motor-driven, stainless-steel stirrer kept the soil particles continuously in suspension while 20-millilitre aliquots of soil suspension were transferred into plastic bottles with a pipette. These bottles had a nominal volume of 60 millilitres. The 20-millilitre volume of liquid is sufficient to ensure a uniform suspension when agitated and the 60-millilitre bottle provides the necessary room for vigorous agitation. A total of 630 bottles were filled for each run and stored (7°C and high humidity) until needed.

Twelve Winchester flasks containing 24 litres of soil suspension were initially emptied into the vat for each run but only 13 litres were necessary to fill the bottles. The large excess volume was used to ensure uniformity among the aliquots. At all times, the aliquot was being taken from a substantial volume of soil-water mixture which was being vigorously stirred and hence all aliquots should have been identical within the limitation of an error of less than 1% in the volume of the aliquot taken.

One bottle of soil suspension was transferred to each sedimentation cylinder per soil addition step. In most cases, the bottles contained 1 gram of soil (20 millilitres of 50-gram-per-litre suspension). However, this was altered in one run to achieve the experimental objective.

The manner in which the suspended-sediment concentration in the sedimentation cylinder itself was controlled is explained in a subsequent section. It is sufficient to note at this point that one of the controlling factors was the amount of soil added to the cylinder from each bottle. If more or less than 1 gram of soil was to be added to the sedimentation cylinder per sediment addition, the amount of 50-gram-per-litre suspension transferred to the bottles was adjusted accordingly. Sufficient deionized water was then added to bring the volume within the bottle to either 20 or 30 millilitres.

As part of the experimental procedure, it was decided that 20 millilitres would be the minimum, and 30 millilitres the maximum, volume of soil-water mixture to be contained in each bottle. With between 20 and 30 millilitres in each bottle, it was possible to produce good agitation and mixture of the suspension on the reciprocating shaker and transfer of the soil from the bottle to the sedimentation cylinder was more efficient.

2.4.4 Adjustment of Particle-Size Distribution

In one run, the particle-size distribution of the normal soil material was altered. This was done by adding either silt or clay to the normal soil material.

The silt and clay were obtained by repeated washing of a separate batch of normal soil material that had been placed in Winchester flasks and dispersed in the usual manner. The suspensions in the flasks were allowed to settle and the less-than-2-micron decant was siphoned off into a separate flask. Make-up water was added to the flasks and the soil material dispersed again by vigorous shaking. The whole process was repeated as many times as necessary to split the normal soil material into the two fractions.

2.4.5 Addition of SiO_2 to Soil Material

Colloidal SiO_2 (<0.15 micron diameter) was added to the normal soil material for some of the samples of one run. An attempt was made to maintain the usual clay/silt ratio characteristic of the "normal" soil samples in the experiment so that comparisons could be made on the basis of differences in the particle mineralogy alone.

This was accomplished by adding an appropriate amount of silt, obtained in the washing process described in the previous section, concurrently with the SiO_2 . The resulting mix therefore differed from the normal soil material in only two respects: the extra SiO_2 in the clay fraction; and the enrichment in primary rock minerals due to the silt addition.

2.5 Addition of Soil

Each morning during the soil addition stage, a tray of bottles with appropriate aliquots was taken from the storage chamber and agitated for one hour on the reciprocating shaker to ensure dispersion of the soil within the bottles. The first soil addition for that day was then made to each cylinder. Prior to each subsequent soil addition during the day (usually each hour), the shaking was repeated for fifteen minutes.

It was found that the build-up of sediment in the bottom of the sedimentation cylinders limited the number of such additions in one day to between 4 and 6. This intermittent addition of soil to the cylinders was meant to be an analog of the diurnal and seasonal additions of sediment to the Champlain Sea. The 4 to 6 hourly additions of soil represented the diurnal or short-term variations of sediment influx to the Champlain Sea while the remaining 18 to 20 hours of each day were considered analogous to the seasonal period of reduced sediment input.

One of the controlling variables chosen for this experiment was the concentration of suspended sediment immediately after a soil addition. Two mechanisms were used to control the suspended-sediment concentration. One of these was the amount of soil transferred to the sedimentation cylinder in each addition. The second technique was to control the volume of water in the sedimentation cylinder into which the soil was mixed. A proper combination of these two mechanisms could provide whatever suspended-sediment concentration was desired.

A paddle, consisting of a vertical stem and horizontal disk was used to define the discrete volume of the sedimentation cylinder into which the soil was mixed. The stem had an adjustable pin so that the disk could be set at any desired depth when the pin rested on the lip of the sedimentation cylinder.

The horizontal disk was equipped with vanes and pierced by slots and when properly manipulated could be used to mix and disperse a soil addition throughout the desired volume.

After the paddle had been inserted into the sedimentation cylinder and adjusted to the desired depth, a bottle containing a soil aliquot was given a final shaking by hand and immediately emptied. The paddle was then raised and lowered several times with a twirling motion. In practice, this technique was found to successfully confine and mix the soil material within the desired volume.

If the volume occupied by the soil is ignored, then 20 to 30 millilitres of deionized water was added to a saline solution with each aliquot. Repeated additions would have caused an unwanted reduction in the salinity of the sedimentation medium. Therefore, after each soil aliquot had been added and mixed with the paddle, the salinity was readjusted to its original value. This was done by adding a solution of appropriate salinity and volume with a precision automatic Oxford pipette and then mixing with the paddle.

From time to time throughout the sedimentation phase of the experiment a sample of the sedimentation medium was taken in order to determine whether or not there had been any significant drift in its salinity.

The suspension was allowed to settle until the next addition which was usually one hour later. Just prior to the next addition, a suction device was used to remove 40 to 60 millilitres from the top of the sedimentation cylinder, thus restoring the original water level which had existed before the previous addition of sediment and saline solution.

In most cases, the sedimentation medium was quite saline. This caused a rapid flocculation and it was observed that the upper reaches of the sedimentation cylinder cleared very rapidly of all soil material. As a consequence, the withdrawal of 40 to 60 millilitres one hour later did not remove a significant amount of soil material from the cylinder.

2.6 Consolidation During Sedimentation

The success of the sedimentation phase required, among other things, that a substantial depth of water be maintained above the water-sediment interface. Ideally, the sediment should have at all times been confined to the centre section of the cylinder shown in Figure 2.2. However, the sediment structure produced under the conditions described was so open and porous that a light, fluffy sediment pack rapidly built up. Under these conditions, the whole sedimentation cylinder was incapable of holding the 65 to 70 grams of soil to be added even though some settlement and consolidation of the soil would occur due to its own weight.

This problem was solved by applying a hydraulic head across the sediment pack in order to promote consolidation. One of the leads to the porous stone in the base of the cylinder was allowed to drain through a spout into a test tube attached to the side of the sedimentation cylinder. The level of the spout was adjusted to provide a head difference across the sediment pack. The hydraulic head was applied in gradual increments as the density of the sediment pack increased. The initial head difference was only 4 centimetres. By the end of the sedimentation phase, the applied head was 22 centimetres.

The movement of water through the sediment pack into the test tube created sufficient drag on the soil particles to produce the desired consolidation and at the beginning of each day's sedimentation, the top of the sediment pack had dropped to some point within the centre section.

CHAPTER 3

CONSOLIDATION -- EQUIPMENT AND PROCEDURE

3.1 General Considerations

Consolidation of the sediment pack was undertaken in four distinct phases. The first phase, described in Section 2.6, was concurrent with the sedimentation and the load was applied by means of a hydraulic head across the sediment pack.

In the subsequent three phases of consolidation, the load was applied in a fashion more closely resembling a standard engineering consolidation test. The consolidation undertaken in this experiment, however, employed smaller load increments and was more gentle in nature than that of the standard engineering test. This was considered necessary because of the open, loose structure of the sediment as well as the desire to simulate the slow, natural loading rate and to minimize any disturbance other than that due to the consolidation itself. Although the time required for the consolidation phases of this experiment is much longer than that normally recommended in the standard engineering test, it is nonetheless very short in comparison to the time for consolidation of a natural sample.

3.2 Second Phase of Consolidation

After the addition of the last sediment aliquot, the sediment pack was left for from one to two weeks to allow further settlement under its own weight and the continuing load imposed by the hydraulic head. In most cases, the top of the sediment pack remained slightly above the junction between the centre and top sections of the sedimentation cylinder.

The internal diameter of the centre section of the cylinder was machined to close tolerances in order to accommodate a loading plate with the minimum clearance necessary to allow free movement. The loading plate was used to transmit the load to the soil in the latter phases of consolidation. A conical taper on the top portion of the centre section guided the loading plate smoothly into the centre section.

With the top of the sediment pack above this taper and above the junction between the two sections, it seemed unlikely that the loading plate could be properly guided into the centre section during a loading sequence. As a consequence, it was decided that an intermediate phase of consolidation was necessary in order to lower the sediment-water interface to some point below the taper.

This was accomplished using a plastic tube fitted with an end plug to which a porous polyethylene disk was rigidly attached. The diameter of the disk was less than that of the loading plate, allowing more freedom of movement in the sedimentation cylinder. Before insertion of this device, a membrane filter was floated down onto the top of the sediment in order to minimize disturbance by the disk and to prevent clay minerals from clogging the porous disk.

The tube was maintained vertically along the axis of the sedimentation cylinder by the disk attached to its end and by a collar which fitted into the top of the sedimentation cylinder. The diameters of the

porous disk and the hole in the collar were such as to provide proper vertical alignment without restricting movement of the device. The collar also had a smaller hole in it which allowed the addition or withdrawal of water from the cylinder.

The tube with the porous polyethylene disk attached was introduced into the cylinder where it floated some distance above the soil. Water was then withdrawn until the disk just touched the membrane filter resting on the surface of the soil and the water level at this point was marked.

The final hydraulic head used for the first phase of consolidation was re-established and additional load was applied by lowering the water level in successive steps. This method of loading the soil was especially useful under these circumstances where the soil structure was so open and fragile because it was, in effect, self-limiting. For the initial load, the water level was lowered from the point where the tube-and-disk assembly was just touching the soil. Some of the weight of this assembly was then borne by the soil structure, the exact amount being proportional to the cross-sectional area of the tube. As the soil structure consolidated, the assembly sank and the load on the soil decreased by a corresponding amount. This continued until the load applied was that which the sediment could carry without further consolidation. Subsequent loads were applied in the same manner. The steps by which the water level was lowered formed a loading sequence with a nominal loading factor of 1.25.

The physical arrangement was such that, as the water level was lowered, the hydraulic head established in the first phase could not be maintained. As a consequence, the actual load applied by the tube-and-disk assembly in each step was somewhat less than that due to the lowering of the water level. However, consolidation did take place, probably because the tube-and-disk assembly applied its load principally to the upper portion of the sediment pack whereas with the hydraulic head, the

load was applied principally to the lower portion of the sediment pack where the permeability was lower and the energy loss was consequently higher.

The total nominal load applied in this manner ranged from less than 4 grams (20 Pa.) to about 35 grams (179 Pa.). Eventually, it was no longer practical to lower the water level further. The subsequent load increments in this second phase were added as lead shot in a little basket fitted to the top of the tube. The loading factor was 1.33 and at the completion of the second phase of consolidation, the total load applied to the soil by the tube-and-disk assembly was 150 grams (767 Pa.).

The arrangement described above allowed drainage during consolidation to take place in two directions, upward through the porous polyethylene disk and downward through the porous stone in the base plate. Consolidation was quite rapid and a new load could be applied each day.

3.3 Third Phase of Consolidation

The tube-and-disk assembly used in the second phase of consolidation was floated free of the sediment by adding small increments of water to the sedimentation cylinders. When well away from the soil-water interface, the assembly was slowly withdrawn from the cylinder and a new membrane filter was introduced and allowed to float down onto the soil surface. The water level in the cylinder was restored to its original position near the top of the cylinder with a solution of the same salinity as that originally used in the sedimentation phase. Thus, the chemical composition of the overlying liquid and the pore water within the soil remained the same as during sedimentation.

The loading device used in the third phase of consolidation is shown in Figures 3.1 and 3.2. This device may be described in terms of five sub-assemblies:

- (a) A plexiglass loading plate had been machined to closely fit, but freely move in, the centre section of the sedimentation cylinder. It was equipped with a porous carborundum stone similar to that in the base plate.
- (b) A plexiglass loading tube was attached to the loading plate with a pin and slot arrangement. The end of the loading tube was hemispherical in order to transfer the load to the loading plate in a vertical direction only.
- (c) The loading tube was equipped with a ring of thin-walled polyethylene tubes which were used to increase the buoyancy of the whole assembly.

Figure 3.1: Schematic diagram of load-application assembly.

Figure 3.2: Sedimentation cylinder with load-application assembly inserted.

(d) A plexiglass platform rested on the top of the loading tube and was secured by means of a stem inserted into the loading tube. A hole which pierced the platform and stem allowed access to the interior of the loading tube.

(e) A collar on the top of the sedimentation cylinder guided the loading tube. The hole through which the loading tube passed was tapered so that the loading tube was effectively guided by a knife edge.

The porous stone in the loading plate was purged of entrained air by placing it in water and applying a vacuum until the water boiled. The whole assembly was then introduced into the sedimentation cylinder and floated above the soil as simulated in Figure 3.2. Lead shot could then be slowly added to the loading tube through the hole in the loading platform, thus lowering the assembly until it just touched the soil surface.

The first loading steps in this phase were accomplished by adding measured amounts of lead shot to the loading tube in the same manner. A short loading sequence was used to re-establish the final load which had been applied in the second phase of consolidation. The loading factor for this short sequence was 1.78.

After the short sequence, the regular loading for the third phase of consolidation was begun. The loading factor was 1.33.

When the loading tube was filled with lead shot, load increments were added in the form of pre-packaged cannisters of lead shot which were placed on the loading platform. This is simulated in Figure 3.3. Because a tall stack of cannisters on the loading platform might prove unstable, from time to time a cannister would incorporate the new load

Figure 3.3: Application of load by means of prepared canisters of lead shot.

increment and several previous loads, thus reducing the height of the stack.

During consolidation, drainage was allowed through both the porous stone in the loading plate and the porous stone in the base plate. The latter drained to a test tube attached to the side of the sedimentation cylinder, with the drainage outlet maintained 4 centimetres below the water level in the cylinder. With this arrangement, consolidation proceeded rapidly enough that a new load could be added on a daily basis.

Upon completion of the third phase of consolidation, the sample could no longer be considered fragile and could be moved without serious disturbance.

3.4 Fourth Phase of Consolidation

Although sufficient consolidation of the soil might have been achieved using the arrangement and procedures of the third phase, it was decided during the design of the experiment that a new approach was desirable for the final phase of consolidation. Equipment flexibility would provide more options both for this experiment and for future investigations which might use the same equipment.

The maximum load which can be applied using the arrangement of the third phase is limited by the ability of the loading tube to transfer that load to the plunger. Situations could be envisaged where it might be desirable to apply much higher loads to a sample than is possible with that particular arrangement. It was therefore decided that a more robust piece of equipment would have to be used for the final phase of consolidation.

After the sample had completed its consolidation under the final load of the third phase, the loading tube was disconnected from the loading plate. This was possible because of the pin and slot arrangement noted earlier. The upper section of the sedimentation cylinder was drained and detached from the centre section. The centre section, with loading plate and base plate, was then moved to another location.

The samples were placed on two loading racks like that shown in Figure 3.4. Loads were applied by adding prepared cannisters of known weight containing lead shot to a bucket suspended from a steel yoke. The yoke transferred the load to a steel pin that passed through a brass guide and applied the load to the soil sample by means of the loading plate. A hemispherical plexiglass tip on the end of the steel loading pin ensured that the hard steel did not bear directly upon the plexiglass of the loading plate and also ensured that saline liquids which might be around

Figure 3.4: Use of loading rack to apply loads to samples.

the loading plate did not come in contact with the steel.

The brass guide was a close fit to the steel loading pin and kept the pin aligned vertically. The guide was made of brass to take advantage of the lubricating qualities of a brass-steel contact.

The upper end of the steel loading pin was hemispherical and fitted into a matching cup made of brass which carried the yoke. The same brass cup was equipped with a platform upon which a dial gauge rode. The dial gauge was used to measure consolidation of the sample under the applied loads. In other phases, vertical displacements were measured with precision calipers.

The combined weight of the bucket, the yoke and the loading pin was slightly less than the total load applied at the end of the third phase of consolidation. Therefore, by adding a small make-up load to the bucket, the final load of the third phase was re-established and loading continued. This loading sequence was simply a continuation of that used in the latter part of the third phase and the loading factor remained 1.33.

The tapered annulus above the loading plate was filled with water of appropriate salinity in order to prevent drying of the sample and also to maintain saturation in the upper stone. The lower stone was allowed to drain to a point somewhat below the water level in the annulus, thus establishing a very minor hydraulic head difference across the sample and encouraging drainage in two directions during consolidation.

With the provision of drainage in two directions, consolidation proceeded rapidly enough that it was possible to add load increments on a daily basis. Loading continued until the desired load per unit area was achieved.

CHAPTER 4

LEACHING -- EQUIPMENT AND PROCEDURE

4.1 Preliminary Considerations

At the completion of consolidation, the loose soil material of the sediment pack had become a coherent soil sample confined within the centre section between 2 porous carborundum stones. Each stone was provided with two drainage tubes as shown in Figure 4.1. Because air had been purged from the stones, any liquid that was passed through a stone between its two drainage tubes had access to every part of the stone and hence was in full contact with the soil along the surface of the stone.

If, for example, deionized water was allowed to flow through each stone, a chemical gradient was established between the saline pore water of the soil sample and the deionized water within the stones. This caused ions to diffuse from the soil water into the porous stones where the continuing flow carried them out of the system. It was possible to leach a large proportion of the ions from the pore water of a soil sample in this manner.

This situation may have been analogous to what actually happened in nature within some parts of the Champlain Sea sediments. Horizontal sand lenses are known to occur intermittently throughout the vertical extent of the clay deposits and it is quite possible that in some cases, groundwater percolating through sand lenses has removed the original ions from the pore water by a diffusion process (Torrance, 1979).

Figure 4.1: Leaching of soil by passing
solution through porous stones.

4.2 Leaching Apparatus

The leaching took place on the consolidation racks and the final consolidating load was maintained throughout leaching in order to simulate a natural sample being leached while under the pressure of the overlying sediments.

The inlet to each stone was connected with plastic tubing of small diameter to a laboratory wash bottle which served as a reservoir containing a solution of appropriate salinity. The water level in the reservoir for the loading plate was maintained at or above the water level in the annulus surrounding the loading plate in order to prevent draining of the annulus and was also maintained at a level above that in the lower reservoir in order to avoid upward flow through the sample.

The presence of gas bubbles either in the stone or in the connecting tubing would seriously hamper the efficiency of the leaching system. As was noted earlier, the stones had been treated to expel gas from them. It was also important to properly flood the connecting tubing so that pockets of air were excluded. This was accomplished by means of a Y-junction near the inlet to each stone which provided access to the connecting tubing. Very tiny flexible tubing connected to a hypodermic needle and syringe was inserted through the Y-junction into the tubing and a solution of the appropriate salinity was injected to flood the tubing between the porous stone and Y-junction. A natural flow was used to flood that section of tubing between the reservoir and the Y-junction and then to flood the outlet tubing.

From time to time, air bubbles collected along the tubing. These bubbles were dislodged by gentle tapping and moved to the Y-junction where they were purged from the system.

The flow through the porous stones could be controlled in a number of ways. These included: the hydraulic head of the reservoir itself; a laboratory clamp which pinched the tubing leading from the outlet of the stone; and, a length of micropipette tubing with a bore of 0.5 millimetre which was connected to the end of the outlet tubing.

It was found that by balancing the length of the pipette tubing, the adjustment on the clamp, and the head on the reservoir, it was possible to control the flow through each stone. A volume of from 100 to 200 millilitres of solution per day through each stone proved sufficient to leach a soil sample from a salinity of 26 grams per litre to any desired salinity in from 1 to 3 months, the time required being a function of the sample thickness and permeability.

The flow rate through the porous stone was not constant. As the water level in the reservoir dropped, it concurrently rose in the beaker which collected the effluent from the submerged tip of the micropipette tubing. Daily attention to the reservoir and the receiving beaker was necessary in order to ensure a more or less steady flow of solution through the porous stones. A continuous flow, of course, is the most efficient way to leach a soil using this diffusion technique.

4.3 Leaching Solutions

The above technique was used to alter the pore-water chemistry at will. If the objective was to reduce the pore-water salinity to nearly zero, deionized water was flushed through the stones. In other cases, the pore-water salinity was reduced to specific values by using leaching solutions of slightly lower salinity as shown in Table 4.1. The leaching solutions were prepared by diluting aliquots of 26 grams per litre stock solution with deionized water. In this way, the ionic suite in the leaching solution was identical to that in the pore water.

In the same manner, specific ions could be introduced into the pore water of the soil by diffusion from the stones into the soil. This would be accomplished by passing solutions containing appropriate concentrations of the desired ion through the stones. The above technique might prove useful in investigations of phenomena such as weathering of clays and other fine-grained soils.

Table 4.1: Examples of leaching solutions.

Desired Salinity (g./l.)	Leaching Solution (g./l.)
4	3.3
2	1.8
1	0.8
0.5	0.3
0	0

CHAPTER 5

MEASUREMENT OF SHEAR MODULUS -- EQUIPMENT AND PROCEDURE

5.1 Nature of Test

A recent theory developed by Selvadurai (1979) allows the calculation of the linear elastic shear modulus of a soil when the relationship between the applied torque and the measured twist or deformation has been established. It is based upon the use of a vane consisting of two circular or ellipsoidal blades at right angles to each other. A summary of the relevant theory and calculations relating to the test are presented in Appendix "B".

5.2 Vane Apparatus

The device which was designed and constructed to undertake the testing based upon the theory of Selvadurai is illustrated in Figure 5.1. It consisted of a rigid framework made of 1.27-centimetre aluminum plate which was bolted together. Devices for carrying the sample and applying the torque to it were mounted upon this rigid structure. A separate assembly, illustrated in Figure 5.2, was used to measure the resulting deformation. Each apparatus was mounted on a heavy wooden platform equipped with levelling screws.

5.2.1 Application of Torque

The means by which a torque was applied to the sample will be described in terms of: the vane and shaft assembly (Figure 5.3); and the manner in which loads were applied.

5.2.1.1 Vane and Shaft Assembly

The vane consisted of two stainless steel circular blades with a diameter of 1.27 centimetres which had been soldered into a brass carrying rod. This brass rod was 0.95 centimetres in diameter and tapered from where it first contacted the blades to a point at their centre. It was bolted with a threaded connection to the end of a 0.95-centimetre diameter steel shaft. This provision was made to allow flexibility in the selection of vane sizes for future experiments.

The shaft was made of 0.95-centimetre steel rod in order to minimize twist within the shaft itself under the applied loads and was carried by two ball-bearing mechanisms mounted on the vertical superstructure as shown in Figures 5.1 and 5.3. Ball bearings were chosen in order to minimize frictional resistance to the rotation of the shaft. A mirror, the function of which will be discussed later, was mounted on the shaft.

Figure 5.1: Vane apparatus for application of torque to a soil sample, consisting of, a vane, a mirror, a moveable platform beneath the vane for carrying the sample and a moveable platform for carrying the water bath.

Figure 5.2: Telescope/scale apparatus for measuring soil deformation.

Figure 5.3: Vane and shaft assembly.

The torque was applied by means of a cable wrapped around a pulley fastened to the shaft (Figure 5.3). The pulley illustrated had a moment arm of 1 centimetre but provision was made to allow it to be removed and replaced with others of different diameters in order to vary the moment arm, if desired.

5.2.1.2 Loading of Sample

The cable from the pulley attached to the shaft passed over a second pulley with a horizontal axis and suspended a 25-gram weight made of plexiglass in a bath of water which sat upon a moveable table beneath the pulley (Figures 5.1 and 5.4). The upper portion of the plexiglass weight had been hollowed out by centre-drilling so that it would float in the water bath.

The table moved vertically by means of a screw mechanism with a very fine thread. This allowed precise adjustment of the water level in the bath with respect to the immersed weight. Initially, the table was raised until the plexiglass weight was floating in the bath. Lowering the table transferred a portion of this weight to the cable which then applied a torque to the shaft. This method allowed very small loads to be gently applied without shock or impact.

When the table had been lowered to the point where the plexiglass weight was no longer immersed, the bath was removed and the table moved aside, as shown in Figure 5.5. Loading continued in the following manner. A 2-gram connecting cable was attached to the same point from which the plexiglass weight was suspended, a 4-gram basket was hung from it and a series of 5-gram weights placed in the basket. A second basket, weighing 10 grams, was suspended from the 4-gram basket and a series of 10-gram weights placed in it. Finally, additional weights were suspended beneath the 10-gram basket, as required to complete the desired loading sequence.

Figure 5.4: Application of load
by floating weight.

Figure 5.5: Application of load by
addition of discrete weights.

5.2.2 Measurement of Rotation

Because of its design, the shaft was considered rigid and undeformable under the loads applied in this experiment, and therefore any rotation of the shaft under the applied torque was due to deformation of the soil under the shearing action of the vane. This was confirmed by an analysis which is presented in Appendix "B". An optical system was used to measure this rotation.

The principal components of this optical system were the mirror attached to the vane and shaft assembly (Figure 5.3) and a telescope mounted on the separate apparatus illustrated in Figure 5.2. As with the vane apparatus, this device consisted of a rigid structure made of 1.27-centimetre aluminum plate which was bolted together. The telescope could be raised or lowered, turned or tilted, and then locked in position.

A centimetre scale describing an arc of a circle was mounted above the telescope and the telescope was used to view the reflection of this scale in the mirror attached to the shaft of the vane. As the mirror rotated with the shaft, a hairline in the telescope was used to measure the amount of rotation against the centimetre scale. The sensitivity and precision of the measurement could be varied by changing the distance of the telescope from the mirror.

5.3 Test Procedure

5.3.1 Preparation of Sample

The device was designed to test the suite of controlled samples prepared in this experiment without removing them from the sedimentation cylinder. Provisions were also made to allow testing of a variety of core samples with their wax protective covering still intact.

Preparation of a sample for testing involved the following steps:

- (a) Leaching was stopped and the various tubes disconnected.
- (b) The sample was unloaded and transferred off the consolidation rack.
- (c) A small platform was placed on top of the loading plate and held in position by a stem which was inserted into the hole in the loading plate, as shown in Figure 5.6.
- (d) A plexiglass cover equipped with a large, machined plexiglass bolt was attached to the top of the centre section of the sedimentation cylinder.
- (e) The bolt had a hemispherical tip which was brought to bear upon the platform in order to support the loading plate and soil sample when the cylinder was inverted.
- (f) After inversion of the cylinder, the base plate was removed, exposing an undisturbed sample which could be tested with the vane.

After the vane test had been run on a sample, the bolt was used to extrude the sample from the cylinder as various tests were run and material was removed for analysis.

Figure 5.7: Method of inserting vane into soil by driving sample upwards.

Figure 5.6: Schematic diagram of device to support soil sample during vane test and to subsequently extrude soil for other testing.

5.3.2 Insertion of Vane into Soil

It was decided during the design of this apparatus that the precision necessary for this test required that the movement of the vane and shaft assembly be limited to pure rotation. As a consequence, there was no vertical movement of the vane and instead, the soil was driven up into the vane.

An inverted soil sample, still within the sedimentation cylinder, was first bolted to the moveable table as simulated in Figure 5.7. This table was equipped with three guide rods which passed through closely fitting holes in the main horizontal plate of the apparatus in order to prevent rotation of the table (see Figure 5.1) and was moved up and down by means of a large bolt with a fine thread. In this way, a soil sample was driven up into the vane and held rigidly while a torque was applied to it.

During the process of penetration, the vane was rigidly fixed by means of a locking pin, as shown in Figure 5.3. This prevented any disturbance or movement of the vane before the actual loading commenced.

The theory developed by Selvadurai (1979) allows either full- or half-penetration of the vane. In this experiment, the vane had been designed for only half-penetration.

5.3.3 Cyclic Loading and Unloading

When a triaxial test is used to determine the elastic modulus of a soil (Perloff, 1975), a load equal to the field loading but not exceeding approximately 0.33 of the ultimate strength of the soil is gradually cycled on and off the soil in order to "set" the structure of the soil and anneal the effects of soil disturbance during sampling. The stress-strain relationship is plotted and the elastic modulus is calculated using the initial tangent to the stress-strain curve. This procedure is

repeated until the calculated modulus does not change significantly with continued cycling.

A similar procedure was used in this test. However, the samples in the sedimentation cylinders had experienced no disturbance except that due to insertion of the vane, so it was not necessary to "set" the structure by prolonged cycling. For undisturbed samples, only two cycles were used. The first went from zero load to 25 grams (plexiglass weight) and back to zero and the second went from zero to 56 grams and back to 25 grams.

During the test, the surface of the soil was kept moist in order to prevent drying and consequent drift in the properties of the material. Upon completion of the test, any excess moisture was blotted up.

There are both plastic and elastic components to the deformation of a soil and after the application of a load, the plastic deformation (creep) may continue for an extended period of time. In order to standardize the test, a time limit was established. A load was applied and if creep was apparent, 15 seconds were allowed to elapse before the resulting deformation was measured.

5.3.4. Loading to Failure

After the cyclic loading to determine the shear modulus, the soil was loaded to failure in order to determine its shear strength. As will be noted in a subsequent chapter, this value of the shear strength was compared with that determined by the fall-cone method.

5.3.5 Remolded Shear Strength

A portion of the sample was remolded and placed in a special plexiglass vessel which could be bolted to the moveable table. The

interior sides of this vessel were tapered to permit the use of small volumes of material without appreciable edge effects.

The sample was subjected to one load-unload cycle before being loaded to failure in order to determine the shear modulus of the remolded soil as well as its shear strength.

5.4 Potential for Comparison of Results with Triaxial Test

The most widely accepted method for determining the mechanical properties of soil samples is the triaxial test. Because it is the accepted standard, all newly developed test methods are compared to the triaxial test and it was decided at the design stage that this vane apparatus had to have the capability of testing soil samples which could then be subsequently tested in the triaxial apparatus.

Many soil samples arrive at testing laboratories wrapped in protective materials and sealed in wax or in the original sampling tubes. Shortly after arrival, if it has not already been done, the soil is extruded from the sampling tubes, cut into convenient lengths of from 8 to 16 centimetres, wrapped, waxed, and then stored in a special chamber under conditions of controlled temperature and humidity.

