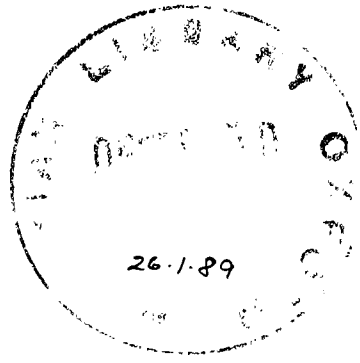
Compression Behaviour and Shear Strength Characteristics of a Natural Silty Clay Sedimented in the Laboratory

by
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A thesis submitted to the University of Oxford for the degree of Doctor of Philosophy. Trinity Term, 1988.

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ABSTRACT

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**Compression Behaviour and
Shear Strength Characteristics
of a
Natural Silty Clay
Sedimented in the Laboratory**

The compression behaviour, shear strength characteristics, and material properties of dense slurries and soft settled beds of natural fine-grained sediments were studied experimentally. Slurries of varying initial density, initial height, and pore fluid salinity were settled one-dimensionally, by self-weight, in the laboratory. Settling behaviour was studied in terms of slurry appearance, particle segregation, height of surface versus time, sediment surface and element settlement rates, and the redistribution of sediment with respect to height and time. Consolidation behaviour was studied in terms of sediment compressibility and pore fluid flow. Shear strength was examined 'in situ' and related to the parameters effective stress and specific volume.

Instruments and techniques were developed to facilitate the measurement of low effective stresses, low strengths, and high specific volumes. A small-scale sediment sampler was developed and used in an attempt to study the arrangement of particles within soft sensitive beds.

The experimental results revealed numerous fundamental reasons why theoretical models of settling and consolidation are unsatisfactory when applied to dense flocculated slurries and beds of high specific volume, respectively. For the sediment studied, well-defined compressibility and shear strength relationships were observed. Pore fluid flow relationships were non-unique at high specific volumes.

The compression behaviour of slurries was found to have a rational basis in terms of electrochemical forces and degrees of particle association. The experimental results are relevant to engineering practice. Recommendations are made regarding future research.

DEDICATION

To my loving and dearly loved parents

And to the family

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TABLE OF CONTENTS

		Page
Title Page		
Abstract		i
Acknowledgements and Dedication		ii
Table of Contents		iii
List of Figures and Tables		v
List of Symbols		viii
Chapter		
1	INTRODUCTION	1
2	SOFT SOIL RESEARCH	
2.0	Introduction	4
2.1	Applications of Soft Soil Research	5
2.2	Soft Soil Behaviour	9
2.2.1	Introduction	9
2.2.2	The Compression Process	10
2.2.3	Microscopic Forces, Behaviour, Macroscopic Parameters, and Models	12
2.3	Factors Influencing Compression, Strength, and Fabric	17
2.3.1	General Review	17
2.3.2	Literature Review	20
2.3.3	Review of Predecessors' Research	29
2.3.4	Summary and Hypothesis	36
2.4	Research Objectives	39
3	EXPERIMENTAL PROGRAMME	
3.0	Introduction - Experiment Purposes and Conditions	41
3.1	Overview of Procedures	43
3.2	Slurry Preparation	46
3.3	Details of Equipment and Data Gathered	49
3.3.1	General Setup	49
3.3.2	CPU - Pore Pressure Measurement	51
3.3.3	X-ray Apparatus - Density Measurements	54
3.3.4	Shear Vane Apparatus - Strength Measurements	60
3.3.5	Fabric Sampling Equipment	68
3.3.6	Particle Size Sampling	70

4 COMPRESSION BEHAVIOUR: SETTLING RESULTS Page

4.0 Introduction 74
4.1 Slurry Appearance During Compression 76
4.2 Particle Size Analysis 81
4.3 Height of Surface versus Time 95
4.3.1 Introduction 95
4.3.2 Results of Experiments RB01-09 96
4.3.3 Results of Experiments RB10-22 107
4.4 Surface Settlement Rate versus Average Specific Volume 110
4.5 Distribution of Mass - Density Profiles 127
4.6 Element Settlement Rate 138
4.7 Summary of Methods of Characterization 141

5 COMPRESSION BEHAVIOUR: CONSOLIDATION RESULTS

5.0 Introduction 145
5.1 Effective Stress versus Specific Volume 145
5.2 Pore Fluid Flow 160

6 FABRIC STUDY

6.0 Introduction 173
6.1 Examination of Fabric 174
6.2 Preparation of Sediment for Examination 177
6.3 Analysis, Conclusions, and Recommendations 182

7 SHEAR STRENGTH RESULTS

7.0 Introduction 188
7.1 Undrained Shear Strength versus Effective Stress 188
7.2 Soil Sensitivity 196
7.3 Peak Shear Strength versus Specific Volume 201
7.4 Discussion 207

8 SUMMARY, INTERPRETATION, CONCLUSIONS, AND RECOMMENDATIONS

8.0 Introduction 211
8.1 Summary and Interpretation of Results From RB Experiments 212
8.2 Conceptual Models of Slurry Compression 228
8.3 The Present Research and Engineering Practice 240
8.4 Application of RB Experiment Results to Engineering Practice 244
8.5 Contribution of the Present Research 245
8.6 Recommendations for Future Research 247

Terminology 251
References 252

LIST OF FIGURES

Chapter 3

		Page
3.1	General Experimental Setup	50
3.2	Detail of Column Port	51
3.3	View of Extended Central Pressure Unit (CPU)	52
3.4	Central Pressure Unit (CPU) in Use	53
3.5	Supporting Electronic Hardware for CPU	53
3.6	Example Pore Pressure Results	59
3.7	Example Density Profiles	59
3.8	Example Total Stress Results	59
3.9	Modified Shear Vane Apparatus: Assembled - I	61
3.10	Shear Vane, Casing, Universal Joint, and Guide	62
3.11	Modified Shear Vane Apparatus: Assembled - II	62
3.12	Example Shear Vane Test Results	64
3.13	Example Shear Strength Profiles	64
3.14	Shear Vane Calibration Apparatus	66
3.15	Components of Fabric Sampling Apparatus	69
3.16	Fabric Sampling Apparatus: Assembled	70
3.17	Extrusion of Samples for Particle Size Analysis	71

Chapter 4

4.1	Average Particle Size Distribution for Combwich Sediment	85
4.2	Particle Size Distributions - Example of Segregation	86
4.3	Particle Size Analysis Results	89
4.4	Particle Size Analysis Results	92
4.5	Example Height of Surface versus Time Results	96
4.6	Height of Surface vs. Time - Influence of Initial Slurry Height	97
4.7	Height of Surface vs. Time - RB04a-c	99
4.8	Height of Surface vs. Time - RB05a-c	99
4.9	Height of Surface vs. Time - RB07a-c and RB09	100
4.10	Height of Surface vs. Time - RB08a-c	100
4.11	Height of Surface vs. Time - Duration of Initial Stability	101
4.12	Density Profile Idealization	104
4.13	Settling Results of Michaels and Bolger	105
4.14	Results Illustrating An Increasing Settlement Rate	106
4.15	Normalized Height of Surface vs. Time - RB10-12	108
4.16	Normalized Height of Surface vs. Time - RB13 and 21	108
4.17	Normalized Height of Surface vs. Time - RB18 and 22	109
4.18	Surface Settlement Rate vs. Average Specific Volume - RB01-04	114
4.19	Surface Settlement Rate vs. Average Specific Volume - RB16-18	115
4.20	Surface Settlement Rate vs. Average Specific Volume - Influence of Pore Fluid Salinity	116
4.21	Surface Settlement Rate vs. Average Specific Volume - Influence of Pore Fluid Salinity	117
4.22	Surface Settlement Rate vs. Average Specific Volume - Influence of Initial Slurry Density	118
4.23	Surface Settlement Rate vs. Average Specific Volume - Summary of Representative Curves	119

4.24 Simplified Settling Rate Model 120
4.25 Density Profiles - RB09 Short Term 129
4.26 Density and Total Stress Profiles - RB09 130
4.27 Compression Behaviour - RB09 Short Term 135
4.28 Compression Behaviour - RB09 Long Term 135
4.29 Density History Graph - RB02 137
4.30 Element Settlement Rate vs. Specific Volume - RB09 139
4.31 Surface Settlement Rate vs. Average Specific Volume - RB09 139
4.32 Element Settlement Rate vs. Specific Volume - RB01 141

Chapter 5

5.1 Diagram of Experiment Conditions 146
5.2 Specific Volume versus Effective Stress - RB18 148
5.3 Specific Volume versus Effective Stress - RB22 149
5.4 Specific Volume versus Effective Stress - RB10 149
5.5 Specific Volume versus Effective Stress - RB11 150
5.6 Specific Volume versus Effective Stress - RB12 150
5.7 Specific Volume versus Effective Stress - RB13-15 151
5.8 Specific Volume versus Effective Stress - RB16-18 151
5.9 Specific Volume versus Effective Stress - RB20 and 21 152
5.10 Summary of Average Compression Curves 154
5.11 Density and Stress Profiles for Been's Experiment KB7 156
5.12 Density Profiles - RB12 158
5.13 Density Profiles - RB02 158
5.14 Settling Velocity versus Hydraulic Gradient - RB13 and 15 164
5.15 Settling Velocity versus Hydraulic Gradient - RB13 and 15 165
5.16 Settling Velocity versus Hydraulic Gradient - RB18 167
5.17 Settling Velocity versus Hydraulic Gradient - RB21 168
5.18 Settling Velocity versus Hydraulic Gradient - RB22 169
5.19 Settling Velocity versus Normalized Hydraulic Gradient - RB13 and 15 171

Chapter 6

6.1 Subsamples and Thin-Sections Within an Impregnated Core 181
6.2 Thin-Section of Core RB13 - Low Magnification 182
6.3 Thin-Section of Core RB13 - High Magnification 183
6.4 Classification of Particle Orientations 184

Chapter 7

7.1 Peak Shear Strength vs. Effective Stress - RB16-18 189
7.2 Peak Shear Strength vs. Effective Stress - RB13-15 191
7.3 Peak Shear Strength vs. Effective Stress - RB19-21 191
7.4 Peak Shear Strength vs. Effective Stress - Long Duration Experiments 192
7.5 Residual Shear Strength vs. Effective Stress - RB16-18 193
7.6 Residual Shear Strength vs. Effective Stress - RB13-15 194

7.7 Residual Shear Strength vs. Effective Stress - RB19-21 194
7.8 Residual Shear Strength vs. Effective Stress - Long Duration Experiments 195
7.9 Sensitivity versus Effective Stress - RB16-18 197
7.10 Sensitivity versus Effective Stress - RB19-21 199
7.11 Sensitivity versus Effective Stress - RB13-15 199
7.12 Sensitivity versus Effective Stress - Long Duration Experiments 200
7.13 Peak Shear Strength versus Specific Volume - RB16-18 203
7.14 Peak Shear Strength versus Specific Volume - RB19-21 204
7.15 Peak Shear Strength versus Specific Volume - RB13-15 204
7.16 Peak Shear Strength versus Specific Volume 205
7.17 Peak Shear Strength versus Specific Volume 206

Chater 8

8.1 Basic Potential Energy of Interaction Model 231
8.2 Extended Potential Energy of Interaction Model 235

LIST OF TABLE

Table 1 Summary of RB Experiments 72

LIST OF SYMBOLS

ρ_i intial density ($M\ L^{-3}$)

h_{s_i} initial height of slurry (L)

h_s height of slurry (L)

C_s pore fluid salinity ($M\ L^{-3}$)

t time (T)

v_s settling velocity ($L\ T^{-1}$)

V specific volume (-)

V_{sur} surface specific volume (-)

$V_{\sigma'=0}$ specific volume at zero effective stress (-)

e void ratio (-)

η normalized material coordinate (-)

ABBREVIATIONS

RB Robert Bowden

DE Don Elder

KB Ken Been

CHAPTER 1 INTRODUCTION

This thesis is concerned with the compression behaviour, shear strength characteristics, and properties of a natural silty clay sedimented in the laboratory, one-dimensionally, under self-weight. The hypothesis studied was that the behaviour, strength, and fabric of a soft settled bed are influenced by the initial height and density characteristics of the slurry from which it originated, the composition of the suspending medium, and effects related to time. The hypothesis was developed on the basis of soft soil knowledge as of 1986, when the present research commenced. The hypothesis was investigated experimentally, and from a geotechnical perspective predominantly. Slurries of varying composition were settled in 1.5 metre tall settling columns, whilst compression behaviour and shear strength characteristics were quantified using a range of purpose-built instruments. Enhanced methods of analysis were developed and applied to the results. Aspects of the hypothesis were found to be true to varying degrees. The primary contributions of the research were to advance the understanding of soft soil behaviour and properties, to suggest an alternative approach to modelling, and to improve the instruments available for studying soft soils.

The next chapter of this thesis is about soft soil research. It begins with an introduction to soft soils (section 2.0), and then shows the relevance of soft soil research to practical applications (2.1), discusses the compression process, microscopic forces, macroscopic parameters and models (2.2), and presents a review of published soft soil research (2.3). The

hypothesis which guided the experimental programme is also presented in section 2.3. In section 2.4 the objectives of the research programme are stated.

In the first section of chapter three (section 3.0) the experimental programme, including experiment purposes and conditions, is introduced. In succeeding sections an overview of experimental procedures (3.1), the study material and its preparation (3.2), and details of experimental apparatus and the types of data gathered (3.3), are presented.

Chapters four through seven present experimental results. Chapter four is concerned primarily with compression behaviour before the onset of effective stress. Aspects of behaviour that are considered include slurry appearance during compression (section 4.1), particle segregation (4.2), surface settlement as a function of time (4.3), surface settlement as a function of average specific volume (4.4), the distribution of mass within a settling slurry (4.5), and the settlement rate of individual elements of a slurry as a function of local solids concentration (4.6). Section 4.7 is a summary of methods of characterizing behaviour explored in chapter four.

Chapter five is concerned with compression behaviour in the presence of measureable effective stresses. The chapter begins with a brief introduction (section 5.0), and then continues with a study of compressibility (section 5.1). The nature of pore fluid flow is examined in section 5.2.

An attempt made to study particle arrangements, that is fabric, and its role in determining compression behaviour and shear strength, is the subject of chapter six. The study is introduced (section 6.0) and then expanded by discussions on the value of examining fabric (6.1), preparation of sediment for examination (6.2), and conclusions and recommendations which the study produced (6.3).

The final results presented are those from shear strength tests. An introductory section (7.0) outlines the relevance of shear strength measurments to many soft soil applications. Undrained shear strength results are related to effective stresses in section 7.1, whilst in section 7.2 soil sensitivity is examined. Peak shear strength results are compared with specific volume data in section 7.3. The chapter closes with a discussion of the shear vane results obtained (7.4).

Chapter 8 summarizes and concludes this thesis. The chapter begins with a summary and an interpretation of the experimental results recorded (section 8.1). In section 8.2 conceptual models for the compression behaviour of flocculated slurries are introduced. The relevance of both the experimental results and the models to engineering practice is demonstrated in sections 8.3 and 8.4 respectively. The penultimate section (8.5) outlines briefly the contribution of the present research to soft soil research, whilst in section 8.6 recommendations for future research are stated.

The reader's attention is drawn to a list of definitions for terms used in this thesis; the list is found succeeding chapter 8.

CHAPTER 2 SOFT SOIL RESEARCH

2.0 Introduction

Natural slurries of fine-grained particles settle under the force of gravity to produce a settled bed of low density and low strength. The geotechnical study of materials with these characteristics is called soft soil research. Sedimentologists, colloid chemists and rheologists studying similar slurries and beds would classify them differently and, in so doing, reveal their particular perspectives on the important attributes of the materials, and how they should be characterized and/or studied. The study of materials like soft soils is a frontier activity in soil mechanics, sedimentology, colloid chemistry, and rheology.

By all disciplines' standards a slurry of natural silty clay is compositionally and behaviourally complex. It is not the type of material upon which the fundamental concepts and models of any of the disciplines were developed, and its complexity is responsible for straining or invalidating traditional models which are applied to describe it and/or its behaviour. To study soft clayey soils of low density specialized instruments are required.

In spite of the hinderance to research caused by the complex and problematic form of soft, natural, clayey soils there are several reasons why a better understanding of soft soil behaviour and properties is needed. One prominent reason is that there are many economically important engineering

activities to which soft soil research is applicable. In the following section of this chapter (2.1) three examples of applications of soft soil research are presented and the need for further research demonstrated.

The aspects of soft soil research which are the most relevant to geotechnical engineering are compression behaviour and shear strength properties: the former of these, which includes both settling and consolidation, is the subject of section 2.2. In this section, discussions on perspectives of studying compression (subsection 2.2.1), the process of slurry compression (2.2.2), and the role of microscopic forces, macroscopic parameters and models (2.2.3) are discussed.

Section 2.3 is an overview of factors that influence soft soil compression, shear strength, and fabric. It begins with a general review (subsection 2.3.1) and literature review (2.3.2) of potentially influential factors, continues with a review of previous soft soil research at Oxford (2.3.3), and ends with a summary and hypothesis (2.3.4).

Chapter two is concluded with a statement of research objectives (section 2.4).

2.1 Applications of Soft Soil Research

When a suspension of sediment encounters a low energy environment, such as a harbour or sheltered water route, particles begin to settle, and upon reaching the surface of an existing bed will raise its altitude, and decrease the depth of free water above. In harbours, where it is necessary

to maintain an adequate navigable depth, the accumulation of sediment must be controlled. This is done by regulating the flux of sediment: inflow of sediment may be reduced by employing prevention schemes, whilst sediment outflow may be increased by re-suspending and/or mechanically removing (ie. dredging) sediment.

The rate of flow of sediment into a facility may be reduced sometimes by constructing prevention barriers outside of the facility. The function of such barriers is to create artificially quiescent conditions which promote the deposition of sediment where accumulation is tolerable, and in so doing decrease the concentration of sediment in the water which flows into the adjacent facility. The design of prevention schemes is based on principles of sedimentation and requires an understanding of the settling behaviour of suspensions.

The accumulation of sediment may also be controlled by regulating sediment outflow. In some instances it is possible to use tides and currents to carry away suspended sediment. Small areas within a harbour may be kept sediment free through the use of mechanical systems, such as aerators and mechanical turbulence generators, which periodically resuspend and disperse settled sediments. Systems of this sort, though sound in principle and intention, have not been particularly successful to date because of a poor understanding of the factors which govern sediment dispersion. Resuspension of sediment is not simply the reverse of sedimentation; with the passage of time and the build up of overburden, settled sediments develop cohesion (bonding between particles) which inhibits the breakdown of a bed into particles or aggregates which are transportable readily. The design of

sediment dispersion systems would benefit from an improved understanding of the factors that influence erosion resistance, sediment cohesion, and shear strength in soft soils.

Few harbours are able to manage the forces of nature to achieve zero net sediment flux: accumulation is the norm and dredging is the most common method of maintaining an adequate navigable depth. An efficient dredging programme is one in which only material which needs to be removed in order to maintain a navigable depth is dredged. It is necessary, therefore, to be able to accurately identify areas of settled sediment which, because of their altitude and shear strength, would offer sufficient resistance to the motion of a vessel to make navigation hazardous, were they left in place.

One definition of navigable depth is the distance between the water surface and a density of 1.2 Mg m^{-3} within the underlying sediment (Parker and Kirby, 1977). Note that this definition is based on density rather than shear strength, even though it is the latter which provides the resistance to motion. This definition is practical - at the present time it easier to estimate the density of settled sediment than it is to measure its shear strength - but it is also potentially unsatisfactory. If sediment of low strength but high density is (unnecessarily) removed then this is inefficient practice, and if sediment of low density but high strength is left in place, then the aim of dredging is missed altogether. It should be clear that if the objective of efficient, effective dredging is to be realized whilst control is exercised on the basis of sediment density, then an understanding of the relationship between the density and shear strength of recently deposited sediment, is essential.

A second application of soft soil research is the assessment of the erosion resistance of marine deposits. Stability is important when the sediment of interest is a host for hazardous colloids and it is desired to prevent the erosion and reintroduction of these materials into the biosphere. Contaminated sediments are produced when low level radioactive colloidal wastes are dispersed in the sea and become attached to settling clay particles. The stability of the bed which forms determines the acceptability of the disposal technique, and stability is largely controlled by the amount of cohesion (bonding) which develops between particles near to the sediment surface. The shear strength of clayey sediments at shallow depths, and changes in strength as a result of disturbance and/or the passage of time, are topics of interest which are central to soft soil research, and yet still not understood well.

Two related applications of soft soil research are hydraulic filling and disposal of fine-grained wastes such as mine tailings. Both involve the deposition of sediments from slurries of low solids concentration and both are concerned with the compression behaviour and shear strength characteristics of the beds which form. In the case of mine tailings, sediment is usually deposited in man-made impermeable basins which prevent the toxic elements within tailings from fouling the environment. Tailings ponds, and the earth embankments which enclose them, are expensive to construct and require vast amounts of land and suitable embankment materials. It is desirable, therefore, to maximize the ratio of storage capacity to plan area. To achieve this, the compression behaviour and shear strength of the wastes must be known so that input conditions can be adjusted to obtain a maximum density in a minimum period of time, with as

great an angle of repose as is possible. A knowledge of compression behaviour and strength properties is also required to plan the reclamation of tailings ponds after the end of filling.

The three applications which have been presented illustrate the relevance of soft soil research to important practical problems. They reveal that, at present, it is not possible to identify with confidence areas where navigation within a harbour may be hindered by deposits of soft sediments. Nor is it possible to predict or quantify the erosion resistance of marine deposits, nor to complete the seemingly simple task of predicting the surface settlement of a tailings pond during filling, or its shear strength afterwards. These facts confirm that additional soft soil research is needed.

All three applications involve prediction, and in order to predict surface settlement and strength development, some form of model is required. Fundamental to all sound models is an understanding of the factors which control the behaviour to be modelled. It was in search of this understanding - that is, how soft soils behave and why, specifically, as they do - that the experimental research reported in this thesis was undertaken.

2.2 Soft Soil Behaviour

2.2.1 Introduction

The present understanding of soft soil behaviour and properties of fine-grained slurries is the result of theoretical and experimental studies in

colloid chemistry, sedimentology, and soil mechanics. Traditionally the types of materials and ranges of behaviour studied by each discipline have differed, but a broadening of interests in recent years has lead to an increasing degree of overlap. The benefits of a multi-disciplinary approach to the study of sediment settling and consolidation are numerous: different perspectives, models, methodologies, and research instruments produce a broad range of observations, interpretations, and conclusions. Results which are either in agreement, contradictory, or complementary are all valuable, albeit in different ways, to the development of a comprehensive understanding of soft soils.

In the discussions which follow in this section, in the references cited in section 2.3, and in the interpretation of results presented in chapter 8, research and ideas from all of the three disciplines stated above, are used. The predominant perspective is geotechnical. This is so because the material studied in the present programme was a natural mud, the majority of research published on the compression behaviour and strength of mud is related to geotechnical engineering, and the applications for which models are sought are more the concern of civil and geotechnical engineers than of colloid chemists and sedimentologists.

2.2.2 The Compression Process

In a very dilute suspension of solids, which consists of either dispersed individual particles or discrete clusters of particles called flocs, the distances between settling units are sufficiently large that particles or flocs effectively settle independent of one another. It is usual to describe the behaviour of dilute suspensions, or components therein, in

terms of the parameter settling velocity. The forces which govern behaviour are gravity, buoyancy, and fluid drag. The most well-known expression relating these forces is Stokes' law: specifically, it equates gravitational and fluid drag forces on a spherical particle at a terminal velocity in an infinitely large, ideal, quiescent, suspending medium. The origins of Stokes' law are theoretical but innumerable experiments have proven both its validity and its value as a model for dilute suspensions.

In suspensions of intermediate concentration, the distances between settling particles and/or flocs are such that interactions occur between settling units. Settling units interact indirectly through hydrodynamic turbulence caused by a boundary layer around and a wake behind each unit. The effect of turbulence is to reduce the settling velocity of neighbouring particles to less than that predicted by Stokes' law. If particles are charged, such as clay minerals in a saline aqueous environment commonly are, then there is the potential also for direct electrochemical interactions. Attractions and repulsions between particles and flocs alters further the behaviour predicted by Stokes' law. As particle concentration increases Stokes' law becomes increasing inadequate and behaviour is referred to as hindered settling.

Within a 'hindered' settling slurry, pore pressures are equal to the total mass of sediment and fluid at any point, and neither flocculation nor particle interactions affect this equality. This statement, that pore pressures and total stresses are equal, remains true as settling proceeds and interparticle distances decrease until a continuous matrix (or assemblage, or framework) of interacting particles extends to a boundary,

such as an underlying bed in nature, or the bottom of a settling column in the laboratory. Structural continuity allows an external force - the supportive reaction of, say, a column base - to be transmitted throughout the sediment via networks of interparticle forces.

Within the system of forces which governs behaviour, external support assists fluid drag forces to counter the gravitational forces acting on a particle or floc. With the development of structure and the onset of support, particles become partially self-supporting and pore pressures reduce to less than total stresses. The degree of support increases (and fluid drag and pore pressures decrease) as the distance between particles decreases. The numerical difference between pore pressure and total stress is called effective stress.

The terminal state of all settling suspensions and slurries is static equilibrium. Therein, interparticle and gravitational forces are in balance. The total buoyant weight of the sediment is transmitted to an external support and pore pressures are simply hydrostatic. The origins of the forces which may act between particles are described in the following section.

2.2.3 Microscopic Forces, Behaviour, Macroscopic Parameters, and Models

In a clay slurry or soil, interparticle attractive forces are of two types, electrostatic and electromagnetic. The former occurs between particle surfaces and edges of different charge. The latter is due to very short range primary valence (chemical) bonding, and longer range van der Waals forces caused by momentary dipole fluctuations. There are four sources of

interparticle repulsion. In order of increasing distance from a particle these are: contacts, whose nature is speculative but is probably solid to solid (Mitchell, 1976); Born repulsion involving overlap of electron clouds; surface and ion hydration, related to the displacement of monomolecular layers of water or ions; and double-layer repulsion.

The diffuse double-layer is of fundamental importance in the settling and consolidation behaviour of clay slurries. The double-layer consists of negative charge on a particle and the distribution of cations near to it in the aqueous phase. Surface charge arises as a result of one or more of, isomorphous substitution of atoms of more negative valence in the crystal lattice of minerals, broken bonds, and/or hydrogen replacement of exposed hydroxyl units. To balance the surface charge, counterions in solution are attracted towards the surface, but the concentration of cations at the surface is prevented by their tendency to diffuse away from the surface in order to equalize their concentration throughout the solution. Electrostatic attraction and diffusion compete, yielding a diffuse charged layer which extends well beyond the physical extent of particles.

It is not possible to quantify the behaviour of a natural clay slurry in terms of the microscopic interparticle forces, body forces, and fluid shear forces that control behaviour: the system is far too complex and dynamic, and individual forces are too small and inaccessible to be measured. Colloid chemists primarily study simple systems of particles of uniform size, shape, and surface characteristics, in search of the elementary principles which, collectively, govern more complex systems. Only recently,

and only at a very basic level, have quantitative relationships been established between microscopic forces and behaviour.

Rather than study simplified systems microscopically, sedimentologists and geotechnical engineers have tended to accept the inherent complexity of natural clay slurries and have sought to characterize their behaviour macroscopically. The parameters most often used are settling velocity and effective stress, and these are applied to the contiguous settling and consolidation phases, respectively, which comprise compression behaviour. Although the engineer's approach is less likely than the chemist's to expose fundamentals of behaviour, the former is more readily applicable to practice.

It is unfortunate that it is not possible practically to divide the parameter effective stress into the individual microscopic forces presented at the beginning of this section; this capability would make it easier to correlate the results of research in chemistry and soil mechanics. Effective stress is, in this thesis, an experimentally deduced quantity equal to the difference between a calculated total stress and a measured pore water pressure. It is a macroscopic parameter which combines all of the microscopic forces which contribute to 'support' of particles, viz. electrochemical, fluid, and gravitational forces. Effective stress is not an ideal research parameter because of its macroscopic nature, but it is a parameter that is invaluable in practice. It is, for instance, the most satisfactory macroscopic means available to quantify the sum of vertical forces between particles, and it is used extensively in soil mechanics practice and theory to formulate behavioural models. It must be emphasized,

however, that the fundamental regulators of behaviour are microscopic forces and that these may not always be represented satisfactorily by the parameter effective stress. This point becomes evident when existing macroscopic models for compression behaviour of slurries are examined.

One model of behaviour has already been introduced: Stokes' law successfully describes the settling velocity of individual particles in dilute suspensions. Another successful model is Terzaghi's equation for one-dimensional consolidation. This model describes the consolidation behaviour of the majority of soils encountered in geotechnical engineering practice, that is, soils of relatively high density. At conditions intermediate to very dilute suspensions and dense soils, viz. the slurries of intermediate concentration and soils of low density of interest to soft soil researchers, existing models of compression are much less satisfactory. There are several reasons why this is so. First among them is the fact that traditional models used in chemistry and soil mechanics cannot accommodate properly the effects of particle-particle interactions at intermediate particle concentrations. Free settling theories, such as Stokes' law, assume that particles settle independent of one another and are free of external support: the first condition is false once particles have aggregated appreciably, whilst the second becomes invalid once a continuous matrix of electrochemically interacting particles exists. On the other hand, traditional consolidation theories fail near the transition from settling to consolidation because they neglect certain microscopic forces and the way in which particles are arranged, both of which influence behaviour but neither of which is represented by either effective stress or other elements of existing models.

The number of factors which must be accounted for when there are substantial hydrodynamic and electrochemical interactions between particles in a heteromineralic, broadly size-graded slurry, might be describable in theory but they cannot be managed adequately in practice. The problem has two facets. First, the present understanding of what factors are relevant to the compression process of clay slurries, and expressions which quantify each factor's influence, is seriously wanting. (A review of potentially influential factors is the subject of section 2.3). Second, even if the understanding were adequate, existing models which might be extended to include this knowledge, are sufficiently complex at present to be insoluble without both simplifying assumptions and extraordinary computational effort. Simplifications and assumptions inevitably decrease the accuracy of predictions, whilst the effort and inputs required to yield predictions make the models impractical.

There is a need for a simple, working-persons model for the compression behaviour of intermediate concentration slurries-cum-soft soils. Traditional, and more recent sophisticated theoretical models of settling and consolidation are inadequate for describing natural clay slurries. Empirically derived models of settling behaviour, such as those of Kynch (1952), Richardson and Zaki (1954), Michaels and Bolger (1962), and McRoberts and Nixon (1976), which are described later in this thesis, are, in general, more successful than theoretical models, but they do not include the consolidation phase of compression, and they are suited best to coarse-grained sediment. If a satisfactory empirical model for the settling and consolidation behaviour of clay slurries is to be developed then a sound physical (or electrochemical) basis for one must be established first.

Soundness arises from a knowledge of the factors which govern the behaviour to be modelled, and understanding is acquired through observation. Observations, in the field and laboratory, are also the source for expressions relating behaviour-controlling factors to parameters of interest, and of values for initial and boundary conditions in models.

2.3 Factors Influencing Compression, Strength and Fabric

2.3.1 General Review

The following section is a brief review of factors which have been observed in a number of disciplines to influence the behaviour and properties of monomineralic and natural mud slurries during settling and consolidation. The review is presented to frame the hypothesis which is stated at the end of the section.

The primary force behind settling and self-weight consolidation is gravity. It is clear from Stokes' law that the settling velocity of a single solid uncharged particle in an aqueous medium under the force of gravity is determined by particle shape and size, the density of the particle relative to the density of the suspending medium, and the viscosity of the latter.

When a system consists of more than one uncharged particle there is the potential for hydrodynamic interaction. The degree of interaction will be determined by the concentration of particles. If particles settle at different velocities or have different velocity vectors then it is possible that particle-particle collisions will occur. If the particles of the system possess a range of characteristics, such as variable size and

density, then the degree of variation of each characteristic will also influence behaviour.

Whilst settling, the attitude in space of a particle will be determined by the position of its centres of mass, buoyancy, and hydrodynamic reaction, and by the outcome of any collisions, if these occur. Upon reaching an underlying bed, a particle will adopt an orientation relative to its neighbours that is influenced by particle characteristics (size, shape, etc.), forces during settling, agitation at the depositional interface, and intensity of deposition. As the depth of overburden above a particle increases and/or as excess pore pressures dissipate, the bulk density of the deposit will increase and the orientation of particles may change.

In systems of surface active or charged particles the influence of electrochemical forces on behaviour is often significant, and factors in addition to those mentioned above for uncharged particles must be considered. Electrochemical forces affect the way in which a particle and the suspending medium interact (particle mobility, and viscosity), and also interactions between particles.

The nature of electrochemical forces is discussed in section 2.2.3; it is stated therein that the principal causes of attraction and repulsion are van der Waals forces and similarly charged electric double layers, respectively. The polarity, strength, and extent of the diffuse double layer is influenced by surface charge density and the composition of the suspending medium. With respect to surface charge density, the following factors are important: chemical composition, crystallographic structure, adsorbed charged groups,

and surface coatings. Suspending medium characteristics which influence the double-layer, and thus behaviour, include pH, ionic strength, and ionic composition.

The process of flocculation has a significant effect on the behaviour and properties of a system. Flocculation is controlled by electrochemical forces (and thus all of the factors listed immediately above) plus fluid shear and collision forces. Floc size, shape, and density are determined by a competition of these physical and electrochemical forces. As floc size increases, the relative significance of gravitational force in determining behaviour increases. An increase in floc concentration produces, first, aggregates (clusters of flocs) and then, through the amalgamation of aggregates, a continuous matrix. With the onset of structural continuity, support from boundaries gives rise to effective stresses and these play an increasingly important role in the behaviour of the system as compression progresses. Effective stress in a clayey system is electrochemical in origin and repulsive in sense. It follows, therefore, that the influence of effective stress on behaviour is influenced potentially by all of the factors which affect electrochemical forces.

In bringing particles together, flocculation gives rise to structure: structure consists of fabric (particle arrangements) and forces between particles. Structure is the source of shear strength, thus it follows that the factors which influence flocculation (physical and chemical forces; solid and suspending medium characteristics, etc.) may also influence shear strength.

In addition to the physical and chemical factors stated above, time is another factor which may influence the behaviour and properties of a slurry or settled bed. The effects of individual forces occur at different rates, hence time is important. The passage of time is also relevant to all material properties which involve rate-dependent processes; shear strength and stiffness are two properties which often show a dependence on time.

It is evident from the foregoing discussion that there are many factors which may potentially influence settling, consolidation, shear strength, and fabric of slurries and settled beds. The number of relevant factors increases with system complexity and a natural silty clay slurry, consisting of charged and uncharged anisotropic particles of varying size and composition, is one of the most complex types of systems possible. In the literature review which follows, proof of the significance of some factors is presented. Because of the difficulty of studying fine-grained natural slurries the influence on behaviour and material properties of few of the factors discussed above have been studied systematically.

2.3.2 Literature Review

The literature which reveals the influence of the factors considered in the preceding section spans a range of disciplines, including chemistry, rheology, oceanography, micromorphology, and chemical, geological, geotechnical and marine engineering. The studies and observations which are most relevant to the present work are those concerned with natural fine-grained slurries or soft soils and which quantify behaviour in terms of settling velocity, effective stress, and/or shear strength. In the following pages a selection of published accounts of the behaviour and

properties of clay minerals, slurries, and soft soils, are presented. Research concerned with flocculation and settling is considered first, then consolidation, and finally shear strength.

Imai (1980) studied the settling behaviour of dilute monomineralic and natural clay slurries, classified behaviour on the basis of slurry appearance, and investigated the influence of suspending medium salinity, mineralogy of the solid fraction, initial slurry density, and total weight of solids. Imai observed that settling behaviour was strongly influenced by the degree of flocculation and the degree of mutual interactions between particles, and that these, in turn, were related to suspending medium salinity and initial slurry density. Natural muds exhibited different behaviours than monomineralic clay slurries, illustrating the influence of mineralogy on behaviour and raising questions about the validity of extrapolating the behaviour of pure slurries to applications involving natural muds. Imai found, in addition, that behaviour was influenced by the total mass of solids composing a slurry.

Pierce and Williams (1966) carried out sedimentation experiments with four natural sediments from British estuaries, which had compositions ranging from sandy silt to clay. Slurries spanning a range of initial densities and salinities were prepared and settled. Pierce and Williams found that the grain size distribution of the sediment, pore fluid salinity, and initial slurry density all exerted an influence on the rate of settlement of the surface, the point at which hindered settling became consolidation, the compressibility of the settled bed, and the clarity of the supernatant

overlying the bed. Supernatant clarity is a visual indicator of the degree of flocculation within a slurry.

Michaels and Bolger (1962a) investigated the settling rates and densities of flocculated kaolin suspensions as functions of initial slurry density, settling tube diameter, and suspending medium composition. Their results, which are considered in detail later in this thesis, showed that the rate of surface settlement is influenced significantly by initial slurry density. In dilute suspensions, settling rate and flocculation were observed to be influenced by the pH and salinity of the suspending medium, chemical treatment of the solids, and mixing procedures for the suspension. Suspensions of intermediate concentration showed settling patterns that Michaels and Bolger attributed to the influence of fabric (ie. particle arrangements). Floc concentration and density were noted to be functions of initial slurry density.

In a recent paper on flocculation, Moudgil and Somasundaran (1985) identified several topics deserving further research. Although the authors did not present experimental results or observations, their comments are relevant here. Their list of suggested studies included floc strength-property relationships (such as floc size, shape and density), floc structures, and shear strength. The justification for carrying out such research was that these factors play an important role in determining floc genesis, settling velocity (ie. behaviour), and the strength of settled beds.

Hogg, Klimpel, and Ray (1985) studied structural aspects of floc formation using slurries of ground quartz and kaolin. They observed that floc density, which affects settling rate, varied with floc size, and ranged from a maximum value equal to the density of a single particle to a minimum value limited by the initial density of the slurry. Floc size and density were thus found to vary with slurry conditions.

Flocculation was also the subject of Gibbs' (1983) study involving illite, kaolinite, montmorillonite, and four natural muds. Gibbs discovered that in a turbulent environment flocculation rates varied with particle size and pore fluid salinity. Natural sediments did not behave as might be predicted for a mixture of standard minerals yielding the same composition. Gibbs attributed this finding to coatings on natural sediments, differences between standard and natural clay minerals, and/or mixtures behaving differently than the sum of their components. Differences in the flocculation behaviours of natural sediments and compositionally similar analogies of refined minerals shows the danger of using one system as a model for the other.

In a later study Gibbs (1985) examined the settling velocity, diameter, and density of flocs of illite, kaolinite, and montmorillonite formed in dilute slurries. Gibbs found that settling velocity was proportional to floc diameter raised to the power 0.35 to 0.645, a value quite different from the exponent proposed by Stokes (which was 2) for individual particles. Gibbs' results suggest that there is a fundamental difference between the settling rate of particles and flocs. Gibbs postulated that floc density, shape, roughness, and/or permeability vary with floc size. Gibbs arrived at the

same conclusion as Hogg et al., namely that floc density decreases as floc size increases.

Yong and Wagh (1985) studied the factors which affect the onset of flocculation, that is, conditions which cause a stable slurry to begin to settle. By examining the energies of interaction of pairs of approaching particles, these authors illustrated the influence of suspending medium composition, solid fraction composition, and particle orientations on the propensity of dispersions to flocculate and settle.

In contrast with Yong and Wagh's study of the onset of settling, Imai (1981) studied behaviour towards the end of settling, at the transition to consolidation. Extending earlier work (Imai, 1980), Imai examined the changes in water content that occur within slurries during settling and consolidation. Working with three natural muds and kaolin, Imai also assessed the propensity of particles within slurries to segregate and found that degree of segregation, which reflects particle mobility and slurry structure, was influenced by the composition of the slurry and initial slurry height. In regards to changes in water content during compression, Imai's results revealed numerous differences between the settling behaviour of flocculated natural mud slurries and behaviour predicted by Kynch's classic settling theory for hindered settling of particles: Kynch's model was shown to be inapplicable to natural muds. Imai's most important conclusions were that the point at which settling becomes consolidation, and the compressibility of settled muds after this point, are not material constants but vary with the initial water content of the slurry. In

summary, settling and consolidation processes were strongly affected by initial slurry density.

Kos (1985), in an overview of sedimentation published in the proceedings of a conference on flocculation, sedimentation and consolidation, highlighted the importance of particle concentration, hydraulic forces and effective stresses on structure and the compression behaviour of flocculated slurries. To justify the relevance of these factors Kos cited theoretical models which were inadequate because they neglect these terms.

Tiller, Yeh, Chen, and Tsai (1985), in a paper on compression of particulate structures, stressed that it is microscopic phenomena that control behaviour and that the ultimate objective of research is to relate microscopic phenomena to macroscopic models. At present, the latter are empirical. Tiller et al. provide correlations, based on experimental results, for parameters in empirical equations relating specific volume (which is an expression for density) and permeability to effective stress, with degree of aggregation of flocs. The implication of their work is that structure influences specific volume, permeability, and effective stress relationships. Tiller et al. (1985) and Tiller and Khatib (1984) suggest that structure is influenced by particle size and shape, by degree of flocculation, and by initial slurry density.

In 1987 Torresan and Schweb examined near surface sediment from the Shelikof Strait and Alaska prodelta with a view to relating fabric to sedimentological and physical properties. Their hypothesis was that the response of a muddy sample to stress (ie. behaviour) is partially influenced

by fabric and that this is related to (at least) the composition of the solid fraction of the deposit and physico-chemical conditions during deposition. Torresan et al.'s results showed the validity of this hypothesis: very high stresses were required to cause noticeable changes in particle alignment and this was due to a sand and silt component in their samples forming a rigid internal structure which hindered particle reorientation.

Locat and Lefebvre (1982) studied the effect of sediment concentration, suspending medium salinity and time on the accumulation rate of sediments, and the influence of salinity, and time on the compressibility and shear strength of natural sediments artificially deposited. Salinity was observed to influence compression behaviour, shear strength and soil sensitivity. The response of the material was observed to become stiffer with time.

The most comprehensive experimental study of the physical properties and behaviour of illite, kaolinite, and montmorillonite during settling and self-weight consolidation to be found in the published literature is that by Einsele, Overbeck, Schwarz and Unsold (1974). Their research included sedimentation and consolidation, surface loading, sliding, vane and erosion tests, and permeability and void ratio calculations. Einsele et al. observed that the rate of consolidation of settled beds was influenced by the mode of deposition and the electrolyte concentration of the suspending medium. In regards to the strength properties of settled beds, they observed that at very low effective stresses the ratio of undrained peak shear strength to effective overburden pressure was disproportionately high and attributed this to an electrochemical or 'intrinsic' shear strength

component acting in addition to that due to effective stress. Einsele et al. also observed that soil sensitivity (which is the ratio of peak to remoulded vane shear strength) decreased with increasing depth below the sediment surface and suggested that the influence of structure on shear strength diminished as effective stress increased.

In a companion paper to one described earlier, Michaels and Bolger (1962b) examined the influence of particle concentration, shear rate and fluid composition on the rheological or shear behaviour of kaolin suspensions. Michaels and Bolger observed that behaviour was governed by the structure of the suspension, that is by flocs and aggregates of flocs, which were, in turn, functions of initial slurry density, shear rate, and fluid composition.

The influence of time on the strength properties of normally consolidated clay samples was studied by Bjerrum and Lo (1963). These authors observed that the behaviour of the clay changed with time; older samples showed greater strength and smaller failure strains. The authors attributed this response to the growth of cohesive bonds between particles with time and noted that "the additional cohesive component of the shear strength gained with time was destroyed during testing".

Imai's (1981) investigation of the specific volume or density at which effective stresses begin has been mentioned. Imai also examined the compressibility of soils at low effective stresses. Crawford (1963), almost two decades earlier, studied the shear strength of an undisturbed clay at zero effective stress. Crawford identified the relevance of structure to

strength and suggested that soil sensitivity reflects structure. Crawford observed shear strength at zero effective stress, attributed this to intrinsic (ie. electrochemical) stresses, and noted how poorly that these were understood. Crawford's perception of the role of structure and electrochemical interparticle forces in determining shear strength is revealed in the following quotations. "Any development of fundamental shear parameters for undisturbed soils cannot ignore structure". "It is necessary to consider the intrinsic side effects which cannot be evaluated by simply subtracting pore water pressure from total stress" and "...when applied effective stresses are reduced and shear strength is still maintained clearly the accepted effective stress concepts are inadequate and cannot be used with confidence".

Sridharan and Venkatappa Rao (1979) investigated the shear strength behaviour of kaolinite and montmorillonite clays saturated with pore fluids of varying dielectric properties. The premise behind their work was that many factors influence the strength behaviour of clays, such as type of clay mineral and pore fluid, stress history, test conditions and soil fabric, but that (i) intrinsic (or electrochemical) interparticle forces are important and must be accounted for in addition to the conventional effective stress, (ii) the repulsive force aspect of intrinsic stress is primarily due to to interaction of diffuse double layers, and finally, (iii) the magnitude of this repulsive force is proportional to the dielectric constant of the pore fluid. Their experimental results confirmed their premise, demonstrating that net electrical attractive and repulsive forces, shear strength at zero effective stress, and shearing resistance all are sensitive to the dielectric constant of the pore medium.

The foregoing selection of published soft soil related research is not, of course, exhaustive but it is representative. It shows that there have been very few studies of natural mud slurries in which both settling and consolidation have been examined, or studies of self-weight consolidation involving low effective stress levels. Shear strength studies of recently deposited beds with high specific volumes and low effective stresses levels are noticeably absent from the literature and yet materials with these characteristics are relevant to many applications. Structure is often cited as being important with respect to flocculation, compression, and shear strength, but the connection between the components of structure (interparticle forces and particle arrangements) and behaviour and shear strength are vague. There is evidence within the references presented that the macroscopic parameter effective stress is not sufficient to be used alone as a basis for compression and shear strength models of soft soils.

Absent from the preceding review is a very important body of soft soil research produced by the author's predecessors. Their work is considered in detail in the following subsection.

2.3.3 Review of Predecessors' Research

The largest stress based experimental study of settling, consolidation and shear strength of natural sediment reported in the literature is the University of Oxford's soft soil research programme begun in 1977. The works of the primary contributors, Been (1980) and Elder (1985), are reviewed in this section.

Broadly similar equipment, methods and mud were used by Been, Elder and the present author. Been was concerned with the effective stress behaviour of a natural silty clay during sedimentation and consolidation, and his experimental work was an extension of a theoretical study of large strain self-weight consolidation carried out by his contemporary Lee (1977). The fundamental principle underlying Been's work was that the essential difference between a suspension and a soil is effective stress. Been was aware that electrochemical forces were active between particles within his slurries, because flocculation was observed, but resolved, nonetheless, all stresses into two kinds: hydrodynamic, due to fluid drag on flocs, recorded as pore pressure above hydrostatic; and effective stress, due to load transfer through a particle framework, calculated as the difference between pore pressure and total stress. Been developed equipment to measure these stresses and performed 15 settling column experiments (KB1-KB15).

In experiments KB1 through KB5 height of surface versus time data showed that the rate of surface settlement of a slurry depends on at least initial density. Experiments KB6, 7 and 8 exposed the existence of different material phases or states, and Been termed these suspension, intermediate and soil on the basis of an effective stress criterion and compressibility characteristics during settling and consolidation. Experiments KB1-7 showed that within the intermediate phase pore fluid migrates to the surface partly through open channels whilst experiment KB8 showed that the presence or absence of channels depends on initial slurry density. Thus experiments KB1-8 suggested a connection between behaviour and structure, but none demonstrated the profound influence of structure as well as experiment KB9

in which behaviour was radically altered by destroying structure with a deflocculating agent, causing particles to settle individually.

The most illuminating experiments performed by Been (KB10-15) encompassed a range of initial densities (ρ=1.02 to 1.146 Mg m^{-3}), initial slurry heights (0.643 to 1.895 m) and experiment durations (144 to 1853 hours). A combination of surface settlement data, density profiles and effective stress distributions showed that the rate of surface settlement was most rapid before the onset of continuous structure, that is, while a suspension phase existed.

In none of experiments KB10-15 was a unique compressibility relationship between void ratio (or specific volume) and effective stress observed. In examining Been's results the present author found that the degree of departure from a unique relationship decreased as effective stress increased. At the surface of settled beds, where effective stress was necessarily zero, Been observed a decrease in void ratio from 12 to 6 with the passage of time; this is a clear example of behaviour caused by forces not represented by effective stress.

Been's approach to interpreting the compression behaviour of slurries in terms of effective stress was a novel step towards bridging the gap between soil mechanics and sedimentology. However, in concentrating on effective stress behaviour Been was unable to examine the potential influence of pre-depositional events, such as individual particle movements and particle interactions, and the height, density and settling velocity of the suspended phase, on post-depositional behaviour and material properties. In

summarizing his own results Been concluded that segregation (of different particle sizes), flocculation and changes in suspension density were important factors influencing behaviour during sedimentation (ie. suspension settling and the transition to consolidation).

Been's successor, Elder, was motivated by two related interests: a desire to acquire a better understanding of discrepancies between real and model consolidation behaviour, and a wish to resolve some of the many unclear and often contradictory sediment behaviours reported in the literature. Elder carried out eleven tall column self-weight compression experiments (DE1-11) using a silty clay from the same source location as material used by Been and the present author. Elder's tall column settling experiments spanned a range of initial densities (1.020 to 1.251 Mg m^{-3}) and his analysis was, like Been's, in terms of effective stress.

Experiments DE1a and DE1b were performed to assess the importance of boundary drainage conditions on the rate of settlement of the sediment surface. In experiment DE1b drainage was permitted through the base of the column against hydrostatic pressure. Very similar settling and density profiles were observed at equal periods after input, contrary to behaviour predicted by Lee's linear consolidation model. Experiment DE3 also involved variable drainage conditions and confirmed that the real and predicted influence of drainage conditions were different.

Experiment DE4 involved the application of surcharge loads to the surface of a bed after a period of self-weight consolidation. The effect of surcharging was to create rapidly a thin dense layer immediately below the

extra load. This feature was attributed to rapid dissipation of excess pore pressures near to the surface of the bed, and was observed to impede the migration of fluid out of the bed, thereby retarding pore pressure dissipation, effective stress increase and effective stress related strain. Experiment DE4 illustrated the sensitivity of overall compression behaviour to the distribution of material properties within a slurry.

Experiments DE6 and 7 were of identical initial density (ρ_i=1.251 Mg m^{-3}) but different initial heights, and their results showed that initial slurry height influences rate of pore pressure dissipation, rate of surface settlement, and the distribution of mass within a bed with respect to time. In a similar manner, experiments DE7 and DE9 had comparable initial heights but different initial densities (ρ_i=1.251 and 1.094 Mg m^{-3}) and their results showed that a slurry which is less dense at the time of input will create a less dense bed initially but that this bed may consolidate more rapidly and after approximately 5000 hours attain an average density greater than the slurry of initially greater density. The results suggest that the effect of initial density on behaviour in the short and long terms are not simple.

With the aid of Been's x-ray apparatus, Elder was able to study the distribution of mass within slurries and the redistribution of sediment with respect to time. Most of Elder's experiments showed an initial period during which the sediment surface settled a negligible amount. A period of initial stability is not an uncommon characteristic of flocculated slurries of natural mud, but it is a trait which is condition-specific. To the author's knowledge no quantitative models of settling behaviour exist which

include this period. In Elder's experiments the duration of this period varied considerably (0 to 60 hours) for experiments with similar initial conditions, and its effect on subsequent behaviour was not erased or masked by the passage of time. Another feature recorded by Elder which is discordant with existing models is an increase in density towards the sediment surface (referred to as a density inversion by the present author). The implication is that surface settlement models which assume either a uniform density distribution, or a distribution which increases with respect to depth, are in error.

Elder carried out one experiment in which a 35 parts per thousand salt water solution was substituted for the usual tap water suspending medium. This experiment (DESW2) confirmed that surface settling behaviour is affected by pore fluid salinity.

Elder's main contributions to soft soil compression research were his analyses of the variation in void ratio at zero effective stress (ie. surface void ratio), void ratio versus effective stress (compressibility), and void ratio versus settling velocity relationships. Elder also examined the components of compression strain due to changes in effective stress and those occurring at constant effective stress but with the passage of time. In none of Elder's experiments was a unique or constant surface void ratio observed. Below the surface, at low effective stress levels, void ratio and effective stress were non-uniquely related; that is, any particular effective stress was associated with a wide range of void ratios. Elder attributed an irregular correspondence between void ratio and effective stress to time-dependent strain at constant effective stress (creep).

Elder analyzed a limited amount of pore water - solids relative flow data and these disclosed a highly non-linear and non-unique settling velocity versus void ratio relationship. A comparison of settling velocity versus hydraulic gradient data showed that Darcy's law of pore fluid flow, which is a fundamental relationship in most consolidation models, was not satisfied for specific volumes greater than 5. For purposes of comparison this value is approximately equivalent to the minimum specific volume within a slurry after six months consolidation under one-half metre of overburden. Darcy's law is not, therefore, applicable to very young or voluminous near-surface sediments.

In an attempt to rationalize the variable compression behaviour that Elder observed, he postulated that there might exist an 'instant' compression curve which would allow effective stress induced and time related strains to be deduced, and the continuous settling and consolidation stress-strain history of a soil element to be determined. To this end Elder compiled data from 11 experiments with different initial conditions and showed, in the present author's estimation, a clear trend of decreasing void ratio with increasing effective stress but not a unique relationship between these parameters, in the 0.1 to 10 kPa stress range: thus for Elder's natural mud slurries time influenced compressibility, and compressibility was dependent on slurry conditions.

Another valuable contribution of Elder to soft soil research was his study of the shear strengths of settled beds: this study included tests carried out using a fall cone, a shear vane, and a novel spherical cavity expansion instrument. Elder compared peak and residual shear strengths with Liquidity

Index (a relative measure of particle concentration, between liquid and plastic limits) and observed that peak shear strength increased substantially and residual strength slightly with the passage of time, at any given Liquidity Index. Elder did not observe a unique relationship between peak shear strength and vertical effective stress because of a strong creep component in compression behaviour (that is, strain at constant effective stress) which produced a range of specific volumes, and therefore strengths, at any given effective stress. Elder found that residual shear strength and effective stress were more uniquely related; a consequence of a weaker influence of time on residual shear strength.

2.3.4 Summary and Hypothesis

General accounts of the behaviour of monomineralic slurries which appear in colloid chemistry, sedimentology, and geotechnical engineering textbooks, and journal articles which present experimentally observed behaviours of natural systems, confirm that there are many factors which may influence the compression behaviour, shear strength, and fabric of a natural silty clay slurry. In light of the large number of variables, the extreme sensitivity of slurry behaviour to small changes in some factors, interdependence between variables, and the difficulty of evaluating and maintaining constant certain factors in experiments to be compared, it is not surprising that there are many uncertainties, and even apparent contradictions, between similar experiments, and between experiments and theory, reported in the literature, as regards compression behaviour, shear strength, and so on. A meaningful synthesis of published soft soil-related research is a difficult task because of the multitude of variables to be considered and, for the present author, contributed little towards obtaining a coherent

understanding of the fundamentals of soft soil behaviour and properties. Nevertheless, a review of the literature proved useful because certain trends within the literature suggested a behavioural hypothesis for natural clay slurries.

The many potentially influential factors discussed above may be organized into groups relating to the solid phase, fluid phase, and the system as a whole. The following scheme has five categories,

1. Physical characteristics of the solids.
2. Electrochemical or surface charge properties of the solids.
3. Physical characteristics of the suspending medium.
4. Chemistry of the suspending medium.
5. System characteristics.

whilst a sixth, experimental characteristics, might be added to accomodate factors such as test drainage conditions.

In order to progress towards achieving the ultimate aim of the Oxford soft soil research programme, which is to establish the simplest model and accompanying understanding of large-strain self-weight compression behaviour of, and shear strength development within a natural silty clay, the most important factors of those potentially relevant must be established and the influence of these quantified, preferrably in terms of macroscopic parameters.

The research programmes of Elder and Been concentrated on system characteristics (category 5, above). From their results, particularly those showing non-unique relationships between specific volume, permeability, effective stress and shear strength, it was not possible to construct a

rational predictive settling, consolidation and shear strength model. One experiment each of Been (KB9) and Elder (DESW2) showed that natural slurry behaviour is influenced significantly by the composition of the suspending medium. This conclusion is strongly supported by experimental and field evidence in colloid chemistry, sedimentology, and geotechnical engineering.

All of Been's and Elder's experimental results suggested that the behaviour and properties of a slurry are influenced by the passage of time. This observation agrees with the view that a flocculating/settling/consolidating slurry is a system of multiple rate-dependent processes. The relevance of time, as a factor affecting the outcome of competing processes, and thus behaviour, is supported by evidence in the literature.

Been's and Elder's most important conclusions were that compression behaviour cannot be described adequately in terms of the deduced macroscopic quantity effective stress only, and that permeability and settling velocity cannot be described in terms of a single volumetric parameter (void ratio or particle concentration). The first conclusion suggests that not all of the microscopic forces which determine behaviour are represented by effective stress. The second conclusion is evidence that fabric - the arrangement of particles - influences slurry behaviour.

Been's and Elder's work expanded the understanding of soft soils but it also showed that that understanding requires improvement. The implications of Been's and Elder's work are that time, microscopic forces, and particle arrangements are important in determining soft soil behaviour and shear strength development, but that these factors are not well enough understood

to establish a satisfactory model. Collectively, the broad body of multi-disciplinary, theoretical and experimental compression, shear strength and fabric related literature reviewed suggested the hypothesis that, the compression behaviour and fabric of, and shear strength development within a natural silty clay slurry are influenced by (at least) the macroscopic factors initial slurry density, initial slurry height, the salinity of the suspending medium and the passage of time. The present research was an experimental investigation designed to assess the relevance of these factors.

2.4 Research Objectives

The research reported in this thesis was aimed at achieving five objectives. The first was to expand the general knowledge of and experience with the compression behaviour, shear strength and fabric characteristics of natural clay sediments during settling, and soon after deposition, whilst effective stresses are low and specific volumes are high, as a step towards establishing a physically sound predictive model of slurry behaviour and properties. The second objective was to assess the hypothesis stated above (section 2.3.4), that is, to investigate the importance of initial slurry density, initial slurry height, suspending medium salinity and the passage of time on soft soil compression behaviour, strength, fabric and related properties. To accomplish these two objectives it was necessary to improve the instruments available for investigating the behaviour of slurries in the laboratory. To this end three practical objectives were established: to develop a means of measuring small changes (10 Pa) in pore pressure precisely under a relatively large pressure head (1500 Pa) over long periods

of time (up to four months); to develop an instrument and procedures for measuring small shear strengths (as low as 10 Pa) precisely at a range of depths (up to 0.5 m) within a settled bed without altering stress conditions; and to develop equipment and procedures for recovering, preserving, sectioning and examining the fabric of a continuous, relatively undisturbed sample of soft sensitive mud.

The experimental programme, instruments and procedures designed to achieve these five objectives are described in the following chapter.

CHAPTER 3 EXPERIMENTAL PROGRAMME

3.0 Introduction - Purposes and Conditions

In this chapter details of the procedures, materials, and equipment used in the experimental programme are presented. Having established the objectives of the programme in section 2.4, in the present section the purposes and conditions of the experiments carried out to achieve these objectives are stated. Sections 3.1 and 3.3 explain the procedures and equipment used, respectively. The latter section also includes examples of the data collected. In section 3.2 the study material and slurry preparation are described.

The programme consisted of 22 tall column experiments, one series of six 50 millimetre diameter tubes, and one series of 30 small beakers (100 ml). Table 1, located at the end of the chapter, is a summary of experiment conditions. The table includes slurry characteristics, initial conditions, experiment duration, types of data recorded and post-experiment activities. A major change in the programme is shown beginning with experiment RB10 when satisfactory pore pressure, shear vane and fabric sampling equipment became available. Series of experiments with different conditions or purposes are separated with blank rows in Table 1.

Experiment purposes varied. Experiment RB01 had conditions similar to those of Been's experiment RB7 and was performed in order to gain familiarity with and to evaluate experimental procedures, equipment and methods of data

processing used by earlier researchers at Oxford. Experiment RB02, a duplicate of experiment RB01, was performed to assess the inherent variability of self-weight compression experiments. Results of experiments RB01 and RB02 prompted a detailed study of pore pressure measuring procedures and a programme of data processing modernization. Experiment RB03 was carried out to observe the influence of initial height of slurry on surface settlement rate and density profiles.

Four suites of experiments, RB04a-c, RB05a-c, RB07a-c, and RB08a-c, each consisting of three columns, were performed to study the influence of initial slurry density on rate of surface settlement, distribution of mass with respect to time, and degree of particle segregation.

The purpose of test series RB06 was to assess the feasibility of using 50 mm diameter by 0.5 m high Andreasan settling tubes instead of 102 mm diameter by 2 m tall settling columns. This series of six tubes yielded highly variable surface settlement data suggesting severe side wall friction effects. The tubes were considered to be unsatisfactory and no results are presented for this uninstrumented series.

Experiment RB09 was performed to study the redistribution of mass within a slurry during pre- and early post-deposition periods.

Experiments RB10 through RB22 were planned as a single series of experiments with the purpose of revealing the influence of initial slurry density, suspending medium salinity, and time on the compression behaviour, shear

strength and fabric of soft silty clay. Different experiment purposes and conditions resulted in a variety of experiment procedures.

3.1 Overview of Procedures

Procedures varied according to the purpose and conditions of each experiment and as the programme and equipment evolved. Experiments RB01 and RB02 were carried out following procedures used by Been and Elder. Experiments RB03-09 were surface settling experiments involving few measurements. Experiments RB10-22 were rather more sophisticated than earlier tests and included instruments and procedures for measuring pore pressures, determining shear strength, recovering a fabric sample, and taking subsamples for particle size analysis. The procedures for all experiments had three phases: pre-experiment, experiment, and post-experiment. Two pre-experiment activities common to all experiments were slurry preparation and input, and these are described in section 3.2. The following description of procedures is in chronological order.

Intact 102 mm I.D. columns were used in experiments RB01-09 and triple-segmented columns in experiments RB10-22. Each column was fitted with an alloy base of one of three types: total stress base, containing a port for a transducer (RB01-02); solid base (RB03-09, 14-17, 19 and 20); or a base designed for fabric sampling (RB10-13, 18, 21 and 22).

Post-experiment fabric sampling required special preparations during column assembly. Sampling involved coring the settled bed with a permeable wall tube fitted with a cutting shoe and liner, and picking up a snug fitting

plug resting unobtrusively in the base of the column. Plugs were set into recesses in each fabric sampling base (sub-section 3.3.5). To be able to relocate a plug after a bed had settled it was necessary to record the plug position using a guide assembly during assembly. Assembled columns were aligned vertically in the arms of a rotatable stand (sub-section 3.3.1).

In experiments RB01 and RB02 pore pressures were recorded using individual transducers set into housings in the column wall. This method was found to be unsatisfactory. In experiments RB10-22 pore pressures were recorded using a single transducer in a central pressure unit (CPU) with tubes connecting individual ports and the transducer. With both systems settling columns were filled with water, and permeable filters in the column wall, housings and tubing purged of air. Port elevations were then recorded and a constant transducer signal under static hydrostatic conditions established. In experiments RB01 and RB02 sets of transducers were calibrated before each experiment by varying the water level in a column. In experiments using a central pressure unit, a single transducer was calibrated before each set of readings using a portable reservoir. CPU readings were recorded manually. Multi-transducer experiments were connected to a data acquisition system and monitored automatically.

