



**Analysing Ground Deformation Data to Predict
Characteristics of Smear Zone Induced by Vertical Drain
Installation for Soft Soil Improvement**

A thesis in fulfilment of the requirement
for the award of the degree

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from

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by

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CERTIFICATION

I, Ali Parsa-Pajouh, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Department of Civil and Environmental Engineering, University of Technology, Sydney, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualification at any other academic institution.

Ali Parsa-Pajouh

February 2014

DEDICATION

This work is sincerely dedicated to the following special people:

To My Lovely Wife, Neda

For her endless encouragement and patience, without her love and support, I could have never completed this journey.

To My Father, Davoud

He was my role-model of hard work, persistence and personal sacrifices. He inspired me how to be strong, how to be honest.

To My Late Beloved Mother, Maryam

For all the sacrifices she has made to ensure that I obtain the best education possible, for her beautiful mind and unconditional love.

ABSTRACT

The use of prefabricated vertical drain (PVD) assisted preloading has been recognised over the last two decades as a very efficient method of ground improvement for sites with deposits of deep soft soil. One of the major parameters influencing the PVD assisted consolidation process, and consequently the required preloading time, is the formation of a smear zone around the vertical drains, and the corresponding soil properties. In this research a systematic procedure integrated with a developed numerical code is proposed to accurately back calculate the properties of the smear zone based on the consolidation data collected in the laboratory and in the field. Furthermore, an expanded back calculation method is developed to determine the minimum required degree of consolidation and corresponding time after the construction of the trial embankment that would result in accurately predicted smear zone characteristics. The explicit finite difference program FLAC 2D was used to develop the numerical code, simulate the laboratory testing and PVD assisted preloading case histories. Furthermore a comprehensive parametric study was conducted to investigate the effect of smear zone properties variations on the preloading process, and back calculated characteristics of the smear zone.

A large and fully instrumented Rowe cell apparatus was used to investigate the effect of the smear zone on the consolidation process and verify the developed numerical code. The Rowe cell was filled with the intact zone, smear zone, and vertical drain materials to evaluate the permeability and extent ratios of $k_h/k_s=4$ and $r_s/r_m=3$, respectively. The back calculation procedure was used to conduct the parametric study and predict the properties of the smear zone. According to the results, the predicted properties of the smear zone were similar to the properties of the applied soil, proving that the proposed back calculation procedure integrated with the developed numerical simulation can successfully predict these properties.

The developed numerical code was used to simulate five PVD assisted preloading case studies, including four trial embankments and a large scale consolidometer, while the back calculation procedure was used to conduct a parametric study to determine the extent and permeability of the smear zone. According to the results, integration of the back calculation procedure in the

numerical code can be used as a reliable tool to make an accurate prediction of the smear zone characteristics in PVD and vacuum assisted preloading projects.

The developed method in this research can be considered as a practical, accurate and cost effective tool, due to its capability in precise estimation of the extent and permeability of the smear zone in the early stages of constructing the trial embankment. In this study, the proposed systematic back calculation procedure was extended to determine the minimum degree of consolidation (i.e. the minimum waiting time after constructing the trial embankment), and accurately predict the properties of the smear zone. The numerical results of the simulated case studies were used to conduct the analyses. Accordingly, it is found that the extent and permeability of the smear zone can be predicted very well with the proposed calculation procedure when at least 33% of predicted final settlement has been reached (i.e. 33% of the degree of consolidation).

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TABLE OF CONTENT

ABSTRACT	IV
ACKNOWLEDGEMENT	VI
TABLE OF CONTENT	VIII
LIST OF FIGURES	XIV
LIST OF TABLES	XXIII
LIST OF SYMBOLS	XXV

1. INTRODUCTION

1.1 General	1
1.2 Accelerating the Consolidation Process	4
1.3 Installation of Vertical Drains and Smear Zone	7
1.4 Trial Embankment Monitoring to Obtain the Smear zone Properties	9
1.5 Objectives and Scope of Present Study	9
1.6 Organisation of the Thesis	11

2. LITERATURE REVIEW

2.1 History and Development of Vertical Drain Assisted Preloading	13
2.2 Vacuum Preloading via Prefabricated Vertical Drains	14
2.2.1 History and Developments of Vacuum Preloading	15
2.2.2 Vacuum Preloading Using Membrane	17
2.2.3 Vacuum Preloading (Membrane Free Techniques)	18
2.3 Factors Affecting Consolidation of Clay with PVDs	20
2.3.1 Equivalent Diameter	20
2.3.2 Filter and Apparent Opening Size (AOS)	22
2.3.3 Tensile Strengths	23
2.3.4 Discharge Capacity and Well Resistance	24
2.3.5 Smear Zone	26
2.3.6 Soil Macro Fibre	26
2.3.7 Mandrel Size and Shape	27
2.3.8 Installation Procedure	28
2.3.9 Drain Spacing and Influence Zone	29
2.4 Smearing Effect	29

