



UNIVERSITY OF
TECHNOLOGY SYDNEY

**Enhanced Analysis of Load Transfer
Mechanism and Deformation Estimation
for Ground Improvement Using Concrete
Injected Columns**

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

Doctor of Philosophy

from

University of Technology Sydney (UTS)

by

BALAKA GHOSH, BEng, MEng (UTS)

School of Civil and Environmental Engineering,

Faculty of Engineering and Information Technology

2018

CERTIFICATE OF ORIGINAL AUTHORSHIP

I confirm that the work done in this thesis has been an original work which has not previously been submitted for an evaluation unless as acknowledged within the text.

I also affirm that I have authored the thesis. All assistance for my research and preparation of this thesis has been acknowledged. Moreover, I also affirm that all literature and sources of information used in this research are indicated.

This research is supported by the Australian Government Research Training Program.

Balaka Ghosh

July 2019

ABSTRACT

This thesis presents analytical solutions to predict the response of the load transfer platform (LTP) on columns stabilised soft soil subjected to any shape of pressure loadings. The effect of the bending and shear deformations of LTP and the nonlinear stress strain behaviour of soft soil are incorporated into the analytical model. The cracked reinforced Timoshenko beam is proposed and implemented to model LTP to consider the shear and flexural deformations. Soft soil is idealised by spring-dashpot system to include the time-dependent non-linear behaviour. The columns and geosynthetics are modelled with linear Winkler springs in the applied range of stresses and rough elastic membrane, respectively. Influence of negligible tensile strength compared to the compressive strength of granular materials in LTP is also considered. Furthermore, a parametric study has been conducted to investigate how the parameters such as the column spacings, the thickness of LTP, the tensile stiffness of geosynthetics, and the degree of consolidation of the soft soil affect the response of LTP on improved soft soil. Moreover, the results from the proposed cracked Timoshenko beam theory (capturing the combined shear and bending stiffness of LTP) have been compared with results from the Euler-Bernoulli model (capturing deflection due to bending only) and the Pasternak model (capturing deformation due to shear only).

This research also provides rigorous solutions to estimate the settlement of the soft soils under embankment load when double layer of geosynthetics reinforcements have been used in the load transfer platform. The response function of the system in plane strain condition has been attained by developing governing differential equations for the proposed mechanical model and its solutions. To develop analytical equations, the basic

differential equations of a Timoshenko beam subjected to a distributed transverse load and a foundation interface pressure, generated from the Kerr foundation model is applied. Furthermore, the suitability of the Kerr foundation model for engineering calculations of LTP are evaluated. In addition, the results from the proposed model simulating the soft soil as the Kerr foundation model are compared to the corresponding solutions when the soft soil is idealised by Winkler and Pasternak foundations. Additionally, to assess the overall behaviour of the multilayer geosynthetic reinforced granular layer as well as that of the single layer geosynthetic reinforced granular layer parametric studies are also carried out. The developed analytical model can be applied by practicing engineers to predict the deflection of the LTP and mobilised tension in the geosynthetic reinforcement.

In addition, this research presents the results of a numerical investigation into the performance of geosynthetic-reinforced column-supported embankment in soft ground. A three-dimensional finite-element model was employed to compare the results with a case study on a number of governing factors such as the downward and lateral movement of soft soil, the stress transferred to column, and the developed excess pore water pressure. The soft soil is represented by the Modified Cam-Clay model (MCC) while the linear elastic and perfectly plastic model adopting the failure criterion of Mohr-Coulomb is applied for medium dense to dense gravel, cobble soil, the granular platform and the embankment. By adopting Hoek-Brown model (HB) to simulate concrete injected columns, non-linear stress-strain relationship is considered in this study. It should be noted that the geometry and other physical properties of the soils and columns considered in this study have been adopted from Gerringong upgrade project, a ground improvement mission taken place in New South Wales, Australia.

To my father, *Ramendra Sundar Ghosh*, my mother, *Bandana Ghosh*, and my beloved husband *Soumya Das*, who shared love and strength with me throughout this marvellous journey.

ACKNOWLEDGEMENT

A casual discussion with my supervisor during my Masters' days gave me the opportunity of a lifetime to pursue doctoral studies at University of Technology Sydney (UTS). Not only I have developed a flavour and passion for my subject, this journey has also offered me profound experience in my academic career. Such achievements have been possible only because of the support and guidance from my supervisors, assistance from my geotechnical research fellows, encouragement from work colleagues and lastly sacrifices made by my family.

