



AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING

SOIL IMPROVEMENT USING REINFORCED GRANULAR COLUMNS

A THESIS

**SUBMITTED IN FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF DOCTOR
OF PHILOSOPHY IN STRUCTURAL
ENGINEERING**

By

Mohammed Gamal EL Din Labeeb EL Kaissouny

Supervised by

Prof. Dr. Mona Mostafa Eid

Prof. of Geotechnical Engineering
Department of Structural Engineering
Faculty of Engineering
Ain Shams University

Dr. Hesham Mohamed Helmy

Associate Prof. of Geotechnical Engineering
Department of Structural Engineering
Faculty of Engineering
Ain Shams University

**Cairo
2014**

STATEMENT

This dissertation is submitted to Ain Shams University in partial fulfillment for the requirements of the degree of Doctor of Philosophy in Structural Engineering.

The work included in this thesis was carried out by the author in the Structural Engineering Department, Ain Shams University.

No part of this thesis has been submitted for a degree or a qualification at any other University or Institution.

Date : / /2014

Signature:

Name : Mohammed Gamal El Din Labeed El Kaissouny

EXAMINER COMMITTEE

Name, Title and Affiliation

Signature

1- Prof. Dr. Ahmed Wael El Gamal

Prof. of Structural Engineer
Department of Structural Engineering
University of California, San Diego

2- Prof. Dr. Ali Abdel Fattah Ali Ahmed

Prof. of Geotechnical Engineering
Department of Structural Engineering
Faculty of Engineering-Ain Shams University

3- Prof. Dr. Mona Mostafa Eid

Prof. of Geotechnical Engineering
Department of Structural Engineering
Faculty of Engineering-Ain Shams University

4- Ass. Prof. Dr. Hesham Mohamed Helmy

Associate. Prof. of Geotechnical Engineering
Department of Structural Engineering
Faculty of Engineering-Ain Shams University

Date / / 2014

ACKNOWLEDGMENTS

I would like to express my deep gratitude to **Professor Dr. Mona Mostafa Eid**, Professor of Geotechnical Engineering, Ain Shams University, for her supervision, constant support, scientific assistance and precious advice and strong support throughout all the phase of this research.

Also, very grateful to **Dr. Hesham Mohamed Helmy**, Ass. Professor of Geotechnical Engineering, Ain Shams University, for his inspiration, encouragement, excellent guidance and endless support through all phases of this research.

Finally, deep thanks are dedicated to my Parents , my wife and my sister who continuously supported and encouraged me throughout the course of my tuition period and their prayers enabled me to successfully pursue my study.

Above all, praise and thanks to a gracious and loving **God**, for the strength, hope and mercy provided throughout my life.

Mohammed Gamal El Din Labeeb EL Kaissouny



AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING
STRUCTURAL ENGINEERING DEPARTMENT

Abstract of the Ph.D. Thesis submitted by:

Eng. Mohammed Gamal El Din Labeeb El Kaissouny

Title of Thesis:

**SOIL IMPROVEMENT USING REINFORCED
GRANULAR COLUMNS**

Supervisors:

- 1) Prof. Dr. Mona Mostafa Eid**
- 2) Ass. Prof. Dr. Hesham Mohammed Helmy**

ABSTRACT

The stone column technique is suitable for improvement of weak soil as it increases the bearing capacity, reduces the total settlement, and accelerates consolidation settlement due to reduction in flow path lengths. Recently, encasement, besides increasing the strength and stiffness of the stone column, prevents the lateral squeezing of stones when the column is installed even in extremely soft soils. A three-dimensional numerical model using the finite element system ABAQUS was developed to investigate the behavior of encased stone column (ESCs) in soft soil. A series of finite element simulations are carried out to

evaluate the benefits of integrating a high modulus geosynthetic material with the stone column technique for soil improvement. Parametric analyses were carried out to study the effect of different parameters which help in increasing efficiency of the encased stone column technique. These parameters are encased stone column diameter and depth, stiffness and length of encased material, angle of internal friction (ϕ) of the stone column, and properties of soft clay around the stone column. The results are compared with those obtained from ordinary stone column. In addition, the finite element model for grouping of ESC is noticed to be resilience of fulfilling a limiting displacement criterion under maximum loads and a good bearing resistance of weak soil using different parameters.

