THE INFLUENCE OF SPATIAL VARIABILITY ON THE GEOTECHNICAL DESIGN PROPERTIES OF A STIFF, OVERCONSOLIDATED CLAY

Mark B. Jaksa
B.E.(Hons), M.I.E.(Aust), CPEng

THESIS SUBMITTED FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

in

The University of Adelaide
(Faculty of Engineering)

December 1995
To my wife Marie,

and my parents Stan and Maria
Preface

The work described in this thesis was undertaken over the period of 7½ years, between February 1988 and October 1995, within the Department of Civil and Environmental Engineering, at the University of Adelaide. Throughout the thesis, all materials, techniques, concepts and conclusions obtained from other sources have been acknowledged in the text. Listed below are those sections of the thesis for which, to the best of his knowledge, the author claims originality, as well as papers which have been published as a direct result of this study.

In Chapter 3:

• the design and development of the hardware of the micro-computer based data acquisition system used for the cone penetration tests. The hardware was designed in collaboration with Mr. Bruce Lucas of the Department of Civil and Environmental Engineering, The University of Adelaide;

• the complete design and development of the computer programs: CPTTest; CPTView; CPTPlot; and CPTPrint, associated with the CPT data acquisition system;

• the data transformation technique of depth rationalisation.

In Chapter 4:

• the measurement of closely-spaced CPT data, both vertically and laterally, to enable the small-scale spatial variability of undrained shear strength to be examined;

• the design, development and implementation of the horizontal cone penetration test performed at the Keswick site. The design and testing was performed in collaboration with undergraduate students Dirk van Holst Pellekaan and Julian Cathro.
In Chapter 5:

- the complete design and development of the computer programs: SemiAuto; CPTSpace; and Monte;
- the association between the correlation distance, the scale of fluctuation, $\delta_v$, and Bartlett’s limits, $r_B$, as well as the development of relationships between $a$, $r_B$ and $\delta_v$;
- recognition of the rebound phenomenon associated with sleeve friction measurements in the Keswick Clay, as well as the use of the cross-correlation function to quantify the shift distance associated with the CPT;
- development of a nested semivariogram model to represent the lateral spatial variation of the undrained shear strength of the Keswick Clay;
- identification of factors which result in inaccuracies with respect to Baecher’s technique for the evaluation of random measurement errors;
- the use of rescaled residuals in the random field theory estimation process;
- the use of random field theory to forecast and simulate geotechnical data;
- the use of geostatistics to estimate and forecast geotechnical data.

In Chapter 6:

- the complete development of KESWICK, the data base of geotechnical properties of the Keswick and Hindmarsh Clays.

In Chapter 7:

- the development of the framework to provide preliminary estimates of the undrained shear strength of the Keswick Clay.

In Chapter 8:

- the complete design and development of the computer program: LCPCSIm;
• the significance of the spatial variability of undrained shear strength in the design of piled foundations;

• the use of geostatistical simulation techniques to generate data to enable the influence of spatial variability of undrained shear strength on the design of piled foundations to be examined.

A list of publications that have been prepared as a result of this research is presented below.


Abstract

The research presented in this thesis focuses on the spatial variability of the Keswick and Hindmarsh Clays within the Adelaide city area. Keswick Clay is locally significant since many of Adelaide’s multi-storey buildings are founded directly on it, and internationally significant, since it has been shown by Cox (1970), that this clay exhibits remarkably similar properties to those of the well-documented London Clay.

The assessment of the small-scale variability of the undrained shear strength of these clays is based on measurements obtained using the electrical cone penetration test (CPT), and a micro-computer based data acquisition system, designed specifically for this study. A significant feature of the data acquisition system is that it enables measurements to be obtained at intervals of 5 mm, both reliably and efficiently. The development of the data acquisition system is discussed, and the accuracy of its measurements is examined. The small-scale variability of the undrained shear strength of the Keswick Clay is based on more than 200 vertical CPTs, performed within an area of 50 × 50 metres at a site located in the Adelaide city area. The CPTs were spaced at lateral intervals varying between 0.5 and 5 metres, with each vertical CPT extending to a typical depth of 5 metres. In addition, the small-scale horizontal spatial variability of the Keswick Clay is examined using an electrical cone penetrometer driven horizontally into the face of an embankment, again located within the Adelaide city area. The accuracy of the CPT measurements is examined, and discussion is given of the shortcomings associated with a commonly used technique, by Baecher (1982), for estimating the random measurement error associated with various test procedures.

The assessment of the large-scale spatial variability of the undrained shear strength of the Keswick and Hindmarsh Clays is founded on a data base of geotechnical engineering properties, compiled from a number of consulting engineering practices and government instrumentalities. The data base, known as KESWICK, contains approximately 160 site investigations, 380 boreholes, and 10,140 measurements obtained from a number of different laboratory and in situ tests. In addition, KESWICK is used to establish generalised
Abstract

v
trends and bounds, associated with the various geotechnical engineering design properties contained within the data base.

The techniques of random field theory and geostatistics are used to quantify, model and predict the spatial variability of the Keswick and Hindmarsh Clays. These techniques are compared with one another in order to assess the suitability and shortcomings of each, when applied to the study of the spatial variability of geotechnical engineering materials. Furthermore, a number of specifically-written computer programs, which were developed to enable the various spatial variability analyses to be performed, are discussed. It is demonstrated that the lateral undrained shear strength of the Keswick Clay, within the Adelaide city area, exhibits a nested structure; that is, one which is the compound effect of several genetic sources of spatial variation. In addition, it is shown that this nested structure can be adequately modelled by means of a spherical semivariogram model.

The nested structure is used, together with the kriging estimation process, to provide preliminary estimates of the undrained shear strength of the Keswick Clay, within the Adelaide city area. The analyses demonstrate that the nested model and the kriging process provide a useful facility for generating preliminary estimates of the strength of the clay.

Finally, the significance of the spatial variability of the undrained shear strength of clay soils is examined, with reference to the design of embankments and pile foundations. It is demonstrated that the correlation distance can greatly influence the design of each of these geotechnical systems.
Statement of Originality

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying.

Signed: .............................................  Date: .....................................................
Acknowledgments

This PhD research began in February 1988 and has been carried out on a part-time basis ever since. I owe an enormous debt of gratitude to my supervisors, Dr. William Kaggwa, of the Department of Civil and Environmental Engineering, and Dr. Peter Brooker, of the Department of Geology and Geophysics, for their time, patience, guidance and continual support throughout this research programme. In addition, their advice and encouragement have been of great value to me, and this thesis would not have been possible but for their contribution. The assistance of Prof. Stephen Priest and Dr. J. Neil Kay in the first two years of this project is also greatly appreciated. In addition, I wish to thank Dr. Ari Verbyla and the late Dr. W. B. Taylor, of the Department of Statistics, for their patience and assistance with respect to time series analysis and related techniques.

I wish to thank the Department of Civil and Environmental Engineering for their continual support and patience during my candidature. I wish to acknowledge the enormous support given to me by Mr. Tad Sawosko who spent many weeks, and long, tiring days, in the field performing the 223 cone penetration tests. In addition, Tad’s suggestions, laboratory support and warm nature, are gratefully acknowledged. The micro-computer based data acquisition system was developed, largely as the result of the electronic expertise of Mr. Bruce Lucas. His support and dedication to this research programme is greatly appreciated. In addition, I wish to thank other members of the Department’s technical staff, in particular: Messrs. Stan Woithe; Werner Eidam; Colin Haese; Robert Kelman; Laurie Collins; and Ms Deborah Hammond, who each contributed to this research in one form or another.

The field study was carried out with the generous support of the Department of Transport and the Adelaide City Council. I thank both of these organisations, and in particular, Messrs. Roman Washyn, Richard Herraman, Ian Forrester and Mark Underhill for their significant contribution to this study. In addition, I am grateful for the generosity and assistance provided by Australian National, and in particular, Mr. Peter Gaskill, for allowing testing to be carried out at the Keswick site. I also wish to thank Dr. K. S. Li, Mitchell, McFarlane, Brentnall and Partners, Hong Kong, and Dr. S.-C. R. Lo and Mr. G. R. Mostyn, University of N.S.W., for permission to use the program PROBSN.
I wish to acknowledge the assistance and kindness of the following organisations and individuals for allowing their test information and job files to be inspected so that the *KESWICK* data base could be compiled:

<table>
<thead>
<tr>
<th>Organisation</th>
<th>Individuals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coffey Partners International Pty. Ltd.</td>
<td>I. Hosking, R. Grounds</td>
</tr>
<tr>
<td>Connell Wagner (SA) Pty. Ltd.</td>
<td>G. Benny, W. Graham</td>
</tr>
<tr>
<td>Golder Associates Pty. Ltd.</td>
<td>C. Fitzhardinge, I. Shipway</td>
</tr>
<tr>
<td>(formerly Woodburn Fitzhardinge Geotechnical)</td>
<td></td>
</tr>
<tr>
<td>ACER Wargon Chapman (SA) Pty. Ltd.</td>
<td>R. Stevens</td>
</tr>
<tr>
<td>(formerly Hosking Oborn Freeman and Fox)</td>
<td></td>
</tr>
<tr>
<td>Kinhill Engineers</td>
<td>R. Perry</td>
</tr>
<tr>
<td>Koukourou and Partners</td>
<td>P. Bayetto, R. Bryant,</td>
</tr>
<tr>
<td></td>
<td>P. Lambert, Q. Jones</td>
</tr>
<tr>
<td>Rust PPK Consultants Pty. Ltd.</td>
<td>P. Mitchell</td>
</tr>
<tr>
<td>(formerly PPK Consultants Pty. Ltd.)</td>
<td></td>
</tr>
<tr>
<td>SACON</td>
<td>S. Wawryk, L. Sanders</td>
</tr>
</tbody>
</table>

Considerable assistance was given to me via the Cathie Fund, in the form of a series of Release Time Scholarships, which allowed me to be released from some of my teaching duties, and hence enabled me to devote more time to my PhD research. I wish to thank all who assisted me in this regard, particularly Ms Sharon Mosler. In addition, I wish to acknowledge the assistance of the S.A. Department of Environment and Natural Resources, and in particular, my brother Daniel for the map of Australia, as well as invaluable surveying advice; Mr. Malcolm Sheard from the Mines and Energy, S.A. for useful information regarding the Keswick and Hindmarsh Clays; and Mr. Mike Vowles of the Bureau of Meteorology for the climatic data presented in Chapter 4.

I wish to thank fellow postgraduate students: Philip Crawley; Tony Meyers; and Holger Maier for their friendship, encouragement and advice. In addition, thanks are also due to Paul Morgan, and my wife, Marie, for proof-reading the thesis.

Since 1992, a series of enthusiastic and capable final year, undergraduate students assisted with various aspects of this research. I wish to thank Stuart Potter, Phuc Do, Dirk van Holst Pellekaan, Julian Cathro, Rachel Hawtin, Lynn Lim, Greg Dufour, and Kelly Manning for their contributions to this research.

Finally, I will always be indebted to my family, particularly my wife, Marie, for her constant love, sacrifice and support throughout the period of my candidature, and my parents, Stan and Maria, for the considerable sacrifices which they have made on my behalf throughout my life. Lastly, I am indebted to my Lord for the strength, nourishment and opportunities which I have been blessed with during this period of study.
Contents

Note: All blank pages have been given page numbers.