Firstly, I would like to appreciate my principal supervisor A/Prof Behzad Fatahi and my co-supervisor A/Prof Hadi Khabbaz for their structured and exhaustive guidance not only limited to the specific field of study but beyond. PhD is a challenge and having such wonderful mentors who constantly support me, equipped me well to deal with that challenge. My PhD thesis could not have been achieved without their constructive feedback and worthy recommendations.

Secondly, I am thankful to Prof Jian-Hua Yin for providing valuable insights and my geotechnical research fellows who have been directly or indirectly involved in my doctoral study. More specifically, I am indebted to my co-researcher Harry Nguyen for his assistance with investigation of field report.

Furthermore, I would sincerely acknowledge the Faculty of Engineering and Information Technology at UTS and the Centre of Built Infrastructure Research (CBIR) for providing me the platform to pursue my PhD. I appreciate Ms Van Le and Ms Phyllis Agius for their flexibility and kind assistance. I would also like to acknowledge the support received from Dr. Richard Kelly, Mr. Mohammad Qazafi, and Mr. Zico Lai from SMEC; Mr.

Graham Yip, Dr. A. H. M. Kamruzzaman, Mr. Daniel Horan, and Mr. Adrian Rouse from Roads and Maritime Services (RMS); Mr. Michael Marix-Evans from Fulton Hogan; and Philippe Vincent (Menard Oceania). Valuable advices from Mr. Roger Santos (Formerly at Fulton Hogan) and Jeff Hsi (formerly at SMEC) are not gone unnoticed.

In addition, I would like to recognise the kind words of encouragement, support and assistance from my work colleagues particularly Anthony Garnaut, James McIntosh and Chris Smyth.

To succeed in a monumental challenge of this sort required a very strong family support. I would like to acknowledge my family for all the sacrifices that they have made to support me through this journey. In particular, my parents who travelled to Australia multiple times to provide support at home, my in-laws for their constant encouragement from overseas. Last but not least, I would like to thank my beloved husband, Soumya Das, who is constantly an epitome of support and strength to me.

LIST OF PUBLICATIONS

❖ Published Journal Articles

Ghosh B., Fatahi B., Khabbaz H., and Yin J.H. (2017), ‘Analytical study for double-layer geosynthetic reinforced load transfer platform on column improved soft soil’, *Geotextiles and Geomembranes*, **45** (5): 508–536.

Ghosh B., Fatahi B., and Khabbaz H., (2017). ‘Analytical solution to analyse LTP on column improved soft soil considering soil nonlinearity’, *International Journal of Geomechanics*. **17** (3): 1–24.

❖ Published Conference Papers

Ghosh B., Fatahi B., Khabbaz H., and Kamruzzaman A. H. M., (2016). ‘Analysis of CMC-Supported Embankments Considering Soil Arching’, *Proceedings of the Geo-China 2016 International Conference, Shandong, China. ASCE Geotechnical Special Publication (GSP 265)*: 286–293.

Ghosh B., Fatahi B., and Khabbaz H., (2016). ‘Mechanical Model to Analyse Multilayer Geosynthetic Reinforced Granular Layer in Column Supported Embankments’, *Procedia Engineering: Proceedings of The 3rd International Conference on Transportation Geotechnics*, **143**: 387–394.

Ghosh B., Fatahi B., Khabbaz H., and Hsi G., (2015). ‘Reinforced Timoshenko Beam Theory to Simulate Load Transfer Mechanism in CMC Supported Embankments’, *Proceedings of 12th Australia New Zealand Conference on Geomechanics, Wellington, New Zealand*, 1099–1106.

Ghosh B., Fatahi B., Khabbaz H., and Kamruzzaman A. H. M., (2015). ‘Assessing Load Transfer Mechanism in CMC-Supported Embankments Adopting Timoshenko Beam Theory’, Proceedings of XVI European Conference on Soil Mechanics and Geotechnical Engineering: Geotechnical Engineering for Infrastructure and development, Edinburgh, 577–582.