An x-ray apparatus was aligned vertically in front of each cluster of columns, a clear water calibration sample set in place, and each water filled column profiled. Blank column profiles were used during analysis to eliminate column inhomogeneities. Immediately prior to beginning an experiment, water within each column was rapidly siphoned out. A homogeneous slug of slurry was then rapidly pumped into each column and the

starting time noted. During all experiments, height of surface measurements and density profiles were recorded using a tape measure and x-ray apparatus, respectively. For most experiments descriptions of the appearance of the slurry during compression were also recorded. Pore pressures were measured in experiments suitably instrumented.

Experiments were terminated after different durations and succeeded by a variety of activities. In all experiments the first activity was to drain off water above the settled bed. In segmented column experiments segments above the bed were also removed. In experiments RB10-22 shear strength profiles of the bed were obtained before carrying out other post-experiment tests. Profiles were made by advancing a small vane on the end of a length of segmented cased rods vertically through a bed and performing shear vane tests at regularly spaced intervals. Matched profiles of staggered tests yielded continuous profiles of strength.

Cores of sediment destined for fabric examination were recovered in certain experiments. In these experiments, the positions of shear vane profiles and of cores were distal. Samples were recovered, with varying degrees of success, using a sample tube and guide, as described earlier. If a plug was missed initially then a rigid sleeve was slid over the sample tube and used to protect the sample whilst guiding the tube onto a plug. Once sealed from below with a plug, tubes were withdrawn slowly from the bed and placed vertically in an acetone bath. After replacing the pore water with acetone, each core was impregnated with resin, cured, sectioned and analyzed. Procedures for fabric-related activities after sample recovery are described in Chapter 6.

All experiments, except RB13, were concluded by recovering samples for particle size analysis. This was completed by placing a sealed plunger against the sediment surface, inverting the column, removing the base, extruding the settled bed, and taking samples at regular intervals. Particle size analyses were carried out using either a British Standards pipette method or a laser granulometric technique (see section 4.2).

All but one type of experimental data was processed and/or combined with other forms of data prior to being analyzed. Data gathering, management, and analysis are described in section 3.3.

3.2 Slurry Preparation

Slurries were prepared from two natural muds, designated Combwich 6 and Combwich 7. The former of these was collected by Elder from the upper 50 cm of an intertidal deposit in a tributary of the River Parrett estuary, near Bridge Water, Somerset. All of Elder's experiments were carried out using this sediment, as were experiments RB1-9 in the present programme. In August 1986, 125 litres of Combwich 7 mud were excavated from the same source location. The entire quantity of Combwich 7 mud retrieved was wet sieved using tap water and a 63 μm sieve. A small quantity of material (<1%) larger then 63 μm (worms predominantly) was discarded. The sieved material was extensively mixed to ensure consistent material properties throughout the five sealed bins in which it was stored.

By virtue of its depositional environment the pore fluid of the excavated mud was saline. During sieving the pore fluid was diluted, and clear

supernatant decanted off as consolidation occurred. The mud was stored at a density of 1.3 to 1.5 Mg m^{-3}. When mixed with tap water to a density of 1.10 Mg m^{-3} the pore fluid salinity was approximately 5 parts per thousand (PPT). In experiments RB01-09 (ρ_i=1.047 to 1.10 Mg m^{-3}) the pore fluid salinity was not measured but was estimated to have been 2 to 5 PPT. Elder's experiments, which were conducted with sieved slurries of higher density (typically 1.25 to 1.4 Mg m^{-3}) were probably more saline, although Elder neither measured nor controlled this parameter.

In experiments RB10 through RB22 the salinity of the suspending medium was controlled. Pore fluid salinities of 0.2 and 0.68 g l^{-1} were achieved by washing sediment with deionized water, centrifuging and decanting. These operations had an observable effect on the flocculation characteristics of the sediment. Salinity was determined by measuring the conductivity of the supernatant and converting this to an equivalent sodium chloride concentration using physical chemistry tables. Concentrated slurries were diluted using a solution of deionized water and Analar grade sodium chloride.

A brief attempt was made to produce an inorganic slurry for the purpose of assessing the influence of organics on behaviour. Vereet et al. (1986) stated that the general understanding of the effect of organics on cohesive sediment behaviour is poor because surface active sediments are often extremely sensitive to small changes in the type and quantity of organics in a system, and small amounts and changes are difficult to measure. Of the numerous methods available for destroying organics within a slurry, oxidation with hydrogen peroxide was chosen because this method does not

alter the inorganic fraction of the sample. It does not, however, destroy all of the organic material present. Because there were no accurate means of determining what fraction of organics remained (as is required for control), and because large quantities of hydrogen peroxide were required to achieve a substantial reduction in organics, the process was abandoned and the presence of an unknown organic fraction acknowledged.

Elder compared batches of Combwich mud used by Been (1980), Sills and Thomas (1983) and himself (Elder, 1985; Combwich 6) and concluded that they were all similar. The average specific gravity of solids was 2.66 ±0.01. The clay was mainly illitic with some kaolinite and a smaller amount of chlorite. The silt fraction consisted of 35-40% quartz, with lesser amounts of calcite, feldspar, illite, and kaolinite in approximately descending order (Sills et al., 1985). The mineralogy of Combwich 7 was assumed to be similar.

Particle size analyses of Combwich 6 and Combwich 7 muds revealed different distributions for the two sediments (see section 4.2) but similar d_{50} values (≈7 μm).

In experiments RB01-09 and RB10-22 initial slurry densities were prepared by dilution using tap water and salt solutions, respectively. Densities were measured using a handheld densimeter accurate to ±0.001 Mg m^{-3}. For 15 to 30 minutes before the start of each experiment slurries were circulated within a 25 litre container using a diaphragm pump. The temperature of the slurry was maintained within ±2°C of room temperature although the latter was not controlled; prolonged pumping tended to raise slurry temperature.

Slurry was input to each column using a 21 mm I.D. tube. The end of the tube was maintained either at the bottom of the column (RB10-12) or just below the rising surface of the slurry. Near to the desired initial height for each experiment a T-junction was closed and the input tube withdrawn. The time t=0 was recorded and monitoring begun.

3.3 Details of Equipment and Data Gathered

3.3.1 General Setup

Figure 3.1 shows a general view of the experimental apparatus, including the lower portions of two three-segment 102 mm I.D. acrylic columns, cluster arms and a central rotatable stand. Pore pressure ports, tubing and two central pressure units (section 3.3.2) are also shown. In front and behind of one of the columns are an x-ray source and detector, respectively (section 3.3.3). General views of the shear vane apparatus (sub-section 3.3.4; Figure 3.9), fabric sampling equipment (sub-section 3.3.5; Figure 3.16), and the method of recovering subsamples from a bed for particle size analysis (sub-section 3.3.6; Figure 3.17), are shown in the sub-sections indicated.

In experiments RB10-22 segmented columns were necessary in order to gain access to settled beds for shear vane testing and fabric sampling. Simple, O-ring sealed lap joints were developed and used (Figure 3.2). Push-fit construction minimized bed disturbance during disassembly of segments above the bed. A central cluster support arrangement was developed to house columns and minimize susceptibility to disturbance, to allow columns to be

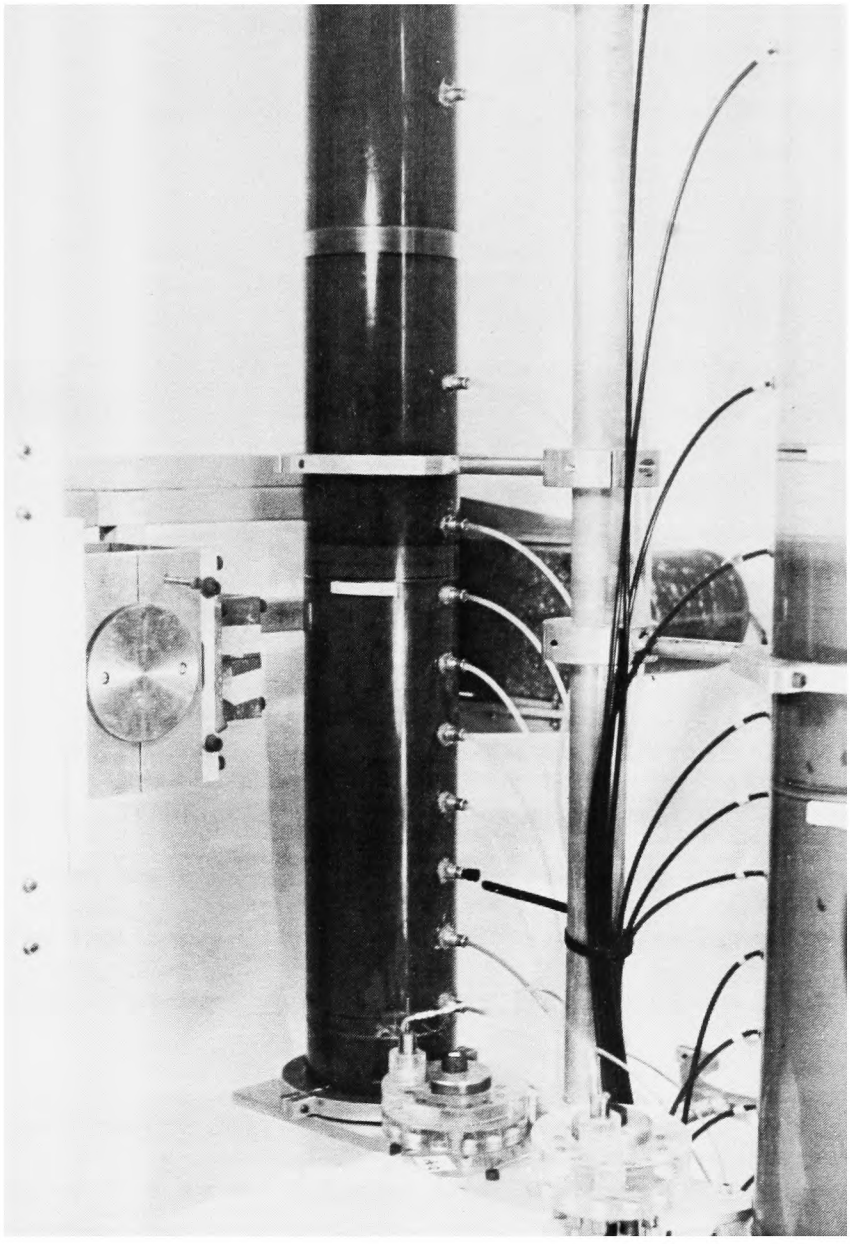


Figure 3.1 General Experimental Setup

profiled in quick succession, and to make accurate and repeatable column - x-ray alignment possible.

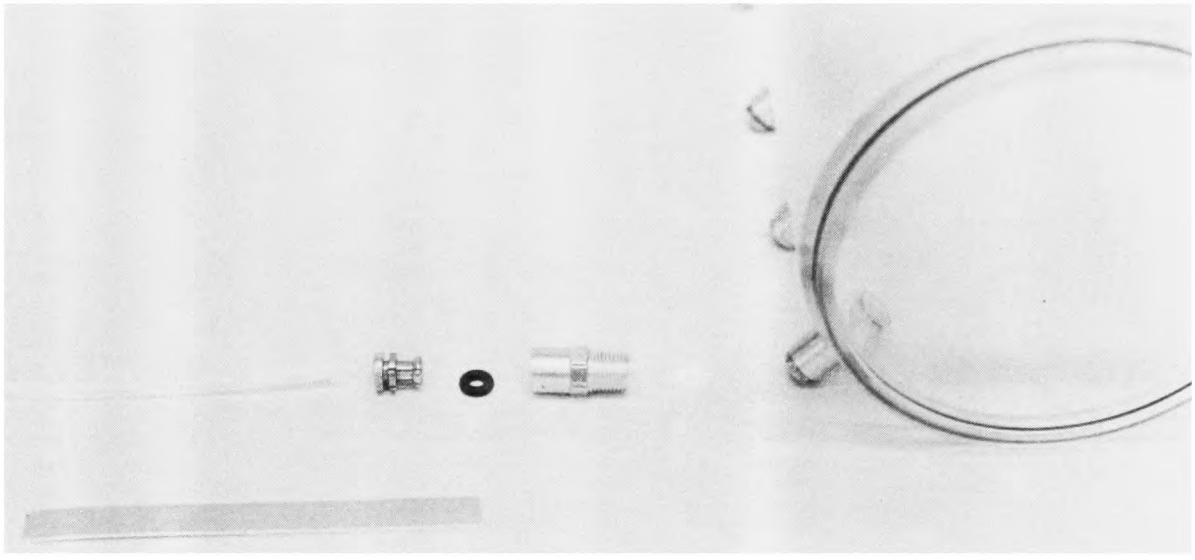


Figure 3.2 Detail of Column Port

The height of the sediment surface above the base of the column was measured either visually with a scale (with 1 mm divisions) on the outside of the column or, when indistinguishable from an overlying cloudy supernatant, by using an x-ray apparatus. Slurry surface heights were recorded with respect to elapsed time and needed no processing prior to analysis.

3.3.2 Central Pressure Unit - Pore Pressure Measurements

Figures 3.2, 3.3, 3.4, and 3.5 show details of the pore pressure measuring system developed and used in experiments RB10-22. Figure 3.2 shows the components of a column port: a 0.75 mm thick synthetic filter set into the column wall flush with the inside surface, and an Enot fitting with an internal O-ring and pressure catch for holding 5 mm O.D. no volume change tubing. Figures 3.3 and 3.4 show views of a Central Pressure Unit (CPU) extended and in operation respectively. CPU's consisted of two mated

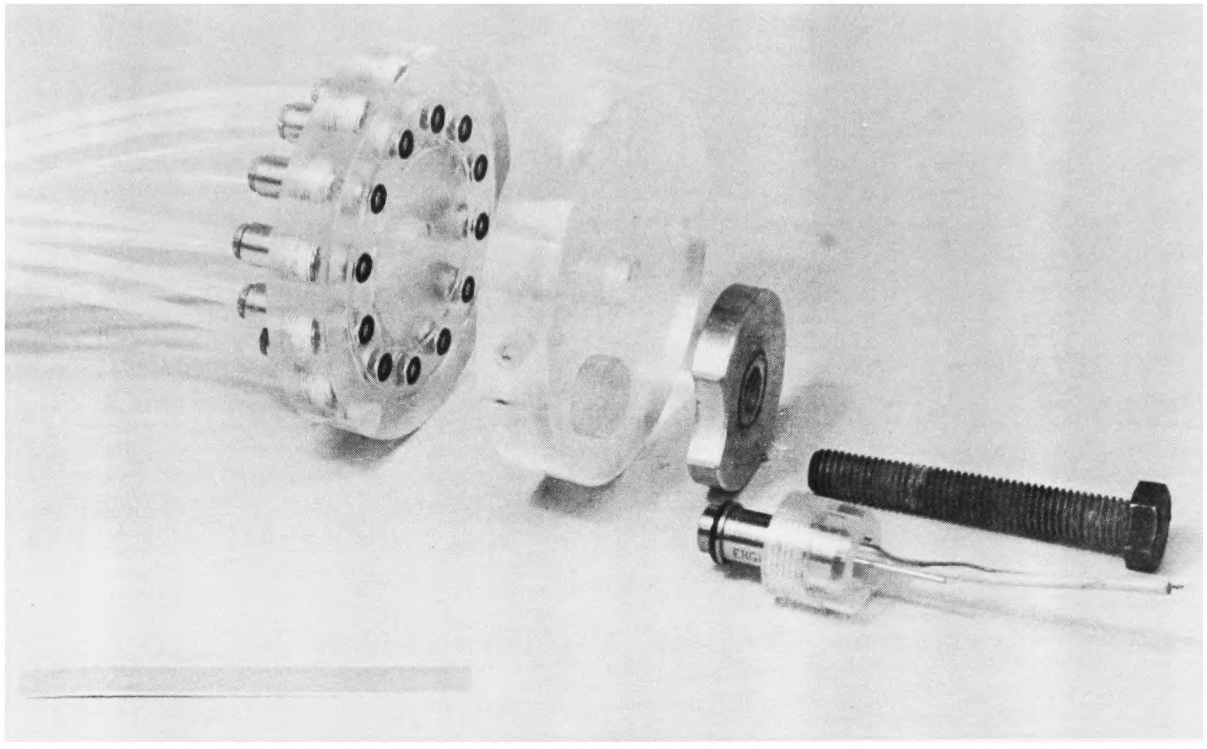


Figure 3.3 View of Extended Central Pressure Unit

perspex dials. The lower dial consisted of twelve Enot fittings, eleven tubes from column ports, and one tube from a portable reservoir. Each port hole through the lower dial of the CPU was surrounded by a separate O-ring so as to seal against the flat bottom of the upper dial. A single 1 mm diameter hole through the upper dial terminated in a sealed transducer housing. The two dials were held together by a nut, bolt, and washer.

CPU's were operated manually by rotating the upper dial and aligning the 1 mm diameter hole therein with a port in the lower dial; this action provided hydraulic continuity between the pore fluid adjacent to a column port filter and the transducer in the CPU. Negligible flow occurred. A

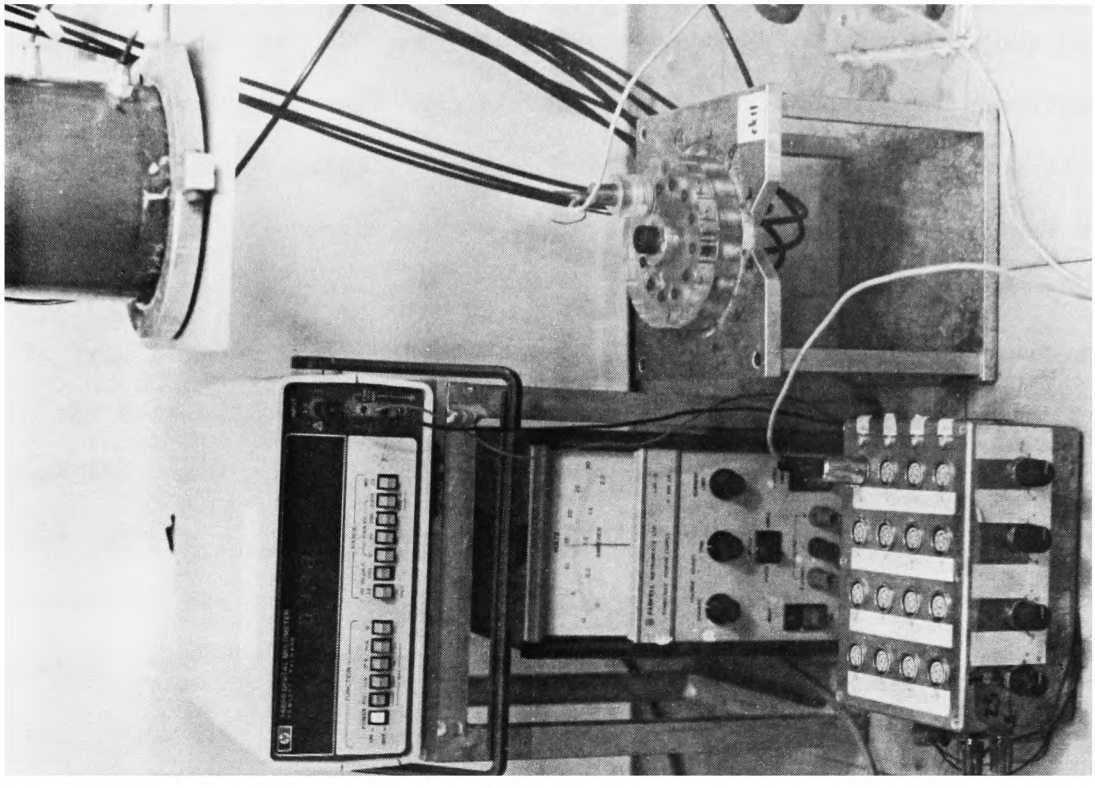


Figure 3.5 Supporting Electronic Hardware for CPU

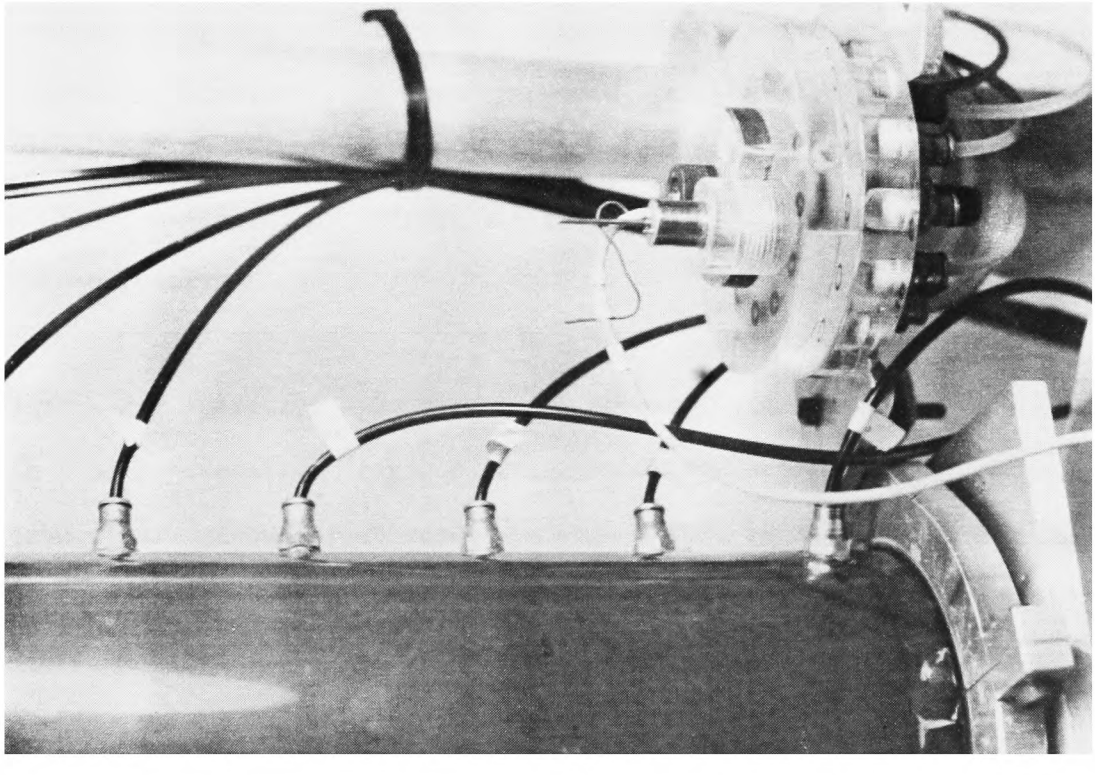


Figure 3.4 Central Pressure Unit (CPU) in Use

small amount of system compliance resulted in equilibration times of approximately 5 to 300 seconds. The transducer in each CPU (one CPU per column) was checked and calibrated prior to each set of measurements. Calibration was carried out via a CPU port connected to a portable reservoir, the elevation of which was varied relative to a fixed scale. This procedure eliminated earlier problems with severe transducer signal drift and yielded trustworthy results. The accuracy of the readings was ±1 mm of head of water (±0.01 kPa), based on measurements made under hydrostatic and uniform slurry conditions. Total stresses and maximum excess stresses were of the order of 14 and 1 kPa respectively which illustrates the high relative accuracy of the pore pressure measuring system.

Pore pressures were derived from transducer voltage signals. Transducers from up to 16 CPU's were connected to a central voltage regulated power/switching box (Figure 3.5). Signals from transducers were directed to a digital voltmeter and converted to pressures above hydrostatic using calibration equations. Data were combined and stored with port elevation and elapsed time data. Figure 3.6 (page 59) is a graphical example of pore pressure results.

3.3.3 X-Ray Apparatus - Density Measurements

Bulk soil density may be determined non-destructively using x-ray attenuation. X-radiation passed through a soil is attenuated by absorption and scattering. The beam emerging from a soil sample consists of x-radiation transmitted directly, and scattered radiation. An ideal narrow

beam contains direct radiation only and attenuation occurs in accordance with the equation,

$$I = I_o \exp(-\mu_m \rho x) \quad \ldots 3.1$$

where I_o = incidental radiation intensity

I = transmitted radiation intensity

μ_m = total mass absorption coefficient

ρ = density of absorbing material

x = absorber thickness

The practical equivalent of equation 3.1 for a soil is,

$$N = N_o \exp(-\mu_m \rho x) \quad \ldots 3.2$$

where N_o = scintillation count rate with no sample present

N = scintillation count rate with sample present

ρ = bulk soil density

x = sample thickness or column diameter

In order for equation 3.2 to be valid the x-ray detector must be shielded from scattered radiation, a condition achieved satisfactorily by collimation. In practice, several problems hinder the theoretical determination of bulk density. For instance, the parameter total mass absorption coefficient is strongly dependent on the radiation energy, and the atomic chemistry of the absorbing material. The Oxford x-ray source is not mono-energetic, rather it emits a broad spectrum of radiation energies. In addition, soil is a chemically complex material. Both factors make it very difficult to specify a total mass absorption coefficient. The parameter N, which is the scintillation count rate with sample present, is influenced by variations in the dimensions of the column, by fluctuations in the beam intensity, and by the statistical nature of x-ray generation. The problem of relating attenuation to density is best treated empirically.

The Oxford x-ray apparatus was developed by Been (1980, 1981), modified by Elder (1985) and used without further alteration by the author. The apparatus consists of several components: x-ray source and detector; vertical lead screw and stepper motor; 160 kilovolt power source; scintillation counter, DC chart recorder, and digital height display.

Been (1981) discussed important practical aspects of bulk density determination using x-ray attenuation. These include control of the x-ray energy distribution, x-ray detection using a phosphor crystal, photomultiplier tube and light emissions counter, details of count rate discrimination levels and accuracy, and the geometry of the various components of the system. The spatial resolution of the measuring system when held in a stationary position is controlled by the degree of collimation of the x-ray beam. The accuracy of the count rate recorded is determined by the time constant of the rate meter and by the stability of the power applied to the x-ray source and scintillation detector. Count rate accuracy increases with increasing time constant, but the responsiveness of the system during the recording of a density profile decreases. The choice of a time constant is, therefore, a compromise between accuracy and response time. In the present research a traverse speed of 2 mm per second and a time constant of 0.4 seconds were used, thus density was averaged over a distance of 0.8 mm. The detector was collimated by a 0.125 mm slit. The potentiometrically determined and digitally displayed height of the source was accurate to $\pm$0.5 mm.

X-ray count rate versus height profiles were made using the following sequence of procedures: (i) establish a constant x-ray generation rate

through a clear water calibration sample; (ii) traverse the source and detector parallel to a column twice whilst making a chart record of count rate as a function of height; and (iii) confirm the stability of the x-ray by re-examining the calibration sample. Step (ii) was repeated if pairs of profiles differed significantly, whilst the entire process was repeated if the x-ray generation rate was observed to vary during recording.

Continuous count rate profiles were digitized into between 50 and 150 straight line segments. Count rate profiles were then converted to density profiles by back calculating an average attenuation constant for each profile and applying equation 3.5, below.

In general, when the same incident radiation intensity is applied to a column filled first with water (density ρ_w) and then slurry (density ρ) the transmitted count rates for water only (N_w) and the slurry (N) are related by,

$$\rho-\rho_w=\frac{-1}{k_x}\ln(N/N_w) \qquad \ldots 3.3$$

where $k_x=\mu_m x$, with μ_m and x as defined earlier, and k_x is the average attenuation constant. N_w can be measured by projecting an x-ray beam either through clear supernatant above a settled bed, or through a clear calibration sample contained in a short column section.

The difference $(\rho-\rho_w)$ is the buoyant weight of sediment at a particular point. The total vertical stress above hydrostatic (σ_{ex}) at the base of a column is the cumulative sum of the buoyant weight over the height of the bed, that is,

$$\sigma_{ex} = \int_{o}^{h_s} (\rho - \rho_w)\, g\, dh \qquad \ldots 3.4$$

where g = gravitational constant

h = height

h_s = height of slurry surface

Substituting equation 3.3 into equation 3.4, and expressing the resulting integral as a sum of discrete linear segments yields,

$$\sigma_{ex} = \frac{-g}{k_x} \left[\sum_{i=1}^{n-1} \{ \ln(N_i N_{i+1}) \Delta h_i \} - 2h_s \ln N_w \right] \qquad \ldots 3.5$$

where N_i and N_{i+1} are count rates at consecutive elevations, and Δh_i is the difference in elevation. The quantity σ_{ex} was determined in each experiment by measuring initial slurry density and height, and by applying equation 3.4. Equation 3.5 was then solved to yield k_x. Each digitized count rate was converted to a bulk density using equation 3.3, yielding a finely discretized profile of density versus height (Figure 3.7). Profiles of total stress above hydrostatic were calculated by applying equation 3.5, knowing k_x, and summing down from the sediment surface rather than up from the base of the column. Figure 3.8 shows total stress profiles calculated using density profiles shown in Figure 3.7.

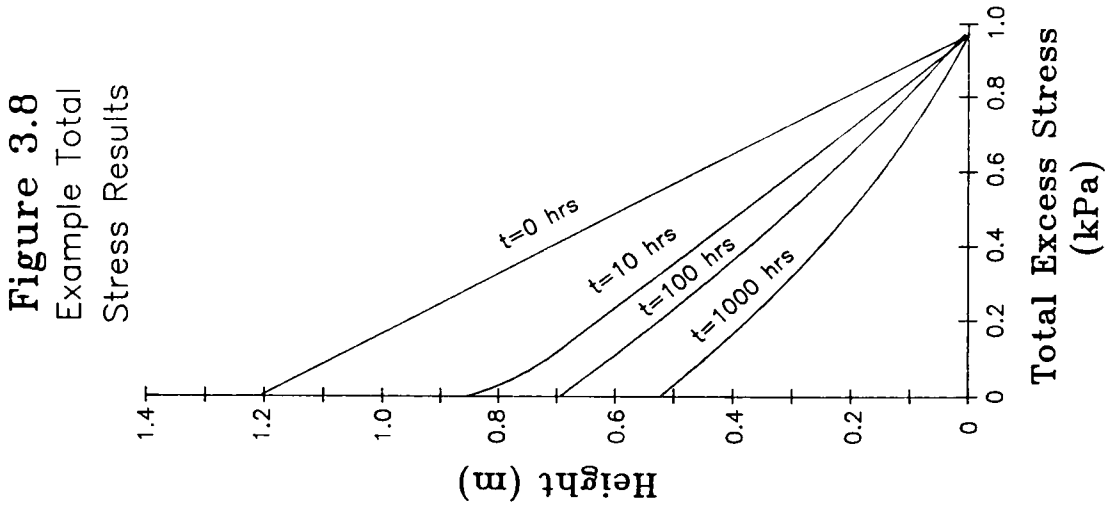


Figure 3.8 Example Total Stress Results

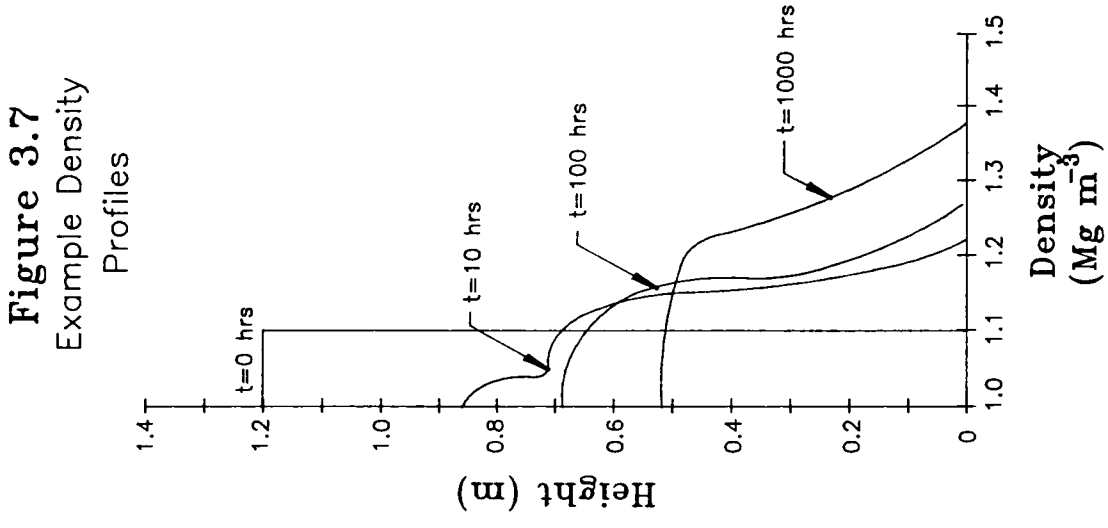


Figure 3.7 Example Density Profiles

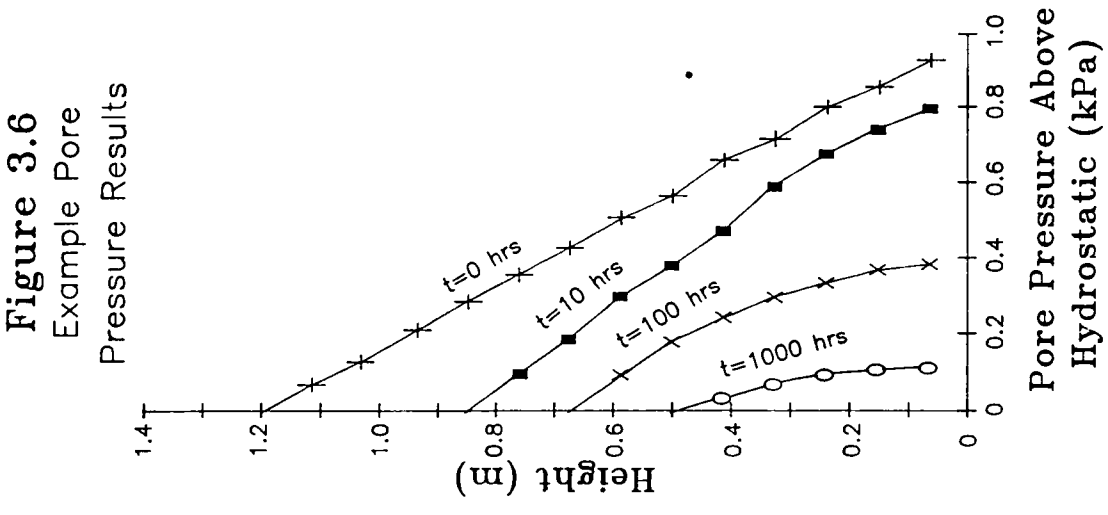


Figure 3.6 Example Pore Pressure Results

In section 3.2 the practice of profiling a water filled column prior to beginning an experiment was mentioned. The purpose of this was to provide a basic or 'blank' column x-ray count rate profile against which subsequent profiles could be compared, and the undesirable effects of segment joints and column inhomogeneities eliminated. Consistent column - x-ray alignment was achieved by using alignment pins attached to the cluster support stand.

The accuracy of the x-ray apparatus was governed by fluctuations in the x-ray power source. Fluctuations were limited to ±2000 counts per second (cps) about an average count rate for two passes of approximately 10^5cps. These bounds represent accuracies of ±0.014 and ±0.020 Mg m^{-3} at densities of 1.10 and 1.30 Mg m^{-3}, respectively. In terms of the volumetric parameter specific volume, these accuracies are approximately ±2.3 and ±0.37 at specific volumes of 16.5 and 5.5, respectively; note that the accuracy of the x-ray apparatus is greater at low than at high specific volumes when viewed in terms of absolute specific volumes.

3.3.4 Shear Vane Apparatus - Strength Measurements

Shear strength measurements were made in the terminal beds of experiments RB10-22 using a modified laboratory shear vane apparatus. The principle components of the system are shown in Figure 3.9 and include: a stepper motor; strain-gauged torque cell; a universal joint, segmented vane rods, and vane; segmented casing, casing guide and guide platform; and ancillary electronic hardware. In Figures 3.10 and 3.11 components of the system are shown individually and assembled.

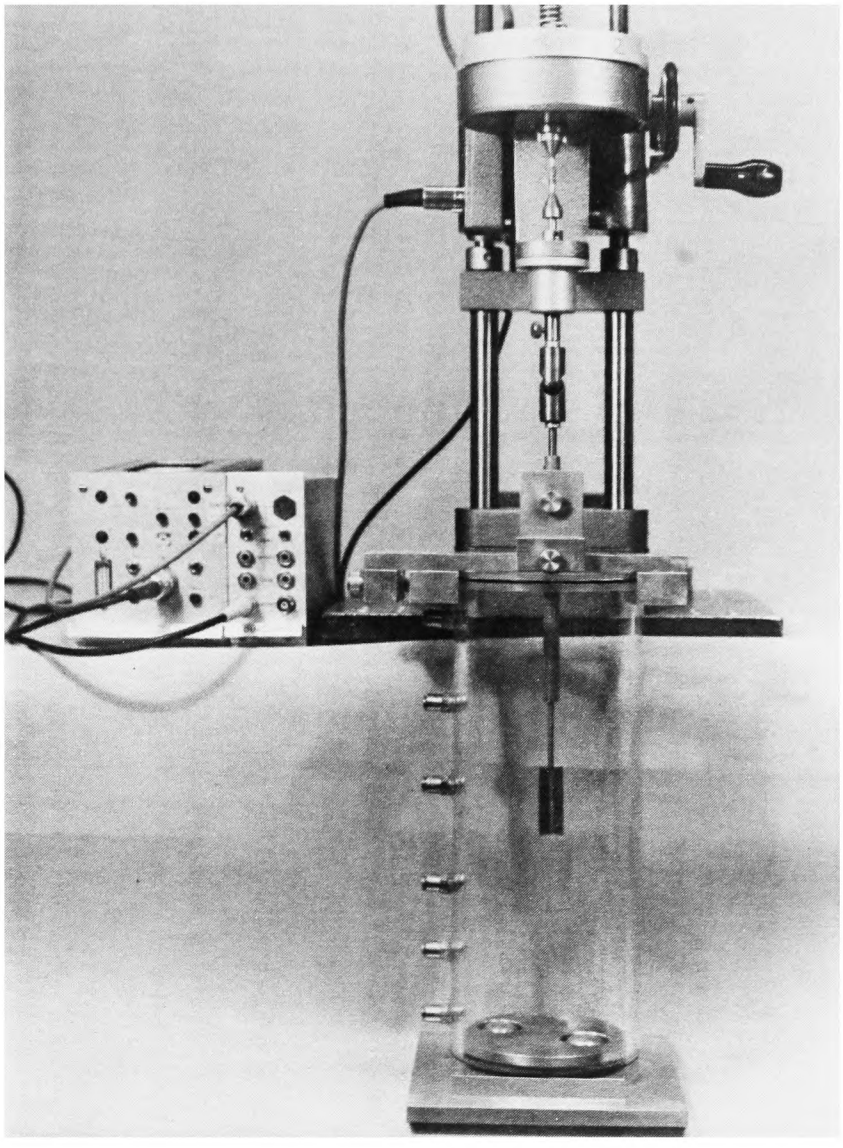


Figure 3.9 Modified Shear Vane Apparatus: Assembled - I

The apparatus was operated as follows: segments of rod and casing, the vane, the universal joint, the casing guide and guide platform were assembled, as shown in Figure 3.11. Using the rod guide to maintain a vertical line, the vane, rods and casing were advanced into the sediment by the head of the shear vane apparatus; at a tip depth of two vane heights

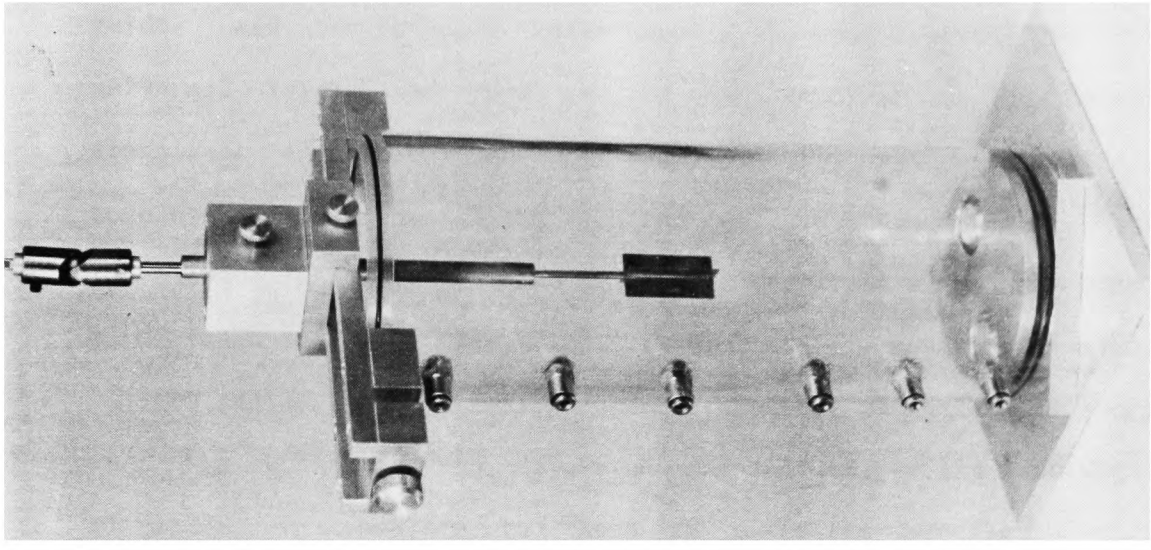


Figure 3.11 Modified Shear Vane Apparatus: Assembled

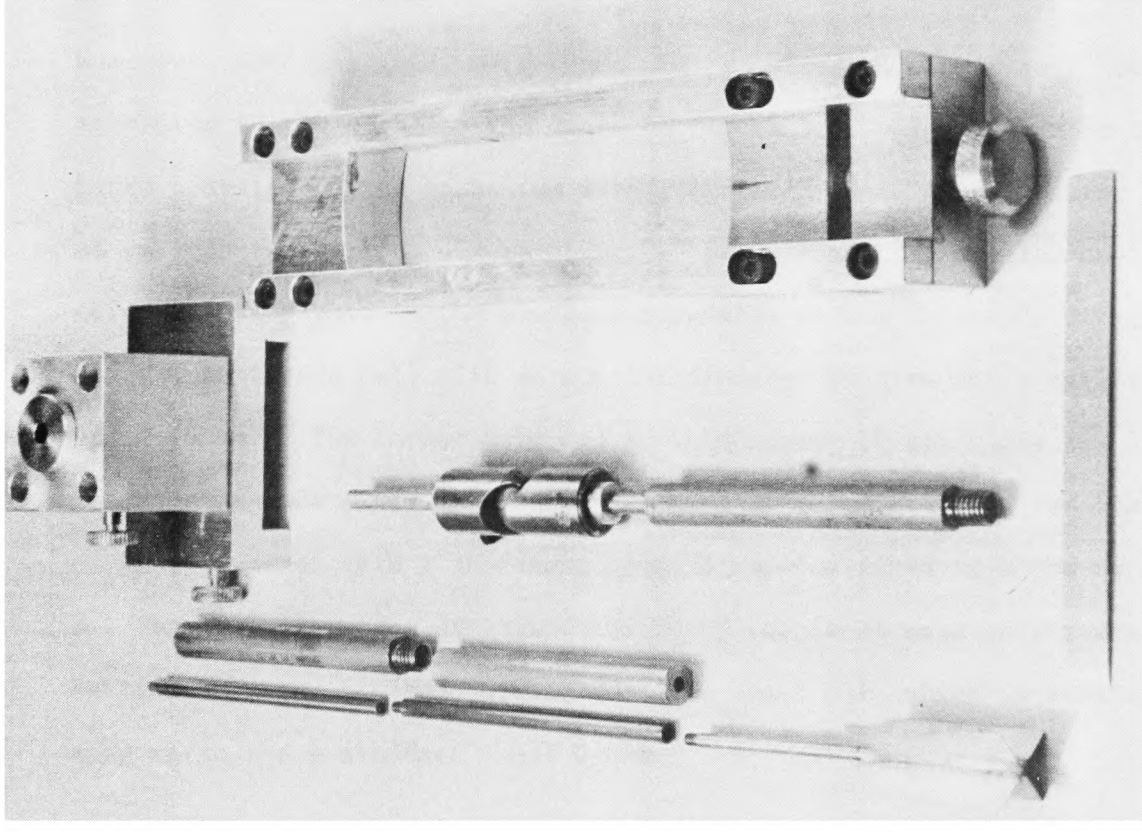


Figure 3.10 Shear Vane, Casing, Universal, and Guide

below the sediment surface the rods were held stationary and the casing lowered 2 mm so as to be free of the rods; the casing was locked to the guide, and the stepper motor turning the vane (through the torque cell, universal joint, and rods) and the chart recorder tracing the torque cell transducer signal output were simultaneously set in motion; after two complete revolutions of the vane the test was stopped and the stability of the torque cell checked; rods and casing were then added, the vane advanced a distance of two vane heights (thus leaving a zone of untested material between tests), and the test procedure repeated; at the end of a profile the vane was withdrawn and relocated, and another profile made with tests at elevations intermediate to those in preceding profiles. Output from individual tests had the form shown in Figure 3.12. Figure 3.13 shows the combined results of shear strength profiles.

Numerous modifications were made to a standard laboratory shear vane apparatus to yield the system shown in Figure 3.9. Elder replaced the usual hand operated drive mechanism with a variable speed stepper motor operated at a constant rate of rotation, 1° per second. Elder also replaced the torque spring used on the standard apparatus with a thin-wall strain-gauged brass tube torque cell with an outside diameter of 3 mm and a wall thickness of 0.15 mm. The torque cell had a yield torque of approximately 180 N mm. The custom made shear vane was 40 mm high by 20 mm wide and was constructed of sheet metal with a thickness of 0.35 mm, and fixed to a rod of diameter 3.2 mm. The ratio of the vane cross-sectional area to circular cross-sectional area scribed during rotation was 0.011, which is similar to the same ratio for a standard vane, 0.010.

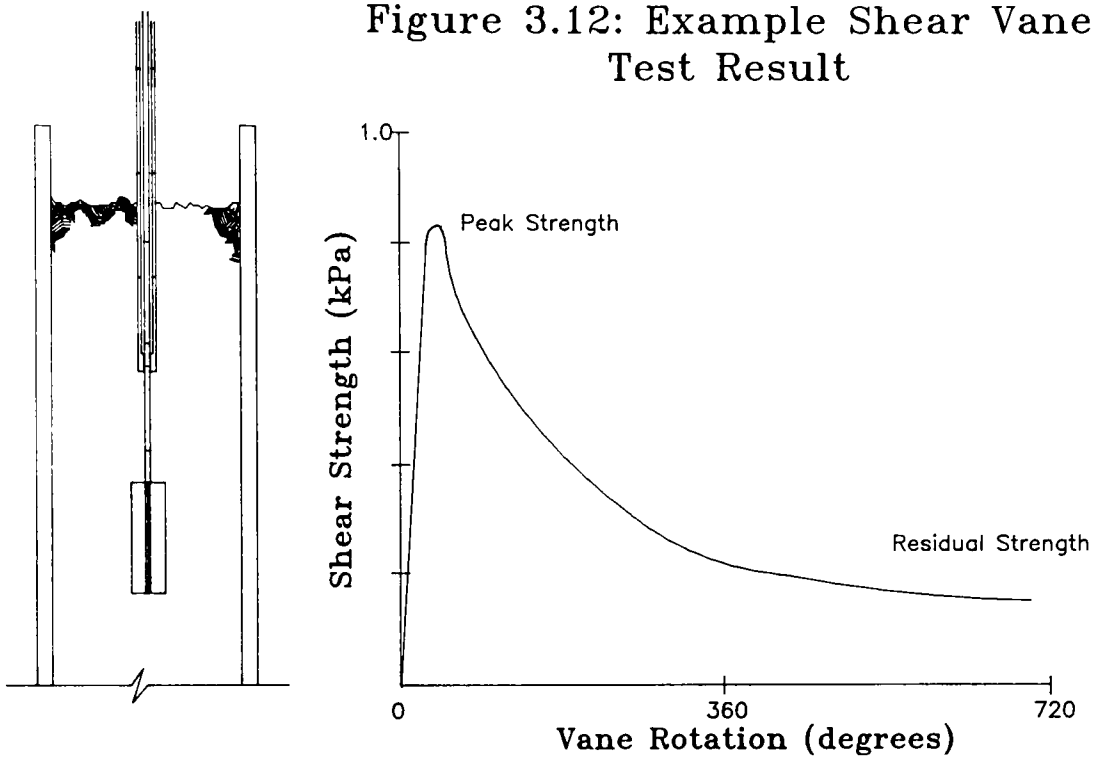


Figure 3.12: Example Shear Vane Test Result

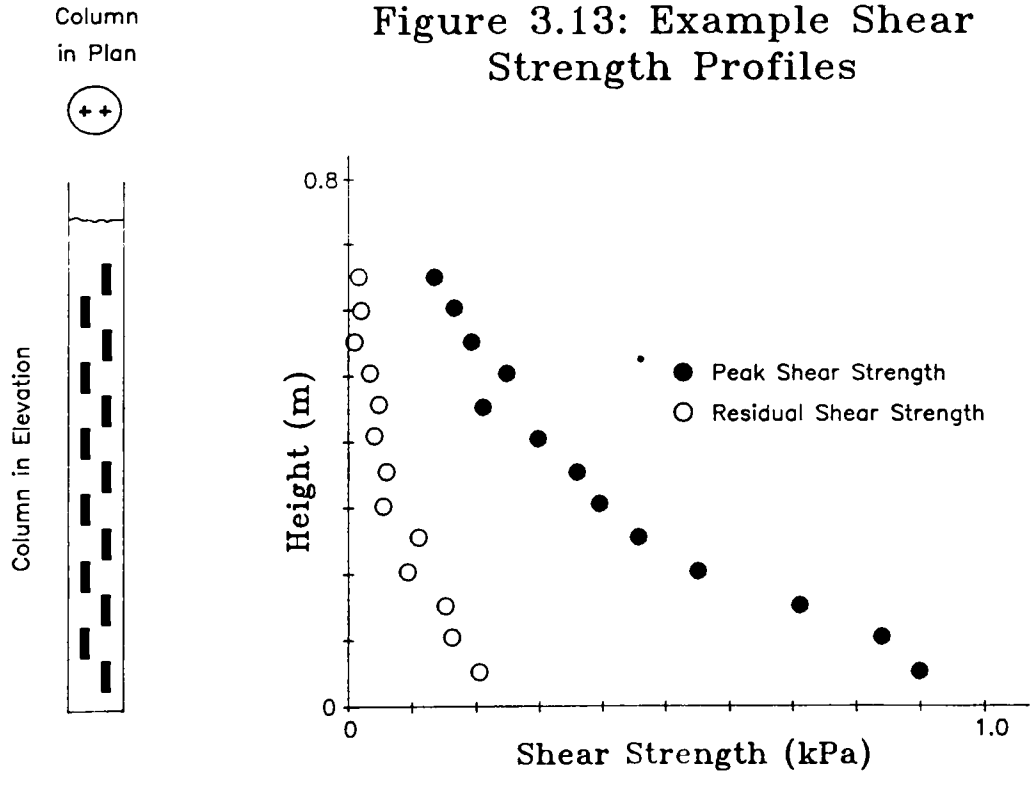


Figure 3.13: Example Shear Strength Profiles

The standard vane apparatus is designed for testing at a constant depth of penetration below the sediment surface. In order to obtain measurements throughout a thick deposit with the standard apparatus, excavation of sediment and frequent sectioning of the column are necessary: this procedure was used by Elder. Both activities potentially disturb the sediment which is an unacceptable when the settled bed is sensitive, and thus strongly affected by disturbance. To minimize sediment disturbance and to avoid uncertainties regarding the influence of removing overburden on stress conditions and shear strengths, a system of segmented rods and casing was developed by the author. Segmented rods were developed to permit shear vane testing in situ over the full bed thickness whilst segments of casing were used to eliminate soil-rod friction that would have otherwise contributed to the torque-rotation response recorded during testing. A guide assembly was used to guide casing and rods during penetration, and to maintain the casing independent of the rods during testing. A universal joint was included to reduce the effects of imperfect alignment between the axes of the rods and the rod holder. With the universal joint in place the vane was free to rotate about an axis through its shaft, as in conventional testing.

The torque cell was calibrated using the apparatus shown in Figure 3.14. Sacks of lead shot of known mass were suspended by threads over wheels with PTFE axle liners at right angles to a moment arm connected to the torque cell. The torque-transducer signal response was linear over the range of torques encountered in the present programme, hence a single calibration constant was used to convert transducer signals to applied torques. The accuracy of the torque cell, determined by its sensitivity and the calibration technique, was ± 0.1 N m.

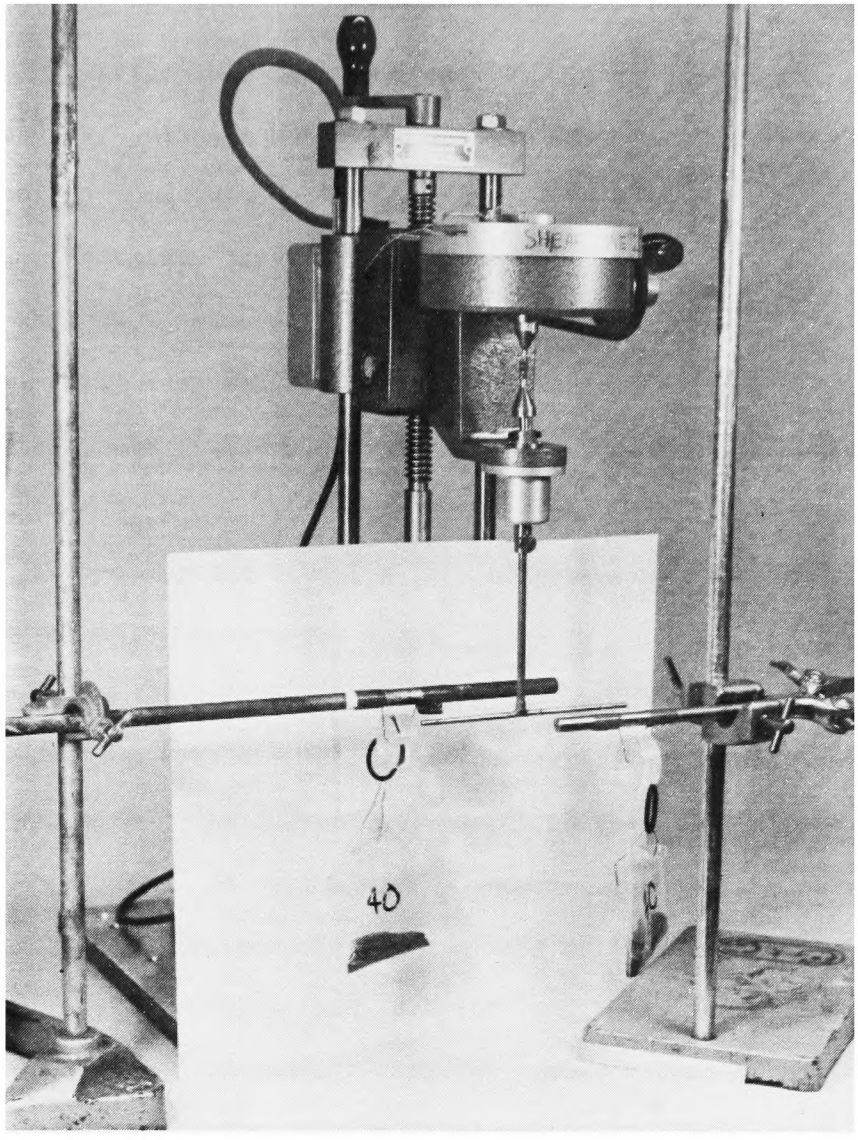


Figure 3.14 Shear Vane Calibration Apparatus

The accuracy of vane shear strength measurements is, in general, subject to considerable criticism. The reasons for this relate to (a) the influence of test equipment and methods on torque response and (b) uncertainties about the conversion of torque to shear strength. Factors known to influence torque response include (i) disturbance during vane insertion, (ii) vane rotation rate, (iii) boundary conditions, (iv) strength anisotropy, (v)

shear stress distributions along the vertical and horizontal edges of the vane, and (vi) the position of the failure surface. Factor (i) was minimized by using a vane with a small cross-sectional area and by testing as soon as possible after insertion, a period not exceeding two minutes. The vane rotation rate (ii) was held constant at 1° per second, as used by Elder, and undrained conditions were assumed, although not proven. Boundary effects (iii) were rendered negligible by conducting tests at a distance of three vane radii from the column wall, as suggested by Stevenson (1973). As a check on the effect of conducting multiple shear vane profiles in a single column the staggered results of neighbouring profiles were compared; no evidence of interference was found.

Factors (v) and (vi) are important in regards to the conversion of torque to shear strength. It is generally accepted that the failure surface about a rectangular vane is cylindrical, however, the size of the cylinder and stress conditions surrounding it are less well understood. Based on work by Donald et al., (1977) and Menzies and Merrifield (1980), Wroth (1984) proposed a method of interpreting vane shear strength test results in which stress conditions are approximated with a stress distribution which is uniform along the vertical edges and highly non-linear along the horizontal edges. Wroth's suggested pattern yields the following torque-shear stress equation,

$$T = \frac{\pi d^3 \tau_m}{2(n+3)} + \frac{\pi d^2 h \tau_m}{2} \qquad \ldots 3.6$$

where T = torque (N m), τ_m = shear stress, d = vane diameter, h = vane height, and $n \simeq 5$. Shear strength (s_u) may be calculated by substituting

the measured torque T into equation 3.6, solving for τ_m, and equating shear stress to shear strength ($\tau_m = s_u$).

In the present research the accuracy of strength measurements was less important than their precision because the objective was to study the relative influence of experimental conditions and time on shear strength and its development. Using consistent procedures, the precision of torque measurements was $\pm$ 0.1 N m or, equivalently, a shear strength of $\pm$ 4 N m^{-2} (based on equation 3.6 and a 40 x 20 mm vane). Residual and peak strengths were of the order of 10 to 80 and 60 to 500 N m^{-2}, respectively.

3.3.5 Fabric Sampling Equipment

In each of experiments RB10-13, 18, 21, and 22 a core of sediment was recovered for fabric examination. This was carried out using the equipment shown lain out in Figure 3.15, and shown assembled in Figure 3.16. The principle components of the system include: recessed column base; O-ring plugs; permeable wall sample tube, permeable sample tube sheath, tube cutting shoe, and tube piston; sample tube guide assembly; and rigid sample tube sleeve (not shown). Both the general method of sampling and the need for pre-experiment sample tube-plug alignment are discussed in section 3.1. A few equipment specifications and details of methodology are presented here.

Each sample tube was manufactured by rolling and thermally seam sealing rectangular sheets of 0.75 mm thick permeable polystyrene. Finished tubes had an inside diameter of 23.5 mm and a length of 400 to 500 mm Each

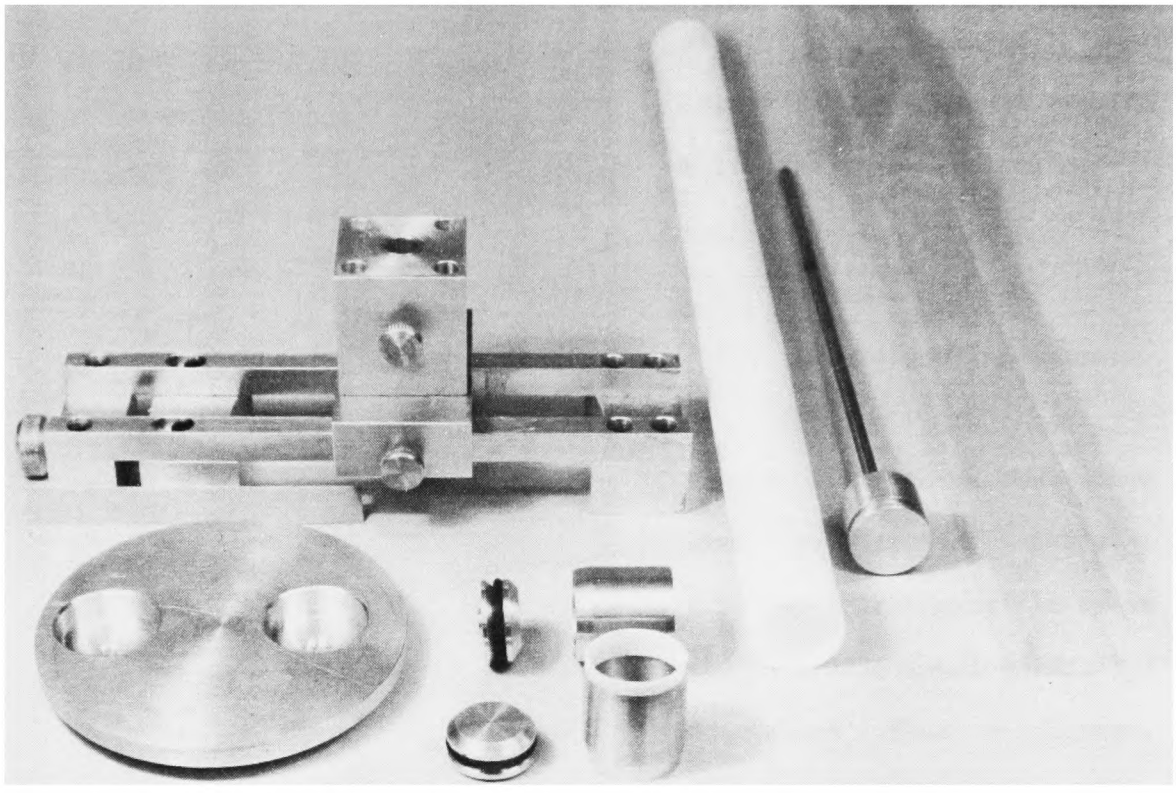


Figure 3.15 Components of Fabric Sampling Apparatus

tube was fitted with a 1 mm thick by 23.5 mm I.D. by 25 mm high cutting shoe. The ratio of the cross-sectional area of the shoe to that of the sample was 0.18, approximately one-sixth that of a standard core barrel used in the field for Standard Penetration Testing (area ratio of 1.12). Excess sediment was prevented from entering the tube during sampling by maintaining a piston at the sediment surface. To minimize sample disturbance caused by soil-internal sidewall friction an ultra-thin sheath of high density plastic film was drawn down the outside and up the inside of the sample tube at the rate of tube penetration. A high degree of care was exercised during sampling and recovery rates (ratio of length of core

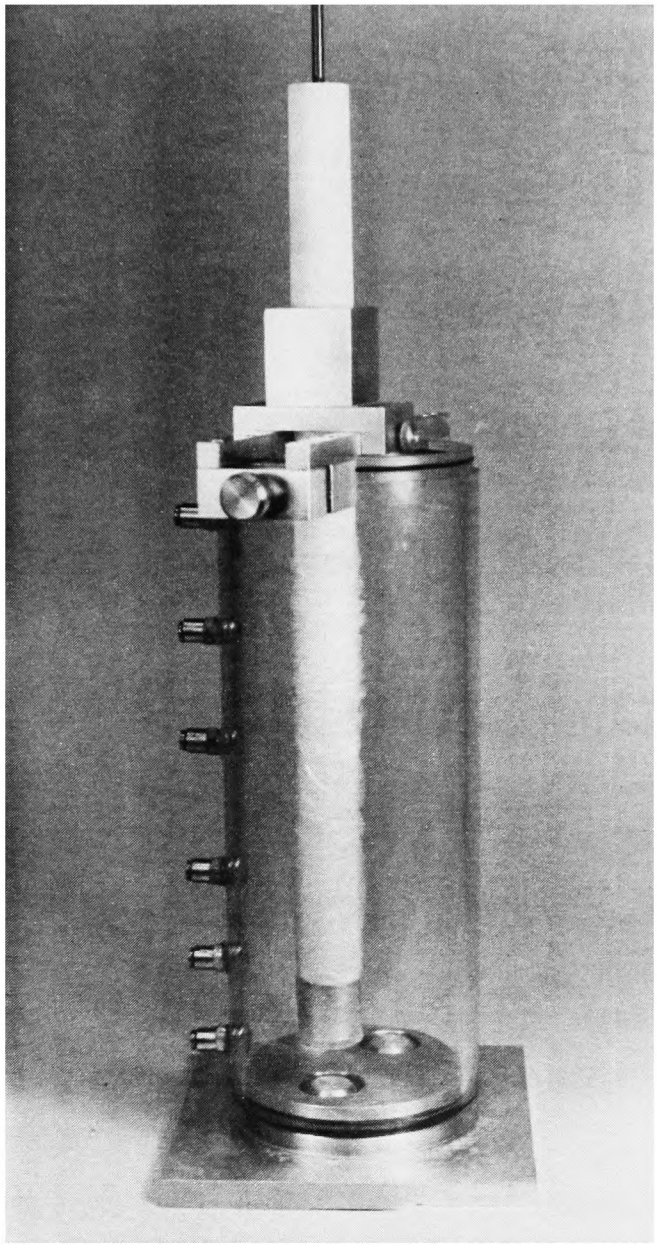


Figure 3.16 Fabric Sampling Apparatus

recovered to depth penetrated) of up to 97 percent were achieved. Post-sampling activities are described in section 6.2.

