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# Soft clay foundation improvement via prefabricated vertical drains and vacuum preloading

Chamari Bamunawita  
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**SOFT CLAY FOUNDATION IMPROVEMENT VIA  
PREFABRICATED VERTICAL DRAINS AND VACUUM  
PRELOADING**

A thesis submitted in fulfilment of the  
requirements for the award of the degree

**Doctor of Philosophy**

from

**University of Wollongong**

by

**Chamari Bamunawita, BSc Eng (Hons)**

Department of Civil Engineering

2004

## **CERTIFICATION**

I, Chamari Inomika Bamunawita, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Department of Civil Engineering, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

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Chamari Inomika Bamunawita

23 February 2004

## ABSTRACT

This thesis includes the numerical modelling of prefabricated vertical drain (PVD) subjected to vacuum loading in a 2-D plane strain finite element model employing the modified Cam-clay theory, and the experimental evaluation of effectiveness of combined vacuum and surcharge preloading using a large scale, radial drainage consolidometer. The original axisymmetric analysis and plane strain analysis of vertical drains including the effect of smear and well resistance have been well documented in the past for surcharge preloading. In this study, the existing axisymmetric and plane strain theories of a unit cell are modified to incorporate the vacuum pressure application. Unsaturation of drain soil boundary owing to the vacuum pressure is also considered in the numerical modeling. Thereafter, a multi-drain, plane strain analysis is conducted to study the performance of the entire embankment stabilised with vertical drains subjected to vacuum preloading, for two case histories taken from Thailand.

A laboratory technique of evaluating the effectiveness of combined vacuum and surcharge preloading is elaborated. In this approach, a central vertical drain was installed in soil specimens placed in a large stainless steel cell (450 mm in diameter and 950 mm in height) using a specially designed mandrel, and then the vacuum and surcharge loads were applied using the two different loading systems. The results clearly show the effectiveness of vacuum preloading. Following initial laboratory simulation in the large-scale radial drainage consolidometer, a different approach to conventional analysis is adopted to analyse the vacuum assisted consolidation around vertical drains. It is assumed here that a linear variation of negative pore pressure along

the drain length and a constant (maximum) suction head at the ground surface are realistic and sufficient. The observed retardation of pore pressure dissipation is explained through a series of finite element models, which consider the effect of unsaturation at the drain-soil interface. The results indicate that the introduction of an unsaturated soil layer adjacent to a PVD improves the accuracy of numerical predictions.

The knowledge gained from the modeling of large-scale consolidometer cell is applied to study the behaviour of two embankments built on soft clay, stabilised with vertical drains subjected to vacuum loading. A multi-drain analysis is conducted and the field measurements are compared with a series of numerical model predictions. The best predictions of settlement, lateral displacements and pore pressures are obtained when the numerical analysis included the time and depth dependent changes in vacuum pressure, in addition to having an unsaturated layer of elements along the external boundary of the PVD. Finally, a comprehensive multi-drain analysis is used to predict the failure height of embankment, considering various parameters such as embankment geometry, construction method, sub soil properties and soil improvement techniques.

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## TABLE OF CONTENTS

|   |           |
|---|-----------|
| <b>ABSTRACT</b>   | iii       |
| <b>ACKNOWLEDGMENTS</b>  | v         |
| <b>TABLE OF CONTENTS</b>  | vi        |
| <b>LIST OF FIGURES</b>  | xi        |
| <b>LIST OF TABLES</b>   | xviii     |
| <b>LIST OF SYMBOLS</b>  | xix       |
| <br>  |           |
| <b>1 INTRODUCTION</b>   | <b>1</b>  |
| 1.1 General   | 1         |
| 1.2 Purpose and Application of Vertical Drains                        | 3         |
| 1.3 Application of Surcharge and Vacuum Preloading                    | 6         |
| 1.4 Analysis of Soft Clay Foundations Stabilized with Vertical Drains | 8         |
| 1.5 Objectives and the Scope of Study                                 | 9         |
| 1.6 Organisation of the Thesis  | 10        |
| <br>  |           |
| <b>2 LITERATURE REVIEW</b>  | <b>12</b> |
| 2.1 History and Development of Vertical Drains                        | 12        |
| 2.2 Installation and Monitoring of Vertical Drains                    | 13        |
| 2.3 Drain Properties  | 16        |
| 2.3.1 Equivalent drain diameter for band shaped drain                 | 16        |
| 2.3.2 Filter and apparent opening size (AOS)                          | 18        |
| 2.3.3 Discharge capacity  | 19        |
| 2.4 Factors Influencing the Vertical Drain Efficiency                 | 22        |
| 2.4.1 Smear zone  | 22        |
| 2.4.1.1 Mandrel size and shape  | 25        |
| 2.4.1.2 Soil macro fabric   | 27        |
| 2.4.1.3 Installation procedure  | 27        |