TABLE OF CONTENTS

ABSTRACT	iii
ACKNOWLEDGEMENT	vi
LIST OF PUBLICATIONS	viii
TABLE OF CONTENTS	x
LIST OF FIGURES	xvii
LIST OF TABLES	xxvi
LIST OF ABBREVIATIONS	xxvii
NOMENCLATURE	xxix
CHAPTER 1	1
1. INTRODUCTION	1
1.1. General	1
1.2. Statement of Problem	4
1.3. Objectives and Scope of Research	7
1.4. Organisation of Thesis.....	10
CHAPTER 2	14
2. LITERATURE REVIEW	14
2.1 General	14
2.2 Ground Improvement Using Concrete Injected Columns (CICs)	15
2.3 Theory of Soil Arching in Column-Supported Embankments	17

2.4	Load Transfer system in Geosynthetic Reinforced Column-Supported Embankments.....	18
2.5	Design of Geosynthetic Reinforcement.....	20
2.5.1	Parabolic Method	21
2.5.2	Tensioned Membrane Method	21
2.6	Numerical and Experimental Studies of Column-Supported Embankments ...	22
2.7	Empirical and Analytical Model of Column-Supported Embankments	26
2.7.1	Method of Hewlett and Randolph (1988)	26
2.7.2	Method of Low et al. (1994)	29
2.8	Design Guidelines	36
2.8.1	British Standard: BS8006 (2010).....	36
2.8.2	German Standard: EBGEO (2010).....	42
2.9	Mechanical Behaviour of Geosynthetic Embedded Granular Fill Layer	46
2.10	Summary	60
	CHAPTER 3	62
	3. ANALYTICAL SOLUTION OF LTP ON COLUMN-IMPROVED SOFT SOIL CONSIDERING SOIL NONLINEARITY	62
3.1.	General	62
3.2.	Nonlinear Response of Soft Soil	63

3.3.	Development of Analytical Model	64
3.3.1.	Equivalent Properties of Cracked Load Transfer Platform.....	67
3.3.2.	Formulation for Load transfer Platform on Soft Soil.....	70
3.4.	Solutions of Governing Differential Equations.....	73
3.4.1.	Rotation of LTP	77
3.4.2.	Bending Moment and Shear Force in LTP	79
3.4.3.	Tension Mobilised in the Geosynthetics	82
3.5.	Boundary and Continuity Conditions.....	83
3.6.	Model Evaluation and Parametric Study.....	86
3.6.1.	Comparison of Predictions Adopting Different Beam Theories.....	88
3.6.2.	Effect of Column Spacing.....	100
3.6.3.	Effect of LTP Thickness	102
3.6.4.	Effect of Tensile Stiffness of Geosynthetics.....	104
3.6.5.	Effect of Degree of Consolidation (U).....	106
3.7.	Summary	108
CHAPTER 4	110
4.	ANALYTICAL STUDY FOR DOUBLE-LAYER GEOSYNTHETIC REINFORCED LOAD TRANSFER PLATFORM ON COLUMN IMPROVED SOFT SOIL.....	110

4.1.	General	110
4.2.	Formulation of the problem.....	111
4.3.	The Analytical Solutions	120
4.3.1.	Rotation of LTP	126
4.3.2.	Bending Moment and Shear Force in LTP	128
4.3.3.	Tension in Geosynthetic Reinforcement.....	131
4.3.4.	Pressure Distribution under LTP.....	131
4.3.5.	Boundary and Continuity Conditions	132
4.4.	Results and Discussions	136
4.4.1.	Predictions of Kerr Foundation Versus Other Foundation Models	140
4.4.2.	Effects of Column Spacing	149
4.4.3.	Effects of LTP Thickness.....	151
4.4.4.	Effects of Soft Soil Stiffness.....	154
4.4.5.	Effects of Tensile Stiffness of Geosynthetic Reinforcement.....	156
4.5.	Summary	159
CHAPTER 5		162
5. REINFORCED TIMOSHENKO BEAM TO SIMULATE LOAD TRANSFER MECHANISM IN CIC SUPPORTED EMBANKMENT		162
5.1.	General	162

