

CONTROLLING TUNNEL INDUCED GROUND SURFACE AND PILE
MOVEMENTS USING MICROPILES

HOUMAN SOHAEI

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

AUGUST 2017

I dedicated this thesis to my beloved father and mother for their support and
encouragement

ACKNOWLEDGEMENTS

I would like to express my gratitude to my supervisor, Prof. Dr. Aminaton binti Marto for her guidance, advice, constructive feedback, and critical review of this thesis. Her support, time and help are the motivations for me to strive harder in my academic journey. I sincerely thanks Universiti Teknologi Malaysia for giving me the opportunity to do my research in a supportive academic environment.

My fellow friends should also be recognized for their supports in particular Dr. Mohsen Hajihassani and Dr. Eshagh Namazi. I also would like to thank all researchers in the Soft Soil Engineering Research Group (SSRG) for their friendship and critical feedbacks on my research. My sincere appreciation also extends to all colleagues and friends who have provided assistance at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space.

Last but not least, I would like to acknowledge the emotional and financial supports given by my family members. Their continued support and encouragement are the motivation for me to complete my study in due time. I appreciate it very much and will cherish it forever.

ABSTRACT

Tunnelling in densely populated areas is generally associated with undesirable ground movement and subsequent damage to adjacent buildings. Hence, the main concern of designers are to accurately predict ground movements and propose mitigation measures in severe cases. Nowadays, different techniques are used as a mitigation measure to reduce the impact of tunnel construction on ground settlement. Nevertheless, implementation of some of these methods is a source of unpredictable damage or undesirable effects such as the effect of installing micropiles between existing pile building foundation and tunnel which have yet to be understood. Hence, this research aims to establish a micropiles method as a mean to minimise ground surface settlement, and the settlement and lateral movement of the existing pile due to tunnelling through cohesionless soils. The study was carried out by means of laboratory physical model tests and numerical simulation using ABAQUS software. Three different relative densities of sand; 30%, 50%, and 75% were investigated while the overburden (cover to diameter) ratios used were 1, 2, and 3. A row of 3.7 mm diameter micropiles, d_{mp} with two different lengths (11 cm and 14.5 cm) was embedded in between the tunnel (5 cm diameter, D) and the existing pile at four different locations. In model tests, settlement, bending moment and axial force of the existing pile were monitored accordingly. Generally, the results showed that increasing the value of relative density of sand reduces the ground movements. However, shallow tunnelling in loose sand produces remarkable movement on the ground surface. With the usage of micropiles, the ground surface settlement was reduced to nearly 40%. The micropiles also reduced over 85% and 75% of the piles lateral and axial movements respectively. A good compatibility was found between the experimental and numerical approaches which illustrates that the presented numerical simulation is a reliable model to predict tunnel-pile-soil and tunnel-pile-soil-micropiles interactions. Within the limitation of the study, it is recommended that the most suitable length and location of micropiles to use is 14.5 cm or about $40d_{mp}$ (closest to the tunnel crown) and located at $0.5D$ (in the middle between tunnel and pile), based on the reduction observed on the vertical and lateral movements of pile as well as the bending moment and axial force.

ABSTRAK

Penerowongan di kawasan penduduk yang padat secara umumnya dikaitkan dengan pergerakan tanah yang tidak diinginkan dan kerosakan bangunan berdekatan. Oleh itu, kebimbangan utama perekabentuk adalah untuk meramal pergerakan tanah yang tepat dan mengusulkan langkah-langkah mitigasi pada kes yang teruk. Pada masa ini teknik yang berbeza digunakan sebagai langkah mitigasi untuk mengurangkan kesan pembinaan terowong pada enapan tanah. Walau bagaimanapun, pelaksanaan beberapa kaedah ini adalah punca kerosakan yang tidak dapat diramalkan atau kesan yang tidak diinginkan seperti kesan memasang cerucuk mikro antara asas cerucuk bangunan sedia ada dan terowong yang masih belum difahami. Oleh itu, kajian ini bertujuan untuk mewujudkan kaedah cerucuk mikro sebagai kaedah meminimumkan enapan permukaan tanah dan enapan serta pergerakan sisi cerucuk sedia ada akibat pembinaan terowong melalui tanah tak jeleket. Kajian ini dilakukan melalui ujian model fizikal makmal dan simulasi numerikal menggunakan perisian ABAQUS. Tiga kepadatan relatif pasir; 30%, 50%, dan 75% telah dikaji sementara nisbah tanah atas (penutup dan diameter) yang digunakan adalah 1, 2, dan 3. Sederet cerucuk mikro berdiameter, d_{mp} , 3.7 mm dengan dua kepanjangan yang berbeza (11 cm dan 14.5 cm) telah dipasang antara terowong (diameter, $D = 5$ cm) dan cerucuk sedia ada di empat lokasi berbeza. Dalam ujian model, enapan, momen lentur dan daya paksi cerucuk sedia ada telah dipantau dengan sewajarnya. Secara umumnya hasil kajian menunjukkan bahawa peningkatan nilai kepadatan relatif pasir mengurangkan pergerakan tanah. Namun, penerowongan cetek dalam pasir longgar menghasilkan pergerakan yang luar biasa di permukaan tanah. Dengan penggunaan cerucuk mikro, enapan permukaan tanah dikurangkan kepada hampir 40%. Cerucuk mikro juga berkurangan masing-masing lebih dari 85% dan 75% dari pergerakan sisi dan enapan cerucuk. Keserasian yang baik telah ditunjukkan antara pendekatan eksperimental dan numerikal yang menggambarkan bahawa simulasi numerikal yang dibuat oleh model tersebut dapat digunakan bagi meramal interaksi terowong-cerucuk-tanah dan terowong-cerucuk-tanah-cerucuk mikro. Dalam keterbatasan kajian, disyorkan bahawa panjang dan lokasi paling sesuai bagi cerucuk mikro adalah 14.5 cm atau lebih kurang $40d_{mp}$ (paling dekat dengan atas terowong) dan terletak $0.5D$ (tengah-tengah di antara terowong dan cerucuk) iaitu berdasarkan pengurangan pada pergerakan tegak dan sisi cerucuk selain dari momen lentur dan daya paksi.