Preface ................................................................................................................... i
Abstract ............................................................................................................ iv
Statement of Originality...................................................................................... vi
Acknowledgments............................................................................................... vii
Contents ............................................................................................................... ix
List of Figures ...................................................................................................... xv
List of Tables ...................................................................................................... xxvi
Notation ................................................................................................................ xxx
Glossary ............................................................................................................... xxxviii

Chapter 1. Introduction ...................................................................................... 1
1.1 INTRODUCTION ....................................................................................... 1
1.2 AIMS AND SCOPE OF THESIS ......................................................... 3
1.3 LAYOUT OF THESIS .............................................................................. 6

Chapter 2. Literature Review ......................................................................... 8
2.1 INTRODUCTION ....................................................................................... 8
2.2 THE STUDY AREA .................................................................................. 8
2.3 KESWICK AND HINDMARSH CLAYS .................................................. 9
   2.3.1 Geological History ........................................................................... 9
   2.3.2 Geotechnical Characteristics .......................................................... 13
      2.3.2.1 Stratigraphy ........................................................................... 14
      (i) Keswick Clay .............................................................................. 14
      (ii) Hindmarsh Clay Sand Member ............................................. 15
      (iii) Hindmarsh Clay Layer ......................................................... 16
      2.3.2.2 Mineralogy ........................................................................... 16
      2.3.2.3 Plasticity .............................................................................. 18
      2.3.2.4 Moisture Regime ................................................................. 18
      2.3.2.5 Specific Gravity ................................................................ 19
      2.3.2.6 Degree of Saturation ........................................................... 19
      2.3.2.7 Instability Index, \( I_{pt} \) ....................................................... 20
      2.3.2.8 Coefficient of Earth Pressure at Rest, \( K_0 \) ......................... 20
   2.3.3 Structural Features ......................................................................... 21
      2.3.3.1 Gilgais ................................................................................ 22
2.3.4 Groundwater ................................................................. 24
2.3.5 Summary ........................................................................ 25

2.4 THE CONE PENETRATION TEST ........................................... 25
2.4.1 Introduction ................................................................. 25
2.4.2 Equipment ................................................................. 26
2.4.3 Procedure ................................................................. 28
2.4.4 Applications and Data Interpretation ............................... 29
2.4.5 Determination of the Undrained Shear Strength of a Clay from the CPT ......................................................... 30
2.4.6 Extent of the Failure Zone Due to Cone Penetration .............. 34
2.4.7 Accuracy of the CPT .................................................... 35
2.4.7.1 Equipment Errors of the CPT ...................................... 36
2.4.7.2 Operator/Procedural Errors of the CPT ......................... 37
2.4.7.3 Random Errors of the CPT ........................................ 38
2.4.7.4 Total Measurement Errors of the CPT ............................ 39
2.4.8 Summary ................................................................. 39

2.5 SPATIAL VARIABILITY OF SOILS ......................................... 39
2.5.1 Mathematical Techniques Used to Model Spatial Variability ... 40
2.5.1.1 Regression Analysis .................................................. 40
2.5.1.2 Random Field Theory .............................................. 44
(i) Stationarity ................................................................. 44
(ii) Data Transformation ................................................... 46
(iii) Autocovariance and the Autocorrelation Function ............... 48
(iv) Partial Autocorrelation Function .................................... 51
(v) Estimation - Random Field Models .................................. 52
(vi) Cross-Covariance and the Cross-Correlation Function ......... 59
2.5.1.3 Geostatistics ......................................................... 60
(i) Semivariogram ............................................................. 61
(ii) Estimation - Kriging ..................................................... 65
2.5.1.4 Tests for Non-Stationarity ......................................... 69
2.5.2 Historical Studies Concerned with the Spatial Variability of Geotechnical Materials ................................................. 73
2.5.2.1 Random Field Theory .............................................. 74
2.5.2.2 Geostatistical Analyses ............................................ 96

2.6 SUMMARY ........................................................................ 100

Chapter 3. Development of a Micro-Computer Based Data Acquisition System for the Cone Penetration Test ........................................ 101
3.1 INTRODUCTION ................................................................ 101
3.2 EXISTING DATA ACQUISITION SYSTEMS ......................... 101
3.3 DESIGN CRITERIA FOR DATA ACQUISITION SYSTEM ..........104
3.4 DESIGN AND CONSTRUCTION OF UNIVERSITY OF
ADELAIDE DATA ACQUISITION SYSTEM..............................105
  3.4.1 Equipment.......................................................................105
  3.4.1.1 Electric Cone Penetrometer..........................................105
  3.4.1.2 Depth Box .................................................................105
  3.4.2 Measurement and Recording..........................................107
  3.4.2.1 Hardware.....................................................................107
    (i) Microprocessor Interface ..............................................107
    (ii) Micro-Computer..........................................................109
    (iii) Alarm Button.............................................................109
  3.4.2.2 Software ....................................................................110
    (i) CPTRead.......................................................................111
    (ii) CPTest ........................................................................112
  3.4.3 Post-Processing............................................................115
  3.4.3.1 CPTView.................................................................115
  3.4.3.2 CPTPlot.................................................................115
  3.4.3.3 CPTPrint...............................................................121
3.4.4 Description of Overall Data Acquisition System.................121
3.5 CALIBRATION AND ACCURACY OF EQUIPMENT ............123
  3.5.1 Resolution of Measured Data ........................................123
  3.5.2 Calibration Tests to Quantify Measurement Errors............123
    3.5.2.1 Depth Box and Depth Measurements .......................124
    3.5.2.2 Measurements of $q_c$ and $f_s$..................................125
    3.5.2.3 Microprocessor Interface Sampling Rate....................126
  3.5.3 Random Measurement Errors......................................126
3.6 FIELD PERFORMANCE .....................................................127
  3.6.1 Falling Off.................................................................127
  3.6.2 Noise Spikes ...............................................................129
  3.6.3 Limitations of Data Acquisition System .........................129
3.7 SUMMARY .........................................................................129

Chapter 4. Experimental Programme ....................................131
  4.1 INTRODUCTION ............................................................131
  4.2 LOCATION OF SITE FOR FIELD STUDY .......................131
  4.3 FIELD TESTING - SOUTH PARKLANDS SITE ....................132
    4.3.1 Layout of Field Testing .............................................132
    4.3.2 Equipment and Methods...........................................135
    4.3.3 Sampling and Logging ...............................................139
    4.3.4 Reduction of Errors During Field Testing ....................141
4.3.5 Level Survey of South Parklands Site ........................................... 143

4.4 FIELD TESTING - KESWICH SITE .................................................. 148
4.4.1 Location of Site for Horizontal Spatial Variability Field Study .... 149
4.4.2 Horizontal CPT Equipment and Methods .............................. 150

4.5 DETERMINATION OF CONE FACTOR, \( N_k \) ................................. 155

4.6 SUMMARY .......................................................................................... 166

Chapter 5. Examination of the Small-Scale Spatial Variability of
the Keswick Clay ................................ ................................ ................... 167

5.1 INTRODUCTION .................................................................................. 167

5.2 DEVELOPMENT OF SOFTWARE ...................................................... 167
5.2.1 SemiAuto ...................................................................................... 167
5.2.2 Monte .......................................................................................... 169
5.2.3 CPTSpace .................................................................................... 171

5.3 ANALYSIS OF SPATIAL VARIABILITY OF KESWICH CLAY ...... 171
5.3.1 Vertical Spatial Variability............................................................ 172
5.3.1.1 Random Field Theory Analyses......................................... 176
5.3.1.2 Geostatistical Analyses ..................................................... 183
5.3.1.3 Spatial Variability Models Derived From \( s_u \) Compared
With \( q_c \) ................................................................. 189
5.3.2 Horizontal Spatial Variability ....................................................... 192
5.3.2.1 South Parklands Site......................................................... 192
5.3.2.2 Keswick Site..................................................................... 202
5.3.2.3 Discussion of Horizontal Spatial Variability Results .......... 205
5.3.3 Relationship Between \( \delta_v \), \( r_B \) and \( a \) ..................................... 211
5.3.4 Analysis of Sleeve Friction Measurements .............................. 213
5.3.5 Cross-Correlation Analysis: \( q_c \) and \( f_s \) ........................................ 220
5.3.6 Discussion of Spatial Variability Results ................................. 225
5.3.7 Summary...................................................................................... 228

5.4 MODEL FORMULATION, PARAMETER ESTIMATION,
FORECASTING AND DATA SIMULATION ........................................ 229
5.4.1 Random Field Theory................................................................. 230
5.4.1.1 Re-examination of Ravi’s (1992) Analysis......................... 230
5.4.2 Random Field Analyses of Keswick Clay ................................. 234
5.4.2.1 Model Formulation and Parameter Estimation................... 234
5.4.2.2 Forecasting ....................................................................... 247
5.4.2.3 Data Simulation .................................................................. 249
5.4.3 Geostatistical Analyses ............................................................... 254
5.4.3.1 Forecasting ....................................................................... 254
5.4.4 Summary of Random Field and Geostatistical Modelling of Keswick Clay ................................................................. 265

5.5 ASSESSMENT OF ACCURACY OF MEASURED DATA........... 266
5.5.1 Inadequacies of Baecher’s Method ........................................ 266
  5.5.1.1 Nugget Effect ................................................................. 267
  5.5.1.2 Sample Spacing .......................................................... 267
  5.5.1.3 Trend Removal from Data ........................................... 268
5.5.2 Case Studies ................................................................... 268
  5.5.2.1 Sensitivity of Vertical Spatial Variability ....................... 269
    (i) Effect of Trend Removal ................................................. 269
    (ii) Effect of Sample Spacing .............................................. 270
  5.5.2.2 Sensitivity of Horizontal Spatial Variability ................... 274
    (i) Effect of Trend Removal ................................................. 274
    (ii) Effect of Sample Spacing .............................................. 274
5.5.3 Conclusions .................................................................. 278

5.6 SUMMARY .......................................................................... 279

Chapter 6. Compilation of a Data Base of Geotechnical Properties of the Keswick and Hindmarsh Clays ........................................ 282
6.1 INTRODUCTION .................................................................. 282
6.2 GEOTECHNICAL DATA BASES DISCUSSED IN THE LITERATURE .............................................................................. 282
6.3 FORMULATION OF THE KESWICK DATA BASE .......... 284
6.4 DESCRIPTION OF THE KESWICK DATA BASE ............... 285
6.5 APPLICATION OF THE KESWICK DATA BASE ................. 291
  6.5.1 Contours of Layer Surfaces ............................................... 291
  6.5.2 Moisture and Density Relationships with Depth ............... 292
  6.5.3 Specific Gravity and Degree of Saturation ....................... 301
  6.5.4 Shear Strength ............................................................... 305
  6.5.5 Young’s Modulus of Elasticity ........................................ 312
  6.5.6 SPT Number .................................................................. 315
  6.5.7 Soil Suction .................................................................... 317
  6.5.8 Contours of Undrained Shear Strength ......................... 318
6.6 SUMMARY ........................................................................ 324

Chapter 7. Examination of the Large-Scale Lateral Spatial Variability of the Keswick Clay ......................................................... 325
7.1 INTRODUCTION .................................................................. 325
7.2 INPUT DATA AND TRANSFORMATIONS ............................ 325
7.3 GEOSTATISTICAL MODEL .................................................. 329
7.4 ASSESSMENT OF THE GEOSTATISTICAL MODEL.............. 336
  7.4.1 Cross Validation Analyses........................................... 336
  7.4.2 Ordinary Kriging Analyses........................................... 339
7.5 SUMMARY.......................................................................... 348

Chapter 8. Significance of Spatial Variability with Respect to
Geotechnical Engineering Design........................................... 349
  8.1 INTRODUCTION................................................................. 349
  8.2 SLOPE STABILITY ANALYSIS............................................. 349
  8.3 PILE DESIGN....................................................................... 352
    8.3.1 LCPC Method................................................................. 353
    8.3.2 Hypothetical Field Problems........................................... 355
      8.3.2.1 South Parklands Site............................................... 355
      8.3.2.2 Simulated Data......................................................... 360
  8.4 SUMMARY.......................................................................... 370

Chapter 9. Summary and Conclusions...................................... 372
  9.1 SUMMARY.......................................................................... 372
  9.2 RECOMMENDATIONS FOR FURTHER RESEARCH.................. 376
  9.3 CONCLUSION...................................................................... 378

References................................................................................ 379

Appendix A Selected Cone Penetration Test Results from Field Study...... 397

Appendix B Engineering Borehole Logs............................................. 443

Appendix C Data Base of the Geotechnical Properties of the Keswick and
Hindmarsh Clays........................................................................ 451
List of Figures