Testing of one of these conventional soil samples with the vane can be accomplished in the following manner. The end of an 8 to 16 centimetre long/core sample is trimmed off, exposing the soil. The waxed end is then placed in a special two-piece plexiglass ring and wax is added to bond the core sample to the plexiglass. If it is thought that the bond between the wax and the plexiglass will not be sufficient to resist the torque applied to the soil by the vane, means have been provided to clamp a piece of sandpaper between the two sections of the ring and wax the core sample to this sandpaper, thus increasing the frictional resistance.

The upright core is placed in the vane apparatus in the same manner as a sample in a sedimentation cylinder. After testing with the vane, the wax covering can be removed from the core sample which is then transferred to a triaxial apparatus and tested in the usual manner. This allows a direct comparison of results.

Although it might have seemed opportune, the samples generated in this experiment were not used to compare the vane and triaxial tests for the following reasons: the aspect ratio (length to diameter) of the samples was inappropriate for the triaxial test; some of the tests performed on the samples were incompatible in many ways with the triaxial test; and from a conceptual point of view, this comparison was considered beyond the scope of this thesis.

CHAPTER 6

MEASUREMENT OF LOW-FREQUENCY ELECTRICAL PROPERTIES - EQUIPMENT AND PROCEDURE

6.1 Fundamental Considerations and Objectives

Electrical current transfer in soils is accomplished at low frequencies almost entirely by movement of ions in the interstitial pore water. This arises from the fact that the solid phase of most soils is composed of silicate minerals which are effective dielectric materials.

In clay soils, many of these pore-water ions act as counter-ions to balance the surface charge on the clay particles and are not completely free to move. The relevant phenomena are explained in Appendix "A". It is therefore reasonable to suppose that the low-frequency electrical properties will be influenced by the geochemistry of the pore-water electrolyte and in particular, of the electrical potential at the plane of slippage around individual clay particles (the Stern potential in Appendix "A").

The suite of controlled clay samples generated as part of the larger experiment afforded an opportunity to examine in more detail the effect of soil geochemistry on the electrical properties. A low-frequency technique based upon induced polarization (IP) was chosen for this study.

Appendix "C" contains a summary of information pertaining to the phenomenon of induced polarization and a discussion of its possible causes. It is the purpose of this chapter to describe the equipment which has been designed and built to measure the IP response of clays and to indicate the procedures followed.

6.2 General Considerations Governing Design of the System

6.2.1 Wave Form

It was decided that the exciting wave form should possess the following characteristics:

- (a) A square wave was chosen. This meant that with one wave form: the time domain response could be measured directly; and the determination of frequency-dependent properties over one to two decades was possible by means of a Fourier transform.
- (b) A 50% duty cycle (see Figure 6.1) was used which permitted easy examination of the characteristics of both the decay curve and the charging curve.
- (c) The wave form had a variable period which was advantageous because: it permitted selection of the frequency band (that is, the fundamental harmonic); and the sample response could be measured directly at discrete frequencies.

By increasing the frequency an order of magnitude in each step, it was necessary to use the Fourier transform only to supplement the information in the intervening decades, a requirement which is well within the resolution of the Fourier transform.

- (d) A variable amplitude was used which permitted a critical examination of the phenomenon of current dependency.

Figure 6.1: Square wave with
50% duty cycle.

6.2.2 Electrodes

A four-electrode system was chosen to avoid problems of electrode polarization associated with low-frequency measurements.

6.2.3 Receiver

It was decided that the receiver should have a differential input in order to accommodate a freely floating signal.

6.3 Layout of the System

6.3.1 System Block Diagram

The layout of the system is shown in the block diagram of Figure 6.2. The system may be described in terms of four general areas:

- (a) the excitation system consisting of an external timing device, transmitter and constant current source;
- (b) the sample and electrodes;
- (c) the receiver, with associated self-potential buckout circuit;
- (d) data acquisition, storage and processing, including the digital voltmeter and chart recorder.

6.3.2 System Ground Connections

Special care was taken to avoid ground loops. A diagram of the system ground connections is shown in Figure 6.3. It can be seen that the system common was established at the power supply and when the whole system was in operation, this common was tied to the mains ground at one point only, that is, the digital voltmeter.

When the digital voltmeter was not connected to the system, alternate means were provided to establish this link with mains ground. These are shown by the dashed lines in Figure 6.3. Grounding of the whole system required two such connections and ground loops were again avoided.

Figure 6.3: System ground connections.

Figure 6.2: System layout.

6.4 Excitation System

6.4.1 External Timing Device

As the name implies, the external timing device established the operating frequency for the whole system. It also controlled the duty cycle. There were at least three different devices which could be used for this purpose: a precision timing device such as a TTL clock; a square wave oscillator; or a commercial IP transmitter.

6.4.1.1 Precision Timing Device

A precision timing device was designed for use in this project. A functional diagram is shown in Figure 6.4. It was based on a Motorola 6870A microprocessor clock with an operating frequency of 1 megahertz, ± 0.01 percent. By means of appropriate switches, ten fixed frequencies were provided, ranging from 5 hertz to 10^{-4} hertz in one-half-decade steps.

If a device such as this was used, it was important to ensure that the final divide-by-ten or divide-by-two stage put out a signal with a fifty-percent duty cycle. As will become clear from the discussion below, the transmitter required an incoming signal with a fifty-percent duty cycle in order to establish a wave form such as that shown in Figure 6.1.

Figure 6.4: Functional diagram of precision timing device.

6.4.1.2 Square Wave Oscillator

If a square wave oscillator was used as the external timing device, it was necessary that the voltage on the output signal oscillate between approximately 0 and some voltage, V , which was greater than +2 volts. This requirement arose from the nature of the first stage of the transmitter as will become clearer in the discussion of that circuit.

On most oscillators, the establishment of a high-level voltage in excess of +2 volts is simply a matter of adjusting the amplitude control. However, if the oscillator is not equipped with an internal DC offset, it is necessary to hold the low-level voltage to approximately 0 by means of

Figure 6.5: Negative-clipping circuit.

an external circuit. The negative-clipping circuit shown in Figure 6.5 was used for this purpose. It can be seen that the low-level-voltage output from this circuit was not 0 but was slightly negative. This slight negative voltage represented the voltage drop across the diode D1. The resistor R1 was in the circuit in order to avoid a direct short to ground and also to reduce the diode voltage drop so that the low-level output from the circuit did approximate 0 volts.

6.4.2 Transmitter

The purpose of the transmitter was to switch a constant current on and off the sample with alternating polarity. A functional diagram of the transmitter is shown in Figure 6.6. It will be noted that there were three parts or stages to the transmitter:

- (a) switch network;
- (b) signal conditioning;
- (c) switch logic.

A circuit diagram of the transmitter is presented in Figure 6.7. A general note should be made at this point of capacitors C1 through C6 across the voltage supply lines leading onto the circuit board. In each case a 50-microfarad electrolytic capacitor was paired with a non-polarized, 0.1-microfarad capacitor. The electrolytic capacitor was used to suppress

Figure 6.6: Functional diagram of transmitter.

Figure 6.7: Circuit diagram of transmitter.

line ripple. Any oscillation which arose due to the inductance of the electrolytic capacitor was then filtered by the smaller capacitor. Note also that the voltage supply lines to each integrated circuit were also equipped with 0.1-microfarad capacitors to reduce line ripple.

6.4.2.1 Switch Network

The transmitter switches were TTL-compatible, P-MOS analog switches. They were capable of handling the currents used and had the advantage of fast switching speed, low (100 ohms) onstate resistance, high (100 gigohms) offstate resistance and no offset voltage.

The switches were arranged in two banks. Two TL601 switches (Figure 6.7) made up the A-bank of switches in Figure 6.6. These switches controlled the polarity of the current applied to the sample. Two TL604 switches (Figure 6.7) made up the B-bank of switches in Figure 6.6. They switched the current on and off the sample. When the current was off the sample, it was applied to a one kilohm dummy load (R8, Figure 6.7). By using a dummy load in this manner it was possible to avoid wide swings in the load voltage sensed by the constant current source.

In order to produce the desired wave form shown in Figure 6.1, it was necessary to co-ordinate the operation of the switches. This required that each bank of switches be driven by an appropriate pulse train as shown in Figure 6.8. The high-and low-voltage levels of these pulse trains had to be TTL-compatible.

6.4.2.2 Signal Conditioning

The incoming signal from the external timing device was conditioned in the first stage of the transmitter to get a TTL-compatible pulse train which was then used to drive the switch-logic section of the transmitter.

Figure 6.8: Pulse trains for transmitter switches.

Figure 6.9: Development of pulse trains within transmitter.

The signal conditioning was accomplished in three steps:

- (a) The signal was first clipped at 3.6 volts with zener diodes D1 and D2 (Figure 6.7) so that subsequent circuitry would not be overloaded. Resistor R1 was used to avoid a direct short to ground.
- (b) The signal then passed through an absolute-value rectification circuit built around the two OP-07 amplifiers shown in Figure 6.7. This ensured that all voltages would be 0 and above. This was especially important if the external timing device happened to be a commercial IP transmitter, in which case the incoming signal would have resembled the wave form shown in Figure 6.1.

There were two factors which contributed to the accuracy of the given circuit and these should be noted. By using operational amplifiers, it was possible to obtain highly accurate full-wave rectification without significant loss of the signal, in contrast to circuits based entirely on rectifying diodes. Because all resistors in the circuit were of equal value, resistor matching was facilitated and the accuracy was accordingly enhanced. The OP-07 amplifiers were chosen because of their ultra-low offset voltage.

- (c) The signal next passed through the first stage of a dual, four-input, positive-nand Schmitt Trigger (SN7413, shown in Figure 6.7). The Schmitt Trigger was used to ensure a TTL-compatible pulse train which then acted as the driving signal for the switch-logic circuit.

6.4.2.3 Switch Logic

The output from the signal conditioning circuit was fed into the second stage of the Schmitt Trigger which formed the first step in the switch-logic circuit. This buffered and further cleaned the signal and re-established the original polarity.

The output from the second stage of the Schmitt Trigger was used to drive both sides of a dual JK Flip Flop (SN7473, shown in Figure 6.7) and the TL604 switches (B-bank, Figure 6.6). Note the capacitor (C10, 0.47 microfarads, Figure 6.7) on the output from the second stage of the Schmitt Trigger. This was used to suppress ripple and reduce the possibility of false triggering of the Flip Flop and switches.

The non-inverted signal from one side of the JK Flip Flop drove the TL601 switches (A-bank, Figure 6.6). The inverted signal from the other side of the JK Flip Flop was used as an external trigger (for the digital voltmeter).

By driving the TL604 switches with the output of a Schmitt Trigger and the TL601 switches with the output of a JK Flip Flop driven by the same Schmitt Trigger, the pulse trains illustrated in Figure 6.8 were obtained. Triggering of the switches was synchronized in this way in order to give the desired wave form shown in Figure 6.1.

The various steps used to generate the required pulse trains, beginning with their inception in an external timing device, are summarized in Figure 6.9. It is perhaps valuable at this point to re-examine some of the constraints which were alluded to in earlier sections.

The output from the external timing device had to have a 50-percent duty cycle because the JK Flip Flop triggered on the positive-going edge of the output from the Schmitt Trigger. If the pulse train driving the Schmitt Trigger did not have a 50-percent duty cycle, then it was impossible to generate the symmetrical wave form shown in Figure 6.1.

The high-level voltage in the signal from the external timing device had to be no less than +2 volts or the Schmitt Trigger in the signal conditioning circuit would not be activated.

When the external timing device was a square-wave oscillator, a DC offset or negative-clipping circuit had to be used to ensure that the low-level voltage in the output signal was approximately 0. Otherwise, if an incoming signal oscillated between +V and -V, the output from the absolute-value rectification circuit would be a steady voltage of +V.

6.4.3 Constant Current Source

The constant current source which was designed for use in this project was able to supply currents of 10^{-8} , 10^{-7} , 10^{-6} , 10^{-5} , 10^{-4} and 10^{-3} amperes. The maximum load resistance at 10^{-8} amperes was 1200 megohms and the maximum load resistance at 10^{-3} amperes was 11 kilohms.

The functional diagram of the constant current source is shown in Figure 6.10 and the circuit diagram is presented in Figure 6.11. Note that capacitors C1 through C4 were again used on the supply voltage lines as in the transmitter circuit.

2

Figure 6.10: Functional diagram of constant current source.

Figure 6.11: Circuit diagram of constant current source.

The constant current source may be conceptually described in terms of 4 circuits:

- (a) bilateral current source;
- (b) control voltage circuit;
- (c) control resistance circuit;
- (d) switches.

6.4.3.1. Bilateral Current Source

The bilateral current source was a feedback circuit built around two CA3140A operational amplifiers (Figure 6.11). This operational amplifier had a MOS/FET input which resulted in a very high input resistance (1.5 teraohms) and a very low input current (10 picoamperes at ± 15 volts). It also had a very low input-voltage offset.

The second amplifier acted as a unity-gain voltage follower which tracked the output voltage of the constant current source (non-inverting input, pin 3) and introduced this voltage to the first amplifier through resistor R14. A control voltage was applied at the external side of the resistor R13. Resistors R13 and R14 were equal-valued so a voltage equal to the simple average of the two voltages above appeared at the non-inverting input of the first amplifier.

Because resistors R11 and R12 were equal-valued, this average voltage was doubled so that the sum of the control voltage and the output voltage of the constant current source appeared as the output of the first amplifier. This output was first fed through a control resistance and then through a load resistance to ground. Changes in the load resistance provoked appropriate readjustments to maintain a constant current.

The control voltage was positive and the circuit acted as a current source, but if the control voltage had been negative, a current sink would have resulted.

6.4.3.2 Control Voltage Circuit

This circuit supplied the control voltage to the bilateral current source. It consisted of:

- (a) a precision voltage reference;
- (b) a voltage attenuator;
- (c) a unity-gain voltage-follower.

These can be seen in Figure 6.10.

The precision voltage reference was a PMI REF-01 +10 volt precision voltage reference (see Figure 6.11). This device would take an input of 12 to 40 volts. The output was ten volts; adjustable ± 3 percent with resistor R5. It featured excellent temperature stability, low noise and high load-driving capability.

The voltage attenuator consisted of a resistor chain made up of resistors R1, R2, R3 and R4 (Figure 6.11). This allowed the selection of three voltages (1, 0.1, 0.01 volts) in addition to the 10 volt reference.

The unity-gain voltage-follower was the OP-07 shown in Figure 6.11. This device acted as a buffer. In this capacity, it sensed the control voltage selected from the attenuator circuit and introduced this voltage into the bilateral current source. It was used so that the external resistance to ground from both inputs of the first CA3140A remained approximately equal.

6.4.3.3 Control Resistance Circuit

The output of the bilateral current source was first fed through a control resistance, then through an internal load resistance and finally, through the external load resistance to ground. A selection of four control resistors (R6, R7, R8 and R9, Figure 6.11) made up the control resistance circuit.

6.4.3.4 Current Source Switches

Switch S1 was used to select the desired current by introducing appropriate combinations of control voltage and control resistance into the bilateral current source.

The output of each device could be trimmed by means of a potentiometer (R5, R10, R15 and R16, Figure 6.11). All potentiometers were accessible through the front panel. Switch S2 was used when trimming the devices. For example, in the case of an operational amplifier, the inputs were grounded and the output fed to an external voltmeter. The appropriate potentiometer was then adjusted until the output was zeroed.

The constant current source could be completely automated by replacing switches S1 and S2 with C-MOS multiplex switches and by replacing the trim potentiometers with semi-conductor devices and associated feedback systems. This would enable completely computer-controlled operation with automatic trim cycles between each test run.

Figure 6.12: Sample and electrode assembly.

6.5 Sample and Electrodes

An undisturbed sample of clay was first extruded into a plexiglass retaining ring with the dimensions shown in Figure 6.12 and the two faces trimmed flush with the ring.

Considerations affecting the design of the ring included the following: electrical inertness; the use of a minimal amount of soil material; and the ability to transfer an undisturbed and representative sample from another apparatus into the retaining ring. Although intended primarily for use with undisturbed clay samples, it is clear that if appropriate care were taken, the ring could be used with other materials as well, both undisturbed and remolded.

When the two faces of the clay were flush with the ring, the components illustrated in Figure 6.12 were assembled as shown. The porous filters were soaked in a solution which was similar in composition and

salinity to the pore-water electrolyte of the particular sample being tested.

Each of the four electrodes was a patch, 50 millimetres by 50 millimetres square of #52 platinized platinum wire mesh. The wire of the mesh was 0.1 millimetre in diameter.

The rather large size of the wire mesh patch, the fineness of the mesh grid, the small diameter of the wire and the platinized surface of the wire all contributed to a very large metal surface area. This reduced the current density across the metal-solution interface and eliminated many of the problems normally associated with current electrode polarization such as high electrode resistances. Note that the potential electrodes were placed outside the current electrodes. This effectively removed them from the current path so no potentials would likely be developed as a result of current movement across a metal-solution interface.

When being tested, the sample was placed in a grounded steel box and all connecting cables were shielded.

Figure 6.13: Functional diagram of receiver.

6.6 Receiver and Self-Potential Buckout Circuit

The purpose of the receiver was to amplify the signal from the potential electrodes. It was designed to provide gains of 1, 10, 100, 1000 and 5000. The maximum input voltage was 1 volt.

A functional diagram of the receiver is shown in Figure 6.13. The circuit diagram is shown in Figures 6.14 and 6.15. In Figure 6.14 it can be seen that paired capacitors (C1 through C4) were again used across the voltage supply lines coming onto the circuit board as in the transmitter and the constant current source. Capacitors were employed on all the voltage supply lines where they entered each device. This was an added precaution to ensure quiet operation of the amplifiers.

Figure 6.14: Circuit diagram of receiver amplifiers.

Figure 6.15: Circuit diagram of receiver switches.

The receiver and self-potential buckout circuit will be discussed under four headings:

- (a) receiver amplifiers;
- (b) receiver switches;
- (c) self-potential buckout circuit;
- (d) calibration of receiver gain.

6.6.1 Receiver Amplifiers

The signal from the potential electrodes was first fed into either one of two instrumentation amplifiers (amp-1 or amp-3, Figure 6.14; see also Figure 6.13). Instrumentation amplifiers were chosen because: they featured a differential input which is essential when the signal emanates from a floating source as in this case; they possessed a high input impedance (on the order of 10^9 ohms) and therefore did not load down the source; and they had an excellent common-mode-rejection capability.

The AD 522 was the instrumentation amplifier chosen for use in the receiver. It employed the well known three-operational-amplifier configuration and featured low drift, low non-linearity, low noise and high common-mode-rejection ratio. In addition, it had a data-guard input to which the shielding of the input cables was connected. This improved the AC common-mode rejection by "bootstrapping" the cable capacitance. The gain was also conveniently set by a single external resistor.

Although the input to the instrumentation amplifiers of the first stage was differential, the output was single-ended, referenced to system common.

The following discussion outlines those considerations which led to the use of the five amplifier configuration shown in Figures 6.13 and 6.14. The incoming signal had to be met by a differential amplifier. For a receiver gain of 1, a separate circuit could have been constructed around an additional instrumentation amplifier with a set gain of one. However, it was decided to first amplify the signal and then attenuate it by the same amount producing a net gain of 1. This was done because the common-mode-rejection ratio improved with gain. Once the signal-to-noise ratio was enhanced, it was unaffected by subsequent attenuation. Because it was necessary that the receiver have the capability of handling an incoming signal of ± 1 volt, the gain in this initial amplification could not exceed 10. This restriction arose because the limiting output voltage on the AD 522 was ± 10 volts with a supply voltage of ± 15 volts.

After attenuation, an AD 521 amplifier (amp-2, Figure 6.14; see also Figure 6.13) was used as a unity-gain voltage-follower. It acted as a buffer so that the impedance of any external device connected to the receiver output did not change the attenuation ratio. The AD 521 was an inexpensive monolithic differential amplifier. It was used here as a single-input amplifier but it still retained the excellent common-mode-rejection ratio which is characteristic of instrumentation amplifiers.

After an initial gain of 10, the signal could have been successively amplified in a series of operational amplifiers to yield receiver gains of 100, 1000 and 5000. However, considering the practical limits of operational amplifiers and problems such as repeated amplification of input-voltage offsets, it seemed best to ignore the slight extra cost and use another AD 522 (amp-3, Figure 6.14) with a set gain of 100. Because of the increased gain, this amplifier had an even better common-mode-rejection ratio. Two operational amplifiers (amp-4 and amp-5, Figure 6.14; see also Figure 6.13) were then used to boost the receiver gain to 1000 and 5000 respectively.

6.6.2 Receiver Switches

There were five amplifiers in the receiver. For a selected gain, there were a maximum of two amplifiers in operation at any one time. Switch S1 (Figure 6.15) was the gain selection switch. It directed the signal through the circuit and shorted to ground the inputs of all unused amplifiers in order to avoid oscillations or problems with stray voltages.

All amplifiers had trimming potentiometers (R1, R3, R9 and R16 and R21, Figure 6.14) which were accessible through the front panel. Switch S2 (Figure 6.15) was used when trimming the amplifiers. For each amplifier at a time, the inputs were shorted to ground and the output fed to an external voltmeter. The output was then zeroed with the potentiometer.

Switch S3 (Figure 6.15) was used to connect the cable shield to the data-guard pin on the appropriate instrumentation amplifier in the first stage of the receiver.

It would be possible to replace these three switches with C-MOS multiplex switches and to replace the trimming potentiometers with semiconductor devices and associated feedback circuitry. This would permit completely computer-controlled operation with automatic trim cycles between each test run.

6.6.3 Self-Potential Buckout Circuit

In order to sense changes in the electrical field within the soil sample, the potential electrodes had to make electrical contact with the clay sample either directly or through an electrolyte. Because soil is a reactive medium, largely as a result of the pore-water electrolyte, all metal electrodes, including those made of platinum, will react

Chemically with soil and reach some equilibrium potential with respect to it. This equilibrium potential is a function of many factors, some of which are very obscure. As a consequence, the two potential electrodes were never at the same potential with respect to the clay sample and a small residual potential difference therefore existed between them.

This residual potential difference was not due to the applied current and had to be nulled. This was done with a self-potential buck-out circuit such as is shown in Figure 6.16. With this circuit, a back EMF could be applied to the potential electrodes in order to counter the residual potential difference described above.

Switch S2 in Figure 6.16 doubled the effective range of this circuit by reversing the polarity of the EMF applied to the potential electrodes. As designed, the buckout circuit could null self-potential differences ranging from -0.4 volts to +0.4 volts.

Resistor R5 was a ten-turn potentiometer which allowed precise adjustment of the buckout circuit. It was turned until the observed output of the receiver was zero when no current was applied to the soil through the current electrodes.

6.6.4 Calibration of Receiver Gain

All the amplifiers in the receiver were set to fixed gains following the manufacturer's instructions. However, it seemed desirable to calibrate the receiver in order to know the five gains with an accuracy of 1 percent or better. This was done with the circuit shown in Figure 6.17.

A reference voltage (for example, 10 volts) was attenuated through a series of resistors to give a selection of discrete reference

Figure 6.16: Self-potential buckout circuit.

Figure 6.17: Circuit for calibration of receiver gain.

voltages. A selected reference voltage was fed into the receiver, the output measured and the gain calculated. Switch S2 reversed the polarity so that a peak-to-peak voltage was measured. This eliminated the effect of any DC offsets that may have been present in either circuit and allowed a more realistic assessment of the true gain.

The maximum output voltage of the amplifiers in the receiver was about 10 volts. Therefore, if the receiver gain was set at 5000, the maximum voltage which could appear at the input was 0.002 volts. It can be seen that the circuit shown in Figure 6.17 meets this requirement. However, the 0.001 volts shown is a nominal value only. Measurement of its true value was made by a voltmeter at the output of the circuit.

The most reliable and accurate voltmeter available to the author was a digital voltmeter displaying four significant figures. Under these circumstances it was impossible to measure the true value of the 0.001 reference voltage with an accuracy of 1 percent. It therefore became necessary, in effect, to first calibrate the calibration circuit...

This calibration was accomplished by temporarily replacing the 10-volt reference with a 100-volt reference and then measuring the peak-to-peak voltage at each position of Switch S1 with an accuracy of ± 1 percent. It was then possible to calculate what each of these reference voltages would be when the 100-volt reference was replaced by the 10-volt reference.

In practice, the 10-volt reference was supplied from the constant current source. After it had been adjusted to exactly 10 volts, each reference voltage was fed into the receiver and the peak-to-peak voltage was measured at the output with the digital voltmeter. The true gain was then calculated and used in subsequent computations.

6.7 Data Acquisition, Storage and Processing

Data acquisition, storage and processing was controlled by a Hewlett-Packard 9825A calculator. Support devices included a 9885M flexible disk drive, a 9872A plotter and a 9871A printer. The output of the receiver was digitized by a Hewlett-Packard 3437A system voltmeter. These components were linked by a Hewlett-Packard interface bus conforming to the IEEE-488 G.P.I.B. standard. A Gould Brush 222 two channel recorder was used to make an independent record of the analog signal.

Data was obtained for each sample at a number of frequencies and with a range of currents as well. The following testing sequence was used:

- (a) a 2-second period at an initial current, I , which would give a recordable signal with minimum amplification;
- (b) a 20-second period at I ;
- (c) a 20-second period at $I \times 10^{-1}$, at $I \times 10^{-2}$, and so on until the signal was unrecordable; and
- (d) a 200-second period at I .

In all cases except that with the 200-second period, the signal was stacked 4 times to improve the signal to noise ratios.

The digitized signal was stored on magnetic disk and the information was processed to yield diagrams of:

- (a) Voltage versus time;
- (b) amplitude versus frequency;
- (c) impedance versus frequency;
- (d) even-phase spectrum; and
- (e) odd-phase spectrum.

CHAPTER 7

AUXILIARY TESTS AND MEASUREMENTS

7.1 Coefficient of Permeability

The permeability of each sample was determined by making a slight modification in the arrangement used for leaching. The outlet to the upper stone was plugged, leaving only the reservoir connected. One connecting tube to the lower stone was also plugged and the other was connected to a micropipette. The axis of the micropipette was horizontal. The volume of the reservoir was so much greater than that of the micropipette that the arrangement was, in effect, a constant-head permeameter.

The hydraulic head across the soil sample was equal to the elevation difference between the axis of the micropipette and the water in the reservoir plus the capillary head which resulted from the fine bore of the micropipette. For each sample, the hydraulic head was between 14 and 15 centimetres.

The test was continued until approximately three quarters of the micropipette had been filled. This usually took about 36 hours.

7.2 Water Content

The gravimetric water content of the soil sample was determined in the usual manner by weighing and drying a small portion of soil material. Three specimens were taken from each sample along a diameter, the first near the centre, another near the edge and a third in between. This was done in order to discover and monitor any variability in the water content as a result of edge effects.

Because the specimens taken for water-content analysis were rather small, the weighing dish used was a small piece of aluminum foil in order to increase the weight of the soil in relation to the weighing vessel.

The specimens for water-content analysis were taken from a horizon near the bottom of the soil sample. In some samples, the analysis was also done on a second set of specimens taken from a horizon near the top of the soil sample in order to examine variations in the water content across the thickness of the soil sample.

7.3 Particle-Size Distribution

The particle-size distribution was determined for three small specimens of each soil sample. As before, these specimens were taken along a diameter, one at the centre, another at the edge and the third in between, in order to examine any variability due to edge effects.

Because drying of a soil specimen may subsequently prevent the proper disaggregation and dispersion necessary for an analysis of the particle-size distribution, these specimens were not dried, but rather their dry weight was determined by means of the data obtained on the water content. In order that the water-content data should be relevant, the specimens collected for particle-size analysis were taken from points adjacent to those sampled for the water content.

Most methods for the analysis of the particle-size distribution require 40 to 50 grams of soil material. Each of the three specimens contained little more than one gram of dry soil material. This necessitated the use of the falling-drop method of particle-size analysis. This method is described by Moum (1965) and is based upon a micropipette technique. It was developed for use with small specimens such as these but also has the added advantage of being a rapid test, allowing a full analysis to be completed within three to four hours. A further advantage is that many analyses can be undertaken concurrently.

When each specimen for particle-size analysis was taken from a soil sample, it was immediately placed in a test tube and not removed from the test tube until the analysis had been completed. Prior to analysis, it was first dispersed with a sodium hexametaphosphate (Calgon) solution and an ultrasonic device was used to ensure complete disaggregation. After dispersal, the test tube was partially immersed in a constant temperature bath and served as the sedimentation cylinder.

At appropriate ~~time~~ intervals, aliquots were drawn from a pre-determined depth with a micropipette. Each aliquot was then released as a droplet into a column of aniline, an organic liquid which is less dense than water and immiscible with aqueous solutions. The drop therefore retained its form and fell through the column of aniline. The time which elapsed as it fell the distance between two markers was noted. This time was a function of the density of the soil-water droplet. The value of the density was then determined from a calibration curve of time versus density, obtained by using aqueous solutions of sodium chloride. Since the falling time is also temperature dependent, the column of aniline was contained within a cylinder lying along the axis of a larger cylinder filled with water which was held at a constant temperature.

7.4 Pore-Water Chemistry

7.4.1 Initial Estimate of Leaching Effectiveness

Because one of the principal objectives of the experiment was to generate soil samples with predetermined pore-water parameters, it was necessary to assess the effectiveness of the leaching before the samples were tested. Therefore, after what was anticipated to be an appropriate period of leaching, an attempt was made to determine whether the desired pore-water salinity had been attained.

During the course of the experiment, two different techniques were used for this purpose. These will be referred to as:

- (a) the equilibration technique;
- (b) the diffusion technique.

The first of these was employed on the initial set of samples. All subsequent samples were tested using the diffusion technique.

7.4.1.1 Equilibration Technique

The flow of leaching fluid through the porous stones was first stopped for 24 to 48 hours in order to let the water in the stones chemically equilibrate with the pore water of the soil. Flow was then restarted and a series of small aliquots of approximately 3 to 4 millilitres each were withdrawn from each outlet. The electrical conductivity of these aliquots was measured and was seen to characteristically rise from one aliquot to the next until a peak was reached. Then it dropped in a similar step-wise fashion until it levelled off at the conductivity of the supply reservoir.