5.2. Reinforced Timoshenko Beam Theory to Simulate Load Transfer Mechanism in CIC-Supported Embankments	163
5.2.1. Basic Differential Equations for Timoshenko Beam on Elastic Foundation	164
5.2.2. Closed Form Solution	166
5.2.3. Parametric Study	171
5.2.4. Results and Discussions	172
5.3. Mechanical Model to Analyse Multilayer Geosynthetic-Reinforced Granular Layer in Column-Supported Embankments.....	175
5.3.1. Analytical Model.....	176
5.3.2. Analytical Solution	179
5.3.3. Boundary and Continuity Conditions	181
5.3.4. Results and Discussions	182
5.4. Analysis of CIC-Supported Embankments Considering Soil Arching	185
5.4.1. Mechanical Model Development	185
5.4.2. Geometry and Material Properties of a CIC-Supported Embankments..	190
5.4.3. Results and Discussion.....	191
5.5. Summary	193

CHAPTER 6	196
6. FIELD STUDY AND NUMERICAL MODELLING FOR A ROAD EMBANKMENT BUILT ON SOFT SOIL IMPROVED WITH CONCRETE INJECTED COLUMNS	196
6.1. General	196
6.2. Overview of the Case Study	197
6.3. Site Conditions and Soil Properties	200
6.4. Instrumentation	205
6.5. Numerical Modelling Details	206
6.5.1. Boundary and Initial Conditions	208
6.5.2. Modelling of Concrete Injected Columns	211
6.5.3. Modelling of Geosynthetics and Soft soil	213
6.5.4. Construction and Modelling Sequence	215
6.6. Results and Discussion	218
6.6.1. Soil Deformation and Evolution of Excess Pore Pressure	218
6.6.2. Soil-CIC Interaction	224
6.6.3. Tensile Forces in Top and Bottom Geosynthetics	231
6.7. Summary	234
CHAPTER 7	237

7. CONCLUSIONS AND RECOMMENDATIONS.....	237
7.1. Summary	237
7.2. Key Concluding Remarks	239
7.3. Recommendations for Future Studies	245
LIST OF REFERENCES	247
Appendix A: Algebraic Equations Obtained from the Boundary and the Continuity Conditions.....	I
Appendix B: Summary of Thirteen Algebraic Equations Obtained from the Adopted Boundary and Continuity Conditions	VIII
Appendix C: MATLAB 2016a Code to Solve Non-Linear Equations.....	XVI

LIST OF FIGURES

Figure 1.1. Range of ground improvement techniques.	2
Figure 1.2. Load transfer mechanism of concrete injected columns-supported structures.	4
Figure 1.3. Fundamental concepts of mechanics for LTP beam: (a) stresses on LTP of a CIC-supported embankment and (b) details of internal and external forces acting on the finite LTP beam element.	5
Figure 2.1. Principle of load transfer mechanism in: (a) Pile and (b) CIC.	16
Figure 2.2. Different stages of soil arching to demonstrate: (a) the soil mass overlying a potential void; (b) the formation of a true arch (Void under soil mass); and (c) soil mass collapses to form an inverted arch (modified after McKelvey, 1994).	17
Figure 2.3. Load transfer mechanism (modified after Han and Gabr, 2002).	19
Figure 2.4. Augur of a rigid inclusion, concrete injected column.	23
Figure 2.5. Hewlett and Randolph's (1988) proposed: (a) hemispherical domes model in three dimension and (b) semicircular model in two dimensions (modified after Hewlett and Randolph's, 1988).	28
Figure 2.6. Equilibrium analysis of an element: (a) at crown and (b) at just above pile cap (modified after Hewlett and Randolph, 1988).	31
Figure 2.7. Analytical model to illustrate: (a) semi-cylindrical sand arch and (b) distribution of load on soft-soil (modified after Low et al., 1994).	32

Figure 2.8. Geotextile overlying cap beams and soft ground (modified after Low et al., 1994).	34
Figure 2.9. Low et al. (1994) proposed model to display: (a) assumed shape of geotextile deformation; (b) stresses acting on geotextile; and (c) idealized pressure distribution on geotextile (modified after Low et al., 1994).	35
Figure 2.10. Arching dome according to British Standard (modified after Alexiew, 2004).	38
Figure 2.11. Variables used in determination of TRP (modified after BS8006-1, 2010).	39
Figure 2.12. Outer limit of pile caps (modified after BS8006-1, 2010).....	41
Figure 2.13. Lateral sliding at fill and reinforcement interface (modified after BS8006-1, 2010).	42
Figure 2.14. Multi arching model (modified after Zaeske, 2001 and 2002).	43
Figure 2.15. Maximum strain in the geosynthetic reinforcement (Kempfert <i>et al.</i> , 2004)	44
Figure 2.16. Calculation of the resulting force F assigned to the load influence area AL (modified after Kempfert <i>et al.</i> , 2004).	45
Figure 2.17. Gerringong upgrade project site (Roads and Maritime Services, 2015)....	47
Figure 2.18. Beam on elastic foundation: (a) force acting along the length and (b) details of a finite section of the beam.	48