Chapter 2. Literature Review

2.1 Locality plan.........................................................................................................9
2.2 The Adelaide city area.........................................................................................10
2.3 The St. Vincent basin..........................................................................................12
2.4 Distribution of the Keswick Clay.........................................................................15
2.5 Distribution of the Hindmarsh Clay .....................................................................17
2.6 Typical gilgai structures within the Adelaide city area..........................................23
2.7 Suggested origin of gilgai structures....................................................................24
2.8 Schematic diagram of the electric cone penetrometer ..........................................27
2.9 Schematic representation of $r_p$ and $z_p$................................................................34
2.10 Location of the elasto-plastic boundary in cone penetration.................................35
2.11 Hypothetical sedimentary rock data showing straight lines fitted by different methods..............................................................................................................42
2.12 An example of a non-stationary data set ..............................................................45
2.13 Forms of non-stationarity: (a) trend non-stationarity, (b) variance non-stationarity, (c) relationship non-stationarity........................................................46
2.14 Summary of the Box-Jenkins procedure ..............................................................53
2.15 Relationship between the semivariogram, $\gamma_h$, and the autocorrelation, $\rho_h$, for a stationary regionalised variable ...................................................................62
2.16 Commonly used model semivariograms with $C_0$ set to zero .................................63
2.17 Different forms of a soil parameter, $v$, with depth, $z$............................................74
2.18 Examples of variance functions ...........................................................................81
2.19 Spatial variability model of $\tilde{s}_h$ at borehole A1 .................................................89
2.20 Procedure for estimating the random measurement component from the ACVF...91
2.21 Procedure for estimating the random measurement component from the ACF....91
2.22 Estimation technique proposed by Kulatilake and Southworth (1987) .................94

Chapter 3. Development of a Micro-Computer Based Data Acquisition System for the Cone Penetration Test

3.1 Fugro Consultants International Pty. Ltd. data acquisition system .......................103
3.2 Depth box: (a) internal details, (b) attached to drilling rig .................................106
3.3 Schematic diagram of the microprocessor interface ...............................................108
3.4 Micro-computer and microprocessor interface ......................................................110
3.5 Flowchart of the microprocessor interface software, $CPT\text{Read}$..........................111
3.6 An example of the $CPT\text{Test}$ screen..................................................................114
Chapter 4. Experimental Programme

4.1 Location of field study site ................................................................. 133
4.2 Initial layout of field testing ................................................................. 134
4.3 Referencing system used for the one metre, laterally spaced CPTs .... 135
4.4 Edson drilling rig .............................................................................. 136
4.5 Proline drilling rig ............................................................................. 137
4.6 Toyota 4WD drilling rig ..................................................................... 137
4.7 Amended testing layout ...................................................................... 140
4.8 Graphical representation of borehole logs. Contours to surface of:
   (a) Calcareous Mantle; (b) Limy Surficial Layer; (c) Keswick Clay, to AHD;
   and (d) 3D representation. ................................................................. 142
4.9 Maximum and minimum daily temperatures for the Adelaide city area for
   1992 and 1993 ................................................................................... 144
4.10 Average daily relative humidity for the Adelaide city area for 1992 and 1993 .... 144
4.11 Daily rainfall for the Adelaide city area for 1992 and 1993 ..................... 145
4.13 Maximum and minimum daily temperatures for the Adelaide city area for
   3rd July - 14th August 1992 and 16th February - 4th March 1993 ......... 146
4.14 Average daily relative humidity for the Adelaide city area for 3rd July -
   14th August 1992 and 16th February - 4th March 1993 ..................... 146
4.15 Daily rainfall for the Adelaide city area for 3rd July - 14th August 1992
   and 16th February - 4th March 1993 ................................................ 147
4.16 Daily evaporation for the Adelaide city area for 3rd July - 14th August 1992
   and 16th February - 4th March 1993 ................................................ 147
4.17 Contour plot of South Parklands site .................................................. 148
4.18 3-dimensional surface plot of South Parklands site .............................. 149
4.19 Location of site for horizontal spatial variability field study ................. 150
4.20 Trailer mounted CPT equipment for testing in the horizontal direction .... 151
4.21 Layout of steel lateral restraint piers ................................................. 152
4.22 Depth box arrangement used to measure horizontal penetration depths .. 153
List of Figures

4.23 Results of the horizontal CPT at Keswick .........................................................154
4.24 Locations of additional CPTs performed in the determination of $N_k$ ................156
4.25 Variation of $N_k$ with undrained shear strength, $s_u$ ............................................159
4.26 Locations of tests performed by Do & Potter (1992) and van Holst Pellekaan & Cathro (1993) .................................................................160
4.27 Variation of $N_k$ with undrained shear strength, $s_u$, including results from Do & Potter (1992) and van Holst Pellekaan & Cathro (1993) ......................161
4.28 Values of $N_k$ determined from Equation (2.5) compared with those obtained by Teh and Houlsby (1991) .................................................................162
4.29 Values of $N_k$ determined from Equation (2.5) compared with those obtained by Teh and Houlsby (1991) including results from Do & Potter (1992) and van Holst Pellekaan & Cathro (1993) ..............................................................163
4.30 Measured values of $s_u$ compared with $s_u^*$ predicted by Equation (2.7) from Baligh (1975) ........................................................................................................164
4.31 Measured values of $s_u$ compared with $s_u^*$ predicted by Equation (2.8) from Keaveny and Mitchell (1986) ..................................................................................164
4.32 Measured values of $s_u$ compared with $s_u^*$ predicted by Equation (2.9) from Teh and Houlsby (1991) .................................................................165
4.33 Measured values of $s_u$ compared with $s_u^*$ predicted by Equation (2.10) from Teh and Houlsby (1991) .................................................................165

Chapter 5. Examination of the Small-Scale Spatial Variability of the Keswick Clay

5.1 Comparison of semivarioogram output by SemiAuto with that given by Clark (1979) .................................................................................................169
5.2 A typical screen from SemiAuto ........................................................................170
5.3 A typical screen from the program Monte..........................................................171
5.4 Envelope of maxima and minima of measurements of $q_c$ from all CPTs performed at the South Parklands site, except for CD1 to CD50 ......................173
5.5 Envelope of maxima and minima of measurements of $q_c$ from CPTs CD1 to CD50 performed at the South Parklands site ..............................................174
5.6 Histograms of measurements of $q_c$ from all CPTs performed at the South Parklands site ..............................................................................................174
5.7 Measured cone tip resistance, $q_c$, for sounding C8 ...........................................177
5.8 Measured cone tip resistance, $q_c$, within Keswick Clay for sounding C8 .......177
5.9 Residuals of $q_c$, for sounding C8, after removing the quadratic trend ..........178
5.10 Sample and model ACFs obtained from the residuals of $q_c$ for C8 .............179
5.11 Sample ACF, showing Bartlett’s limits, obtained from the residuals of $q_c$ for sounding C8, and used to evaluate Bartlett’s distance ..........................180
5.12 Relationship between the scale of fluctuation, $\delta$, and Bartlett’s distance, $r_B$. ....181
5.13 Experimental and model semivariograms of residual $q_c$ data from C8 ..........185
5.14 Experimental and model semivariograms of residual $q_c$ data from A8 - an example of an **excellent fit** .................................................................187
5.15 Experimental and model semivariograms of residual $q_c$ data from CD30 - an example of a **good fit** .................................................................187
5.16 Experimental and model semivariograms of residual $q_c$ data from D5 - an example of a **poor fit** .................................................................188
5.17 Sample and model ACFs of the residuals of $s_u$, for C8, obtained by converting measurements of $q_c$ using $N_k = 20$, and 40...............................190
5.18 Experimental and model semivariograms of the residuals of $s_u$, for C8, obtained by converting measurements of $q_c$ using $N_k = 20$ .........................191
5.19 Experimental and model semivariograms of the residuals of $s_u$, for C8, obtained by converting measurements of $q_c$ using $N_k = 40$ .........................191
5.20 Horizontal spatial variability data along transect A5 to K5 ..........................193
5.21 Sample ACFs of the residuals of the horizontal spatial variability data for transect A5 to K5 ................................................................................194
5.22 Experimental semivariograms of the residuals of the horizontal spatial variability data for transect A5 to K5 ...............................................................194
5.23 Experimental semivariogram of the residuals of transect A5 to K5, at a depth of 3.5 metres ................................................................................195
5.24 Horizontal spatial variability data along transect CD1 to CD50 ......................196
5.25 Sample ACFs of the residuals of the horizontal spatial variability data for transect CD1 to CD50 ...............................................................198
5.26 Experimental semivariograms of the residuals of the horizontal spatial variability data for transect CD1 to CD50 ...............................................................198
5.27 Experimental semivariogram of the residuals of transect CD1 to CD50 at a depth of 3.5 metres ...............................................................199
5.28 Horizontal spatial variability data, along transect CD1 to CD50, averaged over depths 3.5 m to 4.5 m below the ground surface ................................200
5.29 Sample ACF of the residuals of the data, for transect CD1 to CD50, averaged over depths 3.5 m to 4.5 m below the ground surface .......................201
5.30 Experimental semivariogram of the residuals of the data, for transect CD1 to CD50, averaged over depths 3.5 m to 4.5 m below the ground surface ...........201
5.31 Horizontal CPT data with quadratic trend function ........................................202
5.32 Residuals of the horizontal CPT data after quadratic trend removal ...............203
5.33 Sample and model autocorrelation functions of the de-trended horizontal CPT data ..................................................................................204
5.34 Experimental and model semivariograms of the de-trended horizontal CPT data ..................................................................................205
5.35 Scales of spatial variability modelling in geotechnical engineering ..................206
List of Figures

5.36 The two spherical semivariogram models used to describe the horizontal spatial variability of the Keswick Clay ...............................................................209
5.37 Nested horizontal spatial variability model for Keswick Clay ......................210
5.38 Relationship between $\delta_v$ and $a$, OLS best fit linear function ..........211
5.39 Relationship between $\delta_v$ and $a$, OLS best fit power function ..........212
5.40 Relationship between $r_B$ and $a$, OLS best fit power function ..........212
5.41 Sleeve friction measurements from A0 .........................................................214
5.42 Sleeve friction measurements from horizontal CPT performed at the Keswick site .....................................................................................................214
5.43 Rebound phenomenon from A0 .....................................................................215
5.44 Rebound phenomenon from the horizontal CPT from the Keswick site .........215
5.45 Sleeve friction measurements from CPTs performed in red-brown earth and estuarine sands and clays ..............................................................216
5.46 Sleeve friction measurements from I1 ............................................................217
5.47 Residuals of sleeve friction measurements from I1 ..............................................217
5.48 Sample autocorrelation function and model obtained from residuals of $f_s$ measurements from I1 .........................................................................................218
5.49 Experimental semivariogram and spherical model obtained from residuals of $f_s$ measurements from I1 .........................................................................................219
5.50 Sample cross-correlation function of cone tip resistance and sleeve friction measurements, from within the Keswick Clay, from CPT I1 .................221
5.51 Sample CCF of $q_c$ and $f_s$ measurements from CPT A3 ..............................223
5.52 Sample CCF of $q_c$ and $f_s$ measurements from CPT B10 .........................223
5.53 Sample CCF of $q_c$ and $f_s$ measurements from CPT: (a) A1, and (b) CD40 ..224
5.54 Sample CCF of $q_c$ and $f_s$ measurements from the horizontal CPT performed at the Keswick site .....................................................................................................225
5.55 Extent of the failure zone of the CPT in Keswick Clay .......................................228
5.56 Data from borehole A-1 with models proposed by Asaoka and A-Grivas (1982) and Ravi (1992) ..............................................................................................................230
5.57 Data from borehole A-1 with the model proposed by Ravi (1992) and that obtained by using rescaled residuals ..............................................................................................................233
5.58 Sample PACF obtained from the residuals of $q_c$ for C8 after classical transformation, that is, removal of the OLS quadratic trend .........................................................................................234
5.59 Rescaled residuals after fitting an AR(3) model to the classically transformed measurements of $q_c$ for sounding C8 .................................................................236
5.60 ACF of the rescaled residuals of $q_c$ for C8 after fitting an AR(3) model ..........236
5.61 Measured $q_c$ data from C8 with the AR(3) model obtained by using rescaled residuals ..............................................................................................................237
5.62 Residuals of $q_c$, for sounding C8, after first-differencing ..............................237
List of Figures