It was assumed that the peak conductivity represented the aliquot which had equilibrated with the pore water of the soil. A calibration curve, obtained with solutions of known salinity, was used to estimate the salinity of this peak aliquot from its conductivity value. If this procedure indicated that the pore water had reached the intended salinity, then the leaching was stopped.

7.4.1.2 Diffusion Technique

For most of the samples tested, an estimate of leaching efficiency was obtained using a diffusion technique. The theoretical basis for this technique is presented in Appendix "D".

Equations D.7 and D.8 are the relationships of particular relevance to this application. The surface flux of diffusing substance was first measured experimentally in a manner which will be described below and a diffusion coefficient was calculated from Equation D.8 by an iterative, trial-and-error approach. The diffusion coefficient calculated in this manner was used in Equation D.7 to estimate the mid-plane concentration excess. If this procedure indicated that the mid-plane pore-water salinity had reached the intended value, the leaching was stopped.

Measurement of the surface flux of diffusing substance was accomplished in the following manner. Each porous stone was first flushed by rapidly passing approximately 100 millilitres of leaching solution through it from the reservoir. Flow was then reduced and all fluid passing through the stone was collected in a 100-millilitre volumetric flask. The rate of flow was adjusted so that approximately 70 millilitres of leachate would be collected in 24 to 36 hours. The final 30 millilitres were collected in a few minutes during a rapid flush of the porous stone.

The amount of salt contained within the volumetric flask was estimated by measuring its conductivity and comparing the results with a calibration curve obtained with solutions of known salinity. The conductivity of the reservoir water was also measured and used to calculate the net amount of material collected in the flask.

The time during which the flask was filled had been noted and the area of the soil-stone interface was known, so the surface flux could be calculated. An estimate of surface flux was obtained from both faces of each sample and the two values were averaged before calculation of the diffusion coefficient was attempted.

7.4.2 Pore-Water Extraction

The pore water was squeezed out of a sample of soil material by means of pressure supplied by a tank of compressed nitrogen. The vessel that contained the soil was made of machined nylon which had been chosen for its chemical inertness. The receptacle holding the sample itself was 3 centimetres in diameter and 1.5 centimetres deep.

A surgical rubber membrane (dental dam) was placed over the nylon vessel and a brass cover with pressure-hose fittings was then bolted to the nylon. An O-ring completed the seal between the two halves of the device.

The apparatus was then connected to a nitrogen tank and pressure was gradually increased to 400 kPa and maintained at that level. The rubber membrane stretched and pressed down upon the soil, squeezing the pore water out through a small opening in the bottom of the nylon vessel. The pore water was carried from this opening into a test tube by tiny polyethylene tubing with an outside diameter of approximately 1 millimetre.

It required from one to two hours to collect an adequate sample of pore water in this manner.

7.4.3 Dilution of Pore-Water Sample

The instruments which are used to determine the concentration of ions in aqueous solutions give the most reliable results when the concentration of the particular ion being analysed lies within a preferred range of concentrations. As a consequence, it was necessary to reduce the concentration of certain ions in the pore water for improved analysis of their concentrations. This was done by means of dilution.

An array of dilutions was routinely prepared from all pore-water samples. These dilutions, together with the original pore-water sample ensured that, for each ion whose concentration was analysed, there was a solution of appropriate concentration.

The dilution was accomplished with an automatic dilution machine, in this case a Fisher Scientific Inc. Dilumat, which could be adjusted to give dilutions to any desired ratio. Dilutions of 1:10, 1:100 and 1:1000 were prepared for all pore-water samples.

7.4.4 Measurement of Cation Concentrations in Pore Water

Ionic concentrations, specifically sodium, potassium, magnesium and calcium were determined using a Perkin-Elmer Model 803 Atomic Absorption Spectrophotometer.

The accuracy of atomic absorption spectrophotometry is concentration-dependent. Therefore, a selection of dilutions, as noted above, were provided in order to ensure that the concentration lay within the band of maximum sensitivity.

7.5 Shear Strength

A previous chapter has described a vane apparatus which can be used to determine both the undisturbed and remolded shear strength of a soil. A second method was also used in this experiment, specifically the fall-cone method developed in Sweden and described by Hansbo (1957). This technique is a widely accepted method for rapidly determining the undrained shear strength of both undisturbed and remolded soils. To measure the shear strength, a cone of standard dimensions and weight is allowed to penetrate the soil by dropping under its own weight from a position where the tip of the cone just touches the surface of the soil. The shear strength is proportional to the depth of penetration. A standard set of cones includes: a 400 gram-30 degree cone; a 100 gram-30 degree cone; a 60 gram-60 degree cone; and a 10 gram-60 degree cone.

A modified asphalt penetrometer was used in this experiment to release the cones. This device was chosen because it was equipped with a mechanism to release a cone without disturbance and then to lock it in place after it had penetrated the soil. An attached dial gauge, reading to 0.1 millimetre, was used to measure the penetration.

7.6 Atterberg Limits

The plastic limit was determined using conventional procedures which are described in numerous texts (for example, Bowles, 1970).

Because of the small amount of material available for the various tests, it was necessary to determine the liquid limit using a one-point procedure described by Eden (1959). A conventional Casagrande liquid limit device was used to determine the number of blows corresponding to a single water content. The liquid limit was then calculated with the following equation (presented by Eden from earlier sources in the literature):

$$LL = w \left[\frac{N}{25} \right]^{\tan \beta} \dots \dots \dots (7.1)$$

where: LL is the liquid limit of the soil.
 w is the water content at N blows.
 N is the number of blows.
 $\tan \beta$ is the slope of the flow line on a log water content versus log N plot.

Conventional liquid limit tests employing three points had been run on a number of samples of the same or similar material as that used in this experiment. These data were analyzed according to the method outlined by Eden (1959) to determine a value for $\tan \beta$.

$$\tan \beta = 0.1557 \dots \dots \dots (7.2)$$

The water content of a sample being tested was altered by drying until the number of blows to failure in the liquid limit device

was between 15 and 30. When dealing with samples having saline pore water, care was taken to ensure that drying was not excessive. Significant drying of saline samples could have resulted in corresponding shifts in the value of the liquid limit, a factor which would not have been easy to assess.

7.7 Miscellaneous Chemical Tests

7.7.1 Sample Eh and pH

The Eh of samples was measured electrically on fresh material, immediately after remolding. An Orion Research Ionalyzer Model 407A was used with a Fisher Scientific Inc. platinum-probe electrode and porous-plug Calomel reference electrode (saturated KCl).

The pH was also measured electrically using the same instrument and an Orion Research combination pH electrode (model 91-05).

7.7.2 Cation-Exchange Capacity

The cation-exchange capacity of all samples was determined using the sodium saturation method described by Chapman (1965). The soil was first washed 3 times with 30-millilitre volumes of sodium acetate, followed by 3 washings with isopropyl alcohol. Four 25-millilitre volumes of ammonium acetate were used to displace the sodium and the decant was collected in a 100-millilitre volumetric flask.

The cation-exchange capacity was calculated from the concentration of sodium in the decant which was determined with a Perkin-Elmer Model 803 Atomic Absorption Spectrophotometer.

7.7.3 Ammonium-Acetate-Extractable Cations (Exchangeable Bases)

The procedure used to determine the exchangeable bases consisted of washing the soil 4 times with 25-millilitre volumes of ammonium acetate and analysis of the collected decant. The concentrations of sodium, potassium, calcium, magnesium, iron and aluminum were determined with a Perkin-Elmer Model 803 Atomic Absorption Spectrophotometer.

The ammonium acetate used for the extraction had a pH of 7 and was capable of partially dissolving some of the carbonate minerals in the soil. This resulted in an anomalously high concentration of calcium in the collected decant. The concentration of calcium was corrected by comparing the cation-exchange capacity calculated from the exchangeable bases with that determined by the method of sodium saturation described in the previous section. Any difference was attributed to the presence of excess calcium and the concentration of calcium was corrected accordingly.

7.8 Procedure for Sample Testing

After preparation, each sample was approximately 5 centimetres in diameter and 3 to 4 centimetres thick. The water content was 60-80 percent and the weight of dry soil was between 65 and 70 grams. This constituted a rather small sample for the number of tests to be performed. As a consequence, a rather careful testing sequence had to be devised. This may be summarized as follows:

- (a) A final reading was taken from the dial gauge on the consolidation apparatus.
- (b) The sample cylinders were removed from the consolidation rack and the screw-driven extrusion device illustrated in Figure 5.6 was attached.
- (c) The sample and cylinder were inverted and the base plate removed.
- (d) The sediment thickness was measured accurately with a precision caliper.
- (e) The sample was mounted on the vane apparatus and the torque-twist relationship and the shear strength were determined. This disturbed approximately 6 millimetres of sample.
- (f) The sample was extruded 1 to 2 millimetres and the material trimmed off for determination of the exchangeable bases.
- (g) The soil was extruded a further 3 to 4 millimetres and trimmed off, with the material being sampled for water-content analysis and particle-size distribution at the

centre, middle and edges. The particle-size and water-content samples were taken from alternating quadrants.

- (h) A further 6 to 7 millimetres was extruded into the plastic retaining ring shown in Figure 6.12 for the electrical measurements. After the electrical measurements, some of this material was used to determine the cation-exchange capacity and what remained was added to that reserved for the Atterberg Limits.
- (i) The undisturbed shear strength was determined by the fall-cone method.
- (j) This material was then extruded 6 millimetres and removed for pore-water extraction and analysis. After extraction of the pore water, this soil was added to that reserved for the Atterberg Limits.
- (k) The remaining soil, 10 to 15 millimetres in thickness was extruded and remolded. The Eh was measured immediately.
- (l) The vane was used to determine the torque-twist relationship of the remolded soil and its shear strength.
- (m) The fall cone was also used to determine the remolded shear strength of the soil.
- (n) The pH was measured.
- (o) The liquid and plastic limits were determined.

CHAPTER 8

RESULTS, CONCLUSIONS AND FUTURE DIRECTIONS

8.1 Framework for Presentation of Results

The results of this thesis will be presented within a framework based upon the research objectives and approach established for this experiment. The research objectives were stated in Chapter 1 and may be summarized again as follows:

- (a) to develop simple geotechnical and electrical measurements and procedures to index certain system properties; and,
- (b) to examine the relative impact of certain controlling variables upon selected properties of a soil system.

In order to achieve these objectives, an attempt was made to produce a suite of controlled soil samples employing an unusual approach which involved the sedimentation, consolidation and leaching of natural soil material under conditions similar to those prevailing when the soil originally accumulated.

In accordance with the foregoing, this chapter will address the following topics:

- (a) the degree of success achieved in the preparation of a controlled suite of soil samples;

- (b) the soil properties measured and their relationship to the controlling variables; and,
- (c) the general conclusions to be drawn from this experiment and directions for future research.

Most of the equipment used in this experiment was specially designed and built for this project. Some improvements in equipment and procedures could be made and these are noted at appropriate places in the text.

8.2 Preparation of Samples

For convenience, Table 1.1 has been reproduced as Table 8.1. It is important to once again emphasize that this table records the intended values and states of the controlling variables for this experiment. The preparation of the samples was closely monitored and the assessment which follows will be made with reference to the controlling variables and within the context of the major phases (sedimentation, consolidation and leaching) of the process.

8.2.1 Sedimentation

8.2.1.1 Particle-Size Distribution

The particle-size distribution was analyzed for specimens taken from 8 samples composed of normal soil material. The specimens were taken from the center, mid-radius and edge of horizontal slices through each of the 8 samples. An additional analysis was done at the center of another sample composed of normal soil material, for a total of 25 analyses. There appeared to be no systematic variation between the center, middle and edge. The results are presented in Table 8.2 and indicate that for the normal soil material the silt/clay ratio is, approximately 40/60.

The particle-size distribution was also determined for specimens taken from the centers of samples which had been altered, either with respect to their mineralogy (samples 21 and 22) or their silt/clay ratio (samples 17 and 20). These results are also presented in Table 8.2. In all 4 cases the silt/clay ratio is not that which was intended (see Table 8.1).

Table 8.1: Summary of the intended modes or values of the controlling variables for the 22 samples.

Sam. No.	Temp. (°C)	Orig. Part. Miner. or Compos.	Part.- Size Distrib. (Silt/Clay)	a ³ Chem. of Sed. Envir. (g./l.)	b ³ Susp.- Sed. Conc. (g./l.)	Present (Final) Stress (kPa.)	Stress Hist. (Consol.) (kPa.)	c ³ Present (Final) Pore-Wtr. Chem. (g./l.)	Cement.	Weather.	Wtr./Gas Ratio In Pores
1	20	Normal	40/60	26	5	24.3	57.6	0	None	d ³ Possible-A	Sat.
2	20	Normal	40/60	26	5	24.3	57.6	0	None	d ³ Possible-B	Sat.
3	20	Normal	40/60	26	5	24.3	57.6	0.5	None	None	Sat.
4	20	Normal	40/60	26	5	24.3	57.6	1	None	None	Sat.
5	20	Normal	40/60	26	5	24.3	57.6	2	None	None	Sat.
6	20	Normal	40/60	26	5	24.3	57.6	4	None	None	Sat.
7	20	Normal	40/60	26	5	24.3	57.6	10	None	None	Sat.
8	20	Normal	40/60	26	5	24.3	57.6	0	None	None	Sat.
9	20	Normal	40/60	26	15	18.2	18.2	0	None	None	Sat.
10	20	Normal	40/60	26	7	18.2	18.2	0	None	None	Sat.
11	20	Normal	40/60	26	3	18.2	18.2	0	None	None	Sat.
12	20	Normal	40/60	26	1	18.2	18.2	0	None	None	Sat.
13	20	Normal	40/60	8	5	18.2	18.2	0	None	None	Sat.
14	20	Normal	40/60	4	5	18.2	18.2	0	None	None	Sat.
15	20	Normal	40/60	2	5	18.2	18.2	0	None	None	Sat.
16	20	Normal	40/60	0	5	18.2	18.2	0	None	None	Sat.
17	20	Normal	75/25	26	5	18.2	18.2	0	None	None	Sat.
18	20	Normal	40/60	26	5	18.2	18.2	0	None	None	Sat.
19	20	Normal	40/60	26	5	18.2	18.2	1	None	None	Sat.
20	20	Normal	10/90	26	5	18.2	18.2	0	None	None	Sat.
21	20	SiO ₂ Add.	40/60	26	5	18.2	18.2	1	None	None	Sat.
22	20	SiO ₂ Add.	40/60	26	5	18.2	18.2	0	None	None	Sat.

NOTES: (a) - Ionic suite similar to that of seawater; expressed as grams of salt per liter of solution.

(b) - Expressed as grams of soil solids per liter of suspension.

(c) - Intended final salinity, expressed as grams per liter of NaCl.

(d) - Samples leached to low salinity and allowed to stand for extended periods of time (A < B), raising possibility of weathering.

Table 8.2: Particle-size distributions.

Soil Material	Number of Analyses	Percent Finer Than					
		74 μ	50 μ	25 μ	10 μ	5 μ	2 μ
Normal	25	100	96.2	92.3	82.0	73.2	60.3
High Clay	1	100	94.0	91.8	85.7	76.9	66.6
High Silt	1	100	96.5	89.5	69.8	53.5	39.0
SiO ₂ Added	2	100	89.3	80.6	66.7	61.8	48.4

Table 8.3: Monitoring of the chemistry of the sedimentary environment.

Samp. No.	Intended Salinity (g./l.)	Measured Salinity (g./l.)	Samp. No.	Intended Salinity (g./l.)	Measured Salinity (g./l.)
1	26	*25.8; 25.8; 26.0	12	26	*26.3; 26.4
2	26	25.9	13	8	7.8
3	26		14	4	4.2
4	26		15	2	2.1
5	26		16	0	* 0.12; 0.12; 0.11
6	26		17	26	25.6
7	26		18	26	26.2
8	26		19	26	26.5
9	26	25.3	20	26	26.2
10	26	25.2	21	26	26.4
11	26	26.1	22	26	25.0

*NOTE: The salinity of the sedimentary environment was checked at some time between the middle and end of the sedimentation phase. When the sedimentation phase was unusually long, the salinity was checked more than once.

Table 8.4: Void ratio, water content and Atterberg limits.

(NOTE: Cross-sectional area of all samples was 19.17 cm.²)

Sample No.	Final Thickness (cm.)	Void Ratio	Water Content				Atterberg Limits		Plasticity Index (%)	Liquidity Index
			Centre (%)	Middle (%)	Edge (%)	Average (%)	Liquid Limit (%)	Plastic Limit (%)		
1	3.21	1.51	62.77	62.94	66.81	64.17	56.4	21.0	35.4	1.22
2	3.07	1.40	57.21	59.42	63.85	60.16	53.4	21.4	32.0	1.21
3	3.05	1.38	57.13	58.42	62.48	59.34	51.1	20.0	31.1	1.26
4	3.04	1.38	57.50	58.94	63.83	60.09	54.5	21.0	33.5	1.16
5	3.00	1.34	56.54	58.25	62.66	59.15	52.5	21.3	31.2	1.21
6	3.10	1.42	59.53	59.96	61.65	60.38	51.2	18.6	32.6	1.28
7	3.02	1.36	57.82	58.98	62.72	59.84	53.0	21.3	31.7	1.22
8	3.04	1.38	57.20	58.26	62.36	59.27	49.1	20.6	28.5	1.35
9	3.74	1.64	68.23	71.62	76.87	72.24	48.5	20.5	28.0	1.85
10	3.88	1.78	72.18	76.22	82.09	76.83	52.0	20.4	31.6	1.78
11	3.69	1.60	66.79	70.59	71.23	69.54	52.1	21.0	31.1	1.56
12	3.86	1.65	71.42	74.61	80.90	75.64	46.8	20.2	26.6	2.08
13	3.89	1.74	72.19	75.06	80.22	75.82	52.2	21.2	31.0	1.76
14	3.70	1.61	68.85	72.08	77.85	72.93	52.8	20.7	32.1	1.62
15	3.71	1.62		68.99	73.82		54.2	21.0	33.2	
16	3.78	1.67	78.02	83.58	84.60	82.07	54.9	20.7	34.2	1.79
17(Top)	2.61	0.89	38.28	39.98	39.39	39.22	31.4	17.6	13.8	1.56
17(Bot.)			40.72	42.70	42.50	41.97				1.76
18(T)	3.76	1.73	80.29	77.26	71.02	76.19	55.2	20.9	34.3	1.61
18(B)			71.48	71.72	70.79	71.33				1.47
19(T)	3.69	1.68	75.74	71.66	65.12	70.86	51.5	19.8	31.7	1.61
19(B)			68.92	73.60	76.56	73.03				1.68
20(T)	4.02	1.92	84.84	81.98	78.71	81.84	54.2	23.3	30.9	1.90
20(B)			75.16	77.29	79.66	77.37				1.75
21(T)	8.46	6.16	311.42	314.37	334.25	320.01	160.0	77.2	82.8	2.93
21(B)			246.62	249.37	258.85	251.61				2.11
22(T)	9.06	6.67	287.86	294.29	337.11	306.42	165.0	81.7	83.3	2.70
22(B)			271.62	272.81	276.66	273.70				2.31

For example, an attempt was made to retain a 40/60 silt/clay ratio in samples 21 and 22 in spite of the addition of very finely divided SiO_2 . The measured silt/clay ratio noted in Table 8.2 is approximately 52/48. Two possible explanations for the anomalously high silt/clay ratio appear reasonable.

- (a) During sedimentation, it was noted that the very fine SiO_2 did not flocculate as readily as the natural soil material and as a consequence, a certain proportion of the SiO_2 remained in suspension or sedimented very slowly, occasionally forming layers or lenses of gel-like material within the soil matrix.
- (b) The second explanation refers to the particle-size analysis itself. The specimens taken from samples 21 and 22 would not completely disperse and nodules of gel-like consistency were observed to form. This would influence the analysis by causing an anomalously high silt content to be recorded.

Although the silt/clay ratios of samples 17 and 20 were not as intended, it can be inferred that the discrepancy is probably not due to the particle-size analysis because sample 17 is higher in clay and sample 20 is higher in silt than was intended. Rather, the cause likely lies somewhere in the preparation of the soil material. Perhaps there was incomplete dispersion of the material which was split into the silt and clay fractions.

It is, however, interesting to note that although the silt/clay ratios were not as different from the normal soil material as intended, the effect was nonetheless pronounced. During sedimentation, this was manifested by differences in the thickness of the sediment pack. These

differences persisted as can be noted in Table 8.4. The normal samples, 18 and 19, have a void ratio of about 1.70 as compared to void ratios for the altered samples, 17 and 20, of 0.89 and 1.92 respectively. The liquid and plastic limits of sample 17 are also significantly lower than those of the normal soil material. The plastic limit of sample 20 appears to be significantly higher than that of normal soil material. These differences, of course, could have been predicted on the basis of first principles relating to the influence of clay on the plasticity of soils.

8.2.1.2 Particle Mineralogy

X-ray diffraction analysis of the normal soil material, performed by Mr. Norman Miles of Agriculture Canada, indicated that the minerals chlorite, hydrous mica (illite), quartz and feldspar dominated in the system, with amphibole also present in measurable amounts. Swelling minerals were, at most, present only in trace amounts. Carbonates were also detected with HCl.

Clay minerals are characteristically very fine-grained and clay-mineral particles are usually found within the clay fraction of a soil. It was noted in Chapter 1 (Section 1.1.3) that the question of the relative proportions of clay minerals and primary rock forming minerals in the clay fraction of Leda Clay is unresolved. If, however, one accepts the traditional view that clay minerals predominate in the clay fraction of Leda Clay, one can infer from this that altering the silt/clay ratio results in a change in the mineralogy. Increasing the silt content should cause enrichment in primary rock minerals and conversely, increasing the clay content should cause enrichment in the clay minerals.

On the basis of the above argument, it is unlikely that the particle-size distribution was changed (for samples 17 and 20) without altering the relative abundance of minerals present. The extent of the

resultant changes in mineral proportions in samples 17 and 20 and the degree to which these changes contributed to the differences in void ratio and Atterberg limits of these samples, noted in the section above, are unknown.

The addition of colloidal SiO_2 to samples 21 and 22 has already been noted. It was intended that SiO_2 constitute 25 percent of the soil solids but for reasons explained in the preceding section, it is unlikely that this was achieved. However, the effects on the void ratio, water content and Atterberg limits have been nonetheless dramatic as can be seen by reference to Table 8.4.

8.2.1.3 Chemistry of Sedimentary Environment

The manner in which the salinity of the sedimentary environment was re-established following the addition of a soil aliquot was described in Section 2.5. There was some concern that the salinity might vary over time because the soil aliquots were dispersed in deionized water. In order to ascertain if this was the case, the supernatant solution was analyzed during the latter half of each sedimentation phase. The salinity was determined by means of its electrical conductivity. If, for some reason, the sedimentation phase was unusually long, more than one analysis was done.

The results are presented in Table 8.3. As can be seen, the procedure for maintaining the intended chemistry of the sedimentary environment was adequate.

8.2.1.4 Suspended-Sediment Concentration

Careful observations made during the course of the experiment clearly indicated that if the soil additions were made according to the

Figure 8.1: Vertical cross-section through water-sediment interface along axis of sedimentation cylinder.

procedure described in Section 2.5, the soil material was confined to the desired volume of supernatant solution in the top portion of the sedimentation cylinders and as a consequence, the suspended-sediment concentration was reasonably close to that which was intended.

8.2.1.5 Sediment-Water Interface

After each day's sediment additions, a light, fluffy pack of sediment had been deposited, which then consolidated overnight under the influence of a hydraulic head and its own weight. After the overnight consolidation, the surface of the sediment pack, in the majority of cases, had a cross-sectional profile like that shown in Figure 8.1. When the samples were being tested, concentric rings were sometimes noted if the sample was viewed in the proper light. These rings lay in a plane parallel to the base plate of the sedimentation cylinder and it seems reasonable to assume that they represent successive vertical positions of the sediment-water interface recorded on a horizontal slice through the sample.

The profile in Figure 8.1 also suggests that edge effects were present due to the influence of the cylinder wall. This is supported by the water contents determined on material from the center, mid-radius and edge of each sample. As can be seen in Table 8.4, there is a systematic

variation from lower to higher water content going from the center to the edge. Clearly, edge effects were present, but the surface profile and water content observations are not entirely consistent, in that the profile in Figure 8.1 would suggest that the minimum water content should occur in the mid-radius sample, whereas it normally occurred in the centre.

The process or processes operating to produce the effects noted above had no influence on the particle-size distribution. As was noted in Section 8.2.1.1, there was not significant variation in the particle-size distribution of specimens taken from the center, mid-radius and edge of the samples tested.

8.2.1.6 Flocculation

One group of samples (9 to 16) was prepared to examine the effect of the suspended-sediment concentration and the chemistry of the sedimentary environment on the process of flocculation and the soil properties which depend to some extent upon the degree of flocculation. Observations clearly support the initial assumption of a relationship between these controlling variables and the degree of flocculation.

In all cylinders containing a saline solution, flocculation occurred within a very short period of time and no segregation of silt and clay particles was ever observed. The floccules were sufficiently large in the majority of cases that they fell rapidly and the supernatant solution cleared very quickly. The process resembled a density current and turbulent eddies suggested the presence of a counter current carrying displaced liquid to the top of the sedimentation cylinder.

The largest floccules observed were in the sedimentation cylinder containing sample 9 (26 g./l. salinity; 15 g./l. suspended-sediment concentration). As the suspended-sediment concentration decreased

(samples 10, 11 and 12), the size of the floccules became progressively smaller. The same effect was also noted in the sedimentation cylinders containing samples 13, 14 and 15. The size of the floccules became progressively smaller with decreasing salinity of the supernatant solution.

The processes which occurred in the sedimentation cylinder containing sample 12 (low suspended-sediment concentration) differed somewhat from those in other saline samples. The supernatant solution was saline and visible floccules did form, but they were sufficiently small that a density current did not form. Instead, the supernatant solution cleared slowly from below. It is also interesting to note that the sediment-water interface did not resemble that shown in Figure 8.1 but was flat.

Although the size of the floccules in the various cylinders was reflected in the thickness of the respective sediment packs, these differences were erased during consolidation as can be seen from the data in Table 8.4.

It was noted above that no segregation of silt and clay particles was ever observed. However, reference was made in the previous section to concentric rings which were found during testing of many of the samples. The quality of the light reflected from these rings suggested that they consisted of alternating coarse and fine material. The coarse rings were much narrower than the rings of fine material. Although circumstantial, the evidence suggests that minor segregation of coarse and fine material did occur. An alternative hypothesis would be that the rings represented differences in floccule size. This second hypothesis is more consistent with observations made during the actual sedimentation.

8.2.1.7 Cyclic Banding

In sample 16, sedimentation occurred under fresh-water conditions. The sediment remained suspended for long periods of time. Near the sediment-water interface the suspended sediment concentration increased with time and tiny floccules would begin to form. The thickness of the sediment pack increased only very slowly.

Eventually some critical state was reached and a sudden sedimentation occurred, dramatically increasing the thickness of the sediment pack overnight. During this process the supernatant water cleared substantially.

This cycle was repeated several times during the course of sedimentation. Each cycle was marked by a layer of material of a somewhat different colour (grey) than the rest of the sediment pack (red brown). The result was a cyclical colour-banding which is illustrated in Figure 8.1A. The line of demarcation between the bands was indistinct at first but was accentuated during consolidation.

This same colour-banding was visible in undisturbed blocks of soil at the South Nation River landslide site where the material for this experiment was collected. It has also been reported by Seekings (1974) who determined that differences in particle-size distribution were associated with the colour differences, the red-brown bands being enriched in clay relative to the grey bands.

When sample 16 was tested, it was discovered that the differences in colour did indeed appear to correspond to differences in particle size. In all respects, the banding, at least qualitatively, resembled varves. The process described may suggest a reasonable mechanism for the formation of varves.

Figure 8.1A: Illustration of cyclic banding in Sample 16.

NOTE: Banding of this nature was observed only in Sample 16, which was the only sample sedimented in a non-saline environment.

8.2.2 Consolidation

The procedure and equipment for consolidating the samples worked well. This is reflected in the data of Table 8.4. Variations within groups of similar samples is well within normal experimental error. The one exception to this statement would be samples 21 and 22. The difference in final thickness is significant and cannot be explained by any observations although it was noted that the difference originated during sedimentation and persisted through consolidation. In contrast, many other samples exhibited differences in thickness during sedimentation which were subsequently erased during consolidation.

In a number of samples (17 to 22), as noted in Table 8.4, water-content analyses were done on material taken from the bottom and the top of the samples. These indicated a non-uniformity within each sample which can be attributed to consolidation. Consolidation due to the hydraulic head would be most pronounced in the lower portions of the sediment pack due to the greater head loss in the less permeable material found there. In contrast, consolidation due to conventional loading would be most pronounced immediately below the loading plate in the upper portions of the sediment pack. It was assumed that these two effects would balance each other but the data in Table 8.4 suggest that this assumption was ill-founded.

The sequence of testing was such that the material from the top of the sediment pack was used for tests such as the cation-exchange capacity and the Atterberg limits. Most of the tests which would be sensitive to changes in the water content were performed on material from the bottom of the sediment pack. As a consequence, the differences in water content were not considered important.

There are certain modifications which should be considered in order to improve the equipment and procedure. During the third phase of

consolidation, loads are applied by adding lead shot to the loading tube and then subsequently by adding cannisters which are placed on the loading platform. The method has been described in Section 3.3. Cannisters were added and removed in a pre-determined sequence in order to keep the stack of cannisters as low as possible. During the brief periods of unloading, there was a small but real possibility of elastic rebound. In order to avoid this, a basket could be placed on the loading platform and lead shot added continuously to the basket in the same fashion as it is added to the loading tube, thereby allowing an uninterrupted increase in the load applied to the soil.

At the completion of the third phase of consolidation, some provision should be made to lock the loading plate in position while the sample is transferred onto the loading racks and reloaded. This same mechanism could be used to lock the loading plate again at the end of consolidation while the sample is prepared for testing.

8.2.3 Leaching

The information presented in Table 8.5 supports the conclusion that the equipment and procedure for leaching samples worked well. There appears to be some limiting value of pore-water salinity below which a sample cannot be leached. For example, samples 2 and 8 are similar in most respects except sample 2 has been leached more than twice as long as sample 8, yet the difference in measured pore-water salinity is insignificant. A similar comparison can be made between samples 9 and 14, with the important difference being that the initial pore-water salinity of sample 14 was 4 g./l and that of 9 was 26 g./l.

