## TABLE OF CONTENTS

INTRODUCTION	1
1.1 General	1
1.2 Research Scope and Objectives	2
1.3 Thesis Outline	3
LITERATURE REVIEW	5
2.1 Introduction	5
2.2 Characteristics of Soft Clay	6
2.2.1 Deformation parameter	7
2.2.2 Shear Strength	10
2.2.3 Soil Compressibility	10
2.3 Deep Excavation shoring system	12
2.3.1 Types of In-situ walls	13
2.3.2 Types of Wall Support	18
2.4 Stability of Supported Excavation	19
2.5 Earth Pressure Calculation	22
2.5.1 Rankine's Theory	23
2.5.2 Peck's Diagrams	26
2.6 Pervious Works for Predicting Wall and Ground Movement	27
NUMERICAL MODELING	37
3.1 Introduction	37
3.2 Methods of Analysis	37
2.2 Finite Floment Method	20

3.3.1	Analysis Sequence of finite element method	38
3.3.2	Elements Types	39
3.3.3	Different Methods of Modeling	42
3.4 Ma	terial Modeling Basics	43
3.4.1	Stresses	44
3.4.2	Strains	45
3.5 Coi	nstitutive Material Models	46
3.5.1	Linear Elastic Constitutive Law	47
3.5.2	Non-linear Elastic Constitutive Laws	47
3.5.3	Elasto-plastic Constitutive Laws	48
3.5.4	Elasto-visco plasticity Constitutive Laws	54
3.6 Ap	plied Constitutive Modeling of Soil Materials	55
3.6.1	Hardening soil model (HSM)	55
3.6.2	Soft soil model (SSM)	65
3.6.3	Linear elastic model	71
3.7 Nu	merical Model	71
3.7.1	Geometry and boundary conditions of the model	71
3.7.2	Types of Elements	72
3.7.3	Interface Element	74
3.7.4	Generation of Finite Element Mesh	75
3.7.5	Generation of Initial Stresses and Water Pressure	76
3.7.6	Calculation phases	77
FINITE	ELEMENT MODEL VEDICATION	75

4.1 Introduction	75
4.2 Case Study	76
4.2.1 Project Description	76
4.2.2 Soil Conditions	79
4.2.3 Field and Laboratory Test Result	82
4.2.4 Field Measurements	86
4.3 Back Analysis of the Case Study	96
4.3.1 Soil Parameters	97
4.3.2 Model Geometry	115
4.4 Comparison between Back Analysis Results and Field Measurements	118
4.4.1 Lateral Deformation of Shoring System	119
4.4.2 Settlement of Adjacent Buildings	139
PERFORMANCE OF SHORING SYSTEM	143
5.1 Introduction	143
5.2 Assumptions of Typical Section	143
5.3 Effect of Foundation Piles	144
5.4 Effect of Adjacent Loads	146
5.5 Comparison with Previous Works	147
5.5.1 Peck (1969)	147
5.5.2 Clough and O'Rourke (1990)	149
5.5.3 Ou et al (1993)	151
5.5.4 Hsieh and Ou (1998)	153
5.5.5 Phienwej and Gan (2003)	154

SUMMARY AND CONCLUSIONS	157
6.1 Summary	157
6.2 Conclusions	158
6.3 Suggestions for Future Research	159
REFERENCES	160

## LIST OF FIGURES

Figure 2.1 – Schematic diagram of stress strain behavior of soils8
Figure 2.2 – Change of vertical effective stress excess pore pressure11
Figure 2.3 – Compression and unloaded – reloaded indices as a function of plasticity index (After Kulhawy and Mayne 1990)
Figure 2.4 – Schematic drawing for berlin walls
Figure 2.5 – Steel sheet piles
Figure 2.6 – Types of pile wall
Figure 2.7 – Common types of wall support schemes. (After Kempfert and Gebreselassie, 2006)
Figure 2.8 – Common types of failures in supported excavations. (After Kempfert and Gebreselassie, 2006)
Figure 2.9 – Section through open cut in deposit of soft clay. (After Terzaghi, 1943)21
Figure 2.10 – Development of active and passive earth pressures. (After Ou, 2006)23
Figure 2.11 – Rankine active and passive earth pressures distributions for long term analysis. (After Ou, 2006)
Figure 2.12 – Rankine active and passive earth pressures distributions for short term analysis. (After Ou, 2006)
Figure 2.13 – Active and passive zones
Figure 2.14 – Apparent Pressure Envelopes: (a) Cuts in Sand; (b) Cuts in Soft to Medium Clay; and (c) Cuts in Stiff Clay (After Peck, 1969)27
Figure 2.15 – Summary of surface settlements adjacent to braced excavation in various soils (After Peck 1969)