2.4.1	Smear Zone Generation	30
2.4.1.1	Soil Remoulding Concept	30
2.4.1.2	The Reconsolidation Theory	31
2.4.2	Smear Zone Extent & Permeability Variation	32
2.4.3	Estimation of the Smear Zone Properties	35
2.4.3.1	Experimental Methods	35
2.4.3.2	Cavity Expansion Theory	43
2.4.3.3	Finite Element Methods	48
2.4.3.4	Back Calculation Methods	50
2.4.4	Relationship between Experimental and Practical Results for Smear Zone Properties	54
2.5	Development of Consolidation Theory	55
2.5.1	Vertical Consolidation	55
2.5.2	Radial (or Horizontal) Consolidation Considering Smear Zone Characteristics	57
2.5.2.1	Conversion of Axi-symmetric to Plane-Strain Condition	62
2.5.3	Combined Vertical and Radial Consolidation Theory	67
2.5.3.1	Single Layer Consolidation (Rigorous Solutions)	67
2.5.3.2	Single Layer Consolidation (Approximate Solutions)	68
2.5.3.3	Multi-Layered Consolidation	69
2.5.4	Theoretical Solutions for Vacuum Consolidation	72
2.6	Numerical Simulation of PVD Assisted Preloading	74
2.7	Summary	78

3. PVD ASSISTED PRELOADING SIMULATION AND BACK CALCULATION PROCEDURE USING FLAC

3.1	General	80
3.2	Numerical Modelling	81
3.2.1	Adopted Numerical Simulation Software	81
3.2.2	Explicit Finite Difference Method and Lagrangian Analysis	82
3.2.3	The Grid and Mixed-Discretization Zoning Technique	85
3.2.4	Continuum Expression of the Governing Equations	87
3.2.4.1	Water Flow Equation	90

3.2.4.2	Balance Laws	90
3.2.4.4	Constitutive Laws	91
3.2.4.4	Compatibility Equation	92
3.2.5	Numerical Fluid Flow Formulation	92
3.2.5.1	Basic Scheme	92
3.2.5.2	Constitutive Law: Derivation of Element “Stiffness Matrix”	93
3.2.5.3	Continuity Equation	95
3.2.5.4	Numerical Stability: Fluid Time-step	96
3.2.6	Optimisation of the Mechanical and Fluid Time steps	97
3.2.6.1	Manual Method	98
3.2.6.2	Automatic Method	98
3.2.7	Modified Cam-Clay Model	99
3.2.7.1	Virgin Consolidation Line and Swelling Lines	99
3.2.7.2	Yield and Potential Functions	100
3.2.7.3	Determination of the Input Parameters	101
3.3	Numerical Code Development	102
3.3.1	General	102
3.3.2	Numerical Code Structure	103
3.3.2.1	Input data: Geometry and properties of the Materials	104
3.3.2.2	Grid and Mesh Generation	106
3.3.2.3	Layering and Assigning Material Properties	106
3.3.2.4	Defining location of instrumentations and transducers	107
3.3.2.5	Boundary Conditions, Initial Stresses, and Undrained Analysis	107
3.3.2.6	Simulation of Preconsolidation Stage	108
3.3.2.7	Vertical Drains and Smear Zone	109
3.3.2.8	Vacuum Pressure	110
3.3.2.9	Construction of Trial Embankment and Consolidation Process	111
3.4	Systematic Back Calculation Procedure	111
3.5	Summary	115

4. LABORATORY STUDY TO INVESTIGATE THE SMEARING EFFECT ON THE PERFORMANCE OF PVD ASSISTED PRELOADING

4.1	General	117
4.2	Testing Apparatus and Experimental Procedure	118
4.2.1	Apparatus	118
4.2.2	Material Properties	123
4.2.2.1	Soil samples	123
4.2.2.2	Consolidation test on reconstituted samples	126
4.2.3	Preparation of Rowe cell and initial sample	131
4.2.4	The pre-consolidation process and preparation of final sample	133
4.2.5	Initial drainage and de-airing of the Rowe cell system	136
4.2.6	Vertical drain assisted consolidation test procedure	138
4.3	Test Results	138
4.4	Verification of the Numerical Code	144
4.5	Evaluation of Axi-symmetric to Plane-Strain Conversion Methods	149
4.6	Summary	154

5. CASE STUDIES AND FURTHER VALIDATION EXERCISES

5.1	General	156
5.2	Cumbalum Trial Embankment	157
5.2.1	Introduction	157
5.2.2	Geological Model and Subsoil Condition	159
5.2.3	Installation of Vertical Drains and Embankment Construction	161
5.2.4	Numerical Simulation	163
5.3	Case Study 2: Ballina Bypass Trial Embankment	167
5.3.1	Introduction	167
5.3.2	Geological Model and Subsoil Condition	168
5.3.3	Vacuum Consolidation and Embankment Construction	169
5.3.4	Numerical Simulation	171
5.4	Case Study 3: Sunshine Motorway Trail Embankment	176
5.4.1	Introduction	176
5.4.2	Subsoil Condition	177
5.4.3	Installation of Vertical Drains and Embankment Construction	178