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGMENTS	iv
	ABSTRACT	v
	ABSTRAK	vi
	TABLE OF CONTENTS	vii
	LIST OF TABLES	xii
	LIST OF FIGURES	xiv
	LIST OF ABBREVIATIONS	xxi
	LIST OF SYMBOLS	xxii
	LIST OF APPENDICES	xxiv
1	INTRODUCTION	1
	1.1 Background of the Study	1
	1.2 Problem Statement	4
	1.3 Aim and Objectives	4
	1.4 Scope and Limitation of the Study	5
	1.5 Significance of the Study	6
	1.6 Hypothesis	6
	1.7 Thesis Outline	7
2	LITERATURE REVIEW	9
	2.1 Introduction	9
	2.2 Ground Surface Settlement Prediction	9

2.3	Empirical Prediction of Ground Deformation	10
2.3.1	Transverse Settlement	12
2.3.1.1	Volume Loss	14
2.3.1.2	Inflection Point	18
2.3.2	Longitudinal Settlement	20
2.4	Analytical Prediction of the Ground Deformations	22
2.4.1	Virtual Image Technique	22
2.4.2	Complex Variable Method	29
2.4.3	Airy Function Technique	30
2.5	Analytical Prediction of the Pile Deformations	35
2.6	Estimation of Pile Bearing Capacity in Granular soil	36
2.6.1	Static Formula Using Soil Mechanics Principles	37
2.6.1.1	Skin Friction Capacity	38
2.6.1.2	End Bearing Capacity	40
2.6.2	Estimating of Failure Criteria from Pile Load Test	41
2.7	Numerical Prediction of the Ground Deformation	42
2.7.1	Two Dimensional Analyses	43
2.7.2	Three Dimensional Analyses	46
2.7.3	Numerical Simulation Using ABAQUS Software	50
2.8	Physical Modelling Applications in Tunnelling Aspects	53
2.8.1	Physical Modelling of Tunnelling in Greenfield Condition	55
2.8.2	Physical Modelling of Tunnel-Piles Interaction	60
2.8.2.1	Tunnelling with the existence of single pile	61
2.8.2.2	Tunnelling with the existence of group of pile	64
2.9	Interaction between Tunnel and Existing Piles	67
2.9.1	Pile Movements due to Tunnelling	67

2.9.1.1	Pile Head Settlement Induced by Tunnelling	68
2.9.1.2	Effect of the Tunnelling on Pile Bearing Capacity	71
2.9.1.3	Pile Lateral Movement Induced by Tunnelling	74
2.9.2	Distribution of Load and Bending Moments along the Pile	75
2.9.2.1	Axial force distribution	75
2.9.2.2	Bending Moments along the Pile Induced by Tunnelling	79
2.10	Controlling Ground and Pile Movements Due to Tunnelling	82
2.11	Field Observation of Tunnel-Soil-Pile Interactions	84
2.12	Micropiles as Means of Improving the Soil Strength	85
2.13	Summary	88
3	RESEARCH METHODOLOGY AND MATERIAL PROPERTIES	90
3.1	Introduction	90
3.2	Research Framework	92
3.3	Selection of Material for Soil	92
3.4	Selection of Soil Improvement Method	93
3.5	Case Study of Tunnelling	94
3.6	Laboratory Physical Model Tests	96
3.6.1	Scaling Factor	96
3.6.2	Basic and Engineering Soil Properties	98
3.6.2.1	Particle Size Distribution	98
3.6.2.2	Specific Gravity	100
3.6.2.3	Relative Density	101
3.6.2.4	Shear Strength	102
3.6.3	Model Box Design	103
3.6.4	Tunnel Excavation Model	104

3.6.5	Models of Pile and Micropiles, and Instrumentation	105
3.6.6	Physical Model Test Programme	109
3.6.7	Physical Model Tests Procedure	110
3.6.8	Sand Deposit Preparation for Model Test	112
3.6.9	Tunnelling in Greenfield Condition	113
3.6.10	Micropiles to Control Tunnel Induced Ground Movement	114
3.6.11	Micropiles to Control Tunnel Induced Pile Movements	117
	3.6.11.1 Pile Load Displacement Test	117
	3.6.11.2 Pile Behaviour Induced by Tunnelling	118
	3.6.11.3 Pile Behaviour Induced by Tunnelling with the Existence of Micropiles	119
3.7	3D Numerical Analysis	121
3.7.1	Properties of Materials Used in Numerical Simulation	122
3.7.2	Boundary Condition and Mesh	124
3.7.3	Modelling the Pile and Micropiles	126
3.7.4	Tunnel Construction in Numerical Simulation	126
4	RESULTS AND DISCUSSION	129
4.1	Introduction	129
4.2	Results and Analyses of Physical Modelling	130
4.2.1	Greenfield Condition	130
	4.2.1.1 Longitudinal Ground Surface Settlement	130
	4.2.1.2 Transverse Ground Surface Settlement	132
	4.2.1.3 Maximum Ground Surface Settlement	134

4.2.1.4	Inflection Points	135
4.2.1.5	Effect of Overburden on Lost Ground Ratio	137
4.2.2	Using Micropiles to Reduce Ground Surface Settlement	139
4.2.2.1	Longitudinal Ground Surface Settlement	139
4.2.2.2	Transverse Ground Surface Settlement	141
4.2.2.3	Maximum Ground Surface Settlement	143
4.2.3	Micropiles to Control Tunnel Induced Pile Movements	144
4.2.3.1	Ultimate bearing capacity of the pile	144
4.2.3.2	Ground and pile displacements induced by tunnelling	146
4.2.3.3	Effect of Micropiles in Controlling the Pile Capacity	152
4.2.3.3	Pile Lateral Movement	153
4.2.3.4	Pile Bending Moment	156
4.2.3.5	Axial Force	159
4.2.4	Numerical Simulation Results	161
4.2.4.1	Greenfield Condition	162
4.2.4.2	Pile Settlement Induced by Tunnelling	164
5	CONCLUSION AND RECOMMENDATION	167
5.1	Introduction	167
5.2	Conclusion	167
5.3	Contributions of Research	170
5.4	Recommendation for Future Works	171
	REFERENCES	172
	Appendices A-C	190-199

LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Relationship between volume loss, V_L and ground condition (Ahmed and Iskander, 2011)	16
2.2	Researchers that used ABAQUS in tunnelling simulation	52
2.3	Summary review of some 1g physical modelling on tunnelling research	54
2.4	Laboratory physical model tests performed by some researchers on tunnel-pile interaction	61
2.5	Grout to Ground Bond for Different Rock and Soil Types (Armour, 2000).	87
3.1	Scaling factor from prototype to model	97
3.2	Reduction scale from prototype to model	97
3.3	Basic and engineering properties tests on sand	98
3.4	Summary of particle size distribution test results	100
3.5	Summary of specific gravity test	101
3.6	Physical properties of the sand sample	102
3.7	Sand properties from direct shear test	103
3.8	List of instrumentation used in physical model test	107
3.9	Test programme in greenfield condition (G series)	109
3.10	Test programme with micropiles in controlling tunnel (C/D=3) induced ground movement in 50% relative density of sand (M series)	110
3.11	Test programme on pile behaviour induced by tunnelling (C/D=3) in 50% relative density of sand with and without micropiles (P-T-M series)	110
3.12	Physical properties of sand with 50% relative density	123

4.1	Inflection points from back analysis using Peck (1969) Equation	133
4.2	Empirical coefficient of settlement trough parameter, K	137
4.3	Maximum pile and ground displacement induced by tunnelling	147
4.4	Pile ALPC induced by tunnel excavation	152
4.5	Maximum pile lateral movement induced by tunnelling	154
4.6	Measured and predicted transverse surface settlements in greenfield condition	164