3.3.6 Particle Size Analysis

Figure 3.17 shows the method used to recover sediment samples for particle size analysis. It involved freeing a column from a cluster, disconnecting pore pressure tubes, placing a sealed piston against the sediment surface, inverting the column, removing the base, and advancing the piston. Zones of very weak material, caused by remoulding during shear vane testing and/or fabric sampling were observable during extrusion. Samples of stiff material only were taken at regular intervals throughout the bed and were stored in sealed containers. Particle size analyses were performed using a British Standards' technique for fine-grained soils, and a more modern laser-diffraction method (referred to in this thesis as



Figure 3.17 Extrusion of Samples for Particle Size Analysis

granulometry). The latter method is based on the principle that particles of a given size diffract light through a given angle. When a narrow beam of monochromatic light is passed through a suspension and the diffracted light focussed onto a detector, the angular distribution of scattered light can be analysed to yield a particle size distribution (McCave et al., 1976). Results of particle size analysis are presented in section 4.2.

TABLE 1 SUMMARY OF RB EXPERIMENTS

Expt	Slurry Characteristics				Initial Conditions				Duration	Data Recorded			Post-Expt Activities		
	Solid Phase		Sus.	Medium	h_s	ρ_i	V_i	Mass Solids		pwp	h_s vs t	Density	Shear Vane	PSD	Fabric
	Sediment	Prep	Type	[NaCl]	m	Mg m^{-3}		g	hours			Profiles	Tests		Sample
1	Comb 6	S	Tap		1.514	1.080	21.5	1571	1372	✓	✓	25			
2	Comb 6	S	Tap		1.538	1.080	21.5	1597	4154	✓	✓	18		7	
3	Comb 6	S	Tap		0.710	1.080	21.5	737	2451		✓	14		7	
4a	Comb 6	S	Tap		0.701	1.080	21.5	727	292		✓	1		6	
4b	Comb 6	S	Tap		0.701	1.080	21.5	737	292		✓	1			
4c	Comb 6	S	Tap		0.707	1.080	21.5	734	292		✓	1			
5a	Comb 6	S	Tap		0.682	1.100	17.1	880	841		✓	1		10	
5b	Comb 6	S	Tap		0.679	1.100	17.1	880	841		✓	1			
5c	Comb 6	S	Tap		0.672	1.100	17.1	880	841		✓	1			
6	Comb 6	S	Tap		0.3	1.080	21.5		621		✓				
7a	Comb 6	S	Tap		0.696	1.060	28.9	546	484		✓	2		5	
7b	Comb 6	S	Tap		0.682	1.060	28.9	546	484		✓				
7c	Comb 6	S	Tap		0.692	1.060	28.9	546	484		✓				
8a	Comb 6	S	Tap		0.693	1.047	37.2	430	484		✓	6		10	
8b	Comb 6	S	Tap		0.682	1.047	37.2	423	484		✓				
8c	Comb 6	S	Tap		0.685	1.047	37.2	425	484		✓				
9	Comb 6	S	Tap		0.676	1.060	28.9	530	987		✓	29		9	
10	Comb 7	S,W	DI	5.0	0.977	1.098	17.4	1261	2160	✓	✓	21	9	5	yes
11	Comb 7	S,W	DI	1.0	0.977	1.098	16.9	1262	2500	✓	✓	17	9	6	yes
12	Comb 7	S,W	DI	0.2	0.969	1.098	16.7	1264	2400	✓	✓	16	8	6	yes

For abbreviations see following page.

TABLE 1 continued

Expt	Slurry Characteristics				Initial Conditions				Duration	Data Recorded			Post-Expt Activities		
	Solid Phase		Sus. Medium		h_s	ρ_i	V_i	Mass Solids		pwp	h_s vs t	Density	Shear Vane	PSD	Fabric
	Batch ID	Prep	Type	[NaCl]	m	Mg m^{-3}		g	hours			Profiles	Tests		Sample
13	Comb 7	S	DI	5.0	0.618	1.160	10.6	1277	2256	✓	✓	14	9	-	yes
14	Comb 7	S	DI	5.0	0.616	1.160	10.6	1272	744	✓	✓	9	15	6	no
15	Comb 7	S	DI	5.0	0.587	1.160	10.6	1213	1176	✓	✓	10	14	6	no
16	Comb 7	S,W	DI	5.0	1.255	1.080	21.5	1280	720	✓	✓	9	16	6	no
17	Comb 7	S,W	DI	5.0	1.254	1.080	21.5	1280	1200	✓	✓	11	13	6	no
18	Comb 7	S,W	DI	5.0	1.250	1.080	21.5	1276	2212	✓	✓	11	10	6	yes
19	Comb 7	S,W	DI	0.7	0.615	1.160	10.3	1292	754	✓	✓	5	18	5	no
20	Comb 7	S,W	DI	0.7	0.609	1.160	10.3	1280	1209	✓	✓	7	17	1	no
21	Comb 7	S,W	DI	0.7	0.610	1.160	10.3	1282	2220	✓	✓	11	14	4	yes
22	Comb 7	S,W	DI	0.7	1.210	1.080	20.5	1280	2227	✓	✓	16	9	6	yes

NOTES:

S Sieved
W Washed

Tap Tap Water
DI Deionized Water

h_s Height of Surface
ρ_i Initial Density
V^1 Specific Volume

pwp Pore Water Pressure
PSD Particle Size Distribution
t Time

[NaCl] in g solute/$g_3$solution, as inferred from conductivity measurements
ρ_{solid}= 2.67 Mg m^{-3}

CHAPTER 4 COMPRESSION BEHAVIOUR: SETTLING RESULTS

4.0 Introduction

In this chapter the settling behaviour of sediment is examined, beginning with the most general and qualitative form of examination possible, a description of the appearance of slurries during settling (section 4.1). The appearances of sediment at the column wall and at the surface of the slurry, and the clarity of supernatant above, are presented to convey a notion of the state of the slurry and the physics of settling that is impossible to acquire from either a graph or a formula. Sediment appearance is invaluable in practice where it is often used as an indicator of degree of flocculation and slurry stability.

Qualitative descriptions of slurries are succeeded by a quantitative examination of particle movements (section 4.2), beginning with differential settling, or segregation. Segregation of particles during settling, due to differences in particle densities, shapes or sizes, produces an inhomogeneous bed, the behaviour of which is difficult to interpret. Segregation can be identified by particle size analysis and provides indirect information about particle mobility, interparticle forces, and flocculation.

The simplest means of quantifying settling behaviour is in terms of rate of settlement of the slurry surface with respect to time (section 4.3). This

characterization has the attractive feature of being based on a parameter, height of surface, which is easy to measure in both the laboratory and the field without sophisticated equipment. Ease of attainment does not, however, necessarily imply usefulness. Height of surface versus time results are considered, first, generally - as indicators of phases of behaviour - and then, more closely, to expose the significance of initial slurry density and pore fluid salinity on surface settling rate.

Height of surface versus time results are analyzed further (in section 4.4), in terms of surface settling rate versus average specific volume. It was on the basis of surface settlement rate and particle concentration that the first settling theories for suspensions were formulated. Several of these theories are examined and their inapplicability to flocculated natural mud slurries is shown. A simplified settling rate model is also presented.

Discrepancies between some settling theories and experimental results are due, at least partly, to erroneous assumptions about the distribution of mass beneath the slurry surface. To demonstrate this, typical density profiles are presented (section 4.5) which show the way in which sediment is arranged and rearranged with respect to time. The discussion accompanying the profiles is only semi-quantitative, but it reveals surprising patterns that, like descriptions of slurry appearance, provide insight into the physics of settling behaviour and have implications for some existing models.

In the penultimate section of this chapter density profiles are discretized to show, quantitatively, the behaviour of layers and individual elements of soil as a function of local specific volume.

Chapter four ends with a commentary on forms of characterizing settling behaviour which are presented within the chapter.

4.1 Slurry Appearance During Compression

For most of the RB experiments carried out records were kept of the appearance of each slurry during compression. Considerable differences were observed depending on experiment conditions. The least informative of the 22 experiments carried out were experiments RB13-15 and RB19-21, all begun at an initial density of 1.16 Mg m^{-3}. In each of these experiments the sediment surface was level with few or no features, the settled bed was uniformly fine-grained and featureless, and the supernatant and column wall were always clear. With the passage of time, sediment adjacent to the surface lightened in colour to a depth of 4-6 mm and gas-filled cavities (1-5 mm in diameter) formed within the bed. These characteristics suggest a bed possessing substantial coherence, a hypothesis which is supported by surface and element settlement rates, particle size analyses, and other data presented later. Discolouration and gas generation were probably due to organic activity.

Experiments begun at lower densities and salinities showed greater activity and changes in appearance, which suggests a lower degree of structure. In these experiments the general pattern of behaviour was that of a short period of initial stability or slow settling, succeeded by rapid settling,

and concluded with a long period of slow settling at an ever decreasing rate. All slurries were homogeneous and fine-grained in appearance initially. Slow settling of the surface produced features indicative of structural distress such as domes and cracks on the sediment surface, and horizontal hair-line folds and cracks within the upper 30 mm or so of the slurry. As time elapsed, but before the onset of rapid settling, slurries developed a granular texture, a characteristic indicative of flocculation. Inhomogeneities, such as cracks, became more extensive.

A common precursor to rapid settling was clouding of the supernatant and the linking of cracks to form a network of continuous, predominantly vertical, tortuous channels. Through channels in the upper 40 mm of some beds, aggregates as large as 2 mm were observed in motion. Movement of individual aggregates tended to cease quickly as average slurry density increased with compression, and channels clogged and/or collapsed. With the collapse of channels, these features became less well defined but still capable of conducting clear water.

As particles gathered at the bottom of the column, the rate of settlement of the slurry surface decreased drastically and turbulence within the overlying supernatant diminished. Fine particles either ejected from the bed or left behind as the bulk of the sediment settled during rapid settling, then settled and the clarity of the supernatant increased. Vestiges of channels persisted in the form of fine folds and discontinuous paths visibly different from the bulk of the material. After the cessation of rapid settling, domes, cracks, and dimples typically marked the sediment surface; these are evidence of both a measure of structure and continuing strain.

Within several weeks of input most sediment surfaces had both contracted radially and curled up slightly at the edges. Cavities and organic stains occurred in long duration experiments only.

In experiment RB05a-c (ρ_i=1.10 Mg m^{-3}) extensive channeling led to a complete breakdown of structure in one region, yielding a uniform flowing mass of sediment with a granular texture rather than a network of channels. In this region, the former sediment surface maintained its identity and became buried to a depth of up to 180 mm. Outside of this region, the bed contained channels. The new sediment surface, which consisted of sediment that had flowed into place, was level.

In two experiments, RB08 and RB22, rapid settling occurred without the formation of channels. These slurries had uniform granular appearances which suggests that they were flocculated but had either insufficient sediment and/or strength to form a continuous structure initially. Experiment RB08 was begun at an initial density of 1.047 Mg m^{-3}, and experiment RB22 had a salinity of 0.68 g l^{-1}: these being the lowest initial density and one of the lower pore fluid salinities investigated in the study. In contrast, the fully structured slurries described earlier (experiments RB13-15 and 19-21) had the highest initial density (1.16 Mg m^{-3}) and highest salinity (5 g l^{-1}) of those studied. Only after rapid settling had occurred did the slurry in experiment RB08 show heterogeneities, mostly fine, predominantly horizontal folds; which suggests the development of structural integrity. In experiment RB22 weak flocculation (due to low salinity) and rapid settlement (the result of low initial density) combined to produce an opaque supernatant which cleared

only partially over a period of three and one-half months. The resulting settled bed was fine-grained and featureless.

Descriptions of slurry appearance during compression provide qualitative information about 1) factors responsible for behaviour, 2) structural continuity and strength, 3) the probability of particle segregation, 4) degree of flocculation, and 5) impending rapid settlement. A few generalizations regarding appearance and behaviour may be drawn.

A clear supernatant indicates that interparticle forces are stronger than fluid shear forces, a condition most commonly associated with either slow settling (as in experiments RB13-15) or strong flocculation. Rapid settlement is associated with channels and/or a uniform granular appearance, and a cloudy supernatant. The presence of channels indicates the existence of some amount of structure, whilst no channels, a granular texture, and cloudy supernatant suggest a complete lack of continuous structure. Rapid settlement of the surface occurs because of fluid flow either through channels or between large aggregates.

Supernatant clarity is a good indicator of the probability of particle segregation. A cloudy supernatant suggests redistribution of sediment, a necessary condition for segregation, whilst a clear supernatant implies strong interparticle bonding and no relative particle movements. The appearance of fine particles in a supernatant that was clear previously is a reliable indicator of imminent rapid settlement. The rate at which a cloudy supernatant becomes clear is related to the size of particles suspended within.

The presence of electrochemical forces in a slurry is reflected by a granular appearance in a fine-grained slurry. A course texture indicates flocculation, whilst a fine-grained appearance indicates either incomplete aggregation, particle repulsion or particle charge neutrality. Particle-particle attraction is also indicated by the flow of clear fluid through channels, since cohesion is necessary both to maintain a channel structure and to resist erosion. Further, interparticle attraction is revealed by contraction and curling up of sediment at the surface of a bed, where effective stress is equal to zero. The persistence of heterogeneities, both as time elapses and as effective stress builds up, indicates a measure of resistance to deformation, and thus structure. Surface features (domes, cracks, etc.) reflect a competition between interparticle forces and compressive stresses.

Of the features described above the one that exhibits the strongest influence on behaviour, but which is neither revealed by any of the quantitative results discussed in later sections, nor is explicitly included in any settling-consolidation model, is the presence of channels. The size, extent, and history of channels controls the permeability of settling slurries and, in turn, the rate of surface settlement and bed compression. The life of channels is seen to be dynamic and transient, characteristics which make measuring and/or modeling permeability very difficult. Unlike homogeneous slurries, the permeability of slurries with channels is dictated by the structure of channels, and structure is, in turn, controlled by microscopic forces and fabric - factors which are poorly understood and difficult to quantify.

4.2 Particle Size Analysis

In a broadly graded or polydisperse slurry there is the potential for segregation to occur. Segregation occurs when particles with different characteristics move relative to one another, dividing an initially homogeneous slurry into zones of material of different composition. Variations in composition within a slurry are important because composition and behaviour are strongly related. The behaviour of a segregated slurry is extremely difficult to interpret and to model because such a slurry is effectively an agglomeration of different materials at a range of stresses: it is a state to be avoided.

Segregation occurs if particles of different density, size or shape are allowed to settle freely and independently. The individual effects of density, size, and shape are usually combined in the concept of equivalent spherical diameter, which is the diameter of a spherical particle which would settle freely at a velocity equivalent to that of the anisotropic particle of interest. Because settling is proportional to particle diameter squared, small variations in equivalent diameter can lead to substantial segregation.

There are three factors which influence the degree to which a slurry segregates in addition to its range or distribution of equivalent spherical diameters. Two of these, particle freedom and particle independence, may prevent segregation altogether but the third, settling distance, influences the degree of segregation only. Particle segregation cannot occur if there is insufficient space for differential settling to occur; such is the case

when slurry density is high, even if the particles within the slurry are mutually repulsive. Slurries of low density, with adequate spatial freedom, may be prevented from segregating by the process of flocculation which unites particles with different equivalent diameters so that they settle as a unit. When particles are free and independent, segregation occurs to an extent determined by the relative settling velocities of the particles involved and by the distance over which settling occurs freely. Imai (1981) presents results which illustrate the effect of initial slurry height on degree of segregation, and the effects of segregation on compressibility. In general, the highest degree of segregation occurs in tall dilute suspensions of broadly graded, dispersed sediments.

Particle size analyses are valuable for two reasons. They establish whether or not a settled bed is homogeneous, which is a practical requirement for interpreting behaviour, and they indicate whether particles settled freely and independently of one another.

During planning of experiments RB10-22, several series of small beaker settling tests were performed in order to establish the conditions which cause segregated and non-segregated settling for Combwich mud; the objective was to avoid segregation in full-size settling experiments. Small quantities (≈100ml) of twenty different combinations of pore fluid salinity (0.1, 0.5, 1.0, 5.0, and 30.0 g l^{-1}) and initial density (1.01, 1.02, 1.06, and 1.10 Mg m^{-3}) were prepared and allowed to settle. During the preparation of these slurries it became apparent that insufficient time and sediment were available to settle beds of sufficient thickness and strength for satisfactory subsampling and particle size analyses to be carried out.

The idea of quantitatively analyzing beds settled in small beakers was dismissed and post-experiment particle size analysis made a part of procedures for full-size column experiments.

The small beaker tests were of value qualitatively. In each experiment, supernatant clarity provided a visual indication of degree of flocculation, and thus the likelihood of segregation. As noted in the preceding section, in a fully flocculated slurry particles with different characteristics settle to form a homogeneous bed regardless of the initial density of the slurry. On the other hand, in partially flocculated or dispersed slurries of low density the large-sized fraction settles rapidly, yielding an opaque supernatant consisting of fine particles that settle slowly to produce a segregated deposit. Small beaker test results showed that as the salinity of the suspending medium increased, the rate of flocculation, floc size, the initial rate of settlement of the slurry surface, and the clarity of the supernatant increased likewise. In addition, at all salinities the clarity of the supernatant increased with increasing initial density. At a salinity of 30 g l^{-1} (approximately that of sea water) a slurry with as little as 10 grammes of solids per litre of solution flocculated completely and produced a clear supernatant.

The small beaker test results were encouraging because they provided both qualitative support for the research hypothesis that salinity and initial density influence settling behaviour, and an estimate of lower bounds for these parameters (0.2 g l^{-1} and 1.06 Mg m^{-3}, respectively), above which homogeneous settled beds might, on the basis of supernatant clarity, be expected.

Sedimentation pipette and granulometric methods of particle size analysis (section 3.3.6) were used to obtain particle size distribution data for beds settled in tall columns. The British Standard pipette method was used initially (experiments RB02-05, 08) because it is the traditional civil engineering method for determining particle size distributions. This was replaced later (experiments RB07-22) by a more precise granulometric method. The two methods yielded different results for the same sample: this is shown in Figure 4.1. Technique related differences in results were unimportant, however, because a single method was applied to all of the samples from any one bed and segregation was identified on the basis of relative differences in the quantities of selected particle sizes in subsamples from different elevations, without regard for the absolute accuracy of the particle sizes selected.

Figure 4.1 also shows average particle size distributions for Combwich 6 and Combwich 7 sediment obtained using one method of analysis; differences are evident. These differences are unimportant with respect to the analysis of segregation within a column, but they are relevant to the comparison of compression behaviour and shear strength characteristics. For this reason, comparisons between the behaviour of different muds were not performed.

Figure 4.2 shows example results for a segregated settled bed. Samples taken from layers at five different elevations (as shown in the column at

Figure 4.1
Average Particle Size Distributions for Combwich Sediment
Comparison of BS Pipette and Granulometre Methods

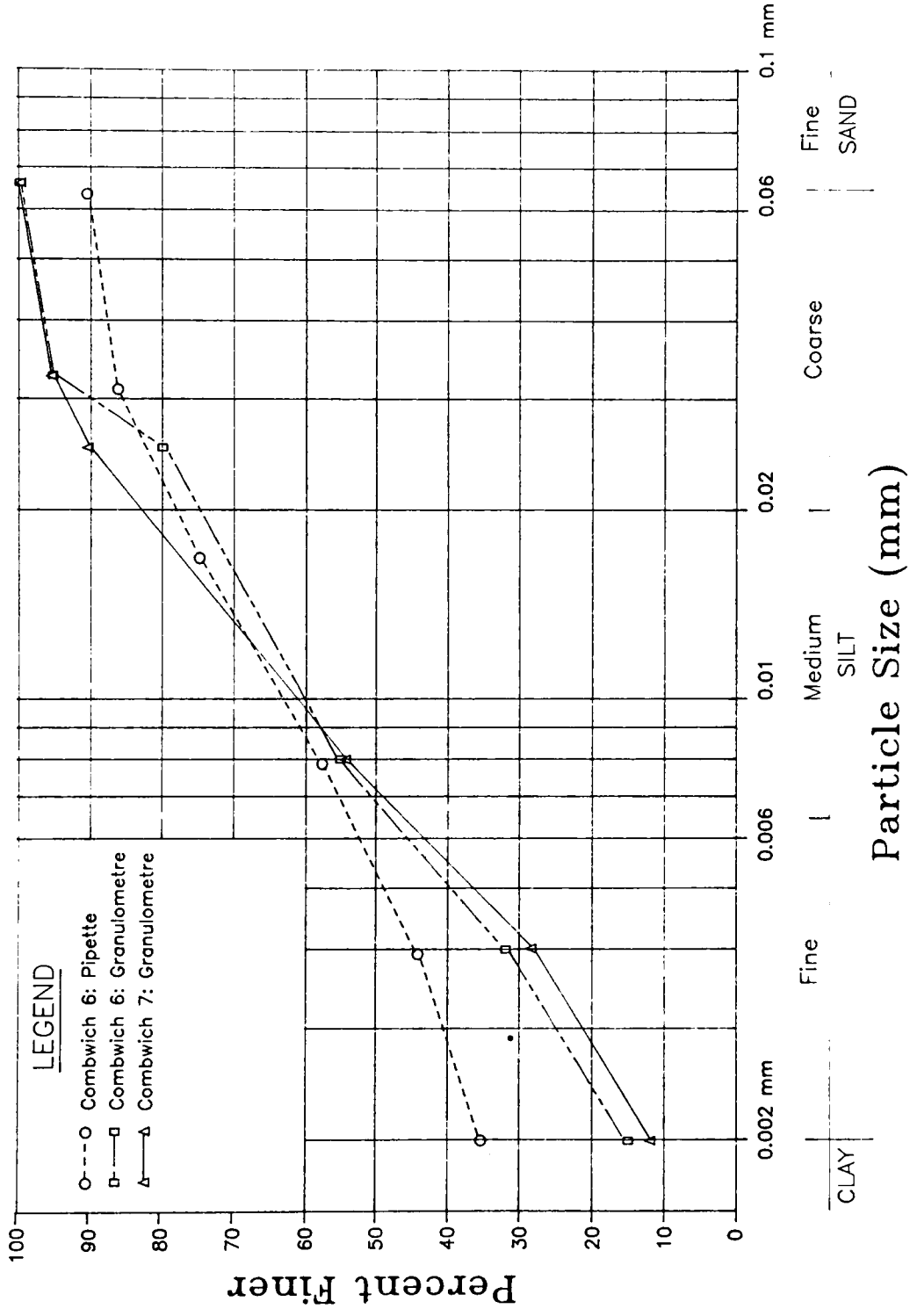
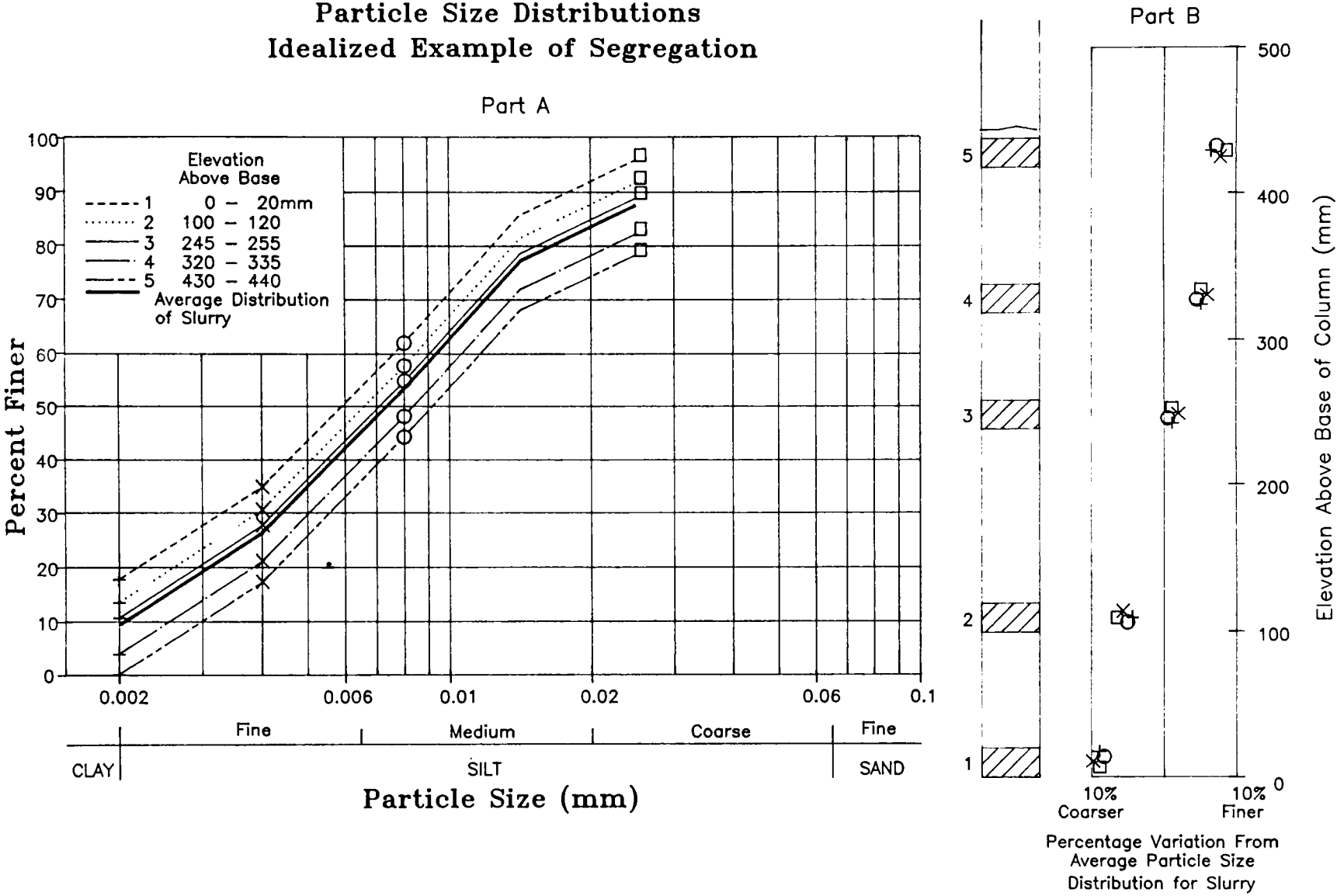


Figure 4.2

Particle Size Distributions
Idealized Example of Segregation



the right of the figure) were analyzed. The upper 3 samples were finer in composition than the average particle size distribution of the slurry, whilst samples lower in the bed were coarser than the average. The percentage variation from the average particle size distribution of five specific particle sizes at different elevations within the bed are shown in part (b) of Figure 4.2. This latter form of presentation (b) is preferred to the standard means (a) because it shows segregation more clearly: total percentage finer values for selected particle sizes are less useful than variations about an average distribution for samples within a column. High resolution plots (form b) require a regard for both the precision of the method of analysis used to determine the data presented and the repeatability of experiments.

The British Standard method of particle size analysis for fine grained soils, pipette method (Test 7C) , is precise to ±1 percent when properly performed. The author feels, however, that his own inexperience with this method renders the results of experiments RB02, 03, 04, 05, and 08 less precise than the standard. A comparison of the results of experiments with similar conditions (RB03 and RB04) obtained using the pipette method, suggested a combined instrument precision and experiment repeatability of ±2.5 percent, in terms of percentage finer values at any particular particle size. The precision of the granulometre instrument was assessed by analyzing eight samples from five experiments twice and comparing the percentage of material finer at four selected particle sizes (2, 4, 8, and 24 μm). The maximum difference in percentage finer values between pairs of distributions for any one of the eight samples and four particle sizes was

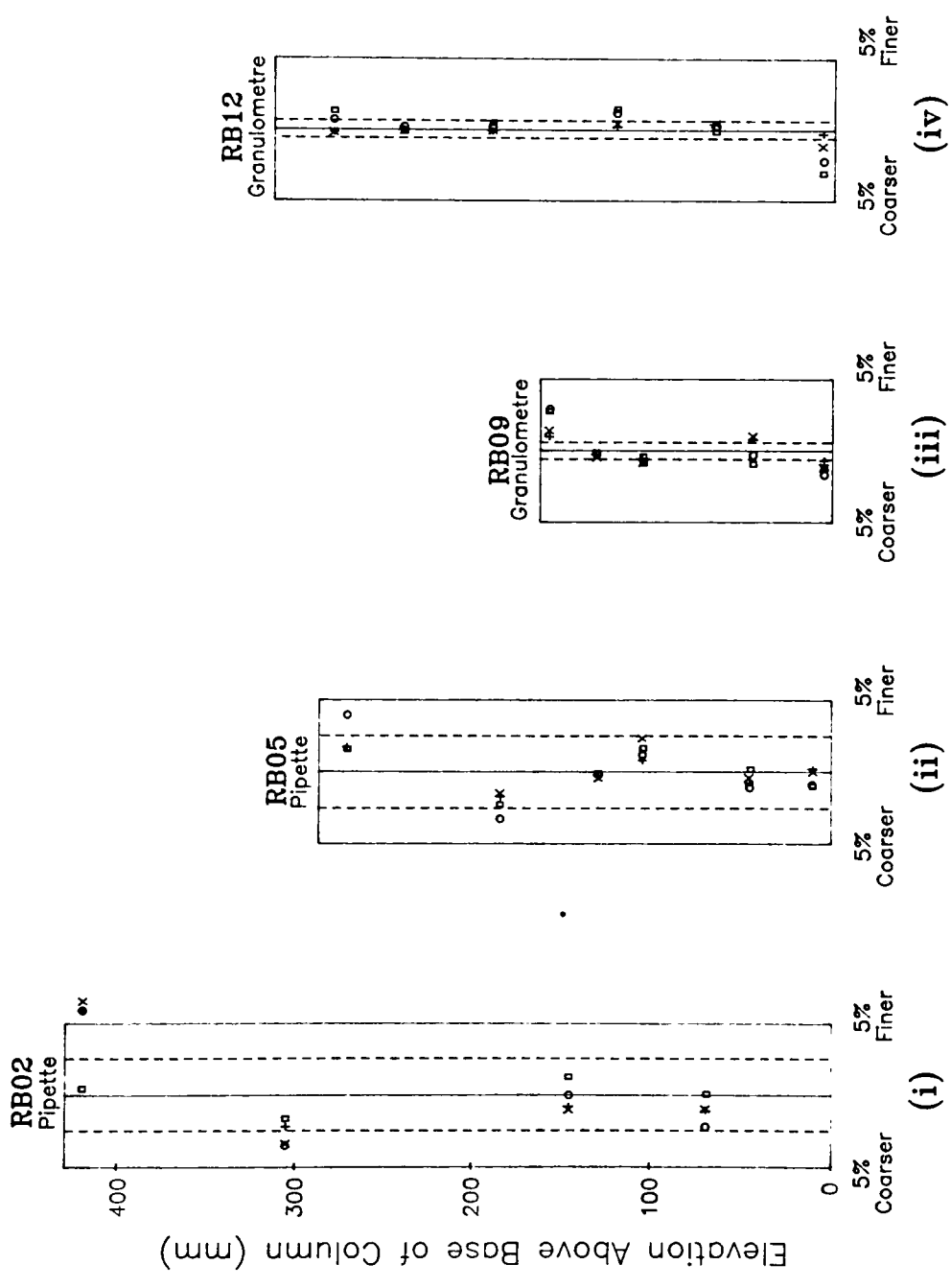
±1.0%. The average maximum difference was 0.6%, whilst typical variations in percentage finer values were even smaller, ±0.3%.

Using the granulometre, the particle size results of three series of experiments (RB13-15; RB16-18; RB19-21) were examined to assess the repeatability of experiments. Comparisons of percentage finer values between experiments in a series (consisting of three identical columns), at the particle sizes stated above, for subsamples recovered from similar positions within each bed, showed that the absolute maximum difference in percentage finer values was ±2.1 percent. The average maximum difference of 13 comparisons was ±0.7%, whilst typical variations were approximately ±0.3%. These results show that the variations in average and typical experimental results were similar to the precision of the instrument which determined them. Therefore, only variations in percentage finer values from the average particle size distribution for a column of slurry greater than ±0.7 percent were deemed to be significant. Note that substantially larger differences in percentage finer values would be necessary before the segregation that such differences imply would be significant from the point of view of material composition or interpretation of behaviour.

Two patterns were evident in the results of experiments RB02-05 and RB08, analyzed using the pipette method. In these experiments particle size distributions of surface samples were consistently finer than the average size distribution of each slurry (by 3 to 6%), whilst samples taken from the upper one-third of a bed were generally coarser (by ≈3%) than the average (Figure 4.3, part i). Lower in the bed no discernable pattern of segregation was observed. These results suggest limited localized

Figure 4.3: Particle Size Analysis Results

Percent Deviation From Average Particle Size Distribution For Each Slurry



segregation, with fine material being redistributed upwards within the near-surface region. Experiments RB02 and RB03, of similar initial density but having different initial slurry heights (1.538 and 0.710m, respectively), showed a trend of increasing segregation in the near-surface region, with increasing height.

These patterns of behaviour have a rational basis. In one-dimensional settling, with surface drainage only, settling velocity, and the distance each particle settles, decreases with depth below the surface. Particles higher up in a slurry settle further than ones lower down, so that a slurry of independently settling particles will produce a bed in which there is an increasing degree of segregation towards the surface.

Settling velocity affects segregation because it controls the magnitude of hydrodynamic shear forces which act to break flocs down into individual particles. Near to the base fluid velocities and, therefore, fluid shear forces are small. In the near-surface region large fluid shear forces enhance floc breakdown and particle liberation, whilst proximity to the surface heightens the prospect of particles being ejected from the bed completely, after which time they can settle to form a segregated surface layer. Fine, rather than coarse particles are redistributed in the near-surface region because these are more amenable to migration. This process, in which small or relatively low density particles in a polydisperse system are carried away by flow, leaving a bed, or portion thereof, enriched in large grains, is called elutriation.

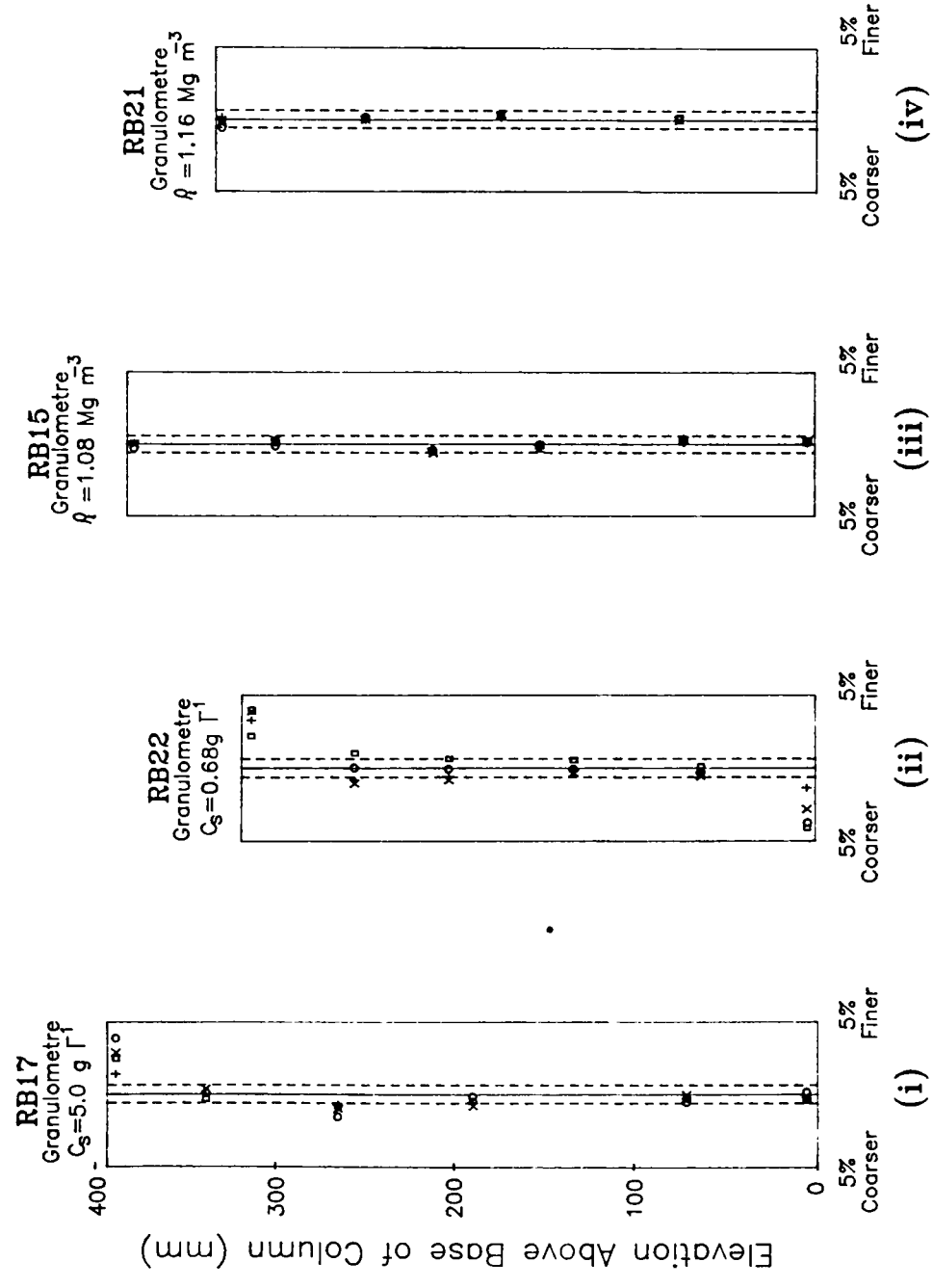
Experiments RB04, 05, 07, 08, and 09, which involved slurries with a common nominal height, 0.7m, but which had different initial densities (1.08, 1.10, 1.06, 1.047, and 1.06 Mg m^{-3}, respectively) showed either little segregation and/or no correlation between degree of segregation and initial slurry density. Parts (ii) and (iii) of Figure 4.3 show particle size results for experiments RB05 and RB09, respectively, and different patterns of segregation with depth. Note that direct numerical comparisons between these two experiments cannot be made because of the different methods of analysis used.

Of the three experiments RB10-12, begun at an initial density of 1.10 Mg m^{-3} but different salinities (5.0, 1.0, and 0.2 g l^{-1}, respectively) only in the lowest salinity experiment was segregation marked (Figure 4.3, iv). Experiments RB17 and RB22 were also begun at a common density (1.08 Mg m^{-3}), but had different salinities (5.0 and 0.68 g l^{-1}, respectively), and their results (Figure 4.4, parts i and ii) confirm that degree of segregation tends to increase with decreasing salinity.

A comparison of experiments of the same salinity but different initial densities reveals the influence of density on degree of segregation. At a salinity of 5.0 g l^{-1} experiments RB15, 10, and 17 (ρ_i=1.16, 1.10, and 1.08 Mg m^{-3}) showed negligible segregation except in the near-surface region where the pattern discussed earlier was observed. Particle size results for the experiment with the highest salinity and initial density of all RB experiments (RB15) are shown in Figure 4.4, part iii: no segregation

Figure 4.4: Particle Size Analysis Results

Percent Deviation From Average Particle Size Distribution For Each Slurry



occurred. These results may be contrasted with results of experiment RB17 (same salinity but lower initial density, Figure 4.4, i) and the conclusion that surface segregation increases with decreasing initial density, drawn. Experiments RB21 (ρ_i=1.16 Mg m^{-3}, C_s=0.68 g l^{-1}; Figure 4.4, iv) and RB22 (ρ_i=1.08 Mg m^{-3}, C_s=0.68 g l^{-1}; part ii) show that segregation throughout a bed increases with decreasing initial density.

A clear pattern is evident within the particle size results presented, especially amongst the more well controlled experiments RB10-22. At high initial density and/or salinity (experiment RB15, for example) complete flocculation and insufficient space prohibit relative particle movement, and no segregation occurs. As salinity and/or initial density decreases, the degree of segregation increases. Segregation becomes apparent first in the near-surface region where high fluid shear forces break down flocs; fine particles are preferentially transported, because of their size, in the direction of fluid flow, that is towards the surface of the bed. As salinity and initial density decrease, particle freedom and independence increase and segregation extends throughout the bed. Conditions of extremely low salinity and initial density produce a bed that is completely graded according to equivalent particle diameter.

The overall pattern of behaviour observed in RB experiments is consistent with the influence of salinity and density observed in experiments with monomineralic clay suspensions reported in the literature. Confirmation for natural polydisperse slurries has been made. Note that the primary reason for carrying out particle size analyses was to establish the homogeneity of settled beds prior to interpreting their settling and compression

behaviours. The present results show that for the majority of experimental conditions studied, segregation was confined to the near-surface region of a bed and, at its maximum, amounted to a variation of a few percent in percentage finer values relative to an average particle size distribution for a slurry. Such slight and local variations were thought not to influence the compression behaviour of a bed sufficiently to warrant analyzing beds as composite materials.

The results of RB-experiments also showed that rapid and significant segregation of coarse particles to the base of a column did not occur even at a slurry density and salinity of 1.08 Mg m^{-3} and 0.68 g l^{-1}, respectively (experiment RB22).

The maximum degree of segregation observed in RB experiments was ±5% about an average particle size distribution, for the slurry in experiment RB22 (Figure 4.4, ii).

Earlier researchers at Oxford, viz. Been, Thomas, and Elder carried out 23 particle size analyses on subsamples from five experiments. Their results yielded three conclusions: suspension forming slurries show a measure of segregation (Been, experiment KB7, ρ_i=1.09 Mg m^{-3}); slurries in which effective stresses are present from the outset do not segregate (Been, KB8, ρ_i=1.22 Mg m^{-3}; Elder, DE5, ρ_i=1.21 Mg m^{-3}); and, the addition of a dispersing agent to the suspending medium enhances segregation (Been, KB9).

Been's 'measure' of segregation was, in fact, a variation of up to ±20 percent in the percentage finer values for particular particle sizes for

samples at the top and the bottom of the bed. This degree of segregation is considerably more than that observed in the present experiments. The second conclusion common to Been and Elder, regarding the influence of effective stress, is a restatement of the fact that segregation cannot occur without sufficient freedom for relative particle movement. The third conclusion, drawn by Been on the basis of a chemically dispersed sediment, does not have an equivalent in the present programme. It does, however, illustrate the importance of particle independence and the role of interparticle forces on degree of segregation.

In summary, numerous detailed particle size analyses of experiments at different initial heights, densities, and pore fluid salinities revealed a logical pattern of segregation, and confirmed that the beds deposited in RB experiments were sufficiently uniform with respect to particle size distribution that they could be considered as being homogeneous, for the purposes of interpreting settling and compression behaviour.

4.3 Height of Surface versus Time

4.3.1 Introduction

The simplest method of characterizing behaviour is to study the change in position of the surface of a slurry with respect to time. Height of surface versus time results were recorded for all experiments. In this section the results are discussed in two parts: experiments RB01-09 first, followed by experiments RB10-22. The grouping is intentional and reflects a change in research philosophy and experimental capabilities. Early experiments did not produce satisfactory pore pressure data so that analysis in terms of

effective stress was not possible. Four of these experiments, RB04a-c, RB05a-c, RB07a-c, and RB08a-c, each consisting of three identical columns of slurry, were undertaken primarily to study surface settlement patterns and experiment repeatability, at a range of initial densities. Later experiments, RB10-22, comprised a separate programme designed to study the particular influence of initial slurry density and salinity on settling behaviour, density profiles, shear strength, and fabric.

Figure 4.5: Example Height of Surface versus Time Results

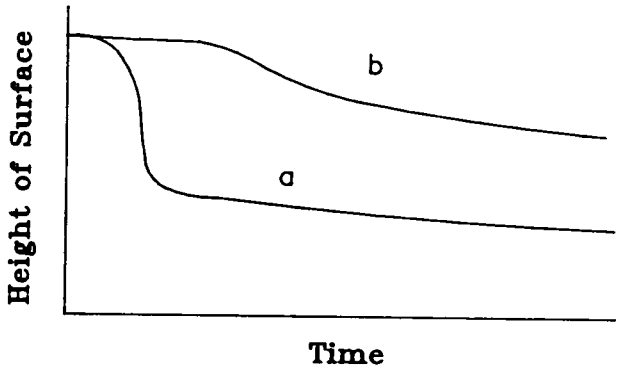
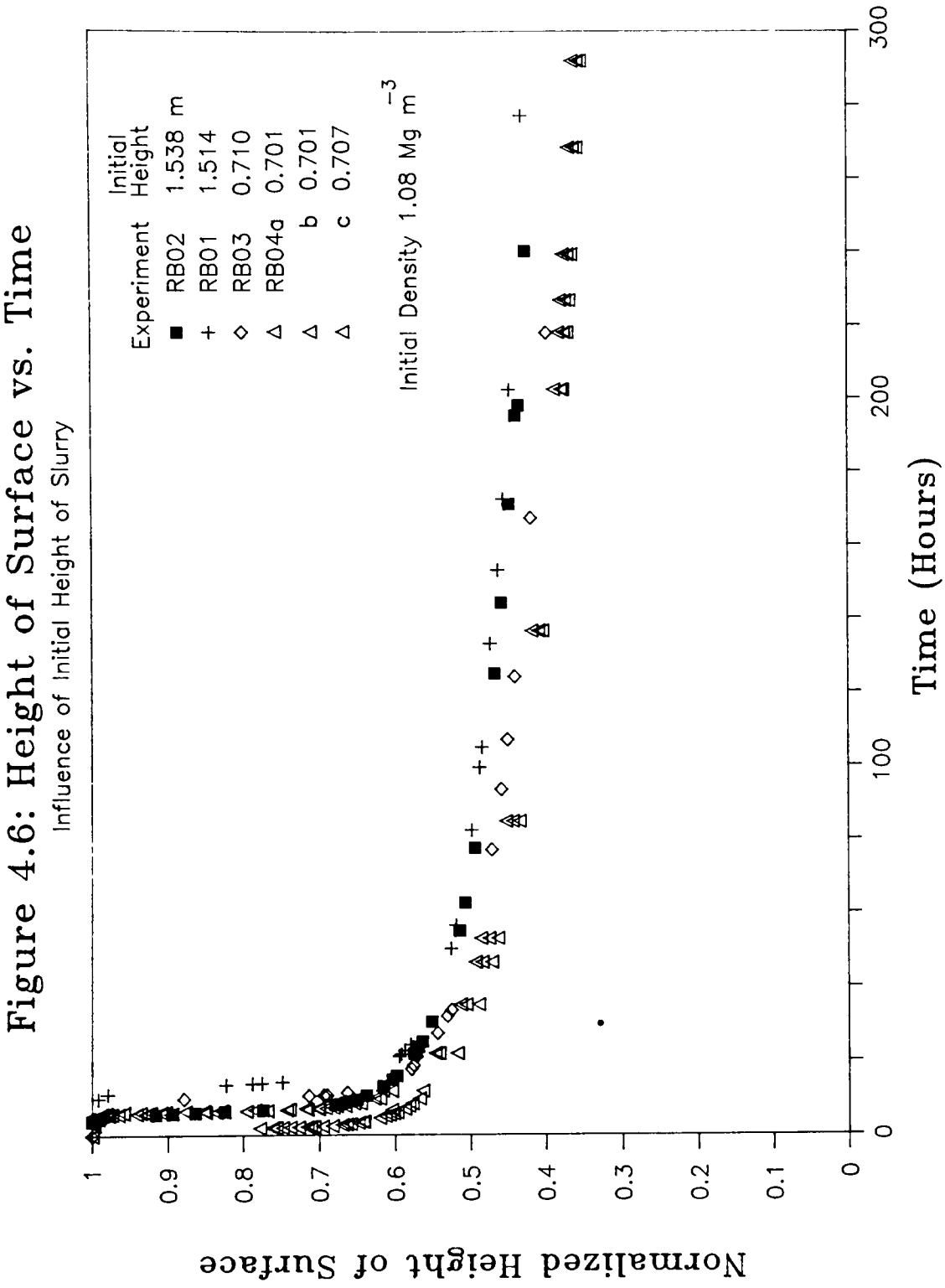


Figure 4.5 shows examples of the two extremes of settling behaviour observed in experiments RB01-22. Curve type (a) was, with variations in proportions, observed in experiments RB01-09, whilst both types of curves were observed in experiments RB10-22. Curve type (a) consists of an initial period of stability, a period of relatively rapid settling and, finally, a long period of slow settling at a decreasing rate. The rate of settling during, and the duration of, each phase varied with experimental conditions.

4.3.2 Results of Experiments RB01-09

Figure 4.6 shows height of surface versus time results for experiments RB01, 02, 03 and 04a-c, the latter consisting of three identical columns. All four experiments were begun at the same initial density, 1.08 Mg m^{-3}, but


Figure 4.6: Height of Surface vs. Time
Influence of Initial Height of Slurry
Initial Density 1.08 Mg m^{-3}
Experiment Initial Height
RB02 1.538 m
RB01 1.514
RB03 0.710
RB04a 0.701
b 0.701
c 0.707
Normalized Height of Surface
Time (Hours)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
100
200
300

different initial heights, hence these results reveal the influence of initial slurry height (h_{s_i}) on surface settling behaviour. Normalized height of surface (h_s/h_{s_i}) is plotted along the ordinate in order to simplify the comparison of experiments with different masses. All of the experiments showed some period of initial stability and there was no apparent relationship between duration and initial height. This was followed by rapid settling, the rate of which was independent of initial height. After 292 hours, when experiment RB04 was terminated, the experiments of shorter initial height had compressed proportionally more than experiments with larger initial height. This result is in accordance with one-dimensional consolidation theory which states that consolidation rate is proportional to the drainage path length squared, all other things being equal. Because satisfactory pore pressure data were either not recorded during experiments RB01-09 or recorded values were unsatisfactory, degrees of consolidation could not be calculated. Had the slurries been left indefinitely, lower normalized heights for the initially higher slurries would have been expected because of the higher average effective stresses that would have arisen within these slurries containing larger total masses of sediment. Detailed discussions of consolidation are found in chapter 5.

Figures 4.7, 4.8, 4.9, and 4.10 show height of surface versus time results for experiments RB04a-c, RB05a-c, RB07a-c, RB08a-c, and RB09. The variation in results illustrated in each graph is a measure of experiment reproducibility: in general, reproducibility was high for the range of initial densities considered, but a slight trend of decreasing

Figure 4.7: Height of Surface vs. Time

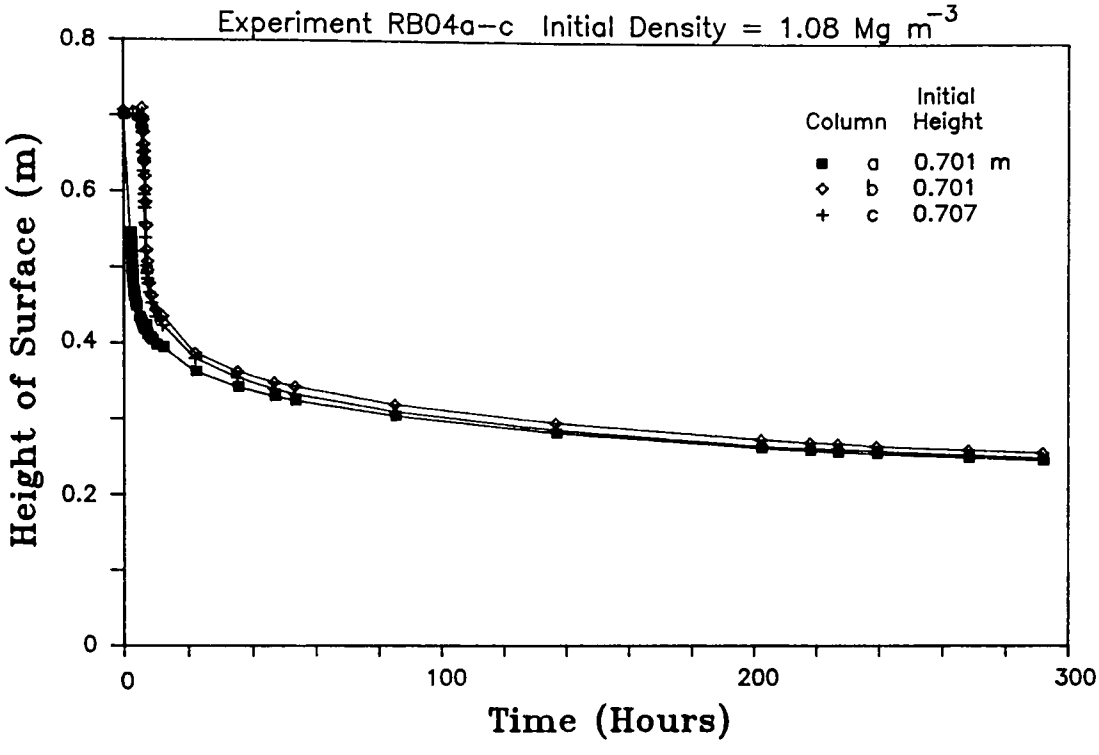


Figure 4.8: Height of Surface vs. Time

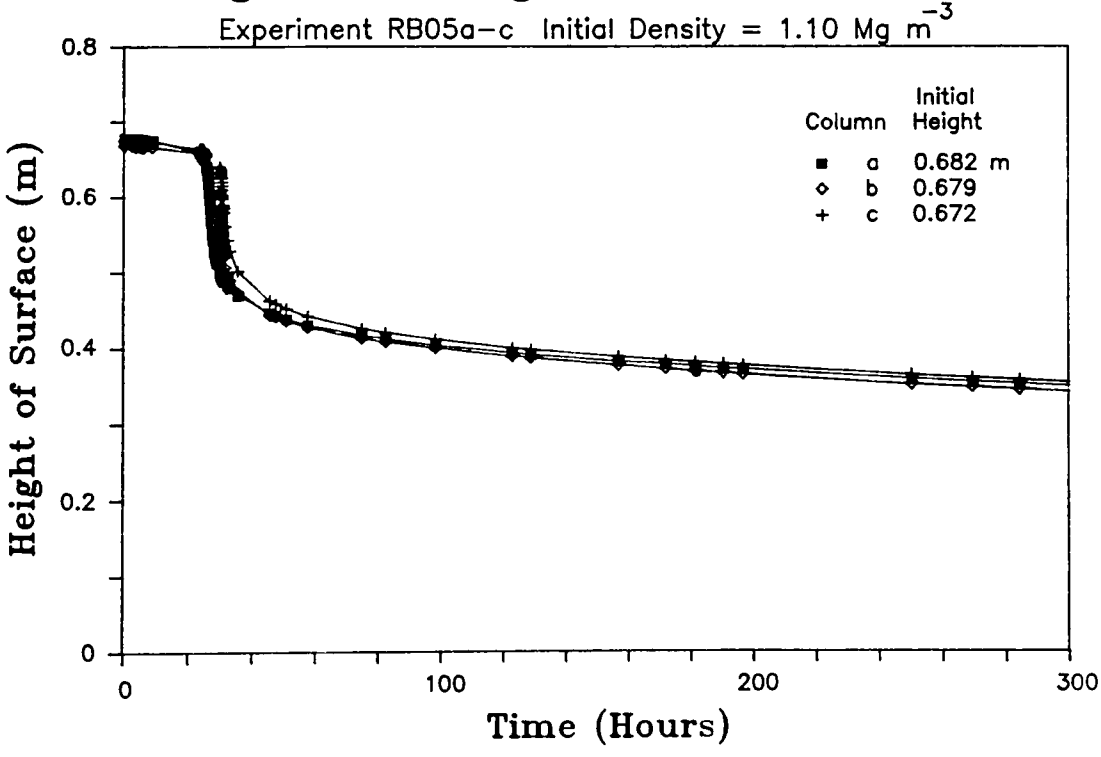


Figure 4.9: Height of Surface vs. Time

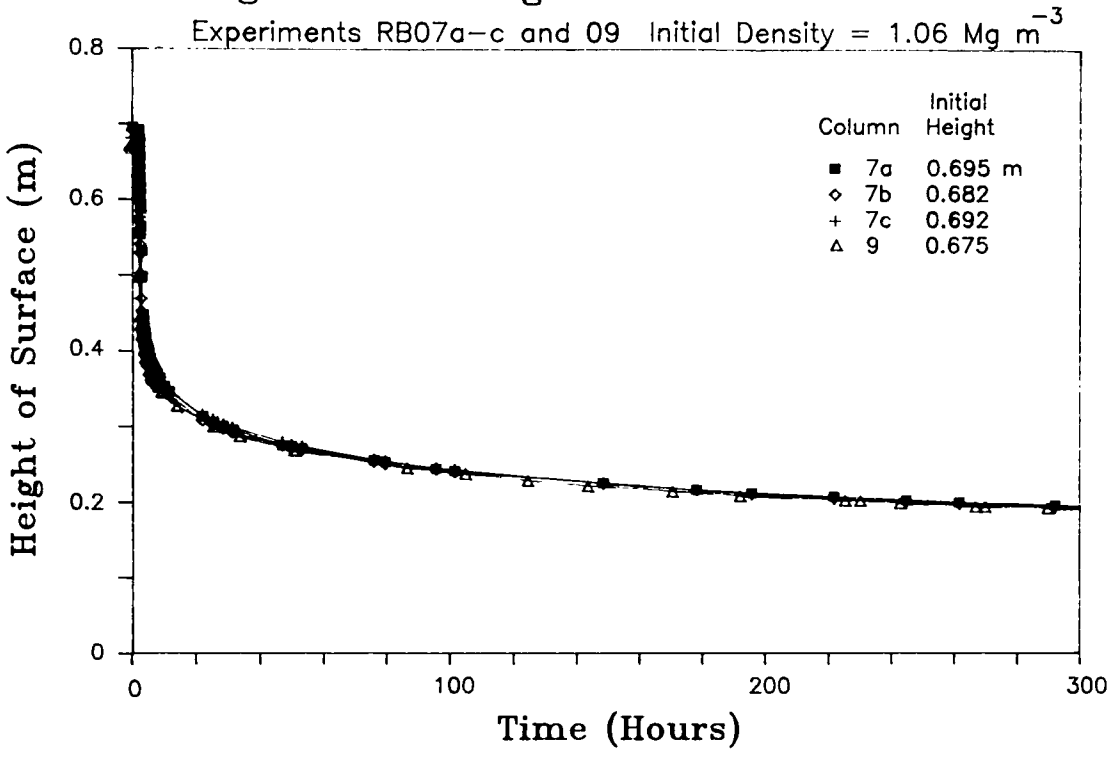


Figure 4.10: Height of Surface vs. Time

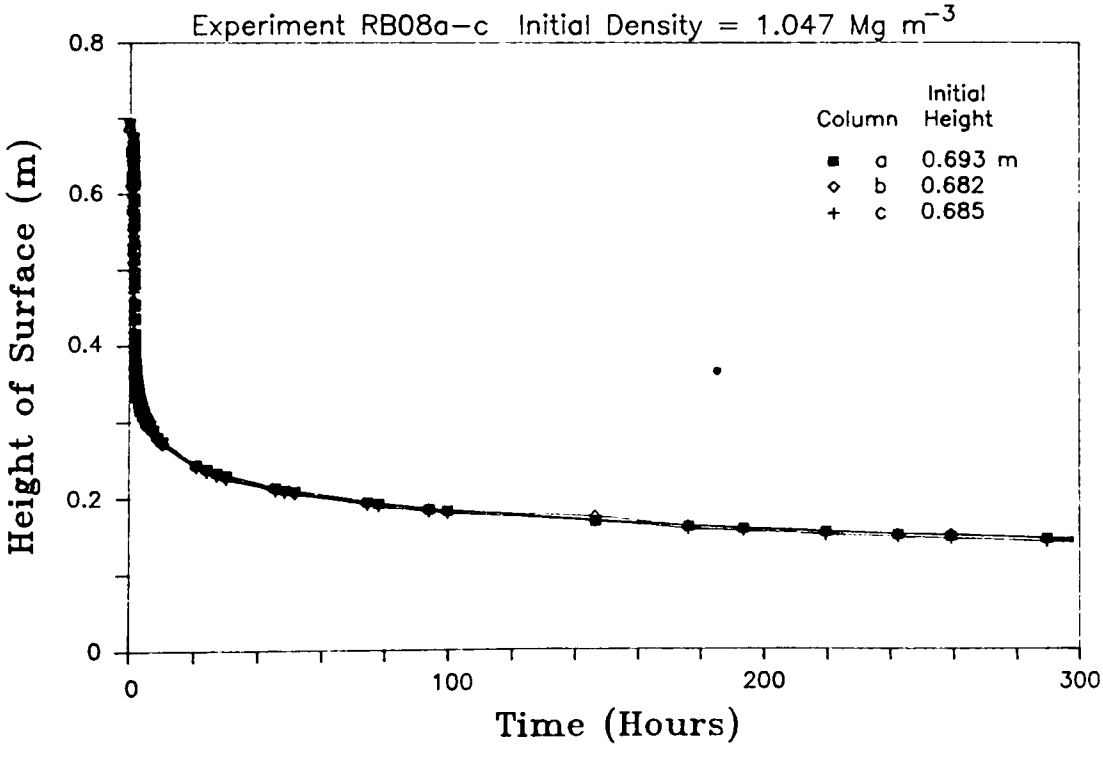
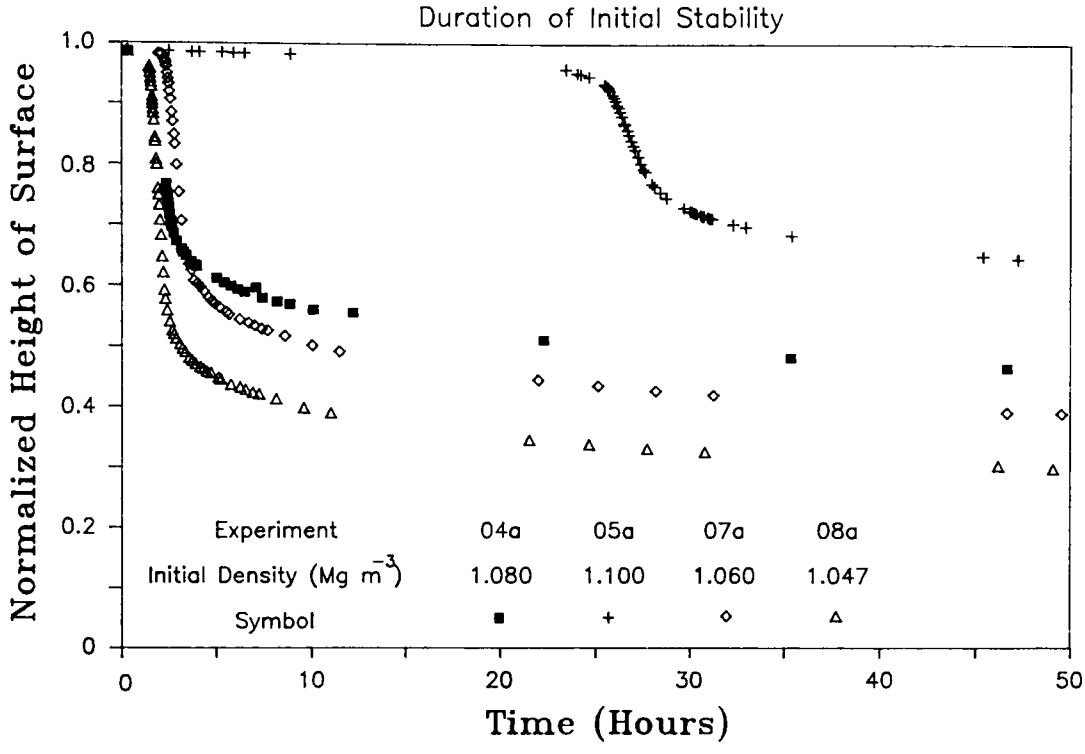


Figure 4.11 Normalized Height of Surface vs. Time



reproducibility with increasing initial density may be regarded as a warning against carrying out 'one-off' experiments at high initial density.