5.4.4 Numerical Simulation	179
5.5 Chittagong Airport Trial Embankment	182
5.5.1 Introduction	182
5.5.2 Subsurface Conditions	183
5.5.3 Soil Properties	185
5.5.4 Installation of Vertical Drain and Embankment Construction	186
5.5.4.1 Monitoring of Settlement	189
5.5.5 Numerical Simulation	190
5.6 Case Study 5: Large-scale Consolidometer	193
5.6.1 Test Apparatus	193
5.6.2 Test Sample	195
5.6.3 Test Procedure	196
5.6.4 Verification of the Developed Numerical Code	197
5.7 Summary	200
 6. DETERMINING THE MINIMUM PERIOD OF MONITORING FOR PREDICTING SMEAR ZONE PROPERTIES OF A TRIAL EMBANKMENT	
6.1 General	203
6.2 Step I: Estimating the Primary Consolidation Settlement	205
6.3 Step II: Conducting Parametric Studies	206
6.3.1 Chittagong Sea Port Trial Embankment	206
6.3.2 Cumbalum Trial Embankment	213
6.3.3 Ballina Bypass trial Embankment	216
6.3.4 Sunshine Trial Embankment	219
6.3.5 Large Scale Consolidometer	220
6.4 Step III: Determining the Error	221
6.5 Step IV: Determining the Minimum Required Monitoring Time	224
6.6 Summary	228
 7. CONCLUSIONS AND RECOMMENDATIONS	
7.1 Summary	230
7.2 Conclusions	231
7.3 Recommendations for Future Research	235

REFERENCES	237
APPENDIX A: Developed FLAC Code to Simulate Trial Embankment	252
APPENDIX B: Developed FLAC Code to Simulate Rowe Cell Test	274

LIST OF FIGURES

Figure 1.1 Procedure to select the appropriate technique for ground improvement (after Arulrajah et al., 2003)	3
Figure 1.2 Typical consolidation settlement	4
Figure 1.3 Preloading method (a) without vertical drains, (b) with vertical drains	6
Figure 1.4 Prefabricated vertical drain, (a) Circular, (b) & (c) Band shape	6
Figure 1.5 Typical Effect of vertical drains on consolidation settlement rate of soft clay	6
Figure 1.6 PVD installation (a) crane mounted installation rig, (b) drain delivery arrangement, (c) cross section of mandrel and drain (after Koerner, 1987), and (d) schematic installation process	7
Figure 1.7 3D schematic diagram of the installation of vertical drains in square patten	8
Figure 2.1 Vacuum preloading system	17
Figure 2.2 Horizontal pipe used for vacuum preloading (a) corrugate flexible pipes, (b) and (c) other types of geo-composites (after Chu et al. 2008)	18
Figure 2.3 Vacuum preloading-membrane free technique (a) PVD and tubing for vacuum preloading, and (b) cross section of vacuum-PVDs method	19
Figure 2.4 Low level vacuum preloading with no membrane (after Chu et al. 2008)	20
Figure 2.5 Equivalent diameter, (a) vertical band shaped drain, and (b) PVD equivalent diameter	20
Figure 2.6 Schematic comparison of different PVD equivalent diameter calculation approach	22
Figure 2.7 Examples of mandrel shapes, (a) rectangular, (b) rhombic, and (c) circular	27
Figure 2.8 PVD installation equipment, (a) crane and drain delivery arrangement, and (b) vertical drain surrounded by hollow mandrel and attached to the anchor plate at bottom	28
Figure 2.9 Influence zone of PVD, (a) square patten and (b) triangular pattern	29
Figure 2.10 PVD surrounding by smear zone (remoulding theory), (a) installed drain, (b) profile A-A, and (c) cross section B-B	31
Figure 2.11 PVD surrounding by disturbed soil (reconsolidation theory), (a) installed drain, (b) profile A-A, and (c) cross section B-B	32

Figure 2.12 PVD surrounded by smear zone, (a) for two zones hypothesis profile, (b) for three zones hypothesis profile, (c) cross section A-A for two zones hypothesis, and (d) cross section B-B for three zones hypothesis	33
Figure 2.13 Variation of permeability in the disturbed zone, (a) two zones hypothesis and (b) three zones hypothesis	34
Figure 2.14 Large-scale consolidation apparatus (after Indraratna and Redana 1998)	36
Figure 2.15 Large scale consolidation apparatus (after Sharma and Xiao 2000)	37
Figure 2.16 Schematic diagram of sampling locations for the Oedometer test specimen (after Sharma and Xiao 2000)	38
Figure 2.17 Radial penetration test, (a) Large-scale consolidometer, and (b) Micro-cone penetrometer (after Shine et al. 2009)	39
Figure 2.18 Directions of MCPs and ERPs horizontal penetration (after Sine et al. 2009)	40
Figure 2.19 Schematic design, (a) Large consolidometer, and (b) radial positions (plannar view) of fast response pore pressure transducers (Ts) relative to the centre of the cell at levels identified in (a) (after Ghandeharioon et al., 2012)	42
Figure 2.20 Expansion of a cavity (after Yu 2000)	44
Figure 2.21 Distribution pattern for the ratio of the plastic shear strain to the rigidity index in relation to the radial distance normalized by the equivalent elliptical radius of the mandrel characterising the disturbed soil surrounding a PVD (after Ghandeharioon et al. 2010)	47
Figure 2.22 Mesh and boundary conditions for the large-scale test (after Rujikiatkamjorn et al. 2009)	49
Figure 2.23 Proposed values for smear zone characteristics	53
Figure 2.24 Average degree of consolidation versus time factor based on Equation 2.9 (after Das, 2008)	56
Figure 2.25 Profile prefabricated vertical drain and smear zone, (a) axisymmetric, (b) plane-strain	65
Figure 2.26 Proposed equivalent plane-strain unit cells, (a) Indraratna et al. (1997), and (b) Tran and Mitachi (2008)	67
Figure 2.27 Partially penetrating drain based on DPM model (after Wang and Jiao, 2004)	70
Figure 2.28 Down drag effects due to mandrel installation in layered soil (after Rujikiatkamjorn and Indraratna 2010)	71