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	Tunnel geometry induced ground settlement (after Attewell <i>et al.</i> , 1986)	10
2.2	Influence lines (boundary of influence zones) proposed from previous studies induced by tunnelling	11
2.3	A typical transverse settlement trough (after Peck, 1969)	13
2.4	Trough volume of surface settlement relationship with volume loss (after Standing and Burland, 2006)	14
2.5	Relationship between width of settlement trough, i and dimensionless depth of tunnel, H/D , for different ground conditions (Peck, 1969)	18
2.6	Typical longitudinal settlement trough (after Attewell and Woodman, 1982)	21
2.7	The virtual image analysis steps (Sagaseta, 1987)	23
2.8	Subsidence model incorporates the combined effects of ground loss and ovalization (Gonzales and Sagasel, 2001)	24
2.9	(a) Ground loss and ovalization induced by tunnel (b) singularity and its image (Verruijt and Booker, 1996)	25
2.10	Definition of the gap parameter (Rowe and Kack, 1983)	26
2.11	The ground loss simulation (Lee <i>et al.</i> , 1992)	27
2.12	Non-uniform soil displacements around deforming tunnel boundary (Loganathan and Poulos, 1998)	28
2.13	Half-plane with hole (Strack and Verruijt, 2002)	30
2.14	Shallow tunnel representations in Airy Function Technique (Chou and Bobet, 2002)	31
2.15	Ground deformation pattern around the tunnel (Park, 2005)	32

2.16	The distribution of stresses around deep and shallow circular tunnels, (Park, 2004)	33
2.17	Boundary conditions of the soil movements around the tunnels (Park, 2004)	34
2.18	Pattern of the soil movements around the tunnel illustrated by Pinto and Whittle (2006)	35
2.19	Pile-tunnel interaction analytical solution (Marshall and Haji, 2015)	36
2.20	Unit frictional resistances for piles in sand (Das, 2007)	39
2.21	Values of N_q and ϕ relationship (Meyerhof, 1976)	40
2.22	Failure surface at the pile tip (after Janbu, 1976)	41
2.23	Tunnelling-induced ground surface settlements wider in FE analysis (Stallebrass <i>et al.</i> , 1997)	44
2.24	Ground surface settlement trough from 2D and 3D FE analyses, and field observation (Dasari <i>et al.</i> , 1996)	45
2.25	Longitudinal settlement troughs developed in 3D FE analysis (Vermeer <i>et al.</i> , 2002)	47
2.26	Longitudinal settlement troughs developed by 3D FE analysis (Möller <i>et al.</i> , 2003)	47
2.27	Comparison of transverse settlement troughs between field data, 2D and 3D analyses in different stages (Franzius <i>et al.</i> , 2005)	48
2.28	Different K_0 values affects to transverse settlement troughs for 2D and 3D analyses (Franzius <i>et al.</i> , 2005)	49
2.29	Longitudinal settlement profiles for different L_{exc} (Tang <i>et al.</i> , 2000)	51
2.30	Tunnel modelling using transparent sand (Ahmed and Iskander, 2011)	56
2.31	Direction of ground movements (Ahmed and Iskander, 2011)	56
2.32	Test set-up for physical model test using transparent sand (Sun and Liu, 2014)	57
2.33	Internal influenced zone in different depth excavated (Sun and Liu, 2014)	58
2.34	EPB shield model developed for laboratory physical model test (He <i>et al.</i> , 2012)	58

2.35	Schematic diagram of a typical plane strain centrifuge twin-tunnel model (Divall <i>et al.</i> , 2012)	60
2.36	Elevation view of centrifuge model tests on tunnel-pile interaction study (Ng <i>et al.</i> , 2013)	62
2.37	Model tunnels and model pile in centrifuge model test (Ng <i>et al.</i> , 2013)	63
2.38	Model test set up for tunnel-pile interaction study in centrifuge model test (Lee and Chiang, 2007)	64
2.39	Elevation view of centrifuge model tests on tunnel-piles interaction study (Ng <i>et al.</i> , 2013)	65
2.40	Tunnel and pile group models in centrifuge model test (Ng <i>et al.</i> , 2014)	66
2.41	Steel casing, threaded rod and inner surface of lining with strain gauge locations (Meguid and Mattar, 2009)	67
2.42	Maximum pile settlement induced by twin tunnel (Ng <i>et al.</i> , 2013)	68
2.43	Settlement of pile group induced by twin tunnel (Ng <i>et al.</i> , 2014)	69
2.44	Zones of influence induced by tunnelling with the respect of pile toe location (Selemetas <i>et al.</i> , 2005)	69
2.45	Pile failure mechanisms induced by tunnelling (Cheng, 2003)	71
2.46	Load settlement relationship of pile with and without tunnelling (Ng <i>et al.</i> , 2013)	73
2.47	Axial force along the pile without working load induced by tunnelling (Lee and Chiang, 2007)	76
2.48	Axial forces along the pile with working load of 1600 kN (Lee and Chiang, 2007)	77
2.49	Bending moment along the pile with working loads of 1600 kN (Lee and Chiang, 2007)	80
2.50	Bending moment in a pile during the tunnelling process (Ng <i>et al.</i> , 2014)	81
2.51	Typical micropile construction sequence (Armour, 2000)	86
3.1	Flowchart of research methodology	91
3.2	Overall framework of research	92

3.3	Tunnels beneath the building founded on piles between station TS15 and station TS16 at the Thomson Line project, Singapore: (a) plan view and (b) cross-section view	95
3.4	Sieves test on granular material	99
3.5	Particle size distribution curve	99
3.6	Box dimensions using for physical modelling	104
3.7	Casing technique for simulation of the tunnel volume loss	105
3.8	Installation of the bored pile adjacent to the tunnel	106
3.9	Micropile models at 1/2 pile length and 2/3 pile length	108
3.10	Driving the micropile into the sand	109
3.11	Overview of the whole test system	111
3.12	Schematic diagram of a typical 3D laboratory physical model test	111
3.13	Mobile Pluviator system	112
3.14	Cross-sections of greenfield condition tests	113
3.15	Location of LVDTs on ground surface in greenfield condition (G series)	114
3.16	Cross-sections of the tests of the micropiles model with 11 and 14.5 cm in length relative to the tunnel position	115
3.17	Plan views of the M series laboratory physical model tests	116
3.18	A row of micropiles placed at various distances from tunnel axis line	116
3.19	Pile load displacement test	118
3.20	Installation of the measurement devices and the test completion	119
3.21	Cross-sections of the tests of the micropile model 14.5 cm in length relative to the tunnel and pile position	120
3.22	Side views of the tests of the micropile model relative to the tunnel and pile position	120
3.23	Micropile placed in between the pile and the tunnel axis line	121
3.24	Calculated Young's Modulus with depth	124
3.25	Schematic view of FE model dimensions	124
3.26	Model-generated mesh in FEM	125
3.27	Simulation of tunnel construction in step 7 and step 9	127