Figure 2.19. Different beam theories displaying: (a) beam on elastic foundation; (b) deformation due to shear only (Pasternak shear layer; CL = centreline); (c) deformation due to bending only (EB = Euler-Bernoulli beam; CS = cross section; NA = neutral axis); and (d) deformation due to bending and shear (TB = Timoshenko beam)	52
Figure 2.20. Free-body diagram of an infinitesimal beam element for (a) Pasternak shear layer and (b) Timoshenko and Euler-Bernoulli beams.	52
Figure 2.21. Structural illustration of a Timoshenko beam: (a) vertical deflection and (b) rotation of cross-section.	57
Figure 2.22. CIC-supported embankment: (a) sketch of a geosynthetic-reinforced CIC-supported embankment over soft soil system and (b) location of tension in the LTP.	58
Figure 3.1. Nonlinear response of soft soil: (a) stress-strain curve and (b) assumed bilinear response of soft soil.	64
Figure 3.2. Deflection pattern and tension cracks in LTP supported on multiple columns improved soft soil foundation.	65
Figure 3.3. (a) Typical sketch of a geosynthetic reinforced column supported granular layer and (b) schematic diagram of the proposed foundation model.	66
Figure 3.4. Different cross sections of LTP when: (a) uncracked; (b) tension at bottom (Sections II and III); and (c) tension at top (Section I).	70
Figure 3.5. Load transfer platform showing: (a) different sections in LTP and (b) pressure distribution in LTP.	72

Figure 3.6. Stress-strain behaviour of soft estuarine clay (CH): (a) stress-displacement curve from Oedometer test and (b) calculated modulus of subgrade reaction for soft soil.	89
Figure 3.7. Illustration of: (a) LTP on soft soil for baseline case; (b) variation of deflection; and (c) variation of slope of CL of LTP (dw/dx) at the end of consolidation.	93
Figure 3.8. Illustration of: (a) LTP on soft soil for baseline case; (b) variation of bending moment; and (c) shear force at the end of consolidation.	95
Figure 3.9. Illustration of: (a) LTP on soft soil for baseline case; (b) variation of rotation of CS of LTP due to bending (θ); (c) variation of shear strain developed in LTP (γ); and (d) variation of mobilised tension in geosynthetics at the end of consolidation.....	98
Figure 3.10. Comparison of stress concentration ratio considering LTP as TB, EB, and PSL.....	100
Figure 3.11. Effect of column spacing on: (a) maximum settlement of LTP and (b) maximum mobilised tension in geosynthetics.	102
Figure 3.12. Effect of thickness of LTP on: (a) maximum settlement of LTP and (b) maximum mobilised tension in geosynthetics.	104
Figure 3.13. Effect of tensile stiffness of geosynthetics on: (a) maximum settlement of LTP and (b) maximum mobilised tension in geosynthetics.....	105
Figure 3.14. Effect of degree of consolidation of soft soil on: (a) maximum settlement of LTP and (b) maximum mobilised tension in geosynthetics.....	107

Figure 4.1. Illustration of: (a) proposed mechanical model of load transfer platform on column improved soft soil in plane strain condition; (b) free-body diagram of element A in sagging part; and (c) free-body diagram of element B in sagging part.....	112
Figure 4.2. Typical diagram of: (a) deflection profile of load transfer platform (LTP), (b) effective cross-section of LTP in sagging region, and (c) effective cross-section of LTP in hogging region.	116
Figure 4.3. Comparison of: (a) settlement and (b) rotation profiles of LTP considering soft soil as Kerr, Pasternak, and Winkler foundation models.....	134
Figure 4.4. Comparison of: (a) bending moment of LTP, (b) shear force in LTP, and (c) shear force developed in soft soil considering soft soil as Kerr, Pasternak, and Winkler foundation models.....	145
Figure 4.5. Comparison of mobilised tensions in: (a) top and (b) bottom geosynthetic layers considering soft soil as Kerr, Pasternak, and Winkler foundation models.....	147
Figure 4.6. Effect of column spacings for the case of LTP on Kerr foundation model on: (a) the maximum deflections of LTP and (b) the maximum normalised tensions in the geosynthetics.....	151
Figure 4.7. Effect of LTP thicknesses for the case of LTP on Kerr foundation model on: (a) the maximum deflections of LTP and (b) the maximum normalised tensions in the geosynthetics.....	153
Figure 4.8. Effect of soft soil stiffnesses for the case of LTP on Kerr foundation model on: (a) the maximum deflections of LTP and (b) the maximum normalised tensions in the geosynthetics.....	155