Figure 2.16 - Observed maximum horizontal deflection of wall for various wall types in
stiff clays, residual soils and sands (After Clough and O'Rourke 1990)29
Figure 2.17 – Observed maximum settlement adjacent to excavations (After Clough and O'Rourke 1990)
Figure 2.18 – Dimensionless settlement profiles recommended for estimating the distribution of settlement adjacent to excavations in different soil types (After Clough and O'Rourke 1990)
Figure 2.19 – Shape of "Spandrel" settlement profile (After Ou, 1993)32
Figure 2.20 – Proposed Method for Predicting Concave Settlement Profile (After Hsieh and Ou, 1998)
Figure 3.1 – Geotechnical methods of analysis (After Rao, 2005)
Figure 3.2 – One dimensional element. (After Rao, 2005)
Figure 3.3 – Two dimensional elements. (After Rao, 2005)
Figure 3.4 – Three dimensional elements. (After Rao, 2005)
Figure 3.5 – Axisymmetric Elements. (After Rao, 2005)
Figure 3.6 – Finite Elements with Curved Boundaries. (After Rao, 2005)
Figure 3.7 – Examples of axisymmetric problem
Figure 3.8 – Examples of plane strain problem
Figure 3.9 – Geometrical representation of the yield criterion in the principal stress space. (After Hill, 1950)
Figure 3.10 – Different yield criteria. (After Chen and Mccarron, 1986; Chen and Mizuno, 1990). (Cited in Kempfert and Gebreselassie, 2006)
Figure 3.11 – Associated flow rule. (After Atkinson, 1993)52

Figure 3.12 – Schematic representation of the yield surface, and the flow rule. (After
Kempfert and Gebreselassie, 2006)52
Figure 3.13 – Perfect plasticity model. (After Brinkgreve, 2002)53
Figure 3.14 – Isotropic hardening rule. (After Chakrabarty. 2006)54
Figure 3.15 – Kinematic hardening rule. (After Chakrabarty, 2006)54
Figure 3.16 – Hyperbolic stress-strain relationship in primary loading for a standard drained triaxial test. (After Brinkgreve, 2002)
Figure 3.17 – Successive yield loci for various constant values of the hardening
parameter (γp). (After Brinkgreve, 2002)59
Figure 3.18 – Yield surfaces of Hardening Soil model in p-q plane. The elastic region can be further reduced by means of a tension cut-off (After Brinkgreve, 2002)62
Figure 3.19 – Representation of total yield contour of the Hardening Soil model in principal stress space for cohesionless soil. (After Brinkgreve, 2002)
Figure 3.20 – Logarithmic relation between the volumetric strain and the mean effective stress. (After Brinkgreve, 2002)
Figure 3.21 – Yield surface of the soft soil model in the p'-q plane. (After Brinkgreve, 2002)
Figure 3.22 – Representation of total yield contour of the soft soil model in principal stress space. (After Brinkgreve, 2002)
Figure 3.23 – Geometry and boundary conditions of the model
Figure 3.24 – Position of nodes and stress points in the 15-node soil element. (After Brinkgreve, 2002)
Figure 3.25 – Position of nodes and stress points in the 5-node beam element. (After Brinkgreve, 2002)

Figure 3.26 – Position of nodes and stress points in the 5-node geogrid element. (Aft	er
Brinkgreve, 2002)	74
Figure 3.27 – Distribution of nodes and stress points in interface elements and their connection to soil elements. (After Brinkgreve, 2002)	75
connection to son elements. (After Brinkgreve, 2002)	13
Figure 4.1 – Location of the building.	76
Figure 4.2 – Shoring wall cross section.	77
Figure 4.3 – Anchors details.	77
Figure 4.4 – Boreholes location.	80
Figure 4.5 – Soil profile of implemented boreholes.	80
Figure 4.6 – Soil profile used in Finite Element Modeling near the south wall	81
Figure 4.7 – Soil profile used in Finite Element Modeling near the north wall	81
Figure 4.8 – Plasticity index results.	82
Figure 4.9 – Standard penetration test results.	83
Figure 4.10 – Cone penetration test results.	83
Figure 4.11 – Pocket penetrometer results.	84
Figure 4.12 – Unconfined compression test results.	84
Figure 4.13 – Menard pressuremeter test results.	85
Figure 4.14 – Piezometers and well location.	86
Figure 4.15 – Location of the inclinometers and reference points	87
Figure 4.16 – Stages of the excavation works.	88
Figure 4.17 – Results of inclinometer (1).	89