Figure 2.29 A schematic diagram of a vacuum preloading system: (a) vacuum and surcharge combining load, (b) vacuum preloading, and (c) surcharge preloading (after Mohamedelhassan and Shang 2002)	72
Figure 2.30 The distribution patterns of vacuum pressure in the horizontal and vertical directions (after Indraratna et al. 2005a)	73
Figure 3.1 Basic explicit calculation cycle (after Itasca, 2008)	83
Figure 3.2 Finite difference mesh, (a) FLAC 2D zone composed of overlaid triangular elements and (b) typical triangular element	86
Figure 3.3 Normal consolidation line swelling lines for an isotropic compression test	100
Figure 3.4 Yield surface of the Modified Cam-Clay model in p' - q plane (after Roscoe and Borland, 1968)	101
Figure 3.5 Generated FLAC mesh, (a) sample of discretised finite-difference mesh of trial embankment and (b) the pattern of meshes in the smear zone and undisturbed region	103
Figure 3.6 Structure of the developed numerical code	104
Figure 3.7 Typical input parameters for numerical simulation	105
Figure 3.8 Input parameters in terms of different groups for numerical simulation	107
Figure 3.9 Boundary conditions of the numerical model	108
Figure 3.10 Schematic model for the preconsolidation stage	109
Figure 3.11 Sample of the simulated vertical drain and adjacent disturbed area, (a) Discretised finite-difference mesh of the trial embankment, (b) Variation of the hydrostatic pressure along the vertical drain and (c) the pattern of meshes in the smear zone and undisturbed region elements	110
Figure 3.12 Simulation of vacuum pressure, (a) variation of vacuum pressure along the vertical drain, and (b) the pattern of meshes in the smear zone and undisturbed region elements	111
Figure 3.13 Back calculation flowchart for smear zone characteristics and the minimum required monitoring time for trial embankment	112
Figure 4.1 Large scale Rowe cell apparatus (a) schematic diagram of the cell and (b) locations of the pore pressure transducers at the base of the cell	119
Figure 4.2 Pressure/volume controller device, (a) a photographic view of the GDS controller and (b) an operational schematic diagram of the instrument	120
Figure 4.3 Infinite volume controller instrument	121
Figure 4.4 Schematic diagram of Rowe cell set-up	122

Figure 4.5 Established setup in the laboratory	123
Figure 4.6 Grain size distribution curve for vertical drain sand	125
Figure 4.7 Pre-consolidation process prior to the oedometer test; (a) cylinder contacting reconstituted sample and (b) samples under pre-consolidation pressure	127
Figure 4.8 Preparing the samples for the oedometer test, (a) placing the oedometer ring, (b) cutting the extra top part, (c) cutting the extra bottom part, and (d) the final sample	127
Figure 4.9 Consolidation test, (a) placing the prepared sample and (b) oedometer apparatus connected to the data logger	128
Figure 4.10 Variation of permeability against void ratio (sample S1)	129
Figure 4.11 Variation of permeability against void ratio (sample S3)	129
Figure 4.12 Variation of void ratio versus effective stress (sample S1)	130
Figure 4.13 Variation of void ratio versus effective stress (sample S3)	130
Figure 4.14 Placing of PVC and brass pipes as the smear zone boundary and the vertical drain border, (a) top view, (b) side view and (c) a typical cross section of the Rowe cell	132
Figure 4.15 Sample placement, (a) filling the undisturbed area (intact zone) with the prepared soil and (b) the setup after placing PVC and Brass pipes as the smear zone boundary and vertical drain border	133
Figure 4.16 Rig set up, (a) geotextile filters, (b) pre-consolidation loading rings, (c) the first two loading rings with drainage grooves and holes, (d) placing of the first loading ring and (e) full loading condition	134
Figure 4.17 Testing procedures, (a) Pouring the vertical drain material and (b) Pulling out the outer pipe	135
Figure 4.18 Testing procedures, (a) pulling out the inner pipe and (b) cutting the extra part of the filter paper	135
Figure 4.19 Testing procedures, (a) leveling the top surface and (b) placing the geotextile on top surface	136
Figure 4.20 Testing procedures, (a) filling the cell with water and (b) placing the cell top	136
Figure 4.21 Schematic diagram of the de-airing process	137
Figure 4.22 Schematic diagram of the instrumentation plan, (a) plan view of the body of Rowe cell and (b) the cross section of bottom of the Rowe cell	139
Figure 4.23 Settlement and corresponding surcharge versus consolidation time	140

