

PHYSICAL AND NUMERICAL MODELLING OF BOTTOM ASH COLUMNS  
INSTALLED IN SOFT SOIL

RAZIEH MORADI

A thesis submitted in fulfilment of the  
requirements for the award of the degree of  
Doctor of Philosophy (Civil Engineering)

Faculty of Civil Engineering  
Universiti Teknologi Malaysia

SEPTEMBER 2016

To my kind husband who stood beside his wife at every single step of the way,

To my beautiful daughter who was patient for her mother's targets,

To my beloved father and mother who constantly encouraged

their daughter to her education.

## ACKNOWLEDGEMENT

First and foremost, praises and thanks to the God, the merciful and the passionate, for providing me the opportunity to step in the excellent world of science. THE Almightyly for giving me the strength and opportunity to do and finish up my work.

During the preparation of this thesis, many things have happened, which at times seemed as though it would never end. What remains in me is their colour. To be able to step strong and smooth in this way, I have also been supported and supervised by many people to whom I would like to express my deepest gratitude. In particular, I would like to express my gratitude to my main supervisor Prof. Dr. Aminaton Marto for her dedication, encouragement, guidance and support. I am also very thankful to my co-supervisor Dr. Ahmad Safuan A Rashid for his support, guidance and advice. It was a great privilege and honour to work and study under their guidance. Without their continued support and interest, this thesis would not have been the same as presented here. They also should be admired because of their knowledge, personality and morality.

Thanks are also due to my friends especially Dr. Payman Alimohammadi and Dr. Ali Dehghanbandaki for their support and help in undertaking the laboratory works.

Last but not least, I would like to thank my beloved parents, my lovely husband and my family for their support, confidence and patience. Special thanks to my lovely and beautiful daughter, Avina, whose childhood was missed, being tolerant and enduring, while accompanying me in fulfilling my thesis.

## ABSTRACT

Stone column technique is one of the most widely used ground improvement techniques over the past 50 years. The technique includes the replacement of the soft soil with granular materials in order to increase the bearing capacity and reduce the settlement. This research investigated the role of a group of bottom ash columns in improving the bearing capacity of soft reconstituted kaolin clay. A series of physical modelling test was conducted to study the behaviour of clay reinforced with bottom ash columns under a rigid footing. The influence of important parameters, including area replacement ratio, length of the columns and the geotextile encasement on the performance of reinforced ground was investigated through a total of 13 model tests. Three (3) different area replacement ratios of 13%, 20 % and 26% and two (2) different lengths of 100 mm (floating) and 200 mm (end bearing) of the columns were investigated in this study. In addition, bottom ash columns were installed in two different methods, which was with geotextile encasement and without encasement. In parallel with physical modelling, finite element analyses were performed using Plaxis 3D Foundation software. The results clearly show that the ultimate bearing capacity of kaolin clay was significantly enhanced by the installation of bottom ash columns. This bottom ash has a great potential to be used as a replacement material for stone column in soft soil improvement work. The area replacement ratio was found to be an extremely important parameter controlling the overall performance of the reinforced foundation in the way that increasing the area replacement ratio resulted with up to 30% increase in the ultimate bearing capacity of composite ground. Increasing the length of the column also enhanced the bearing capacity of the reinforced ground of more than 15%. Floating columns were punched into the clay below the column base, but punching behaviour was eliminated by increasing the length of the column to become end bearing which resulted in the improvement of bearing capacity. Encasing the bottom ash columns with geotextile also resulted in an increase of the ultimate bearing capacity significantly from 25% for end bearing and up to 45% for floating columns. Finally, a design chart was established on the parameters affecting the ultimate bearing capacity of soft clay improved with bottom ash columns.

## ABSTRAK

Teknik tiang batu adalah salah satu teknik pembaikan tanah yang paling banyak digunakan sejak 50 tahun yang lalu. Teknik tersebut termasuk penggantian tanah lembut dengan bahan-bahan berbutir untuk meningkatkan keupayaan galas dan mengurangkan enapan. Kajian ini menyiasat peranan sekumpulan tiang abu dasar dalam meningkatkan keupayaan galas tanah liat lembut kaolin. Beberapa siri ujian pemodelan fizikal telah dijalankan untuk mengkaji kelakuan tanah liat yang diperkukuh dengan tiang abu dasar di bawah asas tegar. Pengaruh parameter penting termasuk nisbah penggantian luas, panjang tiang dan pembungkusan geotekstil ke atas prestasi tanah yang diperkuatkan dikaji melalui sejumlah 13 ujikaji model. Tiga (3) nisbah penggantian luas iaitu 13%, 20% dan 26% dan dua (2) panjang yang berbeza iaitu 100 mm (terapung) dan 200 mm (galas hujung) untuk tiang telah diselidik di dalam kajian ini. Di samping itu, tiang abu dasar telah ditanam dalam dua kaedah yang berbeza, iaitu dengan pembungkusan geotekstil dan tanpa pembungkusan. Selari dengan penyiasatan secara pemodelan fizikal, analisis unsur terhingga telah dilakukan dengan menggunakan perisian Asas Plaxis 3D. Keputusan jelas menunjukkan bahawa keupayaan galas muktamad tanah liat kaolin telah dipertingkatkan secara ketara dengan pemasangan tiang abu dasar. Abu dasar ini mempunyai potensi yang besar untuk digunakan sebagai bahan pengganti kepada tiang batu dalam kerja-kerja pembaikan tanah liat lembut. Nisbah penggantian luas didapati merupakan parameter yang sangat penting dalam mengawal prestasi keseluruhan tanah yang diperkukuh yang mana dengan meningkatkan nisbah penggantian kawasan telah meningkatkan sehingga 30% keupayaan galas muktamad tanah komposit. Meningkatkan kepanjangan tiang juga telah mempertingkatkan keupayaan galas tanah yang diperkukuh melebihi 15%. Tiang terapung telah menembusi ke dalam tanah liat pada dasar tiang, tetapi tingkah laku penembusan telah dihilangkan dengan peningkatan panjang tiang kepada tiang galas hujung yang menyebabkan kepada peningkatan keupayaan galas. Membungkusan tiang abu dasar dengan geotekstil juga meningkatkan keupayaan galas muktamad dengan berkesan dari 25% bagi galas hujung dan sehingga 45% bagi tiang terapung. Akhir sekali, satu carta reka bentuk telah diwujudkan bagi parameter yang mempengaruhi keupayaan galas muktamad tanah liat lembut yang diperkuatkan dengan tiang abu dasar.

## TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	<b>DECLARATION</b>	ii
	<b>DEDICATION</b>	iii
	<b>ACKNOWLEDGEMENT</b>	iv
	<b>ABSTRACT</b>	v
	<b>ABSTRAK</b>	vi
	<b>TABLE OF CONTENTS</b>	vii
	<b>LIST OF TABELS</b>	xiii
	<b>LIST OF FIGURES</b>	xvi
	<b>LIST OF ABBREVIATION</b>	xxv
	<b>LIST OF SYMBOLS</b>	xxvi
	<b>LIST OF APPENDICES</b>	xxviii
<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
	1.1 Background of the Research	1
	1.2 Problem Statement	4
	1.3 Aim and Objectives	5
	1.4 Scope and Limitation of the Research	5
	1.5 Significance of the Research	6
	1.6 Hypothesis	7
	1.7 Thesis Structure	8
<b>2</b>	<b>LITERATURE REVIEW</b>	<b>10</b>
	2.1 Introduction	10
	2.2 Stone Columns	10
	2.2.1 Principle of Stone Columns	11