Figure 4.11 shows settling results for the early period of experiments RB04, 05, 07, and RB08. The durations of initial stability were similar for experiments with $\rho_i \leq 1.08$ Mg m^{-3}, but was much larger for an experiment at an initial density of 1.10 Mg m^{-3}. Flocculation occurred during the transition from stability to rapid settling. During this period of increasing settling rate, fine-grained textures usually developed into granular ones, and networks of channels formed. Tiller and Khatib (1984) observed similar periods of floc creation and acceleration within kaolinite slurries. After floc formation and acceleration, rapid settling occurred, the rate of which increased with decreasing initial density; this trend is in agreement with

the general observation that the hinderance to settling caused by hydrodynamic phenomena decreases as particle concentration decreases. Yong et al. (1984) observed similar behaviour for settling experiments with kaolinite.

The twelve columns of slurry comprising experiments RB04, 05, 07, and RB08 were planned as a set of slurries with similar initial heights, and spanning a range of initial densities (1.047, 1.06, 1.08 and 1.10 Mg m^{-3}). The set was inspired by the work of Michaels and Bolger (1962) who studied and interpreted the sedimentation behaviour of kaolin suspensions in terms of particle-particle forces and structural characteristics such as floc and aggregate size, density, settling velocity, and other parameters.

Experiments RB04, 05, 07, and RB08 were designed to assess the applicability of Michaels and Bolger's analytical methods, which were developed for slurries of narrowly graded (90% by weight, 0.2 to 2.5 μm diameter), acid-bleached kaolin, to broadly graded natural clay slurries. If found to be applicable then the author intended to apply Michaels and Bolger's methods to obtain structural information which could be related to compression and shear strength results, thereby linking structure and behaviour.

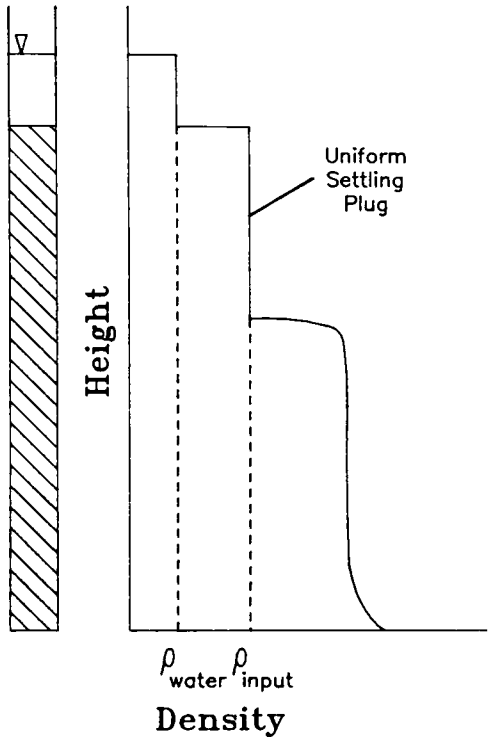
Michaels and Bolger's simplest type of analysis, that for dilute slurries, is based on a derivation of Richardson and Zaki's (1954) equation for the group settling rate of uniform spherical particles, and it yields the Stokes' settling velocity of an aggregate, aggregate diameter, and the ratio of aggregate volume concentration to solids volume concentration. It was quite unfortunate that the results of experiments RB04, 05, 07, and RB08

were similar in form to Michaels and Bolger's experimental results for slurries of intermediate concentration and, thus, were unsuitable for a dilute slurry analysis.

Michaels and Bolger also propose a settling rate model and a method of analyzing slurries of intermediate concentration which yields information about column size effects, maximum settling rate, the influence of initial height of surface and slurry strength on settling rate, average pore diameter, floc volume concentration, and volume concentration ratios of aggregates to flocs, and flocs to solids. In spite of an interest to determine these characteristics for natural slurries, the analysis requires results from experiments with tens of different sets of conditions; an amount beyond the resources of the present author. Michaels and Bolger's model for intermediate slurries, and their results and observations are worth reviewing, nonetheless, because their method of analysis in still in use a quarter of a century after its publication, and their structural explanations of some aspects of behaviour are relevant to the present research.

Michaels and Bolger's intermediate concentration slurry model is based on a force balance of fluid friction, buoyancy, side wall friction and the strength of underlying aggregates. The model assumes that sediment settles as a uniform plug of material (Figure 4.12), an assumption supported by x-ray transviewer data recorded by Gaudin and Fuerstenau (1958). Results recorded by the present author with more modern apparatus, (presented in

Figure 4.12: Density Profile Idealization
(After Michaels and Bolger, 1962)



section 4.5), show, however, that a uniform density plug model is an idealization and that non-uniform settling densities are common.

Michaels and Bolger observed that strongly flocculated slurries settled more rapidly than weakly flocculated slurries and proposed that this was due to the ability of strongly attractive interparticle forces to maintain large pore diameters; fluid shear forces are proportional to pore diameter. They also noted that at low initial slurry densities, pores were so numerous that a continuous aggregate (structured) region could not be maintained. Two RB experiments showed similar behaviour and are described in section 4.1.

Michaels and Bolger observed that settling rate increased during the early part of rapid settling (Figure 4.13). They attributed this to the straightening out of flow channels and the widening of contractions by fluid shear forces. Evidence of structural changes, such as linking of flow paths to form continuous channels, was noted in RB-experiments (section 4.1), and

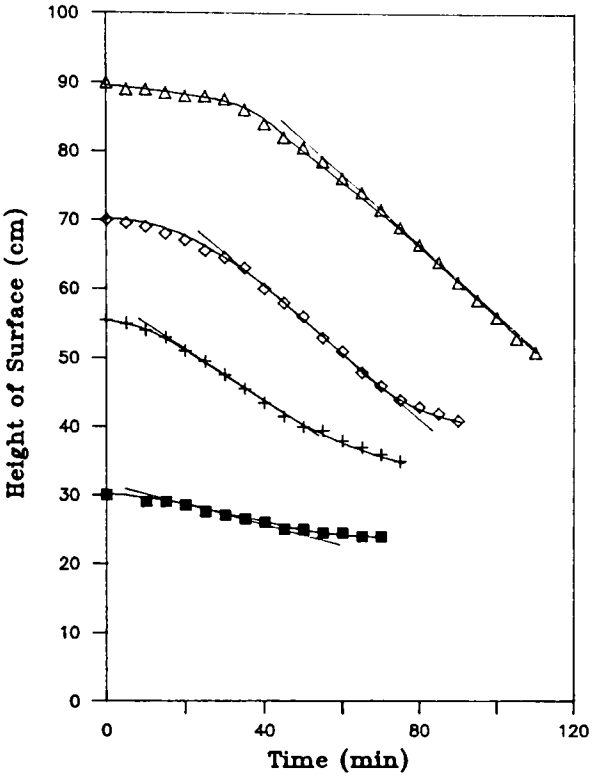
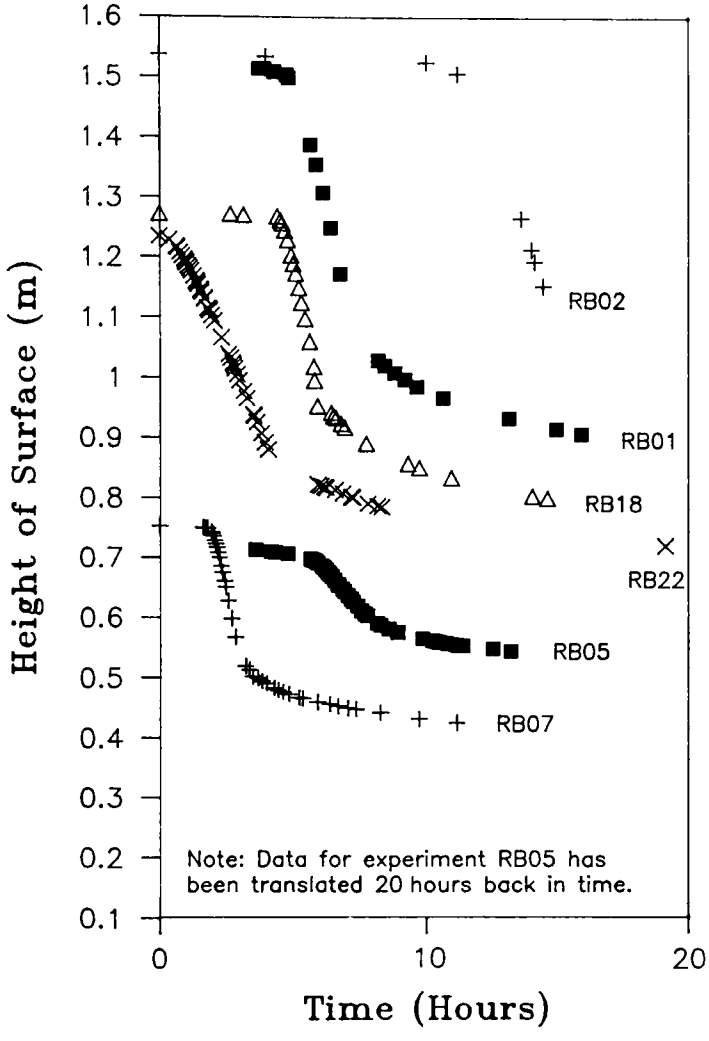


Figure 4.13
Height of Surface vs. Time
(after Michaels and Bolger, 1962, Figure 8)

an increase in rapid settling rate was observed in experiments (RB01, 02, 03, 05, 07, 11, 16, 17, 18, and RB22). Selected results for RB experiments are shown in Figure 4.14 and a more detailed discussion of surface settling rates is presented in section 4.4.

Figures 4.13 and 4.6 (or 4.18 in section 4.4) show radically different influences of initial slurry height on the rate of rapid settling of kaolin and natural mud slurries, respectively. For a three-fold increase in initial height, kaolin slurries showed a change of over an order of magnitude in settling rate. For a doubling in initial height for natural mud slurries, no significant change in rapid settling rate was observed. Because settling rate is controlled by floc characteristics, the data suggest that floc density and size in kaolin slurries are sensitive to initial height but that this is not so for natural slurries. No physical explanation is apparent. The reason for different effects of initial height on rapid settling rate is not known.

Figure 4.14: Period of Rapid Settlement



Michaels and Bolger's approach of interpreting behaviour in terms of structural characteristics, and relating structure to slurry and experiment conditions, is highly commendable. The applicability of their methods to natural mud slurries has yet to be established and requires a large number of experiments with slurries of different heights and concentrations. This requirement prevented the author from applying Michaels and Bolger's analysis to determine the microstructure of Combwich mud during settling. Michaels and Bolger's observation that the composition of the suspending medium influences the size and density of flocs in kaolin suspensions, and thus surface settling rate, is discussed in the following section.

4.3.3 Results of Experiments RB10-RB22

Research by Michaels and Bolger, and numerous others (see section 2.3.2) has shown the important influence of suspending medium composition on the surface settlement rate of monomineralic slurries. One of the objectives of experiments RB10-22 was to assess the relevance of both pore fluid salinity and initial slurry density to the surface setting behaviour of natural mud slurries. Unlike experiments RB04a-c, 05a-c, 07a-c, 08a-c, and RB09, each of which involved a different total mass of sediment, in experiments RB10-22 the mass of sediment input to each column was maintained approximately constant, thereby eliminating the difficulty of interpreting the behaviour of settled beds of different thickness.

Figure 4.15 shows height of surface versus time results for three experiments, RB10-12, carried out at one initial density (1.10 Mg m^{-3}), but three different salinities (5.0, 1.0, and 0.2 g l^{-1}, respectively). At this initial density the salinity of the suspending medium had a significant influence on surface settlement rate. This result was also observed in experiments RB13 and 21 begun at an initial density of 1.16 Mg m^{-3}, Figure 4.16. Experiments RB22 and 18, which were begun at a density of 1.08 Mg m^{-3}, did not, however, show any effect of pore fluid salinity on surface settlement rate, (Figure 4.17). Collectively, the results suggest that slurry surface settling behaviour is a function of both pore fluid salinity and initial density. They do not show a simple relationship between surface settling rate and these parameters, but do illustrate the disadvantage of studying a natural heteromineralic material: patterns such as the influence of salinity on surface settling rate (Figure 4.15), cannot

Figure 4.15: Normalized Height of Surface vs. Time

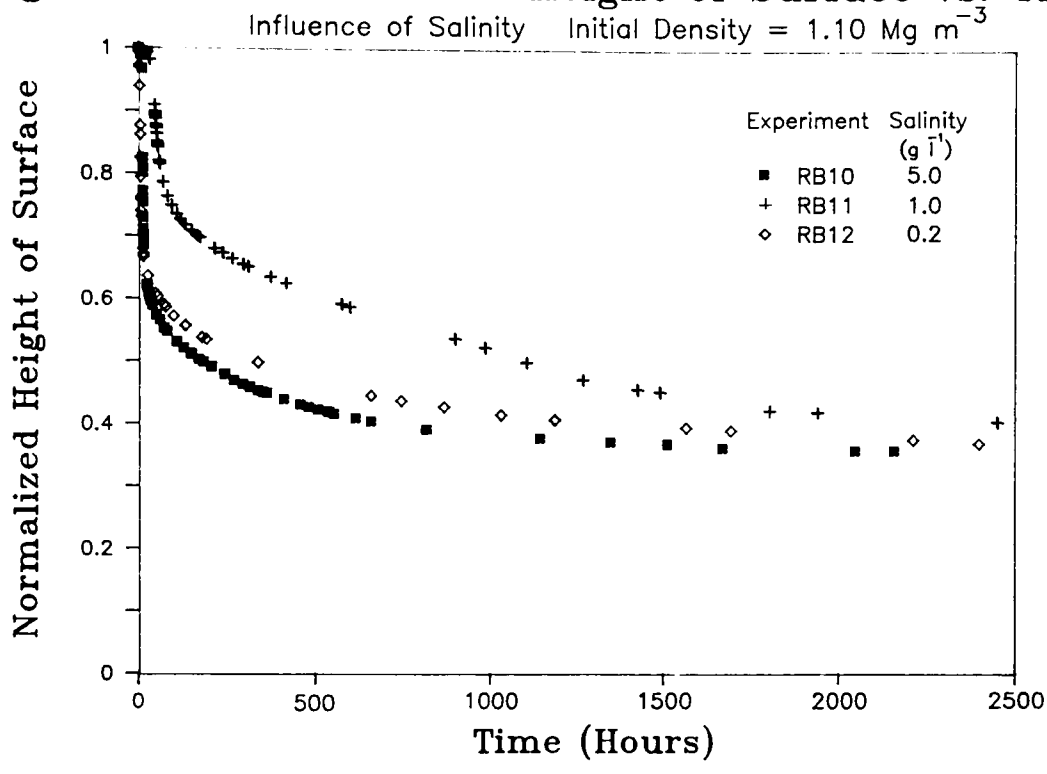


Figure 4.16: Normalized Height of Surface vs. Time

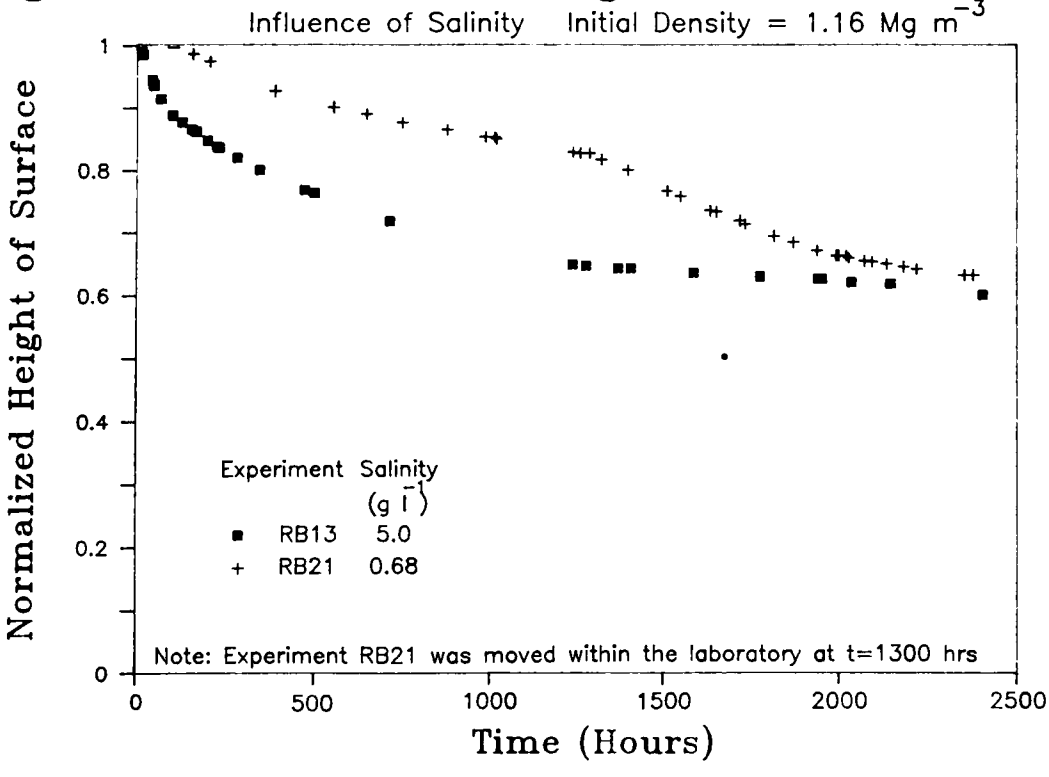
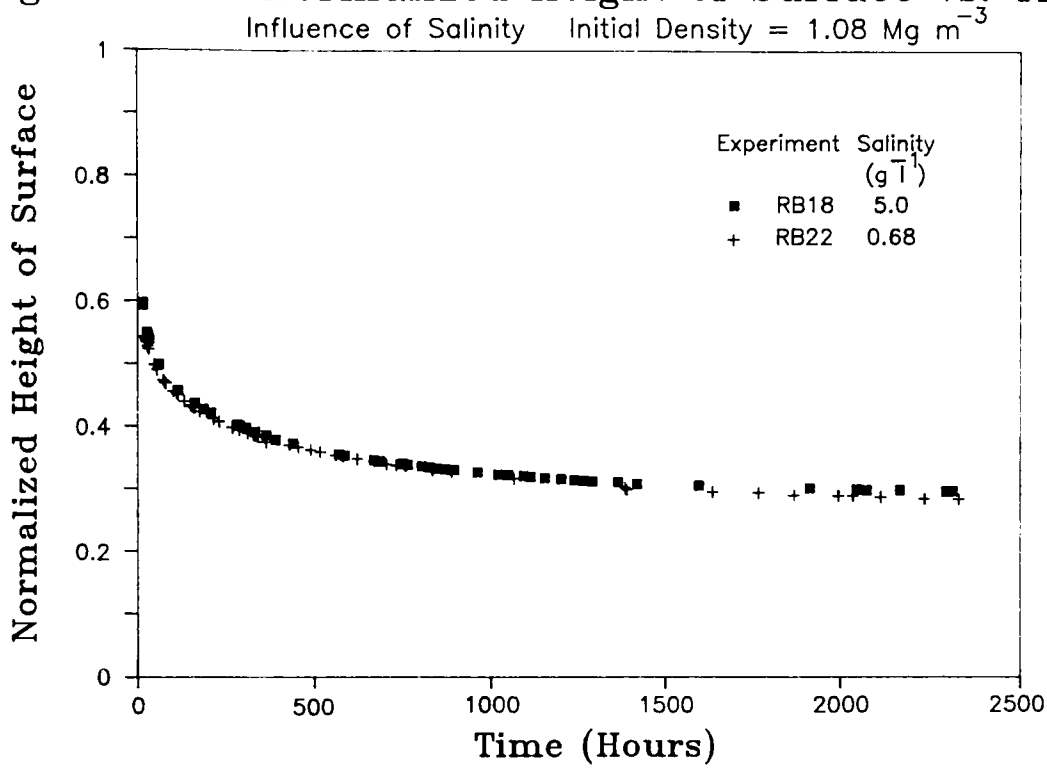


Figure 4.17: Normalized Height of Surface vs. Time



be explained definitively in terms of controlling electrochemical forces because the latter are impossible to specify or estimate. Nevertheless the results show clearly that initial density and salinity are relevant to settling behaviour for natural muds.

Height of surface versus time data is a less than ideal means of describing behaviour. Although it permits the influence of factors to be identified, the causes of influence cannot be discerned without extensive testing and analysis. Activity within a slurry is not revealed, hence factors such as salinity, initial slurry density, and so on, cause each curve to be unique, and require that extensive testing of slurries be carried out if predictions of behaviour are to be made. The basic inadequacy with height of surface versus time data is that activity within a slurry is not revealed; hence

'internal' factors, such as the concentration of particles at any place and time within a column, cannot be evaluated. An alternative means of describing behaviour is in terms of surface settling rate versus average specific volume. Experiments RB1-22 are examined in this way in the following section.

4.4 Surface Settlement Rate versus Average Specific Volume

As a particle, floc or aggregate settles it displaces and locally accelerates fluid along its path. A boundary layer and a wake form on and behind each settling unit, respectively, and these phenomena exert a retarding influence on the settling rate of proximate particles or flocs. At low solids concentration hydrodynamic interference is sufficiently small that Stokes' law, which was devised for solid impermeable spheres, can be applied to predict the settling velocity of flocs if the size and density of the latter are uniform, constant, and can be estimated. With increasing particle concentration the degree of retardation or hinderance increases. The influence of each hydrodynamic component is difficult to calculate when the size, shape, and density of settling units, that is particles or flocs, are non-uniform. Their combined influence is best treated empirically.

One empirical formulation, by Richardson and Żaki (1954), has the simple form,

$$W=W_{\infty}(1-C)^{n} \qquad \ldots 4.1$$

where W is the settling velocity of a spherical particle in a suspension, W_∞ is the settling velocity of that same particle settling alone in an unbounded body of stationary fluid, C is the fractional particle volume concentration, and n is an empirically determined exponent relating to the Reynolds number based on W_∞. Richardson and Zaki's equation was developed for the fall velocity of monodispersed uncharged spherical particles greater than 100 μm in diameter. It cannot be applied rigorously to a polydisperse system because W_∞ varies with particle size. Estimating an average value of W_∞ for the entire suspension is difficult because of the non-linear influences of size and shape on settling velocity, and because heterogeneous suspensions do not behave as a simple combination of uniform suspension behaviours. In flocculated systems Richardson and Zaki's settling equation is even more difficult to apply because the relevant fractional volume concentration (C) is not that of particles but of flocs, and floc size varies with fluid shear force, and floc density varies with floc size (Gibbs, 1983, 1985). The parameter W_∞ is, therefore, effectively inestimable. Clearly, Richardson and Zaki's empirical correlation for suspensions of monodisperse spherical particles cannot be applied to flocculated natural silty clay slurries.

A logical extension of Richardson and Zaki's correlation is to derive an equation which describes the average or overall settling rate of a slurry as the sum of products of particle concentration and settling velocity, for different sizes, shapes, or density fractions comprising a slurry, with appropriate factors to account for the presence of multiple particle types or sizes. Lockett and Al-Habbooby (1974) postulated that the behaviour of a single species in a polydisperse system is a function of the

sum of the concentrations of the species present, but to solve a system of equations expressing this, free fall velocities, calibration exponents, and initial partial concentrations must be known. Lockett et al. found excellent agreement between their theory and experimental results for systems comprised of two species of particles. No results are available at present for more complex mixtures of inert spheres, and natural muds, with a range of particle sizes and shapes, and surface activity causing flocculation, are orders of magnitude more complex.

In light of these facts, and the type of settling data available from the present experiments, but acknowledging the sound hydrodynamic basis for relating settling velocity and particle concentration in systems of inert particles, a simple starting point is evident: the comparison of surface settling rate and average specific volume. Specific volume is defined as the total volume occupied by a unit volume of solid. It is equal to void ratio plus one and is the inverse of the sedimentological term particle concentration. Specific volume is the preferred measure of the proportions of void space to solids volume because it is a common geotechnical term and, in one-dimensional compression, specific volume is proportional directly to soil height.

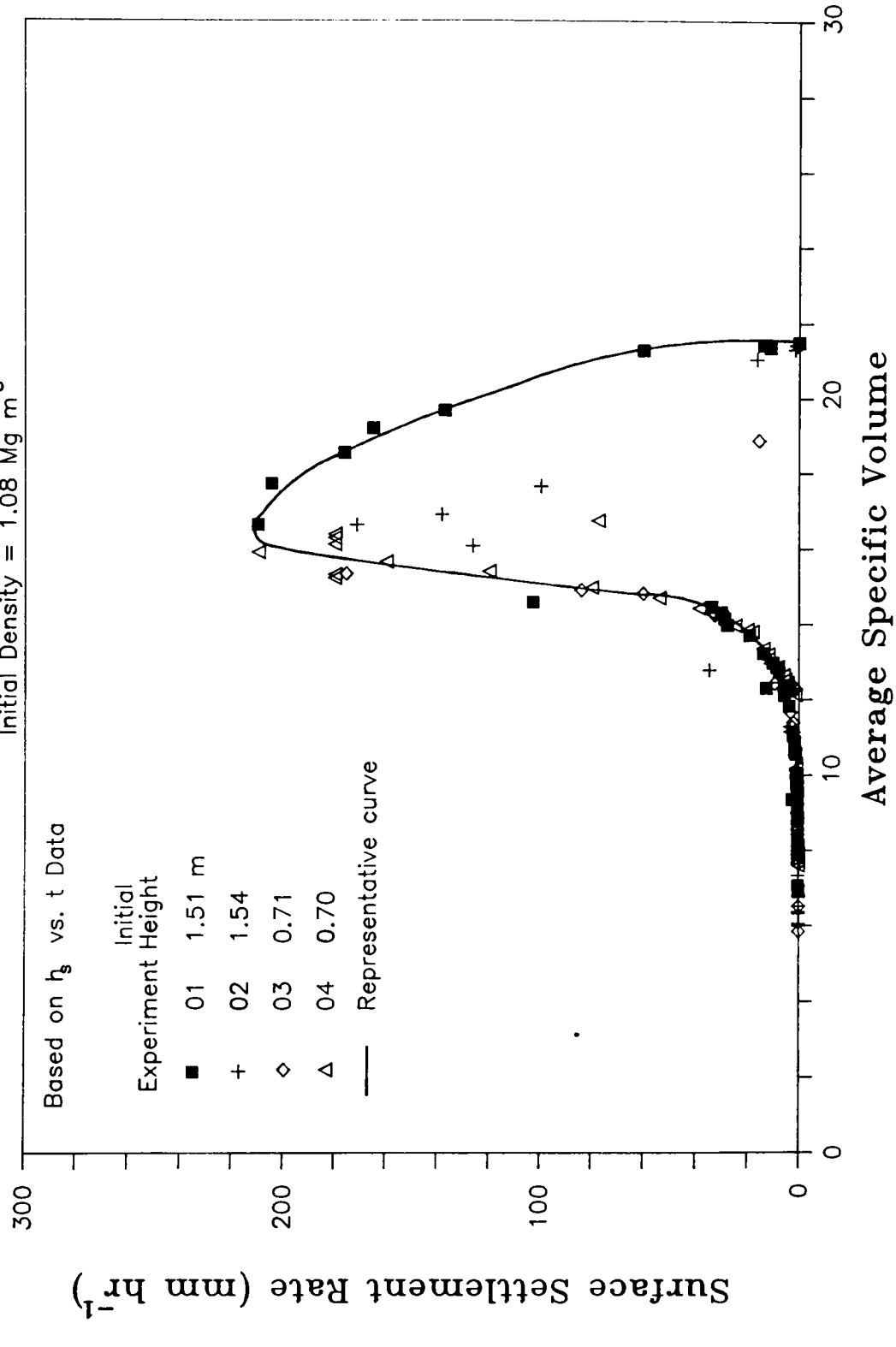
Height of slurry surface measurements were made during 21 of the experiments performed. Rates of surface settlement have been calculated for increments of time and related to the average specific volume for the entire slurry, at the end of an time increment. Figures 4.18, 4.19, 4.20, 4.21, and 4.22 show the calculated results for 15 experiments. The results of six experiments, RB13-15 and RB19-21, begun at an initial density of 1.16 Mg m^{-3} are not

shown because these experiments exhibited maximum rates of settlement several orders of magnitude less than maximum rates observed in other experiments. On the basis of evidence presented in chapter 5, dealing with consolidation behaviour, it is thought that these relatively slow settling rates were due to particles being supported from below. Of greater interest are the 15 experiments which displayed rapid settling, when suspension or unsupported conditions probably existed and a Richardson and Zaki or Kynch-like expression might be definable.

Figure 4.18 shows calculated values of rate of surface settlement versus average specific volume for experiments RB01-04. The data for all four experiments are similar and may be approximated satisfactorily with a single qualitatively defined representative curve.

Figures 4.19, 4.20, 4.21, and 4.22 present surface settling rate versus average specific volume data for other experiments. Representative curves are shown in these figures and the curves are seen to be similar in shape, but different in proportions and position with respect to the axes. In spite of differences in proportions (shown most clearly in Figure 4.23) a simple settling rate model was conceived and is shown in Figure 4.24. In this figure the passage of time increases from right to left. Its basic elements are (a) the specific volume at input, (b) a flocculation limb, (c) a maximum settling velocity or plateau, (d) a hindered settling limb, (e) a transition region between settling and the onset of effective stress, and (f) a compression limb representing very slow effective stress consolidation. Each component deserves a few comments before detailed

Figure 4.18: Surface Settlment Rate vs. Average Specific Volume



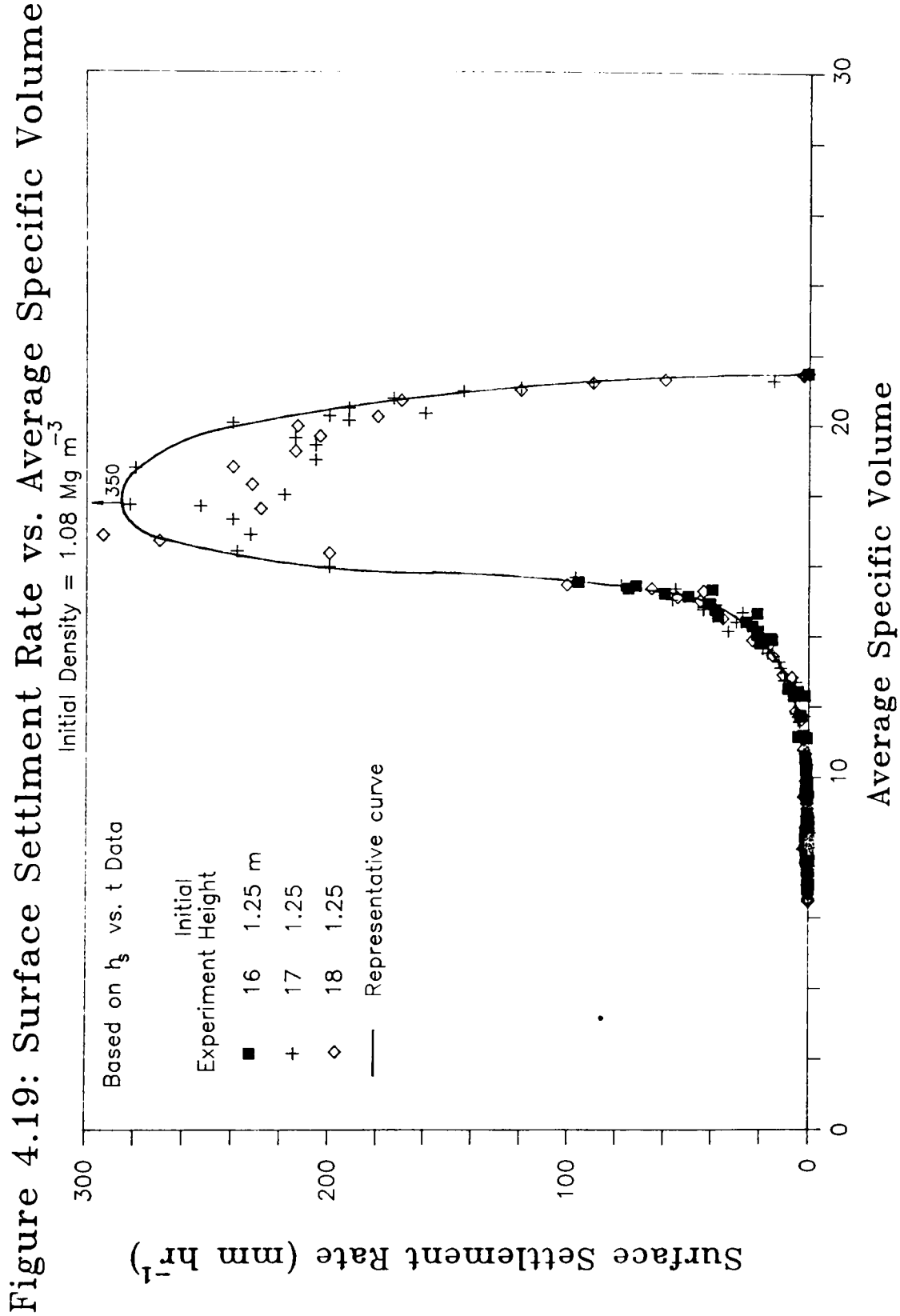


Figure 4.19: Surface Settlment Rate vs. Average Specific Volume

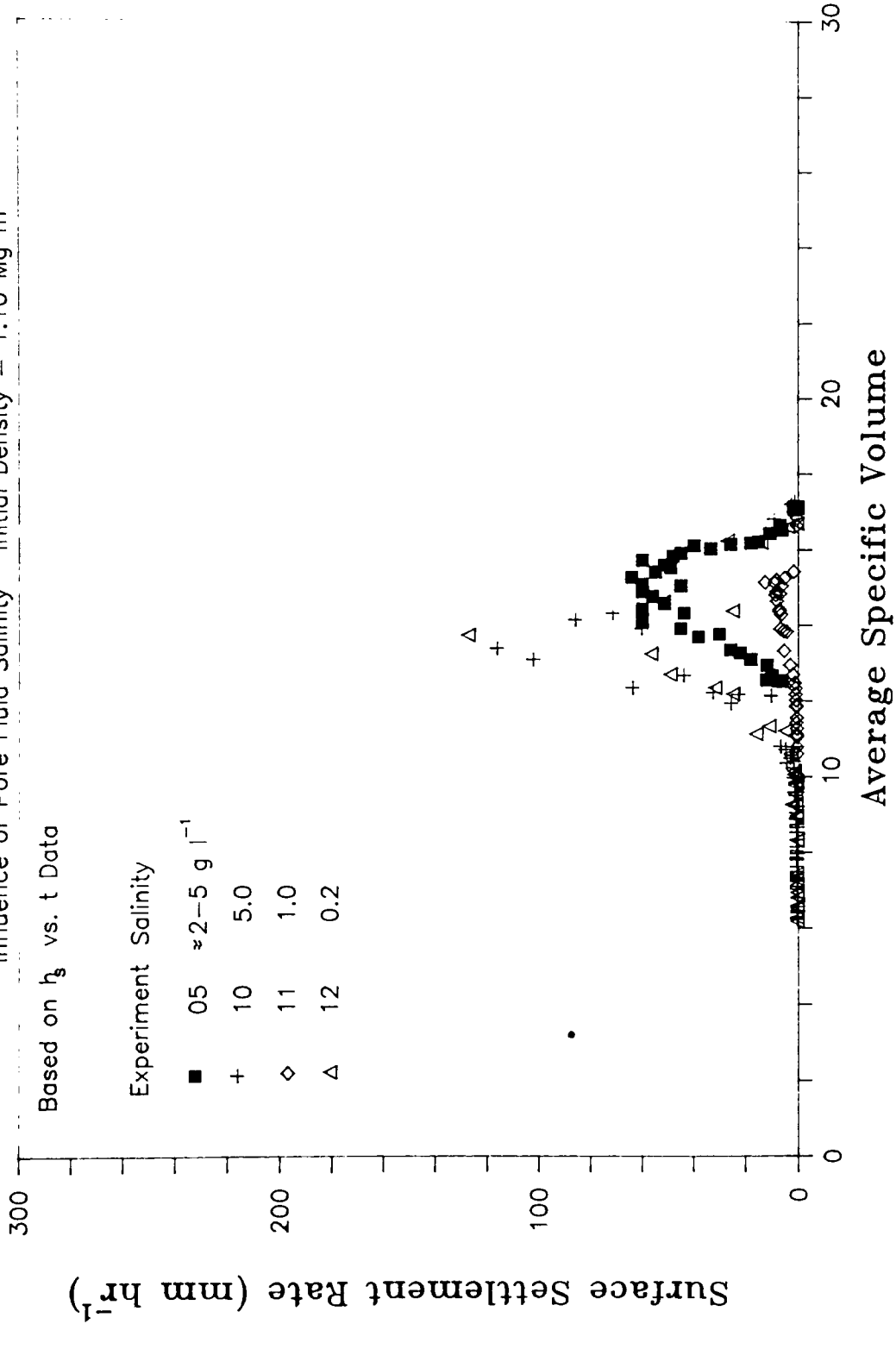


Figure 4.20: Surface Settlment Rate vs. Average Specific Volume

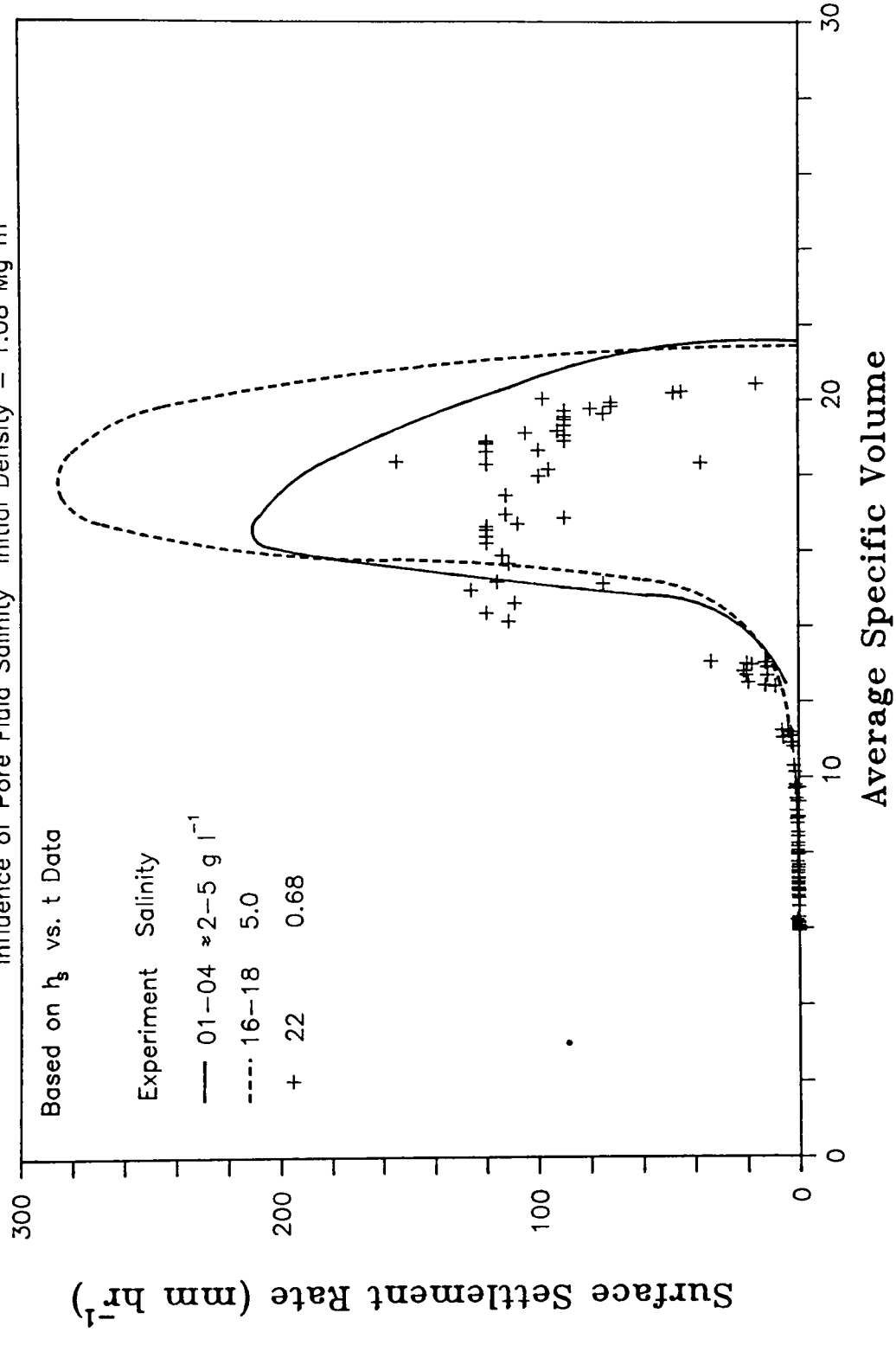


Figure 4.21: Surface Settlement Rate vs. Average Specific Volume

Influence of Pore Fluid Salinity Initial Density = 1.08 Mg m^{-3}

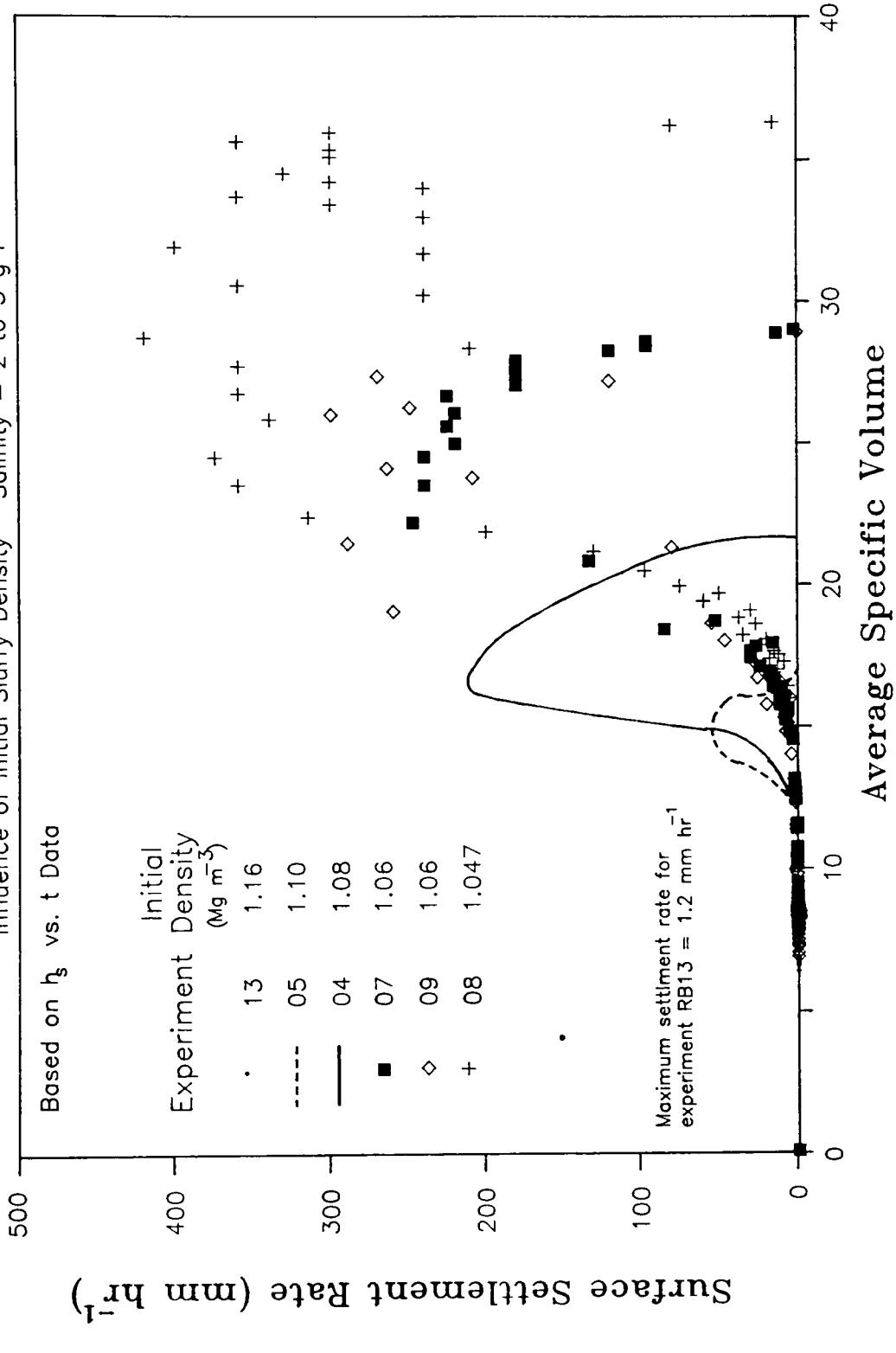


Figure 4.22: Surface Settlement Rate vs. Average Specific Volume
Influence of Initial Slurry Density Salinity = 2 to 5 g l^{-1}

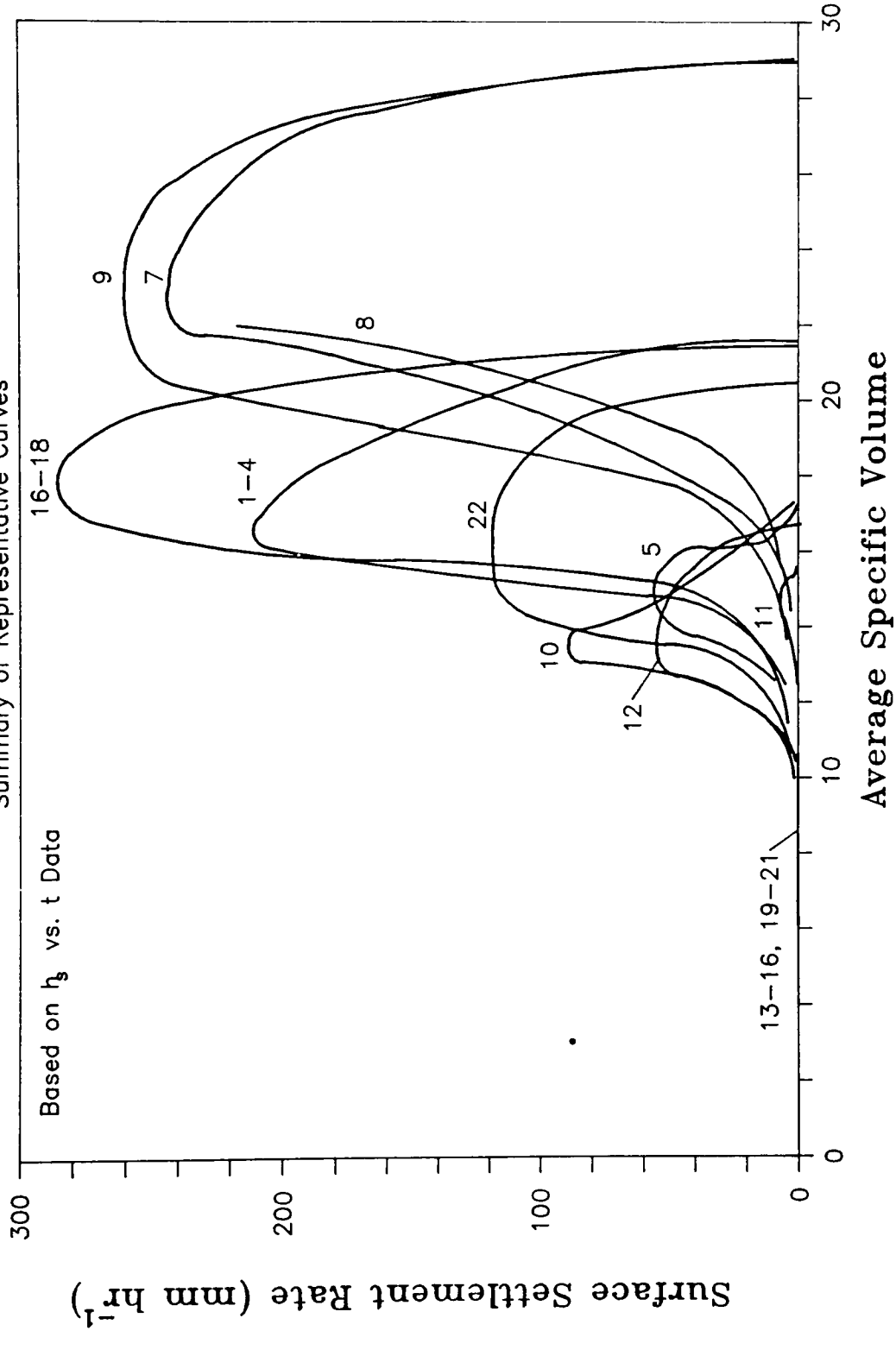
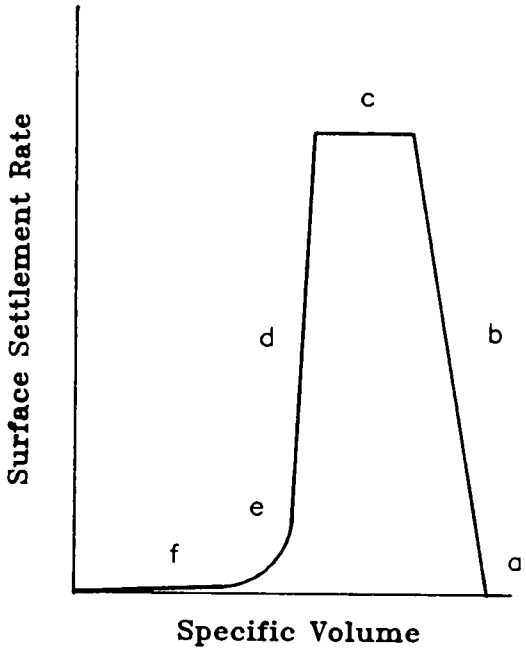


Figure 4.23: Surface Settlment Rate vs. Average Specific Volume

Figure 4.24
Simplified Settling Rate Model



comparisons of surface settlement rate versus average specific volume are made between experiments with different conditions.

Point 'a' in Figure 4.24 is the input specific volume. It is the largest average specific volume possible during an experiment. Larger local specific volumes may arise if there is differential settling leading to dilution, but profiles of sediment mass within a slurry are needed to establish local specific volumes. Only average specific volumes are determinable with height of surface data.

Limb 'b' shows a trend of increasing settling velocity with decreasing specific volume. This relationship is the opposite of limb 'd' and contrary to intuition. It may be attributed to flocculation: as flocculation proceeds, increasing floc size leads to increasing settling velocity. Flocculation also increases the average distance between settling units, thereby reducing hinderance phenomena and the relative viscosity of the suspending medium. The increase in velocity is not instantaneous, however, because flocs require a finite amount of time (or change in volume in settling experiments) to accrete and to accelerate to a terminal velocity.

The data recorded for RB experiments showed either a maximum settling velocity corresponding to a single specific volume or, when the input density and/or pore fluid salinity were/was low, a plateau-like maximum velocity which spanned a range of specific volumes (region 'c'). In flocculated slurries in general, maximum settling rate is governed by floc size and density, and these factors are, in turn, influenced by initial slurry density and pore fluid salinity.

Region 'd' represents hydrodynamically hindered settling. In Richardson and Zaki's empirical equation and Kynch's theory of hindered settling, settling velocity is dictated by hydrodynamic interactions and velocity decreases as particle concentration increases (specific volume decreases).

Region 'e' in the model denotes a transition between hindered settling ('d'), and consolidation ('f'). Several factors govern the shape of this region. First, the relationship between surface settling rate and average specific volume is particularly non-linear at specific volumes near the transition region because there is a disproportionate increase in the effective viscosity of pore fluid as specific volume decreases. For example, in a system of neutrally buoyant monodispersed spheres in a Newtonian liquid, the viscosity at a particle concentration of 95% of the loosest random packing for spheres is approximately 60 times that of the suspending medium alone (Scott, 1960). This relative increase in viscosity due to particle concentration is greatly enhanced by particle anisotropy, polydispersity, decreasing particle size, and surface activity. It is not surprising, therefore, that hindered settling rate models have great

difficulty describing suspensions of natural sediments, particularly as particles aggregate towards a continuous or space filling structure.

Second, in flocculated slurries the transition region is one in which an increasing degree of aggregation leads to a continuously structured bed. Aggregation decreases significantly the mobility of particles, and thus their settling rate, with only slight changes in specific volume. Imai (1980) illustrates this fact with photographs of slurries which showed radical changes in appearance with small changes in specific volume near the transition.

Third, the transition from settling to consolidation is gradual rather than abrupt because natural flocculated slurries consist of a range of particle sizes, shapes, and mineralogies which interact (giving rise to effective stress) at a range of particle distances or, equivalently, specific volumes. Finally, the shape of region 'e' is also a consequence partly of the parameter average specific volume. A settling slurry may consist of regions of both consolidating and effective stress free sediment simultaneously (see section 4.5), hence average values of specific volume and surface settling rate will reflect a combination of both settling and consolidation.

At low specific volumes there is a continuous path of physical or electrochemical interaction between particles and the base of a column. This support or reaction has a profound retarding effect on settling velocity, more so than the purely hydrodynamic phenomena which are responsible for hindered settling at higher specific volumes. The onset of support or effective stress leads to a reduction in settling rate of several

orders of magnitude. Slow compression in the presence of effective stresses is represented by limb 'f' in Figure 4.24.

The simplified settling rate model proposed suggests settling rate curve components which may be compared between experiments with different conditions, to reveal the influences of initial slurry height, pore fluid salinity, and initial density on average settling rate.

In Figure 4.18 results of four experiments begun at a density of 1.08 Mg m^{-3}, but with different initial heights (0.7 to 1.5 m), are shown. Pore fluid salinity was not measured in any of experiments RB01 through RB09 but is estimated to have been between 2 and 5 g l^{-1} (refer to section 3.2), and constant for these four slurries prepared together. Similar maximum settling rates were observed in all four experiments, which suggests that this parameter was independent of initial slurry height. The only noticeable difference in the results is the rate of flocculation in experiment RB01 (h_{s_i} = 1.51 m). This difference is not attributable to initial slurry height because experiment RB02 (h_{s_i} = 1.54 m) flocculated at the same rate as shorter slurries. It is possible that a small variation in turbulence level initially was responsible: mild turbulence would affect the rate of flocculation but would not alter floc characteristics, and the otherwise similarly shaped curves in Figure 4.18 suggest that the floc characteristics were similar.

Figure 4.19 shows data for a set of experiments (RB16-RB18) also begun at a density of 1.08 Mg m^{-3} and a measured salinity of 5 g l^{-1}. The representative curves in Figure 4.18 and 4.19 are similar in terms of the

position and shape of the transition region 'e', and the position and shape of the hindered settling limb 'd'. These results suggest flocs of similar physical and electrochemical 'size'. However, two differences in the results in the figures suggest that other floc characteristics differed. Experiments RB16-18 showed a greater maximum settling velocity, and a larger average specific volume at the onset of hindered settling, than did experiments RB01-04. If differences in floc size are ruled out as a possible explanation (on the basis of evidence given above), then the higher maximum settling rate must be due to either higher floc density and/or lower floc roughness. Results for sets of experiments RB01-04 and RB16-18 illustrate the sensitivity of behaviour to salinity, since salinity was the only factor that may have differed in the two sets of experiments.

The influence of salinity on settling behaviour is revealed more clearly in two sets of data (shown in Figures 4.20 and 4.21) each of which includes results of experiments at a single density (ρ_i= 1.10 and 1.08 Mg m^{-3}, respectively). Figure 4.20 shows data for experiments RB5, 10, 11, and 12, which had salinities ranging from 0.2 to 5 g l^{-1}. These results show considerable variations in all aspects of curve form. The position of the transition region 'e' varies by two units of specific volume and this is a significant proportion of the five unit difference between the input and transition specific volumes. The degree of hinderance on settling (limb 'c') was also sensitive to pore fluid salinity, as were maximum rates of settling, which varied by an order of magnitude. The results of experiment RB11 suggest strongly that in this experiment effective stresses were present from the outset even though the input specific volume was 17

(ρ_i=1.10 Mg m^{-3}). The results in Figure 4.20 show clearly that pore fluid salinity exerts an important influence on surface settling behaviour.

The significance of salinity is confirmed by the results of eight experiments all begun at a density of 1.08 mg m^{-3}, shown in Figure 4.21. Representative curves for experiments RB01-04 and RB16-18 (C_s≈5 g l^{-1}) from Figures 4.18 and 4.19 are presented along with data for experiment RB22 (C_s=0.68 g l^{-1}). Results for experiment RB22 showed lower values of maximum settling velocity, specific volume at the onset of hinderance, and specific volume at the transition to consolidation, than were observed in experiments RB01-04 and RB16-18. All three observations suggest smaller floc size, and thus weaker interparticle forces, at low levels of pore fluid salinity.

Figure 4.22 presents representative settling rate curves for six experiments of similar salinity, which encompassed a range of initial densities (ρ_i=1.047 to 1.16 Mg m^{-3}). The results shown in this figure are as variable as those for experiments of variable salinity (Figures 4.20 and 4.21). Every aspect of curve form identified in the simplified settling rate model, Figure 4.24, was affected by initial density. Of particular note is the fact that the specific volume at which the transition from hindered settling to consolidation occurred was not unique, rather, it increased with decreasing initial slurry density. Similar results were observed by Krone (1962; cited in Owen, 1970) for dilute uniform suspensions of San Francisco Bay mud, by Imai (1980) for slurries prepared from three Japanese muds, and by Pierce and Williams (1966) for slurries of mud from four British estuaries.

Also noteworthy is the trend wherein the maximum settling rate increased as initial density decreased. This pattern is consistent with the hindered settling concept that settling velocity increases with decreasing concentration, with Stokes' velocity for a single settling unit being the maximum velocity possible.

The results confirm and clarify the significant influence on all aspects of settling behaviour that pore fluid salinity and initial slurry density exert. The fundamental factors responsible are the electrochemical forces that surround charged particles, and the concentration of those particles. The range and strength of interparticle forces, and the distances separating particles control the rate of flocculation, floc characteristics such as size and density, the degree to which flocs aggregate, and the strength of the structure that results when aggregation is continuous. These structural factors determine in turn, maximum settling rate, the specific volume at which the maximum velocity begins to decrease as a consequence of hydrodynamic hinderance, the severity of hinderance as specific volume decreases, the specific volume at the onset of significant aggregation (that is, the transition to consolidation), and the maximum specific volume required to yield a continuously structured bed with a finite compressibility.

Figure 4.23 is a summary plot of representative surface settlement rate versus specific volume curves for all RB experiments. It shows clearly that a simple relationship between surface settling rate and average specific volume does not exist for natural flocculated slurries, and that at least two parameters, initial slurry density and pore fluid salinity, must be

considered in any formulation relating settling velocity and specific volume.

4.5 Distribution of Sediment - Density Profiles

The preceding analysis of surface settling rate versus average specific volume has the attractive feature of being based on time and height of surface data only. Both parameters are easy to measure in the field and in the laboratory, and calculations for the analysis are simple. One disadvantage of the approach is, however, that specific volumes calculated on the basis of height of surface represent average values for the bed and may conceal local variations in specific volume that have an impact on settling and compression behaviour, and models thereof. The only way of exposing such variations is to examine the distribution of mass within a bed, a task for which the x-ray apparatus developed by Been (1981) is ideal. Before using density profiles to study the settling rate versus specific volume relationship for elements within a slurry, examples of profiles, a discussion of typical density profile characteristics, and different ways of studying changes in density and element movements with respect to time, are presented.

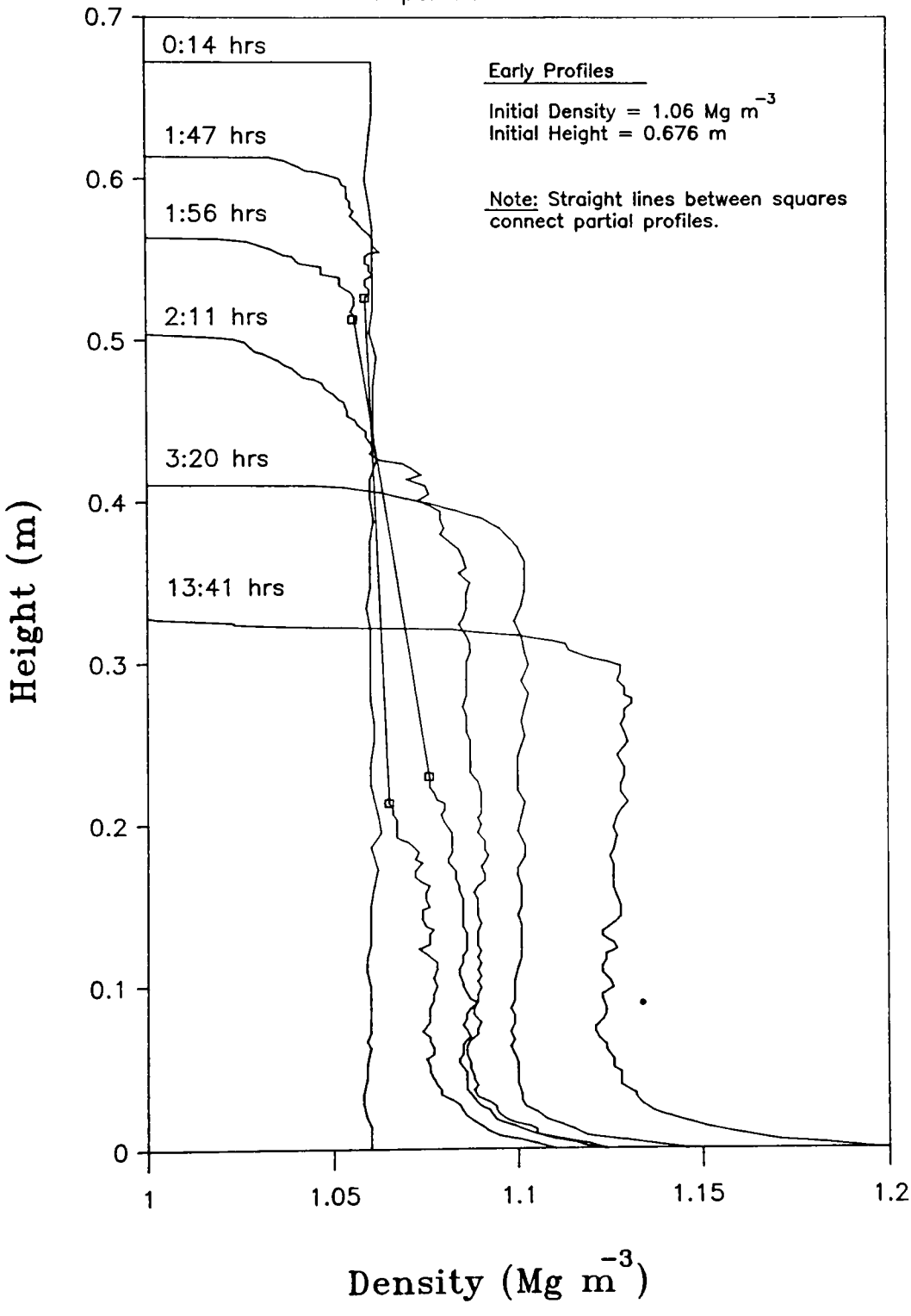
A total of 258 density profiles were made of RB-experiment slurries. Sediment distributions with respect to height and time were made to provide data for total stress calculations used in section 4.6 and in chapter 5, and to permit the study of sediment movement. Too many profiles were recorded for them all to be presented so representative profiles, those for experiment RB09, have been selected and are shown in Figures 4.25 (short

term) and 4.26 (long term). At the beginning of this experiment the density throughout the column was a uniform 1.060 Mg m^{-3} and it remained constant for approximately one and one-half hours. Height of surface versus time data for this period showed a constant height of surface (Figure 4.9). At t=1:33 hours sediment redistribution began, causing a sudden increase in density at the base of the column and a decrease in the elevation of the slurry surface (Figure 4.25). As the height of sediment surface fell dramatically, slurry density near to the surface decreased to less than that at which it was input. After 2:40 hours had elapsed this dilute upper region had vanished leaving a profile which was rounded near the sediment surface, linear and slightly overhanging (inverted) through its middle, and dense near its base. With the passage of time density increased throughout the slurry. The 334 hour profile for experiment RB09 shows a density distribution which increases uniformly with depth (Figure 4.26).