|          |   |           |
|----------|---|-----------|
| 2.4.2    | Well resistance   | 29        |
| 2.5      | Influence Zone of Drains  | 29        |
| 2.6      | Development of Vertical Drain Theory                                    | 30        |
| 2.6.1    | Equal vertical strain hypothesis (Barron, 1948)                         | 32        |
| 2.6.2    | Approximate equal strain solution (Hansbo, 1981)                        | 38        |
| 2.6.3    | $\lambda$ method (Hansbo, 1979 and 1997)                                | 39        |
| 2.6.4    | Plane strain consolidation model (Indraratna & Redana, 1997)            | 40        |
| 2.7      | Consolidation around Vertical Drains                                    | 44        |
| 2.7.1    | Rate of consolidation   | 44        |
| 2.7.2    | Coefficient of Consolidation with Radial Drainage                       | 45        |
|          | 2.7.2.1 Log U vs t approach   | 45        |
|          | 2.7.2.2 Plotting settlement data (Asaoka, 1978)                         | 46        |
| 2.8      | Effect of Horizontal to Vertical Permeability Ratio                     | 47        |
| 2.9      | Application of Vacuum Preloading  | 49        |
| 2.10     | Soft Clay Modelling   | 50        |
| 2.10.1   | Modified Cam-clay   | 55        |
| 2.11     | Salient Aspects Of Numerical Modelling                                  | 56        |
| 2.11.1   | Drain efficiency by pore pressure dissipation (Indraratna et al., 1994) | 56        |
| 2.11.2   | Matching permeability & geometry (Hird et al., 1995)                    | 58        |
| 2.11.3   | Modelling of discharge capacity (Chai et al. 1995)                      | 61        |
| 2.11.4   | Deformation as a stability indicator                                    | 63        |
| 2.11.5   | Application of vacuum pressure (Bergado et al., 1998)                   | 65        |
| 2.11.6   | Equivalent plane strain modelling                                       | 67        |
| 2.12     | Application Of Numerical Modelling In Practice And Field Observation    | 72        |
| 2.13     | Summary   | 78        |
| <b>3</b> | <b>THEORETICAL CONSIDERATIONS</b>                                       | <b>80</b> |
| 3.1      | General   | 80        |

|          |   |            |
|----------|---|------------|
| 3.2      | Modelling of Axisymmetric Solution with Applied Vacuum Pressure                       | 81         |
| 3.3      | Modelling of Plane Strain Solution Incorporating Vacuum Pressure Application          | 92         |
| 3.3.1    | No smear or well resistance   | 92         |
| 3.3.2    | With smear and well resistance  | 95         |
| 3.4      | Comparison of Axisymmetric vs Plane Strain Conditions                                 | 100        |
| 3.5      | Matching Principle and Theoretical Considerations                                     | 101        |
| 3.6      | Summary   | 105        |
| <b>4</b> | <b>LABORATORY TESTING OF PVD INSTALLED CLAY</b>                                       | <b>107</b> |
| 4.1      | General   | 107        |
| 4.2      | Large-scale Tests on Vertical drains  | 108        |
| 4.3      | Tests on Vacuum Preloading  | 109        |
| 4.4      | Apparatus and Test Procedure  | 110        |
| 4.4.1    | Apparatus   | 110        |
| 4.4.2    | Test procedure  | 113        |
| 4.4.2.1  | Test sample   | 113        |
| 4.4.2.2  | Test procedure  | 114        |
| 4.5      | Results and Discussion  | 115        |
| 4.5.1    | With and without vacuum pressure  | 115        |
| 4.5.2    | Effect of removal and reapplication of vacuum pressure                                | 119        |
| 4.6      | Summary   | 122        |
| <b>5</b> | <b>NUMERICAL MODELLING OF VERTICAL DRAINS</b>   | <b>123</b> |
| 5.1      | Introduction  | 123        |
| 5.2      | Conversion of Three-Dimensional Drain Pattern to An Equivalent Two-Dimensional System | 124        |
| 5.3      | Types of Finite Elements  | 125        |
| 5.4      | Modelling of Vacuum and Surcharge Preloading  | 127        |
| 5.5      | Soil moisture characteristic curve  | 134        |