2.2.2	Application of Stone Columns	12
2.2.3	Construction of the Stone Columns	14
	2.2.3.1 Vibro Compaction	14
	2.2.3.2 Vibro Replacement	15
	(i) Dry Top Feed System	16
	(ii) Wet Top Feed System	16
	(iii) Dry Bottom Feed System	16
2.3	Soft Clay	17
	2.3.1 Consolidation	19
	2.3.2 Undrained Shear Strength	20
2.4	Ultimate Bearing Capacity	21
	2.4.1.1 Terzaghi's Bearing Capacity Theory	22
	2.4.1.2 Meyerhof's Equation	23
	2.4.1.3 Skempton's Equation	23
	2.4.1.4 Determination of Ultimate Bearing Capacity from Load Tests	24
2.5	Bottom Ash	26
	2.5.1 Bottom Ash Application	30
	2.5.2 Physical and Mechanical Properties of Bottom Ash	32
	2.5.2.1 Appearance	32
	2.5.2.2 Particle Size Distribution	33
	2.5.2.3 Specific Gravity	35
	2.5.2.4 Permeability	36
	2.5.2.5 Compaction	37
	2.5.2.6 Strength of Bottom Ash	39
	2.5.2.7 Chemical and Heavy Metal Characteristics	40
2.6	Physical Modelling	42
	2.6.1 Single Column	43
	2.6.2 Group of Columns	46
	2.6.3 Geosynthetic Encasement	54
	2.6.4 Previous Study on Geosynthetic Encased Stone Columns	56

2.7	Numerical Modelling	61
2.7.1	Introduction	61
2.7.2	Previous Works	62
2.8	Summary	67
<b>3</b>	<b>RESEARCH METHODOLOGY</b>	<b>69</b>
3.1	Introduction	69
3.2	The Materials	71
3.3	Physical and Mechanical Properties Tests	72
3.3.1	Particle Size Distribution tests	73
3.3.1.1	Sieve Analysis Test	73
3.3.1.2	Hydrometer Test	74
3.3.2	Atterberg Limits Test	75
3.3.3	Specific Gravity Test	75
3.3.4	Permeability Test	76
3.3.4.1	Falling Head Permeability	77
3.3.4.2	Constant Head Permeability Test	77
3.3.5	Compaction Test	78
3.3.6	Consolidation Test	78
3.3.7	Relative Density	78
3.3.8	Unconfined Compression Test (UCT)	79
3.4	Physical Modelling	80
3.4.1	Testing Chamber	81
3.4.1.2	Model Height	82
3.4.1.3	Model Width	83
3.4.2	Pneumatic cylinder	84
3.4.3	Driving Unit and footing	86
3.4.4	Column Installation Equipment	88
3.4.5	Transducers and Data Acquisition System	90
3.4.6	Preparation of the Model Ground	91
3.4.6.1	Kaolin Slurry	91
3.4.6.2	Consolidation Process	91
3.4.6.3	Vane Shear Test	93
3.4.7	Bottom Ash Columns	94



	3.4.8	Column Arrangement	95
	3.4.9	Column Installation	97
	3.4.10	Testing Programme	102
	3.4.11	Loading procedure	104
3.5		Numerical Modelling	104
	3.5.1	Kaolin Clay	105
	3.5.2	Bottom Ash Columns	106
	3.5.3	Rigid Footing	106
	3.5.4	Numerical Modelling Details	107
<b>4</b>		<b>RESULTS AND DISCUSSION OF PHYSICAL MODEL</b>	
		<b>TEST</b>	<b>114</b>
	4.1	Introduction	114
	4.2	Basic properties	114
	4.2.1	Particle Size Distribution	116
	4.2.2	Atterberg Limits	118
	4.2.3	Specific Gravity	119
	4.2.4	Coefficient of Permeability	120
	4.2.5	Compaction Characteristics	120
	4.2.6	Relative Density	121
	4.2.7	Consolidation Characteristics	122
	4.2.8	Undrained Shear Strength	122
	4.3	Physical Modelling	124
	4.3.1	Unreinforced Condition	126
		4.3.1.1 Stress-Displacement Relationships	126
		4.3.1.2 Normalized Bearing Capacity Factor	128
	4.3.2	Clay Reinforced with Uncased Bottom Ash Columns	130
		4.3.2.1 Clay reinforced with Uncased Floating Columns	130
		(i) Stress-Displacement/Width of the Footing Relationship	131
		(ii) Normalized Bearing Capacity Factor	133

	(iii) Column Failure Pattern	133
	4.3.2.2 Clay Reinforced with Uncased End Bearing Columns	135
	(i) Stress-Displacement/Width of the Footing Relationship	136
	(ii) Normalized Bearing Capacity Factor	137
	(iii) Column Failure Pattern	138
4.3.3	Geotextile Encased Bottom Ash Columns	139
	4.3.3.1 Geotextile Encased Floating Columns	140
	(i) Stress-Displacement/Width of the Footing Relationship	140
	(ii) Normalized Bearing Capacity Factor	141
	(iii) Column Failure Pattern	142
	4.3.3.2 Geotextile Encased End Bearing Columns	144
	(i) Stress-Displacement/Width of the Footing Relationship	144
	(ii) Normalized Bearing Capacity Factor	146
	(iii) Column Failure Pattern	146
4.4	Effect of Geotextile-Encasement	148
4.5	Effect of Area Replacement Ratio	151
4.6	Effect of Columns' Length	153
4.7	Summary of the Physical Model Test Results	156
<b>5</b>	<b>RESULTS AND DISCUSSION OF NUMERICAL SIMULATION</b>	<b>159</b>
	5.1 Introduction	159
	5.2 Material properties	159
	5.3 Model Ground Displacement	162
	5.4 The Effect of Parametric Variations	164
	5.4.1 Effect of the Area Replacement Ratio	165

5.4.2	Effect of the Columns' Length	168
5.4.3	Effect of the Geotextile Encasement	168
5.5	Comparison between Experimental Results with Numerical Simulation	171
5.6	Summary of Findings From Numerical Modelling	178
<b>6</b>	<b>CONCLUSION</b>	<b>179</b>
6.1	Introduction	179
6.2	Conclusion	179
6.3	Contributions of Research	180
6.4	Recommendation for Further Work	181
	<b>REFERENCES</b>	<b>182</b>
	Appendices A- I	192- 205

## LIST OF TABELS

<b>TABLE NO.</b>	<b>TITLE</b>	<b>PAGE</b>
1.1	List of coal-fired plants in Peninsular Malaysia (after Hasan, 2013)	2
2.1	Index properties of clay from previous research works	19
2.2	Soil's Compression index (Widodo & Ibrahim, 2012)	20
2.3	Consistency and undrained strength of soil (Das, 2015; Craig, 2004)	20
2.4	Coal ash production of Tanjung Bin Power Plant (Worley Parsons Resources and Energy, 2011)	29
2.5	Results of specific gravity of bottom ash from Tanjung Bin Power Plant	35
2.6	Classification of soil according to permeability value (Head & Epps, 1986)	36
2.7	Permeability of bottom ash obtained by previous researchers	37
2.8	Compaction test results from previous research works	38
2.9	Direct shear test results conducted on bottom ash from previous studies	39
2.10	Friction angles of soils (Budhu, 2007)	40
2.11	Chemical content of Tanjung Bin Bottom ash (Awang, 2015)	41

2.12	Leaching test results for Tanjung Bin bottom ash (Awang, 2015)	42
2.13	Parameters studied by previous researchers working on stone column	68
3.1	Laboratory Tests Performed on Kaolin Clay	72
3.2	Laboratory Tests Performed on Bottom Ash	73
3.3	Typical stone column length and diameter of actual (prototype) and this model	95
3.4	Mass of bottom ash for various column length	98
3.5	Testing programme of the physical model test	103
3.6	Numerical modelling input parameters	109
4.1	Properties of kaolin and bottom ash obtained from laboratory tests	116
4.2	Statistical analysis data of shear stress from vane shear test	123
4.3	Results of undrained shear strength from vane shear test	124
4.4	Comparison of ultimate bearing capacity based on existing equation and results from model tests	128
4.5	Comparison of bearing capacity factor with previous researches	129
4.6	Results of uncased floating columns versus unreinforced clay	132
4.7	Results of uncased end bearing columns versus unreinforced clay	137
4.8	Results of geotextile encased floating columns versus unreinforced clay	141
4.9	Results of geotextile encased end bearing columns versus unreinforced clay	145
4.10	Results obtained from physical modelling tests	156
4.11	Summary of equations relating the ultimate bearing capacity with area replacement ratio for all cases of bottom ash column	157