Figure 4.24 Measured excess pore water pressure at transducers located on the bottom of the cell (r is measured from the centre of the drain)	141
Figure 4.25 Measured excess pore water pressures from transducers located on the sides of the cell (h is measured from the bottom of the impervious boundary of the cell)	141
Figure 4.26 Variation of excess pore water pressures with the vertical distance from the bottom of the impermeable boundary	142
Figure 4.27 Variation of excess pore water pressures with the radial distance from the centre of the drain	143
Figure 4.28 Sample of the grid pattern for the simulated Rowe cell using the developed code (r_s = smear zone extent, and R = width of the cell), and the condition of the pore water pressure distribution boundary along the vertical drain.	145
Figure 4.29 Comparison between predicted numerical settlements and laboratory measurements	146
Figure 4.30 Calculated final cumulative error for the selected cases by using the proposed back calculation procedure	147
Figure 4.31 Variation of excess pore water pressures at PWPT A1 versus consolidation time	148
Figure 4.32 Variation of excess pore water pressures at PWPT B3 versus consolidation time	148
Figure 4.33 Variation of excess pore water pressure versus consolidation time for different equations used to convert permeability from an axi-symmetric to a plane-strain condition	152
Figure 4.34 Cumulative error between plane-strain and axisymmetric results in each loading stage	152
Figure 4.35 Variation of predicted excess pore water pressure versus consolidation time for the adopted equations for permeability conversion from axisymmetric to plane-strain condition	153
Figure 5.1 A map of the Ballina Bypass upgrade route and surrounding surface features (modified after Bishop, 2004)	158
Figure 5.2 Location of the Cumbalum trial embankment (courtesy of Google Maps)	159
Figure 5.3 Interpreted section for Cumbalum trial embankment study area (after Bishop, 2004)	160
Figure 5.4 Moisture content, liquid limit and plastic limit (after RTA, 2000)	161

Figure 5.5 Construction history of Cumbalum trial embankment (after Kelly 2008)	162
Figure 5.6 Layout of the Cumbalum trial embankment (after RTA, 2000)	162
Figure 5.7 Cross section of the Cumbalum trial embankment and subsoil profile	163
Figure 5.8 Finite-difference meshes for the plane-strain analysis of Cumbalum trial embankment	164
Figure 5.9 Numerical parametric study results; Cumbalum trial embankment at SP9	165
Figure 5.10 Variation of excess pore pressure over time for PC2 at a depth 5.8m	166
Figure 5.11 Location of the critical section and trial embankment of the Ballina Bypass (courtesy of Google Maps)	167
Figure 5.12 Interpreted section for Ballina Bypass trial embankment study area (after Bishop 2004)	169
Figure 5.13 Layout of instrumentation for the trial embankment at Ballina Bypass (modified after Kelly and Wong 2009)	170
Figure 5.14 Cross section of the Ballina Bypass trial embankment and subsoil profile	170
Figure 5.15 Construction history of Ballina Bypass trial embankment	171
Figure 5.16 (a) Discretised finite-difference mesh of Ballina Bypass trial embankment, (b) Variation of vacuum pressure along the vertical drain, (c) The pattern of meshes in the smear zone and undisturbed region, (d) FLAC zone composed of overlaid triangular elements	172
Figure 5.17 Results of numerical parametric study; Ballina Bypass trial embankment at SP12	173
Figure 5.18 Variation of excess pore pressure over time for P3 at depth 11.8m	174
Figure 5.19 Location of the Sunshine Motorway study area, (courtesy of Google Maps)	176
Figure 5.20 Profile of the Geotechnical characteristics (Sunshine Motorway Stage 2 Interim Report, 1992)	177
Figure 5.21 Plan view of Sunshine Motorway trial embankment	178
Figure 5.22 Typical cross-section of embankment with selected instrumentation points (after Sathananthan et al. 2008)	179
Figure 5.23 Cross section of the Sunshine trial embankment and the subsoil profile	179
Figure 5.24 Sample of mesh grid pattern for an embankment considering the smear zone and undisturbed region, (r_s = smear zone extent; L_I = intact zone	