4.1	Comparison between longitudinal ground surface settlement troughs obtained by physical modelling for a C/D ratio of 1, 2, and 3 and various relative densities	131
4.2	Comparison between transverse ground surface settlement troughs obtained by physical modelling for C/D ratio of 1, 2, and 3 and various relative densities	133
4.3	Effect of overburden ratio to the maximum ground surface settlement for loose, medium dense and dense sands	135
4.4	Comparison between the effect of overburden ratio of 1, 2, and 3 at relative densities of 30, 50, and 75% to the width of settlement trough	136
4.5	Relationship between width of settlement trough and dimensionless depth of tunnel for different ground conditions (after Peck, 1969)	137
4.6	Ratio of the volume of settlement trough to the volume loss and against the overburden ratio for different densities of sand	138
4.7	Micropiles located in the different influence zones induced by tunnelling	139
4.8	Comparison between longitudinal surface settlement trough for greenfield condition and with micropiles for a C/D ratio of 3 and relative density of 50%	141
4.9	Comparison between transverse surface settlement troughs with and without micropiles obtained by physical modelling for a C/D ratio of 3 and relative density of 50%	142
4.10	Comparison between maximum ground surface settlement controlled by micropiles obtained by physical modelling for a C/D ratio of 3 and relative densities of 50%	143
4.11	Pile load–settlement curve for 1.2 m pile diameter and 23.45 m embedded length in medium dense sand	145
4.12	Pile and micropiles located in the different influence zones induced by tunnelling	147
4.13	Pile axial displacement due to tunnelling in the presence of micropiles with constant length and constant distance	149

4.14	Effect of micropile location and length to the maximum pile settlement and maximum ground settlement	150
4.15	Effect of various numbers of micropiles in a row, located at the centre between tunnel and pile, on the maximum pile and ground settlement	151
4.16	Load–settlement curve obtained from the pile load test	153
4.17	Effect of micropile location and length to the maximum pile lateral movement	155
4.18	Effect of various numbers of 14.5 cm length micropiles in a row, located at the centre between tunnel and pile, on the maximum pile lateral movement	155
4.19	Effect of micropiles (six numbers in a row) to the maximum bending moments along the pile: (a) 11 cm micropiles length and (b) 14.5 cm micropiles length	157
4.20	Effect of various numbers of 14.5 cm length micropiles, located at the centre between tunnel and pile, to the maximum bending moments along the pile	158
4.21	Plan view of pile row and equivalent sheet pile wall (Ellis and Springman, 2001)	157
4.22	Impact of micropiles in six numbers in a row to the axial force along the pile: (a) 11 cm micropiles length and (b) 14.5 cm micropiles length	160
4.23	Effect of micropiles to the maximum axial force along the pile in a row of various numbers of micropiles	161
4.24	Ground displacements around the tunnel and at the surface in greenfield condition obtained by FE analysis	162
4.25	Comparison between longitudinal settlement troughs in greenfield condition obtained by physical modelling and FE analysis	163
4.26	Comparison between transverse settlement troughs in greenfield condition obtained by physical modelling and FE analysis	163
4.27	Comparison between longitudinal settlement troughs obtained by physical modelling and FE analysis	165

4.28	Ground displacements around the tunnel and at the surface in tunnel-pile interactions condition obtained by FE analysis	165
4.29	Ground displacements around the tunnel and at the surface in tunnel-pile-micropiles interaction condition obtained by FE analysis	166

LIST OF ABBREVIATIONS

NATM	-	New Austrian Tunneling Method
UTM	-	Universiti Teknologi Malaysia
TBM	-	Tunnel Boring Machine
EPB	-	Earth Pressure Balance
MC	-	Mohr-Coulomb
FE	-	Finite Element
P-T	-	Pile tunnel
P-T-M	-	Pile tunnel micropiles
PLM	-	Pile lateral movement

LIST OF SYMBOLS

C	-	Cover of tunnel
c	-	Cohesion
D	-	Tunnel Diameter
E	-	Young's modulus
d_p	-	Pile diameter
d_{mp}	-	Micropile diameter
H	-	Tunnel depth to the axis level
i	-	Horizontal distance from tunnel centre line to inflection point
i_x	-	Initial position of the tunnel
k	-	Empirical constant
l_p	-	Pile lateral movement
L_p	-	Pile length
L_{mp}	-	Length of micropile
L_{exc}	-	Excavation length
m	-	Auxiliary elastic constant
R	-	Tunnel radius
S	-	Ground surface settlement
S_p	-	Pile settlement
S_v	-	Vertical settlement
$S_{v,max}$	-	Maximum surface settlement
S_c	-	Vertical settlement at the tunnel crown
S_h	-	Horizontal ground movement
V_L	-	Ground loss
V_S	-	volume of any surface trough
V_d	-	volume lost due to dilation
z_0	-	Tunnel depth
X_M	-	Distance from tunnel axis

X	-	Distance from tunnel centre
x	-	Distance from the tunnel centre line
Z	-	Pile depth
x_f	-	Location of the tunnel face
ε_h	-	Horizontal strain
ε	-	Uniform radial ground loss
δ	-	Long term ground deformation
ν	-	Poisson's ratio
G_p	-	Physical gap
δ_l	-	Clearance required for erection of the lining
u_{3D}^*	-	Three dimensional elasto-plastic deformation
ω	-	Quality of workmanship
u_z	-	Vertical displacements
ρ	-	Ovalization
α	-	Coefficient in elastic region
μ	-	Elastic constant of shear modulus
$\varphi(z)$	-	Complex variable
$\psi(z)$	-	Complex variable
$\varphi'(z)$	-	Notation
γ	-	Unit weight
γ_b	-	Buoyant soil unit weight
γ_w	-	water unit weight
k_0	-	Coefficient of earth pressure at rest
ϕ_p	-	Peak internal friction angle
ϕ_c	-	Critical internal friction angle
β	-	Angular distortion
ψ	-	Dilation angle

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Direct Shear Tests Results	190
B	Calibration of Instrumentation	194
C	ABAQUS Codes	199

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Over the past few decades, the world has been gradually experienced elevation of the urban population. In some countries, speed of the population growth is the most difficult challenge. It is reported that this growth of population in urban areas resulted with the high demand of infrastructures. Demand for the construction of underground infrastructures has increased considerably as a consequence of the growth of urban cities. Tunnels are an inseparable component of underground infrastructures, which have been considered during the last decades. Tunnels as subsurface structures have become ultimate alternative for overcoming the ground surface congestion. Although, tunnels have effectively addressed the ground surface congestion, still a number of challenges and problems occurred when especially tunnelling under urban environment.

The environmental impacts of the tunnel construction have been known as an essential consideration in tunnel design at the urban cities. Tunnelling through densely populated areas is usually associated with undesirable ground movement and damage to adjacent buildings. Consequently, it is essential to investigate the mechanism of the soil movements around the tunnel as well as ground surface and surface structures. An important critical issue in urban tunnelling is the control of ground movement induced by tunnelling in order to protect the surface and subsurface structures and utilities. In this regard, assessment of the potential effects on structures is a necessary aspect of the design and construction of a tunnel in an urban area. Hence

the prediction of the tunnelling-induced ground movements is necessary. Predictions of tunnelling-induced ground movements were first described by Peck (1969) as radial displacements towards the transverse and longitudinal displacements along the cross section of the tunnel. These two sets of movements have been difficult to define and separate, therefore displacements are usually simplified to a plane strain scenario (Franzius *et al.*, 2005).