|          |   |            |
|----------|---|------------|
| 5.6      | Unsaturation of Soil due to Vacuum Preloading                       | 134        |
| 5.6.1    | Effect of surcharge loading   | 145        |
| 5.6.2    | Effect of soil type   | 146        |
| 5.6.3    | Effect of initial saturated permeability                            | 148        |
| 5.7      | Numerical Modelling of Large-scale Consolidometer Cell              | 150        |
| 5.8      | Mandel-Cryer Effect   | 156        |
| 5.9      | Summary   | 162        |
| <b>6</b> | <b>APPLICATION OF NUMERICAL MODEL IN PRACTICE</b>                   | <b>164</b> |
| 6.1      | General   | 164        |
| 6.2      | Numerical Analysis  | 169        |
| 6.3      | Summary   | 187        |
| <b>7</b> | <b>A FEM PERSPECTIVE FOR GENERAL DESIGN</b>                         | <b>189</b> |
| 7.1      | General   | 189        |
| 7.2      | Embankment Constructed on Soft Clay without any Improvement         | 190        |
| 7.2.1    | Soil conditions   | 190        |
| 7.2.2    | Finite element mesh   | 192        |
| 7.2.3    | The effect of the slope of the embankment                           | 194        |
| 7.2.4    | Effect of loading rate of the embankment                            | 198        |
| 7.3      | Staged Construction and Effect of Surface Crust                     | 202        |
| 7.4      | Embankments Constructed on Soft Clay Stabilized with Vertical Drain | 205        |
| 7.4.1    | Effect of smear   | 213        |
| 7.5      | Embankments Constructed on Soft Clay Subjected to Vacuum Loading    | 217        |
| 7.5.1    | Effect of drain spacing upon vacuum application                     | 217        |
| 7.5.2    | Effect of construction rate upon vacuum application                 | 220        |
| 7.5.3    | Effect of smear upon vacuum application                             | 223        |
| 7.6      | Summary   | 229        |

|          |  |            |
|----------|--|------------|
| <b>8</b> | <b>CONCLUSIONS AND RECOMMENDATIONS</b>   | <b>231</b> |
| 8.1      | General Summary  | 231        |
| 8.2      | Specific Observations and Conclusions  | 234        |
| 8.2.1    | Modification to the existing theories to incorporate vacuum application              | 234        |
| 8.2.2    | Laboratory Work  | 235        |
| 8.2.3    | Numerical modeling of vertical drain subjected to vacuum pressure                    | 236        |
| 8.2.4    | Case history analysis  | 237        |
| 8.2.5    | Application of Finite element modeling for general design                            | 238        |
| 8.3      | Recommendations for Future Work  | 240        |
|          | <b>BIBLIOGRAPHY</b>  | <b>243</b> |
|          | <b>APPENDIX A: COMPUTER PROGRAMME TO CONVERT VOLTAGE VALUES TO APPROPRIATE UNITS</b> | <b>253</b> |
|          | <b>APPENDIX B: MODIFIED CAM-CLAY PARAMETERS</b>                                      | <b>254</b> |
|          | <b>APPENDIX C: PARAMETRIC INPUT FILE</b>   | <b>257</b> |

## LIST OF FIGURES

|             |  |    |
|-------------|--|----|
| Figure 1.1  | Effect of vertical drain on drainage path  | 2  |
| Figure 1.2  | Typical types of PVD   | 4  |
| Figure 1.3  | Typical installation rig   | 5  |
| Figure 2.1  | Basic instrumentation of embankment  | 13 |
| Figure 2.2  | Schematic diagram of embankment subjected to vacuum loading  | 14 |
| Figure 2.3  | Equivalent diameter of band-shaped vertical drains   | 17 |
| Figure 2.4  | Typical values of vertical discharge capacity (after Rixner et al., 1986)  | 20 |
| Figure 2.5  | a) Schematic section of the test equipment showing the central drain and associated smear and b) locations of small specimens obtained to determine the consolidation and permeability characteristics (Indraratna & Redana, 1998) | 25 |
| Figure 2.6  | Ratio of $k_h/k_v$ along the radial distance from the central drain  | 26 |
| Figure 2.7  | Approximation of the smear zone around the mandrel   | 28 |
| Figure 2.8  | Plan of drain well pattern and zone of influence of each well  | 30 |
| Figure 2.9  | Schematic of soil cylinder with vertical drain (after Hansbo, 1979)  | 33 |
| Figure 2.10 | Average consolidation rates a) for vertical flow b) for radial flow  | 36 |
| Figure 2.11 | Conversion of an axisymmetric unit cell into plane strain condition  | 42 |
| Figure 2.12 | Aboshi and Monden (1963) method for determining $c_h$  | 45 |
| Figure 2.13 | Asaoka (1978) method to determine $c_h$  | 47 |
| Figure 2.14 | Isotropic normal consolidation line (NCL) plot in critical state theory (after Schofield & Wroth, 1968)  | 52 |
| Figure 2.15 | Position of the critical state line  | 53 |
| Figure 2.16 | Position of the initial void ratio on critical state line  | 53 |
| Figure 2.17 | The yield locus of Cam-clay and modified Cam-clay  | 55 |
| Figure 2.18 | Percentage of undissipated excess pore pressures at drain-soil interfaces (Indraratna et al., 1994)  | 57 |
| Figure 2.19 | Result of axisymmetric and matched plane strain for Porto Tolle embankment: a) average surface settlement and b) excess pore pressure (Hird et al., 1995)  | 60 |