Figure 4.9. Effect of tensile stiffnesses of geosynthetic reinforcement for the case of LTP on Kerr foundation model on: (a) the maximum deflections of LTP and (b) the maximum normalised tensions in the geosynthetics.	158
Figure 5.1. Modified model of Yin’s (2000a) model showing: (a) foundation model for the geosynthetic reinforced granular layer on soft soil proposed by and (b) forces acting on a finite element of reinforced granular layer.	165
Figure 5.2. Schematic diagram of the proposed foundation model for CIC supported embankment.	167
Figure 5.3. Illustration of: (a) stresses acting on proposed 2-dimensional foundation model for geosynthetic reinforced CIC supported embankment and (b) free body diagram of LTP cut at a section A-A.	169
Figure 5.4. Typical cross section of a geosynthetic reinforced CIC supported embankment.	172
Figure 5.5. Effects of the thickness of LTP with GR and without GR on: (a) maximum settlement and differential settlement of the LTP and (b) bending stiffness and shear stiffness of the LTP.	174
Figure 5.6. Variations in: (a) settlement of the LTP in x-direction and (b) tension generated in the geosynthetic reinforcement in x-direction.	175
Figure 5.7. Variations in: (a) shear force developed in the reinforced LTP and (b) rotation angle of the LTP with geosynthetic reinforcement and without geosynthetic reinforcement in x-direction.	175

Figure 5.8. Illustration of: (a) embankment on CIC-improved soft soil and (b) proposed foundation model.	177
Figure 5.9. Proposed mechanical model demonstrating: (a) multilayer geosynthetic-reinforced granular fill soft soil column system and (b) stress application in different infinitesimal LTP section.	178
Figure 5.10. Effect of embankment height with multilayer geosynthetic reinforcements on: (a) settlement profiles and (b) rotation of the LTP.	183
Figure 5.11: Typical profile of normalised mobilised tension in the geosynthetic reinforcement along the length of the LTP from the centreline of CIC.....	184
Figure 5.12. Sketch of: (a) embankment resting on CIC-improved soft soil and (b) proposed foundation model.....	186
Figure 5.13. Illustration of: (a) assumed deformation shape of CIC-improved ground and (b) stresses on the LTP elements within the soil and column region.....	188
Figure 5.14. Effect of arching on: (a) stresses on LTP and (b) deflection of LTP.	192
Figure 5.15. Effect of arching on: (a) shear force and (b) moment in the LTP.	192
Figure 5.16. Effect of arching on: (a) rotation of LTP and (b) tension in GR.	193
Figure 6.1. Ground improvement zones for the northbound bridge abutment approach leading to the north abutment of the Infra 5 bridge.	198
Figure 6.2. A schematic cross-sectional 2-D view of the CIC improved ground near the bridge abutment.....	199

Figure 6.3. The requirement of termination depth during installing CIC.	200
Figure 6.4. Geotechnical investigation at the site: (a) The investigation locations; and (b) geotechnical long section at the section of the northern bridge approach embankment.	201
Figure 6.5. Soil profiles and properties.	203
Figure 6.6. Layout of instrumentation for the section at the Infra-5 close to the North bound North abutment.	206
Figure 6.7. Schematic diagram of the section adopted for finite element modelling (all dimensions are in metre and not necessarily to scale).	207
Figure 6.8. Geometry of adopted numerical modelling: (a) plan view and (b) three-dimensional finite-element mesh.	208
Figure 6.9. Initial results of: (a) hydrostatic pore water pressure and (b) vertical effective stresses in soil deposit.	210
Figure 6.10. Construction sequence and installation of instrumentations in site.	216
Figure 6.11. Locations of instrumentations for field measurements.	219
Figure 6.12. Variation of settlement at the base of the embankment.	219
Figure 6.13. Variation of lateral soil displacement with depth at the locations of inclinometer: (a) I1 (I_M110_1865_N01) and (b) I2 (I_M110_1885_N01).	221
Figure 6.14. Lateral displacement of soil over time at the location of: (a) inclinometer I1 and (b) inclinometer I2.	223