In order to predict the probable pore-water salinity before testing, two techniques were used: one based upon equilibration and the other upon diffusion. These have been discussed in Sections 7.4.1.1 and

Table 8.5: Efficiency of leaching.

Sample No.	Intended Pore-Water Salinity (g./l.)	Salinity of Leaching Solution (g./l.)	Leaching Time (days)	Measured Pore-Water Salinity (as NaCl) (g./l.)	Predicted Salinity	
					Equilib. Tech. (g./l.)	Diffus. Tech. (g./l.)
1	0	0	a* 67 + 45	0.15		
2	0	0	67 + 45 + 86	0.07		0.14
3	0.5	0.3	67 + 45	0.51	0.38	
4	1	0.8	67 + 45	1.06	0.95	
5	2	1.8	67 + 45	2.17	2.1	
6	4	3.3	67 + 45	4.54	4.0	
7	10	8	67 + 45	9.64	10.0	
8	0	b* 26; 0	b* 67 + 86	0.08		0.17
9	0	0	86	0.08		0.14
10	0	0	88	0.09		0.05
11	0	0	88	0.10		0.10
12	0	0	72	0.12		0.33
13	0	0	79	0.09		0.08
14	0	0	80	0.07		0.03
15	0	0	79	0.08		0.01
16	0	0	94	0.08		
17	0	0	86	0.06		0.13
18	0	0	86	0.07		0.10
19	1	0.8	86	0.72		1.25
20	0	0	79	0.11		0.27
21	1	c* 1	c* 60	1.20		
22	0	c* 0	c* 60	0.34		

NOTES: (a) - Two or three discrete periods of leaching separated by prolonged intervals.

(b) - 26 g./l. leaching solution during the first period, followed by 0 g./l. solution during the second period of leaching.

(c) - Leached by flow-through rather than diffusion. The volume of outflow collected during the 60 days represented approximately 3.4 exchanges of the pore water.

Table 8.6: Pore-water cations.

Sample No.	Pore-Water Cations ^a					Final Salinity (as NaCl) (g./l.) (meq./l.)	Ratio Monovalent to Divalent	Percent Monovalent
	Na (ppm.) (meq./l.)	K (ppm.) (meq./l.)	Ca (ppm.) (meq./l.)	Mg (ppm.) (meq./l.)	Hg (ppm.) (meq./l.)			
1	15	0.65	4	0.10	21	1.05	10	0.83
2	7	0.30	6	0.15	10	0.50	3.6	0.30
3	130	5.65	4	0.10	31	1.55	17	1.42
4	290	12.61	7	0.18	43	2.15	38	3.17
5	590	25.65	14	0.36	72	3.60	90	7.50
6	1300	56.52	25	0.64	160	8.00	150	12.50
7	2900	126.09	70	1.79	170	8.50	340	28.33
8	16	0.70	9	0.23	3.7	0.19	3	0.25
9	19	0.83	9	0.23	3.4	0.17	2.7	0.23
10	19	0.83	11	0.28	2.9	0.15	2.6	0.22
11	21	0.91	12	0.31	3.3	0.17	3	0.25
12	34	1.48	10	0.26	2.3	0.12	2.3	0.19
13	20	0.87	9	0.23	3.2	0.16	2.5	0.21
14	11	0.48	4.3	0.11	5.5	0.28	4.2	0.35
15	10	0.43	9	0.23	6.2	0.31	4.6	0.38
16	7	0.30	7	0.18	11	0.55	4.1	0.34
17	9	0.39	6	0.15	5	0.25	1.9	0.16
18	19	0.83	9	0.23	1.8	0.09	0.7	0.06
19	240	10.43	20	0.51	15.2	0.76	6.4	0.53
20	37	1.61	8	0.21	1.7	0.09	0.6	0.05
21	420	18.26	29	0.74	18	0.90	6.5	0.54
22	120	5.22	16	0.41	2.7	0.14	1.1	0.09
							0.34	5.86
							0.07	1.25
							0.08	1.35
							0.08	1.37
							0.06	0.95
							1.32	56.84
							7.07	87.60
							8.48	89.45
							13.00	92.86
							13.19	92.95
							24.48	96.08

NOTE: (a) - Si also determined for samples 17 - 22: Sample No. - 17 18 19 20 21 22
 Si (ppm.) - 1.9 2.4 0.9 5.8 35 62

7.4.1.2. As can be seen from the data in Table 8.5, both methods gave acceptable results. The diffusion method is more complex and one might be inclined to favour the equilibration technique. However, it is important to note that the equilibration technique has not yet been tested on samples of the same thickness as those used for the diffusion technique.

Concentrations of pore-water cations are presented in Table 8.6. The results compare favourably with analyses of pore-water from natural Leda Clay (Torrance, 1975a). The concentration of silica in samples 21 and 22 is of particular interest. It is apparent that some of the colloidal silica has dissolved. Although it is possible that some of this dissolution took place during the sedimentation phase, the dissolved silica concentrations in Table 8.6 would suggest that it was strongly influenced by the reduction in the concentration of other pore-water cations. The pore-water salinity of sample 22 is less than that of sample 21 but the pore water of sample 22 contains nearly twice as much dissolved silica as the pore water of sample 21.

8.2.4 Possibility of Weathering or Similar Chemical Changes

When the soil material was collected from the South Nation River landslide site, its liquid limit ranged from 34% to 38%. There was a moderately strong odour of H_2S from which it can be inferred that the environment of the 3 soils prior to the landslide was characterized by reducing conditions. It is likely that the H_2S was produced through reduction of the sulphate radical present in the pore water (Morris & Stumm, 1967; Stumm & Morgan, 1970). Quigley (1980) summarizes a variety of observations which indicate the widespread occurrence of reducing conditions in Leda Clay.

Prior to storage, each soil was remolded and homogenized. This introduced oxygen into the system and by the time the material was placed in storage, the liquid limits had risen to between 37% and 41%. For low-activity clay soils, a change to less reducing, more oxidizing conditions will result in an increase in the remolded shear strength and hence in the liquid limit (Moum, Løken and Torrance, 1971; Torrance, 1975a; Torrance, 1979; Torrance, 1983), and is usually accompanied by an increase in the proportion of divalent cations in the pore water. The whole process is often referred to as weathering because it occurs under the influence of the surface environment.

The liquid limit determined after storage indicated no appreciable change, but as noted in Table 8.4, most of the liquid limits for the samples composed of normal soil material ranged from 48% to 54%. This is comparable to the high-salinity liquid limits of the fresh soils. Immediately after collection from the landslide site, NaCl was added to specimens of the 3 soils in order to raise the pore-water salinity to 26 g./l. The liquid limits were found to range between 51% and 57%.

It is evident that substantial changes occurred during the preparation of the samples, presumably as a result of the oxidizing conditions. Weathering during leaching had been considered a possibility and provisions were made in the experiment (see Table 8.1) to test this possibility. Samples 1, 2 and 8 are similar in all respects except for the time that elapsed between the completion of leaching and the testing of the sample: sample 8 was tested immediately upon completion of leaching; samples 1 and 2 stood for prolonged periods after leaching was essentially completed. There are differences in the concentrations of the pore-water cations and in the liquid limits. Both samples 1 and 2 have high concentrations of divalent cations in comparison to sample 8 and their liquid limits are also significantly higher than that of sample 8.

It is unlikely that the process of weathering was restricted to the period of leaching but rather, took place throughout the entire period of sample preparation. This conclusion is based upon circumstantial evidence. The necessary oxidizing conditions were present throughout the entire period of sample preparation and although the chemical changes associated with weathering would have been inhibited during periods of high pore-water salinity, the liquid limit of sample 8 is still much higher than when the material was removed from storage. Also, some other saline samples which were tested immediately upon completion of leaching have liquid limits comparable to that of sample 16 which was never buffered by high pore-water salinity. This suggests that the weathering was a more or less continuous process associated with the oxidizing conditions, although the extent undoubtedly varied from one sample to another.

8.3 Chemical Properties of the Soil Systems

8.3.1 Redox Potential and pH

Table 8.7 presents the measured soil potentials and pH as well as several calculated parameters. The soil potential was measured with a Calomel electrode in contact with a saturated KCl solution. This electrode has a potential of 0.2415 volts with respect to the Standard Hydrogen Electrode and addition of this factor to the potential measured with the Calomel electrode gives the redox potential, Eh, which is defined as the energy gained (expressed in volts) when one mole of electrons is transferred from an oxidizing agent to H₂.

Just as the parameter pH is defined as the negative log of proton activity [H⁺], it is possible to define a parameter pE which is the negative log of the electron activity [e⁻]. pE and Eh are related as follows:

$$pE = \frac{F(Eh)}{(2.3)RT} \dots\dots\dots (8.1)$$

where: F is the Faraday constant.
 R is the universal gas constant.
 T is the absolute temperature.

Great caution should be used in the quantitative characterization of a system on the basis of pE or Eh values (Morris and Stumm, 1967; Stumm and Morgan, 1970). Many factors influence the potential measured, among them:

Table 8.7: Oxidation-reduction potential and pH.

Sample No.	pH	E _{Cal.} (mv.)	Eh (V.)	pE	pE + pH
1					
2	8.11	+174.0	+0.416	+7.04	15.15
3	8.05	+113.2	+0.354	+6.01	14.06
4					
5	8.01	+109.3	+0.350	+5.94	13.95
6	7.68	+151.5	+0.394	+6.67	14.35
7	7.76	+108.5	+0.350	+5.92	13.68
8	8.11	+106.0	+0.348	+5.89	14.00
9	8.50	+154.0	+0.396	+6.70	15.20
10	8.42	+ 73.3	+0.314	+5.33	13.75
11	8.39	+143.3	+0.384	+6.52	14.91
12	8.50	+ 99.7	+0.342	+5.79	14.29
13	8.20	+112.8	+0.354	+6.01	14.21
14	8.25	+ 63.3	+0.304	+5.16	13.41
15	7.92	+ 59.5	+0.302	+5.11	13.03
16	8.03	+165.3	+0.406	+6.89	14.92
17	8.26	+142.0	+0.384	+6.50	14.76
18	7.93	+124.0	+0.366	+6.19	14.12
19	8.32	+156.0	+0.398	+6.74	15.06
20	8.48	+124.0	+0.366	+6.19	14.67
21	7.81	+140.7	+0.382	+6.48	14.29
22	8.05	+138.3	+0.380	+6.43	14.48

- (a) the oxidation and reduction reactions proceed at different rates;
- (b) most natural systems are not in equilibrium or even sufficiently metastable;
- (c) the potential measured is, in reality, a mixed potential representing the effect of several processes which may be occurring; and,
- (d) the processes at the electrode may not be electrochemically reversible within the time frame imposed by the electron transfer.

In spite of these limitations with respect to the quantitative application of these data, pE and Eh values can provide useful qualitative information regarding a system. Positive values of pE and Eh do indicate the presence of oxidizing agents. Similarly, negative values pE and Eh indicate anaerobic conditions.

Lindsay and Vlek (1977) suggest the use of the parameter $(pE + pH)$ to qualitatively characterize redox conditions in a soil. In natural systems, the value of this parameter will lie between 0, corresponding to a highly reduced environment (one atmosphere of H_2) and 20.61, corresponding to a highly oxidizing environment (equilibrium with air containing 20% O_2).

On the basis of the foregoing discussion, it is possible to qualitatively characterize conditions in all samples as moderately oxidizing (Table 8.7). This conclusion is consistent with that reached in the previous section on the basis of changes in the liquid limit.

8.3.2 Cation-Exchange Capacity and Ammonium-Acetate-Extractable Cations (Exchangeable Bases)

The cation-exchange capacities and adsorbed cations are presented in Table 8.8. Torrance (1975a) reported a range of cation-exchange capacities from about 31 to 62 meq./100 g. for Leda Clay from another site in the Ottawa area. In general, the cation-exchange capacities for these samples fell within this range.

In the example reported by Torrance (1975a), the cation-exchange capacity varied in a somewhat regular fashion across a vertical soil profile with a significant reduction in the cation-exchange capacity occurring below the weathering crust. Applying the two-layer stratigraphic model of Gadd (1975), it seems probable that at the site examined by Torrance, the lower boundary of the weathering crust could correspond to the contact between undisturbed and redeposited Leda Clay. The reduction in cation-exchange capacity can be correlated with a sudden decrease in the redox potential and a corresponding increase in the sensitivity and with other geochemical parameters. There is no such apparent correlation in the data of this experiment.

Except for samples 17, 20, 21 and 22, normal soil material was used in all the samples of this experiment. This should have resulted in a narrow range of values for the cation-exchange capacity. The dispersion in the values obtained suggests that weathering or similar chemical changes may have taken place, although the exact nature of the processes which may have occurred and their relationship to other variables is not apparent from the data.

An increase in the ratio of adsorbed potassium to sodium (milliequivalents per milliequivalent) is known to accompany weathering as a result of the degradation of potassium-bearing minerals. However,

Table 8.8: Cation-exchange capacity and ammonium-acetate-extractable cations (exchangeable bases).

Sample No.	Ammonium-Acetate-Extractable Cations * a				Cation Exchange Capacity	Ratio Monovalent to Divalent	Percent Monovalent	K / Na
	Na	K	Ca	Mg				
	(milliequivalents per 100 grams)				(meq./100g.)			
1	0.64	1.28	29.20	10.81	41.9	0.05	4.58	2.00
2(#1)	0.17	4.08	12.07	8.49	24.8	0.21	17.15	23.43
2(#2)	0.21	6.94	11.42	6.23	24.8	0.40	28.82	33.30
3	1.04	0.88	16.11	13.00	31.0	0.07	6.18	0.85
4	1.43	0.97	15.08	14.06	31.6	0.08	7.62	0.68
5	2.40	1.11	14.54	13.55	31.6	0.13	11.11	0.46
6	2.30	1.27	15.65	12.88	32.1	0.13	11.12	0.55
7	1.67	1.72	22.30	10.10	35.8	0.10	9.47	1.03
8(#1)	0.39	9.41	2.50	9.62	21.9	0.81	44.72	23.87
8(#2)	0.44	4.89	8.99	7.62	21.9	0.32	24.28	11.13
9	0.43	6.13	11.70	9.96	28.2	0.30	23.23	14.38
10	0.41	7.62	8.46	11.06	27.5	0.41	29.13	18.73
11	0.54	6.55	15.91	11.13	34.1	0.26	20.77	12.11
12	0.74	4.98	22.29	8.61	36.6	0.19	15.62	6.71
13	0.44	5.99	16.19	9.34	32.0	0.25	20.13	13.47
14	0.28	6.64	15.56	8.64	31.1	0.29	22.25	23.27
15	0.30	7.75	17.98	12.35	38.4	0.27	20.98	25.60
16	0.13	5.88	26.33	5.08	37.4	0.29	16.08	43.86
17	0.22	10.58			14.5			48.00
18	0.66	10.21			18.4			15.35
19	0.92	5.63	46.06	11.46	63.9	0.11	9.94	7.86
20	0.96	6.94	28.74	10.06	46.7	0.20	16.90	7.24
21	3.55	6.17	39.49	12.43	61.6	0.19	15.76	1.74
22	0.17	0.27			121.4			1.62

NOTE: (a) - Fe and Al were also analyzed and found to be 1 or 2 orders of magnitude less in concentration than the other cations.

it is not an unequivocal indicator of weathering because the increase in the ratio may be due to a decrease in the proportion of adsorbed sodium (Moum, Løken and Torrance, 1971). Nevertheless, a high proportion of potassium can have a significant impact on behaviour because the influence of potassium is unusually great for a monovalent cation as discussed by Torrance (1975b).

The values for the ratio of adsorbed potassium to sodium obtained in this experiment seem to be unusually high in comparison with similar materials. For example, Torrance (1975a) has presented data on the adsorbed cations present in Leda Clay from two sites near Ottawa and values of the K/Na ratio calculated from his data range between 0.5 and 4. The absolute values for the concentration of adsorbed sodium reported by Torrance (1975a) range between 1 and 10 milliequivalents per 100 grams. The values for sodium shown in Table 8.8 are considerably less than this and consequently it seems reasonable to conclude that the high K/Na ratios obtained in this experiment are mainly due to this reduced concentration of sodium. However, the fact that more exchange sites would be occupied by potassium rather than sodium would be reflected in other properties of the soil such as the remolded shear strength as noted by Torrance (1975b). This different K/Na ratio may be the result of leaching by diffusion rather than flow-through. Both processes are thought to occur in nature but flow-through leaching is probably the more common (Torrance, 1975a; 1979).

The determination of the cation-exchange capacities and the exchangeable bases proved a very onerous task because of the peculiar reaction of the soil material. It was unusual inasmuch as it did not easily disperse in the sodium acetate and the ammonium acetate solutions. Each time the soil was washed with either of the solutions, it was necessary to extensively work the material with a glass stirring rod before it could be brought into suspension as required by the procedure. For this reason, and also because a very limited amount of material was available for this

test, the samples were not duplicated except in two cases: the exchangeable bases for samples 2 and 8 were determined twice and the results are reasonably consistent given the difficulties of working with the material.

8.3.3 Diffusion Coefficient

The "composite" diffusion coefficient referred to in Appendix "D" is reported in Table 8.9. As can be seen, there is reasonable consistency within groups of similar samples. Mitchell (1976) reports that precise information regarding diffusion rates of ions in saturated soils is not available, but that controlled experiments have yielded values for the diffusion coefficient of about 10^{-5} cm.²/sec. The exact nature of the soils tested was not specified by Mitchell which makes a comparison with the present samples very difficult. However, the consistency noted above is encouraging and suggestions will be made in a later section with respect to possible avenues for future research in this area.

Table 8.9: "Composite" diffusion coefficient and coefficient of permeability.

Samp. No.	"Composite" Diffusion Coefficient (cm. ² /sec.) (x10 ⁻⁷)	Coefficient of Permeability (cm./sec.) (x10 ⁻⁸)	Samp. No.	"Composite" Diffusion Coefficient (cm. ² /sec.) (x10 ⁻⁷)	Coefficient of Permeability (cm./sec.) (x10 ⁻⁸)
1		2.96	12	11.04	5.52
2	6.84	2.62	13	10.50	7.26
3		2.62	14	10.62	5.63
4		2.83	15	10.77	5.18
5		2.85	16		6.25
6		2.97	17	5.33	3.42
7		3.03	18	10.86	4.81
8	6.66	2.97	19	7.75	5.67
9	10.46	5.98	20	11.03	3.98
10	12.78	7.25	21		59.9
11	11.10	6.02	22		71.8

8.4 Hydraulic Properties of the Soil Systems

The only hydraulic property measured was the hydraulic conductivity as represented by the coefficient of permeability. This information is presented in Table 8.9. The coefficient of permeability within groups of similar samples is reasonably consistent and the values obtained are comparable to others reported for materials similar to these. On this basis, it is possible to conclude that the procedure for determining the coefficient of permeability described in Section 7.1 was successful.

8.5 Mechanical Properties of the Soil Systems

8.5.1 Nature of Information Obtained

All samples were tested using the equipment and procedures described in Chapter 5. For purposes of illustration, an idealized rendition of torque/twist curves for undisturbed and remolded soils is presented in Figure 8.2. Four segments of the curve for the undisturbed soil have been identified with labels and will be referred to in subsequent discussions. In like manner, two segments of the curve for the remolded soil have been labelled. Figure 8.3 shows the actual test data for sample 18.

8.5.2 Graphical Analysis

The data obtained during the first reloading of both the undisturbed and remolded soil, corresponding to segment B in Figure 8.2, were plotted to an appropriate scale. Examples are shown in Figure 8.4 for sample 18. The initial tangents to the two curves are also illustrated. The slope of each tangent was measured and Equation B.2 was used to calculate values of the shear modulus for both the undisturbed and remolded soil.

8.5.3 Elastic Parameters

Table 8.10 presents the calculated values of the undrained shear modulus and modulus of elasticity for both the undisturbed and remolded soil. Also included are values for the undrained shear strength calculated from the ultimate torque (τ_y in Figure 8.2) and the ratio of the modulus of elasticity to the shear strength.

Figure 8.2: Idealized torque/twist curves to illustrate the general nature of the information obtained for undisturbed and remolded samples.

Figure 8.3: Torque/twist curves for Sample 18, undisturbed and remolded.

Figure 8.4: Reloading curves (segment B) for Sample 18, undisturbed and remolded, showing the initial tangents to the curves.

Table 8.10: Elastic parameters.

(NOTE: G_u = undrained shear modulus; E_u = undrained modulus of elasticity; c_u = undrained shear strength.)

Sample No.	Undisturbed Soil				Remolded Soil			
	G_u^{**} (kPa.)	E_u^{**} (kPa.)	c_u (kPa.)	$\frac{E_u}{c_u}$	G_{ur}^{**} (kPa.)	E_{ur}^{**} (kPa.)	c_{ur} (kPa.)	$\frac{E_{ur}}{c_{ur}}$
1	1318	3954	5.7	691	2336	7008	1.7	4234
2	2270	6810	24.5	278	494	1482	2.7	545
3	2917	8751	14.7	594				
4	2077	6231	11.7	531				
5	2823	8469	15.5	547				
6	2029	6087	9.5	642				
7	2917	8751	11.0	797				
8	3729	11187	13.2	845	894	2682	2.7	986
9	2029	6087	12.5	487	602	1806	1.3	1429
10	1195	3585	9.5	378	355	1065	1.1	959
11	1385	4155	11.7	354	656	1968	1.4	1381
12	858	2574	9.5	271	355	1065	1.3	795
13	1120	3360	9.5	354	379	1137	1.6	721
14	1469	4407	7.2	610	379	1137	2.3	485
15	2393	7179	8.7	823	488	1464	1.4	1027
16	972	2916	12.5	234	942	2826	1.5	1883
17	1430	4290	8.7	492	786	2358	2.7	867
18	1069	3207	8.0	402	458	1374	2.0	671
19	1704	5112	10.2	499	1171	3513	2.3	1499
20	1430	4290	9.5	452	620	1860	1.6	1179
21	467	1401	9.5	148	617	1851	1.6	1173
22	831	2493	8.7	286	355	1065	1.3	843

NOTE: (a) - Accuracy is estimated to be ± 200 kPa.

Selvadurai et al. (1980) report the results of testing carried out with a screw plate in a deposit of Leda Clay near Ottawa. The testing took place at two depths within the deposit. The clay nearer the surface had a shear strength of 10 kPa. as determined in independent testing. Values of 5000 and 6100 kPa. were obtained for the modulus of elasticity of this upper clay-based upon the slope of the initial tangent to a re-loading curve on the plot of load versus settlement for the screwplate test. Corresponding values for the ratio of the modulus of elasticity to the shear strength would be 500 and 610 respectively.

The data presented in Table 8.10 for the undisturbed soil suggest that the samples prepared for this experiment were comparable in many respects to the natural soil tested by Selvadurai et al. (1980). As a general statement, it can be said that an increase in the degree of consolidation (compare samples 1 to 8 with the others) results in a higher shear strength and modulus of elasticity. It is also interesting to note that the ratio of the modulus of elasticity to the shear strength is generally higher for samples 1 through 8 than for the others. This suggests that increasing the degree of consolidation has a more pronounced effect on the modulus of elasticity than on the shear strength. However, some of the samples in this first group do have high pore-water salinities and the influence of this factor is not known. Although the information in Appendix "A" would lead to the conclusion that chemical factors should have some bearing on the elastic response of the soil, no systematic relationship of this kind is apparent from the data of Table 8.10.

Mitchell (1976) notes that a flocculated structure is more rigid than one which is not. The controlling variables for samples 9 through 16 were chosen in an attempt to vary the degree of flocculation. It was reported in Section 8.2.1.6 that the size of floccules observed in samples 9, 10, 11, 13, 14 and 15 were notably larger than those in

sample 12 (lowest suspended-sediment concentration) and sample 16 (fresh-water sedimentary environment). This is reflected in the values for the modulus of elasticity obtained for the undisturbed samples of that group. The values of the modulus for samples 12 and 16 appear to be significantly lower than others.

The elastic response of a clay-water-electrolyte system is a function not only of the particle arrangement and the frictional forces between particles, but the nature and magnitude of the inter-particle surface forces as well. Remolding of a flocculated clay soil will destroy to some extent the degree of flocculation. This should be reflected in the modulus of elasticity and the data of Table 8.10 support this conclusion. In all but 2 cases, the modulus of elasticity of the remolded soil is less than that of the undisturbed soil. Referring again to the group of samples 9 through 16, it is interesting to note that this reduction in the modulus of elasticity upon remolding is least pronounced in sample 16, which was deposited under fresh-water conditions. As was noted in Section 8.2.1.6, the floccules in sample 16 were barely perceptible, so that the undisturbed structure must have been only marginally flocculated to begin with and the structural changes due to remolding would be minor. Therefore, remolding would be expected to cause little difference in the elastic response.

An interesting comparison can be made between the ratios of the modulus of elasticity to the shear strength for the undisturbed and remolded samples. In almost every case, the ratio for the remolded soil is greater than that for the undisturbed soil. This indicates that upon remolding, the reduction in shear strength is more pronounced than the reduction in the modulus of elasticity. The reason for this is not fully apparent but the following observation is suggested by the results. On the basis of the information presented in Appendix "A", it seems probable that intimate particle-to-particle contact existed in the undisturbed

samples due to conditions prevailing during sedimentation and the effect of subsequent consolidation. Remolding would destroy these contacts. From this, it may be inferred that the shear strength generated by a soil is more dependent upon particle-to-particle contacts than is the elastic response.

8.5.4 Elastic Recovery

An attempt was made to portray the elastic response of the samples by means of the approach shown in Table 8.11. In Figure 8.2, the torque/twist curve for the undisturbed soil was divided into four segments representing load cycling through two load ranges: 0.32 to 2.47×10^{-3} N-m; and 2.47 to 5.51×10^{-3} N-m. As can be seen, segment A is paired with segment B and segment C is paired with segment D. The torque/twist curve for the remolded soil was similarly divided into two segments.

The total deformation and the elastic recovery is recorded in Table 8.11 for each sample. The elastic recovery is also presented as a percentage. Several interesting observations may be made on the basis of this information. With respect to segments A and B of the undisturbed soil, it will be noted that in all cases the total deformation during reloading was less than that during the initial loading. This may be partly due to annealing of the effects resulting from the disturbance which occurred when the vane was inserted. A careful examination of Figure 8.3 will reveal that the loading rate was higher in segment B than in segment A and this might be suggested as a possible explanation. However, a similar difference in total deformation exists between segments C and D and the loading rate was the same in both these cases. The relative contributions of sample disturbance and ordinary strain hardening to these differences cannot be ascertained.

Table 8.11: Elastic recovery.

(NOTE: Terms and symbols are defined in text and illustrated in Figure 8.2)

Samp. No.	UNDISTURBED SOIL						REMOVED SOIL						
	Load Range: 0.32 to 2.47×10^{-3} N-m.			Load Range: 2.47 to 5.51×10^{-3} N-m.			Load Range: 0.32 to 10^{-3} N-m.						
	Initial Loading (Seg. A)	Reloading (Seg. B)	Total	Initial Loading (Seg. C)	Reloading (Seg. D)	Total	Initial Loading (Seg. A)	Reloading (Seg. B)	Total	Initial Loading (Seg. A)	Reloading (Seg. B)	Total	
	Total Recovered	Percent Recovered		Total Recovered	Percent Recovered		Total Recovered	Percent Recovered		Total Recovered	Percent Recovered		
.....(Twist: rad. $\times 10^{-3}$).....													
1	2.5	1.0	40	1.5	6.5	1.3	20	4.3	10.5	2.0	19	2.7	1.34
2	0.4	0.2	50	0.3	0.7	0.4	57	0.5	3.3	1.2	36	1.6	1.34
3	0.6	0.2	33	0.3	0.7	0.3	43	0.5	9.9				1.34
4	0.8	0.5	62	0.5	0.8	0.4	50	0.7	7.4				1.34
5	0.6	0.3	50	0.3	0.7	0.3	43	0.5	1.7				1.34
6	0.9	0.4	44	0.4	1.6	0.5	31	0.8	3.5				1.34
7	0.7	0.4	57	0.4	1.0	0.4	40	0.7	1.6				1.34
8	0.7	0.2	29	0.4	0.9	0.3	33	0.5	3.4	1.6	47	1.9	1.34
9	1.1	0.4	36	0.6	1.5	0.5	33	1.0	3.8	1.2	32	1.7	0.93
10	1.5	0.7	47	1.0	3.2	0.7	22	1.4	5.6	0.9	16	1.5	0.83
11	1.4	0.6	43	0.7	2.0	0.5	25	0.9	1.0	1.0	100	1.0	0.83
12	2.0	0.9	45	1.1	2.8	0.7	25	1.5	1.3	1.1	85	1.5	0.83
13	1.6	0.7	44	0.9	2.9	0.7	24	1.4					
14	1.7	0.7	41	0.9	4.4	0.8	18	1.9	2.6	1.1	42	1.3	0.93
15	1.2	0.5	42	0.7	2.8	0.6	21	1.2	3.7	1.8	49	2.0	1.14
16	1.7	0.7	41	0.9	1.8	0.5	28	0.9	0.8	0.8	100	0.8	0.93
17	3.0	1.0	33	1.1	3.5	0.5	14	1.7	2.1	0.9	43	0.7	1.14
18	2.3	1.0	43	1.2	4.7	1.0	21	2.1	2.7	1.7	63	1.6	0.93
19	1.6	0.5	31	0.8	2.4	0.6	25	1.3	2.3	1.0	43	1.1	1.14
20	1.6	0.8	50	0.9	2.9	0.8	28	1.7	1.7	0.7	41	0.9	0.83
21	4.3	2.7	63	3.1	8.9	4.8	54	5.7	1.3	0.7	54	0.7	0.83
22	4.7	3.0	64	3.4	14.2	6.8	48	10.2	1.2	1.1	92	0.8	0.83

(Twist: rad. $\times 10^{-3}$)(Twist: rad. $\times 10^{-3}$)(Twist: rad. $\times 10^{-3}$)

As a general observation, it may be said that the total deformation experienced by samples 1 through 8 (overconsolidated) in each of the loading cycles was less than that experienced by the other samples (9 - 22), which were normally consolidated. This leads to the conclusion that samples 1 through 8 were stiffer than the others, a conclusion which is consistent with that reached in the previous section on the basis of differences in the moduli of elasticity. This stiffness was also manifested with respect to changes in the percent of elastic recovery from one loading cycle to the next. During the first loading cycle, that is, segments A and B, it can be seen that the percent of elastic recovery was similar for all samples. In the second loading cycle, that is, segments C and D, the percent of elastic recovery for all samples was less than that in the first loading cycle. However, it can be seen that this reduction was much less pronounced for samples 1 through 8 than for the others. As a consequence, during the second loading cycle, the percent of elastic recovery for samples 1 through 8 is generally greater than the percent of elastic recovery for the other samples. •

Table 8.11 also contains information pertaining to the elastic response of the remolded samples. As with the undisturbed samples, the total deformation exhibited by the remolded soil during the reloading was less than that which occurred during the initial loading. The percent of elastic recovery was surprisingly high, being comparable to that of the undisturbed soil. It has long been recognized that there is an elastic component to the settlement observed beneath structures but this has often been attributed to frictional forces generated between the soil particles. A remolded soil is generally regarded as a truly plastic medium. The information presented in Table 8.11 clearly contradicts this assumption. In fact, in some cases, the percent of elastic recovery was much higher than in the undisturbed samples (100% in samples 11 and 16; 92% in sample 22; 85% in sample 12).