|             |  |    |
|-------------|--|----|
| Figure 2.20 | Comparison of average degree of horizontal consolidation (Chai et al., 1995)   | 62 |
| Figure 2.21 | Comparison of excess pore pressure variation with depth (Chai et al., 1995)  | 62 |
| Figure 2.22 | Cross-section of embankment TV1 with 15 m long PVD and location of monitoring instruments (Bergado et al., 1998)   | 67 |
| Figure 2.23 | Simplified variation of permeability within and out side smear zone  | 69 |
| Figure 2.24 | Average degree of consolidation vs Time factor   | 70 |
| Figure 2.25 | Comparison of the average surface settlement for axisymmetric and equivalent plane strain analyses with smear and well resistance (Indraratna et. al., 2000) | 71 |
| Figure 2.26 | Comparison of the excess pore pressure for axisymmetric and equivalent plane strain analyses with smear and well resistance (Indraratna et. al., 2000)       | 71 |
| Figure 2.27 | Sub-soil profile, Cam-clay parameters and stress condition used in numerical analysis, Second Bangkok International Airport, (after AIT, 1995)               | 73 |
| Figure 2.28 | Finite element mesh of embankment for plane strain analysis with variable drain lengths (Redana, 1999)   | 73 |
| Figure 2.29 | Finite element mesh of the embankment for plane strain analysis with constant drain length (Indraratna & Redana, 1999)                                       | 74 |
| Figure 2.30 | Construction loading history for embankments TS1, TS2 and TS3 at Second Bangkok International Airport (AIT, 1995)  | 74 |
| Figure 2.31 | Surface settlement at the centre-line for embankment TS1, Second Bangkok International Airport (Indraratna & Redana, 2000)                                   | 75 |
| Figure 2.32 | Variation of excess pore water pressures at 2 m depth below ground level at the centre-line for embankment TS1 (Indraratna & Redana, 2000)                   | 77 |
| Figure 2.33 | Surface settlement profiles after 400 days, Muar clay, Malaysia (Indraratna & Redana, 1999)  | 77 |
| Figure 2.34 | Lateral displacement profiles at 23 m away from centerline of embankments a) after 44 days, and b) after 294 days (Indraratna & Redana, 1999)                | 78 |
| Figure 3.1  | Schematic of soil cylinder with vertical drain (after Hansbo, 1979)  | 81 |
| Figure 3.2  | Distribution of average excess pore water pressure   | 87 |

|             |   |     |
|-------------|---|-----|
| Figure 3.3  | Average excess pore water pressure distribution of axisymmetric unit cell with different permeability ratios (100 kPa vacuum and 25 kPa surcharge)  | 88  |
| Figure 3.4  | Average excess pore pressure distribution at 5m depth with different vacuum pressures (surcharge load=50 kPa, $k_h = 1 \times 10^{-8}$ m/s)   | 88  |
| Figure 3.5  | Average excess pore pressure distribution for different drain lengths when, (a) $q_w=50\text{m}^3/\text{year}$ (b) $q_w=500\text{m}^3/\text{year}$  | 90  |
| Figure 3.6  | Average excess pore pressure distribution with different drain discharge capacity when (a) $l=10\text{m}$ (b) $l=20\text{m}$  | 91  |
| Figure 3.7  | Plane strain unit cell  | 93  |
| Figure 3.8  | Plane strain unit cell with smear zone  | 95  |
| Figure 3.9  | Comparison of average excess pore pressure distribution   | 101 |
| Figure 3.10 | Conversion of an axisymmetric unit cell into plane strain   | 102 |
| Figure 4.1  | Large-scale radial drainage consolidometer  | 110 |
| Figure 4.2  | Schematic of large-scale consolidation apparatus  | 112 |
| Figure 4.3  | Pore pressure transducer used in consolidometer testing   | 112 |
| Figure 4.4  | Schematic section of the large-scale, radial drainage consolidometer showing the central drain, associated smear zone, and typical locations of pore pressure transducers (after Indraratna and Redana, 1998) | 117 |
| Figure 4.5  | Surface settlement associated with surcharge load and combined surcharge and vacuum loading   | 117 |
| Figure 4.6  | Measured excess pore water pressure at (a) transducer T3 (b) transducer T6  | 118 |
| Figure 4.7  | Location of transducer T6 for Test 3  | 120 |
| Figure 4.8  | a) Suction in the drain (240mm from bottom) and b) surface settlement surface settlement associated with simulated vacuum loading and removal   | 120 |
| Figure 4.9  | Pore pressure measured at transducer (a) T2 (b) T5  | 121 |
| Figure 5.1  | Types of elements can be used in consolidation analysis   | 126 |
| Figure 5.2  | Discretised finite element mesh   | 129 |
| Figure 5.3  | Predicted surface settlement  | 130 |
| Figure 5.4  | Pore pressure distribution at different nodes   | 131 |