In urban environments, tunnels are often constructed close to or just below the existing pile foundations of buildings at the ground surface (Lee *et al.*, 1994, Coutts and Wang, 2000, Tham and Deutscher, 2000). The response of a building is governed by the effects of the tunnel excavation on the soil, interaction between soil and piles, and interaction between the piles and the building (Selemetas *et al.*, 2005). The unloading effect of the tunnel excavation leads to displacements of the soil, demolition of the nature of the interface between soil and pile, and therefore soil movements around the piles, causing changes in the vertical and horizontal ground stresses on the piles.

With the increasing the quantity of tunnels in the populated areas, several methods have been developed to provide a comprehensive understanding of the various problems deal with tunnel construction. Empirical, analytical, numerical and artificial intelligence approaches besides the physical modelling techniques have been widely used in analysing the effects of tunnelling on the ground movements and existing surface and subsurface structures. Some general aspects of the surface structural behaviour, in particular pile, are affected by the construction of a tunnel have been studied by previous researchers using different methods such as case studies and full-scale field trials (*e.g.* Jacobsz *et al.*, 2005; Selemetas *et al.*, 2005; Kaalberg *et al.*, 2005), analytical solutions (*e.g.* Marshall, 2012, 2013; Marshall and Haji, 2015), numerical analyses (*e.g.* Lee and Ng., 2005; Bioltta *et al.*, 2006; Yao *et al.*, 2009; Zidan and Ramadan, 2015), physical modelling (*e.g.* Lee and Chiang, 2007; Meguid and Mattar, 2009; Ng *et al.*, 2013; Sun and Liu, 2014). However, among these methods the laboratory physical model is usually preferred as it is able to provide comprehensive results based on its repeatability. Most of previous studies identified

the zones of different pile behaviours, depending on the zone in which the pile toe is located relative to the tunnel position, both in shallow and deep tunnelling work.

A number of laboratory physical model tests have been conducted under single or multiple gravities to investigate the different tunnelling aspects. The physical modelling such as trap door, pressurized air, soil augering, casing and other techniques of tunnels provide the ability to investigate the most significant factors influencing the tunnel behaviour (Meguid *et al.*, 2008). These techniques have been used to investigate different aspects of tunnelling such as arching effect and tunnel stability (*e.g.* Lee *et al.*, 2006; Berthoz, 2012), ground movements and collapse mechanism due to tunnelling (*e.g.* He *et al.*, 2012; Sun and Liu, 2014), interaction of the ground with the existing structures (*e.g.* Ng *et al.*, 2013; Meguid and Mattar, 2009; Lee and Chiang, 2007), and tunnel face stability (*e.g.* Berthoz *et al.*, 2012; Wong *et al.*, 2012).

Various studies had been carried out to improve the soil such as the usage of jet-grouting, forepoling, diaphragm wall and piles in order to minimize the surface settlement due to tunnelling. Bilotta *et al.* (2006) and Bilotta (2008) performed numerical plane strain analyses and centrifuge tests to investigate the effects of a diaphragm wall embedded between a shallow tunnel and an existing pile. A parametric study was performed to optimize the location and length of the diaphragm wall in controlling the ground displacement beneath the building. Bilotta *et al.* (2006) also conducted a series of centrifuge tests to investigate the effect of a line of piles and their spacing in controlling the ground displacement induced by tunnel excavation. They concluded that the use of more piles with shorter distances results in a more effective reduction of ground movements. In general, micropiles are used to increase the bearing capacity and reduce the settlement of weak or loose soils (Juran *et al.*, 1999 and Bruc 2002). However, the technique of using micropiles is still not well published and understood.

1.2 Problem Statement

Numerous attempts have been conducted to investigate ground deformation mechanism induced by tunnelling, particularly the shallow tunnelling in urban settings. It includes the investigation of pile and tunnel interaction based on ground surface settlement, tilting and lateral movement of pile foundation, and load transfer mechanism. Some methods of soil improvements, such as jet grouting and forepoling to stabilise the soil were used besides using the NATM tunnelling method, to minimize the surface settlement. Although these methods could reduce the surface settlement but there are reports on the occurrence of structural damages, in particular the pile foundation. Moreover, these methods are time consuming, thus increase the project cost. Limitations of existing methods urge for the needs of more research on methods of controlling the ground deformation, particularly for tunnelling through cohesionless soils. The effectiveness of the method in minimising the ground and pile settlement, and the tilting and lateral movement of existing piles due to tunnel construction is also important to be studied, using both the physical modelling and numerical analysis.

This research aimed at establishing the micropile method to control the ground movement and the movements of existing pile in cohesionless soils due to shallow tunnelling. For this purpose, a series of three dimensional (3D) physical modelling tests in dry sand were carried out under single gravity. The tests explore the optimum location and length of micropiles for controlling the pile's settlement and lateral movement. Results were simulated based on 3D finite element analysis using ABAQUS 6.11 software.

1.3 Aim and Objectives

The research aimed at establishing the micropiles method as a mean to minimise the ground surface settlement, and the settlement and lateral movement of existing pile due to tunnelling through cohesionless soils. Hence, the objectives of the research are as follows:

- i. To determine the effect of depths of the tunnel and density of the soil on the surface settlements and influence zones, induced by tunnelling in greenfield condition.
- ii. To determine the effects of the micropiles in reducing the ground surface settlements due to tunnelling in greenfield condition.
- iii. To determine the effects of tunnel excavation on the settlement and lateral movement of existing piles.
- iv. To establish the effects of micropiles in controlling the settlement and lateral movement of existing piles due to tunnelling through the development of various graphs, thus determining the optimum location of micropile in between the pile and the tunnel.

1.4 Scope and Limitation of the Study

This research involves both the numerical and the physical modelling. The numerical modelling was carried out using ABAQUS software and the physical modelling has been carried out in the laboratory under single gravity (1g) using a box of 600 mm in length, 600 mm in width and 500 mm in height. In physical modelling test:

- i. The circular shape tunnel was made of aluminium tube with 49 mm inner diameter shielded by a tube of 50 mm outer diameter.
- ii. The cover to diameter (C/D) ratios of the tunnel were 1, 2 and 3, and the relative densities of the sand used were 30%, 50% and 75%.
- iii. The quarry sand used in this study was obtained from a supplier and only the fine sand fractions were used for the physical modelling tests.
- iv. The existing pile, made of aluminium and fixed at 9 mm diameter and 220 mm length, has been placed close to the tunnel alignment at 50 mm distance from tunnel centre (zone of influence).
- v. The 3.7 mm diameter steel micropiles, wrapped with sand papers, were of 110 mm and 145 mm lengths. The micropiles had been installed in a single row with 3.7 mm side to side spacing above the tunnel and at several distances (1.25, 2.5, and 3.75 cm) from the tunnel axis.