The density profiles for experiment RB09 show six important aspects of sediment distribution and movement during settling and consolidation.

Figure 4.25: Density Profiles

Experiment RB09



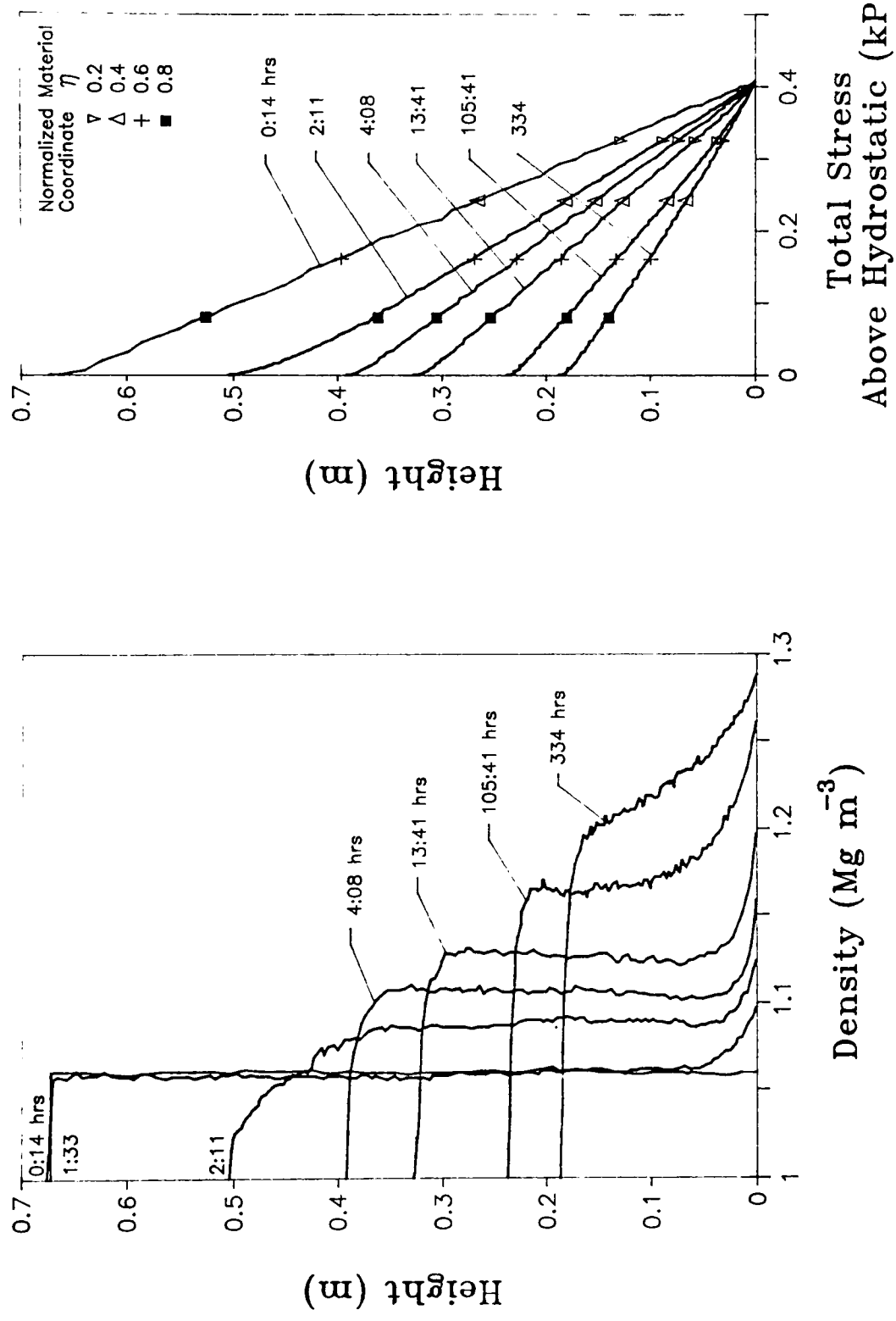


Figure 4.26: Density and Total Stress Profiles

Experiment RB09

1. The profiles confirm that the initial period of constant height of surface was also one of internal stability.

2. Rapid settlement of the surface was accompanied by the development of a dense layer at the base of the column. This layer increased in both height and density as settling proceeded.

3. Sediment near to the surface of the slurry was diluted to less than the input density by differential settling.

4. Density varied with respect to height rapidly and with respect to time slowly near the surface of a slurry.

5. After settling commenced density profiles were not uniform. In general density inversions occurred under a range of conditions and persisted for up to several hundred hours.

6. Density increased monotonically with depth after long durations.

Most, although not all six features listed above were observed in the 229 profiles made for other RB-experiments. There were considerable variations in the proportions, and persistence with respect to time of features, depending on experiment conditions. Features two through six deserve elaboration.

The fact that the sediment surface began to settle and a high density region at the column base began to form simultaneously (that is within the time required to record a density profile) suggests that collapse began at the base of the column and fluid flowed through the height of the slurry rapidly. This behaviour implies that the bulk permeability of the slurry was high, a view consistent with the presence of channels during rapid settling. The high density region at the base of the column was not caused by segregation of coarse material (section 4.2) as postulated by Elder and Sills (1984) for similar behaviour observed by Elder.

A reduction in near-surface slurry density to less than the input density implies differential settling leading to dilution. Differential settling can occur without segregation if settling units consist of flocs.

A characteristic feature of density profiles of slurries begun at low densities is a rounded or rapidly varying density profile near the sediment surface. The cause of this is a combination of low overburden stress and attractive interparticle forces. Attractive forces cause particles to form bridges that are capable of supporting a limited overburden thickness. Density decreases and specific volume increase towards the surface, as the overburden stress decreases to zero at the sediment surface. Flocculation, and the tendency of near-surface sediment to become more dense with the passage of time but without changes in effective stress, are strong evidence of the existence of attractive electrochemical forces. The fact that the density of near-surface sediment varied with height and time makes the task of identifying or predicting a surface specific volume difficult.

It must be noted that all slurries begun at a density of 1.16 Mg m^{-3} showed neither rapid settling, nor a region less dense than the input density, nor a rounded near-surface density profile. An absence of these characteristics suggests an interparticle spacing sufficiently small that particles were forced into reacting with one another from the moment of input. A 'packed' condition prevents channels forming, and thus rapid settlement, and precludes the low density conditions necessary for particle bridges to form.

Features one, and five and six, regarding initial stability and non-uniform density profiles, are significant from the point of view of modelling

behaviour. None of the settling models of Kynch (1952), Richardson and Zaki (1954), and Michaels and Bolger (1962) predict an initial period of stability. Neither do they predict a region of sediment dilution. And Michaels and Bolger's settling model for slurries of intermediate concentration, which assumes a settling plug of uniform density, is incorrect. Elder observed that local variations in density, such as those that occur beneath surcharge loads on the surface of a deposit, influence compression behaviour strongly. Thus, in summary, errors made in modelling the distribution, and changes in distribution, of sediment within a compressing slurry, affect the accuracy of predictions produced by surface settlement models.

Density profiles expose behaviour influencing internal variations in density that height of surface data simply cannot reveal. When presented in their traditional form (as in Figures 4.25 and 4.26) density versus height and time data are useful for identifying qualitative bulk changes in density but they do not show either readily or quantitatively the compression behaviour of portions or elements of a slurry. In order to observe changes in position and density undergone by specific elements of a slurry, total stress profiles must be calculated. This is achieved by integrating the area under a density profile from the top downward. To obtain total stress above hydrostatic, the mass of water is excluded from the sum. In the right hand side of Figure 4.26 symbols have been placed on each total stress curve at points corresponding to constant values (0.2, 0.4, 0.6, and 0.8) of the normalized material coordinate η, defined as follows,

$$\eta = \frac{z}{z_o}$$

where z_o = total mass of solids

z = mass of solid between an element and the base of the column

Each value of η 'tags' a specific soil element. Normalized material coordinates allow the behaviour of layers or individual elements of sediment to be studied quantitatively. As the size of the unit under study decreases from an entire column to specific elements, problems associated with interpreting average behaviour (section 4.4) diminish. Normalized material coordinates also permit clearer, more comprehensible, and more explicit forms of presenting data to be used.

Figures 4.27 and 4.28 show changes in the heights of layers of sediment between material coordinates for experiment RB09 at two time scales. The slope of each line segment is the average rate of compression of a constant mass fraction of sediment over the time increment shown. This quantity differs in two respects from the surface settlement rate parameter discussed earlier: the compression rate is, in this case, that of one fifth of the mass of the slurry; and changes in the height of a mass fraction are expressed relative to its initial height and not as a change in position relative to the base of the column.

Figure 4.27 shows results for the first ten hours of experiment RB09. All of the features evident in traditional profiles for this period can be identified: an initial period of stability; the onset of rapid settlement, preceded and accompanied by an increase in density at the base; dilution of

Figure 4.27: Compression Behaviour

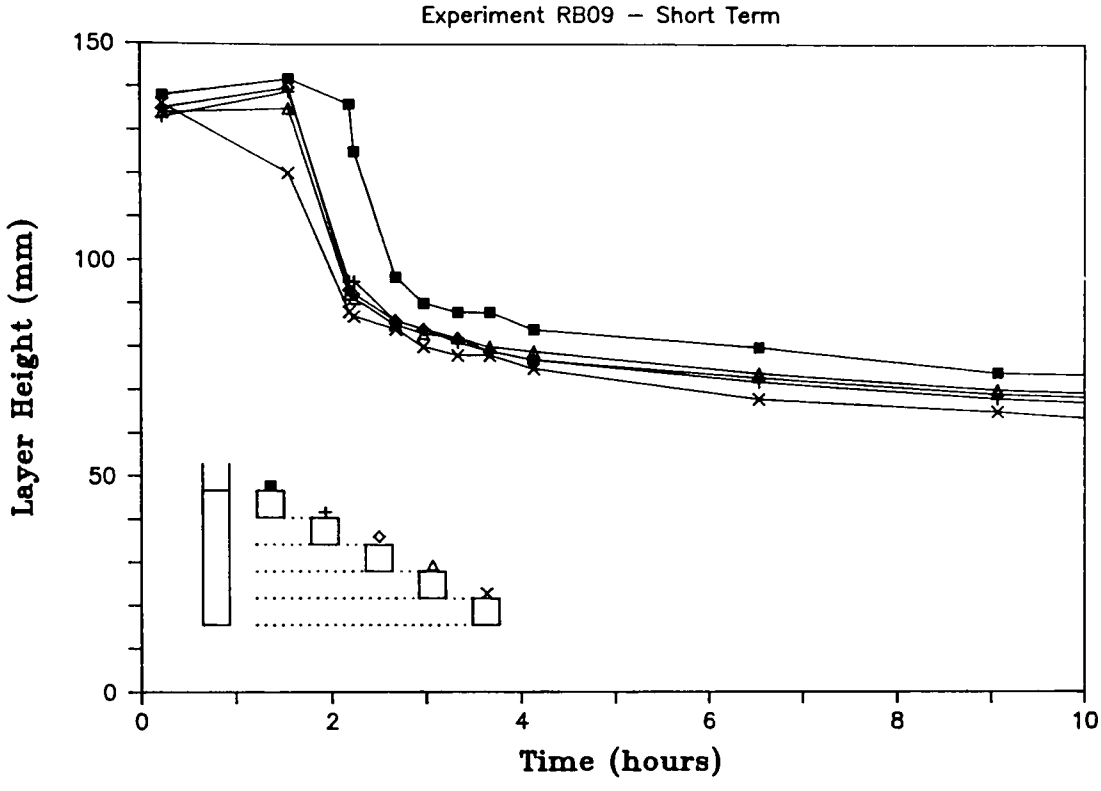
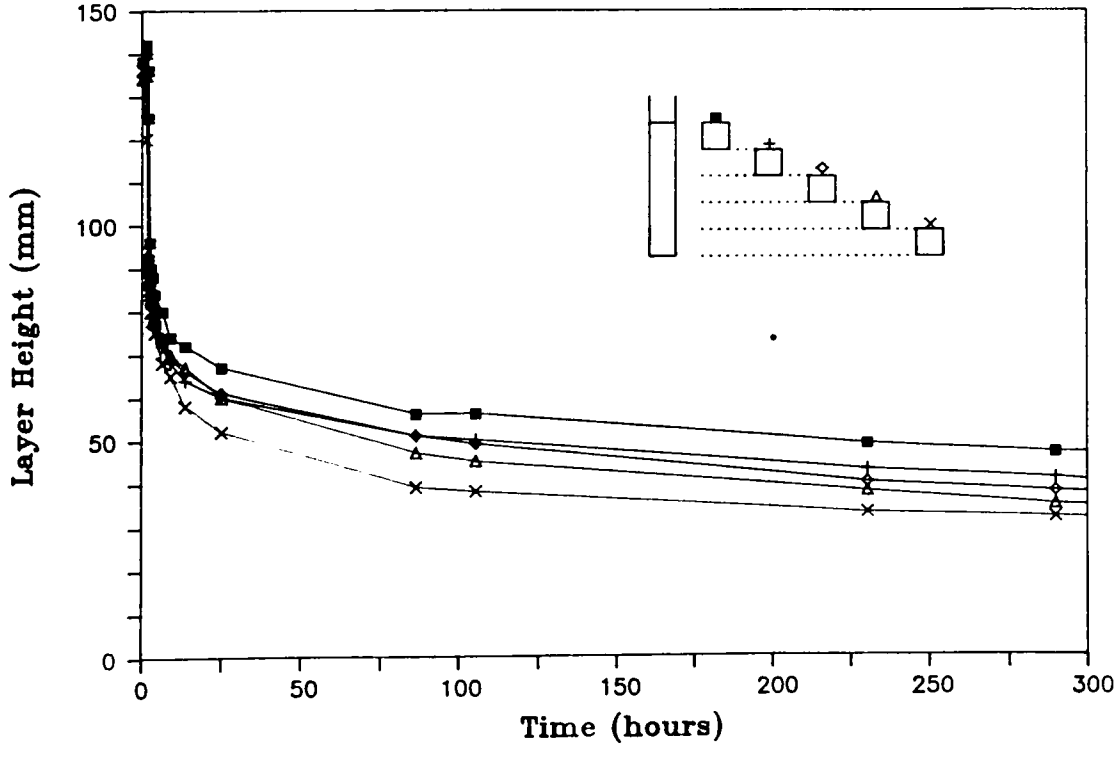


Figure 4.28: Compression Behaviour



the uppermost layer (partly concealed by the large mass increments which have been plotted); and a density inversion (illustrated by a thinner layer overlying a thicker layer of equal mass). In Figure 4.28, which shows results for a longer period, the density inversion vanishes after approximately 85 hours: at times thereafter, layer thicknesses decrease, and thus density increases regularly with depth.

Discretization of a column of slurry into increments of constant mass provides a more accurate and informative account of compression behaviour than is yielded by the parameter average specific volume which is based on height of surface data only. Greater resolution is possible, and a superior overall view of density is conveyed, if height, density and time data, and normalized material coordinates are plotted on a single graph. Figure 4.29 is a comprehensive plot of element density history for experiment RB02. In Figure 4.29 paths for five equally spaced η values are shown: the paths of any particular element may be determined readily. The position and density, and changes in both, of every element within a bed are shown. Settlement rate is equal to the slope of the tangent to a normalized material coordinate path (for example, the slope of the dashed line, η=0.4, t=15 hours). The distribution of density at any time is revealed by examining the density values intersected by a line drawn vertically across the graph (see inset). The rate of change of density with time is equal to the density difference between two contours divided by the difference in the two times at which the element of interest intersects those contours (points A and B on density contours ρ=1.14 and 1.16 Mg m^{-3}, Figure 4.29).

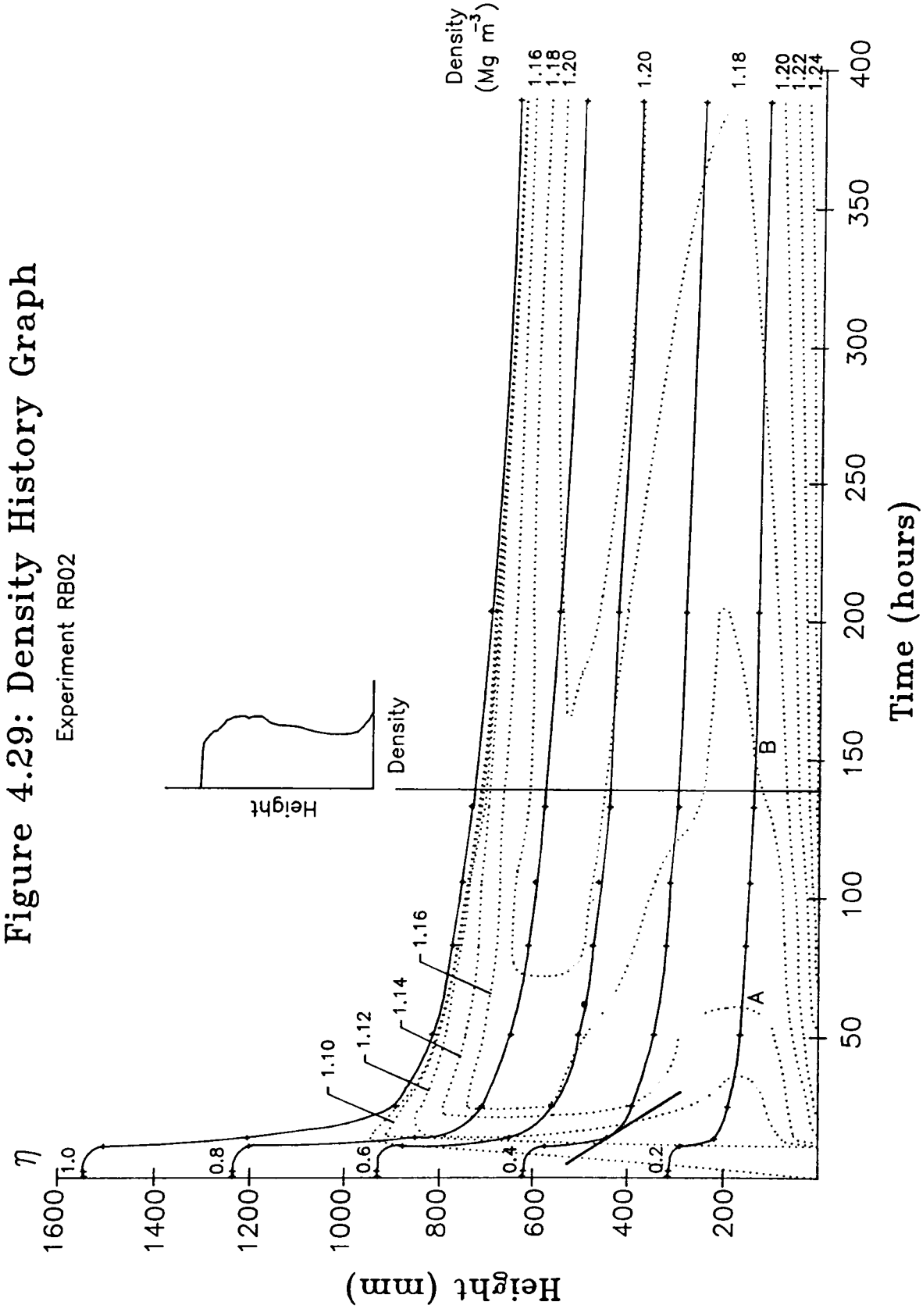

Figure 4.29: Density History Graph
Experiment RB02
Height (mm)
Time (hours)
Density (Mg m^{-3})
η
1.0
0.8
0.6
0.4
0.2
1.10
1.12
1.14
1.16
1.16
1.18
1.20
1.20
1.18
1.20
1.22
1.24
A
B
Height
Density

Figure 4.29 shows clearly a rapid general increase in density early on in experiment RB02, a rapid change in density with respect to height near the surface of the slurry, a density inversion, a slow rate of change of density in the middle of the column and, at later times, propagation of density contours of increasing value up from the base of the column.

4.6 Element Settlement Rate

Figure 4.30 shows element settlement rate versus average specific volume results for experiment RB09. These may be compared with surface settlement rate versus average specific volume results for the same experiment shown in Figure 4.31. The two types of data (average versus element) yield different graphs. This is due partly to the sources of the data: density profiles yield multiple pairs of element settlement rate - specific volume data per profile; height of surface data yield one pair of surface settlement rate - average specific volume results only per measurement.

The main differences between Figures 4.30 and 4.31 are, however, due to the parameter average specific volume. It was stated in section 4.5 that uniform density profiles are both rare and transient. Non-uniformly distributed slurries do not settle at a rate that is related simply to average specific volume because the relationship between settlement rate and specific volume is highly non-linear. Further, when a slurry surface settles more slowly than underlying sediment, such as when dilution occurs, the behaviour of the rapidly settling bulk of the sediment is misrepresented by a slow surface settlement rate. It follows that the parameter average specific volume should not be compared with surface settlement rate without

Figure 4.30
Element Settlement Rate vs. Specific Volume

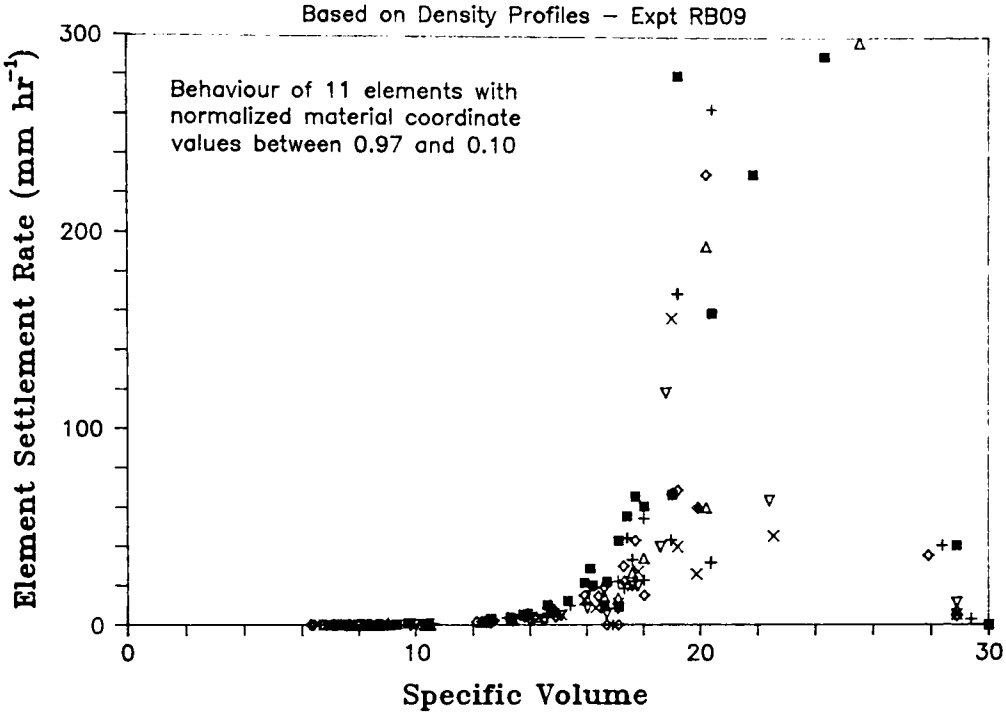
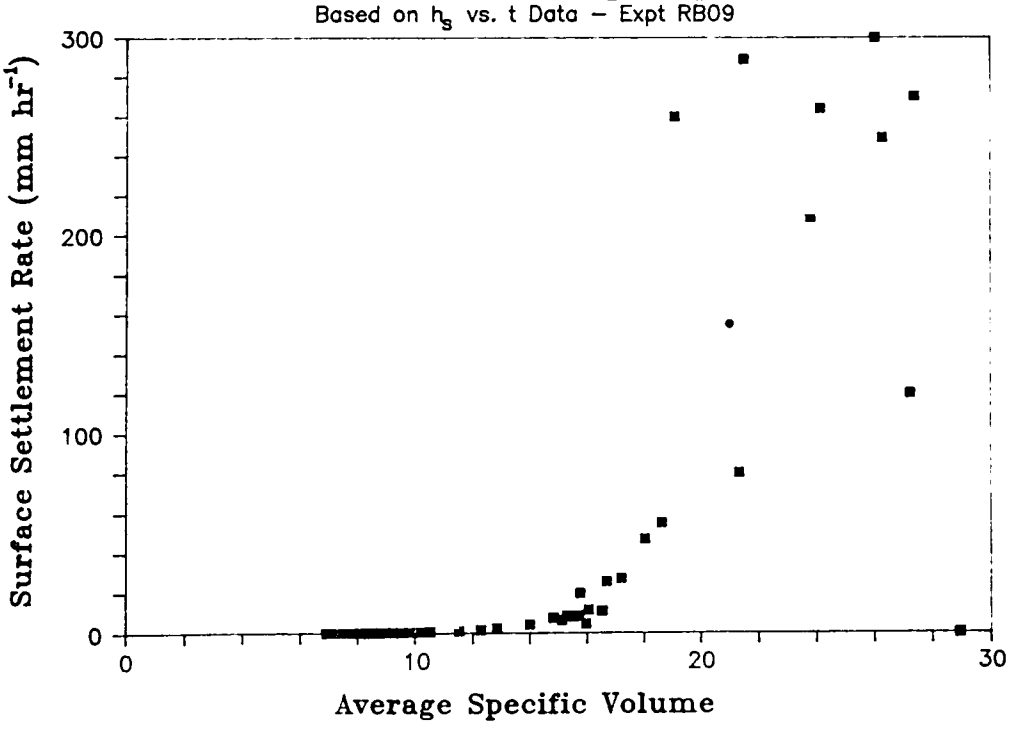


Figure 4.31: Surface
Settlement Rate vs. Average Specific Volume



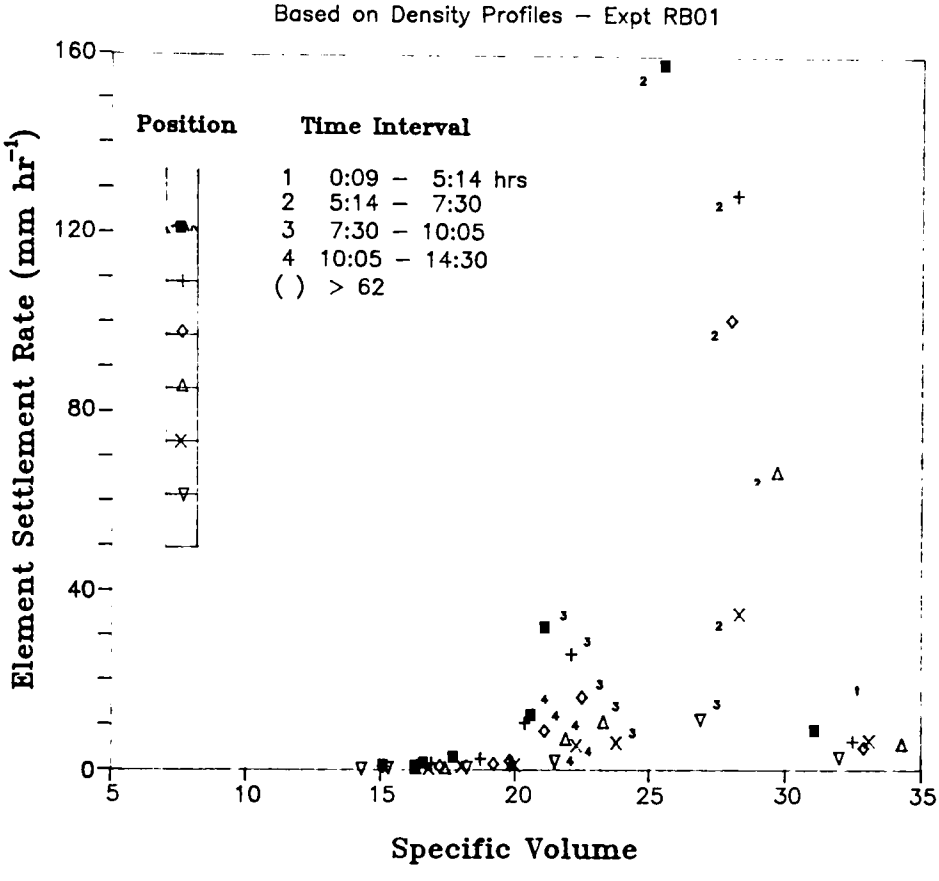
confirming that density is uniform with respect to depth. To obtain this proof density profiles must be made. This requirement eliminates the attractive simplicity of making height of surface measurements only.

In Figures 4.30 and 4.31 similar maximum surface and element settlement rates are shown (295 and 300 mm hr^{-1}). This similarity implies that the most rapidly settling element was at the slurry surface. Scattered data between average specific volumes of approximately 20 and 28 in Figure 4.31, at approximately 250 mm hr^{-1}, suggests a surface settlement rate independent of specific volume, over this range. Below a specific volume of approximately 20 the data in Figure 4.30 show that the rate of settlement decreased very rapidly with decreasing specific volume. The data in Figure 4.30 show a non-unique relationship between element settlement rate and specific volume at a specific volume of approximately 20.

Close examination of data in Figure 4.30 reveals that element settlement rates were position-dependent. Elements higher up in the column settled more rapidly than elements at the same specific volume lower down. Figure 4.32 shows early settlement rate data for experiment RB01, with relative column positions identified. In this experiment a density inversion existed, so that specific volumes decreased towards the surface. In spite of this pattern, elements higher in the column settled more rapidly than elements of higher specific volume lower down.

One explanation of position-dependence is that electrochemical interactions between flocs produced a range of degrees of aggregation within the rapidly settling slurry. The amalgamation of even a few flocs would have a

Figure 4.32
Element Settlement Rate vs. Specific Volume



significant effect on settling rate. Density profiles, upon which specific volumes are based, do not reveal state of aggregation.

4.7 Summary of Methods of Characterization

There are many different ways of characterizing settling behaviour and a number of these have been explored in this chapter.

The least quantitative approach is to describe behaviour in terms of changes in visual characteristics during settling. A substantial amount of

qualitative information about structure can be discerned from the appearance of the supernatant and the bed produced by a settling slurry. Some information is invaluable in terms of gaining an understanding of the cause of behaviour: channels, for example, are the key to rapid settling. Descriptions of appearances and behaviour are useful qualitatively, but they cannot be used as a basis for quantitative prediction.

Particle size analyses of settled beds are both useful and essential. The distribution of different particle sizes within a settled bed yields knowledge about the relative degrees of particle freedom and independence during settling; information which no other parameter can provide. Particle size analyses are the simplest means of assessing the degree of homogeneity of a bed with respect to solid fraction composition. Establishing material homogeneity is a prerequisite to interpreting behaviour.

The simplest quantitative characterization of settling behaviour is in terms of height of surface versus time. It is a popular form because both parameters are easy to measure, and the most common behavioural prediction sought is the position of the surface of a slurry at a particular point in time. Height of surface versus time data does not reveal either the cause of a particular behaviour that might be observed or the behaviour of sediment below the surface.

Another, superior, characterization of behaviour based on height of surface versus time data is surface settling rate versus average specific volume. The historical justification for describing behaviour in this way is that settling velocity is controlled by hydrodynamic hinderance, and hinderance

is proportional to particle concentration or specific volume. Data presented in this way often reveal phases of behaviour which can be related to particular material states and/or structures. This connection is valuable from the point of understanding behaviour, whilst the partitioning of behaviour into distinct phases makes comparisons between experiments easier.

The primary disadvantage of all characterizations of slurry behaviour based on height of surface data is that either an assumption or proof is required before one can suggest that the behaviour of a slurry surface reflects the behaviour of the mass of sediment beneath it. Density distributions, made with respect to height and time, are one means of assessing whether or not the two are indeed related. If the relationship is complex, or if the surface and the bulk of the sediment act independently, then any analysis of height of surface data only will be of little value and potentially misleading.

Density profiles provide more than qualitative insight into the distribution of sediment within a slurry. They may be discretized into layers, and the behaviour of fractions of a complete slurry plotted with respect to time, density, and position, yielding a comprehensive picture of density history. Specific features within a slurry which affect behaviour can then be identified and correctly incorporated into models. Alternatively, density profiles may be used to study the settling behaviour of individual elements within a slurry in terms of local specific volume.

In all instances, the objectives of characterizing behaviour are to expose the causes of behaviour, and to yield a model that allows behaviour to be predicted. Some forms of characterization are superior to others in achieving these goals. It must be appreciated that concomitant with an increase in resolution and quantitativeness achieved by progressing from visual descriptions to the behavioural analysis of individual elements, is an increase in the level of sophistication of the methods and equipment needed to make this progress. Refined forms of characterization may be satisfactory for laboratory-based research but limitations imposed by field conditions, equipment, and procedures must be recognized when it comes to defining a practical model.

Throughout chapter 4 attention has been focussed on the behaviour of slurries before the onset of effective stress; that is, before the reaction between sediment and a boundary is communicated throughout a slurry. As this condition is approached, that is as the degree of aggregation within a system of charged particles increases, even empirical models cease to be adequate. With the onset of effective stresses, settling models which assume that behaviour is governed by purely hydrodynamic phenomena become invalid, and a new form of characterization is required. It is logical that the form should include effective stress because near to the onset of effective stresses, and certainly at all times afterward, particle-particle interactions, rather than particle-fluid interactions, control behaviour. Consolidation, that is compression under the influence of effective stresses, is the subject of chapter five.

CHAPTER 5 COMPRESSION BEHAVIOUR: CONSOLIDATION RESULTS

5.0 Introduction

In this chapter one-dimensional self-weight consolidation of settled beds is examined in search of a relationship between stress and strain at low effective stress levels. The perspective is geotechnical: changes in specific volume are studied in terms of changes in effective stress. Well-defined compressibility relationships are shown to exist and the influences of initial slurry density, pore fluid salinity, and time on compression behaviour are presented. Compression behaviour is also considered from the point of view of fluid movement. The validity of Darcy's law, relating rate of fluid flow (v) and hydraulic pressure gradient (i), is examined and is shown to be invalid for specific volumes greater than seven. No alternative v-i, or other form of fluid flow relationship, is readily apparent. Simple, well-defined compressibility and pore fluid flow relationships are essential in order to model compression behaviour accurately and with a minimum of computational effort.

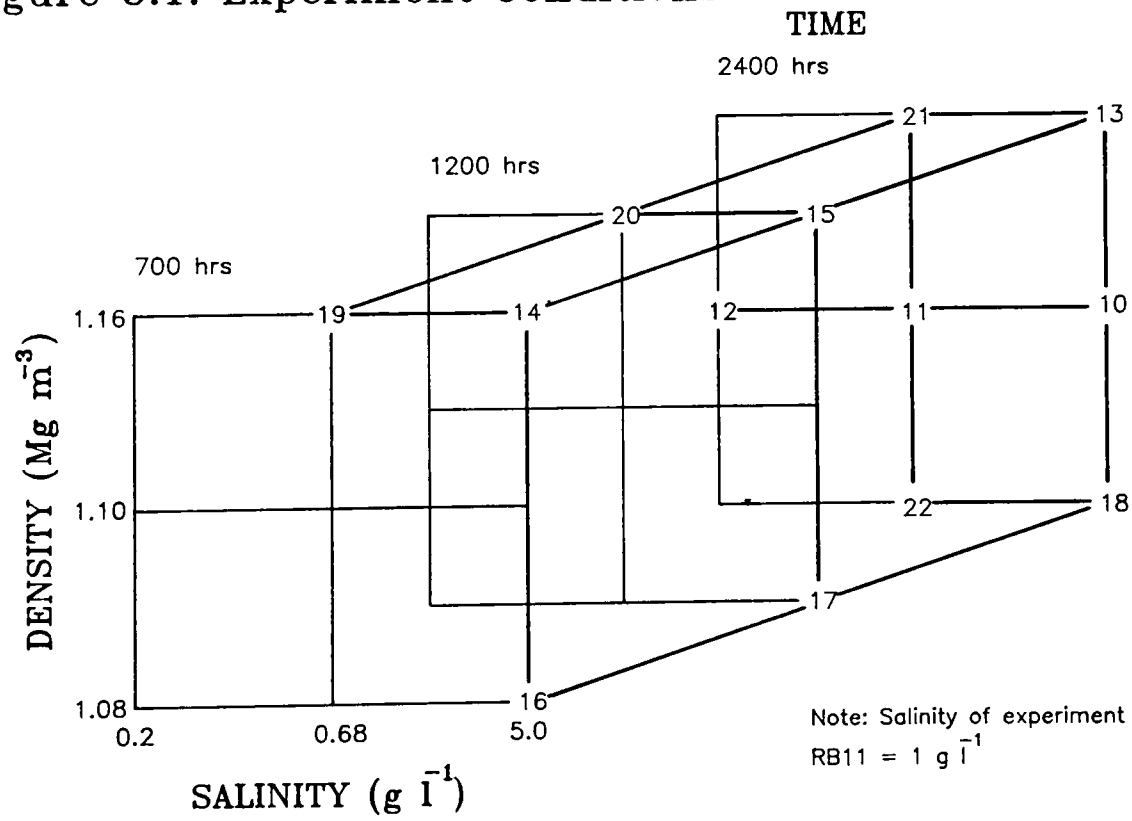
5.1 Effective Stress versus Specific Volume

Compression results in this section are presented in terms of specific volume and effective stress. Specific volume is a convenient parameter because in one-dimensional consolidation it is directly proportional to soil height. Effective stress is, as stated in earlier chapters, the difference

between total stress and pore water pressure. In experiments RB10-22, which spanned a range of initial slurry densities, salinities, and durations (Figure 5.1), density, total stress, and pore pressure data were recorded, and these enabled a study of specific volume versus effective stress to be made.

At low effective stress levels, 0 to 0.1 kPa, and at high specific volumes, 10 to 26, compression data for most experiments showed substantial scatter (Figures 5.2-5.9). This variation may be attributed partially to the lower accuracy of specific volume and pore pressure measurements at low effective stresses and high specific volumes (see sections 3.3.2 and 3.3.3) but, for

Figure 5.1: Experiment Conditions



the most part, the compression results reflect large and variable compressibility. The results suggest a weak, poorly ordered and/or non-uniform structure, one that compresses significantly and erratically under small effective stresses.

It was also observed, at low stress levels, that 'old' soil elements were less voluminous than similarly stressed 'young' elements. This apparent time-dependent behaviour is referred to as secondary consolidation or creep. It is proposed that attractive electrochemical forces were responsible for changes in volume at constant effective stress with the passage of time. Attractive forces influence neither of the two terms total stress and pore water pressure, which are used to calculate effective stress, hence these forces may exist and change without influencing effective stress levels.

Above an effective stress level of approximately 0.1 kPa, the parameters effective stress and specific volume were observed to be closely related under all conditions and at all times. Figure 5.2 shows compression results for experiment RB18, calculated from density and pore pressure data recorded at six times between t=651 and 2212 hours. The data points form a simple, well-defined curve in which coincident effective stresses and specific volumes for data recorded at different times confirms time-independence at stress levels above 0.1 kPa. Figure 5.3 shows results for experiment RB22, another experiment in which compressibility was observed to be independent of time.

Figures 5.4, 5.5, and 5.6 show data for experiments RB10, 11, and 12, at a variety of times, whilst Figures 5.7 through 5.9 show compression results

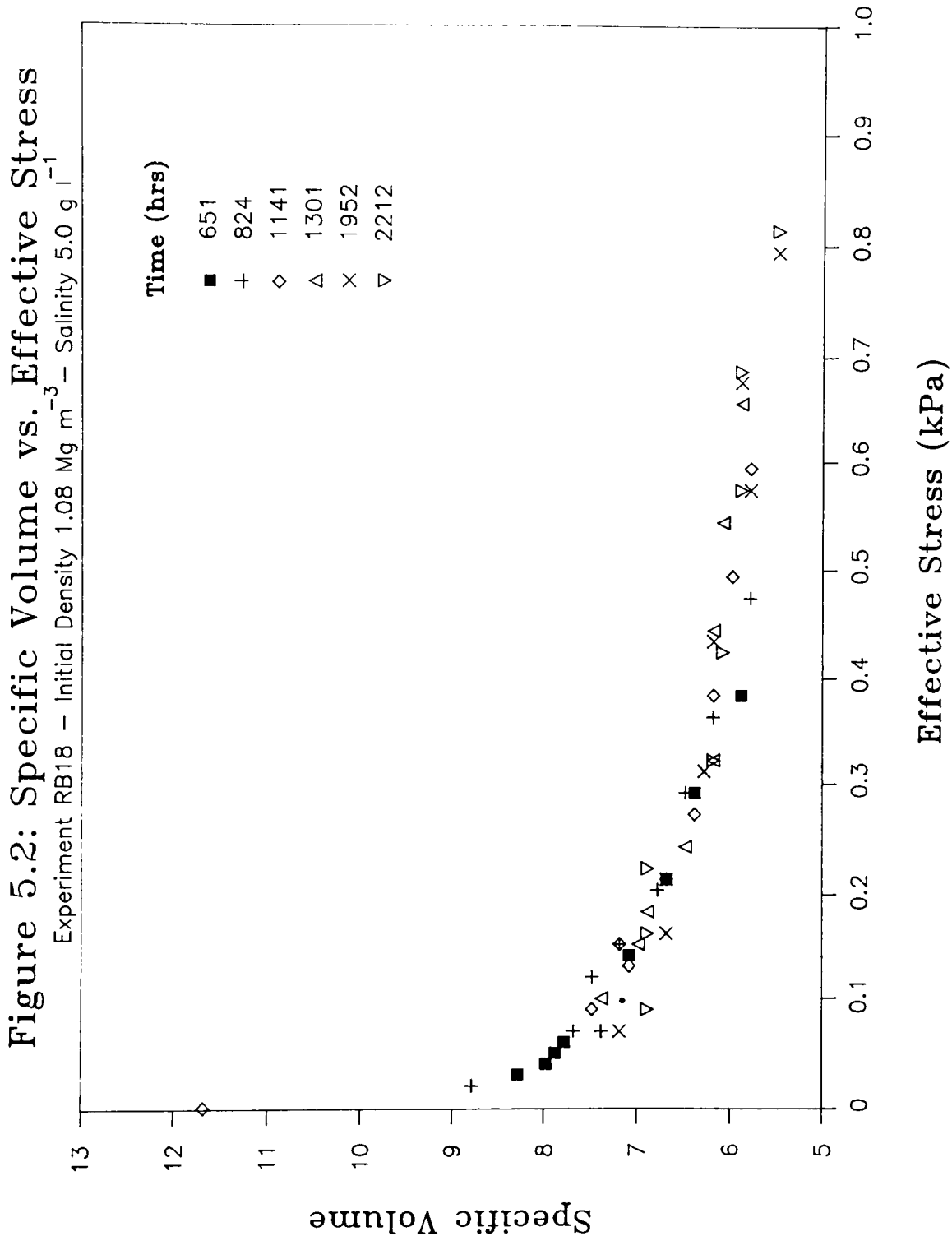

Figure 5.2: Specific Volume vs. Effective Stress
Experiment RB18 – Initial Density 1.08 Mg m^{-3} – Salinity 5.0 g l^{-1}
Time (hrs)
651
824
1141
1301
1952
2212
Specific Volume
Effective Stress (kPa)
13
12
11
10
9
8
7
6
5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

Figure 5.3: Specific Volume vs. Effective Stress

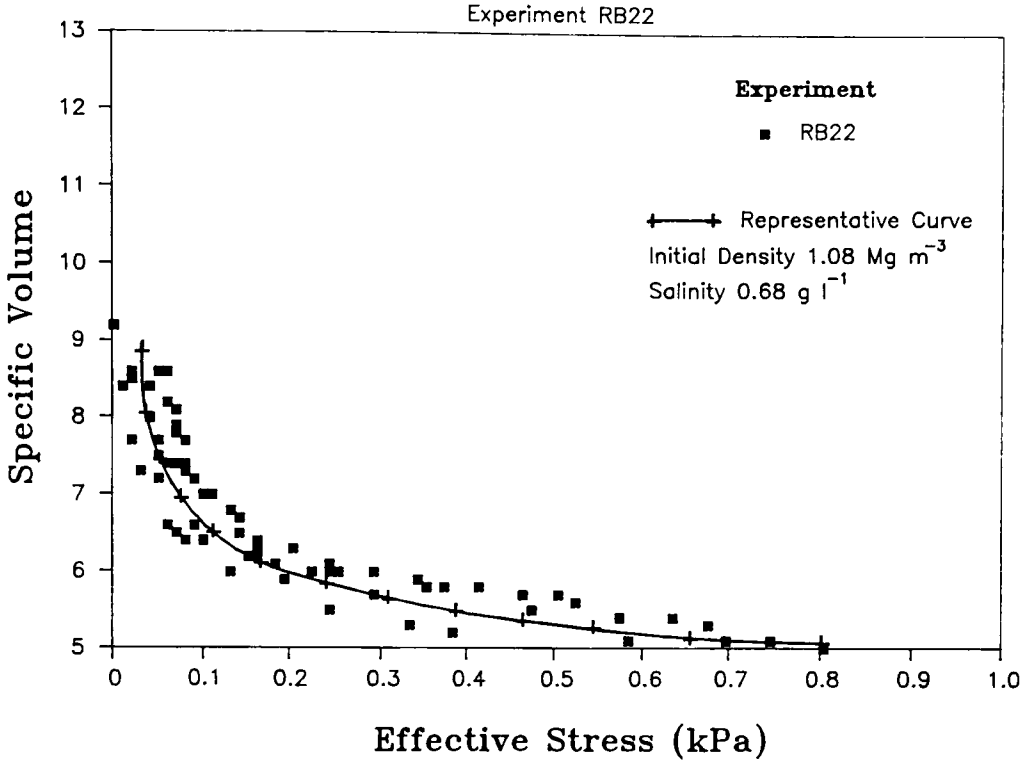


Figure 5.4: Specific Volume vs. Effective Stress

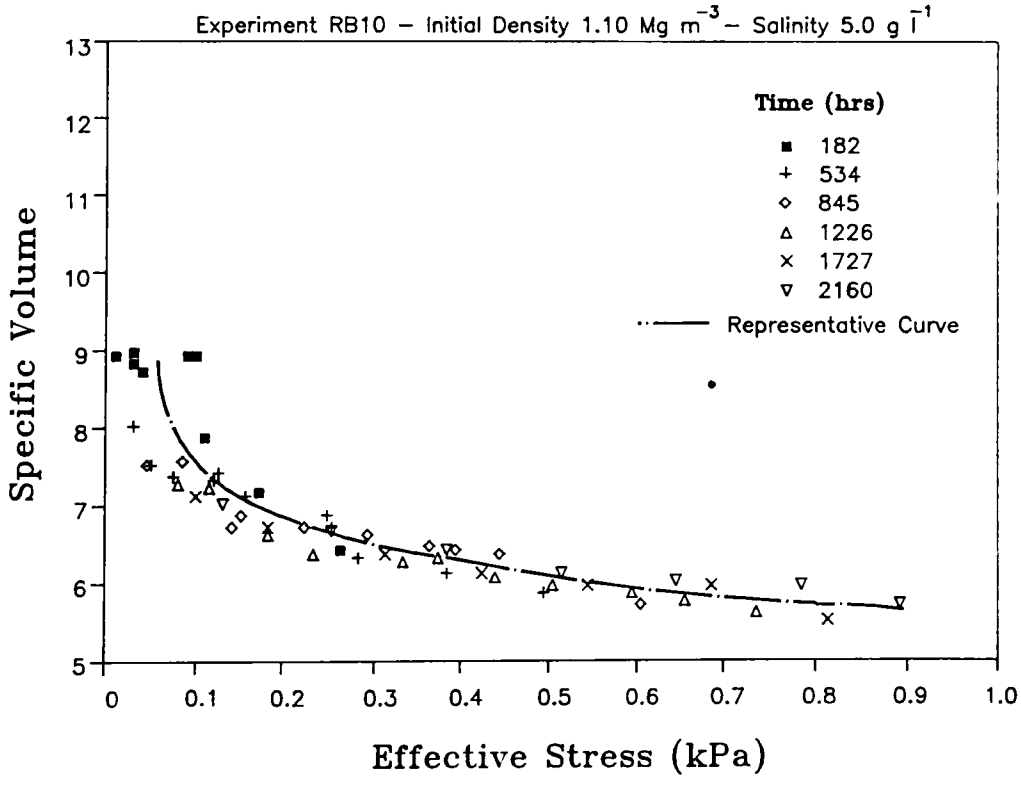


Figure 5.5: Specific Volume vs. Effective Stress

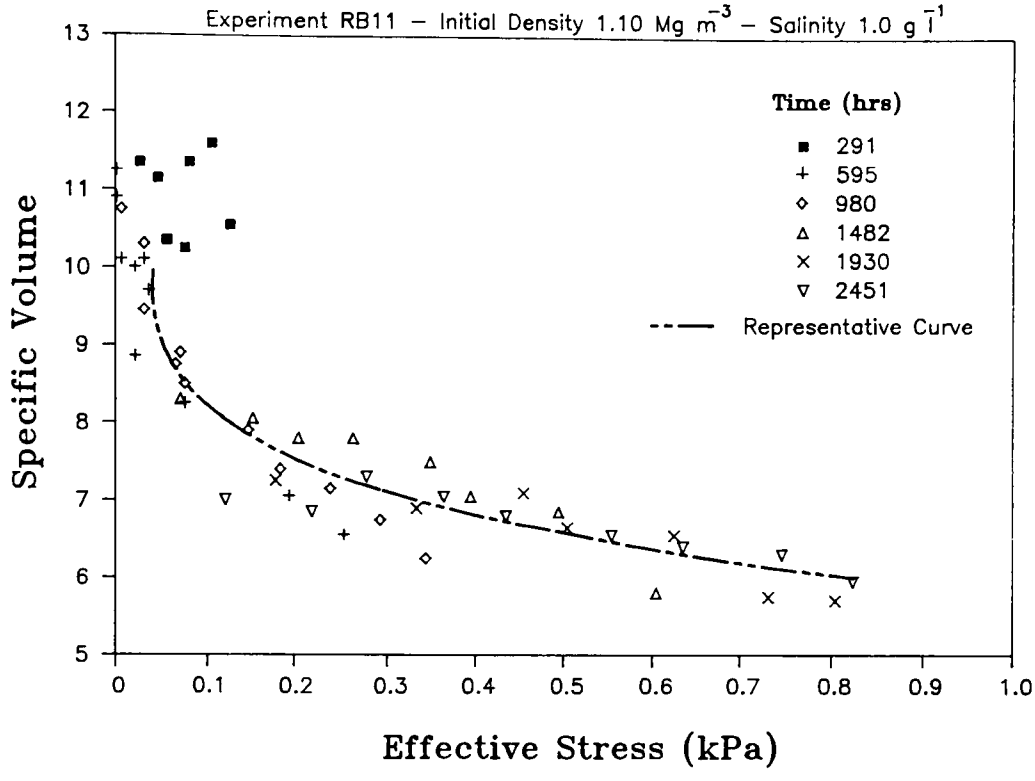


Figure 5.6: Specific Volume vs. Effective Stress

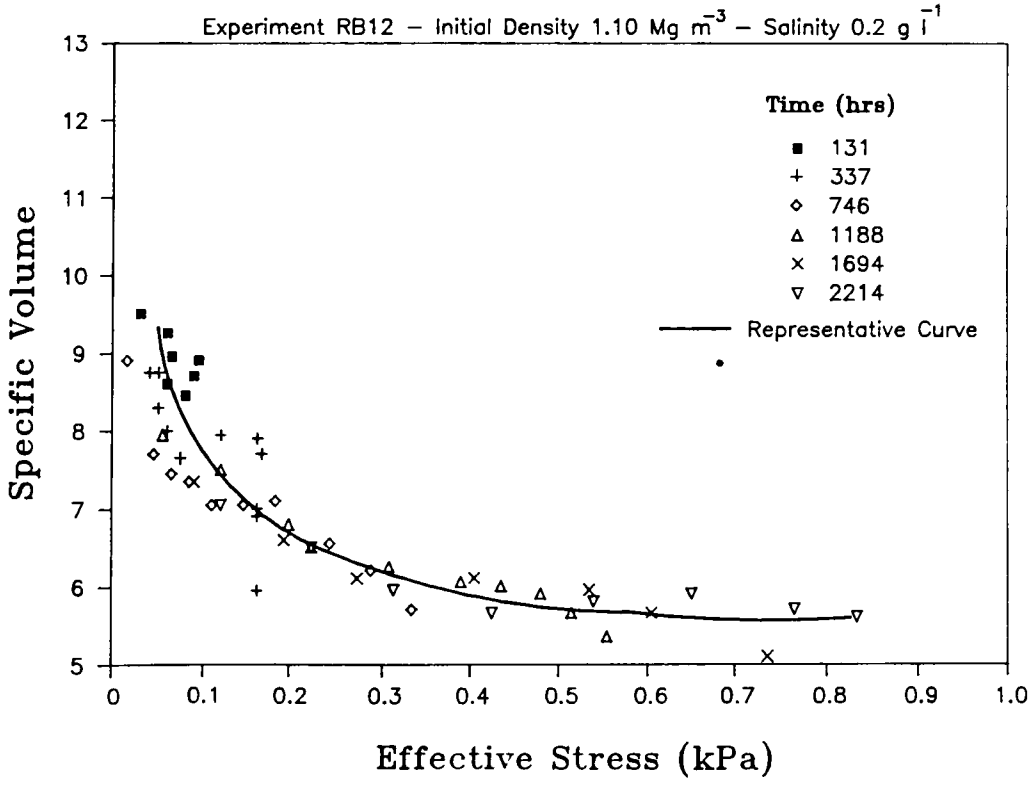


Figure 5.7: Specific Volume vs. Effective Stress

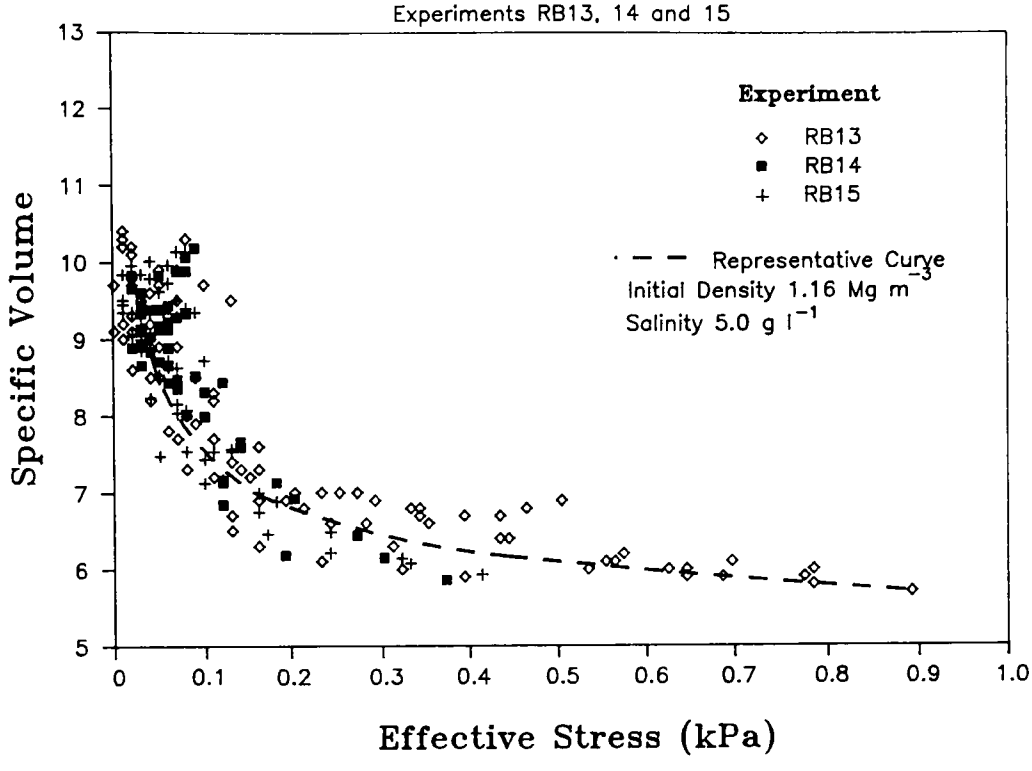


Figure 5.8: Specific Volume vs. Effective Stress

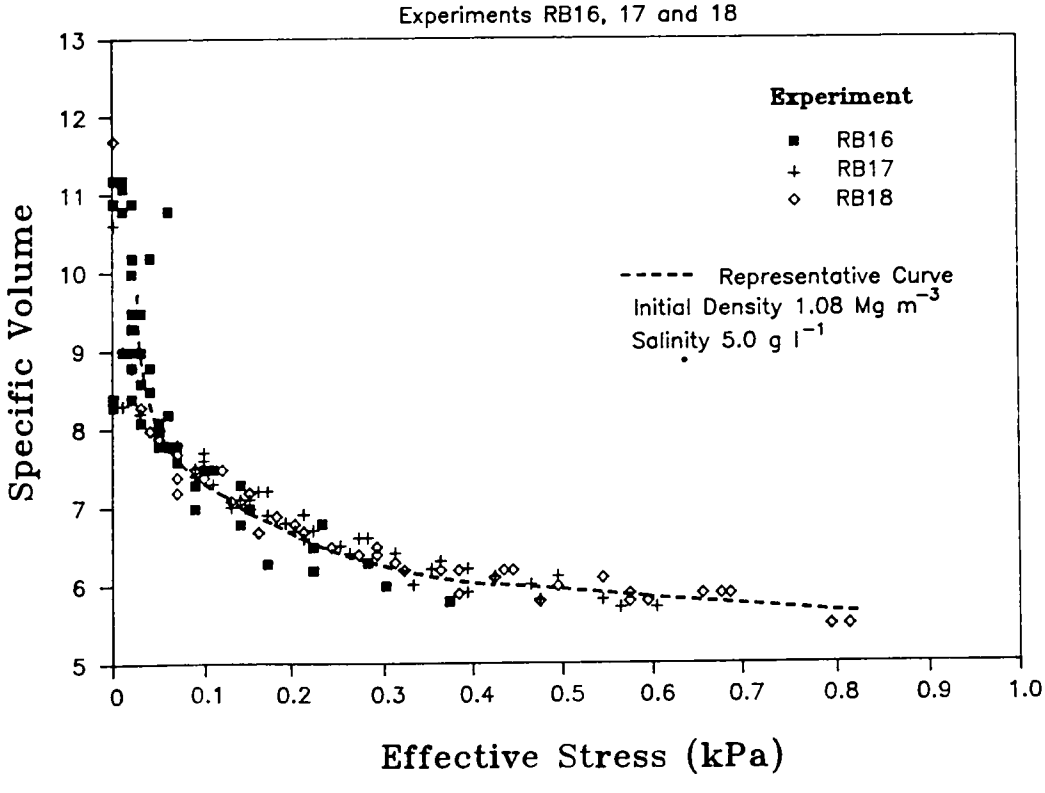
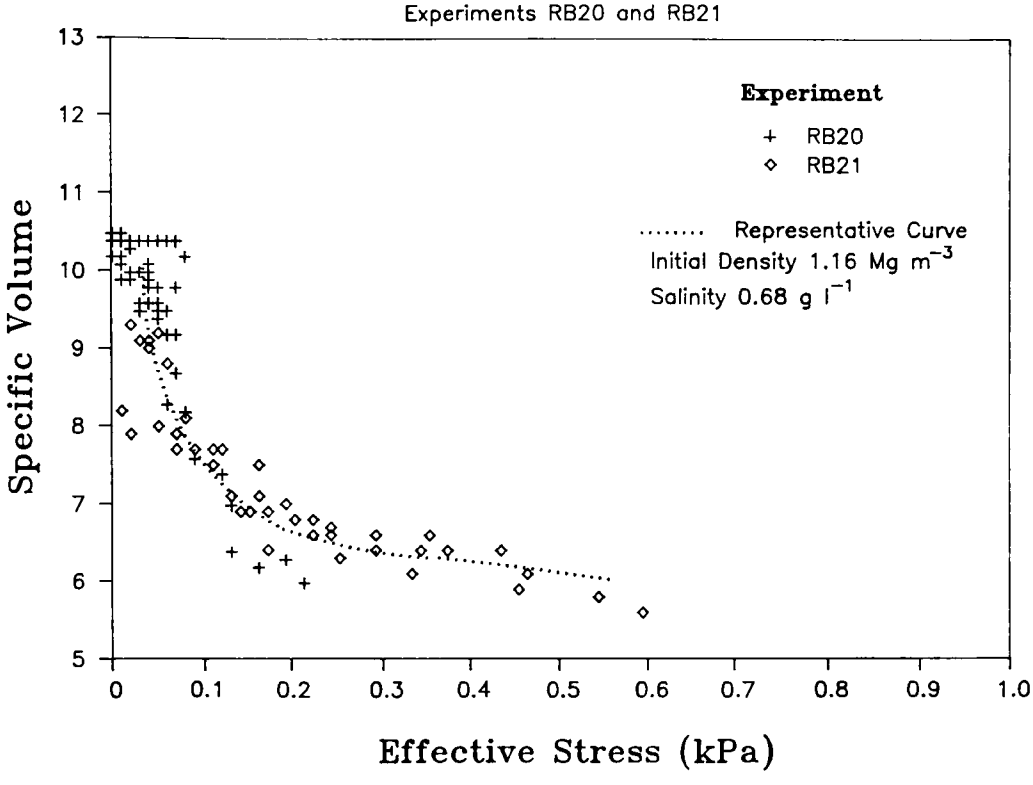


Figure 5.9: Specific Volume vs. Effective Stress



for series of experiments covering a range of conditions. Within Figures 5.3 through 5.9 there is a greater degree of scatter amongst the data than in Figure 5.2. Nevertheless, collectively, these results confirm that compression was controlled predominantly by effective stresses at all but very low levels, and that salinity and initial density exerted no influence on the form of the relationship between effective stress and specific volume.