5.63 Sample ACF obtained from the residuals of $q_c$, for sounding C8, after first-differencing .......................................................... 238
5.64 Experimental semivariogram obtained from the residuals of $q_c$, for sounding C8, after first-differencing............................... 239
5.65 Sample PACF obtained from the residuals of $q_c$, for sounding C8, after first-differencing ..................................................... 239
5.66 Rescaled residuals, after fitting an IMA(1,1) model to the first-differenced measurements of $q_c$, for sounding C8 ......................... 240
5.67 ACF of the rescaled residuals of $q_c$ for C8 after fitting an IMA(1,1) model........... 241
5.68 Measured $q_c$ data from C8 with the IMA(1,1) model obtained by using rescaled residuals .......................................................... 241
5.69 Measured $q_c$ data from horizontal CPT, from the Keswick site, with the AR(6) model obtained by using rescaled residuals ............ 246
5.70 Measured $q_c$ data from horizontal CPT, from the Keswick site, with the ARIMA(3,1,3) model obtained by using rescaled residuals 247
5.71 Forecasts of $q_c$ measurements obtained from classically transformed data, AR(3), and first-differenced data, IMA(1,1), for C8 ........ 248
5.72 Forecasts of $q_c$ measurements obtained from classically transformed data, AR(6), and first-differenced data, ARIMA(3,1,3), for the horizontal CPT .... 249
5.73 Five random realisations of the AR(3) process for CPT C8 obtained from Monte ................................................................. 251
5.74 Envelope of 1,000 realisations of the AR(3) process, for CPT C8, obtained from Monte ............................................................. 252
5.75 Envelope of 1,000 realisations of the IMA(1,1) process, for CPT C8, obtained from Monte .......................................................... 252
5.76 Envelope of 1,000 realisations of the AR(6) process, for the horizontal CPT, obtained from Monte ............................................. 253
5.77 Envelope of 1,000 realisations of the ARIMA(3,1,3) process, for the horizontal CPT, obtained from Monte ..................................... 254
5.78 Results of one-step ahead ordinary kriging of C8 from OKB2D ....................... 256
5.79 Results of one-step ahead ordinary kriging of the horizontal CPT using OKB2D ............................................................... 256
5.80 Results of ordinary kriging using 200 mm spaced input data from C8 ............ 261
5.81 Results of ordinary kriging using 200 mm spaced input data from the horizontal CPT ............................................................... 261
5.82 Ordinary kriged estimates and the 95% confidence limits ($\pm 2\sigma$) using 200 mm spaced input data from C8.............................. 262
5.83 Ordinary kriged estimates and the 95% confidence limits ($\pm 2\sigma$) using 200 mm spaced input data from the horizontal CPT .......... 262
5.84 Ordinary kriged forecasts at 5 mm intervals for C8 .................................. 264
5.85 Ordinary kriged forecasts at 5 mm intervals for the horizontal CPT ...................264
5.86 Sample ACFs after: (a) no trend removal; and (b) a linear trend removal............271
5.87 Sample ACFs for: (a) 50 mm spaced data set; and (b) 200 mm spaced data set..........................................................273
5.88 Sample ACFs for: (a) 20 mm spaced data set; and (b) 100 mm spaced data set..........................276

Chapter 6. Compilation of a Data Base of Geotechnical Properties of the Keswick and Hindmarsh Clays

6.1 Location of boreholes included in KESWICK..................................................287
6.2 Procedure used to determine the three-dimensional coordinates for each test in the KESWICK data base...............................................................290
6.3 Three-dimensional coordinates associated with each test in KESWICK............290
6.4 Variation of the depth below ground of the surface of the Keswick Clay ..........293
6.5 Variation of the depth below ground of the surface of the Hindmarsh Clay Sand Member .................................................................293
6.6 Variation of the depth below ground of the surface of the Hindmarsh Clay Layer ................................................................................295
6.7 Variation of the surface of the Keswick Clay to the AHD...............................295
6.8 Variation of the surface of the Hindmarsh Clay Sand Member to the AHD........297
6.9 Variation of the surface of the Hindmarsh Clay Layer to the AHD..................297
6.10 Relationship between moisture content and the depth below ground for the Keswick Clay, undifferentiated Keswick Clay-Hindmarsh Clay, and the Hindmarsh Clay Layer.................................................................................299
6.11 Relationship between dry density and the depth below ground for the Keswick Clay, undifferentiated Keswick Clay-Hindmarsh Clay, and the Hindmarsh Clay Layer.................................................................................299
6.12 Relationship between \( w \), \( \rho_d \), and \( S_r \) for Keswick Clay with \( G_s = 2.70 \) ..........301
6.13 Relationship between \( w \), \( \rho_d \), and \( S_r \) for Keswick Clay with \( G_s = 2.75 \) ..........302
6.14 Relationship between \( w \), \( \rho_d \), and \( S_r \) for undifferentiated Keswick Clay-Hindmarsh Clay with \( G_s = 2.75 \) .................................................................303
6.15 Relationship between \( w \), \( \rho_d \), and \( S_r \) for the Hindmarsh Clay Layer with \( G_s = 2.77 \) ..................................................................................304
6.16 Relationship between \( S_r \) and depth below ground for Keswick Clay with \( G_s = 2.75 \) ..................................................................................304
6.17 Undrained shear strength, \( s_u \), of the Keswick Clay obtained from the first stage of UU tests .................................................................306
6.18 Undrained shear strength, \( s_u \), of undifferentiated Keswick Clay-Hindmarsh Clay obtained from the first stage of UU tests.........................306
6.19 Undrained shear strength, $s_u$, of the Hindmarsh Clay Sand Member obtained from the first stage of UU tests ........................................................... 307

6.20 Undrained shear strength, $s_u$, of the Hindmarsh Clay Layer obtained from the first stage of UU tests ........................................................... 307

6.21 Histograms of the undrained shear strength, $s_u$, of the Keswick Clay, undifferentiated Keswick Clay-Hindmarsh Clay and the Hindmarsh Clay Layer obtained from the first stage of UU tests ........................................ 308

6.22 Relationship between $s_u$ and depth below ground for the Keswick Clay, undifferentiated Keswick Clay-Hindmarsh Clay and the Hindmarsh Clay Layer obtained from several in situ tests ........................................... 309

6.23 Relationship between $s_u$ and $w$ for the Keswick Clay, undifferentiated Keswick Clay-Hindmarsh Clay, and the Hindmarsh Clay Layer obtained from the first stage of UU tests ................................................... 309

6.24 Relationship between $s_u$ and $p_d$ for the Keswick Clay, undifferentiated Keswick Clay-Hindmarsh Clay and the Hindmarsh Clay Layer obtained from the first stage of UU tests ................................................... 310

6.25 Relationship between $s_u$ and $\sigma_3$ for the Keswick Clay, undifferentiated Keswick Clay-Hindmarsh Clay and the Hindmarsh Clay Layer obtained from the first stage of UU tests ................................................... 311

6.26 Relationship between $s_u/\sigma_{v0}$ and depth below ground for the Keswick Clay, undifferentiated Keswick Clay-Hindmarsh Clay and the Hindmarsh Clay Layer obtained from the first stage of UU tests ................................................... 311

6.27 Relationship between $s_u$ and $\sigma_i$ for the Hindmarsh Clay Sand Member obtained from up to three stages of UU tests ................................................... 312

6.28 Relationship between $E_u$ and depth below ground for the Keswick Clay, undifferentiated Keswick Clay-Hindmarsh Clay and the Hindmarsh Clay obtained from the first stage of UU tests ................................................... 313

6.29 Histograms of $E_u$ of the Keswick Clay, undifferentiated Keswick Clay-Hindmarsh Clay and the Hindmarsh Clay Layer obtained from the first stage of UU tests ................................................... 314

6.30 Relationship between $E_u$ and depth below ground for the Keswick Clay, undifferentiated Keswick Clay-Hindmarsh Clay and the Hindmarsh Clay Layer obtained from a number of in situ tests ................................................... 314

6.31 Relationship between $E_u/\sigma_{v0}$ and depth below ground for the Keswick Clay, undifferentiated Keswick Clay-Hindmarsh Clay and the Hindmarsh Clay Layer obtained from up to three stages of UU tests ................................................... 316

6.32 Relationship between SPT Number, $N$, measured in the Hindmarsh Clay Sand Member and the depth below the surface of this layer ......................... 316
List of Figures

6.33 Relationship between total soil suction, $u$, and moisture content, $w$, for
the Keswick Clay, undifferentiated Keswick Clay-Hindmarsh Clay and
the Hindmarsh Clay Layer ................................................................. 318
6.34 Relationship between total soil suction and depth below ground for:
(a) summer; (b) autumn; (c) winter; and (d) spring ................................. 319
6.35 Contours of $s_u$ for Keswick Clay based on the results of unconsolidated
undrained triaxial tests using an averaging process based on pile design ....321
6.36 Contours of $s_u$ for Keswick Clay based on the results of unconsolidated
undrained triaxial tests using an averaging process based on raft design ....321

Chapter 7. Examination of the Large-Scale Lateral Spatial Variability
of the Keswick Clay
7.1 Locations of the spatially averaged $s_u$ observations from the 0 to
3 metre data set used in the large-scale spatial variability analyses ..........328
7.2 Second-degree polynomial trend surface of $s_u$ (kPa) obtained by least
squares regression of the 0 to 3 metre data set using S-PLUS for Windows ....329
7.3 Convention used by Vario to calculate the semivariogram ..................330
7.4 North-South and East-West experimental semivariograms, with
associated spherical model, of the detrended 0 to 3 metre data set ..........330
7.5 Number of pairs associated with the North-South and East-West
experimental semivariograms of the detrended 0 to 3 metre data set ........331
7.6 Omnidirectional experimental semivariogram, with associated spherical
model, of the detrended 0 to 3 metre data set ........................................332
7.7 Number of pairs associated with the omnidirectional experimental
semivariogram of the detrended 0 to 3 metre data set ............................333
7.8 The three semivariogram models which describe the spatial variability
of the undrained shear strength of the Keswick Clay ..............................334
7.9 Nested model semivariogram of the spatial variability of the
undrained shear strength of the Keswick Clay ........................................335
7.10 Map of the residuals obtained from the cross validation of the 0 to
3 metre data set .................................................................................337
7.11 Scatterplot of the residuals obtained from the cross validation of the
0 to 3 metre data set ............................................................................338
7.12 Locations of the additional data used to obtain kriged estimates ............340
7.13 The spatial variation of $\bar{s}_u$ of Keswick Clay, within a depth of 3 metres
below its surface, as given by ordinary kriging ......................................345
7.14 The variation of the kriging standard deviation, $\sigma_k$, associated with
the estimates given in Figure 7.13 ..........................................................345
7.15 The spatial variation of $\bar{s}_u$ of Keswick Clay, within a depth of 3 metres
below its surface, as given by polygonal estimation via DeltaGraph ..........347
Chapter 8. Significance of Spatial Variability with Respect to Geotechnical Engineering Design

8.1 Keswick Clay embankment analysed using PROBSN..................................................350
8.2 Influence of the scale of fluctuation, δ, on the probability of slope failure, \( P_f \) ........................................................................................................351
8.3 The procedure used to calculate \( q_{ca} \) .................................................................354
8.4 CPTs adjacent to F5 ..............................................................................................356
8.5 Data from the 6 CPTs adjacent to F5, including their mean ....................................357
8.6 Relationship between the percentage error of \( Q_A \) and the radial distance of the CPT, used to determine the pile at F5, using \( q_{s(i)max} = 35 \text{ kPa} \) ........................................358
8.7 Relationship between the percentage error of \( Q_A \) and the radial distance of the CPT, used to determine the pile at F5, using \( q_{s(i)max} = 80 \text{ kPa} \) ........................................359
8.8 Relationship between the percentage error of \( Q_A \) and the radial distance of the CPT, used to determine the pile at F5, using an unlimited \( q_{s(i)max} \) ........................................360
8.9 Plan view of the grid layout used for the simulated 3D data ....................................362
8.10 Isometric view of the grid layout used for the simulated 3D data .................................363
8.11 A typical screen from \( LCPCCSim \) ........................................................................366
8.12 Experimental semivariograms for simulated data, compared with the model semivariogram for \( a = 0.2 \) metres .........................................................................................367
8.13 Experimental semivariograms for simulated data, compared with the model semivariogram for \( a = 1.0 \) metres .........................................................................................367
8.14 Relationship between the range, \( a \), and the maximum and minimum percentage errors, \( E_{Q_A} \), assuming the pile is exclusively founded within the Keswick Clay, and using 100 simulations at each range .........................................................369
8.15 Relationship between the range, \( a \), and the maximum and minimum percentage errors, \( E_{Q_A} \), assuming the pile is founded within soils similar to those encountered at the South Parklands site, and using 100 simulations at each range .........................................................369