Figure 8.5: Torque/twist relationship for Sample 11, remolded, showing complete recovery of strain.

The loading curve for sample 11 (remolded) is presented in Figure 8.5. The points have been numbered to show the loading sequence. Besides the 100% recovery of strain, another interesting observation can be made. When the load was increased from point 1 to point 2, the deformation actually decreased. This effect was observed in a few other samples but was dismissed as an artifact of the testing apparatus. However, it can be seen in Figure 8.5 that the same effect was repeated between points 11 and 12. This would suggest that there was a time-dependent component to the elastic recovery which, in this particular case, was overridden by the timing of the load application between points 11 and 12.

8.5.5 Shear Strength and Sensitivity

The shear strength of both the undisturbed and remolded samples was calculated by inserting the value for the ultimate torque obtained from the torque/twist curve (τ_y in Fig. 8.2) into Equation B.4. An independent determination of the shear strength was made with a fall-cone device (Hansbq, 1957). This information is presented in Table 8.12 together with the calculated values of the sensitivity.

In absolute terms, there is not good agreement between corresponding values for the shear strength measured by means of the two devices. This has been noted by other workers (for example, Kravitz, 1970). Kravitz compared the values for the undisturbed shear strength of very weak, recently sedimented, fine-grained material measured by means of a fall cone, a motorized laboratory vane and the torvane. He concluded that the fall cone gave higher values for the shear strength than either vane apparatus and attributed this to the higher shearing rate characteristic of the fall cone.

The information acquired in this experiment would not support this conclusion as can be seen from Table 8.12. In 12 of 22 cases, the fall cone gives lower values for the undisturbed shear strength. Most of the cases where the fall cone does give a higher value occur in the first group of samples (1 - 8) which were over-consolidated and which experienced the greatest disturbance when the vane was inserted. This may have adversely affected the shear strength measured by the vane. If the analogy is extended to include a comparison of the values for the shear strength obtained for the remolded material, the fall cone gives lower values in 16 of the 22 cases.

The different results may be due to the use of a circular vane in this experiment. The vanes used by Kravitz were rectilinear and high

Figure 8.12: Shear strength and sensitivity.

(NOTE: c_u = undrained undisturbed shear strength; σ'_0 = normal overburden pressure; p'_c = preconsolidation pressure.)

Sample No.	Undrained Undisturbed Shear Strength		Undrained Remolded Shear Strength		Sensitivity		$\frac{c_u}{\sigma'_0}$ (From Vane)	$\frac{c_u}{p'_c}$ (From Vane)
	Vane (kPa.)	Fall-Cone (kPa.)	Vane (kPa.)	Fall-Cone (kPa.)	Vane	Fall-Cone		
1	5.7	8.8	1.7	1.3	3.5	6.9	0.23	0.10
2	24.5	19.1	2.7	2.8	9.0	7.0	1.01	0.43
3	14.7	16.9	3.1	1.9		9.0	0.60	0.26
4	11.7	16.0	2.3	2.4		6.5	0.48	0.20
5	15.5	20.6	3.1	3.0	5.0	6.8	0.64	0.27
6	9.5	16.1	3.1	3.1	3.1	5.1	0.39	0.16
7	11.0	16.7	2.7	3.1	4.0	5.3	0.45	0.19
8	13.2	19.1	2.7	2.9	4.9	6.5	0.54	0.23
9	12.5	8.6	1.3	0.8	9.9	11.3	0.69	
10	9.5	6.8	1.1	0.5	8.5	13.3	0.52	
11	11.7	8.2	1.4	0.7	8.2	11.8	0.64	
12	9.5	4.7	1.3	0.3	7.1	18.5	0.52	
13	9.5	7.1	1.6	0.6	6.0	10.9	0.52	
14	7.2	9.3	2.3	1.6	3.1	5.9	0.40	
15	8.7	9.9	1.4	1.6	6.1	6.3	0.48	
16	12.5	7.6	1.5	1.0	8.3	7.6	0.69	
17	8.7	8.7	2.7	1.5	3.2	5.9	0.48	
18	8.0	5.4	2.0	0.6	4.0	9.5	0.44	
19	10.2	6.2	2.3	1.1	4.4	5.7	0.56	
20	9.5	6.1	1.6	0.3	6.0	23.8	0.52	
21	9.5	6.8	1.6	0.4	6.0	18.2	0.52	
22	8.7	5.5	1.3	0.1	6.9	43.1	0.48	

stresses are typically generated at the corners of these vanes. Strongly localized stresses of this nature are not generated along the periphery of the smoothly varying shape of a circular vane. Because these localized stresses can lead to general failure, it is not unreasonable to conclude that a soil could sustain a higher torque if the load is applied by a circular vane rather than a rectilinear vane. Therefore, for identical material, the shear strength determined by the fall cone might be greater than that measured with a rectilinear vane on the one hand and less than that measured by a circular vane on the other hand.

A second possible explanation for the different conclusions reached in the two studies may rest in differences between the materials tested. Based upon the description given by Kravitz (1970), it is fairly certain that the undisturbed soil material tested in this experiment was more highly consolidated. However, Kravitz does cite the work of others who reached the same conclusion he did and since the soils in this experiment were on the soft end of the spectrum, there is a real possibility that these other researchers were testing soils as stiff or stiffer than the samples of the present experiment. On the basis of this admittedly circumstantial evidence, the first explanation above, based upon differences in the vane shape, is favoured.

Kravitz (1970) also concluded that the repeatability of the fall cone was superior to that of either vane apparatus. This is in agreement with the conclusions reached by other workers whose research he cites. In this experiment, a modified asphalt penetrometer was used to release the fall cone and to measure its penetration. This modification would improve the already well established repeatability of the fall cone. Indeed, for each sample, three measurements were taken with the fall cone and the repeatability was excellent.

Although in absolute terms the values of the shear strength obtained by the fall cone and circular vane in this experiment were not in close agreement, there does appear to be a definite relationship between the two. Support for this conclusion is presented in Figure 8.6. The suggested relationship has the form:

$$\log y = 0.29 + 0.47(\log x) + 0.22(\log x)^2 \quad \dots (8.2)$$

where: y is the shear strength measured by the circular vane with half penetration.
 x is the shear strength measured by the fall cone.

The resulting correlation coefficient is 0.93 indicating a reasonably good fit of the data points to the curve shown in Figure 8.6.

The effect that changes in the salinity of the pore water have on the remolded shear strength can be seen by comparing samples 18 and 19 and also samples 21 and 22. In each case, the remolded shear strength was greater in the sample having the higher pore-water salinity (sample 19 and sample 21). This relationship is also generally evident in the fall-cone data for samples 1 through 8 which differed principally on the basis of their pore-water salinity although the trend is not as pronounced as had been expected. No similar trend is evident in the vane data for samples 1 through 8. The lack of a clear trend suggests that the effect of the pore-water salinity is being masked by some as yet unknown factor, perhaps associated with the weathering of the samples.

Mitchell (1976, Figure 12.8) illustrates a general trend which suggests a relationship between the remolded shear strength and the

Figure 8.6: Relationship between values of shear strength obtained by fall cone and by circular vane.

liquidity index of several clays. In Figure 8.7 the data from this experiment are presented in a similar illustration. For comparison, the approximate limits of Mitchell's data have been superimposed on Figure 8.7. As can be seen, in general, the data points for this experiment lie above Mitchell's general trend. The higher remolded shear strength of the experimental samples contributed to a lower sensitivity.

On a similar theme, Mitchell (1976, Figure 12.2) also illustrates the relationship between sensitivity and the liquidity index for Norwegian marine clays. This relationship is represented in Figure 8.8 by the straight line shown. The data points in Figure 8.8 are those obtained in this experiment and it can be seen that they all lie above Mitchell's line, indicating that for a given liquidity index, a lower sensitivity was obtained for the soils of this experiment, a conclusion which is consistent with that noted above on the basis of the information from Figure 8.7.

An attempt was made to determine under what circumstances the data points shown in Figure 8.8 might be expected to regroup around the straight line representing the relationship established between the sensitivity and liquidity index by Mitchell (1976). The liquidity index is a function of the water content, the liquid limit and the plastic limit. The plastic limit of a sensitive clay is usually about 20% and the liquid limit is normally less than 40% and seldom more than 50% (Mitchell, 1976). This statement is made by Mitchell in conjunction with the discussion pertaining to his Figure 12.2. As can be seen from Table 8.4, the plastic limits of the samples composed of normal material are approximately 20% and these samples can be considered comparable in this respect to the Norwegian marine clays which were analyzed by Mitchell for his Figure 12.2. Therefore, changes in the plastic limit cannot be invoked as a mechanism to shift data points to the line. The plastic limit and liquid limit of sample 8 (20.6%; 49.1%) are approximately equal to those of sample 9 (20.5%; 48.5%) within normal experimental error. However, the water

Figure 8.7: Remolded shear strength versus liquidity index for experimental samples.

Figure 8.8: Sensitivity versus liquidity index for experimental samples.

content of sample 8 is 59.3% and that of sample 9 is 72.2%. The plastic limit and water content of sample 9 are approximately equal to those of sample 14 (20.7%; 72.9%), but the liquid limits are different (48.5% and 52.8% respectively).

The data points representing these three samples are identified on Figure 8.8. As noted above, the plastic limit cannot be invoked as a mechanism to promote movement of a data point to the line. As is illustrated in Figure 8.8, changes in the water content (sample 8 to sample 9) and the liquid limit (sample 9 to sample 14) result in movement of the data point along a path more or less parallel to the straight line. It therefore seems reasonable to conclude that the position of the data points above the straight line represents a real and substantive difference of a fundamental nature between the samples of this experiment and the Norwegian marine clays which the straight line describes. These differences could be attributed to dissimilarities in the mineralogy, either in the natural state or as a result of weathering which has taken place during preparation of these samples.

Mitchell (1976, Figure 11.17) presents a diagram which relates the sensitivity to the percentage of monovalent cations in the pore water. To construct this diagram he used information pertaining to Leda Clay (from Penner, 1965) and to certain Norwegian and Swedish sensitive clays. The curve shown in Mitchell's Figure 11.17 has been reproduced in Figure 8.9, but only the data points from Penner (1965) have been included in order to limit the following discussion to Leda Clay. As can be seen in Figure 8.9, certain data points from this experiment have been added. In accordance with Mitchell's original intention (his Figure 11.17) only those samples with low pore-water salinity have been included in Figure 8.9. On this basis, it has been possible to extend Mitchell's original curve as shown. However, certain points lie far enough from the line that it is possible to imagine a second curve as shown. This suggests that the

Figure 8.9: Relationship between sensitivity and percent monovalent cations (based on concentrations expressed as meq./l.) for Leda Clay with low pore-water salinity (< 2 g./l. expressed as NaCl). Circled points are from Penner (1965); others are from this experiment.

original relationship described by Mitchell (1976, Figure 11.17) may, in fact, be represented by a set of nested curves representing the influence of a third variable.

Torrance (1983) notes that the criteria favoured by Norwegian scientists and engineers for defining a quick clay are: the sensitivity must exceed 30; and the remolded shear strength must be less than 0.5 kPa. On this basis, only sample 22 qualifies as a quick clay. This is particularly interesting because this sample is one to which colloidal SiO_2 has been added. Clearly this area of inquiry deserves further investigation.

The ratios of the undrained shear strength to the preconsolidation pressure and to the normal overburden pressure respectively are also presented in Table 8.12. Dr. K.T. Law, Division of Building Research, National Research Council of Canada reports (personal communication) that for natural samples of Leda Clay, a typical value for the ratio of the undrained shear strength to the preconsolidation pressure is 0.30. There is considerable variability in this ratio and values range from about 0.18 to approximately 0.40.

8.5.6 Equipment Modifications

The vane apparatus for determining the torque/twist relationship performed as expected and it was possible to accurately measure very small elastic deformations. Suggested improvements would include the fabrication of a larger water bath and heavier floating weight. This would permit larger torques to be applied more smoothly than with the present arrangement. The apparatus should also be automated as much as possible. This could include motorizing the drive screw for the moveable table which carries the water bath. An automatic device for sensing and recording the deformation should also be considered.

8.6 Electrical Properties of the Soil Systems

8.6.1 Nature of Information Obtained

As noted in Section 6.7, each sample was tested at a number of discrete frequencies and currents. The signal from the potential electrodes was digitized and stored on a magnetic disk. Computer programs were available to transform this time-domain data into the frequency domain by means of a Fast Fourier Transform. An automatic plotter provided diagrams of the voltage versus time, the energy content of each frequency, the impedance versus frequency and the even-phase and odd-phase spectra. The amount of data collected during this particular part of the experiment was voluminous and only a preliminary analysis has been attempted in this thesis. This analysis is based principally upon graphical rather than numerical methods.

The preliminary analysis focused upon the diagrams of voltage versus time and impedance versus frequency for a 20-second period and a 1-milliampere current. The diagrams for samples 10 and 15 are typical and are shown in Figures 8.10 and 8.11. These two samples illustrate the range of responses observed. Sample 15 (Figure 8.11) appears to have an induced-polarization response similar to that described in Appendix "C", whereas sample 10 (Figure 8.10) does not. However, in spite of this difference, the two samples manifest similarities which will be discussed in subsequent sections.

8.6.2 Conceptual Model of Processes

An electrical current represents a transfer of charge. At the low frequencies used in this experiment, the soil particles may be considered dielectric and charge transfer occurs principally through movement of charged ions in an electric field. In order to carry an

Figure 8.10: Typical diagrams of voltage versus time and impedance versus frequency for a sample showing no induced-polarization response.

Figure 8.11: Typical diagrams of voltage versus time and impedance versus frequency for a sample showing an induced-polarization response.

alternating current, the ions in an electrolyte need only vibrate about their equilibrium position, but to carry a direct current, actual migration of the ions must occur. Because the ions are usually hydrated, the electrical movement results in a coupled movement of the fluid comprising the electrolyte.

It is important to remember that the external excitation circuit imposed a constant current upon the samples. This leads to two useful conclusions: a specified migration of ions had to occur in order to transfer the imposed current; and in accordance with Ohm's Law, the concepts of impedance and voltage may be used interchangeably. The migration of charged ions may be blocked by electrical mechanisms such as membrane polarization illustrated in Figure C.5 or by physical constrictions in the soil. This results in a build-up of charge at the blockages which is expressed as an increase in voltage with time.

Blockages are assumed to have occurred in sample 15 (Figure 8.11) but not in sample 10 (Figure 8.10). This assumption may be supported by the following argument. The impedance of sample 10 did not vary with frequency. In other words, a direct current could be carried with the same ease as an alternating current even though substantial ion migration must have occurred in order to have accomplished the necessary transfer of charge. This is also reflected in the time-domain data where the voltage rose sharply to a discrete value and did not change until the current was switched off. In order for ion migration (direct current) to have occurred as easily as ion vibration (alternating current) there could have been no significant blockages present in sample 10.

Sample 15 presents a useful contrast to the above. The impedance decreased with increasing frequency to a certain limiting value and the voltage increased with time, also approaching a limiting value. In every case where this characteristic charging and discharging of the soil was

observed, it was also noted that the impedance of the sample varied with the frequency in the manner of sample 15.

It is helpful to attempt to analyze the response of sample 15 in more detail. Initially the voltage rose sharply to a discrete value and then more slowly to its steady-state value. The initial voltage represented the energy required to accelerate the ions to some steady-state velocity necessary to transfer the imposed current and is directly related to the high frequency impedance. If no blockages had occurred, the voltage would have remained at this value until the current was switched off. However, in sample 15, blockages did occur and a time-dependent, non-homogeneous charge separation resulted. This charge separation produced a potential difference and contributed to the rise in voltage observed in sample 15. This potential difference also had a secondary effect inasmuch as it acted as a potential barrier to the transfer of charge required by the imposed current. In order to overcome this potential barrier, the external voltage applied to the soil was increased and the time-dependent rise in voltage sensed by the potential electrodes was a result of this increase in the applied voltage.

In summary, the steady-state voltage of sample 15 may be said to have been made up of two components: the first was the voltage necessary to accelerate the ions to their steady-state velocity; the second component was time-dependent and represented the combined effect of the potential difference resulting from the charge separation, and the externally applied voltage increase necessary to overcome the potential barrier established by the charge separation. The energy bound up in the charge separation was recoverable and was expressed as the transient delay voltage when the current was switched off. The energy required to overcome the resistance offered by the charge separation was not recovered but was lost as heat or dissipated in other ways.

The situation is somewhat analogous to what happens when a stress is applied to a soil. Only part of the energy which is introduced into the soil system as a result of the applied stress is recovered in the form of elastic rebound.

As was noted in Appendix "C", several mechanisms have been suggested as possible ways to store the energy which is manifested by the transient decay voltage or IP response. The soil systems studied in this experiment are fairly simple systems in this respect inasmuch as no oxidation or reduction reactions are involved. Keller and Frischknecht (1966) propose a model (expressed as Equation C.2) in which the decay voltage results from the transient current represented by the moving ions of the electrolyte as their velocity decays from its steady-state value. It is a model based upon the inertial movement of the pore fluid as the driving force is removed. However, a detailed analysis reveals that the inertial velocity will decay to an insignificant value in a very small fraction of one second due to viscous forces and this mechanism cannot explain the observed decay voltage. Similarly, thermal and mechanical processes are easily dismissed as possible explanations of the decay voltage, nor are there any significant inhomogeneities in the fluid itself which could provide the necessary explanation. Therefore, by a process of elimination, the conclusion is reached that the initial decay voltage represents the potential difference due to the charge separation resulting from the blockages discussed above. This initial voltage decays with time as the ions migrate back to their equilibrium positions after the external field has been removed. This movement of charge constitutes a transient current. The resistance to this current is related to the viscous forces opposing movement of the hydrated ions.

8.6.3 Parameters Examined

As was noted in an earlier section, the preliminary analysis of the electrical data was accomplished using graphical rather than numerical

methods. A protractor and vernier caliper were used and careful measurements were made of angles, intercepts and distances on the diagrams of voltage versus time and impedance versus frequency. The kinds of measurements made are illustrated in Figure 8.12. They may be summarized as follows:

- (a) the steady-state voltage, V_{ss} ;
- (b) the residual decay voltage, V_d , and its counterpart on the charging curve, V_c , expressed as a fraction of the steady-state voltage in millivolts per volt, as is customary in the mineral exploration industry;
- (c) the area under the decay curve, D, and under the charging curve, C, normalized to the steady-state voltage, expressed as millivolt-seconds per volt, as is customary in the mineral exploration industry;
- (d) the sharp rise in voltage when the current was turned on (charging ramp) expressed as volts per second;
- (e) the sharp drop in voltage when the current was turned off (discharge ramp), expressed as volts per second;
- (f) initial tangent to the decay curve (decay tangent) and charging curve (charging tangent), expressed as millivolts per second;
- (g) characteristic times for the decay and charging curves (t_d , t_c) expressed in seconds;
- (h) residual voltages at the characteristic times for the decay and charging curves (v_d , v_c) expressed in millivolts;
- (i) direct current impedance (ohms) and alternating current impedance (ohms) obtained from the impedance versus frequency curves.

Figure 8.12: Diagram of voltage versus time to illustrate parameters examined.

The information has been assembled in Table 8.13 where the same terminology has been used as above. As can be seen in Figure 8.12, it was possible to make two measurements of each parameter. Table 8.13 contains the average values.

8.6.4 Observed Trends and Relationships

An examination of the data in Table 8.13 will reveal that the following statements can be considered valid for most samples:

- (a) the residual charging voltage is greater than the residual decay voltage;
- (b) the area under the charging curve is greater than the area under the decay curve;
- (c) the discharge ramp is greater than the charging ramp;
- (d) the charging tangent is greater than the decay tangent;
- (e) the characteristic time for the charging curve is greater than the characteristic time for the decay curve.

The ratio of the residual decay voltage to the steady-state voltage is considered a very sensitive indicator of the induced-polarization response. Values of this parameter for the clay samples are comparable to those obtained with mineralized rock containing approximately 2% to 8% disseminated sulphides (Keller and Frischknecht, 1966).

The ratio of the area under the decay curve to the area under the charging curve (D/C) is included in Table 8.13. For most of the samples composed of normal soil material this ratio is approximately 20% to 25%. If the conceptual model presented in an earlier section is accepted, it is possible to conclude that 20% to 25% of the energy input resulting from charge blockages was recovered.

Table 8.13: Electrical measurements,
(NOTE: Terms and symbols are defined in text and illustrated in Figure 8.12)

Comp. No.	Impedances		Voltages			Areas Under Curves		Ramps		Tangents		Char. Times		Residual Volt. & Char. Times					
	DC	AC	V _{BS}	V _C	V _D	G _m	D	D/C	Chg.	Decay	Chg.	Decay	τ _c	τ _d	V _C	V _D	V _e /V _C	V _D /V _C	
	..(ohms)...		(V.)	..(mV./V.)...		(mV.-m./V.)		(Σ)	..(V./m.)...		..(mV./m.)...		(s.)...		..(mV.)...				
1	74.3	72.5	0.07						0.79	0.90									
2	131	122	0.13	148	66	474	104	22.0	1.19	1.24	16.49	11.33	1.23	0.84	12.09	5.78	0.63	0.67	
3	59.4	56.1	0.06	82	57	278	68	24.5	0.62	0.70	12.92	7.64	0.39	0.43	4.03	2.48	0.82	0.73	
4	49.2	45.3	0.05	150	108	547	141	25.7	0.52	0.54	8.65	6.42	0.83	0.83	4.52	3.48	0.60	0.64	
5	33.2	29.1	0.03	204	143	644	268	41.7	0.33	0.35	5.73	5.78	1.37	0.76	3.74	3.07	0.61	0.72	
6	17.4	17.4	0.02						0.16	0.17									
7	10.2	9.5	0.01	49	31	158	50	31.6	0.09	0.12	0.30	0.25	1.62	1.72	0.25	0.14	0.51	0.45	
8	151	145	0.15	65	47	228	42	18.3	1.39	1.70	18.74	14.44	0.55	0.43	6.65	4.52	0.68	0.64	
9	119	119	0.12						1.23	1.36									
10	129	129	0.13						1.23	1.48									
11	135	134	0.14						1.41	1.43									
12	147	141	0.15	97	43	282	74	26.4	1.51	1.53	9.61	4.93	0.83		3.48		0.77		
13	105	98.8	0.11	147	54	455	71	15.6	1.09	1.27	12.66	10.71	1.28	0.59	9.61	4.42	0.59	0.74	
14	143	136	0.14	119	46	363	90	24.7	1.41	1.63	12.73	10.09	1.41	0.66	10.10	4.88	0.61	0.76	
15	117	113	0.12	73	37	245	51	20.7	1.08	1.63	9.97	6.76	0.83	0.61	6.06	3.05	0.69	0.69	
16	141	131	0.14	119	61	381	86	22.5	1.23	1.48	20.35	19.12	0.82	0.45	10.96	5.60	0.66	0.66	
17	228	228	0.23						2.62	2.98									
18	166	159	0.17	111	39	344	54	15.6	1.57	2.01	15.04	13.12	1.21	0.47	11.90	4.85	0.63	0.73	
19	46.5	46.5	0.05						0.56	0.55									
20	173	168	0.17	76	38	233	51	22.0	1.88	1.91	14.44	12.86	0.91	0.47	8.85	4.61	0.68	0.71	
21	21.2	18.3	0.02	260	182	706	384	54.3	0.24	0.22	3.01	2.00	1.66	1.70	3.09	2.12	0.59	0.58	
22	62.5	60.0	0.06	124	42	332	100	30.1	0.65	0.72	5.04	2.67	1.40	0.64	4.95	1.96	0.67	0.78	

Figure 8.13 presents the relationship between the alternating current impedance and the salinity of the pore water, expressed in milliequivalents. The data approximate the straight line shown in the figure, with a correlation coefficient of 0.98. The same kind of relationship exists between the direct current impedance and the salinity. That is, the regression line has the same slope as that shown in Figure 8.13 but as expected, it has different intercepts. With the direct current impedance, there is slightly more scatter in the data, but the correlation coefficient is still very close to 1.0.

The steady-state voltage manifests the same relationship to the pore-water salinity as does the impedance. This could be expected, because in the preliminary analysis attempted here, the data used for all samples are those obtained with a current of 1 milliampere. It is of some interest to note that both the charging ramp and decay ramp are also related to the pore-water salinity according to the same general function as the impedance. That is, the regression lines have the same slope as the impedance and voltage functions, although the intercepts are different as expected. The correlation coefficients are 0.96 and 0.97 respectively.

Although the fit of the data to the power curve shown is excellent, as evidenced by the high correlation coefficients, close examination of Figure 8.13 suggests that a smooth curve could be drawn through the data points. This curve first dips beneath the straight line, rises above it and then falls below it again as the salinity increases. This is not a random arrangement as might be supposed. In spite of the entirely different manner in which the data were obtained, the data points for the charging and decay ramps follow exactly the same curve as that shown in Figure 8.13 for the impedance.

The relationship between the salinity of the pore water and either the impedance or the steady-state voltage is well recognized.

Figure 8.13: Relationship between the alternating current impedance and the salinity of the pore water, expressed in milliequivalents. The pore-water salinity bears a similar relationship to the direct current impedance, the steady-state voltage and both the charging and decay ramps.

The physical significance of the voltage ramps is not yet evident.

Figure 8.14 illustrates the relationship between the charging tangent and the salinity of the pore water expressed as millequivalents. A smooth curve has been drawn through these data. A similar curve may be constructed for the decay tangent. The mathematical expression of this relationship is not evident. An unsuccessful attempt was made to fit the data to exponential, logarithmic, parabolic and power curves by the method of least squares regression.

If the conceptual model based upon membrane polarization or ion sieving, which was presented in an earlier section, is applied to these observations, the following physical process is suggested to explain the observed relationship between the tangents and the pore-water salinity. At high salinities, charge carriers were relatively abundant, so the effect of blockages in the system were not manifested so quickly. The blockages would have been smaller as well, due to a thinner diffuse layer of counterions. Hence, the initial rise in the voltage (charging tangent) was not so sudden as it was when the salinities were low. Similarly, for the decay tangent, an abundance of ions in the pore water had the effect of reducing the potential gradient associated with the charge separation, resulting in a less abrupt reduction in the initial decay voltage and hence a lower value for the decay tangent at high salinities.

As shown in Figure 8.12, the initial tangents were used to define characteristic times for both the charging and decay curves. These results are included in Table 8.13. If either of these curves had been exponential, it is easy to demonstrate that the characteristic time would have equaled the time constant. For a negative exponential, the time constant is defined as the time required for the time-dependent variable to decay to $1/e$ of its original value. Similarly, for a positive exponential, it is the time

Figure 8.14: Relationship between the charging tangent and the pore-water salinity, expressed as milliequivalents. A similar relationship exists between the pore-water salinity and the decay tangent.

3 3

OF / DE

required for the variable to increase to within $1/e$ of its final value.

Clearly, none of the charging or decay curves was a pure exponential. The relevant ratios corresponding to the characteristic times are presented in Table 8.13 and average 0.65 for the charging curve and 0.68 for the decay curve. However, these may be compared to the value of $(1-1/e)$, which is 0.63. The lack of precision inherent in the graphical methods used would suggest that the difference may not be significant. Figure 8.15 shows a typical decay curve and an exponential function with a time constant equal to the characteristic time of the decay curve and having the same voltage range (0 to V_d) as the decay curve.

The following avenue of inquiry appears worthy of further investigation. If the decay curve and the exponential function respectively are represented as follows:

$$Y = f(t) \dots\dots\dots (8.3)$$

$$y = f(t) = V_d - V_d e^{-\lambda t} \dots\dots\dots (8.4)$$

where: V_d is the initial decay voltage; and
 λ is equal to the inverse of the characteristic time,

a third function may be defined as:

$$Z = Y - y \dots\dots\dots (8.5)$$

A numerical analysis could provide a diagram of Z versus time which might make the nature of the function Z more apparent. On the basis of the

Figure 8.15: Typical decay curve and an exponential function with a time constant equal to the characteristic time of the decay curve and having the same voltage range (0 to V_d), as the decay curve.

available information, it is possible to make the following statements:

$$Z|_{t=0} = V_d$$

$$Z|_{t=t_d} = 0$$

$$Z|_{t \rightarrow \infty} = -V_d$$

$$\left. \frac{dZ}{dt} \right|_{t=0} = -\lambda(1 + V_d) = (\text{decay tangent})(1 + V_d)$$

An alternate avenue of inquiry is based upon the suggestion made by Keller and Frischknecht (1966) that the decay curve may be approximated by a sum of exponentials. Let this be represented by:

$$Y = \sum a_i e^{-\lambda_i t} \dots \dots \dots (8.6)$$

Given this model, the following conditions must hold:

$$\sum a_i = V_d$$

$$-\sum a_i \lambda_i = \text{decay tangent}$$

$$\sum a_i e^{-\lambda_i t_d} = V_d(1 - 1/e)$$

8.7 General Conclusions and Directions for Future Research

8.7.1 Objectives Achieved

The research objectives and approach were stated in Chapter 1 and again at the beginning of this chapter. Efforts to achieve these objectives were reasonably successful. The general conclusions may be summarized with reference to the following:

- (a) sample preparation;
- (b) development of soil-property-measurement equipment and testing procedures; and,
- (c) experimental observations.