A comparison of the relative positions of V-σ' curves for experiments with different conditions was made after compiling the results of identical experiments onto a single graph, and then reducing the data on each graph to a single representative curve. Figures 5.7, 5.8, and 5.9 confirm that the results of experiments with identical conditions (RB13,14,15; RB16,17,18;

RB19,20,21) may be represented satisfactorily by a single curve. Figure 5.10 shows representative curves for the seven unique sets of conditions which resulted when the thirteen sets of experimental results (for experiments RB10-22) were combined. In this figure, all curves are similar in shape, and show that specific volume decreased monotonically with increasing effective stress. In spite of the range of experimental conditions encompassed, the representative curves differ by less than 1.5 specific volume units at any effective stress. Variations between extreme individual data points were, of course, greater, but this is of much less interest than representative behaviour which is what models seek, in the first instance, to approximate.

If one excludes the results of experiment RB22, whose bed showed the highest relative degree of segregation of all RB experiments, then it is possible to propose a single representative $V-\sigma'$ curve (for,say, modelling purposes) about which the variation in specific volume is less than ± 0.5 of a specific volume unit. If experiment RB22 is included the variation is slightly larger, ± 0.75 of a specific volume unit. These results are in marked contrast with those of Elder which showed a variation of up to 4 units of specific volume in a single test, at any given effective stress. Elder's tests, which were performed with a similar mud but with different conditions, displayed substantially more effective stress-independent strain than did RB experiments.

If curves representing experiments with similar initial densities are compared to assess the influence of salinity on compressibility it is discovered that salinity affected compressibility by less than one specific

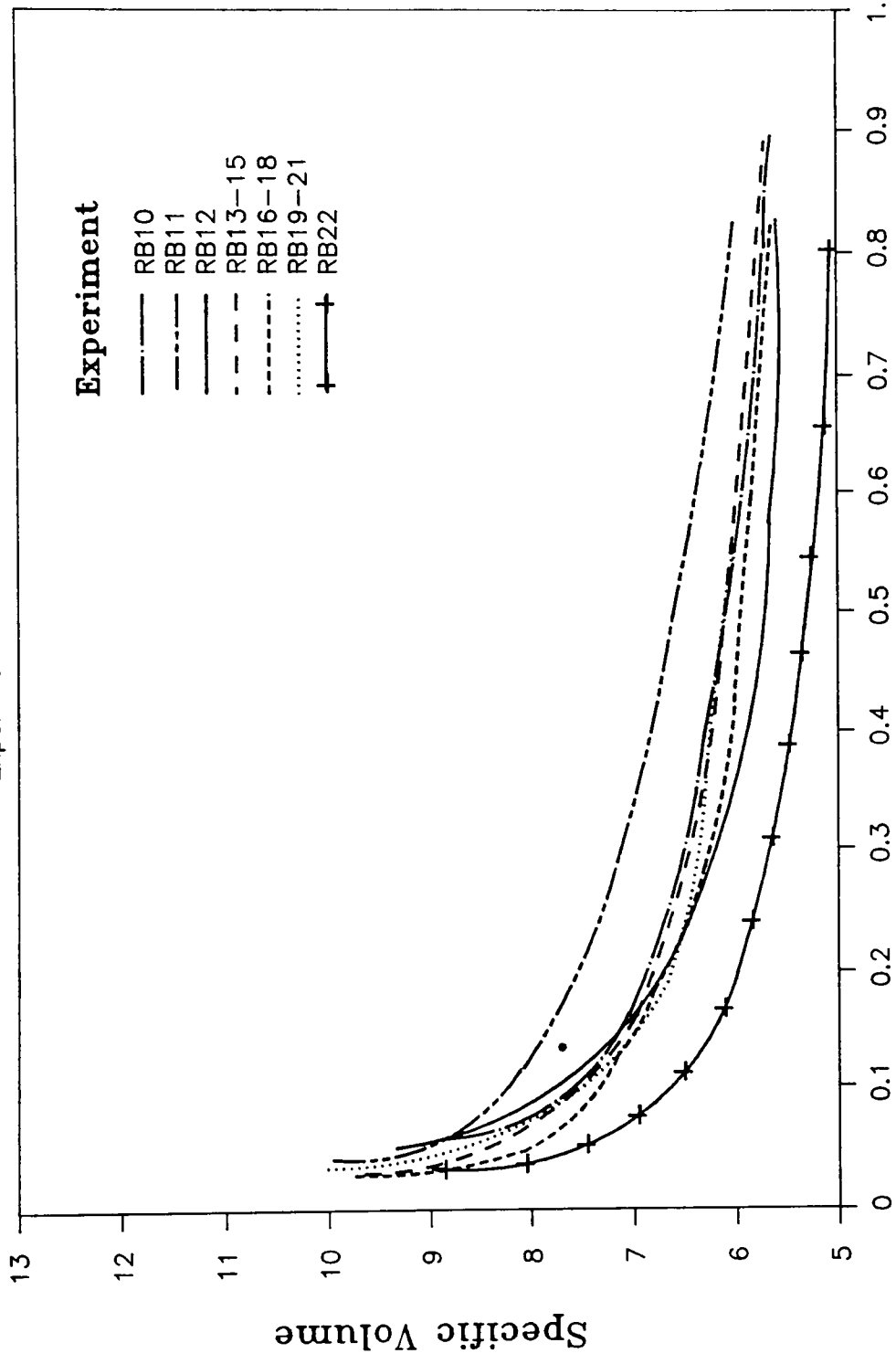


Figure 5.10: Summary of Representative Compression Curves

volume unit at any given effective stress and initial density. Similarly, a comparison of experiments with the same salinity shows a minor and variable influence of initial slurry density on compressibility.

On the basis of slurry appearances and results of particle size analysis, experiments RB22 and 12 were probably the least flocculated slurries of those tested. Compressibility curves for these experiments are, in general, positioned below those of more flocculated slurries. This pattern is in agreement with a postulate stated by Mitchell (1976) relating structure and properties, and it is this: "at a given pressure a flocculated system is less dense than a deflocculated one". A second postulate, that "at a given void ratio a flocculated system is more rigid" is also consistent with the results shown in Figure 5.10.

The specific volume at the onset of effective stress ($V_{\sigma'=0}$) is of practical importance in compression models in which the stages of settling and consolidation are linked at this specific volume. Three methods of estimating $V_{\sigma'=0}$ are,

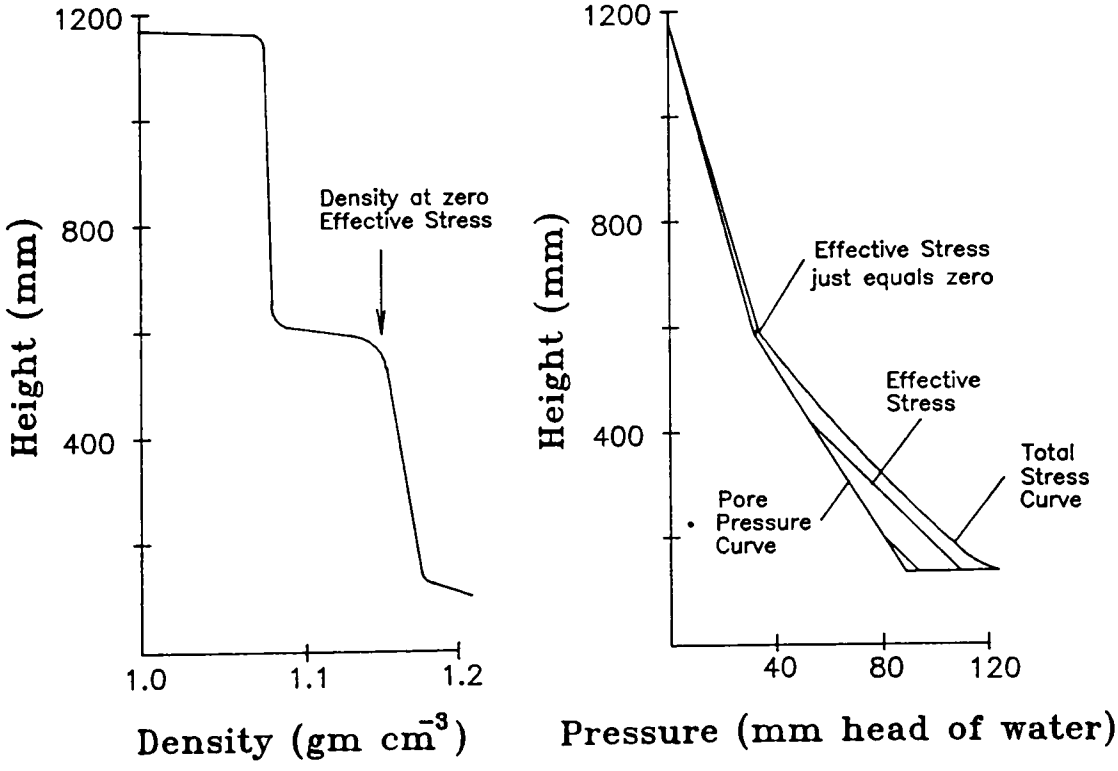
1) extrapolating V-σ' data to $\sigma' = 0$
2) relating density steps on profiles to zero effective stress
3) determining the surface specific volume (V_{sur}), where effective stress must be zero because of an absence of overburden

All three methods have deficiencies. The first method is reliant on accurate measurements of specific volume and effective stress which tend to decrease in accuracy with decreasing effective stress and increasing

specific volume. High compressibility at low effective stress makes it impossible to extrapolate credibly V-σ′ data to zero effective stress.

The second method was first employed by Been (1980) who correlated effective stress data and density profiles, and observed that where effective stress was just zero density profiles were stepped (Figure 5.11). Been assumed that the higher of the two step densities was that at which effective stresses arose. This method requires the good fortune of recording stepped density profiles (which are inherently short-lived) and, in particular, ones

Figure 5.11: Density and Stress Profiles of Been's Experiment KB7 (after Been, 1980)



in which the density step is distinct. Profiles for experiments RB12 and RB02 (Figures 5.12 and 5.13) illustrate the difficulty of interpreting stress conditions from density steps, whilst density profiles for experiment RB09, Figure 4.25, show that the upper step density value is not necessarily unique but rather may vary with the height of settled sediment.

The third method listed above was used by both Elder and Been who examined the void ratio (V=e+1) at the sediment surface of slurries in search of a characteristic void ratio at zero effective stress. Elder estimated surface void ratio using density profiles and a construction method, wherein the upper steeply inclined part of a density profile was approximated by a straight line and the specific volume at the intersection of this line and the surface elevation was determined. This method cannot be applied sensibly to density profiles with density inversions, nor does it seem an appropriate procedure for profiles which include a rapid variation in specific volume near to the sediment surface: a majority of the profiles recorded during RB experiments had these traits. Irrespective of these criticisms, Been's and Elder's results showed a time-dependent decrease in surface void ratio which was substantially greater than the magnitude of the errors which might be attributed to the methods they used. These authors observed decreases in specific volume as large as six (from 12 to 6) in experiments of several thousand hours duration. The surface of beds settled from flocculated slurries of natural mud by Imai (1981) also showed a decrease in specific volume with the passage of time.

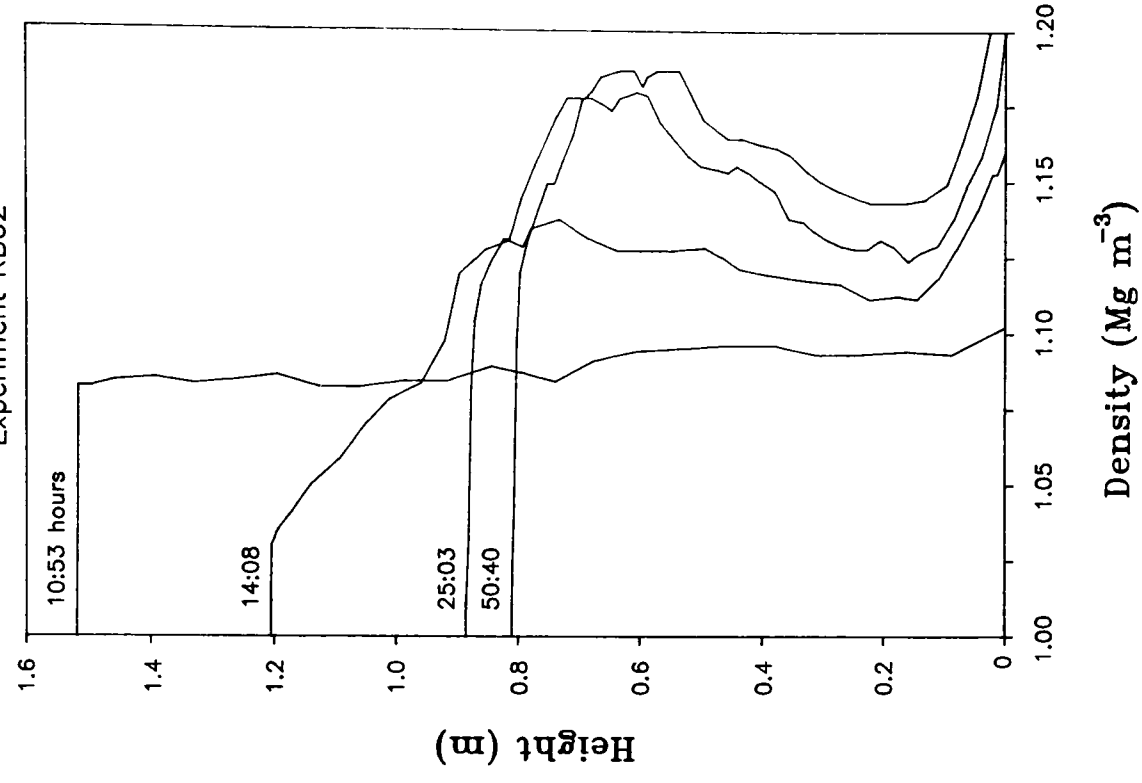


Figure 5.13: Density Profiles
Experiment RB02

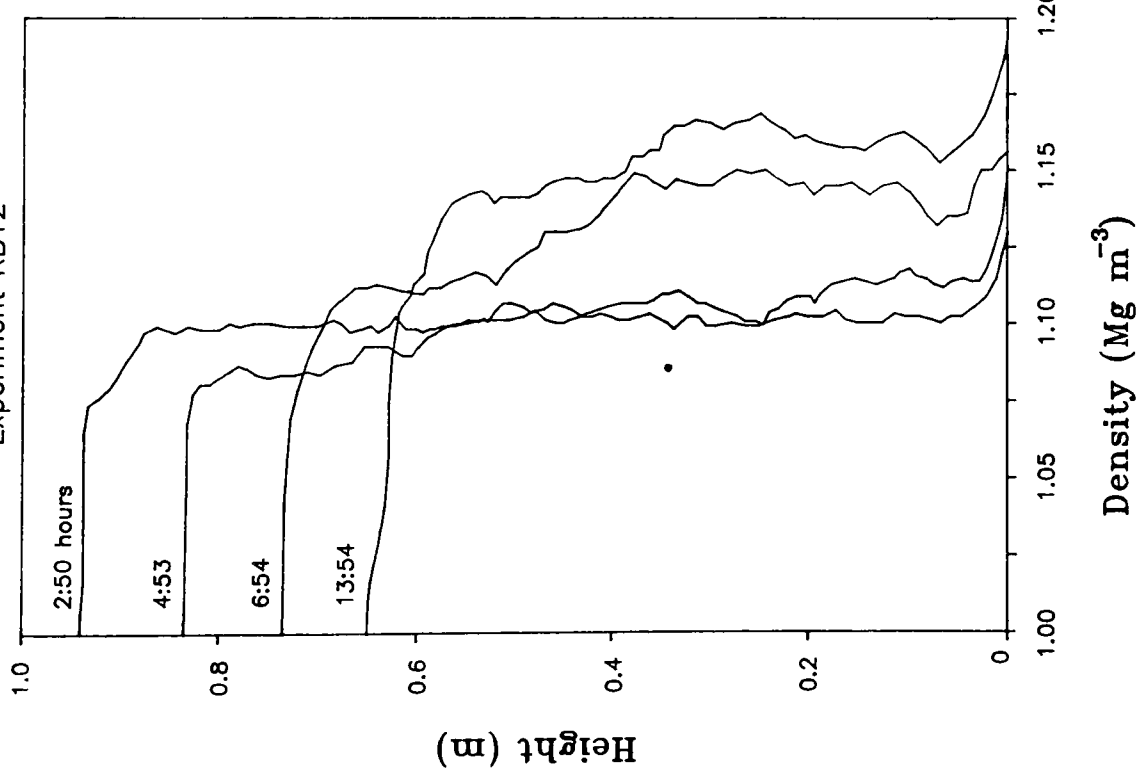


Figure 5.12: Density Profiles
Experiment RB12

The trend noted in the present author's results, that is for specific volume at low effective stress to decrease with the passage of time (Figures 5.2-5.9), is similar to Been's and Elder's finding that there is not a unique specific volume at zero effective stress. The hypothesis that surface specific volume is not unique for all time and all slurries is supported strongly by surface settlement rate versus average specific volume results presented in section 4.4. Figure 4.23 in that section shows a significant dependence of the specific volume at which the transition from hindered to slow settling occurs, on slurry conditions. The combined evidence of settling and compressibility results suggest that the specific volume at which effective stress is just zero is a function of experiment conditions (ρ_i and C_s) and also the passage of time. Pierce and Williams (1966) drew the same conclusion from results of settling experiments carried out with four muds from British estuaries.

The results of the analysis of specific volume versus effective stress data for eleven RB experiments may be summarized as follows. At very low effective stresses (0 to approximately 0.1 kPa) there is considerable scatter in the data due to finite instrument accuracy and the great compressibility of slurries at high (greater than approximately 10) specific volume units. In this stress range compression at constant effective stress occurs, and it is postulated that this is due to time-dependent electrochemical forces. At effective stress levels above 0.1 kPa, specific volume and effective stress are closely related and independent of time, for the sediment and conditions studied. Pore fluid salinity and initial slurry density exhibit a minor influence only on the position of specific volume-effective stress curves, and results for six sets of conditions can be

approximated by a single representative curve about which individual representative curves vary by less than ±0.5 of a specific volume unit. A well-defined compression curve, which is only slightly dependent on slurry conditions and independent of time (σ'> approx. 0.1 kPa), is an encouraging result for model development.

5.2 Pore Fluid Flow

In section 4.3.3 it was shown that height of surface versus time results for experiments RB10-22 were influenced strongly by initial slurry density and suspending medium salinity, and yet it was shown in the preceding section that these same parameters had a minor influence only on compressibility. Considered together, these observations suggest that the rate at which effective stress increases within a slurry is dependent on experiment conditions. Because effective stress arises as a result of pore pressure dissipation, the parameter linking surface settlement rate or consolidation and compressibility is permeability and the process involved is pore fluid flow.

In 1856 Henri Darcy presented a fluid flow relationship which, in its modern form, is,

$$-v = ki \qquad \ldots 5.1$$

where v = superficial flow velocity (m s^{-1})

k = permeability (m s^{-1})

i = hydraulic gradient

The general validity and simplicity of this relationship has led to its incorporation into consolidation theories, most notably Terzaghi's equation for one dimensional consolidation. The coefficient of permeability (k) represents the ease with which viscous water can flow through a porous medium and it is assumed to be constant for a particular soil at a particular specific volume and independent of the magnitude of flow velocity and hydraulic gradient. The principal factors influencing permeability are pore size (which is related to specific volume), channel tortuosity, and pore fluid viscosity. These are, in turn, influenced by particle size distribution, pore fluid chemistry, and fabric. Within a slurry that is homogeneous with respect to particle size distribution, pore fluid composition, and fabric, permeability is related to specific volume only. If, in addition, Darcy's law is valid, then at each specific volume the coefficient of permeability will be constant for all velocities and all hydraulic gradients.

The velocity term in Darcy's law is equal to the volume of flow per unit time (Q, $m^3\ s^{-1}$) divided by the total cross-sectional area (A, m^2) normal to the flow. This velocity is known as the superficial, approach, or apparent velocity. When Darcy's law is used in consolidation theory, the true velocity of the fluid relative to the solid fraction (v_r) should be used; this is greater than the superficial velocity (v) because a fraction of the cross-sectional area is occupied by solids. The exact relationship is,

$$v = nv_r \qquad \ldots 5.2$$

where n is soil porosity (the ratio of void volume to total volume). It follows that,

$$-nv_r = ki \quad \ldots 5.3$$

If fluid and solid phases are assumed to be incompressible then the flow of solids and fluid across a horizontal plane must be equal, that is,

$$v_s(1-n) = -nv_f \quad \ldots 5.4$$

where v_s and v_f are the velocity of the solids and of the fluid with respect to a fixed plane. Rearranging equation 5.4 yields,

$$v_s = -n(v_f - v_s) \quad \ldots 5.5$$

The term in the parentheses of equation 5.5 equals the sum of the phase velocities with respect to the fixed plane, which is precisely the relative velocity v_r. Hence,

$$v_s = -nv_r \quad \ldots 5.6$$

Substitution of equation 5.6 into equation 5.3 yields,

$$v_s = ki \quad \ldots 5.7$$

or the equivalent,

$$k = \frac{v_s}{i} \qquad \ldots 5.8$$

The validity of Darcy's law may be assessed, therefore, by plotting particle settling velocity (determined from total stress profiles, see section 4.5) against hydraulic gradient (the difference in excess hydraulic head at two pressure ports divided by the distance between them), and observing the degree of linearity of the data at each specific volume. Because both the specific volume of a slurry element and hydraulic gradients within a slurry change between profiles, the values of specific volume and hydraulic gradient presented below are necessarily averages for the period spanned by two density profiles. Note that in self-weight compression experiments the investigator has no control over either settling velocity or hydraulic gradient, unlike in standard permeameter tests, so that the range of data available is limited.

Figures 5.14 and 5.15, show at two different scales, settling velocity versus hydraulic gradient results for two experiments (RB13 and RB15) which had identical initial conditions. Set into Figure 5.14 is a plot of the linear flow relationship described by Darcy's law, and examples of the influence of specific volume (V) on the permeability (k) of a homogeneous slurry. The experimental results show that, in general, permeability increased with increasing specific volume but that at specific volumes greater than approximately seven settling velocity and hydraulic gradient were neither linearly nor uniquely related. At specific volumes between six and seven the data show some scatter but may be approximated satisfactorily

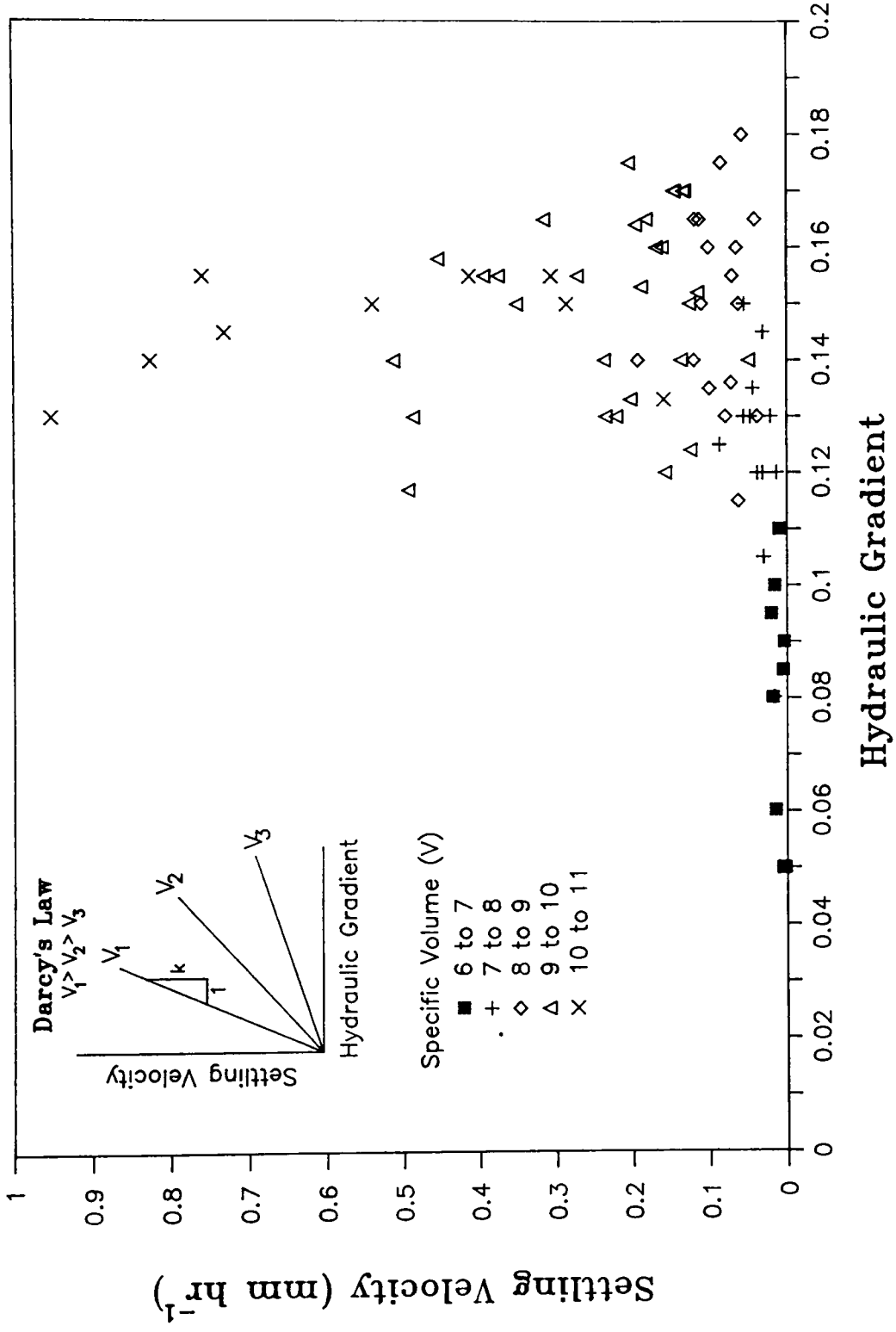
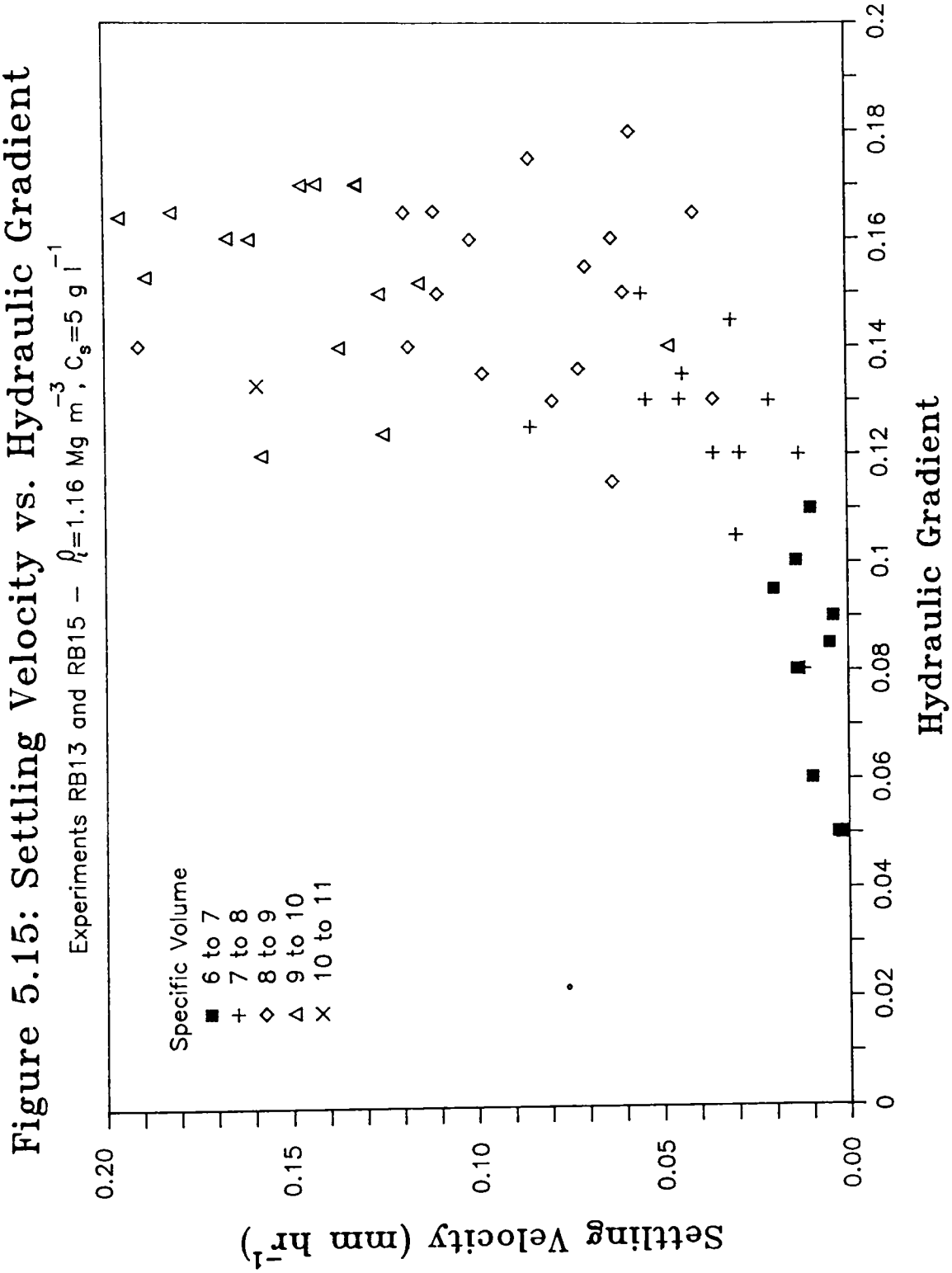


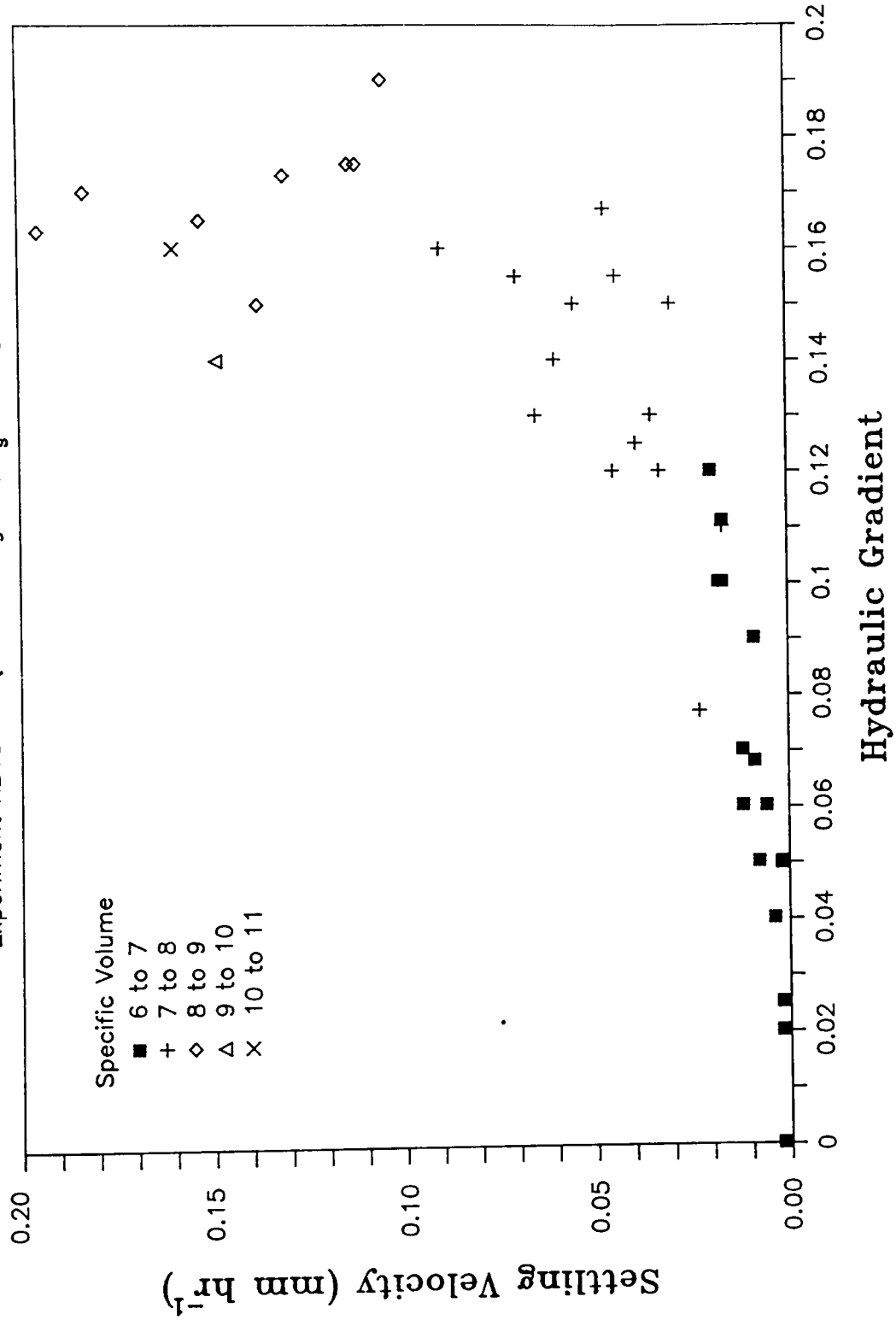
Figure 5.14: Settling Velocity vs. Hydraulic Gradient

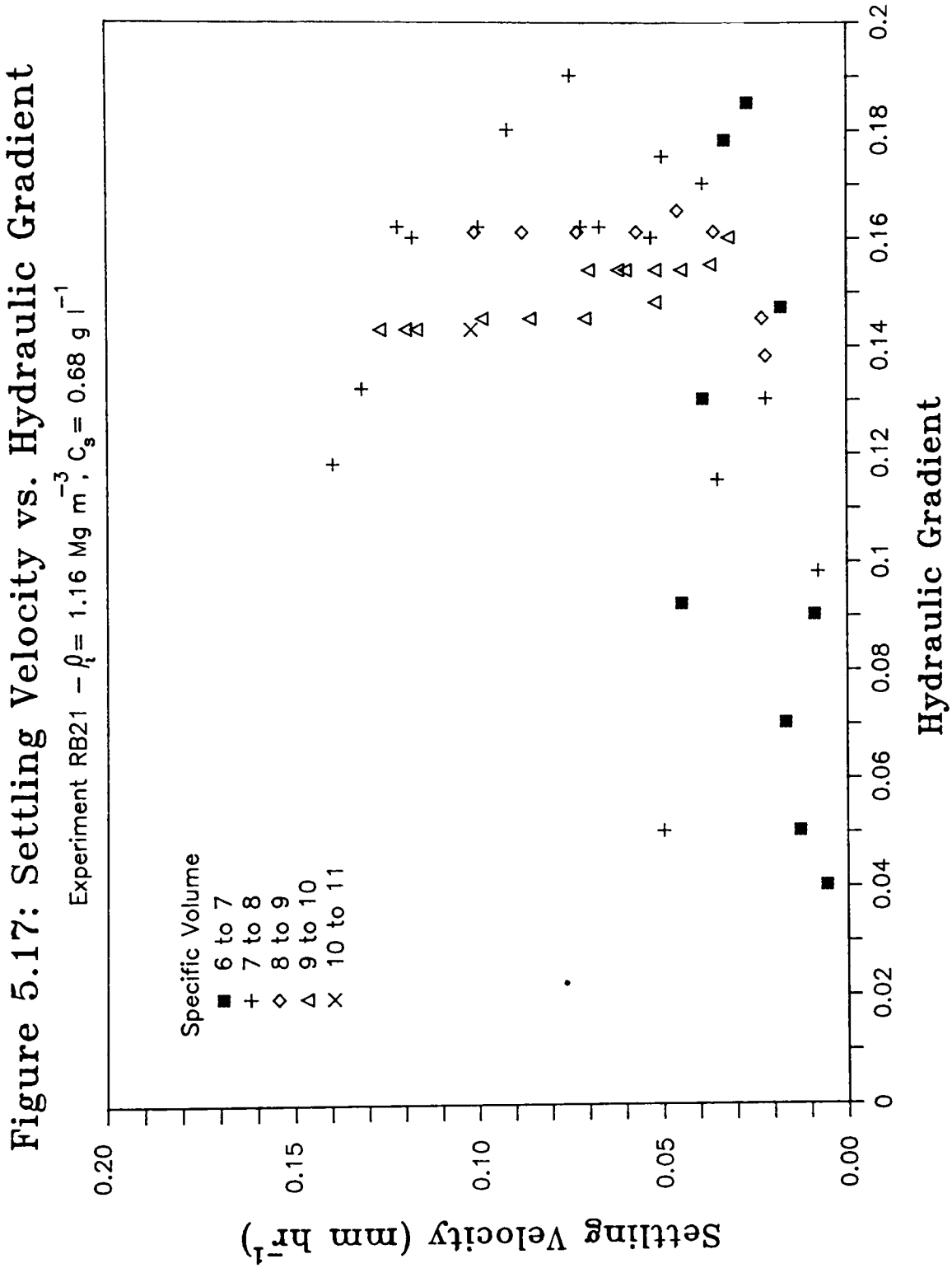

Figure 5.15: Settling Velocity vs. Hydraulic Gradient
Experiments RB13 and RB15 – ρ_f=1.16 Mg m^{-3}, C_s=5 g l^{-1}
Specific Volume
6 to 7
7 to 8
8 to 9
9 to 10
10 to 11
Settling Velocity (mm hr^{-1})
0.00
0.05
0.10
0.15
0.20
Hydraulic Gradient
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2

with a straight line. These conclusions apply equally well to the results of experiments RB18, RB21, and RB22 (Figures 5.16, 5.17, and 5.18) which had a range of initial conditions.

The failure of Darcy's law at specific volumes above seven for natural slurries compressed under self-weight is discouraging because it implies that consolidation models which assume its validity are incorrect. Equally unfortunate is the observed non-uniqueness of settling velocity and hydraulic gradient data which prevents a suitable simple alternative pore fluid relationship for Darcy's law being defined. One practical remedy is to restrict consolidation theories which invoke Darcy's law to specific volumes less than seven and to use some form of a hindered settling model to describe behaviour at higher specific volumes. This approach yields a workable consolidation model but makes modelling the settling phase of compression very difficult because of the extended range of specific volumes that must be encompassed. As is illustrated in Figure 4.23, section 4.4, the range of settling velocities associated with slurry elements with specific volumes above seven is tremendous.

If, instead, one wished to model compression behaviour for specific volumes up to those typically observed for the transition from hindered settling to consolidation using a consolidation model, empirically determined permeabilities, particular to a narrow range of specific volumes and hydraulic gradients, would have to be used, less accurate predictions accepted and greater computational effort expended. The problem at hand is an old one: it is that of attempting to adapt classic models for settling


Figure 5.16: Settling Velocity vs. Hydraulic Gradient
Experiment RB18 – ρ_f = 1.08 Mg m^{-3}, C_s = 5.0 g l^{-1}
Specific Volume
6 to 7
7 to 8
8 to 9
9 to 10
10 to 11
Settling Velocity (mm hr^{-1})
0.20
0.15
0.10
0.05
0.00
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Hydraulic Gradient


Figure 5.17: Settling Velocity vs. Hydraulic Gradient
Experiment RB21 – ρ_f= 1.16 Mg m^{-3}, C_s= 0.68 g l^{-1}
Specific Volume
6 to 7
7 to 8
8 to 9
9 to 10
10 to 11
Settling Velocity (mm hr^{-1})
0.00
0.05
0.10
0.15
0.20
Hydraulic Gradient
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2

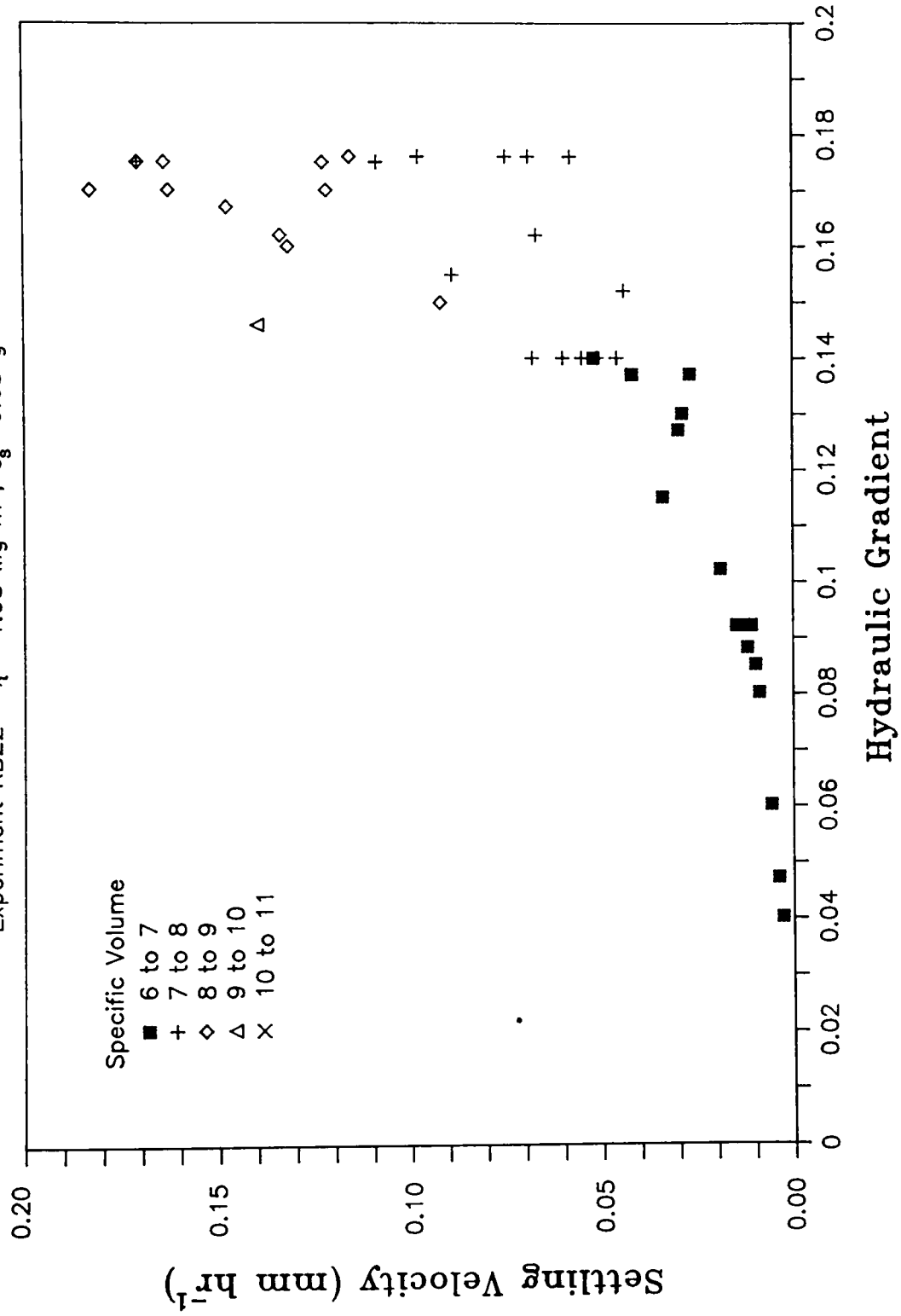


Figure 5.18: Settling Velocity vs. Hydraulic Gradient

and consolidation to describe the behaviour of structure-sensitive intermediate conditions.

Figures 5.14 - 5.18 show that the degree of departure from Darcy's law increased with increasing specific volume and/or hydraulic gradient. In fluid flow applications in which the direction of flow is opposite to the force of gravity, and interparticle forces are due to self-weight only, there is a critical hydraulic gradient (i_{cr}) at which effective stresses are reduced to zero: it occurs when the gradients of excess total stress and excess pore pressure are equal. In self-weight compression experiments hydraulic gradients greater than i_{cr} cannot exist. Figure 5.19 shows settling velocity data for experiments RB13 and RB15 plotted against normalized hydraulic gradient (i/i_{cr}). This figure reveals that the variation in settling velocity at any given specific volume increased as the hydraulic gradient approached the critical hydraulic gradient.

This trend is not surprising because permeability is influenced very strongly by fabric, and fabric is influenced by the competition of interparticle forces trying to maintain a particular arrangement and hydraulic forces trying to alter it. As the critical hydraulic gradient is approached, 'maintaining' forces such as those due to the weight of overburden are reduced, structural integrity is decreased correspondingly, and the probability of fabric heterogeneities arising is increased. Variations in fabric have a significant effect on permeability. Consider, for example, the rapid rate of settlement attributed to the presence of pore fluid channels, in section 4.1. Two soil elements at the same specific

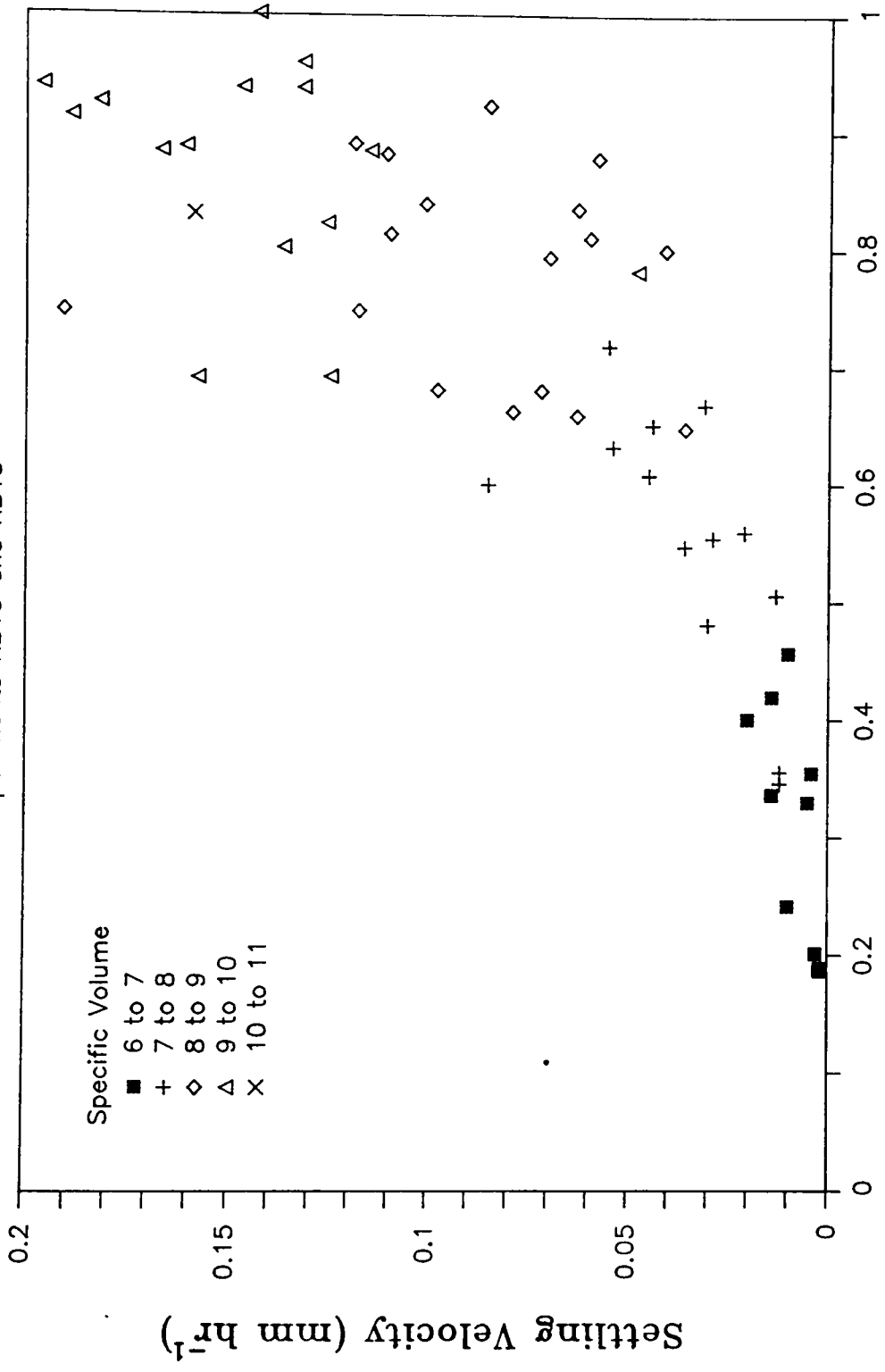


Figure 5.19: Settling Velocity vs. Normalized Hydraulic Gradient

volume may have permeabilities or, equivalently, settling velocities, which differ by two orders of magnitude simply because of different soil fabrics (Lambe and Whitman, 1979). Tavenas et al. (1983) studied the permeability of natural soft clays and concluded that "the permeability of a natural soft clay at its in situ void ratio and structure is dependent on a series of variables the most important of which, the fabric, is not easily assessed or quantified". Further, their results suggested that strains in excess of 20% involve fundamental changes in structural arrangements. In RB experiments strains of 40% after the onset of slow settling were observed typically.

The results of the present section are disconcerting because of the implications that they have for existing compression models formulated using Darcy's law. In regards to future models, the data suggest that fluid flow has to be modelled empirically; this has implications for the accuracy of, and the effort required to obtain solutions for even simple compression problems involving high specific volumes.

The role of fabric in determining permeability, and through it compression behaviour, was anticipated when the present research programme was being planned and it was for this reason that the study of fabric was included in it. Details of the fabric study which was performed are presented in the succeeding chapter.

CHAPTER 6 - FABRIC STUDY

6.0 Introduction

The primary reason for studying particle arrangements within settled beds was to search for relationships between compression behaviour, shear strength, material properties and particle orientations. To carry out this search, instruments and techniques had to be developed to enable the arrangement of particles within a weak, fine-grained material to be examined. The main problems addressed were (a) sample recovery, (b) fabric preservation, (c) thin-section preparation and, (d) orientation analysis. Ideas and instruments from four disciplines were developed or applied: a geotechnical engineering method was used to recover undisturbed samples of sediment; a micromorphological method of resin impregnation was used to preserve fabric; thin sections were prepared using an instrument familiar to life scientists; and a simple geological method was used to quantify the orientations of particles in a plane section. Satisfactory degrees of success were achieved in overcoming each problem, but as a consequence of the sequential nature of the process from sample recovery through to analysis, limitations imposed and compromises made at each stage were cumulative and these, collectively, prevented the principal objective of the fabric study from being attained. Many technical advances were made and the foundations for future fabric studies of soft silty clay sediments laid.

The purposes of this chapter are three fold. In section 6.1 the potential and practically realizable benefits of examining soil fabric are discussed,

four fabric related postulates are introduced, and the goals of the present fabric study are stated. In section 6.2 research relating to post-sampling activities viz. resin impregnation and section preparation, is presented. In the final section, 6.3, the method of analysis selected to quantify fabric is outlined, problems encountered during analysis are discussed, solutions are presented, and an overview of the study drawn.

6.1 Examination of Fabric

Soil structure consists of two components, the way in which particles are arranged (fabric), and forces between particles. Soil structure controls compression behaviour, shear strength characteristics, and material properties such as permeability. Of the two components defining structure only the fabric aspect is amenable to being studied microscopically; individual interparticle forces cannot be measured and must be inferred from measurements of macroscopic parameters.

The initial fabric of a soil deposited under self-weight from a slurry is influenced by compositional factors, such as mineralogy, chemical composition of the suspending medium, and particle size and shape. Environmental factors are also important and these include sediment concentration, total mass of sediment, initial height of slurry, and settling velocity. After deposition, fabric may be altered by the action of forces: forces associated with dynamic equilibrium (ie. consolidation) and forces related to currents, turbulence, unloading, and seepage. The final arrangement of particles within a bed is the product of many processes. It is possible sometimes to determine aspects of the history of a bed from its

final fabric - such as whether particles settled individually or as aggregates, what the size and shape of flocs were if these existed, and whether or not channels formed. It is, however, more common for a fabric to be ambiguous or unrevealing.

Fabric examinations may be used to acquire a fuller understanding of behaviour. For instance, McGown et al. (1980) studied soil sensitivity from the perspective of a particle arrangements and they observed that highly sensitive soils possess particular fabric characteristics that provide a credible mechanism for the loss of strength displayed by sensitive soils when disturbed. It is the possibility of linking structural characteristics to behaviour and properties that is of interest here.

In spite of the potential utility of examining fabric, in traditional soil mechanics fabric examinations are rarely made. There are several reasons why this is so. The effort required to quantify soil fabric, particularly that of fine-grained materials, is large and there are no standard procedures for doing so. Once fabric has been quantified there are few fabric-behaviour relationships available for the engineer to use to convert fabric results into useful engineering information. And, in addition, most soil engineering problems are solvable with a knowledge of how a type of soil behaves only and not why it behaves as it does. Practical difficulties with making examinations, and general inexperience with interpreting and applying fabric results, are responsible for the marked difference that exists between the imaginable and the practically realizable benefits of examining fabric. In civil engineering, examinations of soil fabric are, at present, a research activity exclusively.

The present study of fabric was organized to examine the validity of the following four postulates:

1. Degree of horizontal particle alignment increases with increasing effective stress.
2. Degree of horizontal particle alignment increases with decreasing salinity.
3. Degree of particle alignment decreases with increasing initial density at all effective stress levels and salinities.
4. Permeability decreases with increasing horizontal alignment.

The assumptions upon which these postulates were formed are:

1. Stress reorients or deforms flexible anisotropic particles so that long axes are turned normal to the major stress axis which is vertical in a settling column.
2. Flocculation produces fabrics without a preferred orientation, whilst dispersed slurries of platey particles settle to form beds with horizontally aligned fabrics.
3. All slurries have random fabrics initially and the capacity to adopt an aligned fabric decreases as particle freedom, that is specific volume, decreases.
4. The tortuosity of fluid flow paths is greatest when particles with platey habits are oriented normal to the direction of fluid flow.

To assess postulates one and four, horizontal and vertical sections were to be prepared from samples taken at several elevations over the full height of four settled beds. Horizontal sections were to be studied to evaluate the assumption that settling within each column was one-dimensional and vertical, whilst the degrees of horizontal alignment observed in vertical sections at different elevations were to be compared with calculated effective stress and permeability values to determine fabric-behaviour and fabric-permeability relationships.

To study the influence of pore fluid salinity and initial density on fabric (postulates two and three) cores from experiments RB13, 18, 21 and RB22,

which spanned a range of experimental conditions, were to be recovered. And in addition to studying the four postulates, it was intended that the results of fabric examinations would be compared with shear strength data to investigate relationships between shear strength, sensitivity, and fabric.

In spite of the author's interest to establish the role (or otherwise) of fabric in determining the compression behaviour, shear strength characteristics, and material properties of natural silty clays, the need to borrow all of the equipment required to carry out a micromorphological investigation, dependence on the gratuitous assistance of skilled technicians in the departments of geology, botany, and human anatomy, and a lack of published techniques for studying weak, sensitive, fine-grained soils with a high specific volume, had to be accepted, and a realistic fabric study planned. For these reasons it was decided at the outset that the present fabric study would concentrate on solving the technical problems of recovering, preparing, and examining soft clay samples, and the four postulates stated above would be investigated only if this complemented, and did not compromise, compression behaviour and shear strength research.

6.2 Preparation of Sediment for Examination

The first stage of sediment preparation was to recover undisturbed samples. The sampling apparatus and techniques developed to recover samples from soft beds settled in a column are described in subsection 3.3.5. The two stages succeeding sampling, resin impregnation and thin-section preparation, are discussed in the present section. It should be noted that all four stages of sample preparation (sampling, impregnation, thin-sectioning, and

analysis) were mutually dependent: the sampler was developed with a permeable wall to permit resin impregnation without having to extrude the sample after recovery; resin impregnation was carried out to reinforce the sample so as that it would be able to withstand the stress of thin-sectioning; thin-sections were required for point count analysis.

The stage of preparation which follows sample recovery is typically either dehydration or impregnation. Dehydration methods include air drying, substitution drying, freeze drying, and critical point drying. During dehydration, as bulk water is removed and menisci between particles decrease in radius, considerable stresses are often imposed on the structure of a sample. In soils of low strength and/or high specific volume dehydration methods are unsuitable because they can cause structural collapse, large volume reductions and/or fabric artefacts. It is usual to prepare weak voluminous materials using impregnation methods. The purpose of impregnation is to embed particles in a rigid matrix of impregnant so that the fabric is preserved during preparation of sections. In the present study, in which beds were actively, albeit slowly consolidating at the time of sampling, impregnation also served to arrest the fabric.

During the impregnation of saturated soils the pore fluid of the sample is replaced with a liquid impregnant that is designed to change phase to form a solid after penetration. The ideal impregnant is chemically inert with respect to the soil constituents, is miscible with the pore fluid (natural or substituted), has low viscosity, and sets at a rate which is sufficiently slow that complete penetration is achieved. During penetration and whilst the impregnant is changing phase, there should not be either a change in

volume or rearrangement of particles. Once cured, preferrably at room temperature, the impregnant should be uniformly hard, and possess high strength and ductility.

Of the numerous materials and several methods used for impregnation, Vestopal and epoxy resins, and wet impregnation methods are the most popular (Smart and Tovey, 1982). In the present study, a cold setting polyester resin (trade name Crystic) was selected as the impregnant on the basis of availability and experience within the Oxford Soils group. Crystic resin consists of a solution of unsaturated reactive polyester in a vinyl monomer. The phase is changed from liquid to solid by the copolymerisation of polyester and styrene, that is the building of styrene bridges between polyester chains, and the formation of a spatial net structure. The process is activated by means of a catalyst which is timed to act after penetration has been completed.

Degree of penetration and sample disturbance, and the final strength of an impregnated block are the usual factors by which the successfulness of impregnation is measured. These factors are strongly influenced by sample dimensions, soil permeability and sensitivity, and the viscosity, strength and rate of solidification of the resin. The characteristics of the resin at any time are influenced by the extent of polymerization, and the rate of polymerization depends on the chemical composition of the resin, the concentration and type of catalyst used, the operating temperature, the quantity of resin used and cast shape, the amount of fillers in the resin, the degree of dilution of the resin, the moisture content of the sediment, and the presence of inhibitors. It should be apparent that it is impossible

to predict the properties of a resin impregnated block of soil a priori. In addition, different soils behave differently to any given resin and set of procedures. It was necessary, therefore, to test different Crystic resin mixtures and procedures to determine the most suitable combination thereof for impregnating Combwich mud.

Mixtures of crystic resin, acetone, catalyst, and dye were tested. Acetone was added to reduce the viscosity of the pure resin to enhance penetrability. Dye was added initially to enhance the visual contrast between solids and resin as an aid during thin-section examination; it was discontinued, however, when improvements in thin-section preparation techniques made the additional contrast unnecessary. Resin mixtures with mass ratios of resin to acetone to catalyst of 100:100:7.5 and 100:50:7.5 were found to thicken rapidly (<3 days), harden within a period of weeks, and produce blocks with a high strength. Trial samples were cured at a range of temperatures (up to 60°C) and for different durations (up to eight weeks), as suggested by Fitzpatrick (1984). The simplest procedure tried, that of curing a sample in a fume cupboard at room temperature, was found to be satisfactory. Prior to penetrating samples with resin, the original pore fluid was replaced with acetone: water prohibits most resins from hardening properly. To effect replacement of the water, samples were thrice immersed in baths of pure acetone for durations of 24 hours.

Once impregnated samples were hard and fume free, excess resin, the sample tube, and the plastic film liner were all peeled away, surface features logged, and the recovery ratio (pre-sample bed depth to cured sample length) calculated. At 50mm intervals over the length of each core two blocks, each

approximately 4x4x8 mm were extracted using a fine-tooth saw. The orientations of blocks are shown in Figure 6.1.

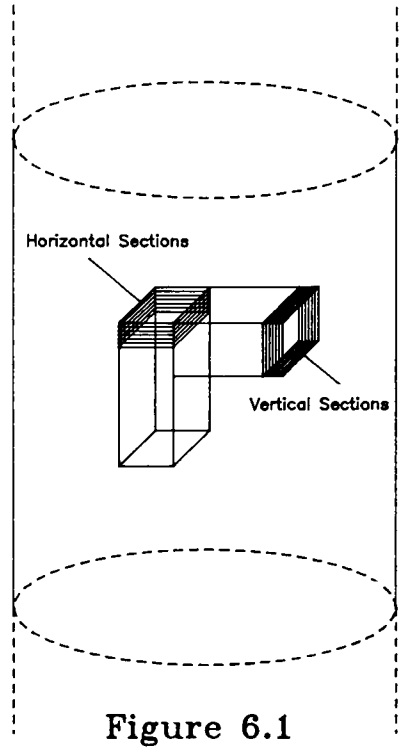


Figure 6.1
Subsamples and Thin-Sections Within an Impregnated Core

Fabric was examined using a transmission optical microscope rather than a scanning electron microscope because of the availability of the latter and its perceived adequacy for evaluating the postulates proposed. An attempt made to prepare thin-sections using geological techniques was unsuccessful because of problems with the delamination of samples from slides and cracking of slides due to stress changes within samples after exposure to a sample-slide bonding agent. Geological thin-sections which survived preparation were typically too thick (approximately 30 μm) to allow the boundaries of individual particles, and therefore particle orientations, to be distinquished because of superposition of particles in different planes.

•

The best method of preparation discovered was that of shaving impregnated blocks of material using a microtome fitted with a glass knife. Sections were floated on to distilled water and then lifted onto glass microscope slides. In the present study vertical and horizontal sections prepared

using a microtome were found to be superior to sections prepared using standard geological techniques.