5.1	Numerical modelling input parameters	160
5.2	Typical input parameters in numerical modelling for granular material stone columns (after Etezad, 2006)	161
5.3	Typical input parameters in numerical modelling for unreinforced clay (after Etezad, 2006)	162
5.4	Numerical results of uncased floating columns	167
5.5	Numerical results of uncased end bearing columns	167
5.6	Numerical results of geotextile encased floating columns	171
5.7	Numerical results of geotextile encased end bearing columns	171
5.8	Comparison of numerical and experimental results	177

## LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	Load transfer mechanism (McCabe <i>et al.</i> , 2007)	11
2.2	The rate of dissipation of excess pore pressure for stone columns and displacement piles (McCabe <i>et al.</i> , 2009)	13
2.3	Vibroflotation technique in stone column construction (ICE, 2015)	14
2.4	Particle size distribution illustrating applicability of Vibro Compaction and Vibro Replacement (McCabe <i>et al.</i> , 2007)	15
2.5	The bottom feed method in stone column installation (McCabe <i>et al.</i> , 2007)	17
2.6	Quaternary sediment in Peninsular Malaysia (Suntharalingam, 1983)	18
2.7	Terzaghi's failure modes of shallow foundation (Barnes, 2010)	21
2.8	Different methods for defining ultimate bearing capacity of shallow foundations from load test results (Lutenegger and Adams, 1998)	25
2.9	Principle coal reserves (Barnes, 2010)	27
2.10	Location of coal fired power plants in Peninsular Malaysia (Mahmud, 2003)	28
2.11	Typical thermal power plant and generated waste (Abubakar & Baharudin, 2012)	30
2.12	Use of coal ash in various sectors (Jayaranjan <i>et al.</i> , 2014)	31

2.13	Bottom ash fragments	33
2.14	Grain size distributions curves of several bottom ash samples (Recycled Materials Resource Centre, 2012)	34
2.15	Grain size distributions for bottom ash from Tanjung Bin Power (Marto <i>et al.</i> , 2014)	35
2.16	Compaction curve for Tanjung bin bottom ash (Muzamir <i>et al.</i> , 2013)	38
2.17	Test set up for single sand column (Hughes and Withers, 1974)	43
2.18	The load carrying mechanism of single stone column (Hughes and & Withers, 1974)	44
2.19	Installation of bottom ash in soft kaolin clay specimen (Marto <i>et. al.</i> , 2013)	45
2.20	Group failure of stone column (Hughes and Withers, 1974)	46
2.21	Failure mechanism of group columns (Bachus and Barksdale, 1984)	47
2.22	load- settlement response of columns by different L/D ratios (A) L/D 5.7 and 9.1 (B) L/D 9.1 and 14.5 (Hu, 1995)	48
2.23	Suggested mode of failure for stone columns (Hu, 1995)	49
2.24	Suggested failure mode for group columns (Hu, 1995)	50
2.25	Mode of columns' failure under strip foundation (McKelvey <i>et al.</i> , 2004)	51
2.26	Deformed shape of sand columns beneath circular footing (McKelvey <i>et al.</i> , 2004)	52
2.27	Column arrangement of group of bottom ash column (Marto <i>et al.</i> , 2013)	53
2.28	Improvement of undrained shear strength by area replacement ratio (Marto <i>et al.</i> , 2013)	53
2.29	The improvement of undrained shear strength by height penetrating ratio (Marto <i>et al.</i> , 2013)	54



2.30	Categorization of geosynthetic (a) geotextile (b) geogrid (c) geonet (d) geomembrane (e) geocomposite (f) GCL (g) geopipe (h) geocell (i) geofoam (Bathurst, 2007)	55
2.31	Load-settlement of clay stabilized with uncased stone column and encased stone column with various encasement (Malarvizi and Ilamparuthi, 2004)	57
2.32	Results of parametric study (a) effect of geotextile encasement (b) effect of column diameter (c) effect of l/d ratio (Ali <i>et al.</i> , 2010)	58
2.33	Stress-displacement relationship of uncased and encased floating columns (Ali <i>et al.</i> , 2014)	59
2.34	Stress-displacement relationship of uncased and encased floating columns (Ali <i>et al.</i> , 2014)	59
2.35	Mode of failure in single and group of stone columns (Ali <i>et al.</i> , 2014)	60
2.36	Summary of test results (Hong <i>et al.</i> , 2015)	61
2.37	Settlement performance of stone column (Balaam <i>et al.</i> , 1977)	62
2.38	Numerical model of stone column supporting embankment (a) model simulation (b) model deformation (c) horizontal displacement profile (Ng and Tan, 2015)	63
2.39	Load-settlement curve from the obtained by Castro (2014)	65
2.40	Assessment of experimental results with numerical outcomes (c : clay, sc : stone column, rsc : reinforced stone column) (Malarvizhi <i>et al.</i> , 2006)	66
2.41	Influence of loading area on column bulging (Malarvizhi <i>et al.</i> , 2006)	66
3.1	Flowchart of the study	70
3.2	Particle size distribution tests	74
3.3	Small pycnometer	76

3.4	Relative density test	79
3.5	Unconfined Compression Test on geotextile encased bottom ash sample	80
3.6	Model apparatus in physical model test	82
3.7	Geometry of Prandtl failure mechanism (Prandtl, 1921)	84
3.8	Consolidation set up in model ground preparation	85
3.9	Driving unit used in loading test	87
3.10	Footing and loading plate	88
3.11	Column installation apparatus	89
3.12	Data logger (Model MPX3000)	90
3.13	Porous paper	92
3.14	Vane shear test done on the model ground	93
3.15	Plan location of vane shear test	94
3.16	Column arrangement	96
3.17	Installation technique of uncased bottom ash column	98
3.18	Geotextile encasement	99
3.19	Installation technique of geotextile encased bottom ash column	100
3.20	Installation of bottom ash column	100
3.21	Plan view of completed bottom ash columns	101
3.22	Loading equipment	104
3.23	Schematization of single embedded pile in a soil mesh (Engin <i>et al.</i> , 2008)	107
3.24	The geometry of clay reinforced with four columns ( $A_r=13\%$ )	108
3.25	The geometry of clay reinforced with six columns ( $A_r=20\%$ )	108
3.26	The geometry of clay reinforced with six columns ( $A_r=26\%$ )	108
3.27	Numerical simulations of unimproved clay bed	110
3.28	Numerical simulations of clay with four floating columns ( $A_r=13\%$ )	110

3.39	Numerical simulations of clay with six floating columns ( $A_r=20\%$ )	111
3.30	Numerical simulations of clay with eight floating columns ( $A_r=26\%$ )	111
3.31	Numerical simulations of clay with four end bearing columns ( $A_r=13\%$ )	112
3.32	Numerical simulations of clay with six end bearing columns ( $A_r=20\%$ )	112
3.33	Numerical simulations of clay with eight end bearing columns ( $A_r=26\%$ )	113
4.1	Bottom ash gathered from Tanjung Bin power plant	115
4.2	Particle size distribution of kaolin and bottom ash	117
4.3	Comparison between particle size distribution of bottom ash	117
4.4	Plasticity chart (ASTM D2487)	119
4.5	Moisture content–dry density relationship of Tanjung Bin bottom ash	121
4.6	Vertical stress- displacement/width of the footing for unreinforced clay	127
4.7	$N_c$ -displacement/width of the footing for unreinforced clay	129
4.8	Vertical stress/width of the footing for uncased columns	130
4.9	Vertical stress-displacement/width of the footing for floating columns	131
4.10	$N_c$ -displacement/width of the footing for floating columns	133
4.11	Failure pattern of uncased floating columns of test P4C100HO ( $A_r=13\%$ )	134
4.12	Failure pattern of uncased floating columns of test P6C100HO ( $A_r=20\%$ )	134
4.13	Failure pattern of uncased floating columns of test P8C100HO ( $A_r=26\%$ )	135