1.5 Significance of the Study

A reliable method to control the tunnelling-induced surface settlement and consequently the risk of adjacent buildings are vital. This research on the use of micropiles and the effect of tunnelling to the existing pile, draw some significant as the followings:

- i. The tunnelling-induced surface settlement of different soil density obtained from this research could contribute to the existing body of knowledge. This research considers the relationship among the different tunnel depth and density of the soil on the influence zones and surface settlements induced by tunnelling to better understand the behaviour of the surface settlement due to tunnelling.
- ii. The utilization of micropiles to minimize the ground surface settlement induced by tunnel in greenfield condition could be used to control the building damage in shallow foundation such as raft foundation.
- iii. The used of micropiles to minimize the surface settlement due to shallow tunnelling through sand has been a breakthrough of the successful method. This method also reduced the settlement and lateral movement of the existing pile.
- iv. The numerical modelling using ABAQUS, verified by physical model test results, could be used by the engineer to predict soil and pile movements due to tunnelling in sandy soils.

1.6 Hypothesis

- (i) In greenfield condition; increasing the value of the relative density of sand reduces the ground movements induced by tunnelling.
- (ii) Micropiles to reduce ground surface settlement; the length and the location of the micropiles affect the ability of micropiles in reducing the maximum ground surface settlement.

- (iii) The pile settlement induced by tunnelling; based on the pile toe location (50 cm, tunnel centre to pile centre), it is expected that the pile settlement is less than the maximum ground surface settlement.
- (iv) Micropiles to reduce pile displacements; the longer micropiles are more effective than the shorter micropiles to reduce the pile movements in terms of settlement and lateral movement of the pile. The micropiles location can be more significant in terms of the pile lateral movement. Moreover, the more the number of micropiles, the more reduction in pile movements will be achieved.

1.7 Thesis Outline

The thesis is composed of six chapters and three appendixes. The summaries of the chapters are as follows:

Chapter 1 explains the background of the study, statement of the problems, aim and objectives, scope and limitation of the study, significance of the study and hypothesis.

Chapter 2 presents and discusses the ground surface settlement and pile movements induced by tunnel construction. The existing methods were reviewed based on transverse and longitudinal surface settlements associated with tunnel construction. Moreover, a number of available methods such as; empirical, analytical, numerical and physical modelling of small-scale tunnel construction in terms of ground settlement and pile movements were reviewed.

Chapter 3 describes the research methodology using the flowchart and overall framework, which have been used for this research. It includes; basic tests on sand, physical modelling tests and numerical analysis.

Chapter 4 shows and discusses all the results obtained from physical modelling tests and numerical analysis. The results of using micropiles in controlling the ground surface settlement, pile settlement and lateral movement induced by tunnelling has been clearly shown in figures and discussed accordingly.

Chapter 5 gives research conclusion, contributions and recommendations for future works.

REFERENCES

- Abaqus 6.10. (2011). Analysis user's manual. Hibbitt, Karlson and Sorenson, Inc.
- Abdull Hamed, H.N., Shamsuddin, S.M., and Salim, N. (2008). Particle Swarm Optimization for Neural Network Learning Enhancement. *Jurnal Teknologi*, 49: 13-26
- Adachi, T., Kimura, M., Kishida, K. (2003). Experimental study on the distribution of earth pressure and surface settlement through three dimensional trapdoor tests. *Tunnelling and Underground Space Technology*. 18(2): 171–183.
- Addenbrooke, T., Potts, D., and Puzrin, A. (1997). The influence of pre-failure soil stiffness on the numerical analysis of tunnel construction. *Geotechnique*. 47(3): 693–712.
- Ahmed, M and Iskander, M. (2011). Analysis of tunnelling-induced ground movements using transparent soil models. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE. 137: 525-535.
- Anagnostou, G., & Kovari, K. (1996). Face stability conditions with earth-pressure-balanced shields. *Tunnelling and Underground Space Technology*, 11(2), 165-173.
- Armour, T., Groneck, P., Keeley, J. and Sharma, S. (2000). Micropile Design and Construction Guidelines Implementation Manual. US *Department of Transport, Federal Highway Administration*, FHWA-SA-97-070.
- ASTM Standard D 2487. (2011). Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). ASTM International West Conshohocken, PA.USA.
- ASTM Standard D 3080. (2011). Standard Tect Method for Direct Shear Test of Soils Under Consolidated Drained Conditions. *ASTM International West Conshohocken, PA.USA*.

- ASTM Standard D 4253. (2010). Standard Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table. *ASTM International West Conshohocken, PA.USA.*
- ASTM Standard D 854. (2010). Specific Gravity of Soil Solid by Water Pycnometer. *ASTM International West Conshohocken, PA.USA.*
- ASTM Standard D422. (2010). Standard test method for particle-size analysis of soils. *ASTM International West Conshohocken, PA.USA.*
- Atkinson, J.H., Potts, D.M., and Schofield, A.N. (1977). Centrifugal model tests on shallow tunnels in sand. *Tunnels and Tunnelling*. 9(1): 59-64.
- Attewell, P.B., Yeates, J., and Selby. A.R. (1986). Soil Movements Induced by Tunnelling and their Effects on Pipelines and Structures. New York, Blackie.
- Augarde, C.E., Burd, H.J., Houlsby, G. T. (1998). Some experience of modelling tunnelling in soft ground using three-dimensional finite elements. Fourth *European conference on Numerical Methods in Geotechnical Engineering*. 14-16 October 1998. Udine, Italy. 603-612.
- Barnes, G., (2010). *Soil Mechanics Principles and Practice*. (Third Edition). *Palgrave Macmillan*.
- Berezantzev V.G., Khristoforv V.S. and Golubkov V.N. (1961). Load-bearing capacity and deformation of piled foundations, *Proc 5 th Int Conf on Soil Mech and Found Eng*, speciality session 10. 2:11-5.
- Bergado, D. T., Balasubramaniam, A. S. and Chai, J. C. (1994). Prediction of Behaviour of Reinforcement Embankment on Muar Clay Deposit. Prediction versus Performance in Geotechnical Engineering. Balkema, Rotterdam.
- Berthoz, N., Branque, D., Subrin, D., Wong, H., & Humbert, E. (2012). Face failure in homogeneous and stratified soft ground: theoretical and experimental approaches on 1g EPBS reduced scale model. *Tunnelling and Underground Space Technology*, 30, 25-37.
- Bezuijen, A. and van der Schrier, J.S. (1994). The influence of a bored tunnel on pile foundations. In: C. F. Leung, F. H. Lee & T. S.Tan(eds), *International Conference Centrifuge 94*, Singapore.
- Bilotta, E. (2008) "Use of diaphragm walls to mitigate ground movements induced by tunnelling," *Geotechnique*, 58, 143-155.