6.3 Analysis, Conclusions, and Recommendations

It was disheartening to discover, at the end of the process of sample recovery, impregnation, and sectioning that the sections produced could not be analyzed automatically using an Image Analysis System (see Delgado and Dorronsoro, 1983). Automatic analysis requires complete images, whilst in the author's thin sections surface rumples or undulations rendered images at high magnification largely out of focus. Figures 6.2 and 6.3 show vertically cut thin-sections from core RB13 removed from 250 and 100 mm

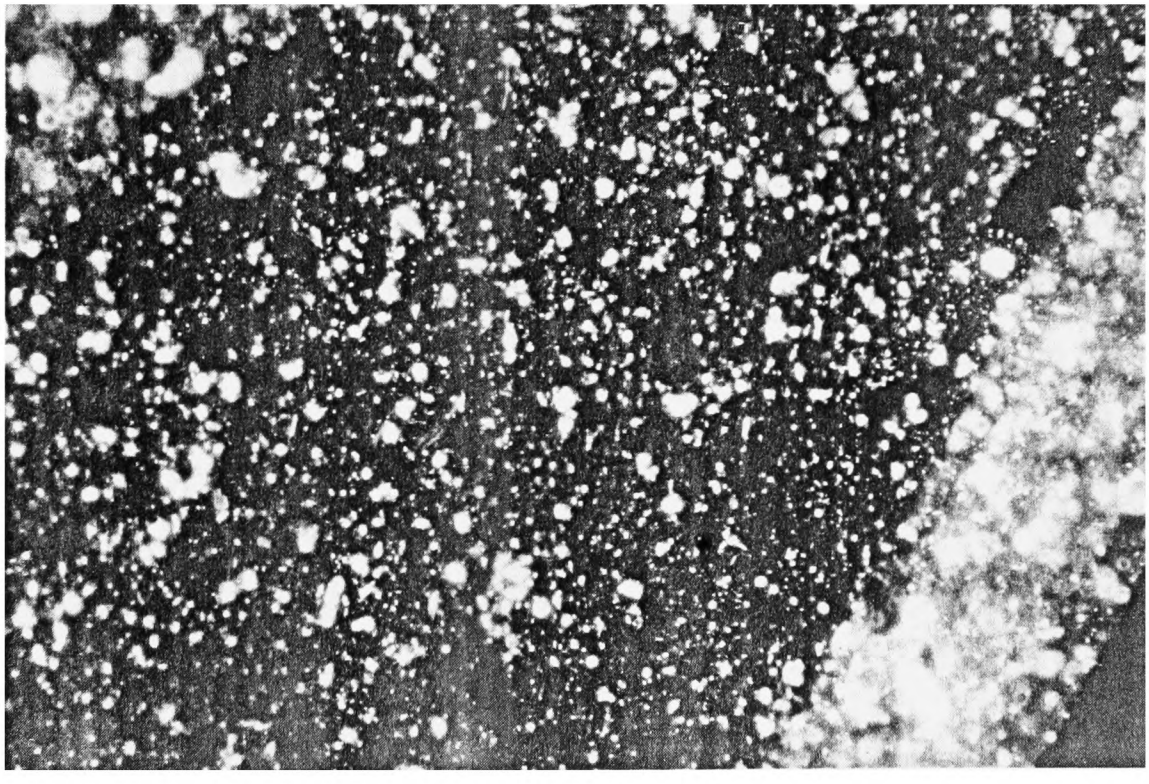


Figure 6.2 Thin-Section of Core RB13 - Low Magnification



100 µm

Figure 6.3 Thin-Section of Core RB13 - High Magnification

above the base of the column, respectively, and photographed at 170 and 430 times magnification under cross-polarized light. Areas of focussed and blurred image correspond to material at different elevations. At the lower magnification (Figure 6.2), the depth of field is greater and the image clearer in general, but the orientations of particles are difficult to resolve.

The idea of an automated analysis had to be abandoned. Analysis was begun using a light microscope an objective with cross-hairs, a key pad counter attached to a ratcheted stage, and a manual point counting technique. Samples were scanned at 50 µm intervals, and the presence or absence, anisotropic or isotropic form of particles beneath the cross-hairs recorded.

The orientations of anisotropic particles were classified into one of four wedge-shaped quadrants as shown in Figure 6.4, which is a crude form of rose diagram. The following are examples of point counting results for the sections shown in Figures 6.2 and 6.3, respectively:

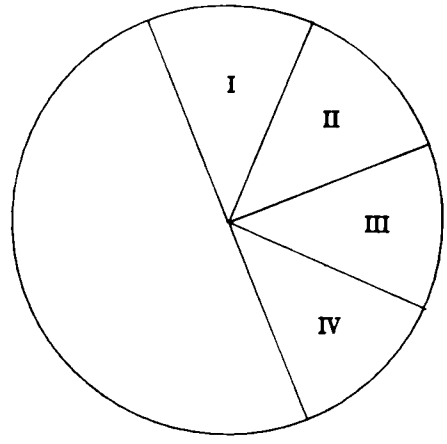


Figure 6.4
Classification of Particle Orientations

Solid	Void	Spherical	Too Small	Orientation I	II	III	IV
148	703	46	26	14	31	20	11
142	748	45	37	22	12	13	23

A very large number of counts had to be made per section in order to observe an appreciable number of orientations. The manual analysis of materials of high specific volume is labour intensive, more so when focussing is required to make each count.

Shortly after analysis commenced it became apparent that the resources needed to carry out even a reduced fabric analysis using manual methods were not available without compromising other aspects of the overall research programme. Nearly one-quarter of one million counts would have been necessary to complete the most spartan analyses. For this reason, plus the fact that difficulties were encountered recovering two of the four cores to

be analyzed, and because one core could not be sectioned at all with a glass knife, the fabric study was terminated and a summary review conducted.

Two factors were deemed to have been responsible for thwarting the study: an inability to recover cores consistently, and inconsistent thin-section preparation. Consistency during preparation was of paramount importance because of the months required to settle, to recover and to prepare samples. The process of preparation was prone to failure because it involved a sequence of difficult operations and an error at any stage was usually fatal.

Inconsistent core recovery was attributable to four causes. The primary reason was that of inexperience on the part of the author with the newly developed sampling apparatus. Second, greater success would have been achieved if shorter beds were to have been cored, but bed thicknesses were controlled by sediment mass requirements related to the study of compression behaviour. Third, one core was disturbed during recovery because of a broken core liner: the replacement of liners improvised from high density freezer bags with more suitable materials might prevent future breakages. Finally, sample tube imperfections, such as variable cross-sectional shape could be eliminated by using factory manufactured sample tubes.

The diagnosis of causes of poor quality thin-sections was aided by the use of Smart and Tovey's (1982) incidence matrix, symptoms by causes, for defects in ultramicrotomy. Of the six categories of symptoms comprising this matrix, coherence and dishevelment are relevant to the present work. The category of coherence includes the sub-categories 'no sections', 'fragmented

sections', and 'holes', which describe the products of three of the four cores sectioned. Possible causes of poor coherence include failure to polymerize, failure to infiltrate, instrument related problems, and excessive block strength. On the basis of thin sections which were viewed, the known expertise of the microtome operator, and observations made during cutting, it is believed that the author's blocks were too hard and too brittle to be cut with a glass microtome knife.

The category of dishevelment includes folds and rumples, both of which were common in the sections examined. Smart and Tovey suggest possible causes: uneven polymerization, and three types of instrument errors relating to the cutting knife.

Remedies to problems of poor quality sections include altering the proportions of the components comprising the resin mixture so as to make it less hard, investigating other impregnants (for examples see, Smart and Tovey, 1982; Jim, 1985; Conway, 1982), investing in a tungsten or diamond cutting knife, and exercising more strict control over the process of impregnation. Alternatively, geological thin sectioning methods might be re-tried using Crystic resin as the sample-to-slide bonding agent. This would remedy problems with delamination, whilst adding a flexibilizer to the resin would probably improve sample-to-slide bonding and reduce problems with stress relief.

For an investigator concerned with examining fabric only and possessing secure and unlimited access to the equipment necessary to do so, then the problems encountered in the present study should be surmountable using the

solutions proposed. An overview of the content and contribution of the present study follows.

The fabric study was initiated to complement compression behaviour and shear strength research. Its objective was to investigate the role of particle arrangements in determining soil behaviour and material properties. To achieve this objective means of preparing samples for examination had to be considered. The steps involved in preparing samples were sampling, impregnation, and thin-sectioning, and these were followed by analysis.

Research was carried out and progress made with regard to the conception and development of a small scale sampling tube and methods for using it, determination of satisfactory water-acetone replacement procedures, the testing of numerous resin-acetone-catalyst mixtures, the evaluation of two methods of preparing thin sections, an attempt to perform automated image analysis, and an assessment of the steps and effort required to perform a manual analysis of fabric. At the premature conclusion of the study a few sections had been produced which were satisfactory for being analyzed using an optical microscope and a laborious point counting procedure. No thin sections suitable for being analyzed automatically were produced. Methods of achieving higher quality thin sections and more consistent core recovery rates have been discussed and advances in these areas should render automatic analysis of fabric possible. Although the fundamental objective of the fabric study was not achieved, the effort expended in its pursuit yielded instruments, methods and knowledge that forms a sound basis for future work.

CHAPTER 7 SHEAR STRENGTH RESULTS

7.0 Introduction

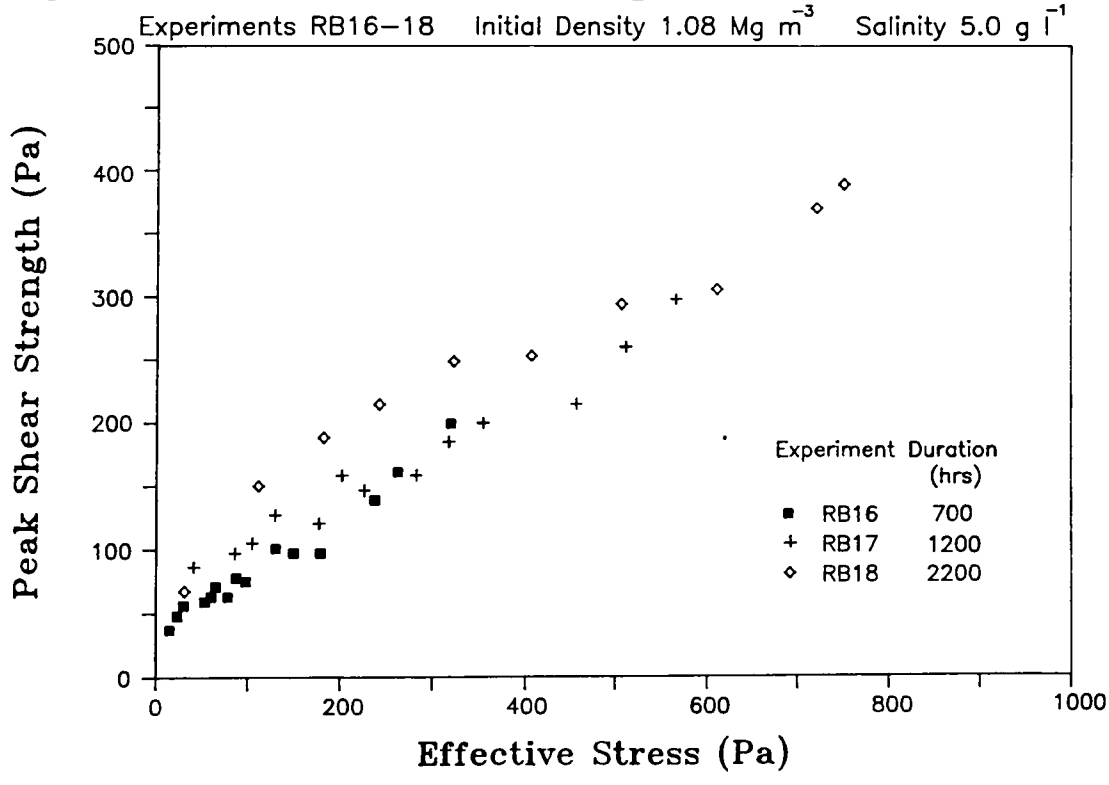
The shear strength of soft soil was studied because of its relevance to many practical problems. Solutions to the problems of predicting the resistance offered by a settled bed to the passage of a vessel, estimating shear strength on the basis of density, designing sediment dispersal systems, determining an optimum dredging strategy, predicting the erosion resistance of marine sediments, and maximizing the angle of repose of a mine tailings deposit, all require an understanding of shear strength, including its origin, factors which influence its magnitude, its development with time, and relationships to other parameters. To obtain this understanding the shear vane apparatus described in section 3.3.4 was developed and 152 vane strength tests were performed in 12 experiments (RB10-22) spanning a range of initial densities and salinities, experiment durations, and final effective stresses and specific volumes. For each shear vane test peak and residual strengths were recorded.

7.1 Undrained Shear Strength versus Effective Stress

The most common geotechnical analysis of shear strength is one in terms of effective stress, and for normally consolidated soils good correlations between the two parameters may usually be found. The most appropriate measure of stress for shear vane testing is the horizontal stress. However, because horizontal stresses could not be measured in the present programme, vertical effective stresses have been calculated and used instead.

Figure 7.1 shows peak shear strength results for three experiments which were similar in all respects but duration (experiments RB16, 17 and 18). Each set of results shows a remarkably linear relationship between peak shear strength and effective stress. Straight line extrapolations intersect the positive ordinate axis which suggests that at zero effective stress the soil had a measure of shear strength; this strength is commonly called true cohesion. Figure 7.1 reveals that peak shear strength increased with the passage of time. True cohesion also increased as time elapsed. A decrease in the slope of straight line approximations to data recorded at latter times suggests that the phenomena responsible for an increase in strength with the passage of time were more effective at lower than at higher effective stress levels.

Figure 7.1: Peak Shear Strength vs. Effective Stress



Figures 7.2 and 7.3 show results for two sets of experiments (RB13-15 and RB19-21) with different experiment conditions. The trends noted above, that is, a linear relationship between peak shear strength and effective stress, a positive cohesion intercept, and an increase in peak shear strength with the passage of time, were all evident. As was noted in Figure 7.1 for experiment RB18, long term experiments RB13 and RB21 (Figures 7.2 and 7.3) also showed a flatter relationship between peak strength and effective stress than experiments with similar conditions but of shorter duration.

To eliminate the effects of time-dependent changes in strength, experiments of similar duration must be compared and as a first approximation one might assume that the degree of time-dependence is independent of initial density and salinity. Figure 7.4 shows shear strength data for six experiments of similar duration but of different conditions. Data for experiments RB11, 12 and 22, not shown in earlier figures, are in accordance with results discussed above; peak shear strength and effective stress are linearly related, whilst at zero effective stress true cohesion is evident. Figure 7.4 shows that, for experiments which had the same intial density, settled beds of low salinity were stronger than beds of high salinity at comparable effective stresses (or specific volumes), over the full stress range examined. Similarly, Figure 7.4 reveals that for beds with the same salinity but which were deposited from slurries of different initial density, initial density exerted only a very slight and variable influence on peak strength behaviour: at low salinities dense slurries (1.16 Mg m^{-3}) were slightly stronger than initially less dense slurries (1.08 Mg m^{-3}) at any given effective stress, whilst at high salinities the opposite was true.

Figure 7.2: Peak Shear Strength vs. Effective Stress

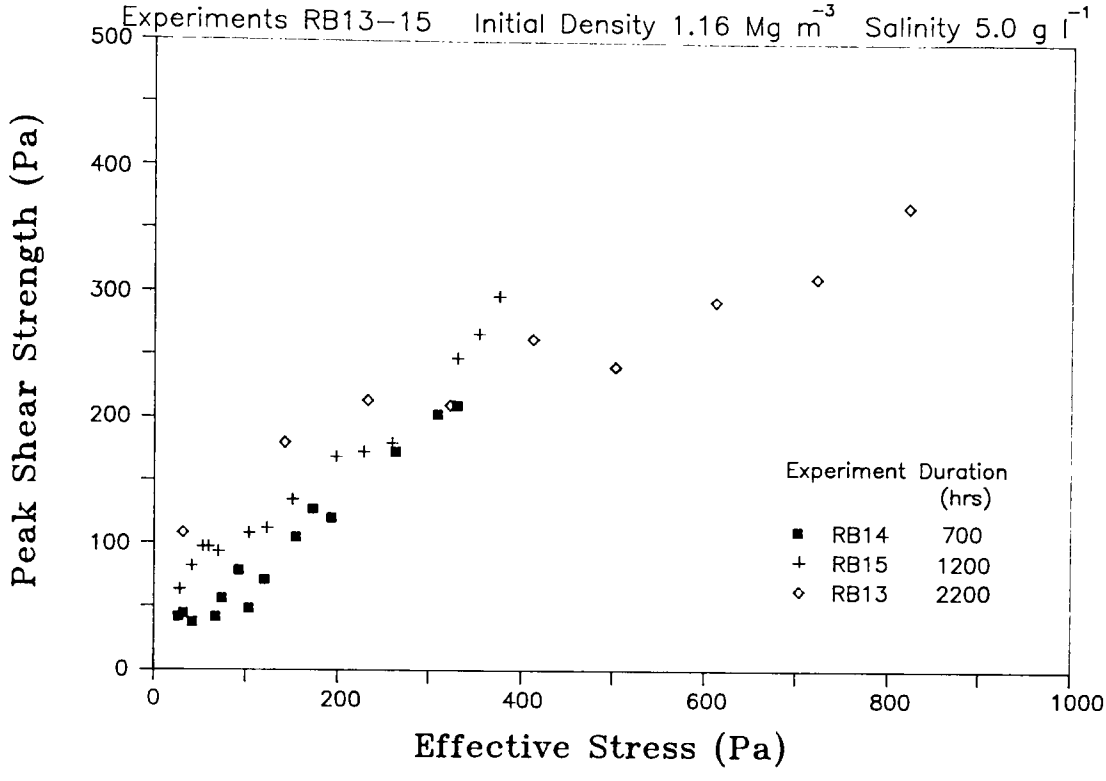
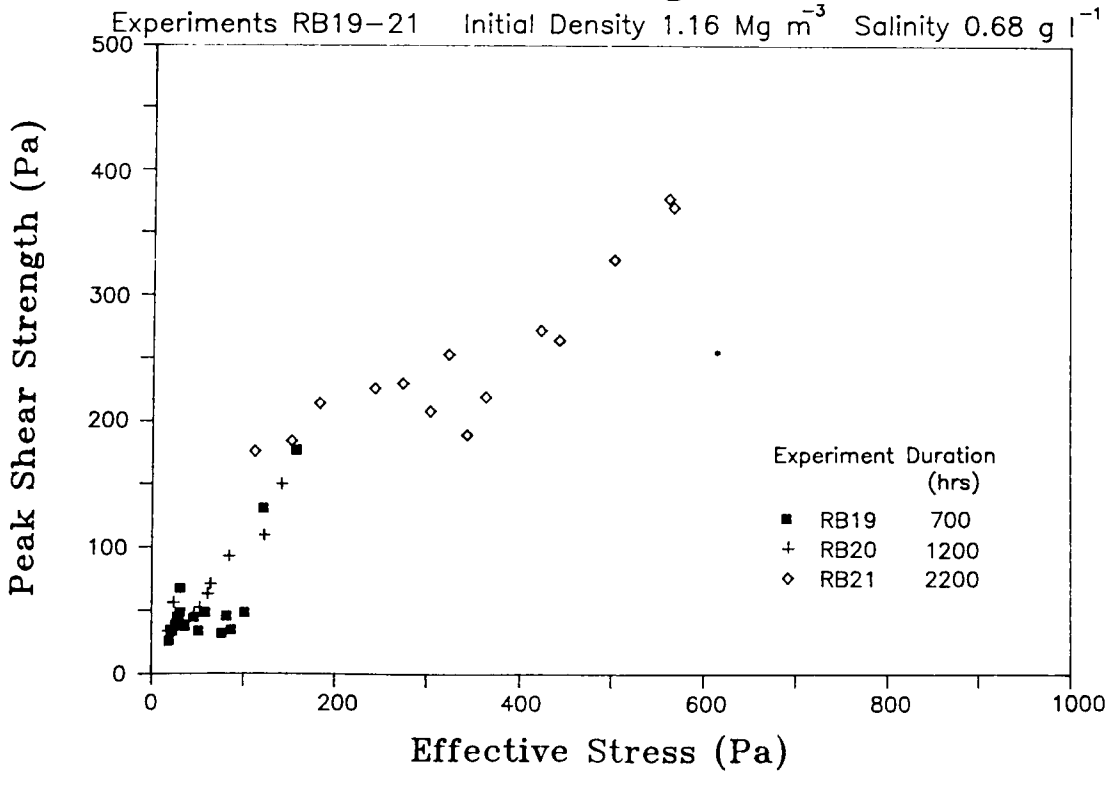


Figure 7.3: Peak Shear Strength vs. Effective Stress



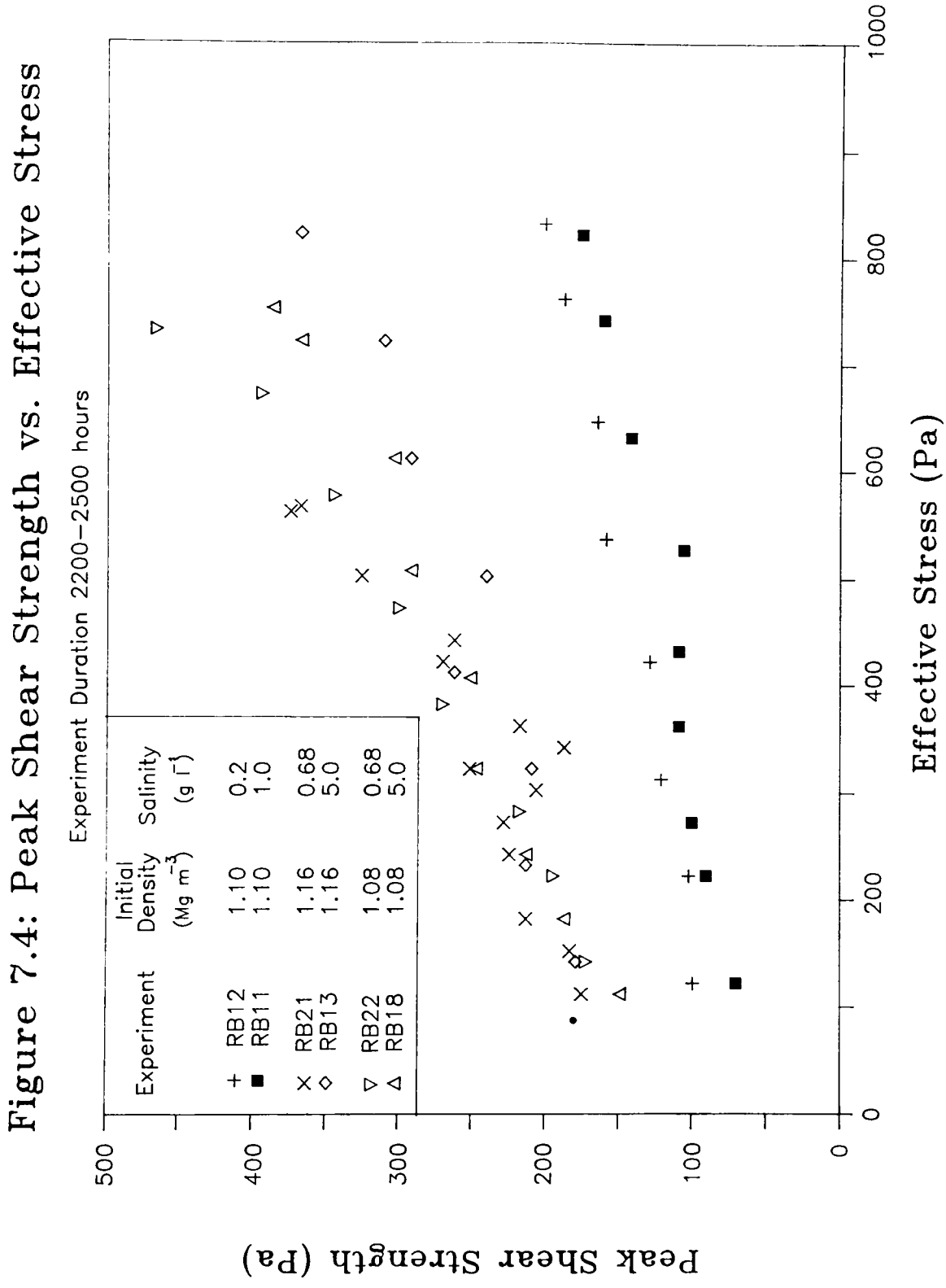


Figure 7.4: Peak Shear Strength vs. Effective Stress

Figures 7.5 through 7.8 show residual shear strength versus effective stress results for experiments RB11-RB22. Residual shear strengths were measured after 720° of rotation and were typically one-quarter to one-eighth of measured peak shear strengths. The degree of scatter amongst the data shown in Figures 7.5-7.8 is relatively large because of the extremely low strengths measured. Recall from section 3.3.6 that the accuracy of shear strength and effective stress measurements were ±4 Pa and ±10 Pa, respectively. Trends are correspondingly more difficult to identify. In all six experiments, residual shear strength increased with increasing effective stress and the data suggest that cohesion existed at zero effective stress. The results shown in Figures 7.5 and 7.7 suggest that residual shear strength increased with the passage of time whilst data in

Figure 7.5: Residual Shear Strength vs. Effective Stress

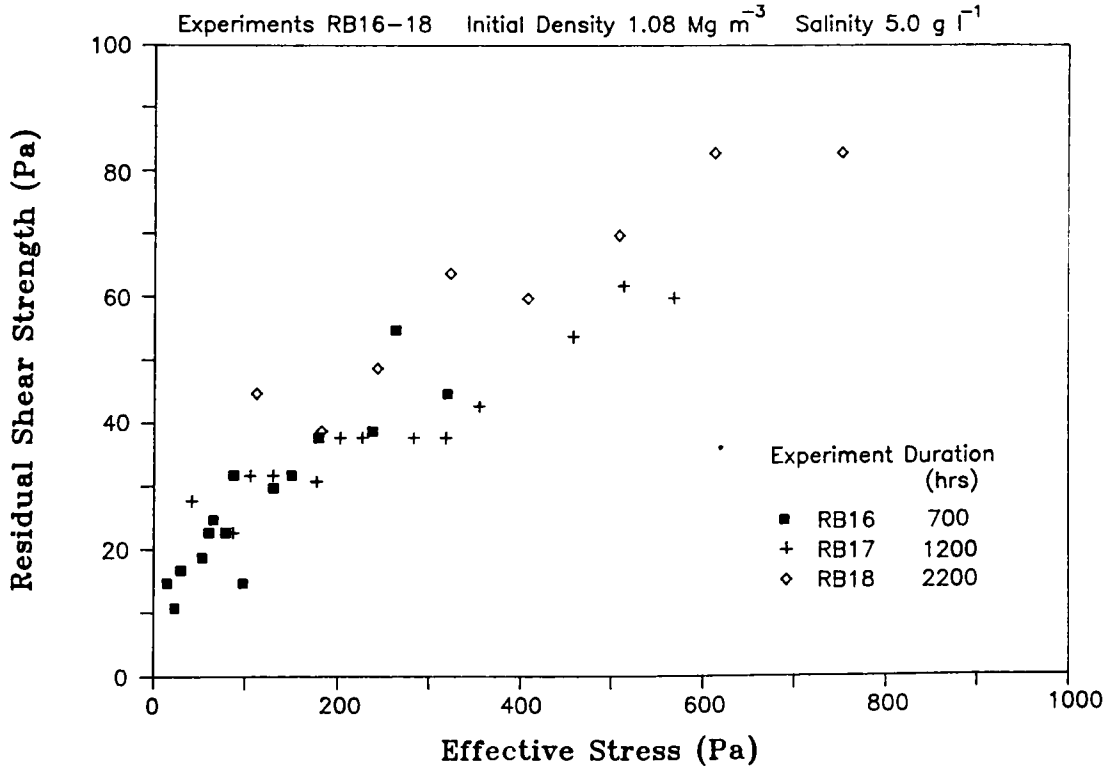


Figure 7.6: Residual Shear Strength vs. Effective Stress

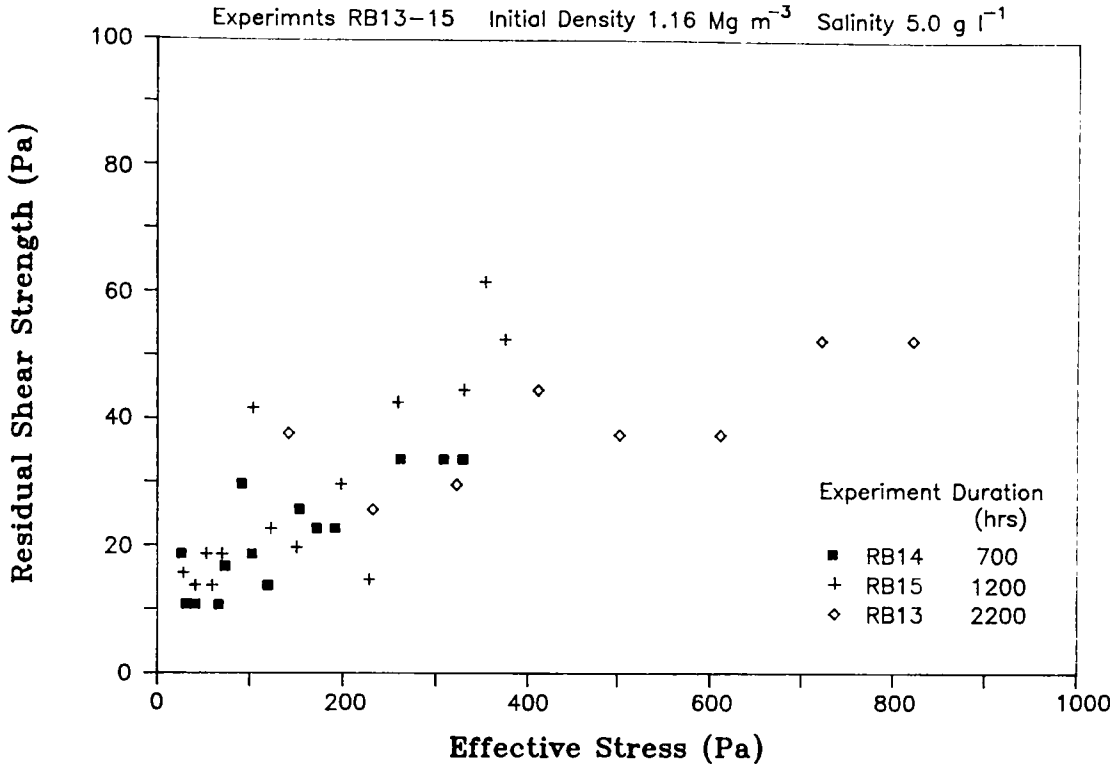
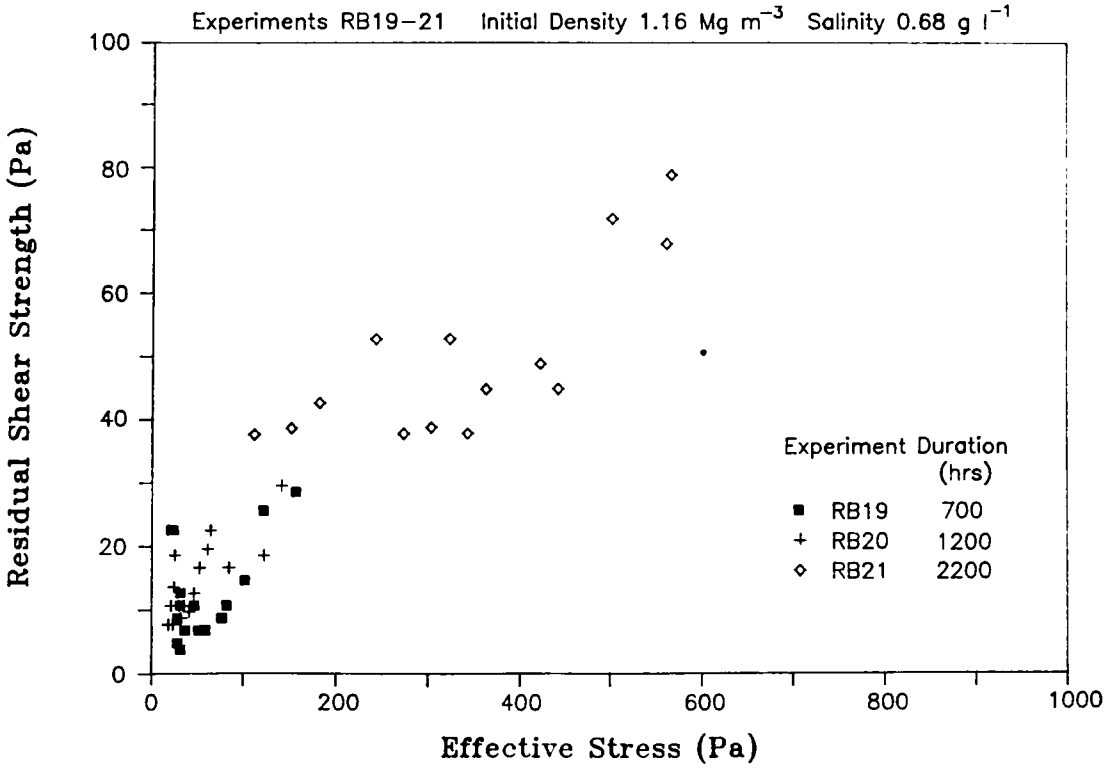


Figure 7.7: Residual Shear Strength vs. Effective Stress



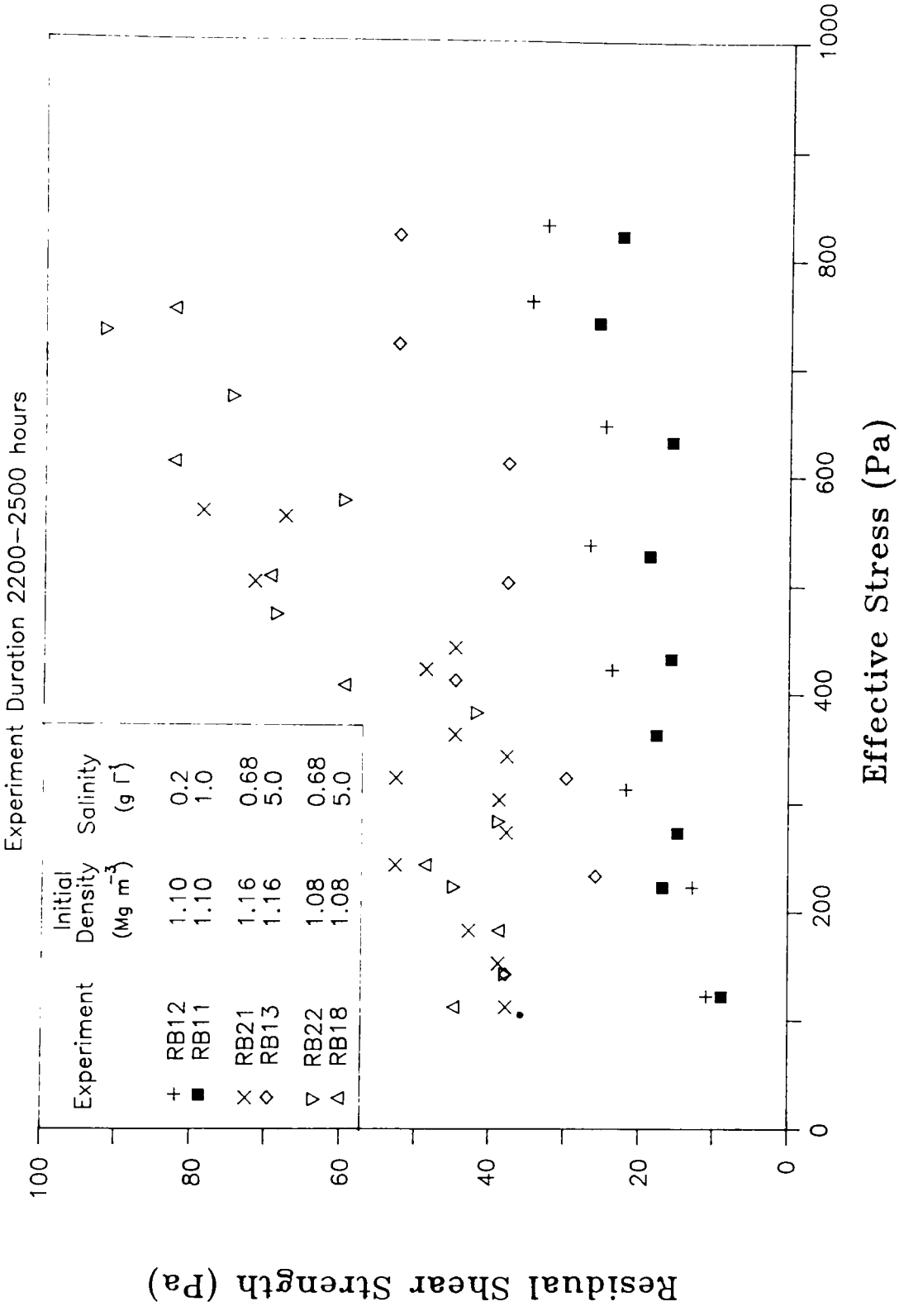


Figure 7.8: Residual Shear Strength vs. Effective Stress

Figure 7.6 suggest time-independence: more data is required to clarify the influence of time-dependent phenomena on residual strength.

Similar to the peak shear strength data shown in Figure 7.4, Figure 7.8 shows residual shear strength versus effective stress data for six experiments of similar duration (2200-2500 hours) but different conditions. In all experiments residual shear strength increased with increasing effective stress: results for experiments RB11, 12, 13, and 18 suggest a linear relationship, whilst variations in results for experiments RB21 and 22 prevent generalizations being made. All data suggest a measure of residual shear strength at zero effective stress, the amount being influenced by experiment conditions. At initial densities of 1.10 and 1.16 Mg m^{-3}, low salinity conditions yielded higher residual strengths, while at an initial density of 1.08 Mg m^{-3} high salinity yielded a stronger bed at all effective stress levels. As was observed in peak strength results, the influence of initial density on residual strength was irregular.

7.2 Soil Sensitivity

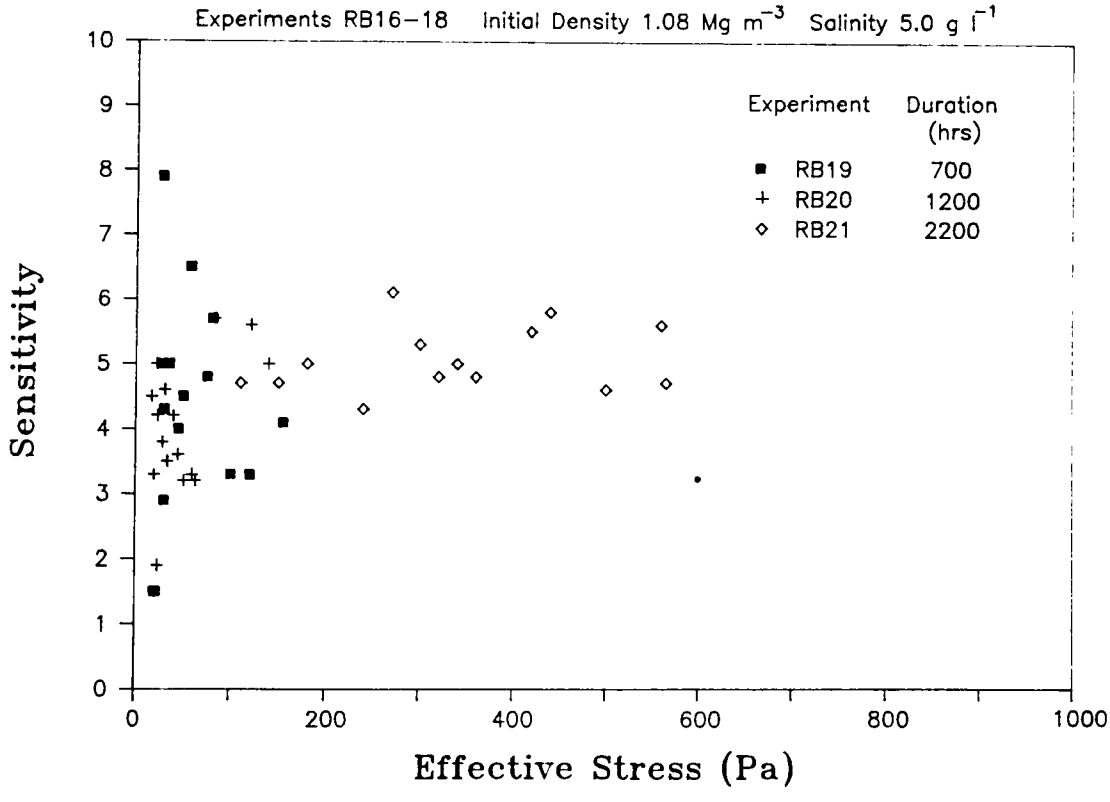
The strict definition of soil sensitivity is the ratio of peak to remoulded shear strength, but it is not uncommon to substitute residual strength for remoulded strength when tests are carried out in situ and remoulded strengths are unavailable. This practice is followed here.

Soil sensitivity exposes the influence of interparticle forces and arrangements (ie. structure) on shear strength behaviour. This is so

because shear vane testing destroys the structure of an intact soil, and creates new particle arrangements and interparticle force balances which offer less resistance to the motion of the vane. Sensitivity is, therefore, a measure of the contribution of original structure to peak shear strength. The influence of factors such as time, salinity, initial density, and effective stress on structure may be revealed by their influence on sensitivity.

Figure 7.9 presents sensitivity versus effective stress data for experiments RB16-18. These results show that soil sensitivity was independent of both level of effective stress and time. Results for experiments with different

Figure 7.9: Sensitivity vs. Effective Stress



conditions (RB19-21, Figure 7.10; RB13-15, Figure 7.11) were more variable, especially at low effective stresses which correspond to low shear strengths. In these latter two figures no trends in sensitivity with respect to time or level of effective stress transcended the degree of variation observed.

Figure 7.12 is a summary of sensitivity versus effective stress results for experiments of similar duration and in it the independence of sensitivity and level of effective stress is confirmed. The influence of salinity and initial density on sensitivity is less than a factor of two and no pattern of influence is evident.

For the sediment and conditions studied, sensitivity varied between approximately 3.5 and 8, and individual values were dependent on experimental conditions (both initial density and salinity) in an irregular way. An influence due to the passage of time was not apparent: one was expected because of the tendency for peak shear strength to increase with the passage of time. It is possible that such a trend indeed exists (as was observed by Elder, 1985) but that it was concealed by the scatter amongst the data. Elder's shear vane tests on Combwich mud yielded sensitivities of 1 to 4 for tests carried out 1 minute to 13500 hours after deposition, respectively. The lower average values of Elder versus those noted for RB experiments are probably a consequence of different test procedures. Elder's 'residual' values were recorded after 210° of rotation, versus 720° for the author, which would produce higher average residual strengths, and thus lower values of sensitivity.

Figure 7.10: Sensitivity vs. Effective Stress

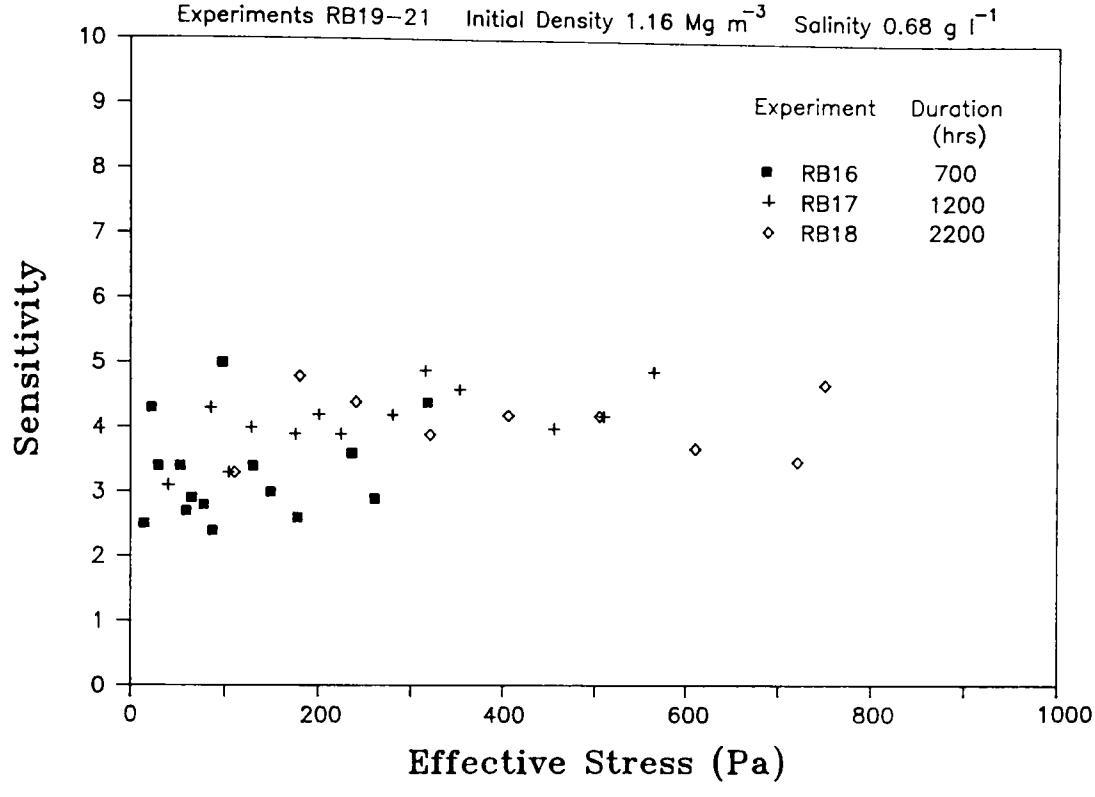
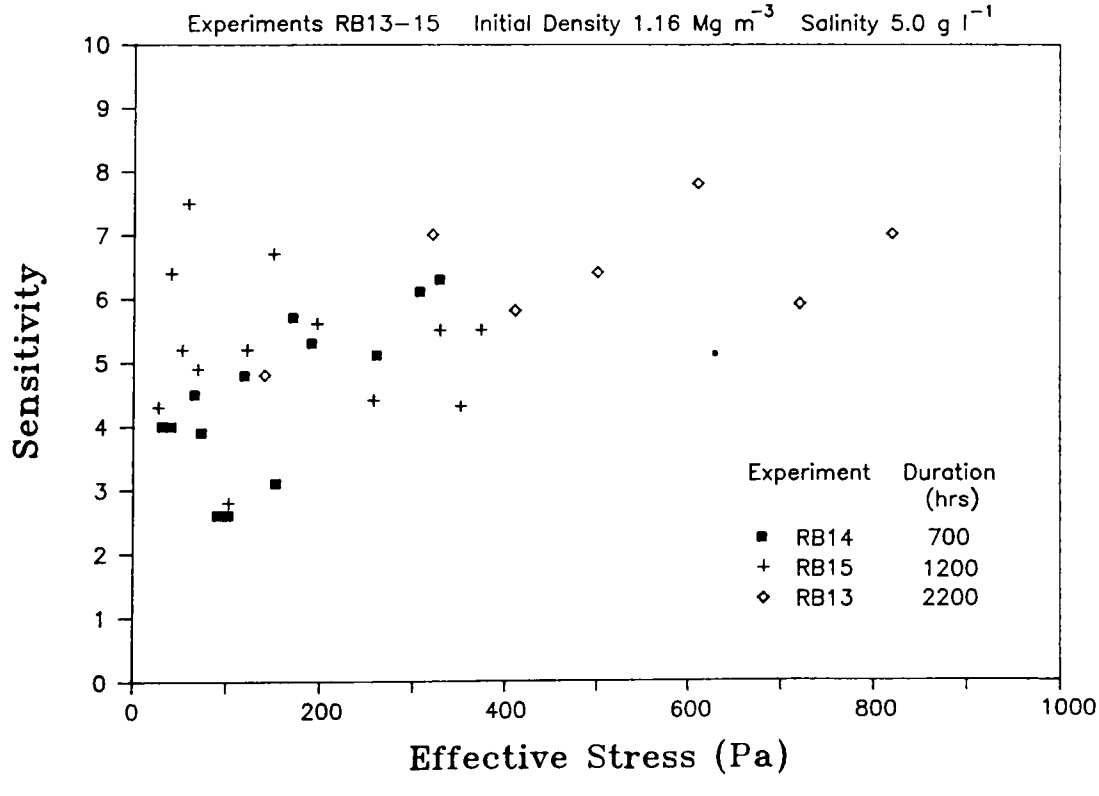
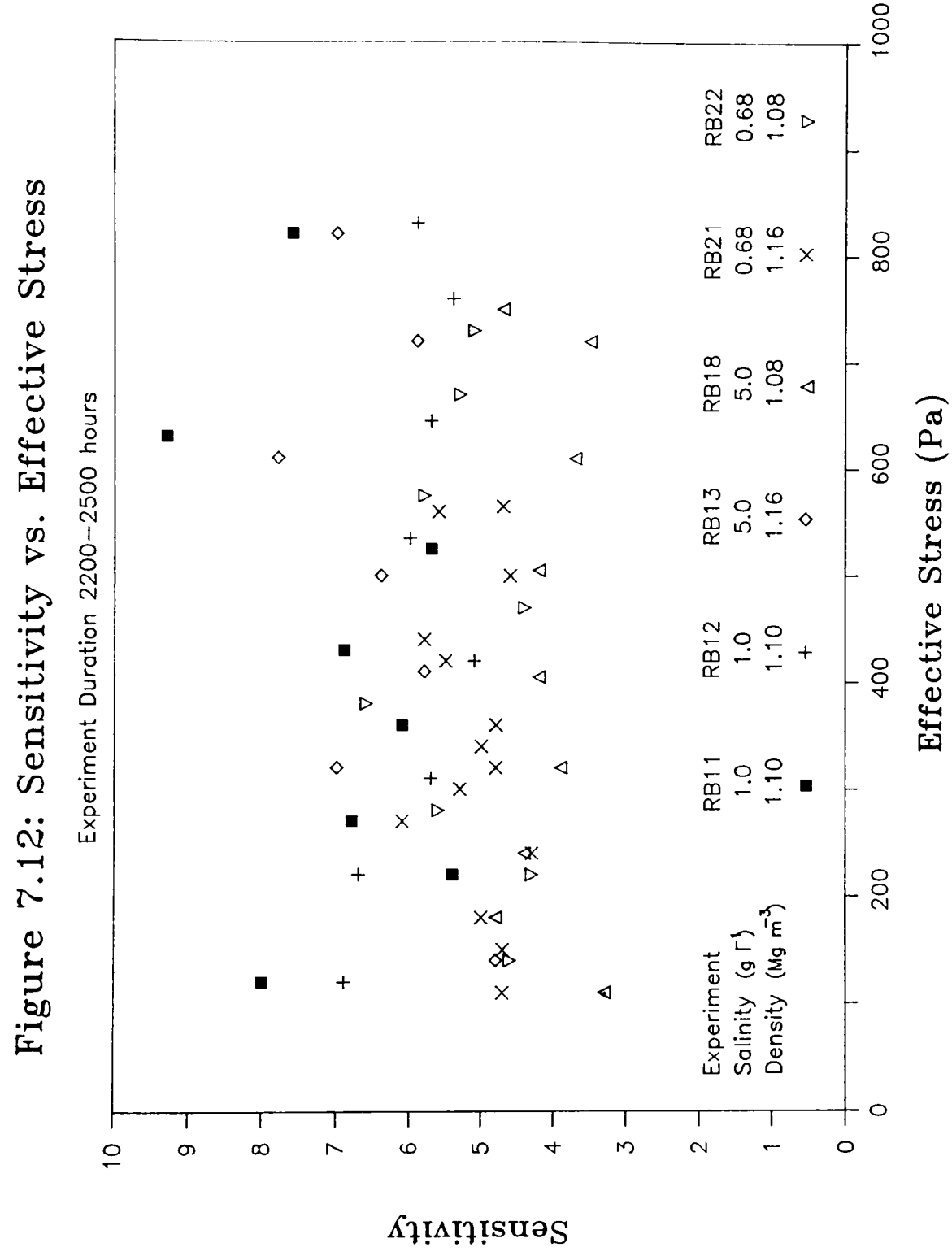


Figure 7.11: Sensitivity vs. Effective Stress




Figure 7.12: Sensitivity vs. Effective Stress
Experiment Duration 2200–2500 hours
Sensitivity
Effective Stress (Pa)
0
1
2
3
4
5
6
7
8
9
10
0
200
400
600
800
1000
Experiment RB11 RB12 RB13 RB18 RB21 RB22
Salinity (g l⁻¹) 1.0 1.0 5.0 5.0 0.68 0.68
Density (Mg m⁻³) 1.10 1.10 1.16 1.08 1.16 1.08

Sensitivity was independent of level of effective stress. A high degree of variation was observed and future studies of beds of greater average peak and residual shear strength should reveal clearer trends.

7.3 Peak Shear Strength versus Specific Volume

In certain civil engineering applications a relationship between shear strength and specific volume (or density) is more valuable than one between shear strength and effective stress. One example of this, presented in section 2.1, is the identification of unnavigable areas in harbours. Typically this is attempted by estimating in situ density and then assuming or invoking an empirical density-shear strength correlation. This approach is more convenient than trying to measure either shear strengths directly or measure effective stresses and then applying a strength-effective stress relationship (Figures 7.1-7.4). However, the usual approach demands that a unique shear strength-specific volume relationship exist and be known.

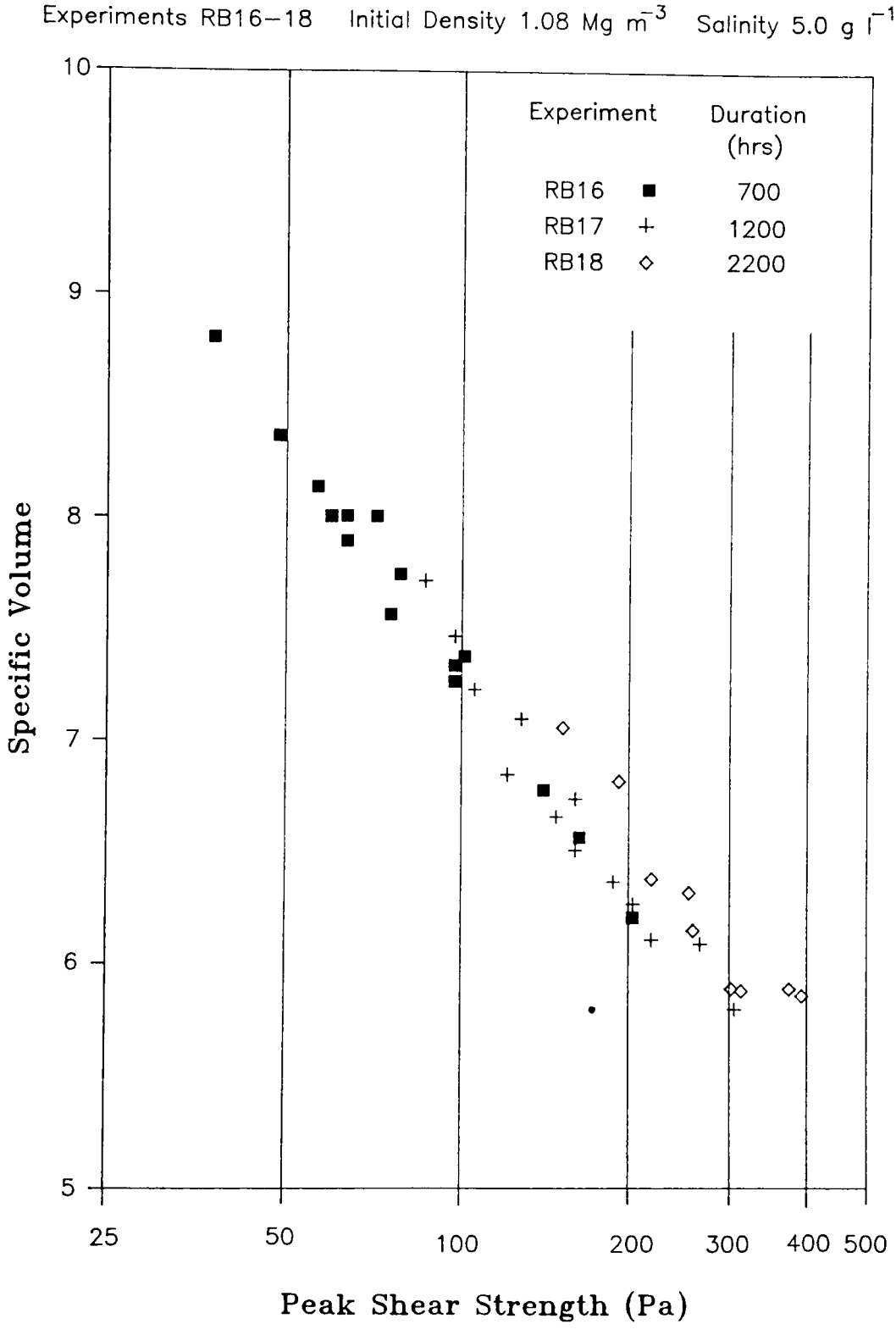
For most soils which share a similar history but which have different specific volumes, specific volume (V) and the logarithm of peak shear strength ($\log s_{u_p}$) are linearly related. Einsele et al. (1974) observed this type of relationship in beds of clay minerals settled under self-weight, for effective stresses greater than 1 kPa. Data for RB experiments were plotted to assess the validity of this relationship for soils of high specific volume and low strength, and, in addition, to determine whether such a relationship is affected by the passage of time, and/or changes in salinity or initial slurry density.

The shear strength versus specific volume data shown in figure 7.13 describe a well-defined linear relationship between log peak shear strength and specific volume. At any given specific volume peak shear strength increased slightly with the passage of time. These conclusions are also true for other experimental conditions, data for which are shown in Figures 7.14 and 7.15. These results are not surprising: it was shown in sections 5.1 and 7.1 that relationships between effective stress and specific volume, and peak shear strength and effective stress were well defined, and that the latter was sensitive to the passage of time. One would expect, therefore, that a combination of these relationships would also be well-defined.

Figure 7.16 shows the combined results of Figures 7.13, 7.14, and 7.15. These results show that there is a good correlation between peak shear strength and specific volume, providing that a small allowance is made for the influence of time, for the range of conditions encompassed by the results presented. When the results of experiments for a broader range of conditions are compiled, however, the significant influence of experimental conditions on the relationship between peak shear strength and specific volume is revealed (Figure 7.17): for example, at a specific volume of 6, peak shear strengths varied between 100 and 400 Pa, a range too large to be summarized as a single value, as would be convenient for engineering design purposes.