4.14	Vertical stress-displacement/width of the footing for end bearing columns	137
4.15	$N_c$ -displacement/width of the footing for end bearing columns	138
4.16	Failure pattern of uncased end bearing columns of test P4C200HO ( $A_r=13\%$ )	138
4.17	Failure pattern of uncased end bearing columns of test P8C200HO ( $A_r=26\%$ )	139
4.18	Vertical stress- displacement/width of the footing for geotextile encased floating columns	141
4.19	$N_c$ -displacement/width of the footing for geotextile encased floating columns	142
4.20	Failure pattern of geotextile encased floating columns of test P4C100HG ( $A_r=13\%$ )	143
4.21	Failure pattern of geotextile encased floating columns of test P6C100HG ( $A_r=20\%$ )	143
4.22	Failure pattern of geotextile encased floating columns of test P8C100HG ( $A_r=26\%$ )	144
4.23	The relationship between vertical stress and displacement to the width of the footing for geotextile encased end bearing columns	145
4.24	$N_c$ -displacement/width of the footing for geotextile encased end bearing columns	146
4.25	Failure pattern of geotextile encased end bearing columns of test P6C200HG ( $A_r=20\%$ )	147
4.26	Failure pattern of geotextile encased end bearing columns of test P8C200HG ( $A_r=26\%$ )	147
4.27	Vertical stress-displacement/width of the footing for geotextile encased floating columns in comparison with uncased floating column	148
4.28	Stress-displacement relationship for geotextile encased end bearing columns in comparison with uncased end bearing columns	149

4.29	Ultimate bearing capacity of clay reinforced with uncased and geotextile encased floating columns at various area replacement ratios	150
4.30	Ultimate bearing capacity of clay reinforced with uncased and geotextile encased end bearing columns at various area replacement ratios	150
4.31	Ultimate bearing capacity of clay reinforced with uncased bottom ash columns based on various area replacement ratio	152
4.32	Ultimate bearing capacity of clay reinforced with geotextile encased bottom ash columns based on various area replacement ratio	153
4.33	Vertical stress- displacement/width of the footing for uncased columns	154
4.34	Ultimate bearing capacity of clay reinforced with uncased bottom ash columns according to column embedment ratio	155
4.35	Ultimate bearing capacity of clay reinforced with uncased bottom ash columns according to column embedment ratio	155
4.36	Comparison between bearing capacity factor of all tests	157
5.1	Deformed mesh of displacement on shading results of unreinforced clay and clay reinforced with six uncased end bearing columns	161
5.2	Axial displacement of the column for the test P8C200HO	164
5.3	Effect of area replacement ratio on uncased floating columns (Numerical simulation)	165
5.4	Effect of area replacement ratio on uncased end bearing columns (Numerical simulation)	166
5.5	Effect of columns' length from numerical simulation	168

5.6	Effect of geotextile encasement by numerical simulation ( $A_r=13\%$ )	169
5.7	Effect of geotextile encasement by numerical simulation ( $A_r=20\%$ )	169
5.8	Effect of geotextile encasement by numerical simulation ( $A_r=26\%$ )	170
5.9	Comparison of load- displacement response between numerical prediction (Plaxis 3-D Foundation) and the physical model tests	172
5.10	Comparison of numerical modelling with experimental results (uncased floating columns)	173
5.11	Comparison of numerical modelling with experimental results (uncased end bearing columns)	173
5.12	Comparison of numerical modelling with experimental results (geotextile encased floating columns)	174
5.13	Comparison of numerical modelling with experimental results (geotextile encased end bearing columns)	174
5.14	Comparison of numerical and experimental results for $A_r=13\%$	175
5.15	Comparison of numerical and experimental results for $A_r=20\%$	175
5.16	Comparison of numerical and experimental results for $A_r=26\%$	176
5.17	Bearing capacity factor, $N_c$ from numerical modelling and experimental results	176

**LIST OF ABBREVIATION**

AAS	-	Atomic Absorption Spectroscopy
AASHTO	-	American Association of State Highway and Transportation Officials
ASTM	-	American Society for Testing and Materials
BS	-	British Standard
LL	-	Liquid Limit
PI	-	Plasticity Index
PL	-	Plastic Limit
SL	-	Shrinkage Limit
TWBT	-	Thin Wall Brass Tube
USCS	-	Unified Soil Classification System

## LIST OF SYMBOLS

$A_c$	-	Area of bottom ash column
$A_r$	-	Area replacement ratio
$A_s$	-	Area of sample
$c$	-	Cohesion
$C_C$	-	Coefficient of curvature
$C_U$	-	Coefficient uniformity
$C_c$	-	Compression index
$c_v$	-	Coefficient of consolidation
$C_s$	-	Swelling index
$c_u$	-	Undrained shear strength
$d_c$	-	Diameter of bottom ash column
$D_g$	-	Diameter of soil grains
$e$	-	Void ratio
$G_s$	-	Specific gravity
$H_c$	-	Height of bottom ash column
$H_s$	-	Height of soil (model ground)
$k$	-	Coefficient of permeability
$kN$	-	Kilo newton
$kPa$	-	Kilo pascal
$m$	-	Moisture content
$m_v$	-	Coefficient of volume change
$Mg$	-	Mega gram
$MN$	-	Mega newton
$m/s$	-	Metre per second
$mm$	-	Milimetre
$\mu m$	-	Micrometre
$q$	-	Deviator stress



$q_u$	-	Ultimate bearing capacity, ultimate deviator stress
$q_{max}$	-	Maximum deviator Stress
$w_{opt}$	-	Optimum moisture content
$\rho_d$	-	Dry density
$\phi$	-	Internal friction angle
$\sigma_n$	-	Normal pressure
$\gamma_{min}$	-	Minimum unit weight
$\gamma_{max}$	-	Maximum unit weight
$\gamma_{dry}$	-	Dry unit weight
$\gamma_{sat}$	-	Saturated unit weight

**LIST OF APPENDICES**

<b>APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
A	Calibration of Instrumentation	192
B	Particle Size Distribution	194
C	Atterberg Limits Test	196
D	Specific Gravity Test	197
E	Permeability Test	198
F	Standard 'Light' Compaction Test	201
G	Relative Density Test	202
H	Oedometer Test	203
I	Properties of Polyfelt TS20	205

## **CHAPTER 1**

### **INTRODUCTION**

#### **1.1 Background of the Research**

Due to the increasing rate of population and the need for development of the human societies, the utilization of marginal sites and poorer soils became inevitable nowadays. Among the growing methods of ground treatment, stone column technique is considered as an efficient, cost effective and environmental friendly for improving the soft cohesive soils. The technique involves the replacement of 10-35% of the in-situ soil with granular materials compacted in long cylinder holes to improve the strength and consolidation characteristics of soils under light to moderate loaded structures; such as embankments, storage tanks and highways (Killeen, 2012). The rigidity and high stiffness properties of the aggregates improve the bearing capacity and decrease the overall and differential settlement of the in-situ soil. Moreover, the high permeability of the aggregates reduce the consolidation time.

In addition, there is some urgency in the world today to consider sustainable development in construction industry. The unmanageable use of non-renewable natural materials such as gravel, rock, sand, timber, concrete, steel and the waste products from the construction sector, have direct impact on the environment. The utilization of by-products or waste instead of natural material is one of the ways that shall be considered in order to achieve sustainable development.

In Malaysia, the coal-fired power plant plays an important role in the power generation sector, and is the main source of energy. According to Baruya (2010) the

coal demand in Malaysia is more than 30 Mtonne/year. The major reason of this high demand of coal is because coal-fired power plant plays an important role in the power generation sector. As shown in Table 1.1, Tanjung Bin, Jimah, Sultan Salahuddin Abdul Aziz Shah and Sultan Azlan Shah are the existing power plants in Peninsular Malaysia. These power plants produce lots of waste and surpluses of by-product material as they generate electricity from the burning of coal.