Appendix A  Selected Cone Penetration Test Results from Field Study

A.1 Cone penetration test results from sounding A0 ......................................................399
A.2 Cone penetration test results from sounding A1 ......................................................400
A.3 Cone penetration test results from sounding A2 ......................................................401
A.4 Cone penetration test results from sounding A4 ......................................................402
A.5 Cone penetration test results from sounding A6 ......................................................403
A.6 Cone penetration test results from sounding A8 ......................................................404
A.7 Cone penetration test results from sounding A10 ....................................................405
A.8 Cone penetration test results from sounding B1 ......................................................406
A.9 Cone penetration test results from sounding B5 ......................................................407
A.10 Cone penetration test results from sounding B8 ....................................................408
A.11 Cone penetration test results from sounding C0 ....................................................409
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.12</td>
<td>Cone penetration test results from sounding C4</td>
<td>410</td>
</tr>
<tr>
<td>A.13</td>
<td>Cone penetration test results from sounding C8</td>
<td>411</td>
</tr>
<tr>
<td>A.14</td>
<td>Cone penetration test data from sounding C8 (1 of 13)</td>
<td>412</td>
</tr>
<tr>
<td>A.15</td>
<td>Cone penetration test data from sounding C8 (2 of 13)</td>
<td>413</td>
</tr>
<tr>
<td>A.16</td>
<td>Cone penetration test data from sounding C8 (3 of 13)</td>
<td>414</td>
</tr>
<tr>
<td>A.17</td>
<td>Cone penetration test data from sounding C8 (4 of 13)</td>
<td>415</td>
</tr>
<tr>
<td>A.18</td>
<td>Cone penetration test data from sounding C8 (5 of 13)</td>
<td>416</td>
</tr>
<tr>
<td>A.19</td>
<td>Cone penetration test data from sounding C8 (6 of 13)</td>
<td>417</td>
</tr>
<tr>
<td>A.20</td>
<td>Cone penetration test data from sounding C8 (7 of 13)</td>
<td>418</td>
</tr>
<tr>
<td>A.21</td>
<td>Cone penetration test data from sounding C8 (8 of 13)</td>
<td>419</td>
</tr>
<tr>
<td>A.22</td>
<td>Cone penetration test data from sounding C8 (9 of 13)</td>
<td>420</td>
</tr>
<tr>
<td>A.23</td>
<td>Cone penetration test data from sounding C8 (10 of 13)</td>
<td>421</td>
</tr>
<tr>
<td>A.24</td>
<td>Cone penetration test data from sounding C8 (11 of 13)</td>
<td>422</td>
</tr>
<tr>
<td>A.25</td>
<td>Cone penetration test data from sounding C8 (12 of 13)</td>
<td>423</td>
</tr>
<tr>
<td>A.26</td>
<td>Cone penetration test data from sounding C8 (13 of 13)</td>
<td>424</td>
</tr>
<tr>
<td>A.27</td>
<td>Cone penetration test results from sounding C10</td>
<td>425</td>
</tr>
<tr>
<td>A.28</td>
<td>Cone penetration test results from sounding CD1</td>
<td>426</td>
</tr>
<tr>
<td>A.29</td>
<td>Cone penetration test results from sounding CD30</td>
<td>427</td>
</tr>
<tr>
<td>A.30</td>
<td>Cone penetration test results from sounding CD40</td>
<td>428</td>
</tr>
<tr>
<td>A.31</td>
<td>Cone penetration test results from sounding D5</td>
<td>429</td>
</tr>
<tr>
<td>A.32</td>
<td>Cone penetration test results from sounding D8</td>
<td>430</td>
</tr>
<tr>
<td>A.33</td>
<td>Cone penetration test results from sounding E1</td>
<td>431</td>
</tr>
<tr>
<td>A.34</td>
<td>Cone penetration test results from sounding E7</td>
<td>432</td>
</tr>
<tr>
<td>A.35</td>
<td>Cone penetration test results from sounding G0</td>
<td>433</td>
</tr>
<tr>
<td>A.36</td>
<td>Cone penetration test results from sounding G5</td>
<td>434</td>
</tr>
<tr>
<td>A.37</td>
<td>Cone penetration test results from sounding G10</td>
<td>435</td>
</tr>
<tr>
<td>A.38</td>
<td>Cone penetration test results from sounding H7</td>
<td>436</td>
</tr>
<tr>
<td>A.39</td>
<td>Cone penetration test results from sounding H10</td>
<td>437</td>
</tr>
<tr>
<td>A.40</td>
<td>Cone penetration test results from sounding I1</td>
<td>438</td>
</tr>
<tr>
<td>A.41</td>
<td>Cone penetration test results from sounding I9</td>
<td>439</td>
</tr>
<tr>
<td>A.42</td>
<td>Cone penetration test results from sounding J8</td>
<td>440</td>
</tr>
<tr>
<td>A.43</td>
<td>Cone penetration test results from sounding K0</td>
<td>441</td>
</tr>
<tr>
<td>A.44</td>
<td>Cone penetration test results from sounding K10</td>
<td>442</td>
</tr>
</tbody>
</table>
# List of Tables

## Chapter 2. Literature Review

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Summary of stratigraphic units underlying the Adelaide city area</td>
<td>11</td>
</tr>
<tr>
<td>2.2</td>
<td>Summary of Atterberg limit tests</td>
<td>18</td>
</tr>
<tr>
<td>2.3</td>
<td>Summary of Atterberg limit tests</td>
<td>18</td>
</tr>
<tr>
<td>2.4</td>
<td>Some of the variables which influence $N_k$</td>
<td>31</td>
</tr>
<tr>
<td>2.5</td>
<td>Variables contributing to CPT equipment error</td>
<td>36</td>
</tr>
<tr>
<td>2.6</td>
<td>Variables contributing to operator/procedural errors</td>
<td>38</td>
</tr>
<tr>
<td>2.7</td>
<td>Commonly used model semivariograms</td>
<td>63</td>
</tr>
<tr>
<td>2.8</td>
<td>Summary of statistical properties</td>
<td>75</td>
</tr>
<tr>
<td>2.9</td>
<td>Theoretical autocorrelation functions used to determine the scale of fluctuation, $\delta$</td>
<td>83</td>
</tr>
<tr>
<td>2.10</td>
<td>Autocorrelation functions, correlation distances and scales of fluctuations given by various researchers</td>
<td>85-87</td>
</tr>
<tr>
<td>2.11</td>
<td>Relationship between the scale of fluctuation, $\delta_v$, and the correlation distance, $v_o$, for various ACF models</td>
<td>88</td>
</tr>
<tr>
<td>2.12</td>
<td>Model semivariograms and their parameters as given by various researchers</td>
<td>99</td>
</tr>
</tbody>
</table>

## Chapter 3. Development of a Micro-Computer Based Data Acquisition System for the Cone Penetration Test

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Data conversion factors</td>
<td>112</td>
</tr>
<tr>
<td>3.2</td>
<td>Relationships used to calculate data conversion factors</td>
<td>113</td>
</tr>
</tbody>
</table>

## Chapter 4. Experimental Programme

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Cone penetration testing programme</td>
<td>139</td>
</tr>
<tr>
<td>4.2</td>
<td>Summary of borehole logs</td>
<td>141</td>
</tr>
<tr>
<td>4.3</td>
<td>Summary of unconsolidated undrained triaxial tests</td>
<td>156</td>
</tr>
<tr>
<td>4.4</td>
<td>Summary of additional CPT results and calculated values of $N_k$</td>
<td>157</td>
</tr>
<tr>
<td>4.5</td>
<td>Undrained shear strengths, $s_u^*$, predicted from values of $N_k$ determined from Equations (2.5) and (2.7) to (2.10)</td>
<td>163</td>
</tr>
</tbody>
</table>

## Chapter 5. Examination of the Small-Scale Spatial Variability of the Keswick Clay

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Global statistics of measurements of $q_c$ from all CPTs performed at the South Parklands site</td>
<td>172</td>
</tr>
<tr>
<td>Table Number</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>-------------</td>
<td>-----------------------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>5.2</td>
<td>Interpolated depths below ground to the surface of the Keswick Clay, relevant to the CPTs performed at the South Parklands Site</td>
<td>175</td>
</tr>
<tr>
<td>5.3</td>
<td>Results of random field theory analyses on detrended residuals of $q_c$ measurements obtained from 30 of the 222 vertical CPTs at the South Parklands site</td>
<td>182</td>
</tr>
<tr>
<td>5.4</td>
<td>Results of the runs tests and Kendall’s $\tau$ tests performed on detrended residuals of $q_c$ measurements obtained from 30 of the 222 vertical CPTs at the South Parklands site</td>
<td>184</td>
</tr>
<tr>
<td>5.5</td>
<td>Results of geostatistical analyses performed on measurements of $q_c$ obtained from 30 of the 222 vertical CPTs at the South Parklands site</td>
<td>186</td>
</tr>
<tr>
<td>5.6</td>
<td>Measurements of $q_c$ from vertical CPTs A5 to K5 used to generate horizontal spatial variability data</td>
<td>193</td>
</tr>
<tr>
<td>5.7</td>
<td>Results of random field theory and geostatistical analyses of horizontal spatial variability data, from transect A5 to K5, at various depths</td>
<td>195</td>
</tr>
<tr>
<td>5.8</td>
<td>Results of random field theory and geostatistical analyses of horizontal spatial variability data, from transect CD1 to CD50, at various depths</td>
<td>197</td>
</tr>
<tr>
<td>5.9</td>
<td>Summary of random field theory analyses, performed on the residuals of the horizontal CPT data, obtained from the Keswick site</td>
<td>203</td>
</tr>
<tr>
<td>5.10</td>
<td>Results of cross-correlation analyses performed on measurements of $q_c$ and $f_s$, from 60 of the 222 vertical CPTs, from the South Parklands site</td>
<td>222</td>
</tr>
<tr>
<td>5.11</td>
<td>Summary of vertical and horizontal correlation distances ($\equiv \delta_i$) of $q_c$, $q_c$, and $f_s$ of clay soils published in the literature</td>
<td>227</td>
</tr>
<tr>
<td>5.12</td>
<td>Undrained shear strength data from borehole A-1 presented by Asaoka and A-Grivas (1982) and re-examined by Ravi (1992)</td>
<td>231</td>
</tr>
<tr>
<td>5.13</td>
<td>Results of random field analyses performed on classically transformed residuals of $q_c$ measurements obtained from 30 of the 222 vertical CPTs performed at the South Parklands site</td>
<td>243</td>
</tr>
<tr>
<td>5.14</td>
<td>Results of random field analyses performed on first-differenced residuals of $q_c$ measurements obtained from 30 of the 222 vertical CPTs performed at the South Parklands site</td>
<td>244</td>
</tr>
<tr>
<td>5.15</td>
<td>First 10 forecasts of $q_c$ (MPa) for CPT C8</td>
<td>248</td>
</tr>
<tr>
<td>5.16</td>
<td>First 10 forecasts of $q_c$ (MPa) for the horizontal CPT from the Keswick site</td>
<td>250</td>
</tr>
<tr>
<td>5.17</td>
<td>Results of one-step ahead ordinary kriging from OKB2D</td>
<td>255</td>
</tr>
<tr>
<td>5.18</td>
<td>Results of one-step ahead ordinary kriging from OKB2D, compared with those obtained from random field analyses</td>
<td>257</td>
</tr>
<tr>
<td>5.19</td>
<td>Results of forecasts at 5 mm spacings obtained by ordinary kriging using OKB2D</td>
<td>260</td>
</tr>
<tr>
<td>5.20</td>
<td>Comparison of the sum of the squared differences, SSD, (MPa$^2$) between linear interpolation and ordinary kriging of C8 and the horizontal CPT</td>
<td>260</td>
</tr>
</tbody>
</table>
List of Tables