8.7.1.1 Sample Preparation

Equipment and procedures were developed to sediment, consolidate and leach natural soil material in order to produce a controlled, reproducible suite of experimental samples having desired characteristics. The success achieved is qualified by the fact that, in the present case, the oxidizing conditions of the experiment did result in weathering of the soil material and alteration of the pore-water chemistry from that which was intended. The oxidizing conditions took on an added significance because the soil material used was relatively "young" and unweathered. However, many soils which are studied are already mature and well weathered so the equipment and procedures developed here would likely produce even better results with soils of this kind than were achieved in the present study.

8.7.1.2 Development of Soil-Property-Measurement Equipment and Testing Procedures

A vane apparatus and procedures were developed to measure the strength and deformation characteristics of laboratory soil samples by means of their torque/twist response. Results show that the apparatus and procedures worked well, allowing the measurement of very small elastic deformations.

An electrical-property measurement system and procedures were developed to determine the low-frequency electrical response of soil samples. The system performed as expected, yielding data which can be analyzed to determine a number of different electrical properties of soils.

A method has been developed for measuring the diffusion coefficient of soils. The results obtained appear to be reasonable although no real basis for assessment has been found.

Procedures have been developed to undertake many standard tests on small specimens of soil. The results are comparable to those obtained by more conventional procedures.

All of the tests and measurements were integrated into a coherent testing sequence which allowed a great many index properties and other parameters to be determined on a single, relatively small, soil sample.

8.7.1.3 Experimental Observations

This study was able to establish a number of relationships between the controlling variables and the soil properties. These and

other observations may be summarized as follows:

- (a) As the degree of consolidation increased, the shear strength (undisturbed) and modulus of elasticity were observed to increase. Increasing the degree of consolidation had a more pronounced effect on the modulus of elasticity than on the shear strength.
- (b) During a given load-unload cycle, the total deformation of the overconsolidated samples was less than that of the normally consolidated samples. The fraction of this deformation recovered through elastic rebound was greater for the overconsolidated samples than for the normally consolidated samples.
- (c) The size of floccules was controlled by the chemistry of the sedimentary environment and the suspended-sediment concentration. The largest floccules were observed under conditions of high salinity and high suspended-sediment concentration.
- (d) Cyclic colour banding was observed only in the sample sedimented in a non-saline environment.
- (e) The modulus of elasticity was greater for those samples having a higher degree of flocculation.
- (f) Upon remolding, the samples experienced a loss of shear strength which was proportionately greater than the corresponding reduction in the modulus of elasticity.
- (g) Generally, the shear strength measured with the vane was greater than that determined with the fall cone. An empirical relationship has been established between the two values.

- (h) The liquidity index was related to both the remolded shear strength and sensitivity respectively. In both cases, the data points for these experimental samples plotted above curves established for other clays (Mitchell, 1976), suggesting the existence of a family of curves.
- (i) The results of this experiment were consistent with the relationship between the sensitivity and the percent of monovalent cations in the pore water which was established by Mitchell (1976). However, they suggest that this relationship may extend to a family of curves.
- (j) The addition of colloidal SiO_2 to the soil resulted in a pronounced increase in the void ratio, liquidity index and sensitivity.
- (k) Some soil samples exhibited an induced-polarization response comparable to rock containing 2-8% disseminated sulphides.
- (l) The diagram of voltage versus time for each sample which did have an induced-polarization response indicated that the residual charging voltage was greater than the residual decay voltage and the area under the charging curve was greater than the area under the decay curve.
- (m) For all samples, regardless of whether or not an induced-polarization response was present, the diagram of voltage versus time indicated that the discharge voltage ramp was greater than the charging voltage ramp. A relationship

was established between the voltage ramps and the pore-water salinity. The same relationship was found to exist between the pore-water salinity and the impedance (AC and DC) and steady-state voltage respectively.

- (n) When induced polarization occurred, charging and decay curves were present on the diagram of voltage versus time. It was found that the initial tangent to the charging curve was greater than the corresponding tangent to the decay curve. The tangents were related to the pore-water salinity.
- (o) When induced polarization resulted in a charging curve and a decay curve on the diagram of voltage versus time, it was possible to define characteristic times for the two curves. It was found that the characteristic time for the charging curve was greater than that for the decay curve. At the characteristic time for the decay curve, the decay voltage was approximately $(1 - 1/e)$ of its original value.
- (p) During each cycle of electrically charging and discharging the soil, approximately 20-25% of the electrical energy put into the soil was recovered.

8.7.2 Future Research

This thesis has addressed a broad range of topics. Some of these have been adequately dealt with in the present investigation, but many deserve additional study. Indeed, during the course of this research, many new avenues of inquiry became apparent. The following sections will discuss a few of these possibilities for future research.

8.7.2.1 Controlling Variables

In this experiment, the chemistry of the sedimentary environment reflected the suite of ions found in natural sea water. This, in conjunction with chemical changes due to the oxidizing environment, may have unduly complicated the system. It might be interesting to repeat certain aspects of this experiment with a homoionic system.

The addition of colloidal SiO_2 produced samples (21 and 22) which differed markedly in their properties and behaviour from the other samples of the experiment. This investigation should be expanded to include admixtures of other primary rock minerals. X-ray diffraction and other techniques could be used to quantify the mixtures before they were used for experimental purposes.

The results of consolidation, particularly with respect to the response of samples 21 and 22, suggest that the effect of consolidation deserves further examination. A water content well above the liquid limit is a prerequisite for high sensitivity (Torrance, 1983) and the water content is, in part, a function of the consolidation experienced by the soil.

8.7.2.2 Determination of Poisson's Ratio

For saturated soils, Poisson's ratio is normally assumed to have a value of 0.5. However, there is information to suggest that this assumption may be incorrect in some cases (Perloff, 1975; Bozozuk, 1963).

In accordance with the design objectives established for the vane apparatus, a conventional soil sample can first be tested with the vane and then subsequently in a triaxial apparatus. This was described in Section 5.4. In this way, independent determinations of the shear modulus and modulus of elasticity can be made on the same sample. From the two parameters, Poisson's ratio could be calculated.

Although the use of the triaxial apparatus for this purpose was considered beyond the intent and scope of this experiment, the research suggested above appears worthy of further consideration. It should be done on a wide range of natural samples and the results should be correlated with as many controlling variables as possible.

8.7.2.3 Shear Strength Determinations With the Vane and The Fall Cone

It has been possible with the data obtained in this experiment to establish a relationship between the value of the shear strength obtained by means of the vane apparatus and that obtained with a conventional fall cone. It may be possible to develop a theoretical basis for the observed relationship by considering the fundamental mechanisms which operate as a soil is sheared by the vane and by the fall cone.

8.7.2.4 Full Penetration of the Vane

A new vane should be fabricated which will allow full penetration of the vane and certain aspects of this experiment should be repeated.

8.7.2.5 Extended Analysis of the Electrical-Property Data

The graphical analysis of the electrical-property data reported in this thesis should be repeated using numerical methods in order to obtain improved accuracy. The scope of the work should be expanded to include the data obtained at currents other than 1 milliamperes with the purpose of determining whether any of the electrical properties were current-dependent.

8.7.2.6 Field Application of Induced Polarization to Soils

Induced polarization is a well established exploration technique in the mineral exploration industry. Field equipment is readily avail-

able. If further experimentation can firmly establish some of the relationships between soil properties and the IP response suggested by the results of this experiment, consideration should be given to extending its use to the assessment of soils in the field. The IP technique is preferable to conventional resistivity methods inasmuch as the range of information acquired by this technique is more extensive.

8.7.2.7 Correlation of IP Response With Electrokinetic Potential

Electro-osmosis is an accepted technique for determining the electrokinetic potential of materials. It is a tedious procedure at best. In contrast, the IP response of soils can be quickly and easily determined using the equipment and procedures developed in this experiment. An attempt should be made to correlate the two measurements. A procedure similar to that used by Penner (1965) could be used to determine the electrokinetic potential of soil samples which could then be subsequently tested to determine their response to induced polarization. If a correlation could be established between the two measurements, the IP technique could be used to determine the electrokinetic potential of soils, both in the laboratory and in the field.

If an empirical relationship can be established between the IP response and the electrokinetic potential, an attempt should be made to develop a theoretical model based upon the recognition that the transient decay voltage is proportional to the current resulting from the movement of hydrated ions back to their equilibrium positions. The only ions free to move initially to the blockages and to subsequently contribute to the transient decay current are those situated outside the Stern layer.

8.7.2.8 Examining the IP Response of Soils as an Aid to Mineral Exploration

As noted in Section 8.6.4, the IP response exhibited by some of the samples in this experiment is comparable to that of mineralized rock containing approximately 2% to 8% disseminated sulphides. In the field, the presence of clays can adversely affect the interpretation of IP-survey results by giving a spurious indication of mineralization or by masking the response from an underlying body of mineralized rock.

A systematic study of the IP response of clays as a function of the controlling variables might provide information which would permit the IP response of mineralized rock to be distinguished from that of clay and other soils. The results of this experiment provide one such example. It was noted that in all samples displaying an IP response, the area under the charging curve was greater than that under the decay curve. This is not normally the case for the IP response from mineralized rock.

8.7.2.9 Diffusion in Soils

Mitchell (1976) reports that information pertaining to diffusion in soils is not readily available. The apparatus designed for this experiment and the theoretical presentation in Appendix "D" form the basis of a broader investigation of this phenomenon. A suite of samples identical in every respect could be prepared using the methods described in this thesis. The following steps would form the outline of the suggested experiment:

- (a) Leach each member of a suite of identical samples for a different period of time.
- (b) Measure the surface flux from each sample.

- (c) Extrude each sample in steps, taking thin slices from which the pore water could be extracted.
- (d) Analyze the pore water.
- (e) With the information obtained, construct diffusion isochrons and time-diffusion curves and attempt to devise a method for determining a time factor, applying techniques similar to those used in the study of consolidation.

Initially, a homoionic system should be used. It was determined during this experiment that the calculated diffusion coefficient was very sensitive to the measured value of the flux. For this reason, any new investigations should use atomic absorption spectrophotometry or other accurate analytical technique in order to obtain the concentration information necessary for determining the flux.

APPENDIX A

A SUMMARY OF DIFFUSE DOUBLE-LAYER THEORY WITH APPLICATION TO CLAY-WATER-ELECTROLYTE SYSTEMS

A.1 Introduction

A.1.1 Terminology

The term, "clay", has acquired a variety of different meanings in the literature. For example, it is sometimes used to denote the clay minerals. These minerals are hydrous aluminosilicates which form a distinct subset within the group known as the phyllosilicates. They possess a layered structure, the basic building blocks of which are two distinctly different two-dimensional sheets. One of these sheets consists of silicon in tetrahedral coordination with oxygen and the second is composed of aluminum or magnesium in octahedral coordination with oxygen and the hydroxyl radical. These sheets may be bonded together in a variety of characteristic assemblages called layers which form the basis of the distinctions between the various clay minerals. The layers constitute the basic structural unit for the clay minerals and one or more layers will form a clay particle. These particles are normally plate-shaped and are usually fine-grained, with equivalent spherical diameters of about 2 microns or less.

In a macroscopic sense, the term, "clay", is also applied to soils which are dominated by "clay-sized" particles. It may also refer specifically to the finest fraction (<2 microns) of a soil. The term, "clay fraction", is also used in this latter sense.

It is important to realize that the clay fraction of certain soils, especially those derived from the glacial scouring of igneous and metamorphic rocks, may include significant amounts of other silicates, oxides and amorphous material in addition to the clay minerals described above.

In this paper, the general terms, "clay" and "clay particles", will be used in all the above senses and in most cases the intended meaning should be clear from the context. When this is not the case, a more specific term such as clay minerals, colloidal quartz et cetera will be used.

A.1.2 A Colloidal Solution

A colloidal solution (also called a colloidal system or a colloidal dispersion) consists of a homogeneous dispersion of particles in a medium. The particles, although much larger than the molecules and ions of classical chemistry, are too small to settle out of the medium within a reasonable period of time under the influence of gravity because the diffusion process, which results from Brownian motion, effectively counteracts gravitation (Glasstone and Lewis, 1960; Kruyt, 1952; Overbeek, 1952a; Quagliano, 1958; van Olphen, 1963).

A colloidal solution therefore consists of two phases: a molecular or ionic fluid, called the dispersion medium and the dispersed colloidal particles, referred to as the disperse phase. When the disperse phase is a solid and the dispersion medium is a liquid, the colloidal solution is called a sol. A colloidal system is said to be stable when the particles remain dispersed (Glasstone and Lewis, 1960; Quagliano, 1958). Sols have traditionally been called lyophobic or lyophilic (hydrophobic or hydrophilic if water is the dispersion medium). The distinction is based on the reaction of the system to the addition of

an electrolyte. A stable, hydrophobic sol is difficult to produce and the particles will readily coalesce and settle out of the dispersion medium. The disperse phase of a hydrophobic sol is essentially insoluble in the dispersion medium (Glasstone and Lewis, 1960; van Olphen, 1963).

The finest particles of the clay fraction are small enough to form a colloidal system when dispersed in water. It is sometimes referred to as a clay sol and is hydrophobic.

A.1.3. Particle Charge

Colloidal particles acquire a charge as a result of surface effects associated with the interface between the particles and the dispersion medium. It can be demonstrated that when a hydrophobic sol is placed in an electrical field; the particles of the disperse phase will move along lines of force in one direction indicating that they all possess either a positive or negative charge. This migration in an electric field is called electrophoresis.

Because all the particles in a particular sol are similarly charged, they repel one another. Flocculation is prohibited and the sol remains stable until conditions change. The particle charge is therefore the dominant factor in the behaviour of hydrophobic sols.

The mechanisms by which the disperse phase acquires an electrical charge will be described in more detail below.

The existence of phenomena such as electrophoresis is indicative of another important aspect bearing upon the behaviour of colloidal systems, namely the relative importance of surface as opposed to body forces. Colloidal particles are so small that surface forces, particularly those due to electrical charge, generally predominate over body forces which are proportional to the mass of the particles.

A.1.4 Soil Structure

As a general statement, it may be said that the engineering properties of a soil are a function of its structure, where the structure is determined by the size, shape and arrangement of the constituent particles. If the size of the particles is small enough that surface forces predominate over body forces, it is more appropriate to say that the structure is a function not only of the size, shape and arrangement of the particles, but also of the nature and magnitude of the inter-particle surface forces (Lambe, 1958).

Indeed, soils containing clay-sized particles will exhibit certain distinctive bulk properties, namely plasticity and cohesion, which are characteristic of fine-grained soils. The degree of plasticity and cohesion exhibited by a soil is a function not only of the percentage of clay-sized particles in the soil but also the mineralogy of this clay fraction.

The important contribution which the clay fraction makes to the behaviour of a soil is manifested in other ways as well. For example, under drained conditions, the elastic response of a clay soil should be a function not only of the elastic properties of the particles but also of the restorative forces generated by the inter-particle surface forces.

A.1.5 Clay-Water-Electrolyte System

As will be made clear in subsequent sections, the nature and magnitude of the inter-particle forces is to some extent determined by the characteristics of the surrounding medium. The importance of surface forces and the influence of the surrounding medium means that a clay soil is more appropriately analyzed in terms of it being a clay-water-electrolyte system, a term which is increasingly applied to clay soils (Mitchell, 1976) and which will frequently be used in this thesis.

A.2 Processes by Which Particles Acquire Charge

A.2.1 Usual Process Due to Surface Effect

In the case of most colloidal particles other than clay minerals, the particles are initially uncharged. This is easy to demonstrate if a pure aqueous medium is produced by persistent dialysis. The particles will then no longer respond to an electric field. The sol cannot maintain its stability under these conditions and flocculation usually ensues (Glasstone and Lewis, 1960; Mysels, 1959; Quagliano, 1958).

In contrast, it has been observed that the stability of most hydrophobic sols is enhanced by the presence of a very small amount of electrolyte in the dispersion medium. The electrolyte is referred to as a peptizing or stabilizing electrolyte and is most effective if it contains the same ions as those found in the particle lattice (van Olphen, 1963). This is particularly true in the case of ionic crystals such as AgI, but an electrolyte with ions of a comparable size to those found in the lattice will also be an effective peptizer (Glasstone and Lewis, 1960; Overbeek, 1952a).

The particles of such sols are therefore thought to acquire their charge by preferential adsorption of ions from the peptizing electrolyte. The adsorption of these ions probably results from unsatisfied valences and broken bonds at the edge of the crystal. For instance, there are strong, highly localized electrostatic fields at the edges of ionic crystals where ionic bonds have been broken, and there would be a natural tendency for the crystalline lattice to extend itself by preferential adsorption of common ions or ions of appropriate size. Adsorption is also thought to result from unsatisfied covalent bonds, Van der Waals forces and hydrogen bonding (Glasstone and Lewis, 1960; Mysels, 1959; van Olphen, 1963).

A.2.2 Factors Which Control the Nature and Magnitude of Charge

The example which is most often used to illustrate the charging mechanism is a sol composed of finely divided silver iodide crystals in a saturated solution (Mysels, 1959; van Olphen, 1963). AgI is not very soluble and the two ions differ with respect to how strongly attached to the lattice they are. The larger I^- is more polarizable and is more firmly held while the Ag^+ escapes more easily, so if the two ions are present in equal amounts in the solution, the particle will be negatively charged.

A dynamic equilibrium evolves with ions leaving the surface and ions depositing. If the concentration of Ag^+ is raised by adding a soluble silver salt to the solution, it will be harder for the Ag^+ to leave the surface with the new concentration gradient, while the likelihood of an Ag^+ depositing on the surface is increased. The Ag^+ which is deposited will be adsorbed at regular lattice positions and if the concentration of Ag^+ in the solution is sufficiently high, the particle will become positively charged.

Only the relative concentrations of Ag^+ and I^- are important because if the concentration of either Ag^+ or I^- is raised, the other will decrease so that the solubility product remains constant. Therefore, the particle will be positive or negative depending on the relative availability of Ag^+ and I^- . Because the particle can be either positively or negatively charged, somewhere between these two conditions it must be neutral. The point of neutrality is called the zero point of charge.

From the argument above it can be seen that the concentrations of Ag^+ and I^- will determine the surface potential of the particle. Therefore, in addition to being the peptizing ions for the AgI sol, the Ag^+ and I^- are also referred to as the potential-determining ions for this sol.

Another example of charge reversal is given by van Olphen (1963). The charge on the aluminum hydroxide sol is dependent upon the pH. In this case the potential-determining ions are Al^{+3} , $(\text{OH})^-$, and $(\text{AlO}_3)^{-3}$, but the relative concentration of these ions is pH-dependent. At low pH, there is an excess of Al^{+3} and the particles are positively charged. At high pH, $(\text{OH})^-$ and/or $(\text{AlO}_3)^{-3}$ are in excess and the particle acquires a negative charge. As before, somewhere between these extremes the particle is neutral. This point is called the isoelectric point and it need not be at pH 7.

Colloidal silica is usually negatively charged. According to Bungenberg de Jong (1949) this charge arises from the dissociation of silicic acid which forms at the surface of the particles. Iler (1973) notes that although silica will adsorb hydroxyl ions or lose hydrogen ions as above to become negative at high pH, it does not lose hydroxyl ions to become positive at low pH. He attributes some of the negative charge to replacement of Si by Al in the tetrahedral structure and at low pH, he considers this to be the sole charging mechanism. Iler also reports that recent studies with very pure silica show that the isoelectric point can be as high as pH 7. However, as noted above, most silica contains trace amounts of Al which tends to depress the isoelectric point to as low as pH 2.5. It is for this reason that silica is normally considered to be permanently negative.

The presence of certain highly charged and/or strongly adsorbed ions can cause a charge reversal which is largely independent of the potential-determining ion concentration (Bungenberg de Jong, 1949; Overbeek, 1952c; van Olphen, 1963). The higher the valence, the more pronounced the effect. The most notable examples are Al^{+3} and Th^{+4} . There is good evidence to suggest that, except at very high concentrations, the ions themselves do not cause the charge reversal. For example, it is thought that the Al^{+3} and Th^{+4} are incorporated into either hydrated complexes or even larger hydroxide and oxide complexes formed as products

of hydrolysis. The hydrolized solution would be slightly acid so the hydroxides would be positively charged. These positively charged complexes are strongly adsorbed onto negative particles and a reversal of charge can result in certain circumstances.

The situation is a very complicated one. The reversal of charge is a function of the concentration of Al^{+3} or Th^{+4} ions because this determines the availability of the complex ions, but these complex ions in turn have a pH-dependent charge of their own.

The brief summary above presents the findings of studies which examined rather simple, idealized laboratory systems. One must bear in mind that the charging mechanism might not be so simple in every case, especially given the inherent variability of naturally occurring soils.

A.2.3 The Origin of Charge on Clay Minerals

The clay minerals, unlike the vast majority of colloidal particles, acquire their principal charge from lattice vacancies and imperfections, or from isomorphous substitution within the crystal lattice when the substituting ion has a different valence than the ion it replaces. For example, aluminum may substitute for silicon in the tetrahedral sheet while in the octahedral sheet magnesium and ferrous iron may replace aluminum.

Along the edges of the clay particles, additional charge sites exist as a result of broken chemical bonds at the edge of the crystal. There are both negative and positive charge sites created by this mechanism and the broken edges of the clay particles are thought to acquire a charge in the same manner as other colloidal particles.

The clay minerals are therefore unusual for two reasons. Their principal charge is acquired from ionic substitution and there are two charging mechanisms operating in each particle.

The isomorphous substitution results in a net negative charge within the crystal lattice which is non-varying for a given clay particle. Because of the thin, platey nature of clay particles, this net negative charge is generally considered to reside on the basal plane surfaces of the clay mineral particles.

In contrast, the charge on the edge of the clay particles will be a function of the geochemistry of the surrounding medium. For instance, the edges of the octahedral sheet may have a pH-dependent charge like the aluminum hydroxide described in the preceding section. The potential-determining ions, Al, Mg, Fe, (OH), etc., are readily available in most soils. The edges of the tetrahedral sheets will behave in a manner similar to silica particles and acquire a charge which is a function of both the pH and the concentration of Al^{+3} in the pore water. The ability of Al^{+3} to govern the charge on the exposed tetrahedral sheets will be a function of its concentration and the pH.

Therefore, the broken edges of the clay mineral particles may acquire either a positive or negative charge in contrast to the basal plane surfaces which are always negative. The charge on the edges will, in effect, be a net charge because under the same conditions it is possible that the tetrahedral and octahedral sheets could be oppositely charged.

There is experimental evidence to suggest that the edge charge does vary with the pH. Schofield and Samson (1953) have shown that a reversal of charge occurs on the edges of kaolinite particles as the pH is changed. The charge variation is said to result from the interaction of hydrogen ions with the oxygen and hydroxyl ions along the broken edges.

A.3 Description of the Diffuse Double Layer

A.3.1 Ion Distribution Adjacent to a Charged Particle

In the previous section, the mechanisms by which the particles of most hydrophobic sols acquire a charge were outlined. The process always began with the introduction of a neutral particle into a neutral medium. Then the particle adsorbed certain specific ions from the solution onto its surface and in so doing became positively or negatively charged. The charged particles could be expected to attract a cloud of oppositely charged ions from the solution in response to the electrostatic forces. These counter-ions, as they are called, would have to be drawn from the solution as were the charging ions, if the electroneutrality of the system is to be maintained. The charge on the particle also causes the repulsion of similarly charged ions, called co-ions, and their exclusion from the solution in the immediate vicinity of the particle.

In contrast, the principal charge on the clay minerals arises within the lattice, so if a clay mineral were placed in a neutral solution, a charged system would result. This violates the principle of electroneutrality and has not been observed. Therefore, the charge on the clay mineral must have been neutralized before it was placed in the solution. This implies that the clay mineral carries its compensating charge with it, probably in the form of oppositely charged ions attached to the surface. Once in the solution, these ions would be free to dissociate to some degree and form an ion cloud adjacent to the surface as in the example above.

A counter-ion atmosphere can therefore be acquired by a charged particle in contact with a solution in two ways, depending on the nature of the charge. The counter-ions will either be attracted to the particle from the bulk solution, or swarm out from the surface into the bulk solution. With the clay minerals, both of these processes will occur

because the clay mineral platelets acquire their face and edge charges in fundamentally different ways.

The counter-ions form a diffuse cloud or atmosphere around the charged particles in response to two influences. They are electrostatically attracted to the particle, but their thermal agitation promotes diffusion and an even distribution throughout the system. Without this diffusion tendency, a simple double layer would develop, consisting of the charging ions and the counter-ions immediately adjacent to them. However, in reality, a diffuse double layer exists because the counter-ions are subject to thermal agitation (Mysels, 1959; van Olphen, 1963).

An analysis of the diffuse double layer can begin with a qualitative description of its development. Consider an isolated, infinite, uniformly charged plane in contact with a solution containing counter-ions. The electric field intensity will be constant and the potential will decrease linearly with distance from the plane. The first counter-ion which is attracted will tend to screen the plane from other possible counter-ions and a slight potential drop will occur across it. If it were possible to form a simple, compact double layer, the potential would drop to zero across the layer of counter-ions. However, thermal agitation causes the counter-ions to diffuse away from the charged plane. Despite this diffusion tendency, the counter-ions do tend to concentrate in the vicinity of the plane and act as a screen to other counter-ions in the bulk solution. As a result of the reduced electrostatic attraction, the concentration of counter-ions drops off away from the plane. The electric field intensity therefore decreases, rapidly at first near the plane, and then more slowly

Figure A.1: Decay of the potential with distance in the diffuse double layer adjacent to a charged plane.

(from Shaw, 1966, Figure 7.1)

farther out in the bulk solution. The electric potential follows the same trend, theoretically approaching zero at infinity, as shown in Figure A.1.

In the same way that it attracts counter-ions, the plane will repel co-ions. Thermal agitation will tend to diffuse these ions back towards the plane, so that, as in the case of the counter-ions, the distribution of co-ions represents a balance between the electrostatic force and the molecular kinetic energy. The exclusion of each co-ion has the same effect electrically as the attraction of a counter-ion and the development of the diffuse part of the double layer is a function of the distribution of co-ions as well as counter-ions. However, the concentration of counter-ions near the plane is increased many times while the concentration of co-ions can only be reduced to zero. Most colloidal systems are of sufficiently high charge that this co-ion exclusion is not important, and it is the distribution of counter-ions which dominates the development of the diffuse part of the double layer (Mysels, 1959).

A.3.2 Mathematical Description of the Diffuse Double Layer

The mathematical description of the diffuse double layer is often called the Gouy or the Gouy-Chapman equation after the men who first succeeded in treating the problem analytically. Because Gouy and Chapman employed the well known equations of Poisson and Boltzmann in their treatment, the resulting equation is also known as the Poisson-Boltzmann

equation. A summary of the analytical development will be presented below. More complete presentations are available in Mitchell (1976), Shaw (1966), Sonntag and Streng (1970), van Olphen (1963) and others.

In the qualitative description of the diffuse double layer given above, the instantaneous position of individual ions was ignored, and the charge density, which is a function of the ion concentration, was assumed to vary in a continuous fashion with distance from the charged plane. It was also assumed that after an equilibrium was reached, the charge density at a particular point did not vary with time. These assumptions are not unreasonable on a macroscopic scale. However, in reality, the charge density could be expected to vary discontinuously with time at all points in the ion atmosphere because of the erratic movements of the individual ions (Mysels, 1959).

The potential also varies with the ion concentration because of the screening effect of the counter-ions. The charge density and potential are therefore both functions of the same variable and can be related to one another. If the charge density is assumed to vary continuously, then the potential and charge density are related by Poisson's equation. For an infinite plane, this equation is:

$$\frac{d^2\psi}{dx^2} = -\frac{4\pi\rho}{D} \dots\dots\dots (A.1)$$

where:

ψ is the potential.

x is the distance from the plane.

ρ is the volume charge density.

D is the dielectric constant of the medium.

The equilibrium distribution of ions which are subject to the combined effect of an electrical potential and thermal agitation can be described by the Boltzmann distribution, as follows:

$$n_1(x) = n_1(\infty) \exp \left[\frac{-v_1 e \psi(x)}{kT} \right] \dots\dots\dots (A.2)$$

where: $n_1(x)$ is the number of ions per cm.³ of species 1 at a distance x from the plane.
 $n_1(\infty)$ is the number of ions per cm.³ in the equilibrium or bulk solution, well beyond the influence of the charged plane.
 v_1 is the valence of the ions.
 $\psi(x)$ is the potential at a distance x from the plane.
 k is the Boltzmann constant.
 T is the absolute temperature.
 e is the electronic charge.

Equation A.2 may also be used to express the cation and anion concentrations separately by simply defining n_1 as the number of cations or anions respectively. If, in addition, a single, symmetrical electrolyte (that is, monovalent-monovalent, divalent-divalent, etc.) is assumed, then electroneutrality requires that:

$$n^+(\infty) = n^-(\infty) = n(\infty) \dots\dots\dots (A.3)$$

With this condition, Equation A.2 indicates that the distribution of cations and anions adjacent to a negatively charged plane will be as shown in Figure A.2.

Figure A.2: Counter-ion distribution in the diffuse double layer adjacent to a negatively charged plane.

(from van Olphen, 1963, Figure 10)

In Equation A.2, the ion concentration is a function of the potential. However, Poisson's equation (Equation A.1) shows that the potential is a function of the volume charge density which in turn is determined by the ion concentration. In other words, the two functions are interdependent and must be solved simultaneously. This yields:

$$\frac{d^2\psi}{dx^2} = \frac{8\pi v n(\infty)}{D} \sinh \left[\frac{ve\psi(x)}{kT} \right] \quad \dots\dots\dots (A.4)$$

Equation A.4 is the fundamental differential equation of the diffuse double layer. It can be solved with the following boundary conditions;

$$\begin{aligned} \text{when } x = 0; \psi &= \psi_0 \\ x \rightarrow \infty; \psi &\rightarrow 0 \text{ and } \frac{d\psi}{dx} \rightarrow 0 \end{aligned}$$

where: ψ_0 is the surface potential of the plane.

The solution can be expressed in a number of forms. One of these is:

$$\psi(x) = \frac{2kT}{ve} \ln \left[\frac{\{\exp(A) + 1\} + \{\exp(A) - 1\} \cdot \{\exp(-Kx)\}}{\{\exp(A) + 1\} - \{\exp(A) - 1\} \cdot \{\exp(-Kx)\}} \right] \quad \dots\dots\dots (A.5)$$

where: $A = \frac{ve\psi_0}{2kT}$ and $K = \sqrt{\frac{8\pi e^2 n(\infty) v^2}{DkT}}$ \dots\dots\dots (A.6)

Equation A.5 is the function which is shown in Figure A.1.