Figure 4.18 – Results of inclinometer (2)
Figure 4.19 – Results of inclinometer (3)90
Figure 4.20 – Results of inclinometer (4)
Figure 4.21 – Lateral movements of the north reference points
Figure 4.22 – Vertical movements of the north reference points
Figure 4.23 – Lateral movements of the south reference points
Figure 4.24 – Vertical movements of the south reference points
Figure 4.25 – Location of reference points at the building front side93
Figure 4.26 – Vertical displacement of upper reference points at the building front side.
Figure 4.27 – Vertical displacement of intermediate reference points at the building front side
Figure 4.28 – Vertical displacement of lower reference points at the building front side.
Figure 4.29 – Location of reference points at back side of the building95
Figure 4.30 – Vertical displacement of upper reference points at the building back side.
Figure 4.31 – Vertical displacement of lower reference points at the building back side.
Figure 4.32 – Corrected SPT results
Figure 4.33 – Undrained cohesion calculated from SPT results
Figure 4.34 – Friction angle calculated from SPT results
Figure 4.35 – Lower boundary of c <sub>n</sub> calculated from CPT results

Figure 4.36 – Upper boundary of c <sub>u</sub> calculated from CPT results10	01
Figure 4.37 – Estimated values for friction angle (φ) according to CPT results.  (Robertson and Campanella, 1983)	02
Figure 4.38 – Unconfined compressive strength obtained from pocket penetrometer an unconfined compression test results.	
Figure 4.39 – Undrained cohesion calculated from pocket penetrometer and unconfine compression test results	
Figure 4.40 – Mohr's circle of stress used to drive relation between undrained shear strength and drained shear parameters	05
Figure 4.41 – Comparison between measured and computed c <sub>u</sub> values10	05
Figure 4.42 – Stiffness modulus calculated from SPT results10	07
Figure 4.43 – Lower boundary of E calculated from CPT results	08
Figure 4.44 – Upper boundary of E calculated from CPT results	08
Figure 4.45 – Stiffness modulus calculated from menard pressuremeter results1	10
Figure 4.46 – Relation between E <sub>u</sub> and c <sub>u</sub> (After Duncan and Buchignani,1976)1	11
Figure 4.47 – Lower and upper boundary of $E_u$ calculated from $c_u$	11
Figure 4.48 – Determination of coefficient of permeability by pumping from wells1	13
Figure 4.49 – Location of analyzed sections	16
Figure 4.50 – Section (1)	17
Figure 4.51 – Section (2)	17
Figure 4.52 – Section (3)	17
Figure 4.53 – Section (4).	18

Figure 4.54 – Corrected results of inclinometer (1) on 30 <sup>th</sup> of August 2008
Figure 4.55 – Corrected results of inclinometer (1) on 10 <sup>th</sup> of October 2008120
Figure 4.56 – Comparison between the horizontal deformations calculated using HSM and corrected inclinometer (1) results on 30 <sup>th</sup> of August 2008
Figure 4.57 – Comparison between the horizontal deformations calculated using HSM and corrected inclinometer (1) results on 10 <sup>th</sup> of October 2008
Figure 4.58 – Comparison between the horizontal deformations calculated using SSM and corrected inclinometer (1) results on 30 <sup>th</sup> of August 2008
Figure 4.59 – Comparison between the horizontal deformations calculated using SSM and corrected inclinometer (1) results on 10 <sup>th</sup> of October 2008
Figure 4.60 – Comparison between the best model from HSM and SSM analysis and corrected inclinometer (1) results on 30 <sup>th</sup> of August 2008
Figure 4.61 – Comparison between the best model from HSM and SSM analysis and corrected inclinometer (1) results on 10 <sup>th</sup> of October 2008
Figure 4.62 – Corrected results of inclinometer (2) on 30 <sup>th</sup> of August 2008125
Figure 4.63 – Corrected results of inclinometer (2) on 10 <sup>th</sup> of October 2008125
Figure 4.64 – Comparison between the horizontal deformations calculated using HSM and corrected inclinometer (2) results on 30 <sup>th</sup> of August 2008
Figure 4.65 – Comparison between the horizontal deformations calculated using HSM and corrected inclinometer (2) results on 10 <sup>th</sup> of October 2008
Figure 4.66 – Comparison between the horizontal deformations calculated using SSM and corrected inclinometer (2) results on 30 <sup>th</sup> of August 2008
Figure 4.67 – Comparison between the horizontal deformations calculated using SSM and corrected inclinometer (2) results on 10 <sup>th</sup> of October 2008