5.21 Results of forecasts obtained by ordinary kriging, using OKB2D, compared with those obtained from random field theory ................................................................. 263
5.22 Summary of trend removal analyses (vertical spatial variability - C8) .............. 270
5.23 Summary of sample spacing analyses (vertical spatial variability - C8) ......... 272
5.24 Summary of trend removal analyses (horizontal spatial variability) ............... 275
5.25 Summary of sample spacing analyses (horizontal spatial variability) .......... 277

Chapter 6. Compilation of a Data Base of Geotechnical Properties of the Keswick and Hindmarsh Clays

6.1 Information stored in GEOSHARE .................................................................. 283
6.2 Statistics associated with w and ρ_d of the various soil layers stored in KESWICK .................................................................................................................. 300
6.3 Statistics associated with s_u (kPa) obtained from UU tests............................ 305
6.4 Statistics associated with E_u (MPa) obtained from UU tests .......................... 313
6.5 Statistics associated with E_u (MPa) obtained from SPLT and SBPTs ............ 315

Chapter 7. Examination of the Large-Scale Lateral Spatial Variability of the Keswick Clay

7.1 Summary statistics of the results of cross validation analyses compared with the original data ............................................................................................................... 337
7.2 Summary of additional s_u data from UU tests on Keswick Clay, used to assess the spatial variability model and estimation procedure ..................................... 339
7.3 Summary of results of ordinary kriged estimates from Krige using original non-detrended data .............................................................................................. 341
7.4 Summary of results of ordinary kriged estimates from Krige using detrended data .............................................................................................................. 341
7.5 Summary of results of estimates of s_u* (kPa) and sum of the squared differences, SSD, (kPa^2) from polygonal, inverse distance and inverse distance squared estimation regimes ......................................................... 343

Chapter 8. Significance of Spatial Variability with Respect to Geotechnical Engineering Design

8.1 Global statistics of measurements of q_c within the Keswick Clay, as well as all soils encountered at the South Parklands site ......................................................... 364

Appendix C  Data Base of the Geotechnical Properties of the Keswick and Hindmarsh Clays

C.1 Data from Coffey Partners International Pty. Ltd. ............................................ 455
C.2 Data from Rust PPK Consultants Pty. Ltd. ...................................................... 457
C.3 Data from SACON ......................................................................................... 459
C.4 Data from Golder Associates Pty. Ltd.
(formerly Woodburn Fitzhardinge Geotechnical) ..............................................461
C.5 Data from ACER Wargon Chapman Pty. Ltd.
(formerly Hosking Oborn Freeman and Fox) ....................................................463
C.6 Data from Koukourou and Partners .............................................................465
C.7 Data from Connell Wagner (SA) Pty. Ltd......................................................467
C.8 Data from Kinhill Engineers Pty. Ltd.............................................................469
Notation

Throughout the thesis, the following terms refer to the properties presented below. Abbreviations and additional descriptions are given in the Glossary.

\[ A_b ; A_m ; A_s \]  
area of the base of the cone, usually 1000 mm\(^2\) = \(\frac{\pi D^2}{4}\); net area ratio of the cone = \(\frac{d^2}{D^2}\); surface area of the friction sleeve;

\[ A_p \]  
area of the base of a pile;

\[ a \]  
range of influence - the distance at which samples become independent of one another;

\[ a_c \]  
radius of the electric cone penetrometer;

\[ a_t \]  
random component, or shock, used in ARMA models with a mean of zero and a variance equal to \(\sigma_a^2\);

\[ B \]  
backshift operator;

\[ C \]  
a parameter, when added to \(C_0\), represents the sill of a transitive type of semivariogram;

\[ C_p \]  
circumference of the shaft of a pile;

\[ CV \]  
coefficient of variation = \(\frac{\sigma}{m}\times100\%\);

\[ C_{XY} \]  
covariance between data sets \(X\) and \(Y\);

\[ C_0 \]  
nugget effect - arises from the regionalised variable being so erratic over a short distance that the semivariogram goes from zero to the level of the nugget in a distance less than the sampling interval;

\[ \frac{C_0}{C + C_0} \]  
relative nugget;
c parameter used in Kendall’s τ test, where the probability of concordance is $c$ times as large as the probability of discordance;

c_k; c^*_k autocovariance at lag $k$; sample autocovariance at lag $k$;

c_{k_{xy}}; c^*_{k_{xy}} cross-covariance coefficient between time series $X$ and $Y$ at lag $k$; sample cross-covariance coefficient at lag $k$;

c_u; c' undrained and drained cohesion intercept;

c_v coefficient of consolidation;

$D$ diameter of the base of the cone, usually 35.7 mm;

$D_p$ the width of a pile, or in the case of a circular cross-section pile, its diameter;

$D_{50}$ diameter of the grain for which 50% of the particles in the sample are finer, by weight;

d_i distance from the estimation point to the $i$th neighbour (used in inverse distance and inverse distance squared weightings);

d_o smallest diameter of the cone at the o-ring seal;

$\bar{d}_v$ is the average distance between the intersections of the fluctuating property, $\nu(z)$, and its mean, $\bar{\nu}$;

E[...] expected value, or mean;

$E; E_u; E_{u(50)}$ Young’s modulus of elasticity; undrained Young’s modulus of elasticity; undrained Young’s modulus of elasticity given by the secant modulus at 50% of the peak axial strain;

$E_{Q_A}$ percentage error between the ‘true’ $Q_A$ and that based on measurements;

$E^+; E^-$ Young’s modulus of elasticity at peak shear strength on the increasing portion of the stress/strain curve and the decreasing portion of the stress/strain curve;

e void ratio;

$e_i$ random testing error term in an ARMA model as proposed by Wu and El-Jandali (1985);
**Notation**

- $F_c, F_s$: total force acting on the cone tip and the friction sleeve;
- $F_R$: friction ratio \( \frac{f_s}{q_c} \times 100\% \);
- $FoS$: factor of safety \( \frac{\text{Forces resisting instability}}{\text{Forces causing instability}} \);
- $f$: initial shear stress ratio \( \frac{\sigma_{v0} - \sigma_{u0}}{2s_u} \);
- $f_s$: sleeve friction, as measured by the cone penetration test;
- $G$: shear modulus;
- $G_s$: specific gravity of solids;
- $h$: the displacement between data pairs;
- $I_p$: plasticity index \( w_L - w_p \);
- $I_{pl}$: instability index;
- $I_r$: rigidity index \( \frac{G}{s_u} = \frac{E_u}{3s_u} \);
- $K$: the maximum number of lags, $k$, that $r_k$ and $r_{kk}$ should not be calculated beyond;
- $K_i(x)$: modified Bessel function of the second kind and first order;
- $K_0$: coefficient of earth pressure at rest; that is, at zero lateral strain;
- $k$: lag;
- $k_c$: penetrometer bearing capacity factor;
- $L_p$: length of a pile;
- $m$: mean, or average value;
- $m_{v_x}$: measurement of the parameter, $v_x$;
- $N_k; \bar{N}_k$: cone factor; average cone factor (note that $k$ does not refer to lag);
- $n$: number of observations, or data, in a data set;
$n_1; n_2; n_3$  number of observations greater than the mean, less than the mean, and equal to the mean, respectively, as used in the runs test;

$n_p$  number of parameters that must be estimated in the model under consideration, and which equals $p - q$, where $p, q$ are the number of AR and MA terms, respectively;

$OCR$  overconsolidation ratio;

$P_f$  probability of failure;

$PRE$  percentage random testing error as proposed by Wu and El-Jandali (1985);

$p$  mean normal stress;

$Q$  Box-Pierce chi-square statistic;

$Q_A; Q'_A$  allowable axial capacity of a statically loaded pile; estimate of the allowable axial capacity of a statically loaded pile based on measurements;

$Q_b; Q_s$  axial capacity of the base, and shaft, of a statically-loaded pile;

$Q_u$  ultimate axial capacity of a statically loaded pile;

$q$  lag number at which $\rho_k$ is thought to be equal to zero;

$q_i; \bar{q}_i; q_r$  cone tip resistance, as measured by the cone penetration test; average of the measured values of cone tip resistance over the length of the triaxial specimen; cone tip resistance corrected for the influence hydrostatic pressures acting on the notched section of the cone;

$q_{ca}; q_{ca}'$  clipped average cone tip resistance and intermediate clipped average cone tip resistance, at the level of the pile base (kPa);

$q_{ul(max)}$  limit unit skin friction of the $i$th soil layer;

$R$  number of runs used in the runs test;

$RAW$  An irrigation/soil science parameter which measures the water reservoir of the soil between full point, $-8$ kPa, and refill point, $-60$ kPa, and is expressed in mm (Brooker et al., 1995);

$RD$  relative density of sands;
Notation

$R_t$ residuals used in the *significance test on trends* method for assessing stationarity;

$R_q$ residuals, or the difference between measurements of $q_c$ and the trend function obtained by the method of OLS;

$R_0$ the ACF nugget: the difference between unity and the value of the autocorrelation coefficient at lag zero, $r_0$, obtained by extrapolating the sample ACF back to lag zero;

$r, r^2$ correlation coefficient; coefficient of determination;

$r_B$ Bartlett’s distance; that is, the distance at which the sample ACF intersects the limit obtained from Bartlett’s formula;

$r_k$ sample autocorrelation at lag $k$; autocorrelation at lag $k$ of residuals;

$r_{kk}$ sample partial autocorrelation coefficient at lag $k$;

$r_{kx}$ sample cross-correlation coefficient between time series $X$ and $Y$ at lag $k$;

$r_p$ the radial distance of the plastic boundary from the axis of penetration measured at a large enough distance above the cone penetrometer tip;

$S$ the difference between the number of concordant pairs and the number of disconcordant pairs (used in Kendall’s $\tau$ test);

$S_i$ the $i$th sample;

$S_i$ degree of saturation;

$SSD$ sum of the squared differences = $\sum_{i=1}^{n}{(Y_i - Y'_i)^2}$. The lower the value of $SSD$, the better the estimate;

$s_u; s_u^{*}; \bar{s}_u$ undrained shear strength; estimated undrained shear strength; average undrained shear strength;

$s_X$ sample standard deviation of time series $X$;

$t_i$ thickness of the $i$th soil layer;

$t_i$ trend component of a random field;
**Notation**

- **U** a point, line, area, or block;
- **u** total soil suction;
- **u_k** standardised random variable at location \( k \), with properties of zero mean, and standard deviation of unity;
- **u_{pw}** porewater pressure at the depth of \( q_c \) measurements;
- **V** a block or domain of some volume;
- **v_k; \hat{v}_k** soil property, \( v \), at point \( k \) in a soil mass; measurement of soil property, \( v \), at point \( k \) in a soil mass;
- **v_o** correlation distance of some property, \( v \);
- **\hat{W}_t; \hat{W}_t^{(r)}** one-step prediction errors, or residuals; rescaled residuals;
- **w** moisture content;
- **w_i** weight applied to the \( i \)th sample;
- **w_L; w_P** liquid limit; plastic limit;
- **X_i** the value of the property, \( X \), at location, \( i \);
- **X_t** a time series, or a random field;
- **Y_t; \hat{Y}_t** a time series, or a random field; best linear mean-square predictor of \( Y_t \) based on the observations up to distance, \( t - 1 \);
- **z; z_k** depth of the electric cone penetrometer; depth of the soil property at point \( k \);
- **z_p** the distance between the cone tip and the plastic boundary measured along the axis of the cone penetrometer;
- **z_k; z_e** a parameter used in the runs test and Kendall’s \( \tau \) test, respectively, which is normally distributed, with zero mean and unit variance;
- **\alpha** a constant used in the variance function, ACF, and semivariogram models, and is known as the *absolute dispersion* in the de Wijsian semivariogram model;
\( \alpha_f; \alpha_s \) roughness factor of the cone face = \( \frac{\sqrt{3}}{2} \frac{\tau_f}{s_u} \) and cone shaft = \( \frac{\sqrt{3}}{2} \frac{\tau_s}{s_u} \);