The significance of this conclusion regarding the influence of slurry conditions on peak strength depend on the degree of variation in conditions expected for a particular application. It may, for instance, be reasonable to assume that the salinity within a harbour is constant and that,

Figure 7.13: Peak Shear Strength vs. Specific Volume



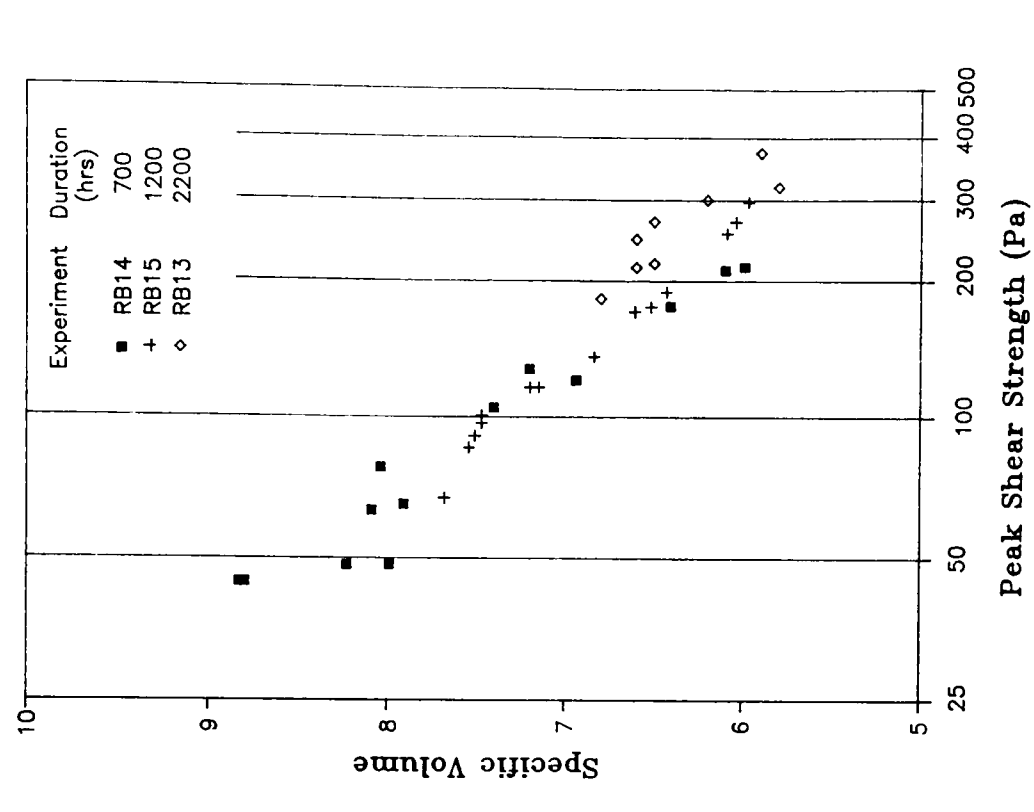


Figure 7.15
Peak Shear Strength vs. Specific Volume
Experiments RB13–15 Initial Density 1.16 Mg m^{-3} Salinity 5.0 g l^{-1}

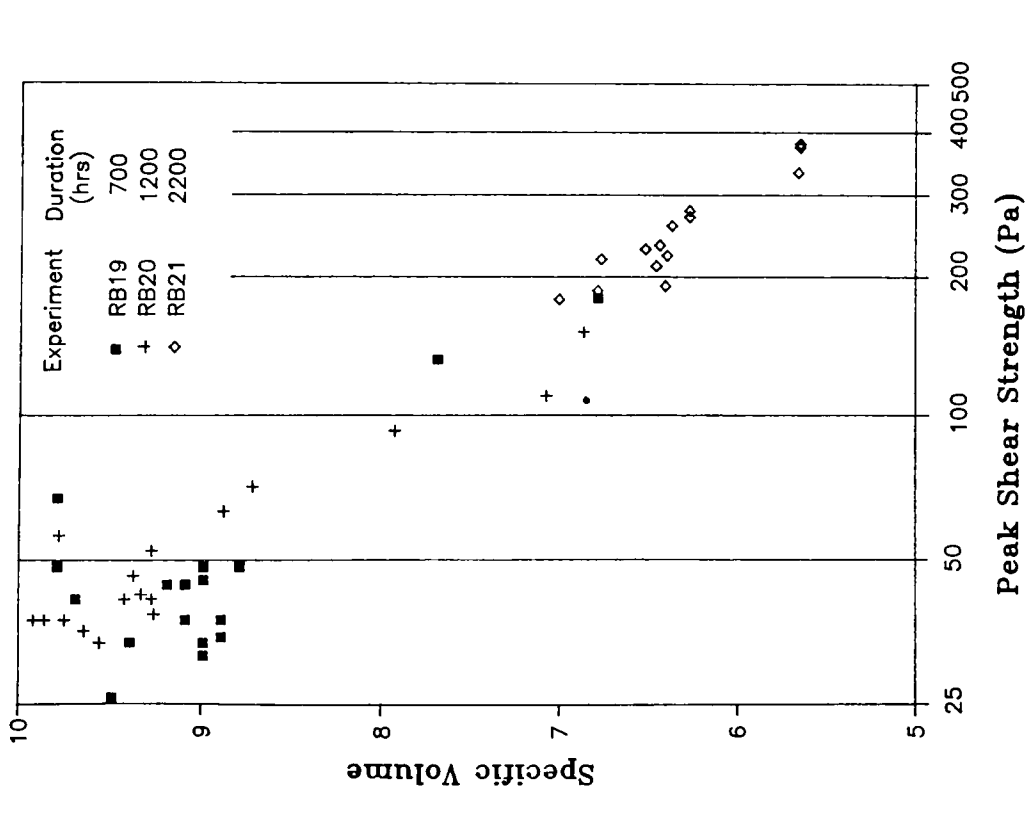


Figure 7.14
Peak Shear Strength vs. Specific Volume
Experiments RB19–21 Initial Density 1.16 Mg m^{-3} Salinity 0.68 g l^{-1}

Figure 7.16: Peak Shear Strength vs. Specific Volume

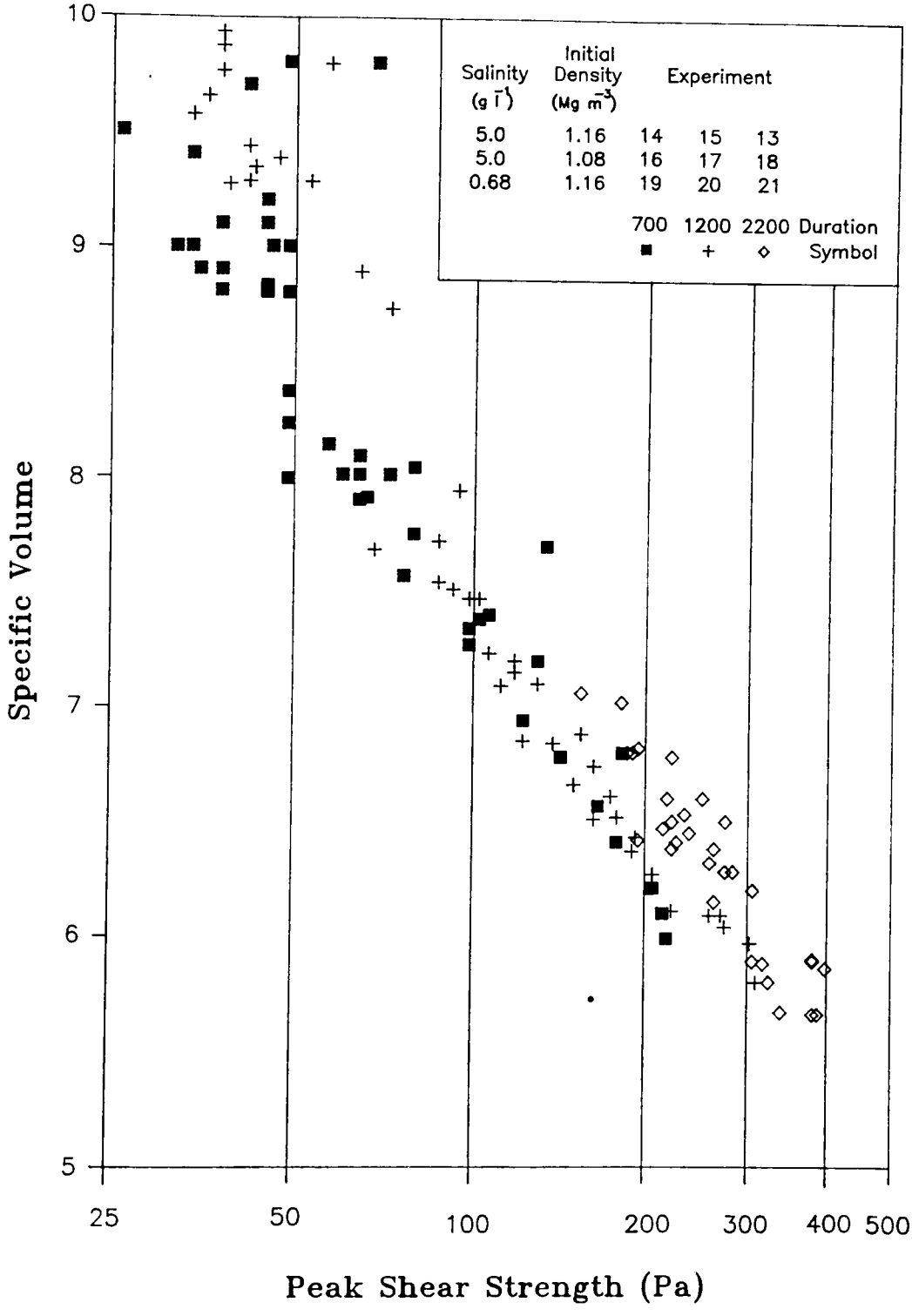
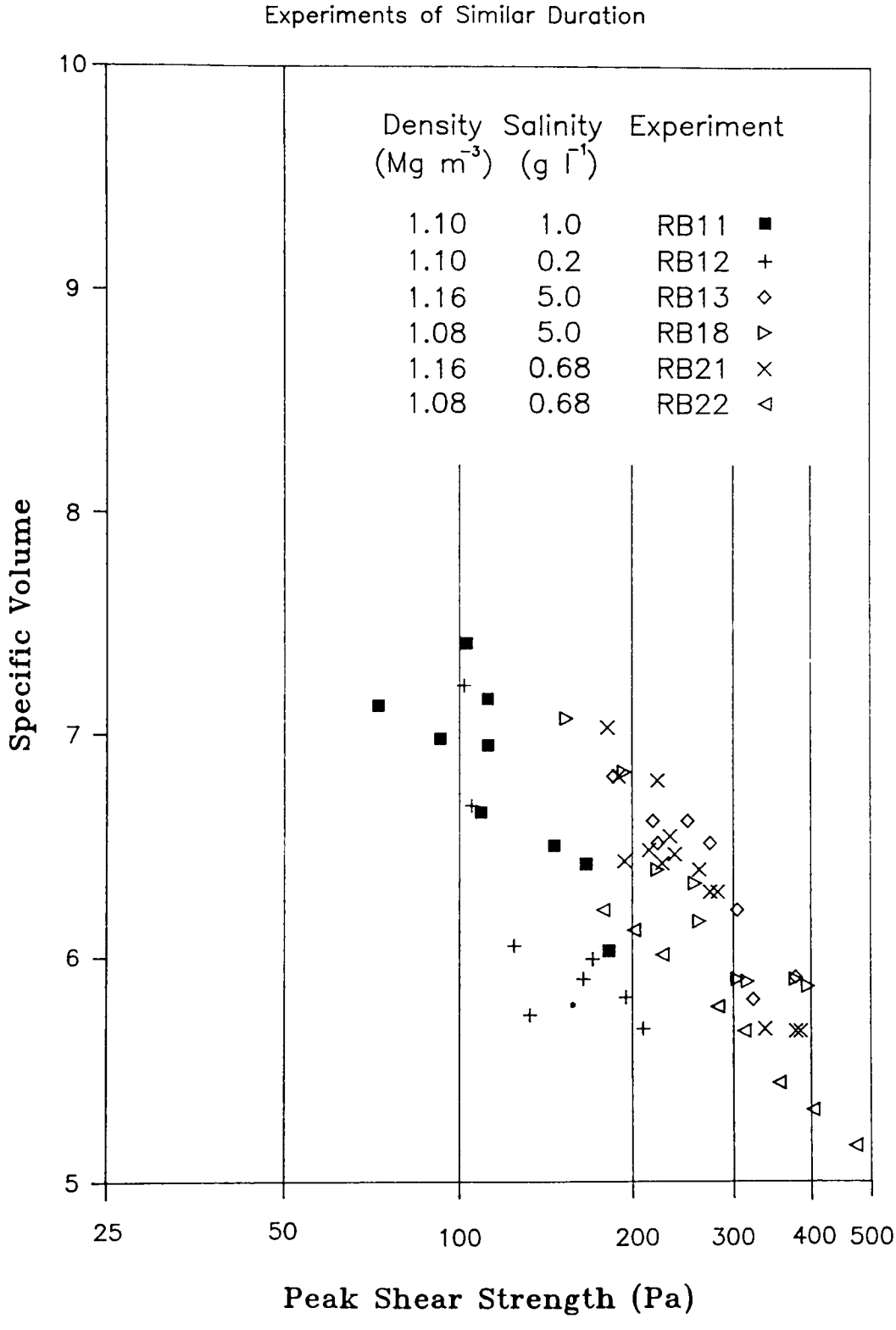


Figure 7.17: Peak Shear Strength vs. Specific Volume



therefore, only the influence of initial density on s_{u_p} - V needs to be considered. The data in Figure 7.17 reveal that the variation in peak shear strength at any given salinity and effective stress was less than the total variation for conditions of variable salinity and density. A smaller variation was also observed when initial density was maintained constant. Thus if one applies realistic limits to the conditions likely to occur, then narrowly-banded relationships between peak strength and specific volume may be defined and used in practice to estimate peak shear strength on the basis of specific volume (or soil density). For very restricted conditions, single curves such as those shown in Figures 7.13, 7.14, and 7.15, might be used. Peak shear strength versus specific volume curves for the sediment type and range of conditions peculiar to the facility would, of course, have to be determined, as would the influence of the passage of time if this was significant.

7.4 Discussion

The present results may be compared with similar earlier work by Elder who carried out a large number of shear vane tests on beds formed by the self-weight compression of initially dense slurries of Combwich mud. Elder's tests were performed after different durations but always at a fixed depth below the sediment surface; in thick beds the sediment surface was lowered by excavation, with an unknown effect on stress conditions.

Elder did not observe a unique relationship between either peak or residual shear strength and vertical effective stress because of substantial amounts of creep compression. The effect of the latter was to produce a range of

specific volumes at each value of effective stress and duration after input. Shear vane tests at different specific volumes yielded different shear strengths and, therefore, non-unique relationships when plotted against effective stress. Elder suggested that when the effects of creep were removed analytically, residual shear strength and equivalent vertical effective stress (σ'_{ve}) were related as follows,

$$s_{u_r} = 0.03\ \sigma'_{ve}. \qquad \ldots\ 7.1$$

The coefficient 0.03 is considerably less than that given by Skempton (1957) in a similar form of relationship,

$$s_{u_r} = (0.11 + 0.0037\ PI)\ \sigma' \qquad \ldots\ 7.2$$

where PI is the Plasticity Index (equal to 32 for Elder's soil), yielding a coefficient of 0.23. In the present work values for the ratio s_{u_r}/σ' varied between approximately 0.017 and 0.121 depending on experiment conditions. The size of the range was due in part to the large variation observed in residual shear strength at very low values. A similar ratio, defined in terms of peak shear strength (s_{u_p}/σ') yielded values of between 0.14 and 0.86 for vane tests in RB experiments.

If one accepts the supposition that soil is a frictional material whose shear strength is governed by effective stress, a concept which is supported by linear shear strength-effective stress relationships within the data, then an explanation is required for cohesion at zero effective stress. Two explanations may be advanced: the cohesion observed was apparent and due to

viscous effects; and/or the cohesion observed was genuine and due to attractive electrochemical forces.

The viscosity based argument is, simply, that all viscous mixtures sheared at a finite rate display an apparent shear strength. For soils, it is not possible to determine the contribution of viscosity to the undrained vane shear strength at zero effective stress because the nature of vane tests change as the rate of testing changes. The strength measured in an infinitely slow shear vane test may be free of viscous effects, but it is also a drained strength and is, therefore, different in kind to the tests reported here. Evidence within the recorded data suggests that non-viscous effects were also responsible for strength at zero effective stress. It is, for example, difficult to explain time-dependent increases in shear strength at zero and non-zero effective stress levels in terms of viscosity because viscosity is a function of the composition and quantity of constituents within a slurry only, and these factors are independent of time. Attractive interparticle forces are a plausible alternative or supplementary explanation for cohesion at zero effective stress. These forces create a small 'intrinsic' stress which generates shear strength. Abundant evidence, presented in earlier chapters, suggests that attractive forces were active and influential at low effective stress levels.

According to discussions presented in chapter 2, the effect of increasing pore fluid salinity is to decrease the range of diffuse double layers surrounding charged particles. For particles at a fixed specific volume it follows that the magnitude of electrochemical interactions, and therefore shear strength, should decrease as salinity increases. This pattern was

observed in RB experiments: at any given specific volume, peak shear strength decreased with increasing salinity.

Sridharan et al. (1979) studied the influence of pore fluid composition on the shear strength behaviour of saturated clays. Their results, analyzed in terms of a modified effective stress concept involving electrochemical attractive and repulsive forces, showed a clear pattern of influence of pore fluid dielectric constant on shear strength. Sridharan et al.'s study and the present one are similar in their conclusions: cohesion at zero effective stress exists and is due to attractive electrochemical forces, and the latter are influenced by pore fluid composition. Additional comparisons between Sridharan et al.'s and the author's results cannot be made because of a fundamental difference in experiment procedures. Whereas samples in RB experiments were formed by settling particles through different pore fluids and may, therefore, have produced beds with different fabrics, Sridharan et al intentionally avoided this source of variability by saturating samples with different fluids after a consistent procedure of dry compaction. In RB experiments the contributions of fabric and interparticle attractive forces to shear strength are inseparable.

The shear strength data for RB experiments are insufficient in number to permit either the extrapolation of shear strength and cohesion back to the time of input, or to fit the data with curves to facilitate the prediction of strengths at future points in time. Long duration tall column experiments are an inefficient way of collecting the volume of data required to establish numerical trends. Elder's method of consolidating many short, high density slurries in uninstrumented columns is a superior approach.

CHAPTER 8

SUMMARY, INTERPRETATION, CONCLUSIONS, AND RECOMMENDATIONS

8.0 Introduction

This chapter has several purposes. The first of these is to draw together results presented in chapters four through seven, and to explain the behaviour that these results describe in terms of interparticle forces and physical phenomena. Recall from section 2.4 that the first objective of the present research was to gain an improved understanding of how natural flocculated slurries behave and why, specifically, as they do. The summary and interpretation of results presented in section 8.1 reveals the state of the understanding of flocculated slurries in light of the latest results.

Problems with existing traditional models of compression, as applied to natural flocculated slurries, are reviewed briefly in section 8.2. Results of the present experimental programme suggest a more satisfactory perspective and this is presented in the form of basic and extended conceptual models of compression behaviour. With these models, phases of activity and their causes are explained.

In section 8.3 the relevance of the conceptual models to practice is established: their roles are those of illustrators and qualitative guides. The contribution of RB experimental results and analyses towards developing a practical model of slurry compression is outlined and the best method of

studying and classifying flocculated slurries which is available at present, is described.

The research is brought full circle in section 8.4; therein the results of RB experiments are applied to the engineering problems introduced in section 2.1 (page 5).

The penultimate section (8.5) is a statement of the contribution of the author's research. The concluding section (8.6) consists of recommendations for future research.

8.1 Summary and Interpretation of Results From RB Experiments

The least quantitative means of describing compression behaviour is in terms of the visual characteristics of a slurry - the bulk of the sediment, sediment surface, and supernatant. Slurry appearance reflects the degree of, and changes in structure, and it is dependent upon both slurry conditions and time. In RB experiments, slurries of high initial density and/or salinity displayed a constant, uniform, fine-grained texture, indicative of a high degree of structural uniformity and stability. In contrast, slurries of low initial density and/or salinity showed distinct heterogeneities and extensive changes in appearance with the passage of time, features which suggest less structural stability.

In well structured slurries the supernatant liberated by compression was clear continuously. In less stable slurries the appearance of a hazy supernatant preceded the development of coarse-texture and channels, rapid

settlement, and the generation of an opaque supernatant. In two experiments which had low initial density and salinity, visible features were scant, and this may be attributed to insufficient material to create, and/or structural strength to maintain, heterogeneous forms.

Visual indicators of degree of structure include: supernatant clarity; slurry texture; presence and extent of channels; surface cracks, curled edges, and domes; and sediment flow. The most important visible change that occurred as initial stability changed to rapid settling and then to consolidation was the creation, inter-connection, and then collapse or infilling of channels. Whilst channels existed the rate of settlement was rapid. Observation is the only means of detecting channels. Qualitative descriptions of slurry appearance may be used to infer degrees of slurry structure, and may be combined with other information to predict behaviour (section 8.3).

A slurry composed of sediment with a range of characteristics has the potential to segregate. Segregation is caused by differential particle settling and for it to occur particles must be mobile, independent of one another, and settle through a distance. Degree of segregation within a material must be established before behaviour is interpreted because of the influence that solids composition exerts on compression behaviour.

One indicator of the likelihood of segregation is supernatant clarity; a cloudy supernatant implies that differential settling has occurred. The author studied the appearance of small volumes of slurry with a range of initial densities and salinities to estimate the experimental conditions

which divide segregated and non-segregated settling for Combwich mud. These tests showed that as initial density and salinity increased the propensity of a slurry to flocculate, and the clarity of its supernatant, also increased. If one interprets these observations in terms of particle freedom and mobility, then a trend of decreasing segregation with increasing initial density and salinity is predicted. This pattern was observed in 21 full-scale experiments in which particle size analyses were carried out. As salinity decreased, initial density decreased, and initial slurry height increased, the degree of segregation increased from none, to near-surface only. Had more extreme conditions been investigated, examples of complete segregation, might have been observed.

The objective in the present programme was to confirm the homogeneity of settled beds, and this was completed successfully: in all RB experiments, segregation was restricted to less than ± 5 per cent of the average particle size distribution of each slurry, an amount considered to be insufficient to warrant analyzing beds as composite materials. In addition, the analysis of particle size distributions produced almost no evidence of rapid settling of coarse particles, in spite of behaviour in some experiments which suggested that this might have occurred. Limited segregation observed within beds settled from low density slurries in tall columns suggests that the slurries in RB experiments were highly flocculated. This conclusion is consistent with descriptions of the appearance of slurries in RB experiments.

The simplest quantitative characterization of behaviour possible is in terms of height of surface versus time. In RB experiments the most common pattern observed consisted of an initial period of stability, a period of

accelerating settling rate, a period of near-constant rapid settlement and, finally, slow settling at an ever decreasing rate. Durations of, and settling rates during each phase varied with experiment conditions. The only exceptions to this pattern were experiments begun at high initial density, and in these no period of rapid settlement was observed. Settling experiments were repeatable to high degree.

A period of initial stability was almost always observed and its duration was independent of initial slurry height. The duration of initial stability increased rapidly with increasing initial density. With the onset of flocculation, and the generation of flocs with sizes and settling velocities orders of magnitude larger than those of individual particles, stability yielded to a period of rapid settling. The rate of rapid settlement was also independent of initial slurry height but increased with decreasing initial density. During rapid settling the rate thereof usually increased slightly as settling proceeded. Subsequent to rapid settling, when a slow and ever-decreasing rate of settlement was observed, shorter beds compressed more quickly than taller beds. Overall patterns of surface settling behaviour were influenced by salinity and initial density; no trends of influence were apparent, but this may have been a consequence of the limited range of conditions studied only.

It is proposed that general patterns of behaviour, and trends with respect to initial slurry density and height, have the following physical basis. The initial period of stability is a consequence of there being a very large number of particles of small mass which, because of their surrounding charged diffuse layers, effectively occupy a large proportion, if not all,

of the space available. Weakly repulsive or attractive interparticle forces create a meta-stable matrix.

The destabilizing force that precipitates collapse is gravity, and it is aided by the presence of attractive electrochemical forces and the existence of a range of particle sizes. Fluctuations in electrochemical forces and differential settling of individual particles cause particles within the meta-stable matrix to vacate lattice points and heterogeneities to develop. Particles gather into flocs of tremendous size with correspondingly large settling velocities. Concomitant with flocculation is the effective release of water into the bulk form, since flocculated particles occupy less average volume per particle than do stable particles. At the end of flocculation the overall permeability is large. Note that as initial slurry density increases, the stability of the meta-stable structure also increases, and results in longer periods of stability. At a sufficiently high initial density a complete matrix is formed upon input: heterogeneities do not develop, bulk water is not generated, and slow settling occurs only.

The meta-stable matrix has negligible strength. Its ability to prevent settling is through the maintenance of homogeneity. The formation of heterogeneities causes non-uniform settling and turbulence. The rate of destabilization is rapid because perikinetic (turbulent) flocculation occurs at a rate to the fourth power more rapidly than does orthokinetic (quiescent) flocculation.

During rapid settling the rate of settlement typically increased slightly. This behaviour may be attributed to the development and/or widening and

straightening of preferred flow paths. This mechanism was suggested by Michaels and Bolger (1962) and is consistent with changes in appearances recorded during RB experiments. The causes of behaviour presented thus far are noted to be independent of slurry height and this is in agreement with the independence of initial period of stability and rate of rapid settlement on slurry height observed in RB experiments.

Rapid settlement ends with the formation of a continuously structured, stable matrix of particles (a bed). Compression continues, of course, as excess pore pressures dissipate, but changes in particle arrangements are comparatively small because of restrictions imposed by interparticle forces and/or physical constraints at low specific volumes. Behaviour is dominated by the compressibility of the newly formed structure and the resistance that it offers to fluid flow. These factors, compressibility and permeability, are cornerstones of consolidation theory. Terzaghi's theory of one-dimensional consolidation predicts that compression rate is inversely proportional to bed thickness (squared). This general trend was observed in RB experiments.

An alternative means of studying height of surface versus time data is in terms of the parameters surface settling rate and average specific volume, the latter being a measure of particle concentration. The usual justification for comparing these parameters is that settling velocity is controlled by hydrodynamic hinderance and that this is, in some way, proportional to particle concentration. The originator of this approach was Kynch (1952) and he proposed the model for systems of large, uniform, solid, rigid, electrochemically neutral spheres. Kynch's model is empirical and it

assumes that all hinderance is hydrodynamic. Structure, which is inherent in flocs, aggregates, and continuous matrices of charged particles, is assumed not to exist.

Graphs of surface settling rate versus average specific volume for RB experiments showed distinct phases: flocculation and the acceleration of flocs; rapid settling and increases in settling rate due to flow path straightening; a maximum settling rate, which sometimes spanned a range of specific volumes; the onset of hydrodynamic hinderance; the severe effects of hinderance on settling rate; aggregation and the transition to consolidation; and the consolidation of a continuously structured bed. The various phases, presented with respect to specific volume, provided a basis on which the influences of salinity, initial slurry density, and initial height, on behaviour could be studied.

Examining the results in this way the independence of surface settling behaviour and initial slurry height was confirmed. Results for experiments with identical initial densities but slightly different salinities produced flocs of similar size but of different density and/or roughness. Results of experiments with a common initial density, but which spanned a range of salinities, displayed large variations in all aspects of behaviour: maximum settling rates varied by an order of magnitude, and the transition specific volume by two units. Clear differences in rate of flocculation, specific volume at the onset of hinderance, and the severity of hinderance phenomena, were also observed. The analysis of results of experiments of similar salinity but different initial density showed that the influence of initial slurry density on behaviour was also significant and extensive.

The analysis of surface settling data in terms of surface settlement rate and average specific volume allowed differences in overall behaviour (h_s vs. t) to be divided into one or more phases of activity. Each phase could then be associated with a particular type or state of structure - flocs, aggregates, or a continuous bed. The results reinforced the fact that structure does not begin with the onset of effective stress. Structure arises as soon as two particles come together and it influences behaviour from that moment onwards.

The analysis also revealed that models which assume a unique relationship between settling velocity and average specific volume, for example Kynch's theory of hindered settling, are not applicable to flocculated slurries. The reason for this is that, in contrast to the inert particles modelled by Kynch the primary settling unit in flocculated slurries is the floc, and it is altered by collisions and shear forces during settling.

The transition from settling to consolidation in flocculated slurries is brought about by the aggregation of flocs to form a continuously structured bed. Aggregation occurs by degrees over a range of (decreasing) specific volumes. The position and bounds of the range are controlled by floc characteristics and fluid shear forces. Because both of these factors are sensitive to slurry conditions, there is not a universal point at which structural continuity arises and effective stresses begin.

Analyses which use height of surface data to represent the behaviour of an entire slurry are adequate only as long as the surface simply and directly reflects the behaviour of the mass of sediment beneath it. It is, in

addition, assumed that the bulk of the sediment behaves monolithically. If significant local variations in conditions occur within a slurry, then the behaviour observed at the surface may be unintelligible, and thus beyond modelling and prediction. Compression models based on surface behaviour, such as Kynch's theory and derivations thereof, which assume that sediment compresses in the form of uniform blocks, are inaccurate in some instances because this assumption is an unrealistic simplification of actual sediment distribution patterns.

The study of hundreds of density profiles recorded for RB experiments disclosed the following general observations: (a) the period of initial stability of the surface reflects genuinely internal stability, (b) rapid settlement of the surface is accompanied by the growth of a dense basal layer, (c) during rapid settlement dilution of the slurry to less than the input density may occur, (d) the density of sediment near the slurry surface varies with height rapidly and the passage of time slowly, (e) density inversions within deposits are common, and (f) after long durations density increases monotonically with depth.

A physical interpretation of several of these observations is possible. The simultaneous development of a dense layer at the base of a slurry and settlement of the sediment surface suggests that fluid expelled at the base is readily passed through the entire height of a slurry and, therefore that the bulk slurry density is large. This conclusion is consistent with the presence of channels observed during rapid settling. Dilution of the slurry is the result of differential settling, wherein large and/or dense flocs settle rapidly leaving behind a region of smaller flocs with a reduced

average density. A rapid spatial variation in density near the surface of beds settled from slurries of low initial density, is the result of particle bridges caused by attractive interparticle forces, and a decrease in overburden stress towards the sediment surface. Attractive electrochemical forces are also responsible for slow decreases in surface specific volume with the passage of time. A uniformly increasing density with depth after long durations is merely a reflection of the distribution of effective stress after excess pore pressures have dissipated.

It is proposed that density inversions arise because of vertical non-uniformities in permeability within a slurry. A region of low permeability overlying one of high permeability acts as a 'cap' on the latter. Settling separates the lower layer into a high density base and an overlying region of reduced density where water expelled from beneath is prevented by the cap from being expelled from the bed. The resulting overall pattern is a sequence of high-low-high density. The mechanism that produces variations in permeability may be related to the history and distribution of channels during rapid settling.

Density profiles are amenable to quantitative study. They may be discretized into layers and the behaviour of these studied in a manner similar to that for entire columns. Further, density profiles may be discretized into elements and the behaviour of individual soil elements compiled to form a comprehensive time-height-density record of compression. This form of presentation allows the evolution of density anomalies to be traced and the influence of such features on the behaviour of neighbouring elements to be observed.

Density history graphs contain information about element settlement rates. By studying the behaviour of soil elements directly assumptions about sediment surface - sediment bulk continuity are eliminated. The analysis of element settlement rate versus local specific volume data for two RB experiments revealed that during the hindered settling phase, the settlement rate of elements at any given specific volume varies with the position of the elements within a column: elements higher in a column typically settled more rapidly than those lower down. Higher settling velocities imply greater floc sizes and/or densities, or a smaller degree of hydrodynamic hinderance.

Density profiles provide both qualitative and quantitative insight into the distribution and redistribution of mass within a slurry, with respect to height and time. Patterns occur commonly which are inconsistent with those assumed in surface settling models.

With the onset of structural continuity, external support from boundaries may be transmitted throughout a slurry. This condition, the onset of effective stress, renders models which assume that behaviour is governed by hydrodynamic phenomena only invalid. Particle-fluid interactions which control settling yield to a growing influence of particle-particle interactions, manifested as bed compressibility, which control the magnitude of compression. However, particle-fluid interactions remain relevant as long as hydraulic gradients exist because these control compression rate.

In RB experiments effective stress versus specific volume data showed that at low stress levels (0 to approximately 0.1 kPa) and high specific volumes

(10 to 26) compressibility was both large and variable. In physical terms, this behaviour suggests a weak, poorly ordered structure, a credible state for a bed formed by the aggregation of charged flocs in a turbulent environment.

At low but constant effective stress levels, the specific volume of elements decreased with the passage of time. This behaviour is attributable to attractive electrochemical forces, the presence of which is not revealed in either of the macroscopic parameters, pore pressure and total stress, and the action of which draws particles together, decreasing specific volume.

At effective stress levels above approximately 0.1 kPa the parameters effective stress and specific volume were related closely under all conditions and at all times. The relationship was one of monotonically decreasing specific volume with increasing effective stress. The influences of pore fluid salinity and initial slurry density were observed to be small and irregular, hence the compressibility results for six different sets of experiment conditions could be represented satisfactorily by a single average curve about which representative compressibility curves for each condition varied by less than ± 0.5 of a specific volume unit.

Increasing effective stress level was observed to reduce the significance of attractive electrochemical forces. For example, compression at constant effective stress was observed to diminish to none as effective stress level increased.

A superior example of the diminution of influence of attractive electrochemical forces with increasing compression, are the contrasting observations of salinity-sensitive settling behaviour and salinity-insensitive compressibility. Salinity influences settling behaviour strongly, through the sequence, attractive electrochemical forces → floc size → settling rate, whilst the magnitude of attractive forces is of the order of other forces (such as fluid shear) within the system, and the sphere of influence extends to a few neighbouring particles. With the creation of structural continuity and the dissipation of excess pore pressures, however, particles come under the influence of all overlying particles. The cumulative effect generates very large forces, and attractive forces are, in comparison, minute, and may, therefore, be incapable of exerting a significant influence on behaviour. In RB experiments changes in pore fluid salinity produced a wide range of settling rates and settling-to-consolidation transition specific volumes, but once a continuous bed had formed, the compressibility thereof was well-defined and nearly independent of experiment conditions. Been (1980) noticed that variations in compressibility curves for different experiment conditions decreased as the level of effective stress increased.

Consolidation behaviour is controlled by compressibility and permeability. Permeability is controlled in turn by the size, shape, and distribution of void spaces which, in a two phase system, are dictated by the arrangement of solids. Permeability is defined as the proportionality constant in Darcy's law, and Darcy's law is a common relationship in consolidation models. Results of RB experiments showed that, in general, permeability increased with increasing specific volume but that at specific volumes greater than

approximately seven, settling velocity and hydraulic gradient were neither linearly or uniquely related. The degree of departure from Darcy's Law increased with increasing specific volume and hydraulic gradient.

These results and their trend have a logical physical basis: permeability is controlled by fabric, and fabric by the balance of interparticle and fluid shear forces. As hydraulic gradient increases, fluid shear forces increase, effective stresses decrease, and the potential for particles to rearrange themselves, so as to increase permeability, increases. Structural changes within a settled bed due to hydraulic forces are analogous to changes in floc characteristics during settling. The process is the reverse of that when flocs aggregate and aggregates link to form a continuous structure, as fluid shear forces and their disruptive effects diminish. One consequence of structural changes induced by fluid flow is, however, that Darcy's law, which states that permeability is independent of hydraulic gradient, is invalid, and models which involve the law are incorrect for weakly structured beds subject to large hydraulic gradients. A stable arrangement of particles is a necessary condition for Darcy's law to be valid.

The present research included an attempt to study particle arrangements within settled beds, in search of relationships between compression behaviour, shear strength, material properties (such as permeability), and particle orientations. The programme of fabric study did not come to fruition because of the manifold difficult problems that have to be overcome to prepare a sample of soft, sensitive, fine-grained soil for examination.

Vane shear strength tests were performed in 12 RB experiments spanning a range of initial densities, salinities, and experiment durations. Tests were performed in situ and without altering stress conditions. Peak and residual shear strengths were measured and compared with effective stress, specific volume, and sensitivity values.

The vane tests revealed a linear relationship between peak shear strength and effective stress under all conditions. Extrapolations of the data suggested the existence of a small amount of shear strength at zero effective stress (true cohesion). Peak shear strength was observed to increase with the passage of time at all effective stress levels, though the rate of increase was, in general, slower at higher stress levels. Pore fluid salinity influenced peak shear strength, with low salinity conditions producing stronger beds than more saline conditions, at comparable effective stress levels or specific volumes. Initial slurry density displayed only a very slight and irregular influence on peak strength-effective stress relationships.

Residual shear strength results showed a greater degree of scatter than peak strength results because of the lower range of strengths involved. Nevertheless, residual strength data showed an increase in strength with increasing effective stress, a very small amount of true cohesion, and conflicting trends with respect to the influence of time. As was noted in peak shear strength results, residual shear strength values were higher in low salinity beds at comparable stress levels. However, an effect due to initial slurry density reversed this trend in beds of initially low density.

Substantial variations in the sensitivity quotient (s_{u_p}/s_{u_r}) were observed because of variations in residual shear strength values. Values of sensitivity varied between 3.5 and 8 and individual values were dependent on experimental conditions, both initial slurry density and salinity, in an irregular way. Sensitivity was independent of both the passage of time and level of effective stress.

Specific volume versus the logarithm of peak shear strength data for RB experiments displayed well-defined linear relationships. At any given specific volume, peak shear strength increased with the passage of time, and time-related effects were more significant at higher effective stress/shear strength levels. Both salinity and initial density displayed an influence on peak shear strength versus specific volume results.

The shear strength results recorded may be explained in terms of a modified frictional soil model in which shear strength is linearly proportional to stress and the effect of electrochemical forces is recognized. Shear strength at zero effective stress, and time-dependent increases in peak shear strength, are attributable to electrochemical forces and increases therein, which do not contribute to the parameter effective stress, but which do generate an 'intrinsic' stress that gives rise to shear strength.

For any given set of conditions, the specific volume of an element of soil at equilibrium is dictated by interparticle forces. At all but very low stress levels interparticle forces are predominantly repulsive, and behaviour can be represented adequately by the parameter effective stress: well-defined specific volume versus effective stress relationships were

observed in RB experiments (section 5.1). When an element of soil behaves as a frictional material, then shear strength and effective stress will be uniquely related also. Materials with these two characteristics, of which Combwich 7 is an example, display a unique relationship between specific volume and peak shear strength. The relationship is dependent on experiment conditions, viz. initial slurry density and salinity, and/or time, if these factors affect either the strength or the specific volume attained at any given effective stress. Note that a unique relationship between peak shear strength and specific volume may not be observed if any of the following conditions occur: segregation; compression at constant effective stress; or large variations in fabric.

8.2 Conceptual Models of Slurry Compression

In this section a conceptual model which is often used in chemistry to describe the stability of colloidal suspensions is introduced and then used to explain phases of slurry behaviour viz. initial stability, flocculation (rapid settling), and consolidation, and the factors that determine rates of activity. The basic model is one-dimensional in space and relates interparticle forces (expressed in terms of net potential energy of interaction) to particle separation distance. It discloses a potential cause of compression at constant, low effective stress levels.

The basic model is then extended to include the influence of particle orientations. This development renders the model more representative of natural slurries composed of anisotropic particles. Furthermore, the extended model reveals a mechanism for compression at constant, high

effective stress levels. Both the basic and the extended models are used to describe slurry behaviour observed in experiments by the author, Elder (1985), Sills and Thomas (1983), and others.

There is a need for an alternative perspective within geotechnical engineering for the problem of modelling the compression behaviour of natural flocculated slurries. There are several reasons why existing models for settling and consolidation are inadequate. Traditional hindered settling models assume that the units which settle have fixed characteristics and that all interactions are hydrodynamic. In flocculated slurries, floc characteristics vary during the process of settling as hydraulic gradients and fluid shear forces vary, and, at non-dilute slurry densities, inter-floc forces which are clearly not hydrodynamic, cause aggregation, and this affects behaviour. Imai (1981) states clearly five important differences that exist between Kynch's model and the behaviour of clay-water slurries.

On the other hand, consolidation models assume that unique compressibility and permeability relationships can be specified for a slurry. For natural flocculated slurries a compressibility relationship cannot be defined for conditions of low effective stress and high specific volume because the material is weak, highly compressible, and poorly ordered; it displays a highly variable response to stress. Imai (1981) in an experimental study of sedimentation mechanisms and sediment formation of clay materials concluded that for any given clay material countless compression curves may exist under low effective stresses, depending on initial slurry density. Attractive forces may, in addition, cause compression at constant effective

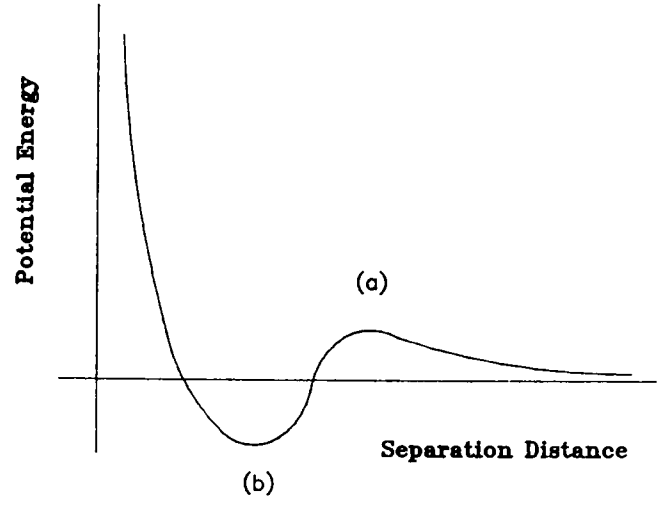
stress which invalidates the ideas that compression is controlled entirely by the dissipation of excess pore pressures and that a unique time-independent compressibility curve exists. A unique permeability relationship cannot be defined for even moderately high specific volumes because at and above these, Darcy's law is invalid. Finally, even if it were possible to propose satisfactory settling and consolidation models for flocculated slurries, the need to link these at some point, such as the onset of effective stress, would remain. As has been shown by the author, Elder (1985), Imai (1981), Been (1980), and others, this 'point' is in fact a zone of increasing aggregation, and the zone is highly sensitive to experiment conditions.

An alternative model for the compression behaviour of natural flocculated slurries is thus in order. It follows from results reported in earlier chapters that the model should include interparticle forces, slurry density (or particle spacing), and fabric (mutual particle orientations), and it is preferred that the model describe the complete compression process without any sort of partition. Basic and extended models satisfying these requirements are proposed below.

Figure 8.1 shows a typical example of a potential energy of interaction (PEI) curve. It is impossible to define quantitative curves for all but the simplest of particle types, and PEI curves are almost always used as qualitative descriptors of behaviour. Natural slurries can be portrayed qualitatively only, as is done below. The basic model relates the potential energy of interaction (PEI) between two charged particles of fixed mutual orientation, at a range of particle spacings. The curve which describes the

energy-distance relationship is determined by summing all of the electrochemical forces that may act between two particles. The origins of the two types of attractive and four types of repulsive forces possible are described in subsection 2.2.3. The magnitude of each force is determined by pore fluid composition, mineralogy, crystallography, particle orientation and so on but, for a given set of conditions and particle orientations, the net force between two particles varies with distance only.

Figure 8.1
Basic Potential Energy of Interaction Model



The principle that governs the behaviour of particles is that they seek to minimize their potential energy. The potential energy of interaction of two particles separated by an infinite distance is zero, as is implied by the curve shown in Figure 8.1. As particles approach one another, net repulsive forces cause an increase in the potential energy between them. Point (a) is termed an energy barrier because it prevents particles from approaching one another without the input of energy from external sources. The energy barrier is responsible for the initial period of stability observed in RB experiments. In colloidal systems composed of particles of small mass, particles vibrate about their input separation distance because of thermal energy. In natural slurries, particles are forced by gravity and/or fluid shear forces (turbulence) to separation distances less than the input

spacing. The relative magnitudes of the energy curve gradient up to point (a) and external forces determine the duration of stability. It is difficult for natural slurries composed of large particles to remain stable at large specific volumes for long periods of time because of gravity. On the other hand, emulsions such as paints are extremely stable because the relative density of their constituents is similar to that of the suspending medium and the energy barrier is engineered to be large.

Transient forces, such as turbulence and vibrations, are effective in ending stability; once a particle is 'over' the barrier, it will move spontaneously toward its partner. The motivation for doing this is the opportunity to effect a decrease in potential energy. The result is manifested as flocculation. The gradient between points (a) and (b) is the magnitude of the attractive force between particles. The distance between points (a) and (b) is proportional to the amount of water liberated by flocculation to become bulk water. When the gradient and change in spacing are both small then flocculation proceeds slowly, weak flocs are produced, settlement occurs slowly, and the period of 'rapid' settlement is short or even non-existent.

Once particles have attained point (b) their potential energy of interaction is at a minimum and an input of energy or a force is required to cause any change in position (particle spacing). The changes in slope of the curve to the left and to the right of of this point determine the moduli of compression and extension respectively. The PEI curve at distances smaller than point (b) is, in one dimension, analogous to traditional soil mechanics compressibility curves of effective stress versus specific volume in three

dimensions. At point (b) effective stresses are just zero: at smaller spacings support from a boundary is transmitted through a slurry by repulsive forces. Theoretical PEI curves for close separation distances are always steeply inclined and concave-up, which implies, first, that very large forces (relative to those required to cause flocculation) are required to cause compression and, second, compressibility decreases with decreasing particle spacing. These trends mirror familiar soil behaviour and strengthen the credibility of PEI diagrams, which are based on theoretical calculations of interparticle forces, as being correct models of compression behaviour. The force that moves particles within natural slurries to less than the potential energy minimum is gravity in the form of overburden stress.

The gradient between points (a) and (b) is the attractive force between particles. The energy difference between (a) and (b) is the work required to separate completely two particles resting at the potential energy minimum spacing. The force most often responsible for separating particles in slurries or settled beds is fluid shear. When it acts on the surface of a settling floc or along the surface of a settled bed, the relative magnitudes of the shear force and the gradient (a) to (b), determine whether or not flocs are broken down, or a settled bed is eroded.

Whereas PEI curves represent the behaviour of two particles only, real slurries do, of course, consist of vast numbers of particles and each particle within the slurry reacts simultaneously with its many neighbours. Physical factors such as viscosity, inertia, and particle interlocking should be considered because these cause particles to behave less ideally

than the instantaneous, perfectly elastic behaviour implicit in PEI diagrams.

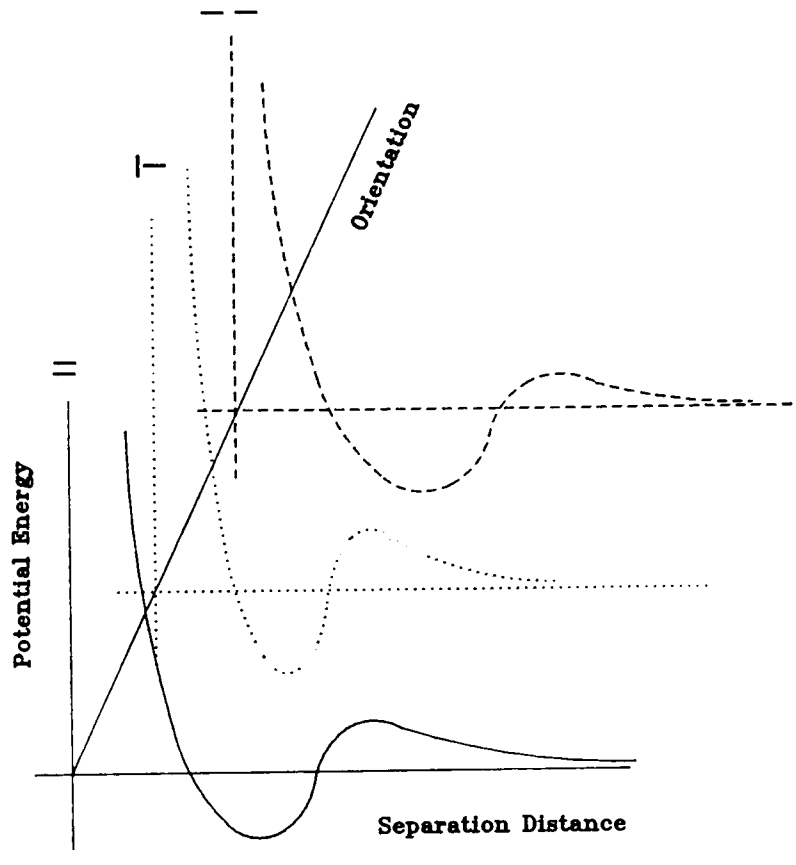
Non-ideal slurry behaviour tends to prevent particles attaining the potential energy minimum immediately, so that particles will be deposited at separation distances greater than that at point (b). Particles at spacings between points (a) and (b) are less stable energetically than particles at the spacing of the energy minimum, hence the former will, if possible, progress towards closer spacings. Changes in fluid forces, vibrations, and structural adjustments are mechanisms which permit attractive forces to effect a decrease in particle spacing (specific volume) with the passage of time. This model of compression is most applicable to particles at the sediment surface where effective stresses are zero. Slurries at low effective stress levels, which are on average repulsive, may also display time-dependent compression because in any given system of particles there will be a proportion of particles that are attractive.

Two conclusions follow logically from these arguments. First, as time elapses, and more particles achieve the potential energy minimum, the rate of compression at constant effective stress should diminish; this trend is consistent with that observed during secondary consolidation. Second, compression at constant effective stress should be more prominent at low than at high effective stress levels; this pattern was observed in RB experiments.

The basic model presented describes successfully the phases of activity commonly observed in slurry compression experiments. The theoretical basis

of PEI curves is sound. By taking into consideration characteristics of real systems, the model describes plausibly the cause of compression at constant low effective stress levels. The factor particle orientation shall now be introduced. With the inclusion of this factor, known from RB experiments to be relevant to compression behaviour, and with the repetition of ideas presented above, a basis for compression at constant high effective stress is disclosed.

Figure 8.2
Extended Potential Energy of Interaction Model



An extended PEI model is shown in Figure 8.2. The single PEI curve discussed previously will vary in form as the mutual orientation of two anisotropic particles is changed. Yong and Wagh (1985) present PEI diagrams for pairs of clay minerals at different orientations. Three possible interaction curves are shown in Figure 8.2; the sum of interaction curves for an infinite number of orientations generates an interaction surface in potential energy - separation distance - orientation space (ψ-δ-θ space).

The surface is non-uniform but continuous and it possesses one potential energy minimum (or well) corresponding to a particular separation distance and orientation. Local minima may exist, but these will be omitted here for simplicity. In the extended model the restriction of fixed particle orientation imposed in the basic model is removed. The principle which governs the behaviour of particles in ψ-δ-θ space remains unchanged; particles seek to minimize their potential energy.

The orientation of two particles pumped rapidly into a settling column may be assumed to be random initially, and separation distance will be set by the initial slurry density. If the particles are infinitely free to change their orientation and separation distance then they will move along the interaction surface in the direction of the maximum decreasing potential energy gradient or the minimum increasing potential energy gradient, depending on the local topography. Non-uniformity of the interaction surface, will cause particles to change orientation during compression. As was discussed earlier, non-ideal behaviour of real slurries will tend to prevent particles attaining the conditions of the potential energy well immediately and compression at constant low effective stress may, as a consequence, occur with the passage of time.

Particles not near the sediment surface will be subjected to overburden stresses and these will be resisted by particle-particle repulsion forces. In this state, particles will not move closer spontaneously at a fixed orientation because the outcome is an increase in potential energy. Particles may, however, achieve a momentary decrease in potential energy by changing orientation towards a less energetic orientation at a closer

spacing. The decrease is only momentary because load which is shed onto the pore fluid by a small change in particle orientation and spacing is returned to the particles as soon as excess pore pressures dissipate. Thus, by a succession of small-scale particle reorientations, the spacing between particles subject to constant large effective stresses, may decrease with the passage of time. The extent of the decrease at constant effective stress will depend on two factors: the curvature of the interaction surface at constant values of potential energy, and the orientation of particles with respect to the orientation of the minimum separation distance for a given potential energy.

If one assumes that the distribution of particle orientations in a slurry is random initially, then one might predict that slurries which are permitted to settle freely after input will possess a higher number of particles with energetically stable orientations, than slurries which do not settle freely. All other factors being equal, initially dense (restricted) slurries should, therefore, display greater amounts of compression at constant effective stress. This conclusion is a possible explanation of the vast differences in compression behaviour at constant effective stress observed in RB experiments and in experiments performed by Elder. All of these experiments were carried out with Combwich mud and yet Elder's experiments, initiated at densities typically above 1.2 Mg m^{-3}, displayed changes in specific volume of up to four units at constant effective stress whilst the author's experiments, initiated at lower initial densities (1.047 to 1.16 Mg m^{-3}) displayed negligible compression at constant effective stress. Different particle size distributions for Combwich 6 and 7 (see section 4.2) is another possible cause of differences in behaviour.

The extended model also suggests a conclusion relating to rigidity. As an increasing number of particles move to lower potential energies or smaller separation distances at the same potential energy, the rate of change of the gradient of the interaction surface in the direction of decreasing separation distance increases: this term is rigidity, and the implication is that it may increase with the passage of time. Locat and Lefebvre (1982) studied the compressibility of natural sediments deposited artificially, and observed that the response of settled beds became stiffer with the passage of time. In RB experiments no increase in rigidity was observed, but neither was compression at constant effective stress.

Using arguments given above, it may be postulated that slurries deposited at low density (under relatively free conditions) should form beds of greater rigidity than ones deposited from initially dense slurries. Experiments at Oxford by Thomas (Sills and Thomas, 1983) using Combwich mud demonstrated this behaviour; specifically, slurries input continuously at very low densities formed beds resistant to compression, whilst beds deposited rapidly were less resistant. Experiments by Einsele et al. (1974), involving beds of settled kaolinite, showed a similar response.

Both the basic and extended potential energy of interaction models presented are excellent for the purpose of illustrating the potential causes of behaviour in flocculated slurries. The models are, however, less useful as tools for prediction. The models are, at present, qualitative: only very recently have semi-quantitative PEI curves for systems of two uniform size, monomineralic particles been published. Second, the models describe compressibility and not compression behaviour, where the latter involves the

dimension of time. Thus a supplementary relationship, equivalent to permeability in consolidation theory, is needed to define the rates of activities which the models describe. Third, the models are very much idealizations, even though they recognize some aspects of real slurry behaviour: the interactions of two, versus that of very many particles are represented; no account is (nor can readily be) made of the large number of different interaction surfaces associated with a broadly graded, heteromineralic natural slurry; and inertia, viscosity, and the presence of uncharged particles, are all neglected. Finally, in contrast to traditional settling models which do not include electrochemical forces, potential energy of interaction models do not include explicitly the forces of gravity and fluid shear.

The models are, nevertheless, worthy. The basic model is a fundamental one within colloid chemistry, and it is founded on established theory. The elements of the basic and extended models viz. potential energy, particle separation distance, and particle orientation, are known through experimental research involving related factors viz. interparticle forces (pore fluid salinity) and initial density, to be factors that genuinely influence the behaviour of natural flocculated slurries. The models describe and suggest behaviour that is observed experimentally. The models describe the entire process of slurry compression - settling and consolidation - and both models describe and explain behaviour that traditional models do not.

8.3 The Present Research and Engineering Practice

What relevance have the conceptual models to practice? They provide a basis for interpreting the influence of factors such as salinity and initial slurry density on behaviour. For example, if the objective of a particular engineering application is to decrease the duration of the period of initial stability, then the models suggest that increasing pore fluid salinity, so as to decrease the height of the energy barrier, will be beneficial. Further, by causing mild turbulence after input, and maximizing the breadth of the particle size distribution, flocculation will tend to be initiated more rapidly. Finally, if the slurry is input at low enough initial density, insufficient material will be present to establish a meta-stable repulsive matrix, and no period of initial stability will be observed.

If, as another example, the objective sought is to maximize the rate of settlement then pore fluid salinity should be varied so as to achieve the following: maximize the distance between the energy barrier and the potential energy well, so that the volume of bulk water released is maximized; minimize the particle separation distance at the energy well, to achieve maximum floc density; and, maximize the energy gradient between the energy barrier and the potential energy well, because this represents the attractive force between particles, and it affects floc size. The effects of varying salinity and initial density on PEI curves can be estimated theoretically for very simple systems, whilst in natural slurries, indications of the effects can be gained from analyses such as Michaels and Bolger, from studying slurry appearance, and from analyzing settling data in terms of surface settling rate versus average specific volume.

These two examples show that the present function of the proposed conceptual models is that of qualitative guide, and the assumed solution approach is one of trial and error. In light of the complexity of natural slurries and the manifold microscopic particle-particle and particle-fluid interactions and structural changes that occur during compression, there are grounds for believing that an adequate practical theoretical model for compression behaviour (and shear strength) of flocculated slurries might never be developed or, at least, that empiricism will be an unavoidable component of modelling for some time to come.

In recognition of this fact, the experiments reported in this thesis were undertaken to assess the influence of four factors (ρ_i, C_s, h_{s_i}, and t) on the compression behaviour of flocculated silty clay slurries. And in addition to searching for a suitable model <u>basis</u>, attention was also given to the best practical <u>form</u> that a model might have. Numerous methods of characterization were explored in Chapter 4.

The outcome of this experimental and analytical work may be summarized tersely: structure is fundamentally important in determining the behaviour of flocculated slurries; the most practical means of characterizing behaviour are in terms of visual appearance, particle size distributions, and height of surface versus time data (plus the derivative $v_s - V$); and several aspects of the behaviour of flocculated slurries are understood most easily from a structural perspective.

The primary contribution of the models and the interpretation of RB experimental results to engineering practice is to recommend a study

perspective. In their wake the author hopes that when, for instance, a variation in salinity causes a change in compression behaviour that the observer asks not, what change has occurred in the specific volume at zero effective stress? but rather, is this change a consequence of structure that is visible (such as channeling)?, or is it due to segregation?, or is a change in floc size or degree of aggregation responsible and detectable on a plot of surface settling rate versus average specific volume? From the answers obtained to questions such as the latter, a rational estimate of the consequences of increasing or decreasing salinity, or changing initial density, should be possible. Structure-behaviour relationships may also be inverted and, as an example, the appearance of supernatant within a tailings pond used to predict the relative rate of settlement, the probability of segregation, and the strength of interparticle forces within an underlying bed.

In the absence of a theoretical model for flocculated slurries, the need to conduct series of experiments to determine, for instance, the optimum conditions for a particular application, or to estimate the compression behaviour and strength of a bed over a range of conditions, is unavoidable. To minimize the effort involved factors which may vary and their ranges of variation, must be specified judiciously. In the case of mine tailings disposal, the operator usually has control over two factors, initial density and rate of slurry input. The same factors are relevant to sedimentation in harbours. Once factors and bounds of variation have been established, the influence of each factor on compression behaviour and/or shear strength can be studied systematically, in the field if possible, and from a structural perspective.

Research reported by Imai (1980, 1981) demonstrates this approach. Imai (1980) studied the influence of initial slurry density and pore fluid salinity on the behaviour of flocculated slurries of kaolinite, bentonite and three natural muds. Using three visual and one measured characteristics - slurry texture, supernatant clarity, presence of flow paths, and degree of segregation - Imai divided settling into four classes of behaviour viz. dispersed free settling, flocculated free settling, zone settling, and consolidation settling. Each class represents a different degree of flocculation and degree of mutual interaction. Imai applied his classification scheme to results of experiments varying in salinity and initial density in order to generate a behavioural chart from which the behaviour of slurries with conditions either intermediate or slightly extraneous to those tested, may be predicted. By studying patterns within behavioural charts for different minerals, Imai related trends of influence of salinity and initial density to plasticity index.

The recommended method of studying and classifying flocculated slurries is not elegant, rather it is practical and it is the best method available at the present time. It permits patterns of behaviour to be identified, and durations of phases and rates of compression to be estimated qualitatively. Detailed testing is required to quantify behaviour.

To illustrate how the knowledge gained from series of self-weight slurry compression experiments may be applied to engineering designs and procedures, the results of RB experiments are, in the following section, applied to the engineering problems of sediment accumulation in harbours, marine sediment stability, and mine tailings disposal, presented in

Chapter 2. It is assumed that results recorded in the laboratory represent behaviour in the field: field validation of behaviour observed in the laboratory is a seriously neglected area of soft soil research.

8.4 Application of RB Experiment Results to Engineering Problems

Section 2.1 begins with an overview of the problem of sediment deposition in harbours and it includes discussions on prevention, maintenance, and identification. Two forms of maintenance are dispersion and dredging. The primary factor governing the capacity of dispersive systems, such as aerators and turbulence devices, is the shear strength of sediment to be dispersed and, in particular, strength variation with depth and time. Results of RB experiments suggest that, for a given set of conditions, shear strength increases with the passage of time, increases with increasing effective stress, and is uniquely related to specific volume. To avoid the development of strength in excess of the capacity of a system, sediment should be dispersed frequently, so as to eliminate time-dependent bonding and to prevent the build up of effective stresses and shear strength. The observed relationship between the logarithm of peak shear strength and specific volume can be applied in conjunction with a density probe profile and an estimate of the time elapsed since deposition, to determine the effort required to disperse sediment. The same s_{u_p} - V relationship is useful for planning dredging: the maximum permissible shear strength may be related to a unique specific volume at a given time, and the altitude of that specific volume determined by density probe surveys.

The erosion resistance of fine-grained beds, as it relates to the stability of contaminated sediments, was not investigated directly in the present programme, but because shear strength and erosion are commonly believed to be related the results of RB experiments are relevant. The experimental results suggest that the surface of a settled bed of Combwich mud possesses a small amount of cohesion and that cohesion increases with the passage of time. The results also suggest that depositional environment is important, since both initial density and salinity were observed to influence cohesion.

In regards to mine tailings disposal, the most cost-effective method is the one which deposits sediment at the highest density and highest angle of repose thereby maximizing the volume of sediment contained within a given length of embankment. Results presented in Figures 5.10 and 7.4 show that the most favourable input conditions for Combwich 7 are those of low initial density and low salinity, since these conditions yield the best combination of low specific volume and high shear strength, at any given effective stress.

8.5 Contribution of the Present Research

The main contributions of the present research are the exposition of soft soil behaviour through experimental results, and the interpretation of these: collectively, these products advance the experience with and understanding of the compression behaviour and shear strength characteristics of natural flocculated slurries compressed by self-weight. This knowledge is valuable in an area of research in which the development of theoretical models has outpaced supporting experimental work.

The results disclose that there are fundamental and practical problems with the application of traditional models to flocculated slurries. The need for a different perspective has been demonstrated and alternative conceptual models of slurry compression have been presented. The primary difference between traditional settling and consolidation models and the actual behaviour of natural silty clay slurries is the influence of interparticle forces and particle arrangements, and structural changes during compression. These factors have been revealed through the interpretation of behaviour, and they form the basis of the conceptual models presented. The models are useful as illustrators and as guides.

The relevance of four factors viz. initial slurry density, initial slurry height, pore fluid salinity, and the passage of time, on the compression behaviour and shear strength of natural mud slurries has been investigated and relationships between effective stress, specific volume, and shear strength established. Of equal importance, relationships between surface settlement rate and average specific volume have been shown to be non-unique, and Darcy's law proven to be invalid at large specific volumes. Patterns of change in slurry appearance, the redistribution of mass during compression, particle segregation, and height of surface versus time data, have all been exposed and explained.

A practical approach to the classification of compression behaviour of flocculated slurries, as an aid to predicting behaviour and/or determining optimum conditions for a particular application has been presented. Results of laboratory self-weight slurry compression experiments have been applied to engineering problems.

The foundations for future fabric-related studies have been laid: the research has produced a small-scale sampler and technical knowledge relating to the impregnation, sectioning, and analysis of Combwich sediment. The development of a new pore pressure instrument and the modification of shear vane test apparatus has advanced the scope and accuracy of the tools available for carrying out laboratory-based soft soil research: in a research area which is underdeveloped experimentally, these contributions are significant.

The research programme had five objectives, all of which were attained. Recommendations for future research are stated in the following section.

8.6 Recommendations for Future Research

The ultimate objective of the soft soil programme at Oxford remains unfulfilled: a simple, practical, predictive model of the compression behaviour of, and the shear strength development within slurries of natural silty clay is wanting. Several avenues of research directed towards achieving this objective may be proposed. The paths include fundamental, experimental, and field based research, and their aim is to reveal relationships between behaviour and structure within flocculated slurries.

In regards to the extended conceptual model presented, research into interaction energies of clay minerals, effects due to multiple interactions, non-ideal behaviour, systems with broadly-graded size distributions, and so on, is required to develop the proposed model into one that is practical and

applicable to natural slurries. The role of particle orientation in time-dependent compression requires verification. The knowledge and instruments required to carry out this research are specialized and in the domain of the colloid and surface chemist predominantly.

Methods of analyzing settling results of flocculated slurry experiments, as proposed by Michaels and Bolger (1962), might be applied to investigate slurry structure characteristics. Michaels and Bolger used their methods to interpret successfully the behaviour of narrowly-graded suspensions of treated kaolin, and it remains to be proven whether the same might be done for broadly-graded mud slurries. As noted in subsection 4.3.2, their methods require results from extensive series of tests.

During the compression of flocculated slurries, gravitational, hydrodynamic, and electrochemical forces produce a succession of structures - flocs, aggregates, and a continuously structured bed - which determine behaviour. The arrangement of particles affects slurry characteristics, such as floc density, degree of aggregation, and permeability of settled beds, at different stages of compression. Behaviour rate is influenced largely by fabric. The fabric-related research begun in this thesis should be continued, and extended to include the pre-depositional period. To pursue the latter, means would have to be developed to arrest discontinuously structured slurries. This might be achieved by suspending particles in a resin fluid, duplicating classes of behaviour observed in water-based slurries, and then effecting rapid polymerisation at different stages. The analysis of thin-sections would reveal the distribution of floc sizes, floc architecture, extent of aggregation, and so on. This avenue of research

would help to establish behaviour-structure relationships prior to the onset of structural continuity.

With the onset of structural continuity the possibility arises of using pulse shearometry, to characterize structure. The justification for adopting rheological methods is that at the very low stress levels associated with sediments deposited recently or buried shallowly, the parameter effective stress, which is used to define compressibility and is often related to shear strength, is less than adequate because, first, small effective stresses are difficult to measure accurately and, second, attractive electrochemical forces which are not accounted for by this parameter, may be the dominant determinant of behaviour. A more sensitive and more comprehensive measure of interparticle forces at low effective stresses is needed.

Rigidity is one indicator of structural strength, and in continuously structured slurries it may be investigated by measuring the propagation velocity of a pulse shear wave. Pulse shearometry is applicable from the onset of structural continuity through to a time when effective stresses govern behaviour and these can be measured accurately. With careful control of the pulse amplitude, and discrete mounting of pulse transmitters and receivers, the method is both non-destructive and non-intrusive. Changes in rigidity with compression and the passage of time may, therefore, be monitored continually. After sufficient strength has developed within a bed to allow accurate shear strength measurements to be made, strength and rigidity may be correlated. The opportunity then exists to use pulse shearometry to estimate the strength of materials too weak or too dynamic to

be tested with a shear vane, and/or to use shearometry in non-destructive applications. Shearometry is an apt method of studying behaviour-structure relationships after deposition.

Finally, the study of flocculated slurries in the field is an area of soft soil research sorely neglected. Difficult problems with instrumentation and monitoring need to be addressed immediately. Continuing neglect may yield the situation in which laboratory-based research outpaces field research with the same unsatisfactory consequences as that which have arisen due to rapid advances in theoretical modelling without accompanying experimental research.

TERMINOLOGY

Settling Unit	one or more particles which settle as a distinct unit.
Slurry	generic expression for a mixture of solids and fluid.
Suspension	mixture in which solids are supported fully by a suspending fluid, and structure is discontinuous.
Settled Bed	mixture in which solids are partially supported by a suspending fluid, and structure is continuous.
Compression	generic expression for a decrease in specific volume.
Effective Stress	measured difference between total stress and pore water pressure. In this thesis vertical stresses only are considered.
Settling	compression at zero effective stress.
Consolidation	compression at increasing effective stress.
Compression at Constant Effective Stress **Creep Compression** **Time-Dependent Compression**	decrease in specific volume at constant effective stress.
True Cohesion **Cohesion Intercept**	extrapolated shear strength at zero effective stress.
Sensitivity	ratio of peak to residual vane shear strengths.
Structure	a combination of the arrangement of and forces between particles.
Fabric	mutual arrangement of anistropic particles.
Specific Volume	total volume occupied by a unit volume of solids.
Void Ratio	ratio of volume of voids to volume of solids.
Particle Concentration	mass of solids per unit volume.
Density	total mass of material per unit volume.
Monodisperse	single particle size.
Narrowly-graded	small range of particle sizes.
Polydispersed **Broadly-Graded**	large range of particle sizes.
Density Inversion	zone of high density overlying a zone of lower density.
Granulometry	application of a laser-based technique for determining particle size distributions.
Dispersed	all particles independent of one another.
Floc	cluster of particles.
Aggregate	cluster of flocs.
Continuously Structured Bed	system of particles linked by forces and in contact with a boundary.

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Abbreviations:

J. Sed. Pet.	Journal of Sedimentary Petrology
Proc. Eng. Found. Conf. on Floc., Sed. and Cons.	Proceedings of the Engineering Foundations Conference on Flocculation, Sedimentation and Consolidation
Trans. Inst. Chem. Eng.	Transactions of the Institute of Chemical Engineers

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