Figure 6.15. Variation of excess pore water pressure with time at the location of piezometer VP at Point B (VP_M110_1865_N01).....	224
Figure 6.16. Variation of vertical stress acting on top of column with time.....	225
Figure 6.17. Predicted variations of: (a) lateral deflection, (b) bending moment, (c) shear force, and (d) axial force in CICs.....	228
Figure 6.18. Vertical stress on the ground surface at the base of the embankment along Section A-A'	229
Figure 6.19. Vertical stress on the ground surface at the base of the embankment in long Section B-B'	230
Figure 6.20. Settlement profiles at the end of several construction stages along section A-A'	231
Figure 6.21. Tensile force produces in the geosynthetics: (a) close to pile along section A-A' and (b) far away from pile.	233
Figure 6.22. Comparison of settlement at various locations after adding 3 m of surcharge.	234

LIST OF TABLES

Table 2.1. Values of Ω (Collin, 2004)	22
Table 3.1. Material properties used in the baseline case	87
Table 3.2. Values of influencing factors used in the parametric study.	87
Table 3.3. Calculated parameters of LTP for baseline case.	88
Table 4.1. Properties of materials used in the baseline analysis.	139
Table 4.2. Adopted range of parameters used in the parametric study.	140
Table 4.3. Calculated parameters of reinforced granular layer for baseline case.....	141
Table 5.1. Calculated material properties and geometry of 0.3m and 0.5m thick LTP.	173
Table 5.2. Material properties adopted in parametric study.....	182
Table 5.3. Material properties used in parametric study.	190
Table 6.1. Soil model parameters used in the numerical modelling.	204
Table 6.2. Material property of concrete columns.	213
Table 6.3. Numerical modelling stages adopted to analysis the behaviour of the embankment built on CIC improved soft soil.	216

LIST OF ABBREVIATIONS

EB:	Euler-Bernoulli beam;
BH:	Borehole;
CD:	Construction day;
CIC	Concrete Injected Column;
CL:	Centreline;
CPT	Cone penetration test;
CS:	Cross section;
DMM:	Deep Soil Mixing Method;
EB:	Euler-Bernoulli beam;
GR:	Geosynthetic reinforcement
GRCS:	Geosynthetic reinforced column-supported;
HB:	Hoek-Brown;
I:	Inclinometer;
LTP:	Load transfer platform;

MC: Mohr-Coulomb;

MCC Modified Cam Clay;

NA: Neutral axis;

OCR: Over consolidation ratio;

PC: Pressure cell;

PSL: Pasternak shear layer;

PVD: Pre-fabricated drain;

SP: Settlement plate;

SRR: Stress reduction ratio;

TB: Timoshenko beam

VP: Vibrating wire piezometer;

NOMENCLATURE

The following notations are used in this research:

a: diameter of the pile (m);

a_r : area replacement ratio (non-dimensional);

A_c : plan area of the column (m^2);

A_p : plan area or cross section area of the column or pile (m^2);

A_h : cross section area of the granular layer in hogging region after cracking (m^2);

A_s : cross section area of the granular layer in sagging region after cracking (m^2);

A_r : cross section area of the geosynthetics (m^2);

A_w : plan area of CIC wall in plane strain (m^2);

C: shear stiffness of the beam (kN/m);

C_h : shear stiffness of the load transfer platform in hogging region (kN/m);

C_s : shear stiffness of the load transfer platform in sagging region (kN/m);

d: diameter of the column (m);

D: bending stiffness of Timoshenko beam (kN.m);

D_h : equivalent bending stiffness of the load transfer platform in hogging region (kN.m);

D_s : equivalent bending stiffness of the load transfer platform in sagging region (kN.m);

e_0 : initial void ratio;

E : efficacy or Young's modulus;

E' : effective stiffness (kN/m^2);

E_c : Young's modulus of the concrete injected column material (kN/m^2);