In summary, the distribution of ions in the diffuse part of the double layer is given by Equation A.2 when the potential varies with distance from the plane according to Equation A.5.

A.3.3 Examination of Assumptions Invoked in Analysis

A number of assumptions had to be made without which an exact and explicit solution of the equations would have been impossible. Some of these have already been mentioned. The volume charge density was assumed to vary continuously with distance from a charged plane of infinite dimensions. Another simplification was the assumption of a single symmetrical electrolyte. It is also necessary to ignore the volume of the ions even though they are usually hydrated and because they are considered point charges, there can be no polarization of ions. It is assumed that the medium influences the diffuse double layer only through its dielectric constant which is assumed to be constant and independent of the electric field intensity. The possibility of chemical reactions or hydrogen bonding between the surface and the counter-ions is ignored. Only electrostatic attraction is recognized. When an ion is transported from the bulk solution into the diffuse double layer, it is assumed that only work

against electrostatic forces is involved and that no other interactions between counter-ions are possible. A discussion of these various assumptions can be found in Bolt (1955), Shaw (1966), Sonntag and Streng (1970) and van Olphen (1963).

Bolt made a further examination of some of these assumptions. He found that if the surface charge density of the particle does not exceed $2-3 \times 10^{-7}$ meq./cm.², then the effects of dielectric saturation (variation of the dielectric constant with the electric field intensity) and ion polarization tend to cancel one another. The net effect of the various ionic interactions is also negligible but he suspects that chemical reactions between counter-ions and the particle surface can be important in some cases. According to the Gouy-Chapman theory, the ratio of ions of equal valence in the diffuse double layer is equal to their corresponding ratio in the equilibrium solution. However, Bolt found that this ratio was a function of the hydrated radii of the ions as well, so that it was important to be careful when applying this theory to ion exchange reactions. He concludes that, in general, the assumptions which he examined are unimportant when the Gouy-Chapman theory is used to describe interactions between colloidal particles.

The assumption of a symmetrical electrolyte is not unreasonable. The importance of the counter-ions in the development of the diffuse double layer was discussed in an earlier section. In the same discussion, the minor role of the co-ions was also noted. If for example, only one electrolyte were present, then both the counter-ions and co-ions would be drawn from it. Because the structure of the diffuse double layer is almost completely determined by the counter-ions, the nature of the co-ions is unimportant, and the electrolyte might just as well be symmetrical.

More than one ion species can be present in the diffuse double layer. If the system is reasonably dilute so that the various ion species

do not interfere with one another, then each ion species can be treated separately by ignoring the presence of the others. In this way Equations A.2 and A.5 can be used to plot the distribution of ion concentrations for each ion species.

A.3.4 The Stern Layer

The assumption of point charges in the Gouy-Chapman model leads to unreasonably high ionic concentrations near the charged plane. This theory was modified by a man named Stern in an effort to correct this anomaly. His model is discussed by Mysels (1959), Overbeek (1952b), Shaw (1966), van Olphen (1963), Mitchell (1976) and many others.

Stern realized that the size of the ions determined how closely the counter-ions could approach the plane, and how many ions could be packed against a unit area of the surface. He also proposed that the electrostatic and Van der Waals attraction between the surface and the counter-ions adjacent to it would considerably exceed the molecular kinetic energy so that these counter-ions would form a compact layer adjacent to the plane which has come to be known as the Stern layer. Stern's model also allows the possibility of specific adsorption of certain counter-ions. This would be an important consideration in ion exchange reactions.

Because of the large size of the hydrated ions within the Stern layer, it is impossible to pack enough of them against the surface to completely satisfy the surface charge. Therefore, the outer portion of the double layer will consist of two parts, the compact Stern layer adjacent to the surface, and a Gouy-Chapman diffuse layer beyond that. A dynamic equilibrium will exist between the Stern and Gouy-Chapman layers.

The charge of the counter-ions in the Stern layer is considered to reside in a plane through their centers. This means that there is a

Figure A.3: Decay of the potential with distance according to Stern's theory.

(from Shaw, 1966, Figure 7.3)

thickness, d , between the surface and this plane, where there is no charge, and therefore the potential drops linearly from ψ_0 at the surface to ψ_d at this plane. In effect, a molecular condenser is formed by the surface charge and the charge in the central plane of the attached counter-ions. d is usually taken for the thickness of the Stern layer, and therefore ψ_d is referred to as the Stern potential. Beyond the Stern layer, the ion concentration and potential have been sufficiently reduced so that the Gouy-Chapman theory gives realistic results with ψ_d substituting for ψ_0 in the equations. The decay of the potential according to Stern's model is shown in Figure A.3.

In Section A.1.3, the phenomenon of electrophoresis was described. The movement of the charged particles in an electric field is due to the difference in potential between the particles and the medium. This potential difference is called the electrokinetic or zeta potential. The charged particles move with an envelope of bound water (if water is the dispersion medium) and therefore the measured zeta potential is the potential of the diffuse double layer at the plane of slippage between the particle with its envelope and the rest of the dispersion medium. Since the water film is usually on the order of one molecule thick, the zeta potential is about equal to, or just slightly less than the Stern potential.

A.4 The Effect of Concentration and Valence Changes on the Diffuse Double Layer

A.4.1 Thickness of the Diffuse Double Layer

It is difficult to define the thickness of the diffuse double layer, because it theoretically extends to infinity. However, the concept of a diffuse-double-layer thickness is useful, so an attempt has been made, to establish a thickness by means of an arbitrary definition. In its most general form, the definition simply states that the thickness of the diffuse double layer, t , is equal to x , the distance from the charged plane to the point where the potential has dropped to some fraction of the potential at the plane. There seems to be general agreement (Mysels, 1959; Shaw, 1966; van Olphen, 1963) that the following equation constitutes a suitable definition of t :

$$t = \frac{1}{K} \dots\dots\dots (A.7)$$

K has been defined in Equation A.6. If $(ve\psi_0)/(kT) \ll 1$ (that is, $v\psi_0 \ll 25$ millivolts at room temperature), then Equation A.5 simplifies to:

$$\psi(x) = \psi_0 \exp(-Kx) \dots\dots\dots (A.8)$$

When $x = 1/K = t$,

$$\psi(x) = \frac{\psi_0}{e} \dots\dots\dots (A.9)$$

From Equation A.9, it can now be seen that the thickness, t , is equal to that distance over which the potential has dropped to $1/e$ of the surface potential. In addition, Equation A.8 describes a purely exponential decay

of the potential and the center of gravity of the space charge will coincide with the plane, $Kx = 1$ or $x = 1/K = t$.

Unfortunately, the requirement of a low surface potential, which resulted in the simplification presented in Equation A.8, is usually not met in colloidal systems. However, this discussion should have helped to explain the rationale behind Equation A.7. In the discussion which follows, only the concept of a diffuse-double-layer thickness will be needed.

A.4.2 Increase of Valence or Concentration

If the concentration of counter-ions in the equilibrium solution is raised and the surface potential remains unchanged, then the probability of finding more counter-ions near the charged plane is increased. The surface charge of the plane will be more effectively screened, and the potential will decay more rapidly than before the concentration was raised (Mysels, 1959).

The effect of doubling the counter-ion valence is even more pronounced. Although the thermal energy per ion remains the same, the electrostatic attraction per ion doubles and the counter-ions will be brought closer to the plane. The screening effect of this swarm of counter-ions adjacent to the charged plane will be more pronounced than before because each ion now carries a double charge. Consequently, the decay of the potential will be very rapid (Mysels, 1959).

Figure A.4 illustrates how the variation in potential with distance from a charged plane is altered when either the concentration or valence of the counter-ions is raised. Because the potential decreases more rapidly if either parameter is increased, then the distance from the

Figure A.4: Effect of - (a) concentration of monovalent-monovalent electrolyte and (b) counter-ion valency at a constant equivalent concentration of 0.001N - on the decay of potential in a diffuse double layer adjacent to a charged plane (the origin on the distance axis must be placed according to the value of the surface potential).

(from Shaw, 1966, Figure 7.2)

plane to the point where the potential has decreased to some fraction of the surface potential will be less in both cases. In other words, the thickness of the diffuse double layer is reduced by increasing either the concentration or valence of the counter-ions. This reduction could have been predicted from a consideration of Equations A.6 and A.7. The relative effect of each parameter could also have been estimated. K varies directly with the valence, and with the square root of the counter-ion concentration. Doubling the valence increases K more than twice as fast as doubling the concentration.

In addition to compressing the diffuse part of the double layer as discussed above an increase in either the valence or concentration means that counter-ions will move from the diffuse atmosphere into

the Stern layer to re-establish the dynamic equilibrium that exists between the two. As a result, the Stern potential will decrease.

There is similar change in the zeta potential (Shaw, 1966; van Olphen, 1963).

A.4.3. Surface of Constant Charge vs. Surface of Constant Potential

The surface potential is measured by work. It represents the work necessary to transport a unit charge from infinity to the surface. Work is the product of a force times a distance. In this case, the force is a function of the surface charge density and the distance is in some way related to the thickness, t , of the diffuse double layer. If for any reason, t is reduced, then the surface potential also decreases unless there is a compensating increase in the surface charge density.

If the surface acquires its charge by the adsorption of certain potential-determining ions and if there are no complicating factors such as the presence of highly charged cations, then the surface potential is a function only of the concentrations of the potential-determining ions. This means that when a reduction in t occurs as a result of an increase in the concentration or valence of the counter-ions, the surface potential must be maintained by a corresponding increase in the surface charge density. This is accomplished by adsorption of additional potential-determining ions onto the surface.

In contrast, the basal plane surfaces of the clay minerals bear a constant surface charge due to isomorphous substitution. The surface charge density cannot change if conditions are altered, so an increase in the concentration or valence of the counter-ions will result in a reduction of the surface potential (Mysels, 1959; van Olphen, 1963).

Figure A.5: Decay of the potential in the diffuse double layer adjacent to a charged plane at two different concentrations of the counter-ions in the bulk solution when the plane is: (a) a surface of constant potential, and (b) a surface of constant charge.

(from van Olphen, 1963, Figure 11)

Figure A.5 summarizes the discussion above. It illustrates what happens to the surface potential and the decay of the potential with distance when there is an increase in the concentration of counter-ions in the bulk solution.

Figures A.6a and A.6b show the effect of these changes on the distribution of counter-ions adjacent to a negatively charged plane. In each case, the concentration of counter-ions has been raised from $n(\infty)$ to $n(\infty)'$. There has been the expected reduction in t (compare the positions of B and B'). However, in Figure A.6b, the case of a surface of constant charge, the area between the two curves (ABC and A'B'C') is the same, because electroneutrality requires that the charge of the counter-ion atmosphere be equal to the surface charge which it compensates. On the

Figure A.6: Counter-ion distribution in the diffuse double layer adjacent to a negatively charged plane at two different concentrations of the counter-ions in the bulk solution, when the plane is: (a) a surface of constant potential, and (b) a surface of constant charge.

(from van Olphen, 1963, Figure 10)

Note: $n(\infty)'$ does not imply the same bulk concentration in the two figures above. $n(\infty)'$ in Figure A.6a is greater than $n(\infty)'$ in Figure A.6b.

other hand, the area between the two curves in Figure A.6b are not equal ($A'B'C' > ABC$) because the surface charge was raised to maintain a constant surface potential.

A.5 Stability and Flocculation

A.5.1 Competing Forces

In an earlier section, the statement was made that the stability of a sol was due to the mutual repulsion of similarly charged particles. This statement can now be refined. Actually, each particle with its surrounding counter-ion atmosphere is an electrically neutral unit. Repulsion between these units occurs only when the similarly charged counter-ion atmospheres begin to interpenetrate (Sonntag and Strenge, 1970).

In the absence of all other forces, this interpenetration of ion clouds would never be very substantial because as soon as the outer edges of adjacent clouds began to interact, there would be repulsion and disengagement. However, the sol particles are subject to Brownian motion and the resulting collisions can cause extensive interpenetration.

It was noted in an earlier section that the presence of a peptizing electrolyte enhances the stability of a sol, and that removal of this electrolyte by dialysis leads to flocculation. Sols are also notably unstable at their zero point of charge. Without the repulsive force exerted by their ion atmosphere, particle collisions are more intimate and they coalesce, forming larger aggregates which then settle out. Van der Waals forces are usually considered to be responsible for this particle adhesion.

It is not necessary that the particles be neutral before flocculation can occur. However, if flocculation does occur, it indicates that the repulsive force generated by the interpenetration of counter-ion atmospheres was not sufficient to overcome the kinetic energy of the particle and Van der Waals forces.

A.5.2 Net Interactive Force

If the kinetic energy is ignored for the time being, the problem can be discussed in terms of the repulsive energy due to interaction of counter-ion atmospheres, the attractive energy due to Van der Waals forces, and the net interactive energy which results from these. As two particles approach one another and the interpenetration of the ion atmospheres becomes more extensive, the repulsive energy increases rapidly. In the same way, the attractive energy also increases very rapidly as the particle separation diminishes. This is shown in Figure A.7a. The attractive energy between two specific particles is a function only of the particle separation, but the repulsive energy between the same two particles is a function of the counter-ion concentration as well as the particle separation. When the counter-ion concentration is low, the thickness of the diffuse double layer will be greater, and a repulsive energy will be generated at greater particle separations than when the counter-ion concentration is higher (van Olphen, 1963).

The new interactive energy for low, intermediate and high counter-ion concentrations is shown by the dashed line in Figures A.7b, A.7c and A.7d. It represents the sum of the repulsive and attractive energies at each particle separation. When the counter-ion concentration is low, repulsion dominates at all but the smallest particle separations. The extremely high repulsive energy as the particle separation approaches zero is due to two factors: the energy necessary to remove the water films adhering to both particles, and the Born repulsion, that is, the resistance to lattice interpenetration (van Olphen, 1963).

Although the repulsive energy barrier is very high at low counter-ion concentrations, it is only moderately high at intermediate concentrations. It is possible that two colliding particles would have sufficient kinetic energy to surmount this barrier. Once over the barrier,

Figure A.7: (a) - Repulsive and attractive energy as a function of particle separation at three different concentrations of the counter-ions in the bulk solution. (b), (c), (d) - Net interaction energy (dashed curve) as a function of the particle separation when the concentration of counter-ions in the bulk solution is: (b) low, (c) intermediate and (d) high.

(from van Olphen, 1963, Figures 12 and 13)

the two particles would be firmly bound together because the deep minimum in the dashed curve at small particle separations represents a very strong net attractive energy. When the counter-ion concentration is high, there is a net attractive energy at all particle separations and flocculation is certain (Shaw, 1966; van Olphen, 1963).

The discussion above explains the observation that while a small amount of electrolyte has a stabilizing influence on a hydrophobic sol, greater concentrations tend to promote flocculation. Because the diffuse double layer will also be compressed by raising the valence of the counter-ions, this will encourage flocculation as well.

A.5.3 Application to Clay-Water-Electrolyte System

The approach outlined above can also be applied in a general way to clay minerals. However, it has to be modified somewhat. While the faces of the clay mineral particles carry a negative charge, evidence was presented in an earlier section which suggested that a positively charged edge was possible. Therefore, in addition to the repulsive and attractive energies discussed above, electrostatic attraction between the face of one particle and the edge of another must be considered when dealing with clay minerals.

The stability of most hydrophobic sols is enhanced if a small amount of electrolyte is present because the particles acquire a stabilizing charge from this peptizing electrolyte. However, clay sols can be stable in pure water, and even a small amount of electrolyte can cause flocculation. In pure water, with a pH of 7, the edges of the particles would be slightly positive (Schofield and Samson, 1953). The compensating counter-ions which were carried into the water on the faces would form a very diffuse atmosphere because of their low concentration. The particles are usually very thin in comparison to their lateral dimensions, so it is likely that the very diffuse atmospheres on the faces would mask the

slightly positive edges, and the particles would behave like negatively charged colloids with a low counter-ion concentration (Figure A.7b).

The addition of an electrolyte will have two effects. First, the ion atmosphere on the face will be compressed, possibly exposing the positively charged edge. In addition, the tiny counter-ion atmosphere adjacent to the edge will also be compressed, but this will result in a higher surface charge density on the edge since it behaves as a surface of constant potential.

Clearly this process would eventually encourage flocculation through edge to face electrostatic bonding. However, the picture presented above is a simplified one because it ignores the effect that the added electrolyte might have on the pH. In addition, Al^{+3} would almost surely be present. Therefore, the real situation is probably many times more complicated than the model outlined above.

Nevertheless, the examination of simplified models can often lead to useful generalizations, so the line of reasoning begun above will be pursued. If the edge is positively charged, the continued addition of electrolyte will eventually lead to an electrostatic bond between edges and faces. This is a very strong bond and this is reflected in the undisturbed, undrained shear strength of soils which possess an edge-to-face particle arrangement. On the other hand, if both the face and the edge are negative, the discussion which accompanies Figure A.7 would apply, and the particles would flocculate in a face-to-face array with Van der Waals forces providing the bond. This will not be as strong a structure as the one above.

A.5.4 Implications With Respect to Leda Clay

The sensitivity of a clay has been defined as the ratio of its undisturbed to remolded shear strength. The leached glacial marine clays of Scandinavia and eastern Canada provide the most notable examples of clay sensitivity. It is perhaps possible to explain this phenomenon in terms of the diffuse-double-layer theory.

These clays were deposited in a marine or brackish environment. Sea water would contain an abundance of possible potential-determining ions for the edges of the clay mineral particles. The relatively high concentrations of these ions would result in a high surface potential and high surface charge on the edges. The very high concentration of NaCl would compress the counter-ion atmospheres on both the face and the edge and would further increase the surface charge on the edge in order to maintain the surface potential at the level dictated by the concentrations of potential-determining ions.

To summarize, deposition of these clays in a marine environment results in a greatly reduced thickness of the diffuse double layer on both the face and edge and a highly charged edge. The severe compression of ion atmospheres means that the repulsive energy is negligible at most particle separations so the particles are free to approach one another. If the edges are assumed to be positive, then a very strong edge-to-face electrostatic bond will form. The fact that these clays are sometimes observed (Gillott, 1968, 1969, 1970) to have an edge-to-face particle arrangement supports the assumption of a positive edge. The electrostatic bond will be especially strong, not only because of the high charge involved, but also because of the negligible repulsive energy.

When these clays are leached, the undisturbed shear strength decreases somewhat, and the remolded shear strength is drastically reduced

so their sensitivity is usually high (Bjerrum, 1954). Leaching would reduce the concentration of potential-determining ions. With the removal of NaCl, the ion atmospheres would expand and the surface potential of the edges would decrease. Both these processes would lead to a reduction in the surface charge of the edges. The positive edges might approach the zero point of charge and perhaps become negative. The electrostatic attraction between edge and face could be reduced to zero or perhaps become an electrostatic repulsion. At the same time, the repulsive force between faces would be increasing due to expansion of the ion atmospheres.

The edge of one particle would still be close enough to the face of another that Van der Waals forces would continue to operate even though the electrostatic attraction may have been reduced to zero. However, because of the rapid decay of Van der Waals forces with distance, the edge-to-face bond would not be strong.

To summarize once again, leaching can cause a reduction in the edge-to-face bond strength, from a strong, high-charge electrostatic bond to a weak, Van der Waals bond, coupled with a large increase in the repulsive energy. This perhaps explains the small reduction in the undisturbed shear strength of Norwegian post-glacial marine clays which has been observed (Bjerrum, 1954).

When the soil is remolded, the Van der Waals bonds are snapped, the edge-to-face particle arrangement is destroyed and the particles are physically separated so that a net repulsive energy exists between them. The situation is likely analogous to Figure A.7b. The counter-ion atmosphere of the face is so diffuse that it probably once again masks the edge and individual particles behave as negatively charged colloids.

There is also the possibility, as noted above, that the edge itself has become negative. In this state, the remolded clay would be

expected to have an even lower shear strength. Indeed, studies have shown (Crawford, 1963, 1968) that the remolded shear strength of some of these clays does approach zero.

It has been observed that weathering reduces the sensitivity of these clays (Moum, Løken and Torrance, 1971). Weathering of the clay minerals releases a number of ions into the bulk solution. This has the effect of increasing the counter-ion concentration and valence, and the ion atmospheres will again contract. It also has the effect of once again providing potential-determining ions for the edges. The role of Al^{+3} cannot be overlooked as a factor determining the charge.

In other words, weathering can reverse to some degree the effect of leaching. The repulsive energy is reduced and the possibility of an edge-to-face electrostatic bond must again be considered. Therefore, the process of chemical weathering principally serves to increase the remolded shear strength and reduce the sensitivity.

APPENDIX B

SUMMARY OF RELEVANT THEORY AND CALCULATIONS PERTAINING TO THE MEASUREMENT OF THE SHEAR MODULUS OF A SOIL BY MEANS OF A CIRCULAR VANE

B.1 Theoretical Basis for Apparatus and Experiment of Chapter 5

B.1.1 Underlying Assumptions

In conventional geotechnical studies, the shear vane has been used to measure the undrained shear strength of saturated cohesive soils. Selvadurai (1979) has presented an analysis which suggests that shear vanes of appropriate shape may also be used to measure the deformability characteristics of cohesive soils. In order to derive useful and realistic relationships between the various parameters it was necessary to make the following assumptions:

- (a) A cohesive soil can be represented as a linearly deformable isotropic homogeneous medium.
- (b) The effects of soil disturbance during introduction of the vane into the soil can be ignored.
- (c) Certain rectilinear vane shapes now in common use can be approximated by circular or elliptical shapes.
- (d) The soil contained within the volume described by the rotation of vane blades about their axis remains undeformed during the initial application of torque and a continuity of displacements exists across the interface between this soil and the surrounding medium.

- (e) The size of the vane is small in comparison to the medium into which it is introduced.

B.1.2 Resulting Equations

By employing the above assumptions, Selvadurai (1979) has been able to establish torque/twist relationships for vanes with circular and elliptical (both prolate and oblate) blade shapes from which the linear elastic shear modulus may be calculated, given the proper experimental conditions.

In the experiment described in Chapter 5, a circular vane was employed. The applicable relationships developed by Selvadurai are as follows:

- (a) for complete penetration of a circular vane:

$$\tau = 8\pi a^3 G\omega \quad \dots\dots\dots (B.1)$$

where: -

- τ is the torque.
- a is the radius of the vane.
- G is the linear elastic shear modulus.
- ω is the rotation (twist).

- (b) for half penetration of a circular vane:

$$\tau = 4\pi a^3 G\omega \quad \dots\dots\dots (B.2)$$

If the experiment is carried to failure of the soil, the undrained shear strength of the soil may be calculated from the following relationships:

(a) for full penetration of a circular vane:

$$\tau_y = \pi^2 a^3 c_u \dots\dots\dots (B.3)$$

where:

τ_y is the ultimate torque.

c_u is the undrained shear strength.

(b) for half penetration of a circular vane:

$$\tau_y = \frac{\pi^2 a^3 c_u}{2} \dots\dots\dots (B.4)$$

B.2 Computational Relationships Pertaining to the Apparatus
Described in Chapter 5

B.2.1 Angular Relationships Existing in the Telescope/Mirror System

If the line of sight of the telescope intersects the axis about which the mirror is rotating, the angle subtended by the circle through the focal point of the telescope will be twice the angle through which the mirror has rotated as shown in Figure B.1.

That is;

$$\phi = 2\theta \quad \dots\dots\dots (B.5)$$

In the torque/twist apparatus as it has been built it is not possible to have the line of sight of the telescope pass through the axis of rotation (the shaft) because the mirror sits like a flag on the shaft. This introduces a slight error in the relationship described above. The angular relationships are shown in Figure B.2. All distances and angles have been distorted for the purpose of illustration.

The applicable relationship in this case is:

$$2\theta = \phi + \alpha \quad \dots\dots\dots (B.6)$$

where: $\sin \alpha = \frac{2d \cdot \sin^2 \theta}{r} \quad \dots\dots\dots (B.7)$

This introduces a small error which can be shown to be much less than 1 per cent in virtually all cases. For this reason, the error has been ignored and the relationship of Equation B.5 has been used in calculating results.

Figure B.1: When the line of sight of the telescope intersects the axis about which the mirror rotates, $\phi = 2\theta$.

Figure B.2: When the line of sight of the telescope does not intersect the axis about which the mirror rotates, $\phi = (2\theta - \alpha)$.

B.2.2 Considerations Pertaining to the Load Added by Means of the Floating Weight

B.2.2.1 Correction for Movement of the Water Bath

When the water bath is raised or lowered, the floating weight enters or withdraws from the bath causing a change in the water level of the bath. By recognizing that the volume of water in the bath does not change, it is possible to show that if the water bath is moved a distance, k , the water level will move a distance, y , equal to:

$$y = \frac{kA}{A - a} \dots\dots\dots (B.8)$$

where: A is the cross-sectional area of the water bath.
 a is the cross-sectional area of the floating weight.

and the floating weight will experience a weight change:

$$\Delta w = \frac{kAa}{A - a} \cdot g \dots\dots\dots (B.9)$$

where: g is the acceleration of gravity and the density of water has been assumed equal to 1 gram/cm.³

The validity of this relationship has been verified by observation and the correction indirectly incorporated into calculations by means of calibration.

B.2.2.2 Initial Load When the Weight is Floating Vertically in the Bath

When using the apparatus, the shaft and mirror are first locked in place and the water bath is lowered until the floating weight is just vertical. This is taken as the zero position.

If allowed to float freely, the weight would not float in a vertical position by itself. When it is vertical, a certain weight is being borne by the connecting cable. Hence, the initial or zero point does not represent a zero load.

An analysis was done of the forces acting upon the weight used in this experiment and it was concluded that at the zero point, the connecting cable carries a load equal to:

$$F = (3.25)g \quad (\text{dynes}) \dots\dots\dots (B.10)$$

where: g is the acceleration of gravity.

The value of F was verified by experiment and the correction was incorporated into all calculations.

B.2.2.3 Correction for Surface Tension

The force applied to the floating weight as a result of surface tension is:

$$S = 2\pi r \gamma \cos\theta \quad \dots\dots\dots (B.11)$$

where: r is the radius of the floating weight.
 γ is the surface tension of water against air.
 θ is the contact angle.

The contact angle, θ , between plexiglass and water was determined experimentally and found to be on the order of 67.5° . Substitution of this value in Equation B.11 yields a value of S :

$$S = (0.14)g \quad \text{dynes} \quad \dots\dots\dots (B.12)$$

where: g is the acceleration of gravity.

This force is significant in the lower range of loading and has been included as a correction where appropriate.

B.2.2.4 Error in Weight Applied Resulting from Rotation of Shaft

As the soil deforms, the shaft twists and the cable unwinds from the pulley on the shaft, lowering the floating weight into the bath. This results in a slight reduction in the actual weight applied to the end of the connecting cable.

An analysis of this effect was undertaken using the most extreme assumptions and it was concluded that the resulting change in weight was much less than that applied by one turn of the driving screw on the water bath. As a consequence, this error was ignored in all calculations.

B.2.2.5 Error Due to Bubbles Attached to Weight

Under certain circumstances, the lift provided by air bubbles attached to the fully immersed floating weight might be a significant fraction of the smallest loads applied and would therefore constitute an error which could not be ignored. The exact magnitude of this lift would vary considerably with the situation and would not be easy to determine.

It is a problem which is best avoided if possible. This was accomplished by keeping the water bath and floating weight clean and by using deionized water which had sat for a long period of time at room temperature. With these precautions, few if any bubbles were observed to form.

B.2.3 Miscellaneous Errors

B.2.3.1 Error Due to Twist in Vane Shaft

The twist in the steel shaft between the vane and the mirror was calculated using fairly conservative values. It was concluded that the

twist in the shaft would at all times in this experiment be smaller than the minimum detectable angle. The error was therefore ignored.

B.2.3.2 Error Due to Friction in Shaft and Pulley Bearings

One of the design objectives for this apparatus was to minimize frictional losses in the torque transmission system. An unsuccessful attempt was made to measure the actual frictional losses in the completed instrument.

However, these losses must be insignificant because the instrument responded sensitively to very small changes in applied load. This was most evident when measuring the elastic rebound of remolded soils.

B.3 Determination of Deformability and Strength Characteristics from Experimental Data

B.3.1 Evaluation of the Modulus of Elasticity

An estimate of the undrained modulus of elasticity which will allow a reasonably accurate prediction of the initial distortion settlement of the soil beneath a structure may be obtained by a cyclic loading and unloading of the soil. The test may be undertaken in situ by means of field loading (for example, Selvadurai et al., 1980) or performed in the laboratory on samples taken from the site (Perloff, 1975).

During the cyclic loading and unloading, the maximum stress experienced by the soil should not approach its shear strength. Selvadurai et al. (1980) used a limiting stress equal to one third of the shear strength. Perloff (1975) recommends that maximum loading of the soil approximate the field loading anticipated beneath the proposed structure. The stress-strain information is plotted and the modulus of elasticity is estimated from the slope of either the secant or initial tangent to the reloading curve as illustrated in Figure B.3.

A similar approach may be used to estimate the undrained shear modulus from the relationship between the applied torque and the resulting twist or rotation. In the present experiment, the slope of the initial tangent to the reload curve was determined and substituted into Equation B.2 to obtain an estimate of the shear modulus.

The elastic parameters, E (modulus of elasticity), G (shear modulus) and ν (Poisson's ratio) are related as follows:

$$E = G(2(1 + \nu)) \dots\dots\dots (B.13)$$

Figure B.3: Estimation of the modulus of elasticity from either the secant or initial tangent to the reloading curve.

(reproduced from Selvadurai et al., 1980)

During an undrained test, saturated soils may be considered incompressible and a value of 0.5 for Poisson's ratio is appropriate. This allows the calculation of a modulus of elasticity which can then be used to predict the initial settlement beneath a proposed structure. It is also more useful for comparison purposes because the body of literature on the subject refers almost exclusively to the modulus of elasticity.

B.3.2. Determination of the Shear Strength

After completion of the cyclic loading and unloading, the soil was loaded to failure. The value of the applied torque at failure was substituted into Equation B.4 to obtain the shear strength of the soil.