extent; h_t = depth of the soil profile; and h_d = length of the vertical drain, s_d = drain spacing)	180
Figure 5.25 Construction history of the trial embankment	180
Figure 5.26 Comparison of numerical results with filed data (for settlement plate P1)	182
Figure 5.27 Location of the container yard at Chittagong Port (courtesy of Google Maps)	183
Figure 5.28 Approximate locations of the boreholes, Chittagong Airport trial embankment (after Dhar et al., 2011)	184
Figure 5.29 General ground profile along with SPT N-values (after Dhar et al., 2011)	185
Figure 5.30 Settlement monitoring program, (a) Settlement gauge and (b) Points of settlement measurement (schematic plan) (after Dhar et al. 2011)	188
Figure 5.31 Schematic details of the ground improvement works (after Dhar et al., 2011)	189
Figure 5.32 Variation of ground settlement with time	190
Figure 5.33 Cross section of constructed embankment at Chittagong Port site	190
Figure 5.34 Construction history (Chittagong Port embankment)	191
Figure 5.35 Sample of mesh grid pattern for Chittagong Port embankment considering the smear	191
Figure 5.36 Comparison of numerical results with filed data at Chittagong Port site	192
Figure 5.37 Numerical variation of excess pore water pressure against consolidation time	193
Figure 5.38 Large scale consolidometer (after Bamunawita 2004)	194
Figure 5.39 Cross section of the large consolidometer (modified after Indraratna et al. 2004a)	195
Figure 5.40 Loading history for the large scale consolidometer	197
Figure 5.41 Sample of grid pattern for the large consolidometer applying developed code (r_s = smear zone extent; l_i = intact zone extent; s_d = drain space, h_c = length of the cell, w = width of the cell), (a) boundary conditions applied to the simulated cell and (b) pore pressure distribution boundary condition along the vertical drain	198
Figure 5.42 Results of large consolidometer cell: Settlement versus consolidation time	199

Figure 5.43 Results of large consolidometer cell: Excess pore pressure versus consolidation time	199
Figure 6.1 Flowchart of the systematic procedure to determine the minimum degree of consolidation resulting in an accurate estimation of smear zone characteristics	204
Figure 6.2 Parametric study results for Chittagong port case history at point G1; (a) $r_s/r_m=2$, (b) $r_s/r_m=3$, (c) $r_s/r_m=4$, and (d) $r_s/r_m=5$	208
Figure 6.3 Results of parametric study using the FLAC code developed to investigate the influence of the smear zone properties on the dissipation of excess pore water pressure for Chittagong port case history at point G2, (a) $r_s/r_m=2$, (b) $r_s/r_m=3$, (c) $r_s/r_m=4$, and (d) $r_s/r_m=5$	210
Figure 6.4 Predicted time to obtain 90% degree of consolidation (Chittagong trial embankment)	211
Figure 6.5 Results of FLAC analysis for points in Table 7 using the Chittagong port case history, (a) Settlement variation, and (b) dissipation of excess pore water pressure	212
Figure 6.6 Settlement variations against consolidation time for the Chittagong trial embankment	213
Figure 6.7 Results of numerical parametric study: Cumbalum trial embankment at SP9	214
Figure 6.8 Variation of excess pore pressure with time for the Cumbalum trial embankment at PC2 (depth 5.8m)	215
Figure 6.9 Results of numerical parametric study: Ballina Bypass trial embankment at SP12	216
Figure 6.10 Variation of excess pore pressure variation with time for Ballina Bypass trial embankment at P3 (depth 11.8m)	217
Figure 6.11 Results of numerical parametric study: Sunshine trial embankment at P1	219
Figure 6.12 Results of numerical parametric study: Large scale consolidometer test	220
Figure 6.13 Normalised cumulative error versus degree of consolidation for different smear zone properties, (a) Cumbalum trial embankment at SP9, (b) Ballina Bypass trial embankment at SP12, (c) Sunshine trial embankment at P1, (d) Chittagong Port trial embankment, and (e) large-scale consolidometer	223
Figure 6.14 Total cumulative error (for the smear zone properties resulting in minimum cumulative error) versus degree of consolidation, (a)	

Cumalum trial embankment at SP9, (b) Ballina Bypass trial embankment at SP12, (c) Sunshine trial embankment at P1, and (d) Chittagong Port trial embankment at G1, (e) Large-scale consolidometer test

226

LIST OF TABLES

Table 1.1 Applicability of ground improvement for different soil types (after Kamon and Bergado, 1992)	2
Table 2.1 PVD assisted preloading projects	14
Table 2.2 Vacuum preloading projects	16
Table 2.3 Suggested equations for equivalent diameter of PVD	21
Table 2.4 Apparatus opening size requirements of PVD	23
Table 2.5 Suggested values for discharge capacity of PVD	26
Table 2.6 Back calculated smear zone properties (after Chai and Miura, 1999)	51
Table 2.7 Back calculated kh/ks ratio (reported by Saowapakpiboon et al., 2010)	52
Table 2.8 Proposed values for Cf (after Chai and Miura, 1999)	55
Table 2.9 Proposed solutions for radial consolidation considering constant smear zone properties	59
Table 2.10 Proposed solutions for radial consolidation considering variable smear zone properties	60
Table 2.11 Summary of conducted numerical studies to simulate PVD assisted preloading process	76
Table 3.1 Comparison of explicit and implicit solution methods (after Itasca, 2008)	84
Table 4.1 Properties of the adopted soil samples in this study	124
Table 4.2 Important sizes	125
Table 4.3 Mix design for the reconstituted samples	126
Table 4.4 Properties of the reconstituted samples	126
Table 4.5 Permeability of mixtures (Surcharge = 20 kPa)	129
Table 4.6 Properties of the intact zone, the smear zone, and drain	130
Table 4.7 Adopted properties for the numerical simulation	131
Table 4.8 Details of consolidation loading stages	138
Table 4.9 Surface settlement at the end of each loading stage	140
Table 4.10 The EPWP increase rate from the centre of the drain to the boundary of smear zone for selected consolidation times	144
Table 4.11 Applied combinations of smear zone permeability and extent in numerical analyses	146
Table 4.12 Adopted equations for converting permeability from axi-symmetric to plane-strain condition	150