|             |  |     |
|-------------|--|-----|
| Figure 5.5  | Contour plot of excess pore water pressure after 50 days   | 133 |
| Figure 5.6  | Soil moisture characteristic curves for three different soils using the filter paper method (Houston et al, 1994)  | 135 |
| Figure 5.7  | Finite element mesh showing the element positions  | 139 |
| Figure 5.8  | Change of saturation at the center of several elements along the drain boundary for (a) Model 2 and (b) Model 4  | 141 |
| Figure 5.9  | Change of saturation at the center of several elements along the radius of the cell for (a) Model 2 and (b) Model 4  | 142 |
| Figure 5.10 | Contour plot of saturation after 40 days   | 143 |
| Figure 5.11 | Variation of settlement at the top of the soil cell  | 143 |
| Figure 5.12 | Excess pore pressure distribution at different nodes in the soil cell  | 144 |
| Figure 5.13 | Change of saturation under different surcharge loading at several elements   | 146 |
| Figure 5.14 | Change of saturation with different moisture characteristic curves at several elements   | 147 |
| Figure 5.15 | Change of saturation with initial saturated permeability at several elements   | 149 |
| Figure 5.16 | a) Simulation of vacuum pressure along drain boundary b) Finite element discretization for plane strain analysis of the soil in large-scale consolidometer | 151 |
| Figure 5.17 | Suction in the drain at 240mm from bottom  | 153 |
| Figure 5.18 | Predicted variation of degree of saturation at the center of various elements along the drain boundary for Model 3   | 155 |
| Figure 5.19 | Predicted and measured settlement at the top of consolidometer cell  | 155 |
| Figure 5.20 | Schematic section of consolidometer cell showing the locations of pore pressure transducers  | 156 |
| Figure 5.21 | Predicted and measured excess pore water pressure at transducers T1 and T5   | 157 |
| Figure 5.22 | Excess pore pressure distribution across the radius of the cell at the level of transducer (a) T1 and (b) T5   | 158 |
| Figure 5.23 | Effect of permeability on distribution of vacuum pressure at the level of transducer (a) T1 and (b) T5   | 159 |
| Figure 5.24 | Excess pore pressure distribution across the radius of the cell at the level of node (a) 615 and (b) 631   | 161 |



|             |   |     |
|-------------|---|-----|
| Figure 6.1  | Site plan for the test embankments at Second Bangkok International Airport (after Sangmala, 1997)   | 164 |
| Figure 6.2  | General soil profile and properties at Second Bangkok International Airport (after Sangmala, 1997)  | 165 |
| Figure 6.3  | Average strength and compressibility parameters at Second Bangkok International Airport (After Sangmala, 1997)                            | 166 |
| Figure 6.4  | Cross section at embankment with sub-soil profile, Second Bangkok International Airport , Thailand  | 167 |
| Figure 6.5  | Construction loading history for embankments TV1 and TV2 at Second Bangkok International Airport  | 168 |
| Figure 6.6  | Observed variation of pore pressure with time and depth in the field for two embankments TV1 and TV2                                      | 170 |
| Figure 6.7  | Finite element mesh for plane strain single drain analysis  | 174 |
| Figure 6.8  | Finite element mesh of embankment for plane strain multi-drain analysis   | 175 |
| Figure 6.9  | Settlement at ground surface for embankment (a) TV1 and (b) TV2   | 178 |
| Figure 6.10 | Surface settlement for embankments (a) TV1 and (b) TV2 of SBIA  | 181 |
| Figure 6.11 | Surface settlement at 6m depth for embankments (a) TV1 and (b) TV2  | 182 |
| Figure 6.12 | Variation of excess pore water pressure at 3m depth below ground level, 0.5m away from the centerline for embankments (a) TV1 and (b) TV2 | 183 |
| Figure 6.13 | Variation of excess pore water pressure at 6m depth below ground level, 0.5m away from the centerline for embankments (a) TV1 and (b) TV2 | 184 |
| Figure 6.14 | Lateral displacement profiles through the toe of the embankments (a) TV1 and (b) TV2 after 150days  | 185 |
| Figure 6.15 | Surface settlement profile predicted for embankments (a) TV1 and (b) TV2 after 150days  | 186 |
| Figure 7.1  | Finite element mesh   | 193 |
| Figure 7.2  | Settlement at the center of the embankment foundation   | 195 |
| Figure 7.3  | Settlement at the toe of the embankment   | 195 |
| Figure 7.4  | Excess pore pressure distribution at 2 m depth (a) 0.5 m away from the centerline (b) at the embankment toe                               | 197 |