**Table 1.1:** List of coal-fired plants in Peninsular Malaysia (after Hasan, 2013)

Power Plant	Capacity (MW)	Type	State
Tanjung Bin	2100	Thermal (3 ST)	Johor
Jimah	1400	Thermal (2 ST)	Negeri Sembilan
Sultan Salahuddin Abdul Aziz Shah	2420	Thermal (6 ST)	Selangor
Sultan Azlan Shah	2295	Thermal (3 ST)	Perak

Coal ashes are the waste materials produced during the coal burning in coal-fired thermal power plants (Singh and Siddique, 2013). The coal waste products that produced from coal fired power plants mostly consist of fly ash, bottom ash and boiler slag (Feuerborn, 2005). The lighter particles that are collected from electrostatic precipitators is called fly ash which forms 75% of coal ash produced, while bottom ash is made by agglomeration of the large ash particles that are too heavy to be carried by the flue gases thus drop in the ash hopper at the bottom of the furnace. Bottom ash that forms up to 25% of the total produced coal ashes, generally consist of merged coarser ash particles, which are porous and look like volcanic lava.

The properties of bottom ash make it useful for a variety of construction applications. Bottom ash particles are physically coarse, porous, glassy, granular and grayish in color. Trivedi and Singh (2004) reported the coefficient of permeability of bottom ash up to  $9.6 \times 10^{-4}$  m/s, which revealed that the bottom ash showed medium degree of permeability. According to Goutam and Ventappa, (2008), the maximum

unit weight of bottom ash by compaction ranging from 11.87 kN/m<sup>3</sup> to 18 kN/m<sup>3</sup> with optimum moisture content ranging from 12 % to 34 %.

Large production of bottom ash from coal burning in Malaysia has resulted in waste issues and since it has similar properties with granular aggregates, with particle size ranging from fine sand to fine gravel, which is between 0.1 mm to 10 mm (Kumar and Stewart, 2003a; Marto *et al.*, 2010), it has the potential to be used as substitute material in stone column. This technique allows the reduction in the project cost and resolve the disposal problem of the bottom ash products. Wood *et al.* (2000) mentioned two advantages of stone columns' installation in soft clay. Firstly, the stiffer properties of granular materials and their higher frictional strength in comparison with clay particles, lead the columns to act as pile and through shaft resistance and end bearing, transfer the load to a greater depth. Secondly, the granular material possess higher permeability than clay particles and by shortening the drainage path, cause the increase in the consolidation rate and improve the strength.

Several design criteria affect the stone column behaviour, for instance the column's stiffness, the area replacement ratio,  $A_r$ , (ratio of area of the column,  $A_c$ , to area of soil,  $A_s$ ), column spacing ( $s$ ) and height penetrating ratio  $H_r$ , (ratio of height of the column,  $H_c$ , to height of soil,  $H_s$ ). Previous work by Hu (1995) on bearing capacity of group of stone columns revealed that the load bearing performance of column inside a group is not similar to single isolated column proposed by Hughes and Withers (1974). He also proposed that area replacement ratio is a very important parameter that control the overall operation of stone column reinforced foundation and high value of area replacement ratio (over 25%) significantly increase the bearing capacity of improved ground. Moreover, Hu (1995) suggested that generally the increase in the column length give rise to the overall stiffness of the reinforced ground.

In a very soft soils with low undrained shear strength, the encased stone columns could be applied for better performance. The concept of encasing stone columns with geotextile traced back to the study conducted by Van Impe and De

Beer (1983). Utilizing the geosynthetic material as confinement around the stone column would prevent extra bulging, ground contamination with granular aggregate and excessive settlement. Moreover, geosynthetic encasement assist the increase in the shear strength of the nearby soil and bearing capacity of the composite ground (Murugesan and Rajagopal, 2006; Malarvizhi and Ilamparuthi, 2007).

## 1.2 Problem Statement

Low bearing capacity and high compressibility are among the features of problematic soils such as soft clay deposit, marine clay and peat. Vertical granular columns (generally known as stone columns) is the ideal ground improvement technique for lightly loaded and flexible structures. However, for a very soft clay the formation of stone column might be problematic because of lateral spread of aggregates. In such cases, encasing the stone column with suitable geosynthetic could be an ideal solution that help in better performance of stone columns. Several researchers conducted studies on the performance of stone columns (Ali *et al.*, 2014; Kumar, 2013; Gniel and Bouazza, 2009; Murugesan, 2009; McCabe, 2007; Malarvizhi and Ilamparuthi, 2004; McKelvey, 2004; Wood, 2000; Hu, 1995, Hughes and Wither, 1974) but few have tried the use of bottom ash as substitute materials in stone columns (Marto *et al.*, 2013). Moreover, none has evaluated the improvement in the bearing capacity of soft soil reinforced by geotextile encased bottom ash columns. Utilization of alternative materials for stone columns is essential while the conventional column's aggregates were from natural non-renewable materials. Furthermore, the bottom ash production has resulted in disposal and environmental problems, in which the need for storage spaces rises the expenses for acquiring large areas. Subsequently the utilization of bottom ash in geotechnical engineering work could help in the reduction of project costs (Hasan, 2013). This is because the bottom ash can be obtained for free or bought in minimal price compared to the non-renewable natural materials.

Besides the experimental investigation, numerical simulation is beneficial, by which it is possible to check several parameters affecting the behaviour of bottom

ash columns. Simulating the columns numerically facilitates in performing the parametric study and helps in considering different parameters affecting the behaviour of bottom ash column simultaneously.

### **1.3 Aim and Objectives**

This study aimed to determine the improvement made by the installation of bottom ash column in soft clay. This is achieved through the following objectives:

- i. To quantify the improvement of bearing capacity achieved by installing small groups of bottom ash columns through 1g physical modelling tests.
- ii. To determine the influence of area replacement ratio, column length and geotextile-encasement on the bearing capacity of small groups of bottom ash columns.
- iii. To predict the ultimate bearing capacity of small groups of bottom ash columns through numerical simulation.
- iv. To produce preliminary design charts on the use of bottom ash columns as soil improvement method.

### **1.4 Scope and Limitation of the Research**

This research investigated the performance of soft kaolin reinforced with small groups of bottom ash columns under a rigid footing with the aid of small-scale laboratory physical model test and numerical simulation. A total of thirteen bearing capacity tests on rigid footing were conducted. One test was performed on the kaolin clay without any reinforcement as a control test, while the rests were in two groups of either clay reinforced with uncased bottom ash columns or with geotextile encased columns.

The bottom ash, which was collected from Tanjung Bin Power Plant in Pontian, Johor was used as the granular material (63  $\mu\text{m}$  to 2.36 mm particle size) in vertical column, while the ‘S300’ white kaolin powder used as ground model in this study was bought from Kaolin (M) Sdn. Bhd., based in Selangor, Malaysia. Polyfelt TS20 with 10 kN/m tensile strength and 115 mm/s permeability was sewn to form a cylindrical shape and used as the geotextile encasement for the bottom ash columns.

The basic tests in accordance to British Standard (BS) and/or the American Society of Testing Material (ASTM) were performed on both the bottom ash and kaolin in order to determine their physical and mechanical characteristics. The tests performed on bottom ash included the dry sieve test, specific gravity test, relative density test, constant head permeability test and standard compaction test. While for kaolin, the physical and mechanical properties were determined through hydrometer test, Atterberg Limit test, specific gravity test, falling head permeability test, vane shear test and one dimensional consolidation test.

The commercial 3D finite element software called “Plaxis 3-D Foundation” Version 2 was used in numerical simulation to evaluate and compare the results obtained from experimental model tests. Soft soil creep and Mohr-Coulomb model were used in simulating the model ground and bottom ash columns, respectively.

## **1.5 Significance of the Research**

In recent years, the engineering community has proposed many alternative methods to improve soft soils. These methods should be sustainable. Accordingly, the stone column technique became more popular nowadays. In order to retain non-renewable natural material in balance there is an urgent need for an alternative method to substitute natural material with waste or by-products. The aim of this study, which was the determination of the improvement made by the installation of bottom ash columns in soft soil was in line with proposing a ground improvement technique that preserve sustainability. The significance of this study includes the followings:



- i. This study offers the uncased and geotextile encased bottom ash columns as ground improvement technique to improve soft clay. The method is practical in improving the bearing capacity of clay and by reuse of bottom ash instead of stone in stone columns can help in recycling this coal by-product and therefore supports the environmental consideration besides being cost effective and economic.
- ii. The performed research considered the effects of geotextile encasement and bottom ash columns arrangement and dimension on improvement of the bearing capacity of soft clay. Thus, the results of the study provided better understanding of the performance of uncased and geotextile encased bottom ash columns as ground improvement technique, which can later be applied in the field.
- iii. The preliminary design charts offered by this research could be used as a design tool for the determination of the bearing capacity of soft clay, particularly that correspond to the 10 kPa undrained shear strength of the soil.