\( \Gamma(n) \) variance reduction factor;

\( \gamma; \gamma_d; \gamma_{sat} \) bulk unit weight; dry unit weight; saturated unit weight;

\( \gamma_h; \gamma_h^* \) semivariogram function at separation distance \( h \); experimental semivariogram, at \( h \), which is based on the sampled data set;

\( \Delta u \) change in total suction;

\( \Delta z_0 \) sampling interval;

\( \delta_H; \delta_V \) scale of fluctuation in the horizontal, and vertical, directions;

\( \delta \) scale of fluctuation of the soil property, \( v \);

\( \delta_{y_1}; \delta_{y_2} \) scale of fluctuation obtained by fitting Vanmarcke’s simple exponential, and squared exponential, model (given in Table 2.9), respectively, to the sample ACF;

\( \varepsilon_v \) vertical strain;

\( \varepsilon_i; \varepsilon_t \) error terms, or white noise components;

\( \zeta_{P} \) standardised normal variate associated with the probability, \( P \); that is, from a normal probability density function with zero mean and a standard deviation of unity;

\( \zeta_x \) the random measurement error at \( x \);

\( \Theta \) angle of a slope, or embankment, from the horizontal;

\( \theta_i \) constants used in a moving average process, where \( i = 1, 2, \ldots \);

\( \lambda \) a parameter used in the Box-Cox variance transformation;

\( \mu \) Lagrange multiplier;

\( \xi_x \) the random perturbation from the trend at \( x \);

\( \rho_d; \rho_w \) dry density; density of water (usually taken as 1000 kg/m\(^3\));

\( \rho_k \) autocorrelation at lag \( k \);
\( \rho_{xyr} \) cross-correlation coefficient between time series \( X \) and \( Y \) at lag \( k \);

\( \sigma; \sigma_X \) standard deviation; standard deviation of data set \( X \);

\( \sigma_3 \) cell, or confining, pressure applied in a triaxial test;

\( \sigma_a^2 \) white noise variance of the fitted ARIMA model;

\( \sigma_e^2 \) variance of the random testing error;

\( \sigma_{\text{equip}}^2 \) variance of equipment effects;

\( \sigma_h^*; \sigma_v^* \) effective horizontal and vertical stress;

\( \sigma_{ho}; \sigma_v \) total in situ horizontal and vertical overburden stress;

\( \sigma_h^2; \sigma_e^2 \) kriging variance; estimation variance;

\( \sigma_{\text{measure}}^2 \) total variance of measurement;

\( \sigma_p^* \) effective preconsolidation pressure;

\( \sigma_{\text{op/proc}}^2 \) variance of operator and procedural effects;

\( \sigma_{\text{random}}^2 \) variance of random testing effects;

\( \sigma_z^2 \) variance of the observed, or transformed, data;

\( \tau \) test statistic used in Kendall’s \( \tau \) test;

\( \tau_h; \tau_s \) shear stress on the cone face and the sleeve face;

\( \phi; \phi^*; \phi_u; \phi_d \) total internal angle of friction; effective internal angle of friction; undrained and drained internal angle of friction;

\( \phi_i \) constants used in an autoregressive, AR, process, where \( i = 1, 2, ... \);

\( \phi_{ki} \) partial autocorrelation at lag \( k \);

\( \psi \) a constant used in the LCPC Method which allows for the nature of the soil and the pile construction and placement methods;

\( \chi_{5;5}^2(z) \) the point on the scale of the chi-square distribution having \( z \) degrees of freedom such that there is an area of 5% under the curve of this distribution above this point;

\( \nabla^k \) difference operator of order \( k \).
Glossary

Note: A term with an asterisk (*) beside it, indicates that the definition was obtained from Olea (1991). A term in *italics* implies a cross-reference to another glossary listed item.

ACF  
Autocorrelation function;

ACVF  
Autocovariance function;

A/D converter  
Analogue to digital converter;

AHD  
Australian height datum - a standard datum surface, effectively a mean sea level, adopted by the National Mapping Council, to which all vertical control for mapping is referred;

AMG  
Australian map grid - a standard map grid established by the National Mapping Council of Australia and derived from a Transverse Mercator projection of latitudes and longitudes, the coordinates of which are in metres;

Analogue output  
Transducer output which is a continuous function of the *measurand* (except as modified by the resolution of the transducer);

AR  
Autoregressive *time series* model;

ARIMA  
Integrated autoregressive-moving average *time series* model;

ARMA  
Autoregressive-moving average *time series* model;

ASCII  
American Standard Code for Information Interchange;

Autocorrelation, $\rho_k$  
The relationship between any two *time series* observations separated by a *lag* of $k$ units;

Bartlett’s distance  
The distance given by the intersection of the sample ACF with *Bartlett’s limits*;
<table>
<thead>
<tr>
<th><strong>Bartlett’s limits</strong></th>
<th>The limits obtained by substitution into Bartlett’s equation; that is, $\pm 1.96/\sqrt{N}$;</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bayesian kriging</strong></td>
<td>An enhancement of <em>indicator kriging</em> which is used when a small number of observations is available, and when significant experience and knowledge about the phenomenon should be accounted for in the estimation process;</td>
</tr>
<tr>
<td><strong>BLUE</strong></td>
<td>Best linear unbiased estimator;</td>
</tr>
<tr>
<td><strong>CCF</strong></td>
<td>Cross-correlation function;</td>
</tr>
<tr>
<td><strong>CGA</strong></td>
<td>Colour graphics adaptor;</td>
</tr>
<tr>
<td><strong>CIRIA</strong></td>
<td>Construction Industry Research and Information Association (UK);</td>
</tr>
<tr>
<td><strong>CIU</strong></td>
<td>Isotropically consolidated, undrained triaxial compression test;</td>
</tr>
<tr>
<td><strong>CK₀ U</strong></td>
<td>Undrained triaxial test where the sample is reconsolidated to in situ $K₀$ conditions prior to shear;</td>
</tr>
<tr>
<td><strong>Correlation distance</strong></td>
<td>The extent over which samples exhibit strong correlation. Vanmarcke and Fuleihan (1975) defined it as the distance required for the $ACF$ to drop from 1 to $e^{-1}$ (0.3679);</td>
</tr>
<tr>
<td><strong>CPT</strong></td>
<td>Cone penetration test;</td>
</tr>
<tr>
<td><strong>Cross validation</strong>*</td>
<td>A validation method in which observations are temporarily discarded, one at a time, from a data set of size $n$, and $n$ estimates are computed using, at most, the remaining $(n - 1)$ measurements;</td>
</tr>
<tr>
<td><strong>CSMD</strong></td>
<td>Colorado School of Mines borehole dilatometer - an in situ test device which measures the modulus of rigidity of rocks;</td>
</tr>
<tr>
<td><strong>Data conversion factor</strong></td>
<td>Each $mpb$ is multiplied by this to yield the digital equivalent of the measured quantity;</td>
</tr>
<tr>
<td><strong>DC</strong></td>
<td>Direct current;</td>
</tr>
<tr>
<td><strong>Digital output</strong></td>
<td>Transducer output which is a stepped function of the <em>measurand</em>;</td>
</tr>
<tr>
<td><strong>DMT</strong></td>
<td>Marchetti flate plate dilatometer;</td>
</tr>
<tr>
<td>Glossary Term</td>
<td>Definition</td>
</tr>
<tr>
<td>---------------</td>
<td>------------</td>
</tr>
<tr>
<td>Drift*</td>
<td>A mathematical description of the low frequency, large-scale variation of a regionalised variable, (cf. trend); also the deviation, from vertical or horizontal, of the CPT;</td>
</tr>
<tr>
<td>DST</td>
<td>Direct shear test;</td>
</tr>
<tr>
<td>EPROM</td>
<td>Erasable programmable read only memory;</td>
</tr>
<tr>
<td>Falling off</td>
<td>A phenomenon associated with measurements of $q_c$ and $f_s$ that occurs when further rods are added to the drill stem and is indicated by these measurements dropping to zero or values significantly less than that recorded immediately above it (cf. Figure 3.15);</td>
</tr>
<tr>
<td>FoS</td>
<td>Factor of safety;</td>
</tr>
<tr>
<td>Friction reducer</td>
<td>Narrow local protuberances outside the surface of the CPT push rods, placed above the cone penetrometer tip, and provided to reduce the total friction on the push rods;</td>
</tr>
<tr>
<td>Geostatistics</td>
<td>A mathematical technique used to estimate properties which are spatially dependent;</td>
</tr>
<tr>
<td>Gilgais</td>
<td>Dome-type undulations of the upper surface of the Keswick Clay and Hindmarsh Clay Formation;</td>
</tr>
<tr>
<td>GLS</td>
<td>The regression analysis method of generalised least squares;</td>
</tr>
<tr>
<td>Heteroscedasticity</td>
<td>Non-constant variance;</td>
</tr>
<tr>
<td>Hole effect*</td>
<td>A semivariogram which is not monotonically increasing and which may reflect periodicities in the random field;</td>
</tr>
<tr>
<td>Homogeneity</td>
<td>The property of a spatial series when its characteristics are independent of location. Homogeneity is equivalent to stationarity;</td>
</tr>
<tr>
<td>Homoscedasticity</td>
<td>Constant variance;</td>
</tr>
<tr>
<td>Indicator kriging*</td>
<td>Simple kriging or ordinary kriging applied to indicator data (samples which have been transformed into binary numbers) sharing the same threshold;</td>
</tr>
<tr>
<td>Interrupt driven measurements</td>
<td>The MPU immediately processes these measurements as soon as an interrupt signal is received;</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
</tr>
<tr>
<td>----------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>ISOPT-1</td>
<td>First International Symposium on Penetration Testing, Orlando, Florida, 1988;</td>
</tr>
<tr>
<td>kb</td>
<td>kilobytes;</td>
</tr>
<tr>
<td>Kriging*</td>
<td>A collection of generalised linear regression techniques for minimising an estimation variance defined from a prior model. In contrast to classical linear regression, kriging takes into account stochastic dependence among the data;</td>
</tr>
<tr>
<td>Kurt., kurtosis*</td>
<td>The kurtosis is a measure of the peakedness of a data distribution around the mode. A kurtosis: equal to 3 suggests a normal, or Gaussian, distribution; &lt; 3 implies a lower concentration near the mean than a normal distribution; and &gt; 3 suggests that the distribution has an excess of values near the mean;</td>
</tr>
<tr>
<td>Lag, $k^*$</td>
<td>The difference in the time of occurrence of two events in a time series, or in relation to a spatial series, the lag is the distance between the locations of two random variables in a random field;</td>
</tr>
<tr>
<td>LCD</td>
<td>Liquid crystal display;</td>
</tr>
<tr>
<td>LCPC method</td>
<td>A method for determining the axial capacity of a statically loaded pile based on CPT data, and developed at the Laboratoire Central des Ponts et Chaussées, France;</td>
</tr>
<tr>
<td>LNS</td>
<td>The regression analysis method of least normal squares;</td>
</tr>
<tr>
<td>Load cell</td>
<td>A device, usually consisting of electrical resistance strain gauges, which generates an output signal proportional to the applied force or weight;</td>
</tr>
<tr>
<td>MA</td>
<td>Moving average time series model;</td>
</tr>
<tr>
<td>Markov process*</td>
<td>A stochastic process in which a prediction is determined solely by the closest $n$ observations, and is stochastically independent from all remaining, more distant observations;</td>
</tr>
<tr>
<td>Measurand</td>
<td>The physical quantity, property, or condition that is to be measured;</td>
</tr>
<tr>
<td>Missing depth</td>
<td>A rationalised depth which has no associated measurement of $q_c$ and/or $f_s$;</td>
</tr>
<tr>
<td>Glossary Term</td>
<td>Definition</td>
</tr>
<tr>
<td>--------------</td>
<td>------------</td>
</tr>
<tr>
<td>Modulus of sub-grade reaction</td>
<td>The elastic modulus of the subgrade which accounts for pavement deformation;</td>
</tr>
<tr>
<td>Monte Carlo* methods</td>
<td>Any number of procedures that use simulated random samples to make inferences about actual populations;</td>
</tr>
<tr>
<td>mpb</td>
<td>Microprocessor bit - the digital unit that is multiplied by the data conversion factor to yield the digital equivalent of the measured quantity. (e.g. 1 mpb of $f_s$ measurements is equivalent to 0.488 kPa);</td>
</tr>
<tr>
<td>MPU</td>
<td>Microprocessor unit - the microchip that forms the core of the microprocessor interface;</td>
</tr>
<tr>
<td>NATA</td>
<td>National Association of Testing Authorities, Australia;</td>
</tr>
<tr>
<td>N/E</td>
<td>Not encountered;</td>
</tr>
<tr>
<td>Nested structures*</td>
<td>A <em>regionalised variable</em> whose spatial continuity is the compound effect of several genetic sources of spatial variation;</td>
</tr>
<tr>
<td>Noise spikes</td>
<td>A phenomenon associated with measurements of $q_c$ and $f_s$ that occurs randomly, and as a result of electrical noise originating from inadequate earthing of the CPT cable (cf. Figure 3.15);</td>
</tr>
<tr>
<td>Nugget effect</td>
<td>When the <em>semivariogram</em> does not pass through the origin and arises from the <em>regionalised variable</em> being so erratic over a short distance that the <em>semivariogram</em> goes from zero to the level of the nugget in a distance less than the sampling interval;</td>
</tr>
<tr>
<td>OLS</td>
<td>The regression analysis method of ordinary least squares;</td>
</tr>
<tr>
<td>Ordinary kriging</td>
<td>The general geostatistical estimation process often simply known as <em>kriging</em>. Unlike <em>simple kriging</em>, the mean is unknown;</td>
</tr>
<tr>
<td>Overshoot</td>
<td>The amount of output measured beyond the final steady output value in response to a step change in the <em>measurand</em>;</td>
</tr>
<tr>
<td>PACF</td>
<td>Partial autocorrelation function;</td>
</tr>
<tr>
<td>PC</td>
<td>Personal computer;</td>
</tr>
<tr>
<td>Permanent mark</td>
<td>A rigid reference point whose <em>AMG</em> and <em>AHD</em> coordinates are known accurately;</td>
</tr>
<tr>
<td>PLT</td>
<td>Plate load test;</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>RAM</td>
<td>Random access memory;</td>
</tr>
<tr>
<td>Random field*</td>
<td>A collection of random variables in an $n$-dimensional euclidean space;</td>
</tr>
<tr>
<td>Random field theory</td>
<td>The application of <em>time series analysis</em> to the spatial variability of geotechnical properties, and unlike <em>time series analysis</em>, random field theory is not confined to one dimension;</td>
</tr>
<tr>
<td>Range of influence*</td>
<td>The maximum distance separating pairs of random variables that have any significant statistical dependence;</td>
</tr>
<tr>
<td>Rationalised depth</td>
<td>A depth below the ground surface which refers to the <em>CPT</em>, and which has been rounded to the nearest 5 mm;</td>
</tr>
<tr>
<td>RAW</td>
<td>An irrigation/soil science parameter which measures the water reservoir of the soil between full point, $-8$ kPa, and refill point, $-60$ kPa, and is expressed in mm (Brooker et al., 1995);</td>
</tr>
<tr>
<td>Rebound phenomenon</td>
<td>A phenomenon observed in measurements of $f_s$ within the Keswick Clay at the depth at which the test is temporarily suspended and later recommenced. It is manifested by a sudden increase in measurements of $f_s$ below the depth at which the test was suspended. It is proposed that this phenomenon is a consequence of rebound of the pseudo-overconsolidated Keswick Clay, and which would not have occurred had the test not been suspended;</td>
</tr>
<tr>
<td>Regionalised variable</td>
<td>A variable which has properties that are partly random and partly spatial, and has continuity from point to point, but the changes are so complex that it cannot be described by a tractable deterministic function;</td>
</tr>
<tr>
<td>Relative nugget</td>
<td>The ratio between the <em>nugget effect</em>, $C_0$, and the level of the sill, $C + C_0$;</td>
</tr>
<tr>
<td>Resolution</td>
<td>The magnitude of discernable (detectable) output changes as the <em>measurand</em> is continuously varied over the range;</td>
</tr>
<tr>
<td>RL</td>
<td>Reduced level;</td>
</tr>
<tr>
<td>RMA</td>
<td>The regression analysis method of reduced major axis;</td>
</tr>
<tr>
<td>SBPT</td>
<td>Self-boring pressuremeter test;</td>
</tr>
</tbody>
</table>
Scatterplot An $x$-$y$ graph on which the $x$-coordinate corresponds to the value of one variable and the $y$-coordinate corresponds to the value of the other variable;