Figure 4.68 – Comparison between the best model from HSM and SSM analysis and corrected inclinometer (2) results on 30 <sup>th</sup> of August 2008128
Figure 4.69 – Comparison between the best model from HSM and SSM analysis and corrected inclinometer (2) results on 10 <sup>th</sup> of October 2008
Figure 4.70 – Corrected results of inclinometer (3) on 30 <sup>th</sup> of August 2008130
Figure 4.71 – Corrected results of inclinometer (3) on 10 <sup>th</sup> of October 2008130
Figure 4.72 – Comparison between the horizontal deformations calculated using HSM and corrected inclinometer (3) results on 30 <sup>th</sup> of August 2008131
Figure 4.73 – Comparison between the horizontal deformations calculated using HSM and corrected inclinometer (3) results on 10 <sup>th</sup> of October 2008
Figure 4.74 – Comparison between the horizontal deformations calculated using SSM and corrected inclinometer (3) results on 30 <sup>th</sup> of August 2008
Figure 4.75 – Comparison between the horizontal deformations calculated using SSM and corrected inclinometer (3) results on 10 <sup>th</sup> of October 2008
Figure 4.76 – Comparison between the best model from HSM and SSM analysis and corrected inclinometer (3) results on 30 <sup>th</sup> of August 2008
Figure 4.77 – Comparison between the best model from HSM and SSM analysis and corrected inclinometer (3) results on 10 <sup>th</sup> of October 2008
Figure 4.78 – Corrected results of inclinometer (4) on 30 <sup>th</sup> of August 2008135
Figure 4.79 – Corrected results of inclinometer (4) on 10 <sup>th</sup> of October 2008135
Figure 4.80 – Comparison between the horizontal deformations calculated using HSM and corrected inclinometer (4) results on 30 <sup>th</sup> of August 2008136
Figure 4.81 – Comparison between the horizontal deformations calculated using HSM and corrected inclinometer (4) results on 10 <sup>th</sup> of October 2008

Figure 4.82 – Comparison between the horizontal deformations calculated using SSM
and corrected inclinometer (4) results on 30 <sup>th</sup> of August 2008
Figure 4.83 – Comparison between the horizontal deformations calculated using SSM
and corrected inclinometer (4) results on 10 <sup>th</sup> of October 2008
Figure 4.84 – Comparison between the best model from HSM and SSM analysis and
corrected inclinometer (4) results on 30 <sup>th</sup> of August 2008
Figure 4.85 – Comparison between the best model from HSM and SSM analysis and
corrected inclinometer (4) results on 10 <sup>th</sup> of October 2008
Figure 4.86 – Comparison between calculated and measured settlement of the adjacent
building and the vertical movement of the supporting piles in section (2)140
Figure 4.87 – Comparison between calculated and measured settlement of the adjacent
building and the vertical movement of the supporting piles in section (3)141
Figure 5.1 – Effect of foundation piles existence and distribution on lateral
deformations of shoring system
Figure 5.2 – Effect of foundation piles existence and distribution on settlement of soil
surrounding the shoring system
Figure 5.3 – Effect of adjacent loads on lateral deformations of shoring system146
Figure 5.4 – Effect of adjacent loads on settlement of soil surrounding the shoring
system
Figure 5.5 – Comparison between calculated surface settlements adjacent to braced
excavation and values concluded by Peck (1969)
Figure 5.6 – Comparison between calculated wall deflection and values concluded by
Clough and O'Rourke (1990)
Figure 5.7 – Comparison between calculated ground settlement and values concluded
by Clough and O'Rourke (1990).

Figure 5.8 – Comparison between calculated ground settlement and values cond	cluded
by Ou (1993)	152
Figure 5.9 – Comparison between calculated wall deflection and values conclude	ded by
Ou (1993)	152
Figure 5.10 – Comparison between calculated ground settlement and values con	ncluded
by Hsieh and Ou (1998)	154
Figure 5.11 – Location of maximum settlement.	154
Figure 5.12 – Comparison between calculated wall deflection and values conclu	ided by
Phienwej and Gan (2003).	155

## LIST OF TABLES

Table 4.1 – SPT correction factors (Skempton 1986)98
Table 4.2 – Estimating unconfined compressive strength from pocket penetrometer values (After Look, 2004)
Table 4.3 – Summary of calculated shear parameters
Table 4.4 – Menard pressuremeter modulus correlation factor. (Briaud, 1992)109
Table 4.5 – Summary of calculated stiffness modulus (kPa)
Table 4.6 – Ranges of k for various soil types. (After Casagrande and Fadum, 1940).
Table 4.7 – Soil parameters implemented in numerical model for sand layers114
Table 4.8 – Soil parameters implemented in numerical model for clay layers115