CONTENTS

Title	Page
List of Figures	v
List of Tables	xiv
List of Symbols	xv
Chapter (1): Introduction	1
1.1 General	1
1.2 Statement of the problem	3
1.3 Purpose and scope of the study	4
1.4 Organization of Thesis	5
Chapter (2) : Literature Review	8
2.1 Introduction	8
2.2 Characteristics of Ground Improvement Systems	10
2.3 Classification of Ground Improvement, its Objective and Expected Results	11
2.3.1 Ground Improvement Methods	11
2.4 Improvement of Soil Characteristics Due To Stone Column Technique	12
2.5 Engineering Behavior of Composite Ground	14
2.6 Failure Mechanism	19
2.7 Literature Performance of ordinary Stone Column	25
2.8 Available Design Methods	44
2.8.1 Ultimate Bearing capacity of Single , Isolated Granular Stone Column	46
2.8.1.1 Capacity Based on Bulging of Column(Q_a)	49
2.8.1.2 Surcharge Effect(Q_b)	51
2.8.1.3 Bearing Support Provided by the Intervening Soil (Q_c)	52
2.8.2 Ultimate Bearing capacity of Granular Stone Groups	52
2.8.3 Design Approaches for Settlement	55
2.8.3.1 Analytical Methods	55

Title	Page
2.8.3.2 Equilibrium Methods	58
2.8.3.3 Empirical Method	61
2.8.3.4 Incremental Method	62
2.8.3.5 Finite Element Method	63
2.9 Geosynthetic Encased stone column	68
2.10 Stone Column Construction	78
2.10.1 Vibro- Technique	80
2.10.1.1 Vibro Replacement Method (Wet Method)	80
2.10.1.2 Vibro Displacement Method (Dry Method)	82
2.10.2 Construction of Geosynthetic Stone Column	84
Chapter (3) : Finite Element Modeling	88
3.1 Introduction	88
3.2 General steps of the finite element method	89
3.3 Abaqus program	93
3.4 Numerical Analysis of Abaqus	95
3.5 General Description of Numerical Model	98
3.5.1 Geometry Model	98
3.5.2 Material property	100
3.5.2.1 Soil behaviour in Abaqus	100
3.5.2.2 Geosynthetic material	107
3.5.3 Loads and boundary conditions	108
3.5.4 Interface Model	109
3.5.5 Contact discretization	114
3.5.5.1 Node-to-surface contact discretization	114
3.5.5.2 Surface-to-surface contact discretization	115
3.5.5.3. Effect of the contact discretization method on solution cost	116
3.6 Initial Condition	117
3.7 Analysis and output request	117

Title	Page
Chapter (4) : The Numerical study	118
4.1 Introduction	118
4.2 Numerical modeling and parametric study	118
4.3 Material modeling	121
4.3.1 Soft clay Model	121
4.3.2 Stone Model	121
4.3.3 Geosynthetic Model	123
4.4 Basic considerations	125
4.4.1 Unit cell concept	125
4.4.2 Boundary condition	126
4.4.3 Interface model	127
4.4.4 Initial conditions	127
4.5 Validation of the Numerical Model	128
4.6 Sensitivity Analysis	132
4.7 Parametric study results	136
4.7.1 Stone column loaded	137
4.7.1.1 Influence of Encased stone column diameter	137
4.7.1.2 Influence of Encased stone column depth	143
4.7.1.3 Influence of stiffness of encasement material	147
4.7.1.4 Influence of Length of Encasement Material	152
4.7.1.5 Influence of angle of internal friction (ϕ) of stone column	156
4.7.1.6. Influence of properties of soft clay medium	158
4.7.2 Stone column–Partially loaded clay	161
4.7.2.1 Effect of stone column diameter	164
4.7.2.2 Effect of stone column depth	168
4.7.2.3 Effect of the stiffness of encased material	170
4.7.2.4 Effect of the Encasement length	173
4.7.3 Stone column–Full loaded clay	176