SDF $\textit{Spectral density function};$

Semivariogram, $\gamma_h$ The expected value, or mean, of the squared difference between pairs of points, $Y_x$ and $Y_{x+h}$, separated by a displacement, $h$;

Shift distance The distance by which $f_s$ measurements are shifted, usually 75 mm, so that measurements of $q_c$ and $f_s$ correspond to the same depth. Such a shift enables the calculation of $F_R$ to be performed correctly;

Sill* The limiting value of the semivariogram which is reached at some finite distance known as the range of influence. The sill is numerically equal to the variance of the random function;

Simple kriging* The same as ordinary kriging, except that the mean is known, and hence the final row is deleted from all matrices, as is the final column of the square matrix;

Skew., skewness The skewness is a measure of the symmetry of a data distribution. A skewness of zero suggests a symmetrical distribution, a positive value indicates a right-hand skew, and a negative value indicates a left-hand skew;

Spatial series A sequence of discrete or continuous data measured at specific locations - the spatial equivalent of a time series;

Spectral density function The Fourier transform of the $ACF$; that is, in the frequency domain;

SPLT Screw plate load test;

Stationarity* A term used to denote different degrees of invariance in the characteristics of random fields. If the mean and autocovariance of the series change with the lag, and not location, the series is said to be weakly stationary. If all higher moments depend on the lag, and not position, the series is said to be stationary in the strict sense. (cf. homogeneity);

Stiction The resistance to movement developed between the writing mechanism and the paper of a chart recorder, resulting in a delayed response to input signals;
**TCD#** Consolidated drained triaxial test with # stages;  
**TCU#** Consolidated undrained triaxial test with # stages;  
**Time series** A sequence of discrete or continuous data measured at specific instances in time - also a 1D random field (cf. spatial series);  
**Time series analysis** A mathematical technique used to estimate properties which are temporally or spatially dependent. When applied to geotechnical engineering, time series analysis is usually referred to as random field theory;  
**Transitive semivariogram** A semivariogram with a finite sill. For example, the spherical, exponential and Gaussian models are all types of transitive semivariograms;  
**Trend** An abstract expression of the low frequency, large-scale systematic variation of a regionalised variable. The trend may also include bias in the test method (cf. drift);  
**TUC** Unconfined triaxial test, or, unconfined compression test;  
**TUU#** Unconsolidated undrained triaxial test with # stages;  
**UC** Universal column - a mild steel I beam primarily used as a compression member;  
**UCS** Unconfined compressive strength;  
**Universal kriging** Simple kriging of the residuals of a regionalised variable after automatically removing optimal estimates of the drift, and is used for non-stationary data, that is, when a deterministic trend exists in the measured data;  
**USCS** Unified soil classification system;  
**UU** Unconsolidated undrained triaxial test;  
**VST** Vane shear test.
CORRIGENDA

"The Influence of Spatial Variability on the Geotechnical Design Properties of a Stiff, Overconsolidated Clay"

by M. B. Jaka

March 1996

pg. vii, Acknowledgments After 3rd paragraph add:

"In addition, I am grateful for the generosity and assistance provided by Australian National, and in particular, Mr. Peter Gaskill, for allowing testing to be carried out at the Keswick site. I also wish to thank Dr. K. S. Li, Mitchell, McFarlane, Brentnall and Partners, Hong Kong, and Dr. S.-C. R. Lo and Mr. G. R. Mostya, University of N.S.W., for permission to use the program PROBSN."

pg. 231, Table 5.12: Replace “kN/m²” with “kN/m²”

pg. 269, Para. 2, Line 2: Replace “from 6% to 41%” with “from 5% to 22%”

pg. 270, Table 5.22 Replace Random Field Theory table with (values which have been corrected are shown in bold):

<table>
<thead>
<tr>
<th>Degree of Polynomial Trend Removed from Data</th>
<th>Kendall’s χ² Test</th>
<th>Degree of Fit, r²</th>
<th>r_s (mm)</th>
<th>r_t</th>
<th>r_e</th>
<th>ACF Nugget, R_n</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>X</td>
<td>-</td>
<td>765</td>
<td>0.95</td>
<td>0.95</td>
<td>5%</td>
</tr>
<tr>
<td>1</td>
<td>X</td>
<td>0.88</td>
<td>680</td>
<td>0.94</td>
<td>0.94</td>
<td>6%</td>
</tr>
<tr>
<td>2</td>
<td>✖</td>
<td>0.719</td>
<td>240</td>
<td>0.88</td>
<td>0.88</td>
<td>12%</td>
</tr>
<tr>
<td>3</td>
<td>✓</td>
<td>0.730</td>
<td>190</td>
<td>0.88</td>
<td>0.88</td>
<td>12%</td>
</tr>
<tr>
<td>4</td>
<td>✓</td>
<td>0.774</td>
<td>190</td>
<td>0.87</td>
<td>0.87</td>
<td>13%</td>
</tr>
<tr>
<td>5</td>
<td>✓</td>
<td>0.818</td>
<td>110</td>
<td>0.86</td>
<td>0.86</td>
<td>14%</td>
</tr>
<tr>
<td>6</td>
<td>✓</td>
<td>0.846</td>
<td>85</td>
<td>0.78</td>
<td>0.78</td>
<td>22%</td>
</tr>
</tbody>
</table>
pg. 271, Figure 5.86  
Replace Figure 5.86(a) with:

![Graph showing autocorrelation (r) against distance (mm).]

pg. 274, Para. 4, Line 2:  
Replace: “substantially, from 3% to 56%, and again demonstrates that the nugget depends greatly on the degree of trend which is removed from the data.”
With: “varies only marginally, from 3% to 4%.”

pg. 275, Table 5.24  
Replace Random Field Theory table with (values which have been corrected are shown in bold):

<table>
<thead>
<tr>
<th>Degree of Polynomial Trend Removed from Data</th>
<th>Kendall’s τ Test</th>
<th>Degree of Fit, $r^2$</th>
<th>$r_0$ (mm)</th>
<th>$r_1$</th>
<th>$r_2$</th>
<th>ACF Nugget, $R_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>-</td>
<td>1.075</td>
<td>0.97</td>
<td>0.97</td>
<td>0.97</td>
<td>3%</td>
</tr>
<tr>
<td>1</td>
<td>✓</td>
<td>0.047</td>
<td>655</td>
<td>0.97</td>
<td>0.97</td>
<td>3%</td>
</tr>
<tr>
<td>2</td>
<td>✓</td>
<td>0.184</td>
<td>135</td>
<td>0.97</td>
<td>0.97</td>
<td>3%</td>
</tr>
<tr>
<td>3</td>
<td>✓</td>
<td>0.297</td>
<td>110</td>
<td>0.97</td>
<td>0.97</td>
<td>3%</td>
</tr>
<tr>
<td>4</td>
<td>✓</td>
<td>0.379</td>
<td>100</td>
<td>0.96</td>
<td>0.96</td>
<td>4%</td>
</tr>
<tr>
<td>5</td>
<td>✓</td>
<td>0.384</td>
<td>100</td>
<td>0.96</td>
<td>0.96</td>
<td>4%</td>
</tr>
<tr>
<td>0</td>
<td>✓</td>
<td>0.394</td>
<td>95</td>
<td>0.96</td>
<td>0.96</td>
<td>4%</td>
</tr>
</tbody>
</table>

pg. 278, Para. 3, Line 4:  
Replace “56%” with “22%”

pg. 356, Line 4:  
Replace the last occurrence of “F3A” with “F51”