Table 4.13 Adopted permeability coefficients for 2D analyses	151
Table 5.1 Summary of simulated case studies	157
Table 5.2 Adopted properties for subsoil layers for Cumbalum trial embankment near SP9	164
Table 5.3 Adopted properties for the layers of subsoil for Ballina Bypass trial embankment near SP12	173
Table 5.4 Adopted properties for the numerical simulation (after Sathananthan et al. 2008)	181
Table 5.5 Applied Properties for Sand Layer (after Sathananthan et al. 2008)	181
Table 5.6 Properties of the cohesive soil samples (Dhar et al., 2011)	186
Table 5.7 Properties of the applied PVD (Dhar et al., 2011)	187
Table 5.8 Adopted soil properties in FLAC simulation (after Dhar et al. 2011)	192
Table 5.9 Soil properties of the reconstituted sample of Moruya clay (after Bamunawita 2004)	196
Table 5.10 Soil properties for Modified Cam-Clay (after Indraratna et al. 2004a)	198
Table 6.1 Primary consolidation settlements and the corresponding degree of consolidations	205
Table 6.2 Back calculated smear zone properties to achieve $t_{90\%} = 34$ days (Chittagong trial embankment)	212
Table 6.3 The final cumulative errors for different combinations of smear zone properties	224
Table 6.4 Minimum required degree of consolidation and corresponding time resulting in predicting reliable smear zone properties	227

LIST OF SYMBOLS

a_o	initial radius of cavity
B	equivalent plane-strain radius of the influence zone
BP	back Pressure
b_s	equivalent plane-strain radius of the smear zone
b_w	equivalent plane-strain radius of the drain
C_c	compression index
C_f	hydraulic conductivity ratio between the field and laboratory values
CP	cell Pressure
Cs	swelling index
c'	cohesion in drained condition
c_f	hydraulic conductivity ratio between field and laboratory values
c_h	coefficient of horizontal consolidation
c_k	permeability change index
c_v	vertical coefficient of consolidation
c_{vc}	coefficient of consolidation for the combined vacuum and surcharge preloading
D_{10}	effective particle size
D_{15}	grain diameter at 15% passing
D_{30}	grain diameter at 30% passing
D_{50}	grain diameter at 50% passing
D_{60}	grain diameter at 60% passing
D_{85}	grain diameter at 85% passing
DL	data logger
dc	diameter of unit cell
de	equivalent drain diameter
d_m	mandrel diameter
d_s	smear zone diameter
d_w	diameter of drain
E	Young's modulus
E_f	final cumulative error
$(E_f)_i$	cumulative error at step i

$(E_t)_s$	corresponding cumulative error to the extent ratio s
E_i	error between numerical predictions and field measurements at step i
$(E_{min})_s$	minimum error corresponding to step s
$(E_t)_n$	normalised cumulative error at time t and step number n
$(E_t)_n$	normalised cumulative error at time t and step number n
$(E_{U\%})_i$	corresponding error to U% at step i
$(E_{U\%})_{min}$	minimum error
$(E_{U\%})_s$	corresponding error to the extent ratio s
$EPWP$	excess pore water pressure
e	void ratio
e_{cs}	void ratio at the critical state
e_o	initial void ratio
F_k	field measurements
F_s	reduction factor
G	shear modulus
G_s	Specific gravity
g_i or g_k	gravity vector
H_d	vertical drainage length
I_r	normalised by the rigidity index
IVC	definite volume controller
K_w	water bulk modulus
k	coefficient of isotropic mobility
$(k_h/k_s)_i$	permeability ratio at step i
$(k_h/k_s)_{max}$	maximum permeability ratio
$(k_h/k_s)_{min}$	minimum permeability ratio
$(k_h/k_s)_o$	assumed initial permeability ratio
$(k_h/k_s)_{opt}$	predicted permeability ratio at $U\%_{min}$
$(k_h/k_s)_s$	permeability ratio corresponding to step s that gives the minimum error
$\hat{k}(s)$	relative permeability
k_l	ratio between the vacuum pressure at the top and bottom of the drain
$k_{e,ax}$	equivalent horizontal permeability for the axi-symmetric unit cell