Title	Page
Chapter (5) : Behavior of group of stone columns	181
5.1 Introduction	181
5.2 Numerical Modeling	183
5.2.1 Material Models	183
5.2.2 Boundary condition	184
5.3 Contact Behavior	185
5.4 Discussion of Finite Element Results	187
5.4.1 Influence of number of stone column (area ratio a_r).	188
5.4.2 Influence of Spacing between stone column in grouping manner	196
5.4.3 Influence of raft thickness and type of loading	201
5.4.4 Influence of arrangement of ESC and OSC in the load-carrying capacity of the composite medium	204
5.4.5 Influence of stone column position	206
5.5 Comparative study on the behavior of stone column group and the unit cell model	208
5.6 Case Study	212
Chapter (6) : Summary and Conclusions	220
6.1 Summary	220
6.2 Conclusion	222
6.2.1 Stone column loaded only	222
6.2.2 Stone column –Partially loaded clay	224
6.2.3 Stone column –Fully loaded clay	225
6.2.4 Grouping of Stone Columns	226
6.3 Recommendation of Future Researches	228
References	230
Arabic Summary	-

LIST OF FIGURES

Fig. No.	Title	Page
(2-1)	Unit Cell Concept (Barksdale and Bachus, 1983)	15
(2-2)	Typical Column arrangement, triangular grid (left) and square grid (right)	16
(2-3)	Unit Cell Concept (Bergado et al,1996)	19
(2-4)	Failure Mechanisms of a Single Stone Column in a Homogeneous Soft layer (Ghanti and Kashiwal,2008)	20
(2-5)	Stone Column Failure Mechanism in Non-homogeneous Cohesive Soil	21
(2-6)	(a) Deformed mesh (b) vertical stress on soil ,after Kirsh and Sondemann (2001)	22
(2-7)	(a) Plastic deformation in the column (b) the surrounding soil during bulging after Kirsh and Sondemann (2001)	23
(2-8)	Physical model and simulated result, after Kirsh and Sondemann (2001)	24
(2-9)	(a) Shape of the failed stone column after the area of stone column was loaded (b) the whole area of the Sc and surrounding soil was loaded, after Ján Pivarc (2011)	25
(2-10)	Different Type of loading Applied To Stone Columns, after Mitchell et al. (1995)	27
(2-11)	Photographs of sand column beneath circular footing, before ,during and after loading (a)L/d=6, (b) L/d=10 , (McKelvey et al (2004)	28
(2-12)	Model tests on stone column showing characteristic bulging behavior	29
(2-13)	Single column test arrangement (a) column area loading (b) entire area loading after Ambily and Shailesh (2007)	31
(2-14)	Effect of S/d and ϕ on axial capacity of stone column, after Ambily and Shailesh (2007)	32
(2-15)	Stress settlement behavior under entire area loading, after Ambily and Shailesh (2007)	33

(2-16)	Comparison of group column test and single column test) , after Ambily and Shailesh (2007)	34
(2-17)	The test setup for single and group column test, after Isaac and Grirish (2009)	35
(2-18)	Load –Settlement curve for clay with single column, after Isaac and Grirish (2009)	36
(2-19)	Comparison of stress –settlement relation for clay with group of seven columns (a)s=2.5d, (b) (s=3d), after Kais et al. (2009)	36
(2-20)	Schematic diagram of the experimental set-up, after Kais et al. (2009)	38
(2-21)	q/cu versus S/B for the soil treated with stone column, u=6Kpa and L/D=6 (b) cu=6Kpa and L/D=8, after Kais et al. (2009)	39
(2-22)	Bearing improvement ratio versus (S/B) for the soil (a) cu=6Kpa and L/D=6 (b) cu=6Kpa and L/D=8, after Kais et al. (2009)	39
(2-23)	Simulation of composite system for calculation of bearing capacity	41
(2-24)	Curves of loading against settlement for (B=2m , d=1m), after Zahmatkesh and Choobbasti (2010)	42
(2-25)	The effect of footing width on BCR, after Zahmatkesh and Choobbasti (2010)	43
(2-26)	Stress settlement behavior under entire area loading, after Zahmatkesh and Choobbasti (2010)	43
(2-27)	Effect of diameter of column on SRR, after Zahmatkesh and Choobbasti (2010)	44
(2-28)	Application ranges for vibro techniques, after Priebe (1998)	45
(2-29)	Granular Columns Group Analysis, after Brarksdale and Bachus,(1983)	53
(2-30)	Van Impe and De Beer method	56
(2-31)	Design chart for stone column, after Priebe (1995)	57