|             |  |     |
|-------------|--|-----|
| Figure 7.5  | Surface settlement profile at failure  | 198 |
| Figure 7.6  | Patterns of settlement under embankment (Du and Zhang, 2001)   | 199 |
| Figure 7.7  | Predicted centerline surface settlement for different construction rates   | 200 |
| Figure 7.8  | Settlement (heave) at the toe of the embankment  | 200 |
| Figure 7.9  | Contours of resultant displacement for construction rate of (a) 0.1m / week (b) 0.35m / week (units in m)  | 201 |
| Figure 7.10 | Construction loading history   | 203 |
| Figure 7.11 | Centerline surface settlement  | 204 |
| Figure 7.12 | Predicted heave at the toe of the embankment   | 204 |
| Figure 7.13 | Predicted excess pore pressure distribution at 2m depth below the embankment toe   | 205 |
| Figure 7.14 | Predicted centerline surface settlement for different drain spacing at a construction rate of (a) 0.1m / week (b) 0.35m / week   | 207 |
| Figure 7.15 | Predicted surface settlement at the toe of the embankment for different drain spacing at a construction rate of (a) 0.1m / week (b) 0.35m / week                               | 209 |
| Figure 7.16 | Predicted excess pore pressure distribution at 2m depth below the toe of the embankment for different drain spacing at a construction rate of (a) 0.1m / week (b) 0.35m / week | 210 |
| Figure 7.17 | Excess pore pressure distribution at 0.5m away from the centerline and 2m depth for different drain spacing at a construction rate of (a) 0.1m / week (b) 0.35m / week         | 211 |
| Figure 7.18 | Contour plots of resultant displacement for drain spacing (a) 1 m (b) 1.5 m (c) 2 m (d) 3 m (construction rate =0.35m / week) (units in m)                                     | 212 |
| Figure 7.19 | Predicted centerline settlement for different permeability ratio   | 214 |
| Figure 7.20 | Predicted heave/ settlement at embankment toe  | 214 |
| Figure 7.21 | Predicted excess pore water pressure at 2 m depth (a) 0.5 m away from the center line (b) at toe   | 215 |
| Figure 7.22 | Contour plots of resultant displacement vectors for (a) $k_h/k_s = 2$ (b) $k_h/k_s = 5$ and (c) $k_h/k_s = 5$ (units in m)   | 216 |
| Figure 7.23 | Predicted centerline surface measurement for different drain spacing at a construction rate of 0.35m / week  | 219 |

|             |  |     |
|-------------|--|-----|
| Figure 7.24 | Surface settlement at the toe of the embankment for different drain spacing at a construction rate of 0.35m / week                             | 219 |
| Figure 7.25 | Excess pore pressure distribution at 2m depth below the embankment toe   | 220 |
| Figure 7.26 | Predicted centerline surface settlement for different construction rates   | 222 |
| Figure 7.27 | Settlement at the toe of the embankment for different construction rates   | 222 |
| Figure 7.28 | Contour plots of resultant displacement vectors for construction rate of (a) 0.35m / week (b) 0.5m / week after 365 days                       | 223 |
| Figure 7.29 | Excess pore pressure distribution at 2m depth (a) 0.5m away from the centerline (b) below the embankment toe for different construction rates  | 224 |
| Figure 7.30 | Predicted centerline settlement for different permeability ratios upon vacuum application  | 226 |
| Figure 7.31 | Predicted settlement at embankment toe   | 226 |
| Figure 7.32 | Excess pore pressure distribution at 2m depth (a) 0.5m away from the centerline (b) below the embankment toe for different permeability ratios | 227 |
| Figure 7.33 | Contour plots of resultant displacement vectors for (a) $k_h/k_s = 2$ (b) $k_h/k_s = 5$ and (c) $k_h/k_s = 5$ after 365 days (units in m)      | 228 |
| Figure 8.1  | Nature of stress paths in various locations within the soft clay foundation (Indraratna et al., 1997)  | 239 |