## 1.6 Hypothesis

Utilization of uncased and geotextile encased bottom ash columns in group is expected to enhance the bearing capacity of kaolin clay. In particular, the following hypotheses are expected.

- i. The area replacement ratio,  $A_r$ , has great effect on the performance of bottom ash columns in which the increase in  $A_r$  is expected to increase the bearing capacity of the composite ground.
- ii. Increasing the column length from floating to end bearing condition would enhance the bearing capacity of the composite ground.
- iii. The utilization of the geotextile by encapsulating the bottom ash column is expected to improve a better bearing capacity results as compared to the uncased bottom ash column composite ground.

- iv. Results of the ultimate bearing capacity of small groups of bottom ash columns through numerical simulation are estimated to be in line with the experimental results.

## **1.7 Thesis Structure**

This thesis consists of six chapters. The essence of each chapter is as follows:

Chapter 1 defines the background of problems and also affirms the aim and the objectives, scopes and limitations, and the significance of the study.

Chapter 2 provides brief background information of stone column foundations and reviews previous research works relevant to the subject of the present study. Most existing theories and approaches similar to this research in design practice were reviewed.

Chapter 3 describes the research methodology that included the design and manufacturing of testing apparatus and experimental equipment used in the laboratory physical model study. Details on the specimen preparation and general procedures used for the model testing and the construction of bottom ash columns are also discussed.

In the Chapter 4, the results from the physical modelling tests are presented and discussed. The discussion covers several issues such as bearing capacity of clay reinforced with group of columns through physical modelling. The failure mechanism for bottom ash columns reinforced foundation under a rigid footing load is presented based on information deduced from the deformed shapes of columns after tests. The properties of research materials used in this research that includes the basic properties and classification of kaolin and bottom ash along with supplementary tests are also presented.

Chapter 5 discusses and summarises the results obtained from numerical simulation tests and compares with experimental results.

Finally, the conclusion and the contributions of this study as well as the recommendations for future research are described in Chapter 6.

## REFERENCES

- Abdul Talib, N. R. (2010). Engineering Characteristics of Bottom Ash from Power Plants in Malaysia. Final Year Project Report. Universiti Teknologi Malaysia, Skudai, Malaysia.
- Abubakar, A. U., and Baharudin, K. S. (2012). Potential use of Malaysian thermal power plants coal bottom ash in construction. *International Journal of Sustainable Construction Engineering and Technology*. 3(2), 25-37.
- Adalier, K., and Elgamal, A. (2004). Mitigation of liquefaction and associated ground deformations by stone columns. *Engineering Geology*. 72(3), 275-291.
- Afshar, J. N., and Ghazavi, M. (2014). Experimental Studies on Bearing Capacity of Geosynthetic Reinforced Stone Columns. *Arabian Journal for Science and Engineering*. 39(3), 1559-1571.
- Al-Tabbaa, A., and Wood, D. M. (1987). Some measurements of the permeability of kaolin. *Geotechnique*. 37(4), 499-514.
- Ali, K., Shahu, J. T., and Sharma, K. G. (2014). Model tests on single and groups of stone columns with different geosynthetic reinforcement arrangement. *Geosynthetics International*, 21(2), 103-118.
- Ali, K., Shahu, J. T., and Sharma, K. G. (2010). *Behaviour of Reinforced Stone Columns in Soft Soils: An Experimental Study*, Geotechnical Conference, India. 620-628.
- Ambily, A., and Gandhi, S. R. (2007). Behavior of stone columns based on experimental and FEM analysis. *Journal of Geotechnical and Geoenvironmental Engineering*. 133(4), 405-415.
- Arulrajah, A., Abdullah, A., Malaysia, L., & Bo, M. W. (2009). Civil Engineers Ground Improvement 162 February 2009 Issue GI1.
- Awang, A. R., Marto, A., and Makhtar, A. M. (2011). Geotechnical properties of Tanjung Bin coal ash mixtures for backfill materials in embankment construction. *EJGE*, 16, 1515-1531.

- Bachus, R., and Barksdale, R. (1984). *Vertical and lateral behaviour of model stone columns*. International Conference on In-situ Soil and Rock Reinforcement, Paris. 99-110.
- Balaam, N., and Booker, J. (1985). Effect of stone column yield on settlement of rigid foundations in stabilized clay. *International journal for numerical and analytical methods in geomechanics*. 9(4), 331-351.
- Balaam, N., and Brown, P. (1977). *Settlement analysis of soft clay reinforced with granular piles*. Southeast Asian Conference on Soil Engineering, 5th, Bangkok, Thailand.
- Barksdale, R. D., and Bachus, R. C. (1983). *Design and Construction of Stone Columns Volume II, Appendixes*. Washington, DC, USA: Federal Highway Administration.
- Barnes, I. (2010). Ash utilisation—impact of recent changes in power generation practices. *IEACC Centre (Ed.), 1*.
- Baruya, P. (2010). Prospects for Coal and Clean Coal Technologies in Vietnam. CCC/164. London: IEA Clean Coal Centre.
- Bathurst, R. J. (2007). Geosynthetics Classification. IGS Leaflets on Geosynthetics Applications.
- Bera, A. K., Chandra, S. N., Ghosh, A. and Ghosh, A. (2009). Unconfined compressive strength of fly ash reinforced with jute geotextiles. *Geotextiles and Geomembranes*. 27(5), 391–398.
- Black, J., Sivakumar, V., Madhav, M., and McCabe, B. (2006). An improved experimental test set-up to study the performance of granular columns. *Geotechnical testing journal*. 29(3), 193-196.
- Black, J. A., Sivakumar, V., Madhav, M. R., & Hamill, G. A. (2007). Reinforced stone columns in weak deposits: laboratory model study. *Journal of Geotechnical and Geoenvironmental Engineering*, 133(9): 1154-1161.
- Black, J., Sivakumar, V., and McKinley, J. (2007). Performance of clay samples reinforced with vertical granular columns. *Canadian geotechnical journal*. 44(1), 89-95.
- Bouassida, M., Jellali, B., and Porbaha, A. (2009). Limit analysis of rigid foundations on floating columns. *International Journal of Geomechanics*. 9(3), 89-101.

- Bowles, J. E. (1988). *Foundation analysis and design*. 4th. ed., McGraw Hill: New York.
- Briaud, J., & Jeanjean, P. (1994). Load settlement curve method for spread footings of sand. *Vertical and Horizontal Deformations of Foundations and Embankments*. 1774-1804.
- Brinkgreve, R. B. (2005). Selection of soil models and parameters for geotechnical engineering application. *Soil constitutive models: Evaluation, selection, and calibration*. 69-98.
- Budhu, M. (2008). *Soil mechanics and foundations*, John Wiley and Sons, Inc: New York.
- Castro, J. (2014). Numerical modelling of stone columns beneath a rigid footing. *Computers and Geotechnics*. 60, 77-87.
- Chesner, W., Collins, R., and MacKay, M. (1997). *User Guidelines for Waste and By-product Materials in Pavement Construction* (No: FHWA-RD-97-148).
- Chindaprasirt, P., Jaturapitakkul, C., Chalee, W., and Rattanasak, U. (2009). Comparative study on the characteristics of fly ash and bottom ash geopolymers. *Waste Management*. 29(2), 539-543.
- Christensen, T. H. (2011). *Solid waste technology and management* (Vol. 1). Chichester, West Sussex, UK: Wiley
- Couch, G. R. (2006). *Ash management in coal-fired power plants* (p. 69). London, UK: IEA Clean Coal Centre.
- Cox, M., Nugteren, H., and Janssen-Jurkovičová, M. (2008). *Combustion residues: current, novel and renewable applications*. John Wiley and Sons.
- Craig, R. F. (2004). *Craig's soil mechanics*: CRC Press, London.
- Das, B. (2012). *Fundamentals of geotechnical engineering*: Cengage Learning.
- Das, B. (2015). *Principles of foundation engineering*: Cengage learning.
- Dash, S. K., Krishnaswamy, N. R., & Rajagopal, K. (2001). Bearing capacity of strip footings supported on geocell-reinforced sand. *Geotextiles and Geomembranes*. 19(4), 235-256.
- Datye, K. R. (1982). Settlement and bearing capacity of foundation system with stone columns. Symposium on recent developments in ground improvements techniques held at Bangkok. 85-104
- De Beer, E. E. (1970). Experimental determination of the shape factors and the bearing capacity factors of sand. *Geotechnique*. 20(4), 387-411.