(2-32)	Comparison of Greenwood and Equilibrium method For Predicting Settlement of Stone Column Reinforced Soil, after Greenwood (1975)	62
(2-33)	Load vs settlement of soft clay (c) and stone column (sc) of different stone	65
(2-34)	Bulging of stone column under different stress applied Malarvizhi and Ilamparuthi (2007)	66
(2-35)	Vertical stress-strain behavior of encased column test using different encased Length, after Gniel and Bouazza (2009)	72
(2-36)	Photographs of bulging behavior of encased stone column with different encased length, after Gniel and Bouazza (2009)	73
(2-37)	The Typical finite –element mesh, after Majid et al., (2010)	75
(2-38)	(a) Displacement vs. stress (b)Lateral bulging vs depth at a vertical settlement of 50mm, , after Majid et al., (2010)	75
(2-39)	Stress-displacement response of partially encased columns and conventional stone column (CSC), after Majid et al., (2010)	76
(2-40)	Basic Axisymmetric Finite Element Mesh Used for the Parametric Study after Fattah and Khudair (2010)	77
(2-41)	Relation between the bearing improvement ratio of and length to Diameter of Floating Stone Column ,(C _u =20 KPa for surrounding, and different a _s) after Fattah and Khudair (2010)	78
(2-42)	Blanket feed method, after Rodríguez, (2010)	81
(2-43)	Vibro Replacement Method (Wet Method), after Rodríguez, (2010)	81
(4-44)	Top Feed method of stone column construction, after Rodríguez, (2010)	83
(2-45)	Bottom Feed method of stone column construction, after Rodríguez, (2010)	84

(2-46)	Welded geogrid encasement, after Niroumand et al., (2011)	86
(2-47)	Proposed method of replacement installation Gniel and Bouazza (2010)	87
(3-1)	Abaqus CAE, Abaqus Viewer and Analysis Module, Arul M Brito (2005)	94
(3-2)	Commonly Used Element Families	97
(3-3)	Examples of number of element nodes (Linear brick, quadratic brick, and modified tetrahedral elements	97
(3-4)	The Unit Mesh	99
(3-5)	Clay yield surfaces in the p–t plane	103
(3-6)	Clay yield surface sections in the II-plane	103
(3-7)	Pure compression behavior for clay model.	104
(3-8)	Mohr-Coulomb failure model	105
(3-9)	Mohr-coulomb in meridional and deviator plane	106
(3-10)	Performance pull out test on geosynthetic encased material	108
(3-11)	The representation of pile-soil interface in ABAQUS	112
(3-12)	Contact frictional behavior for slipping and sticking	113
(4-1)	Isometric Unit Cell	119
(4-2)	The Mesh Elements	122
(4-3)	The column arrangements, (a) triangular grid and (b) square grid	128
(4-4)	Finite element mesh for test model ($s/d = 2$), Ambily, A.P and Gandhi, S.R.(2004)	130
(4-5)	Comparison Load – settlement curves results between Abaqus Model and Ambily, A.P and Gandhi, S.R.(2004) results for different shear strength	130

(4-6)	Comparison between Load vs settlement curves resulted from Abaqus Model and those obtained by Malarvizhi and Ilampraruthi (2007) for different L_s/d_s ratio	132
(4-7)	Stress – settlement characteristic using different ratio of (Sc/d_s) for OSC and ESC	134
(4-8)	Settlement trough for variable ratio of Sc/d_s	135
(4-9)	The lateral bulging profile of ESC using different area (Sc/d_s)	135
(4-10)	Settlement for OSC/ESC using different surrounding clay diameter (different area ratio)	136
(4-11)	Load – settlement curves for different stone column diameters	140
(4-12)	The lateral bulging profile of OSC and ESC for different stone column diameters	140
(4-13)	The settlement reduction factor of stone column for different stone column diameters	141
(4-14)	Vertical settlement of unit cell for different stone column diameters	141
(4-15)	The contour shape of lateral bulging of OSC for different stone column diameters at applied stress 150kpa	142
(4-16)	The contour shape of lateral bulging of ESC for different stone column diameters at applied stress 150kpa	142
(4-17)	Stress – settlement curves for different stone column depths	144
(4-18)	Influence of depth of stone column on the settlement in case of ESC and OSC	145
(4-19)	The lateral bulging profile of OSC and ESC for different stone column depths	145
(4-20)	The contour shape of lateral bulging of OSC for different stone depths at applied stress 550 kPa	146
(4-21)	The contour shape of lateral bulging of ESC for different stone depths at applied stress 550 kPa	146