APPENDIX C

A COMPENDIUM OF INFORMATION PERTAINING TO THE MEASUREMENT OF THE LOW-FREQUENCY ELECTRICAL PROPERTIES OF A SOIL BY MEANS OF AN INDUCED POLARIZATION TECHNIQUE

C.1 Introduction

C.1.1 Electrical Phenomena Associated With a Clay-Water-Electrolyte System

As discussed in Appendix "A", the particles comprising the clay fraction of soils acquire an electrical charge and a compensating cloud of counter-ions. The counter-ions are of two types: those which are more or less firmly bound to the soil particle and comprise what is known as the Stern layer; and those which form the diffuse cloud of ions adjacent to the particle.

That the cloud of diffuse ions is free to move with respect to the particle is evidenced by the phenomenon of electrokinesis. This phenomenon is manifested in four different ways:

- (a) Electro-osmosis
- (b) Streaming Potential
- (c) Electrophoresis
- (d) Sedimentation Potential

These are well described and illustrated by Mitchell (1976).

The electrical potential with respect to the bulk solution at the plane of slippage between the mobile diffuse ion cloud and the immobile attached ions is known as the electrokinetic or zeta potential.

C.1.2 The Electrokinetic Potential of Leda Clay

C.1.2.1 Previous Study

Penner (1965) has reported the results of a study in which the electrokinetic potential of Leda Clay was measured using electro-osmosis. He used an ingenious but delicate instrument to measure the osmotic flow and applied the Smoluchowski-Helmholtz equation to calculate the electrokinetic potential.

$$E_k = \frac{4\pi n v \lambda}{\epsilon i} P \dots\dots\dots (C.1)$$

where: E_k is the electrokinetic potential.
 n is the viscosity of the diffuse layer.
 ϵ is the dielectric constant of the diffuse layer.
 v is the osmotic flow.
 i is the current.
 λ_p is the specific conductivity of the pore fluid.

Penner had reasoned on the basis of double-layer theory that as the diffuse layer expanded and the zeta potential increased, the inter-particle repulsion would also increase. This would lead to a reduction in remolded shear strength and a consequent increase in the sensitivity of a soil. Indeed, his experiment did confirm, on the basis of a number of natural samples of Leda Clay, that the expected relationship between the sensitivity and the electrokinetic potential did exist. There were only two exceptions and these soils were notable for their low specific surface area in comparison to the other soils tested.

C.1.2.2 Present Study

Penner's equipment is very delicate and requires a great deal of care in its use if accurate results are to be obtained. The author wanted to devise a simple test for measuring the electrokinetic potential of soils, one which employed more robust equipment and a simpler procedure and which, once established, could be used on a routine basis.

The larger experiment within which this smaller study would be undertaken provided the opportunity to make electrical measurements on a suite of controlled samples.

After considering the possibilities, it was decided that perhaps induced polarization could be used for this purpose. Upon investigating the literature available on the subject, it was discovered that work had already been done on the induced-polarization response of clays. Some of the results of these studies will be noted below.

C.2 The Phenomenon of Induced Polarization or Overvoltage

C.2.1 The Observed IP Effect

C.2.1.1 Transient Decay Voltage

If a current is made to flow through the ground from one electrode to another by establishing a potential difference between the electrodes, the voltage difference between two independent electrodes in the electric field will reach some steady-state value. It has been noted that under certain circumstances, upon interruption of the current, the voltage difference registered by the independent potential electrodes does not drop immediately to zero. Instead, it drops rapidly to some finite value and subsequently decays logarithmically (Sumner, 1976) with time. This is shown in Figure C.1. Ward and Fraser (1967) suggest that the decay curve is best approximated by the sum of a series of exponentials.

Similarly, upon introduction of the current, the voltage does not rise immediately to the steady-state value, but a certain time elapses during which the ground is "charged". The charging and discharging curves are shown in Figure C.2. This response is said to be in the "time domain".

C.2.1.2 Frequency Dependence

Another way in which the IP response can be manifested involves a frequency dependence or dispersion. If the current is introduced into the ground at several different frequencies by means of two current electrodes, the voltage difference registered by the potential electrodes will vary according to the frequency. This is illustrated in Figure C.3 and measurements made on this basis are said to be in the "frequency domain".

Figure C.1: Voltage decay with time upon interruption of current.

Figure C.2: A charging curve followed by a discharge or decay curve.

Although the amplitude of the current is the same in both cases, the ground impedance (or conversely, conductivity) as manifested by the voltage difference between the potential electrodes, is different in each case. There is a frequency dependence or dispersion because the polarization or charging of the ground takes time.

C.2.1.3 Equivalence of Time and Frequency Responses

In earlier sections, it was noted that an IP response could be obtained in either the time domain or frequency domain. The two responses are fundamentally equivalent (Sumner, 1976; Ward and Fraser, 1967). This equivalence rests upon the fact that the IP response is linear. The linearity is exhibited in a number of different ways:

- (a) The frequency of the output is equal to the frequency of the input.
- (b) The input (current) and output (measured potential) are proportional.
- (c) The specific impedance is independent of either the applied voltage or current.
- (d) The charging and decay curves have identical forms, the one being a mirror image of the other.

Because the response is linear, measurements made in one domain can be expressed in the other domain by either a Fourier or Laplace transform.

A conceptual understanding of the equivalence may be obtained by consideration of Figures C.3 and C.4. The charging takes time, so higher frequencies do not fully charge the soil. However, if the differences in voltage amplitude in Figure C.3 are ignored and the charging portions of the various curves superimposed, the resulting

Figure C.3: IP frequency-method waveforms, showing a controlled, constant inducing current, I , at frequencies f_1 and f_2 being detected as two different voltages, where the smaller voltage results from the higher frequency.

(from Sumner, 1976, Figure 1.2)

Figure C.4: An IP charge and decay curve, using a long-period square wave.

The logarithmic decay curve displays decay voltages at geometrically spaced times, t_1 , t_2 and t_3 . The charge curve is the inverse of the voltage decay with geometrically spaced frequencies, f_1 , f_2 and f_3 .

(modified from Sumner, 1976, Figure 1.4)

frequency response envelope shown in Figure C.4 is equivalent to the charging portion of the time-domain curve. In addition, because of the fundamental relationship between frequency and time:

$$f \propto \frac{1}{t}$$

the voltage difference between two frequencies is equal to the decay voltage between the corresponding times as shown in Figure C.4.

C.2.2 The Causes of IP or Overvoltage

C.2.2.1 Electrode Polarization

A metal electrode in contact with an electrolyte will acquire a surface charge and a compensating cloud of ions for reasons explained in Appendix "A". This gives the electrode an electrical potential with respect to the bulk electrolyte even when there is no current. If a current is made to flow into the electrode, an impedance is encountered due to the reduction or reversal of the normal potential gradient at the interface which results from the cloud of ions required to compensate the zero-current charge on the surface of the electrode.

Electrochemists have long recognized this phenomenon and refer to the added voltage required to drive a given current across the interface as an overvoltage (Marshall and Madden, 1959; Keller and Frishknecht, 1966; Ward and Fraser, 1967; Sumner, 1976).

A metallic mineral grain in contact with an electrolyte will behave like an electrode. If a current passes through the grain, there is an additional factor to be recognized. The transfer of charge will occur by oxidation and reduction reactions at opposite faces of the grain. These reactions will tend to proceed at different rates and the potential gradient must increase on the slow side so that current into

and out of the grain will be equal. The necessary added potential will be exhibited as an overvoltage (Keller and Frischknecht, 1966).

In addition to the two mechanisms above, another source of resistance to current flow is the various coatings found on metallic mineral grains in the natural environment (Keller and Frischknecht, 1966).

Because these processes are the result of surface effects and phenomena, the greater the surface area involved, the greater the magnitude of the measured overvoltage. For this reason, induced polarization has been used with most success as an exploration tool in the search for deposits of disseminated metallic minerals.

Within individual mineral grains, charge transfer is accomplished by electrons and is virtually instantaneous. However, the chemical reactions which transfer the charge across the surfaces require a measurable amount of time as does the return to equilibrium conditions after current flow ceases. The characteristic charging and decay curves have been described in a previous section.

C.2.2.2 Membrane Polarization and Ion Sieving

It has been widely recognized (Vacquier et al, 1957; Marshall and Madden, 1959; Mayper, 1959; Madden and Cantwell, 1967; and others) that the presence of clay minerals in rocks can result in an IP response.

The mechanism by which clays are thought to cause an IP response is termed "membrane polarization". The cationic clouds adjacent to the negative faces of the clay mineral particles act as semipermeable membranes by restricting the passage of anions but allowing free movement of cations. This is illustrated in Figure C.5.

Figure C.5: Depiction of ions in a pore space forming an ion concentration barrier which creates membrane polarization. (a) - Pore path before application of an electric potential. (b) - Pore path after application of a direct-current driving force.

(reproduced from Sumner, 1976, after Ward and Fraser, 1967)

A variation of this model postulates an actual physical sieving of hydrated ions at constrictions in the pores. (Keller and Frischknecht, 1966).

Both models require zones of free movement interspersed with the blockages. The ions then migrate to the blockage zones, giving the familiar charging curve as the ions pile up and the decay curve as they return to their equilibrium positions.

The membrane-polarization hypothesis consequently requires that there not be an excessive amount of clay present in the rock. Although observations (Vacquier et al, 1957; Marshall and Madden, 1959; Keller and Frischknecht, 1966) support this conclusion, it must be noted that research has concentrated on sands and sandstones in which the quartz grains were coated with clay minerals and clay slurries and shales in which the clay minerals probably had a pronounced parallel orientation. An open, flocculated clay structure would probably provide the necessary conditions for membrane polarization.

Membrane polarization diminishes as the salinity of the pore water increases because the size of the cation clouds is compressed (Ward and Fraser, 1967).

C.2.2.3 Electrokinetic Polarization

Although Marshall and Madden (1959) and Mayper (1959) reject electrokinesis as a possible cause of induced polarization, the conclusion is not based upon a rigorous analysis of direct evidence. It is also true that no direct evidence exists which suggests that a specific IP response has been due to electrokinesis (Keller and Frischknecht, 1966).

Keller and Frischknecht present a model in which an electro-osmotic flow is allowed to decay after removal of the driving potential. The still moving ions constitute a current which decays as the ions drift to a stop. The equation which results is:

$$\int_0^{\infty} \frac{E_o}{E_{ss}} dt = \frac{\rho_w a_o \epsilon \zeta K}{4 \phi \pi F \eta^2} \quad \text{..... (C.2)}$$

where: • the integral on the left is the area under the voltage decay curve, normalized to the steady-state voltage, E_{ss} .

ρ_w is the resistivity of water.

a_o is the concentration of ions adsorbed on the solid surface.

ϵ is the specific capacity of the liquid.

η is the viscosity of the liquid.

ζ is the zeta potential.

K is the coefficient of permeability.

F is the Faraday constant.

ϕ is the fractional pore volume.

They conclude that electrokinesis might result in a significant IP response under the following conditions:

- (a) high permeability;
- (b) high cation adsorption capacity;
- (c) high resistivity pore water which would also promote a high zeta potential.

C.2.2.4 Miscellaneous

Electrochemists recognize an overvoltage due to the back diffusion of ions. The "Warburg impedance" is the term applied to this phenomenon. However, the time constants due to the Warburg impedance are orders of magnitude too small to explain the observed IP effect (Parasnis, 1972).

It has also been suggested that the IP response is another manifestation of the dielectric effect. However, the dielectric effect is a microscopic phenomenon consisting of a charge separation at the molecular or atomic level as a result of an electric field. The IP effect, on the other hand, is a macroscopic phenomenon arising from electrochemical processes induced by an electric current. The voltage decay times for induced polarization are much longer than those due to the dielectric effect (Sumner, 1976).

APPENDIX D

SUMMARY OF ANALYTICAL BASIS FOR DIFFUSION EXPERIMENT

D.1 General Equations

D.1.1 Fick's Laws of Diffusion

Fick's first and second laws may be stated as follows
(Crank, 1975):

$$F = -D \frac{\partial c}{\partial x} \dots \dots \dots (D.1)$$

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} \dots \dots \dots (D.2)$$

where: F is the rate of transfer (flux) per unit area of section
(moles/sec./cm.²) or (g./sec./cm.²).

D is the diffusion coefficient (cm.²/sec.).

c is the concentration (moles/cm.³) or (g./cm.³).

t is time (sec.).

x is distance (cm.).

D.1.2 Heat Transfer Analogues

Diffusion and heat transfer are similar phenomena inasmuch as each is the result of random molecular motion. As a consequence, the two

processes may be described by similar equations (Crank, 1975).

Because the study of heat transfer is more advanced, the analytical treatment of diffusion will frequently refer to the equations and methods developed in the field of heat transfer.

The heat transfer equations corresponding to Fick's first and second laws are:

$$q'' = -k \frac{\partial T}{\partial x} \dots\dots\dots (D.3)$$

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \dots\dots\dots (D.4)$$

where:

q'' is the heat flux per unit area of section (cal./sec./cm.²).

α is the thermal diffusivity (cm.²/sec.).

k is the thermal conductivity (cal./°C/cm./sec.).

T is temperature (°C).

t is time (sec.).

x is distance (cm.).

$$\alpha = \frac{k}{\rho c} = \frac{k}{C}$$

where:

ρ is the density (g./cm.³).

c is the specific heat (cal./g./°C).

C is the volumetric heat capacity (cal./°C/cm.³)
and is equal to ρc .

D.1.3 Corresponding Parameters

Diffusion

Heat Transfer

c

T

D

k

D

 α

(Crank, 1975)

If D is to be equivalent to both k and α , then:

$$\rho c = 1$$

This is a consequence of identifying the concentration with the temperature. In heat transfer, it is heat which is "diffusing". The temperature is converted to the amount of heat per unit volume by the factor ρc .

In diffusion, the concentration is by definition the amount of diffusing substance per unit volume. Therefore no factor comparable to ρc is needed.

D.2 Specific Solutions

D.2.1 Transient Heat Conduction in a Plate of Infinite Extent

Given a plate of infinite extent and thickness $2L$ which is initially at a uniform temperature, T_i , throughout. At some time zero, the surfaces of the plate are suddenly lowered to temperature, T_o .

Define the temperature excess, θ :

$$\theta = T - T_o$$

$$\theta_i = T_i - T_o$$

Initial and boundary conditions:

$$\theta = \theta_i \quad \text{at} \quad t = 0; \quad 0 \leq x \leq 2L$$

$$\theta = 0 \quad \text{at} \quad t > 0; \quad x = 0$$

$$\theta = 0 \quad \text{at} \quad t > 0; \quad x = 2L$$

Solving (Gebhart, 1971):

$$\theta = \frac{-4\theta_i}{\pi} \sum_{n=1, 3, 5, \dots}^{\infty} \frac{e^{-\gamma^2 \alpha t}}{n} \sin(\gamma x) \quad \dots \dots \dots (D.5)$$

where: $\gamma = \frac{n\pi}{2L}$

$$q'' = \frac{-4k\theta_i}{2L} \sum_{n=1, 3, 5, \dots}^{\infty} e^{-\gamma^2 \alpha t} \cos(\gamma x) \quad \dots \dots \dots (D.6)$$

The midplane ($x = L$) temperature excess and surface ($x = 0$) heat flux may be obtained from the above equations.

D.2.2 Diffusion Analogue

By analogy with the above, define the concentration excess, C :

$$C = c - c_0$$

$$C_1 = c_1 - c_0$$

Midplane concentration excess:

$$C = \frac{4C_1}{\pi} \sum_{\substack{n=1, \\ 3, 5, \dots}}^{\infty} \frac{e^{-\gamma^2 Dt}}{n} \sin(\gamma L) \quad \dots\dots\dots (D.7)$$

where:

$$\gamma = \frac{n\pi}{2L}$$

Surface flux of diffusing substance:

$$F = \frac{-4DC_1}{2L} \sum_{\substack{n=1, \\ 3, 5, \dots}}^{\infty} e^{-\gamma^2 Dt} \quad \dots\dots\dots (D.8)$$

D.3 Practical Considerations

D.3.1 Limiting Assumptions

The following assumptions, although perhaps not in every case explicitly stated, have been invoked in the preceding analysis:

- (a) The diffusion is one-dimensional.
- (b) The diffusion medium is isotropic.
- (c) The diffusion coefficient is not a function of either the concentration or time.
- (d) Initially, there is a uniform distribution of diffusing substance throughout the soil.
- (e) The concentration adjacent to the two surfaces of the soil is lowered to the same value at the same time.

D.3.2 Factors Influencing the Diffusion Rate in Soils

Information regarding ion diffusion rates in soils is not precise (Mitchell, 1976). This is no doubt due to the inherent complexity of the problem. A partial list of those factors thought to have a bearing on diffusion rates in soils is:

- (a) ion size and valence;
- (b) ion mix (species present and their relative abundance);
- (c) ion-exchange reactions;
- (d) chemical reactions and phase changes;
- (e) the permeability of the soil;
- (f) the tortuosity of the diffusion pathways;
- (g) the bulk density of the soil.

D.3.3 Composite Diffusion Coefficient

To deal separately with the many factors influencing the diffusion rate in soils was beyond the scope of this experiment.

Instead, the approach adopted consisted of measuring the flux across the surfaces of the soil and using this information to calculate a diffusion coefficient. Under the circumstances, this would not be a diffusion coefficient in the purest sense of the term but rather some kind of composite diffusion coefficient which incorporated in an ill-defined way the influences of the various factors noted above.

REFERENCES

- Bentley, S.P. and Smalley, I.J., 1978a. Mineralogy of sensitive clays from Quebec. *Can. Mineralogist*, V.16, pp. 103-112.
- Bentley, S.P. and Smalley, I.J., 1978b. Inter-particle cementation in Canadian post-glacial clays and the problem of high sensitivity ($S_t > 50$). *Sedimentology*, V.25, pp. 297-302.
- Bjerrum, L., 1954. Geotechnical properties of Norwegian marine clays. *Géotechnique*, V.4, No. 2, pp. 49-69.
- Bjerrum, L., 1955. Stability of natural slopes in quick clay. *Géotechnique*, V.5, No. 1, pp. 101-119.
- Bolt, G.H., 1955. Analysis of the validity of the Gouy-Chapman theory of the electric double layer. *Jour. Colloid Sci.*, V. 10, No. 2, pp. 206-218.
- Bowles, J.E., 1970. Engineering properties of soils and their measurement. New York, McGraw-Hill Book Co., 187 p.
- Bozozuk, M., 1963. The modulus of elasticity of Leda Clay from field measurements. *Can. Geot. Jour.*, V.1, No. 1, pp. 43-51.
- Brydon, J.E., and Patry, L.M., 1961. Mineralogy of Champlain Sea sediments and a Rideau Clay soil profile. *Can. Jour. Soil Sci.*, V.41, pp. 169-181.
- Bungenberg de Jong, H.G., 1949. Reversal of charge phenomena, equivalent weight and specific properties of the ionized groups. In: H.R. Kruyt (editor), *Colloid science, volume II, reversible systems*. Amsterdam, Elsevier Publishing Co., Inc. (753 p.), pp. 259-334.
- Cabrera, J.G., and Smalley, I.J., 1973. Quick clays as products of glacial action: a new approach to their nature, geology, distribution and geotechnical properties. *Eng. Geol.*, V.7, pp. 115-133.

Carson, M.A., 1977. On the retrogression of landslides in sensitive muddy sediments. *Can. Geot. Jour.*, V.14, No. 4, pp. 582-602.

Chapman, H.D., 1965. Cation-exchange capacity. In: C.A. Black et al. (editors), *Methods of soil analysis*. Madison, Wisconsin, American Society of Agronomy, Inc. (1572 p.), Chapter 57, pp. 891-901.

Crank, J., 1975. *The mathematics of diffusion*, 2nd ed. Oxford, Clarendon Press, 414 p.

Crawford, C.B., 1963. Cohesion in an undisturbed sensitive clay. *Géotechnique*, V.13, No. 2, pp. 132-146.

Crawford, C.B., 1968. Quick clays of eastern Canada. *Eng. Geol.*, V.2, No. 4, pp. 239-265.

Eden, W.J., 1959. Use of a one-point liquid limit procedure. *A.S.T.M. Spec. Tech. Publ.* No. 254, pp. 168-177.

Eden, W.J., 1978. On the retrogression of landslides in sensitive muddy sediments: a discussion. *Can. Geot. Jour.*, V.15, No. 3, pp. 451-453.

Eden, W.J., Fletcher, W.B. and Mitchell, R.J., 1971. South Nation River landslide, 16 May 1971. *Can. Geot. Jour.*, V.8, No. 3, pp. 446-451.

Eden, W.J. and Mitchell, R.J., 1973. Landslides in sensitive marine clay of eastern Canada. *Highway Research Record* No. 463, pp. 18-27.

Fahnestock, R.K., 1963. Morphology and hydrology of a glacial stream - White River, Mount Rainier, Washington. *U.S.G.S. Prof. Paper* No. 422A, 70 p.

Gadd, N.R., 1975. Geology of Leda Clay. In: E. Yatsu, A.J. Ward and F. Adams (editors), *Mass wasting - 4th Guelph symposium on geomorphology*. Guelph, Canada, Univ. of Guelph Dept. of Geog. (202 p.), pp. 137-151.

Gebhart, B., 1971. *Heat transfer*, 2nd ed. New York, McGraw-Hill Book Co., 596 p.

- Gillott, J.E., 1968. Clay in engineering geology. Amsterdam, Elsevier Publishing Co., Inc., 296 p.
- Gillott, J.E., 1969. Study of the fabric of fine-grained sediments with the scanning electron microscope. Jour. Sedimentary Petrology, V.39, No. 1, pp. 90-105.
- Gillott, J.E., 1970. Fabric of Leda Clay investigated by optical, electron-optical, and X-ray diffraction methods. Eng. Geol., V.4, No. 2, pp. 133-153.
- Gillott, J.E., 1971. Mineralogy of Leda Clay. Can. Mineralogist, V.10, No. 5, pp. 797-811.
- Glasstone, S. and Lewis, D., 1960. Elements of physical chemistry. Princeton, N.J., D. Van Nostrand Co., Inc., 758 p.
- Hansbo, S., 1957. A new approach to the determination of the shear strength of clay by the fall-cone test. Royal Swedish Geotechnical Institute Proceedings No. 14, 47 p.
- Iler, R.K., 1973. Colloidal silica. In: E. Matijević (editor), Surface and colloid science, volume 6. New York, Wiley-Interscience, pp. 1-100.
- Keller, G.V. and Frischknecht, F.C., 1966. Electrical methods in geophysical prospecting. Oxford, Pergamon Press, 519 p.
- Kravitz, J.H., 1970. Repeatability of three instruments used to determine the undrained shear strength of extremely weak, saturated, cohesive sediments. Jour. Sedimentary Petrology, V.40, No. 3, pp. 1026-1037.
- Kruyt, H.R., 1952. Colloid science, volume I, irreversible systems. Amsterdam, Elsevier Publishing Co., Inc. (389 p.), pp. 1-57.
- Lambe, T.W., 1958. The structure of compacted clay. Proc. A.S.C.E., Jour. Soil Mech. and Found. Div., V.84, No. SM2, Paper 1654, 34 p.

LaRochelle, P., Chagnon, J.-Y. and Lefebvre, G., 1970. Regional geology and landslides in the marine clay deposits of eastern Canada. *Can. Geot. Jour.*, V.7, No. 2, pp. 145-156.

Lindsay, W.L. and Vlek, P.L.G., 1977. Phosphate minerals. In: R.C. Dinaver, J. Nagler and J.H. Nauseef (editors), *Minerals in soil environments*. Madison, Wisconsin, Soil Science Society of America (948 p.), pp. 639-672.

Madden, T.R. and Cantwell, T., 1967. Induced polarization, a review. In: *Society of Exploration Geophysicists, Mining geophysics, volume II, theory*. Tulsa, Okla., Society of Exploration Geophysicists (708 p.), pp. 373-400.

Marshall, D.J. and Madden, T.R., 1959. Induced polarization, a study of its causes. *Geophysics*, V.24, No. 4, pp. 790-816.

Mayper, V., Jr., 1959. The normal effect - part I, part II. In: J.R. Wait (editor), *Overvoltage research and geophysical applications*. New York, Pergamon Press (158 p.), pp. 125-157.

McAllister, R.F. and Corcoran, E.F., 1969. Chemical oceanography. In: J.J. Myers, C.H. Holm and R.F. McAllister (editors), *Handbook of ocean and underwater engineering*. New York, McGraw-Hill Inc. (1094 p.), pp. 1-16 to 1-23.

Mitchell, J.K., 1976. *Fundamentals of soil behavior*. New York, John Wiley and Sons, Inc., 422 p.

Morris, J.C. and Stumm, W., 1967. Redox equilibria and measurements of potentials in the aquatic environment. In: *Equilibrium concepts in natural water systems - a symposium sponsored by the American Chemical Society*: W. Stumm, symposium chairman; *Advances in Chemistry Series 67*, R.F. Gould, ed. Washington, American Chemical Society (344 p.), pp. 270-285.

Moum, J., 1965. Falling drop used for grain-size analysis of fine-grained materials. *Sedimentology*, V.5, pp. 343-347.

Moum, J., Løken, T. and Torrance, J.K., 1971. A geochemical investigation of a normally consolidated clay from Drammen, Norway. *Géotechnique*, V.21, No. 4, pp. 329-340.

Mysels, K.J., 1959. Introduction to colloid chemistry. New York, Interscience Publishers, Inc., 475 p.

Overbeek, J. Th.G., 1952a. Phenomenology of lyophobic systems. In: H.R. Kruyt (editor), Colloid science, volume I, irreversible systems. Amsterdam, Elsevier Publishing Co., Inc. (389 p.), pp. 58-89.

Overbeek, J. Th.G., 1952b. Electrochemistry of the double layer. In: H.R. Kruyt (editor), Colloid science, volume I, irreversible systems. Amsterdam, Elsevier Publishing Co., Inc. (389 p.), pp. 115-193.

Overbeek, J. Th.G., 1952c. Stability of hydrophobic colloids and emulsions. In: H.R. Kruyt (editor), Colloid science, volume I, irreversible systems. Amsterdam, Elsevier Publishing Co., Inc. (389 p.) pp. 302-341.

Parasnis, D.S., 1972. Principles of applied geophysics, 2nd ed, London, Chapman and Hall Ltd., 214 p.

Penner, E., 1965. A study of sensitivity in Leda Clay. Can. Jour. Earth Sci., V.2, No. 5, pp. 425-441.

Perloff, W.H., 1975. Pressure distribution and settlement. In: H.F. Winterkorn and H.-Y. Fang (editors), Foundation engineering handbook. New York, Van Nostrand Reinhold Co., (751 p.), pp. 148-196.

Quagliano, J.V., 1958. Chemistry. Englewood Cliffs, N.J., Prentice-Hall, Inc., 854 p.

Quigley, R.M., 1980. Geology, mineralogy, and geochemistry of Canadian soft soils: a geotechnical perspective. Can. Geot. Jour., V.17, No. 2, pp. 261-285.

Schofield, R.K. and Samson, H.R., 1953. The deflocculation of kaolinite suspensions and the accompanying change-over from positive to negative chloride adsorption. Clay Minerals Bull., V.2, No. 9, pp. 45-50.

- Seekings, D.R., 1974. A geochemical-geotechnical analysis of a borehole from the site of the South Nation River landslide. M.A. Thesis, Geography Department, Carleton University, Ottawa.
- Selvadurai, A.P.S., 1979. On the estimation of the deformability characteristics of an isotropic elastic soil medium by means of a vane test. *Inter. Jour. for Numer. and Anal. Methods in Geomechanics*, V.3, pp. 231-243.
- Selvadurai, A.P.S., Bauer, G.E. and Nicholas, T.J., 1980. Screw plate testing of a soft clay. *Can. Geot. Jour.*, V.17, No. 4, pp. 465-472.
- Shaw, D.J., 1966. *Introduction to colloid and surface chemistry*. London, Butterworths, 186 p.
- Smalley, I.J., 1971. Nature of quick clays. *Nature*, V.231, p. 310.
- Soderman, L.G. and Quigley, R.M., 1965. Geotechnical properties of three Ontario clays. *Can. Geot. Jour.*, V.2, No. 2, pp. 167-189.
- Sonntag, H. and Streng, K., 1970. *Koagulation and Stabilität disperser Systeme (Coagulation and stability of disperse systems)*. Translated from the German by R. Kondor. New York, Halstead Press, 1972, 139 p.
- Stumm, W. and Morgan, J.J., 1970. *Aquatic chemistry - an introduction emphasizing chemical equilibria in natural waters*. New York, Wiley-Interscience, 583 p.
- Sumner, J.S., 1976. *Principles of induced polarization for geophysical exploration*. Amsterdam, Elsevier Scientific Publishing Co., 277 p.
- Tavenas, F., Chagnon, J.-Y. and LaRochelle, P., 1971. The Saint-Jean-Vianney landslide: observations and eyewitness accounts. *Can. Geot. Jour.*, V.8, No. 3, pp. 463-478.
- Torrance, J.K., 1975a. Leaching, weathering and origin of Leda Clay in the Ottawa area. In: E. Yatsu, A.J. Ward and F. Adams (editors), *Mass wasting - 4th Guelph symposium on geomorphology*. Guelph, Canada, Univ. of Guelph Dept. of Geog. (202 p.), pp. 105-116.

Torrance, J.K., 1975b. On the role of chemistry in the development and behavior of the sensitive marine clays of Canada and Scandanavia. *Can. Geot. Jour.*, V.12, No. 3, pp. 326-335.

Torrance, J.K., 1979. Post-depositional changes in the pore-water chemistry of the sensitive marine clays of the Ottawa area, eastern Canada. *Eng. Geol.*, V.14, pp. 135-147.

Torrance, J.K., 1983. Towards a general model of quick clay development. *Sedimentology*, (In Press).

Vacquier, V., Holmes, C.R., Kintzinger, P.R. and Lavergne, M., 1957. Prospecting for ground water by induced electrical polarization. *Geophysics*, V.22, No. 3, pp. 660-687.

van Olphen, H., 1963. An introduction to clay colloid chemistry. New York, Interscience Publishers, 301 p.

Ward, S.H. and Fraser, D.C., 1967. Conduction of electricity in rocks. In: *Society of Exploration Geophysicists, Mining geophysics, volume II, theory*. Tulsa, Okla., Society of Exploration Geophysicists (708 p.), pp. 197-223.

Yong, R.N., Sethi, A.J. and LaRoche, P., 1979. Significance of amorphous material relative to sensitivity in some Champlain clays. *Can. Geot. Jour.*, V.16, No. 3, pp. 511-520.

END

105H09H84

FIN