- Dinesh, S. (2011). Consolidation of soils: Technical report, Siddaganga Institute of Technology, Tumkur.
- Domingues, T. S., Borges, J. L., & Cardoso, A. S. (2007). *Parametric study of stone columns in embankments on soft soils by finite element method*. International Workshop on Applications of Computer Mechanics in Geotechnology Engineering. Guimaraes, Portugal, 281-291.
- Dullage, C. R. (1969). *An Investigation into the Feasibility of Small Scale Tests on Granular Piles in Clay*. Ph.D. Thesis, University College of Swansea.
- Elsawy, M. B. (2010). Highway Embankment Constructed on Soft Soil Improved by Stone Columns with Geosynthetic Materials. Duisburg-Essen University.
- Elshazly, H., Hafez, D., & Mossaad, M. (2006). *Back-calculating vibro-installation stresses in stone-column-reinforced soils*. Institution of Civil Engineers-Ground Improvement. 10(2), 47-53.
- Engin, H. (2007). Report on tension pile testing using embedded piles: Plaxis internal report. Delft (The Netherlands).
- Etezad, M. (2006). *Geotechnical performance of group of stone columns*. Ph.D. Thesis, University of Montreal Quebec.
- Feuerborn, H. J. (2005). *Coal ash utilisation over the world and in Europe*. Workshop on environmental and health aspects of coal ash utilization.
- Ghassemi, A. (2001). *Handbook of pollution control and waste minimization*: CRC Press.
- Glanville. (1959). *Soil Mechanics for Road Engineers*: Her majesty's stationery office.
- Gniel, J., & Bouazza, A. (2009). Improvement of soft soils using geogrid encased stone columns. *Geotextiles and Geomembranes*, 27(3), 167-175.
- Habib, P. (1989). Recommendations for the design, calculation, construction of ground anchorages: Balkema.
- Hasan, M. (2013). *Strength and Compressibility of Soft Soil Reinforced with Bottom Ash Columns*. Ph.D. Thesis (unpublished), Universiti Teknologi Malaysia.
- Head, K. H., and Epps, R. (1986). *Manual of soil laboratory testing* (Vol. 3): Pentech Press London.
- Heidrich, C., Feuerborn, H.-J., and Weir, A. (2013). *Coal combustion products: a global perspective*. World Coal Ash WOCA Conference, Lexington, KY.

- Hu, W. (1995). *Physical Modelling of Group Behaviour of Stone Column Foundations*. Doctor Philosophy. University of Glasgow, UK.
- Huang, H. W. (1990). *The use of bottom ash in highway embankments, subgrade, and subbases. Joint highway research project, Final Report*. FHWA/IN/JHRP-90/4, Purdue University, West Lafayette, Indiana.
- Purdue Univ., W. Lafayette, Ind. Hughes, J., and Withers, N. (1974). Reinforcing of soft cohesive soils with stone columns. *Ground Engineering*, 7(3).
- International Construction Equipment (2015). *Vibroflots* <http://www.ice-holland.com/content/261/482/Vibroflots.html>
- Jayaranjan, M. L. D., Van Hullebusch, E. D., and Annachhatre, A. P. (2014). Reuse options for coal fired power plant bottom ash and fly ash. *Reviews in Environmental Science and Bio/Technology*, 13(4), 467-486.
- Ke, T., and Lovell, C. (1992). Corrosivity of Indiana bottom ash. *Transportation Research Record* (1345).
- Kempfert, H. G., Jaup, A., and Raithel, M. (1997). *Interactive behaviour of a flexible reinforced sand column foundation in soft soils*. International Conference on Soil Mechanics and Foundation Engineering. International Society for Soil Mechanics and Foundation Engineering. (Vol. 3, pp. 1757-1760). AA BALKEMA.
- Kempfert, H. G. (1996). *Embankment foundation on geotextile-coated sand columns in soft ground*. European Geosynthetics Conference in Maastrich, Geosynthetics. Applications, Design and Construction (pp. 245-250). AA Balkema.
- Killeen, M. (2012). *Numerical modelling of small groups of stone columns*. Ph.D. Thesis. University of NUI Galway, Ireland.
- Kim Huat, B. (1994). Behaviour of soft clay foundation beneath an embankment. *Pertanika Journal of Science and Technology*, 2(2), 215-235.
- Kirsch, F. (2008). *Evaluation of ground improvement by groups of Vibro stone columns using field measurements and numerical analysis*. International Workshop on the Geotechnics of Soft Soils, Glasgow.
- Kolár, V., and Nemeč, I. (2012). *Modelling of soil-structure interaction*: Elsevier.
- Kumar, S., and Stewart, J. (2003a). Evaluation of Illinois Pulverized Coal Combustion Dry Bottom Ash for Use in Geotechnical Engineering Applications. *Journal of Energy Engineering*. 129 (2), 42 – 55. ASCE.



- Kumar, S., and Stewart, J. (2003b). Utilization of Illinois PCC dry bottom ash for compacted landfill barriers. *Soil and Sediment Contamination*, 12(3), 401-415.
- Kumar, U., Tandel, Y., and Solanki, C. (2013). Effect of geosynthetic encasement on sand column in soft soil. *Structural and Civil Engineering Research*, 2(3).
- Kwiecień, S., & Sękowski, J. (2008). Research on the shape of stone columns formed in the ground with the use of dynamic replacement method. *Architecture Civil Engineering Environment*, 1(2), 65-72.
- Latha, G. M., Rajagopal, K. and Krishnaswamy, N. R. (2000). *Design of Geocell Supported Embankments*. Asian Geosynthetics Conference. May, 29-31. Kuala Lumpur, 97-101.
- Lee, J., and Pande, G. (1998). Analysis of stone-column reinforced foundations. *International journal for numerical and analytical methods in geomechanics*, 22(12): 1001-1020.
- Leonards, G. A., and Bailey, B. (1982). Pulverized coal ash as structural fill. *J. Geotech. Eng. Div., Am. Soc. Civ. Eng. ;( United States)*, 108.
- Lutenegger, A. J., & Adams, M. T. (1998). Bearing capacity of footings on compacted sand 1.21. *Proceeding of the 4th International Conference on Case Histories in Geotechnical Engineering*. 1216-1224.
- Mahmud, H. (2003). *Coal-Fired Plant in Malaysia*. JAPAC International Symposium 19 September 2003.
- Majidzadeh, K., El-Mitiny, R. N., and Bokowski, G. (1977). Power plant bottom ash in black base and bituminous surfacing, executive summary. Final report: Ohio State Univ. Research Foundation, Columbus (USA).
- Malarvizhi, S., and Ilamparuthi, K. (2004). *Load versus settlement of clay bed stabilized with stone and reinforced stone columns*. GeoAsia-2004, Seoul, Korea, 322-329.
- Malarvizhi, S. N., Ilamparuthi, K., & Bhuvaneshwari, S. (2006). *Behavior of geogrid encased stone column and stone column stabilized soft clay bed*. International Conference on Physical Modelling in Geotechnics (pp. 4-6).
- Marto, A., Hasan, M., Hyodo, M., and Makhtar, A. M. (2014). Shear Strength Parameters and Consolidation of Clay Reinforced with Single and Group Bottom Ash Columns. *Arabian Journal for Science and Engineering*, 39(4), 2641-2654.