- Bilotta, E., Bitetti, B., McNamara, A.M., Taylor, R.N., (2006). Micropiles to reduce ground movements induced by tunnelling. *Physical modeling in geotechnics*, 1139-1144.
- Biswas, A., Dash, S.K., Murali Krishna, A. (2013) Influence of subgrade strength on the performance of geocell-reinforced foundation systems. *Geosynthetics International*. 20(6), 376–388.
- Bobet, A. (2001). Analytical Solutions for Shallow Tunnels in Saturated Ground. *Journal of Engineering Mechanics, ASCE*. 127(12): 1258-1266.
- Bolton, M.D., (1986). The strength and dilatancy of sands. *Géotechnique* 36, 65–78.
- Bolton, M.D., Dasari, G.R. and Britto, A.M. (1994). Putting small strain non-linearity into Modified Cam Clay model. *Proc. 8th Conf. Int. Assoc. Computer Methods and Advances in Geomechanics*, Morgantown. 537–542.
- Bradshaw, A. S. (2012). Framework for Scaling 1g Model Pile Tests for Offshore Wind Structures. *In GeoCongress*.
- British Standards Institution (1990). British Standard methods of test for soils for civil engineering purposes: Part 2,. London, BS1377.
- Brown, E. T., Bray, J. W., Ladanyi, B., and Hoek, E. (1983). Ground response curves for rock tunnels. *Journal of Geotechnical Engineering*, 109(1), 15-39.
- Bruce, D. A. (2002). The Basics of Drilling for Specialty Geotechnical Construction Processes. *Geotechnical Special Publications* 1: 752-771.
- Bruce, J., Ruel, M., Janes, M., Ansari, N. (2004). “Design and construction of a micropile wall to stabilize a railway embankment.” Proc. 29th, *Annual Conference on Deep Foundations, Vancouver, British Columbia, Canada*, 1-11.
- Burland J.B., Standing J.R., and Jardine F.M. (2001). Building Response to Tunneling. Case Studies from Construction of the Jubilee Line Extension, London, Vol. 1: Projects and Methods, Imperial College, SIRIA, London, United Kingdom.
- Cadden, A., Gómez, J., Bruce, D., Armour, T. (2004). Micropiles: Recent advances and future trends. *In Current Practices and Future Trends in Deep Foundations*, Los Angeles, CA, 140-165.
- Champan, D.N., Ahn, S.K., Hunt, D.V.L., Chan, H.C., (2006). The use of model tests to investigate the ground displacement associated with multiple tunnel construction in soil. *Tunnels & Tunneling*. 21(3), 413.

- Chen, L., Poulos, H. G., and Loganathan, N. (1999). Pile responses caused by tunneling. *Journal of Geotechnical and Geoenvironmental Engineering*. 125 (3), 207-215.
- Cheng C.Y. (2003). Finite element study of tunnel-soil-pile interaction (Doctoral dissertation, National University of Singapore).
- Cheng, C. Y., Dasari, G. R., Chow, Y. K., and Leung, C. F. (2006). Finite element analysis of tunnel-soil-pile interaction using displacement controlled model. *Tunn. Undergr. Space Technol.*, 22(4), 450–466.
- Cheng, C.Y., Dasari, G.R., Chow, Y.K., Leung, C.F. (2007). Finite element analysis of tunnel–soil–pile interaction using displacement controlled model. *Tunnelling and Underground Space Technology*. 22: 450–466.
- Chiang, K. H., & Lee, C. J. (2007). Responses of single piles to tunneling-induced soil movements in sandy ground. *Canadian Geotechnical Journal*. 44(10), 1224-1241.
- Chou, W. I., and Bobet, A. (2002). Prediction of Ground Deformations in Shallow Tunnels in Clay. *Tunnelling and Underground Space Technology*. 17: 3-19.
- Cording, E.J., and Hansmire, W.H. (1975). Displacement around soft ground tunnels. *Proceedings of the 5th Pan American Conference on Soil Mechanics and Foundation Engineering*. Session IV. Buenos Aires, Argentina. 571-632.
- Coutts, D. R., and Wang, J. (2000). Monitoring of reinforced concrete piles under horizontal and vertical loads due to tunnelling. *Tunnels and Underground Structures, Balkema, London*, 514-546.
- Coyle, H. M., and Castello, R. R. (1981). New design correlations for piles in sand. *Journal of Geotechnical and Geoenvironmental Engineering*, 107 (ASCE 16379).
- Das, B. M. (2007). Principles of foundation engineering. Cengage learning.
- Dasari, G.R., Rawlings, C.G., and Bolton, M.D. (1996). Numerical modelling of a NATM tunnel construction in London Clay. *Geotechnical Aspects of Underground Construction in Soft Ground*. Rotterdam, Balkema. 491–496.
- De Farias, M.M, Junior, A.H.M., de Assis, A.P. (2004). Displacement control in tunnels excavated by the NATM: 3-D numerical simulations. *Tunnelling and Underground Space Technology*. 19: 283–293.
- Deane, A. P. and Bassett, R. H. (1995). The Heathrow Express Trial Tunnel. *Proc. Inst. Civil Engineers*, Vol. 113, July, pp. 144-156.

- Devriendt M., Williamson M.. (2011). Validation of methods for assessing tunnelling-induced settlements on piles. *Ground Eng.* (2011), pp. 25–30
- Di Mariano, A., Persio, R., Gens, A., Castellanza, R., Arroyo, M. (2009). Influence of some EPB operation parameters on ground movements. *2nd International Conference on Computational Methods in Tunnelling*. 9-11 September 2009. Ruhr University Bochum, Aedificatio. 43-50.
- Divall, S. and Goodey, R.J. (2012). Apparatus for centrifuge modelling of sequential twin-tunnel construction. *International Journal of Physical Modelling in Geotechnics*. 12(3): 102-111.
- Divall, S., Goodey, R.J., Taylor, R.N., (2012). Ground movements generated by sequential twin-tunnelling in over-consolidated clay. *In 2nd European Conference on Physical Modelling in Geotechnics, Delft, The Netherlands*.
- Dolezalova, M. (2002). Approaches to numerical modelling of ground movements due to shallow tunnelling. *Soil structure interaction in urban civil engineering*. 2: 365-373.
- El Sawwaf, M. and Nazir, A.K. (2012). Cyclic settlement behavior of strip footings resting on reinforced layered sand slope. *Journal of Advanced Research*. 3(4), 315–324.
- EN 1997, Eurocode 7: Geotechnical Design.
- Finno, R. J., and Clough, G. W. (1985). Evaluation of Soil Response to EPB Shield Tunnelling. *Journal of Geotechnical Engineering, ASCE*. 111: 155-173.
- Franzius, J.K. (2003). Behaviour of buildings due to tunnel induced subsidence. PhD thesis. Imperial College of Science, Technology and Medicine.
- Franzius, J.N. (2004). Behaviour of buildings due to tunnel induced subsidence. PhD Thesis, Imperial College of Science, *Technology and Medicine, University of London*.
- Franzius, J.N., and Potts, D.M. (2005). Influence of mesh geometry on three-dimensional finite element analysis of tunnel excavation. *International Journal of Geomechanics, ASCE*. 5: 256-266.
- Franzius, J.N., Potts, D.M., and Burland, J.B. (2005). The influence of soil anisotropy and K_0 on ground surface movements resulting from tunnel excavation. *Geotechnique*. 55(3): 189-199.