## LIST OF TABLES

|           |   |     |
|-----------|---|-----|
| Table 2.1 | Short-term discharge capacity, in m <sup>3</sup> /year, of eight band drains measured in laboratory (Hansbo, 1981)              | 21  |
| Table 2.2 | Effect of ground improvement on normalised deformation factors (Indraratna et al., 1997)  | 64  |
| Table 2.3 | Parameters of vertical drains   | 66  |
| Table 2.4 | Model parameters and soil properties  | 68  |
| Table 4.1 | Soil properties of the reconstituted clay sample  | 113 |
| Table 5.1 | Modified Cam-clay properties used in analysis   | 129 |
| Table 5.2 | Assumed suction-saturation relationship at PVD-soil boundary  | 137 |
| Table 5.3 | Description of Models   | 148 |
| Table 5.4 | Assumed suction-saturation relationship at PVD-soil boundary  | 151 |
| Table 6.1 | Modified Cam-clay parameters used in FE analysis for Second Bangkok International Airport (Asian Institute of Technology, 1995) | 170 |
| Table 6.2 | In-situ stress condition used in FE analysis for Second Bangkok International Airport   | 171 |
| Table 6.3 | Undisturbed and smear zone permeabilities for embankments TV1 & TV2   | 171 |
| Table 6.4 | Suction-saturation relationship   | 177 |
| Table 7.1 | Modified Cam-clay parameters used in FE analysis  | 191 |
| Table 7.2 | In-situ stress condition used in FE analysis  | 191 |
| Table 7.3 | Axisymmetric and plane strain permeabilities used in the analysis   | 192 |

## LIST OF SYMBOLS

|            |   |
|------------|---|
| $a$        | Width of band drain                                       |
| $a_v$      | Coefficient of compressibility                            |
| $b$        | Thickness of band drain                                   |
| $b_s$      | Equivalent width of smear zone in plane strain            |
| $b_w$      | Equivalent width of drain (well) in plane strain          |
| $B$        | Equivalent half width of the plane strain cell            |
| $c_h$      | Coefficient of horizontal consolidation                   |
| $c_u$      | Undrained shear strength                                  |
| $c_v$      | Coefficient of vertical consolidation                     |
| $C_c$      | Compression index   |
| $C_f$      | Ratio of field and laboratory coefficient of permeability |
| $C_k$      | Permeability change index                                 |
| $C_r$      | Recompression index                                       |
| $C_\alpha$ | Secondary compression index                               |
| $d_e$      | Equivalent diameter of band drain                         |
| $d_s$      | Diameter of smear zone                                    |
| $d_w$      | Diameter of drain (well)                                  |
| $D$        | Diameter of effective influence zone of drain             |
| $D_{15}$   | Diameter of clay particles corresponding to 15% passing   |
| $D_{50}$   | Diameter of clay particles corresponding to 50% passing   |
| $D_{85}$   | Diameter of clay particles corresponding to 85% passing   |
| $e$        | Void ratio  |
| $e_{cs}$   | Void ratio on the critical state line for value of $p'=1$ |
| $e_o$      | Initial void ratio  |
| $E$        | Young's modulus   |
| $E_u$      | Young's modulus for undrained shear                       |
| $F_t$      | Influence factor of drain due to time                     |
| $F_c$      | Influence factor of drain due to drain deformation        |

|           |   |
|-----------|---|
| $F_{fc}$  | Influence factor of drain due to clogging                         |
| $G$       | Shear modulus   |
| $G_s$     | Specific gravity  |
| $H_d$     | The longest drainage path   |
| $H_o$     | Initial thickness of compressible soil                            |
| $i$       | Hydraulic gradient  |
| $i_o$     | Initial hydraulic gradient  |
| $I_c$     | Influence factor  |
| $I_p$     | Plasticity index  |
| $k$       | Permeability  |
| $k_{ax}$  | Axisymmetric permeability   |
| $k_h$     | Horizontal coefficient of permeability                            |
| $k'_h$    | Horizontal coefficient of permeability in smear zone              |
| $k_{hp}$  | Equivalent horizontal coefficient of permeability in plane strain |
| $k'_{hp}$ | Equivalent horizontal coefficient of permeability in plane strain |
| $k_v$     | Vertical coefficient of permeability                              |
| $k_s$     | Saturated permeability  |
| $k_u$     | Unsaturated permeability  |
| $k_w$     | Coefficient of permeability of drain                              |
| $l$       | Length of drain   |
| $L$       | Well resistance factor  |
| $L_L$     | Liquid limit  |
| $m_v$     | Coefficient of volume change                                      |
| $M$       | Slope of critical state line                                      |
| $n$       | Spacing ratio, $R/r_w$  |
| $N$       | Volume on the normal consolidation line corresponds to $p'=1$     |
| $O_{95}$  | Apparent opening size   |
| $O_{15}$  | Apparent opening size   |
| $O_{85}$  | Apparent opening size   |
| $p'$      | Effective mean normal pressure                                    |