- Marto, A., Kassim, K. A., Makhtar, A. M., Wei, L. F., and Lim, Y. S. (2010). Engineering characteristics of Tanjung Bin coal ash. *Electronic Journal of Geotechnical Engineering*, 15, 1117-1129.
- Marto, A. (1996). Volumetric Compression of a Silt under Periodic Loading. Ph.D. Thesis, University of Bradford, United Kingdom.
- McCabe, B. (2009). *A review of field performance of stone columns on soft soils*. ICE Geotechnical Engineering.
- McCabe, B. A., McNeill, J. A., & Black, J. A. (2007). *Ground improvement using the vibro-stone column technique*. Engineers Ireland West Region and the Geotechnical Society of Ireland, NUI Galway, (Vol. 15, pp. 1-12).
- McKelvey, D. (2002). *The performance of Vibro stone column reinforced foundations in deep soft ground*. Queen's University of Belfast.
- Mitchell, J. K., and Huber, T. R. (1985). Performance of a stone column foundation. *Journal of Geotechnical Engineering*.
- Moseley, M. P., and Kirsch, K. (2004). *Ground improvement*: CRC Press.
- Moulton, L. K., Seals, R. K., and Anderson, D. A. (1973). Utilization of ash from coal-burning power plants in highway construction. *Highway Research Record* (430).
- Murugesan, S., and Rajagopal, K. (2007). Model tests on geosynthetic-encased stone columns. *Geosynthetics International*, 14(6), 346-354.
- Murugesan, S., and Rajagopal, K. (2009). Studies on the behaviour of single and group of geosynthetic encased stone columns. *Journal of Geotechnical and Geoenvironmental Engineering*, 136(1), 129-139.
- Ng, K., and Tan, S. (2015). Stress Transfer Mechanism in 2D and 3D Unit Cell Models for Stone Column Improved Ground. *International Journal of Geosynthetics and Ground Engineering*, 1(1), 1-9.
- Pande, G., and Pietruszczak, S. (1986). A critical look at constitutive models for soils. *Geomechanical modelling in engineering practice*. Balkema AA, Rotterdam, the Netherlands, 369-395.
- Pandian, N. (2013). Fly ash characterization with reference to geotechnical applications. *Journal of the Indian Institute of Science*, 84(6), 189.
- Pothal, G. K., and Rao, G. V. (2008). Model studies on geosynthetic reinforced double Layer system with pond ash overlain by sand. *Electronic Journal of Geotechnical Engineering*, 13: 1-12.

- Prandtl, L. (1921). Uber die eindringungsfestigkeit (harte) plastischer baustoffe und die festigkeit von schneiden. *Zeitschrift fur angewandte Mathematik und Mechanik*, 1(1), 15-20.
- Prashant, A., and Penumadu, D. (2005). A laboratory study of normally consolidated kaolin clay. *Canadian geotechnical journal*, 42(1), 27-37.
- Rashid, A. S. A., (2011). *Behaviour of weak soils reinforced with soil columns formed by the deep mixing method*. University of Sheffield.
- Rashid, A. S. A., Black, J. A., Kueh, A. B. H., and Noor, N. M. (2015). Behaviour of weak soils reinforced with soil cement columns formed by the deep mixing method: Rigid and flexible footings. *Measurement*, 68, 262-279.
- Reul, O., and Gebreselassie, B. (2006). *Excavations and foundations in soft soils*: Springer Science and Business Media.
- Rifa, A., Yasufuku, N., Omine, K., and Tsuji, K. (2009). *Experimental study of coal ash utilization for road application on soft soil*. International Joint Symposium on Geodisaster Prevention and Geoenvironment, Asia, JS-Fukuoka.
- Roscoe, K. H., and Burland, J. (1968). On the generalized stress-strain behaviour of wet clay.
- Ross, C. S., and Kerr, P. F. (1930). The kaolin minerals<sup>1</sup>. *Journal of the American Ceramic Society*, 13(3), 151-160.
- Saeed, K. A. H., Kassim, K. A., Yunus, N. Z. M., and Nur, H. (2015). Physico-Chemical Characterization Of Lime Stabilized Tropical Kaolin Clay. *Jurnal Teknologi*, 72(3).
- Sato, A., and Nishimoto, S. (2001). *Effective reuse of coal ash as civil engineering material*. World of Coal Ash Conference, Lexington, April.
- Seals, R. K., Moulton, L. K., and Ruth, B. E. (1972). Bottom ash: An engineering material. *Journal of the Soil Mechanics and Foundations Division*, 98(4): 311-325.
- Sear, L. K., Weatherley, A. J., & Dawson, A. (2003). *The environmental impacts of using fly ash-the UK producers' perspective*. International Ash Utilisation Symposium, Lexington, Kentucky.
- Septanika, E. (2005). A finite element description of the embedded pile model: Plaxis internal report. Delft (The Netherlands).

- Singh, M., and Siddique, R. (2013). Effect of coal bottom ash as partial replacement of sand on properties of concrete. *Resources, conservation and recycling*, 72: 20-32.
- Sloane, R. L., and Kell, T. (2013). *The fabric of mechanically compacted kaolin*. Fourteenth National Conference, Berkeley, California.
- Steerman, S. (1939). A new soil compaction device. *Engineering News Record*, 1: 56-58.
- Suntharalingam, T. (1983). *Cenozoic stratigraphy of Peninsular Malaysia*. Workshop on Stratigraphic Correlation of Thailand and Malaysia.
- Suwanvitaya, P., and Wattanachai, P. (2006). Comparison of metals leaching from Mortar with Mae Moh and Calaca bottom ashes as sand replacement.
- Tan, S. A., Tjahyono, S., and Oo, K. (2008). Simplified plane-strain modelling of stone-column reinforced ground. *Journal of Geotechnical and Geoenvironmental Engineering*.
- Tan, Y., Gue, S., Ng, H., and Lee, P. (2004). *Some geotechnical properties of Klang Clay*. Malaysian Geotechnical Conference.
- Terzaghi, K. (1951). *Theoretical Soil Mechanics*. Wiley, New York.
- Terzaghi, K., Peck, R. B., and Mesri, G. (1996). *Soil Mechanics in Engineering Practice*: John Wiley and Sons.
- Trautmann, C. H., & Kulhawy, F. H. (1988). Uplift load-displacement behavior of spread foundations. *Journal of geotechnical engineering*, 114(2): 168-184.
- Trivedi, A., and Singh, S. (2004). Geotechnical and geoenvironmental properties of power plant ash. *Journal of the Institution of Engineers. India. Civil Engineering Division*, 85(aout), 93-99.
- Vanapalli, S. K., & Mohamed, F. M. (2013). Bearing capacity and settlement of footings in unsaturated sands. *Int. J. Geomate*, 5(1): 595-604.
- Van Impe, W. (1983). *Improvement of settlement behaviour of soft layers by means of stone columns*. European Conference on Soil Mechanics and Foundation Engineering: Improvement of Ground (Vol. 1, pp. 309-312).
- Weber, T., Springman, S., Gäß, M., Racansky, V., and Schweiger, H. (2008). Numerical modelling of stone columns in soft clay under an embankment. *Geotechnics of soft soils-focus on ground improvement*. Taylor and Francis, London, 305-311.

- Widodo, S., and Ibrahim, A. (2012). Estimation of primary compression index (CC) using physical properties of Pontianak soft clay. *International Journal of Engineering Research and Applications (IJERA)*, 2(5): 2232-2236.
- Wood, D. M. (2003). *Geotechnical modelling* (Vol. 1): CRC Press.
- Wood, D. M., Hu, W., and Nash, D. (2000). Group effects in stone column foundations: model tests. *Geotechnique*, 50(6): 689-698.
- Wood, D. (1975). Explorations of principal stress space with kaolin in a true triaxial apparatus. *Geotechnique*, 25(4): 783-797.
- Yoo, C., & Lee, D. (2012). Performance of geogrid-encased stone columns in soft ground: full-scale load tests. *Geosynthetics International*, 19(6), 480-490.