$k_{e,pl}$	equivalent horizontal permeability for the plane-strain unit cell
k_{ep}	horizontal permeability coefficient in the equivalent zone of plane-strain unit
k_f	permeability of the filter
k_h	intact zone horizontal permeability
k_h/k_s	permeability ratio
k_{hp}	horizontal permeability of intact zone in plane-strain condition
k_{ij}	tensor of the coefficient of permeability
k_s	smear zone permeability
k_{sp}	horizontal permeability of smear zone in plane-strain condition
k_v	intact zone vertical permeability
k_{ve}	equivalent coefficient of vertical permeability
k_w	coefficient of permeability of PVD
LL	liquid limit
$LVDT$	linear vertical displacement Transducer
l	drainage length
l_m	the length of the vertical drain
$[M]$	stiffness matrix
M_b	biot modulus
M	slope of the critical state line
MCC	modified cam clay
N	total number of observation points
n	porosity
$n = R/r_w$	ratio of the influence radius to the drain radius
$n = k_h/k_s$	permeability ratio
n_p	isotropic over consolidation ratio
O_{50}	opening size of the filter which is larger than 50% of the fabric pore
O_{95}	the apparent opening size of the filter
OCR	over consolidated ratio
$P/V C$	pressure/volume controller
PL	plastic limit
PVD	prefabricated vertical drain

$PWPT$	pore water Pressure Transducer
p'	mean effective stress
P'_l	reference pressure
P'_c	preconsolidation pressure
PI	plasticity index
P_k	numerical predictions
p_o	initial mean pressure
p'_o	initial effective mean pressure
P_{vo}	vacuum pressure applied at the top of the drain
p'_{yo}	maximum isotropic preconsolidation stress
$\{Q\}$	nodal flow rate
q	deviator stress
q_i	specific discharge vector
q_{req}	required discharge capacity
q_v	intensity of the volumetric water source
q_w	discharge capacity of PVD
q_{wp}	equivalent plane-strain discharge capacity
R	radius of the influence zone
$(r_s/r_m)_i$	extent ratio at step i
$(r_s/r_m)_{max}$	maximum extent ratio
$(r_s/r_m)_{min}$	minimum extent ratio
$(r_s/r_m)_o$	assumed initial extent ratio
$(r_s/r_m)_{opt}$	predicted extent ratio at $U\%_{min}$
$(r_s/r_m)_s$	extent ratio corresponding to step s that gives the minimum error
r_l	instantaneous radius of an elliptical cavity
r_m	mandrel radius
r_o	initial radius (in the direction of the semi-major axis) of an elliptical cavity
r_p	radial distance of the plastic zone around the cavity
r_s	smear zone radius
r_s/r_m & r_s/r_w	extent ratio
r_{tr}	radius of transition zone

r_w	drain radius
S	drain spacing (centre to centre)
S_f	final primary consolidation settlement
S_{pr}	field settlement at the end of preloading time
S_t	field settlement at time t
S_{tp}	predicted settlement at time t
s	extent ratio (r_s/r_w) or (r_s/r_m)
T_{hp}	radial consolidation time factor
T_r or T_h	radial consolidation time factor
T_v	vertical consolidation time factor
T_{vc}	time factor for the combined vacuum and surcharge preloading
$t_{90\%}$	corresponding time at 90% degree of consolidation
t_{min}	corresponding consolidation time to the $U\%_{min}$
t_{pr}	preloading time
\bar{U}	total degree of consolidation in plane-strain condition
$U\%$	degree of consolidation at time t
$U\%_{min}$	minimum required degree of consolidation
$U\%_n$	degree of consolidation at step n
\bar{U}_h	average degree of radial consolidation in axi-symmetric condition
\bar{U}_{hp}	average degree of radial consolidation in plane-strain condition
$U_{pr}\%$	degree of consolidation at the end of preloading
\bar{U}_v	average degree of vertical consolidation
u_o	initial excess pore water pressure
V	total volume associated with the node
w	water Content
z	depth

Greek Letters

α	biot's coefficient
β	pore pressure coefficient
γ_q^p	plastic shear strain
γ_s	unit weight
ΔR	permeability ratio incremental rate

ΔS	extent ratio incremental rate
ΔV_{mech}	equivalent increase in the nodal volume arising from mechanical deformation of the grid
$\Delta \sigma_{oct}$	octahedral normal stress
$\Delta \tau_{oct}$	octahedral shear stress
ϵ	volumetric strain
ζ	variation of water volume per unit volume of porous material
η	stress ratio
κ	slope of the specific volume versus $\ln(p')$ curve for swelling
λ	plastic volumetric strain ratio
λ	slope of the specific volume versus $\ln(p')$ curve for compression
μ	Poisson's ratio
ν	specific volume
ν_λ	specific volume at the reference pressure
ρ_d	bulk density of the dry matrix
ρ_s	density of the solid phase
ρ_w	mass density of the water
σ_c	the lateral pressure
σ_o	initial cavity internal pressure
σ_r	total stress
σ_{rp}	total radial stress at the elastic-plastic boundary
ϕ'	friction angle in drained condition