E_g : Young's modulus of the granular material in load transfer platform (kN/m^2);

E_r : elastic stiffness of the geosynthetic reinforcement (kN/m^2);

f_{ck} : 28-days compressive strength of concrete (MPa);

G : shear modulus of the soft soil (kPa);

h : thickness of the load transfer platform before cracking (m);

h_h : distance of the neutral axis from the compression surface of the load transfer platform for hogging moment (m);

h_h : distance of the neutral axis from the compression surface of the load transfer platform for sagging moment (m);

H : depth of the soft soil (m);

H : height of the embankment (m);

H_c : length of the columns (m);

H_s : depth of the soft soil (m);

I_h : second moment of inertia of the granular fill about neutral axis for hogging (m^3);

I_s : second moment of inertia of the granular fill about neutral axis for sagging (m^3);

J : stiffness of the geosynthetic reinforcement (kN/m);

K_0 : lateral earth pressure coefficient;

K_p : passive earth pressure (kPa);

M : bending moment of the beam (kN.m);

n : modular ratio (non-dimensional) or stress concentration ratio;

k_c : modulus of subgrade reaction for the column ($kN/m^2/m$);

k_{0s} : initial modulus of subgrade reaction for the soft soil foundation ($kN/m^2/m$);

k_{1s} : stiffened modulus of subgrade reaction for the soft soil foundation ($kN/m^2/m$);

k_s : modulus of subgrade reaction for the soft foundation soil ($kN/m^2/m$);

k_{sc} : shear correction coefficient of the Timoshenko beam (non-dimensional);

k_1 : modulus of subgrade reaction for the soft soil foundation attached to the bottom of shear layer ($kN/m^2/m$);

k_{sc} : shear correction coefficient of the Timoshenko beam (non-dimensional);

k_u : modulus of subgrade reaction for the soft soil foundation attached to LTP ($kN/m^2/m$);

K_c : equivalent modulus of the subgrade reaction for column (kN/m);

$(K_c)_{eq}$: equivalent modulus of the subgrade reaction for column (kN/m);

p : transverse pressure on the beam from super structure (kPa);

P_r : distributed load acting on geosynthetics between adjacent piles (kPa);

q : normal stress at the interface of the beam and the soft soil (kPa);

q_0 : surcharge (kPa);

Q : shear force (kN);

s : centre to centre spacing between the two adjacent columns or piles (m);

s' : clear spacing between the two adjacent columns or piles (m);

S_r : tensile stiffness of the geosynthetics (kN/m);

S_r^b : tensile stiffness of the bottom geosynthetic reinforcement (kN/m);

S_r^t : tensile stiffness of the top geosynthetic reinforcement (kN/m);

T : tension mobilised in the geosynthetic layer (kN/m);

U : degree of consolidation of the soft soil (%);

V : shear force in the beam (kN/m);

w : transverse deflection (m);

\hat{w} : deflection of the load transfer platform beyond which k_{0s} becomes k_{1s} (m);

y_h : distance between the neutral axis and the centroid axis of the load transfer platform in hogging region (m);

y_s : distance between neutral and centroid axes of the load transfer platform in sagging region (m);

y_r : distance of the geosynthetic from the centroid axis of load transfer platform (m);

y_r^b : distance of the bottom geosynthetic layer from the centroid axis of load transfer platform (m);

y_r^t : distance of the top geosynthetic layer from the centroid axis of load transfer platform (m);

ε : strain in geosynthetics;

σ_c : stress transferred to pile (kPa);

σ_s : stress transferred to soil (kPa);

γ : unit weight (kN/m^3);

ρ : soil arching ratio;

ν : Poisson's ratio;

ν_g : Poisson's ratio of the granular material (non-dimensional);

ν_r : Poisson's ratio of the geosynthetics (non-dimensional);

ν_r^t : Poisson's ratio of the top geosynthetic reinforcement (non-dimensional);

ν_r^b : Poisson's ratio of the bottom geosynthetic reinforcement (non-dimensional);

λ : slope of the normal consolidation line;

κ : slope of the elastic swelling line;

θ : rotation angle of the cross section of the beam (radian);

ϕ : frictional angle (degree);

ϕ' effective friction angle;

ψ : rotation angle of Timoshenko beam (radian);

ψ' : effective dilatancy angle;