|          |   |
|----------|---|
| $p'_c$   | Isotropic preconsolidation pressure                 |
| $P$      | Normal load   |
| $PI$     | Plasticity index                                    |
| $q$      | Unit load   |
| $q_w$    | Axisymmetric vertical drain discharge capacity      |
| $q_{wa}$ | Axisymmetric discharge capacity                     |
| $q_{wp}$ | Plane strain discharge capacity                     |
| $q_z$    | Plane strain discharge capacity                     |
| $Q$      | Discharge capacity                                  |
| $Q_w$    | Discharge capacity in plane strain                  |
| $r$      | Radius  |
| $r_k$    | Anisotropy ratio                                    |
| $r_m$    | Radius of mandrel                                   |
| $r_s$    | Radius of smeared zone                              |
| $r_w$    | Radius of vertical drain (well)                     |
| $R$      | Radius of axisymmetric unit cell                    |
| $s$      | Smear ratio, $r_s/r_w$                              |
| $S$      | Field spacing of drains                             |
| $S_e$    | Effective degree of saturation                      |
| $S_r$    | Degree of saturation                                |
| $S_{ru}$ | Residual water saturation                           |
| $t$      | Time  |
| $T_h$    | Time factor for horizontal drainage                 |
| $T_{hp}$ | Time factor for horizontal drainage in plane strain |
| $T_v$    | Time factor for vertical drainage                   |
| $T_{50}$ | Time factor for 50% consolidation                   |
| $T_{90}$ | Time factor for 90% consolidation                   |
| $u$      | Pore water pressure                                 |
| $u_a$    | Pore air pressure                                   |
| $u_o$    | Initial pore water pressure                         |
| $u_r$    | Excess pore water pressure in radial direction      |

|               |   |
|---------------|---|
| $u_{sur}$     | Applied surcharge pressure  |
| $u_{vac}$     | Applied vacuum pressure in axisymmetric condition                           |
| $u_{vacp}$    | Applied vacuum pressure in plane strain condition                           |
| $u_w$         | Pore water pressure   |
| $\bar{U}$     | Average degree of consolidation   |
| $U_{10}$      | 10 % degree of saturation   |
| $U_{ax}$      | Degree of consolidation in axisymmetric                                     |
| $U_{pl}$      | Degree of consolidation in plane strain                                     |
| $v$           | Rate of flow  |
| $V$           | Volume  |
| $w$           | Water content   |
| $w_L$         | Liquid limit  |
| $w_P$         | Plastic limit   |
| $z$           | Depth (thickness) of soil layer   |
| $\alpha$      | Geometric parameter representing smear in plane strain                      |
| $\alpha$      | Ratio of maximum lateral displacement to settlement                         |
| $\beta$       | Geometric parameter representing smear in plane strain                      |
| $\beta_1$     | Ratio of maximum lateral displacement to corresponding fill height          |
| $\beta_2$     | Ratio of maximum settlement to corresponding fill height                    |
| $\chi$        | Effective stress parameter  |
| $\varepsilon$ | Strain  |
| $\gamma_s$    | Unit weight of soil   |
| $\gamma_w$    | Unit weight of water  |
| $\eta$        | Stress ratio  |
| $\mu$         | Smear and well resistance factor in axisymmetric                            |
| $\mu_p$       | Smear and well resistance factor in plane strain                            |
| $\Gamma$      | Volume on the critical state line corresponds to $p'=1$ ; $\Gamma=e_{cs}+1$ |
| $\kappa$      | Slope of swelling line  |
| $\lambda$     | Slope of consolidation line   |
| $\nu$         | Poisson's ratio   |



|                   |  |
|-------------------|--|
| $\theta$          | Geometric parameter representing well resistance in plane strain |
| $\rho$            | Settlement   |
| $\rho_{\infty}$   | Settlement at infinity   |
| $\sigma_h$        | Total horizontal stress  |
| $\sigma_v$        | Total vertical stress  |
| $\sigma'_h$       | Effective horizontal stress                                      |
| $\sigma'_v$       | Effective vertical stress  |
| $\sigma'_p$       | Preconsolidation pressure  |
| $\sigma_r$        | Radial stress  |
| $\sigma_z$        | Vertical stress at depth $z$                                     |
| $\sigma'_{vo}$    | Effective overburden pressure                                    |
| $\sigma_{\theta}$ | Circumferential stress   |
| $\sigma_1$        | Axial stress   |
| $\sigma_3$        | Confining stress   |
| $\tau$            | Shear stress   |