- Franzius, Jan Niklas (2003). Behaviour of buildings due to tunnel induced subsidence. *Diss. University of London*.
- Fujita II, P.B., and Woodman, J.P. (1982). Predicting the dynamics of ground settlement and its derivatives caused by tunnelling in soils. *Ground Engineering*. 15(8): 13-22 and 36.
- Galli, G., Grimaldi, A., Leonardi, A. (2004). Three-dimensional modelling of tunnel excavation and lining. *Computers and Geotechnics*. 31: 171–183.
- Gens, A., Di Mariano, A., Gesto, J.M. & Schwartz, H. (2005). Ground movement control in the construction of a new metro line in Barcelona. In proc. 5th int. Symp. Geotech. Aspect of *underground construction in soft ground, Amsterdam* (Pre-print Volume)
- Ghahremannejad, B., Surjadinata, J., Poon, B. and Carter, J.P. (2006). Effects of tunnelling on model pile foundations. In: Proceedings of the 6th International Conference on Physical Modelling in Geotechnics, *ICPMG'06. Hong Kong*
- Gonzales, C. and Sagasetta, C. (2001). Patterns of soil deformations around tunnels: Application to the extension of Madrid Metro. *Comput. Geotech.* 28:445-68.
- Guedes, P.F.M., Santos Pereira, C. (2000). The role of the soil K_0 value in numerical analysis of shallow tunnels. *Proceeding of the International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground*. Rotterdam, Balkema. 379-384.
- Gui, M.W., and Chen, S.L. (2013). Estimation of transverse ground surface settlement induced by DOT shield tunneling. *Tunnelling and Underground Space Technology*. 33: 119–130.
- Gunn, M.J. (1993). The prediction of surface settlement profiles due to tunnelling. *Proceeding of the Worth Memorial Symposium, Predictive Soil Mechanics*. London: Thomas Telford. 304-316.
- Hajihassani, M. (2013). Tunneling-induced ground movement and building damage prediction using hybrid artificial neural networks. (Doctoral dissertation, PhD Thesis, Universiti Teknologi Malaysia).
- He, C., Feng, K., Fang, Y., Jiang, Y.C., (2012). Surface settlement caused by twin-parallel shield tunnelling in sandy cobble strata. *Journal of Zhejiang University SCIENCE A*, 13(11), 858-869.

- Hight, D.W., Gasparre, A., Nishimura, S., Minh, N.A., Jardine, R.J., and Coop, M.R. (2007). Characteristics of the London clay from the Terminal 5 site at Heathrow airport. *Geotechnique*. 57(1): 3–18.
- Hoek, E., Carranza-Torres, C., Diederichs, M.S., Corkum, B., (2008). Integration of geotechnical and structural design in tunnelling. In: *Proceedings University of Minnesota 56th Annual Geotechnical Engineering Conference*, Minneapolis, pp. 1–53.
- Huang, M., Zhang, C. and Li, Z. (2009). A simplified analysis method for the influence of tunneling on grouped piles. *Tunneling and Underground Space Technology*, 24, 410-422.
- ISSMFE, (1985). Axial pile loading test – part 1: static loading. *Geotech. Test. J.* 8, 79–90.
- Jacobsz, S. W., Standing, J. R., and Mair, R. J. (2004). Tunnelling effects on pile groups in sand. In *Advances in geotechnical engineering: The Skempton conference: Proceedings of a three day conference on advances in geotechnical engineering, organised by the Institution of Civil Engineers and held at the Royal Geographical Society, London, UK, Thomas Telford Publishing*. 1056-1067.
- Jacobsz, S.W., Bowers, K.H. & Moss, N.A. & Zanardo, G. (2005). The influence of tunnelling on piled foundations. *Proc. 16th International Conference on Soil Mechanics and Geotechnical Engineering*, 1611–1614, Osaka.
- Jacobsz, S.W., Standing, J.R., Mair, R.J., Hahiwara, T., Suiyama, T., (2004). Centrifuge modeling of tunnelling near driven piles. *Soil Found.* 44 (1), 49–56.
- Janbu (1976). Static bearing capacity of friction pile. *proceedings, sixth European Conference on Soil Mechanics and Foundation Engineering*. 1.2, 479-482.
- Janbu, N. (1976). Static bearing capacity of friction piles. In *Sechste Europaeische Konferenz Fuer Bodenmechanik Und Grundbau* (Vol. 1).
- Józefiak, K., Zbiciak, A., Maślakowski, M., & Piotrowski, T. (2015). Numerical modelling and bearing capacity analysis of pile foundation. *Procedia Engineering*, 111, 356-363.
- Juneja, A., Dutta, S., (2008). Ground loss due to circular tunnel deformation in sands. The 12th International Conference of International Association for Computer Methods and Advances in Geomechanics, India

- Juran, I., Bruce, D. A., Dimillio, A. F., & Benslimane, A. (1999). Micropiles: the state of practice. Part II: design of single micropiles and groups and networks of micropiles. *Proceedings of the ICE-Ground Improvement*, 3(3), 89-110.
- Kaalberg, F. J., Lengkeek, H. J. and Teunissen, E.A. H. (1999). Evaluatie van de meetresultaten van het proefpalenproject ter plaatse van de tweede Heinenoordtunnel (in Dutch). Adviesbureau Noord/Zuidlijn Report no. R981382, Amsterdam.
- Kaalberg, F.J., Teunissen, E.A., van Tol, A.F., and Bosch, J.W. (2005). Dutch research on impact of shield tunneling on pile foundation. In *Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering*, Osaka, Japan. Vol. 3, pp. 1615-1620
- Karakus, M. (2001). Predicting horizontal movement for a tunnel by empirical and FE methods. *17th International Mining Congress and Exhibition of Turkey*. Turkey. 697-703.
- Karakus, M. (2007). Appraising the methods accounting for 3D tunnelling effects in 2D plane strain FE analysis. *Tunnelling and Underground Space Technology*. 22: 47–56.
- Karakus, M and Fowell, R.J. (2003). Effects of different tunnel face advance excavation on the settlement by FEM. *Tunnelling and Underground Space Technology*. 18: 513–523.
- Kasper, T., and Meschke, G. (2004). A 3D finite element simulation model for TBM tunnelling in soft ground. *International journal for Numerical and Analytical in Geomechanics*. 28: 1441–1460.
- Kasper, T., and Meschke, G. (2006). A numerical study of the effect of soil and grout material properties and cover depth in shield tunnelling. *Computers and Geotechnics*. 33: 234–247.
- Katzenbach, R., and Breth, H. (1981). Nonlinear 3D analysis for NATM in Frankfurt Clay. *Proceeding of 10th International Conference on Soil Mechanics and Foundation Engineering*, Rotterdam, Balkema, 315-318.
- Khari, M., Kassim, K. A., & Adnan, A. (2014). Sand samples' preparation using mobile pluviator. *Arabian Journal for Science and Engineering*, 39(10), 6825-6834.

- Kimura, T., & Mair, R. J. (1981). Centrifugal testing of model tunnels in soft clay. In Proceedings of the 10th international conference on soil mechanics and foundation engineering (pp. 319-322). ISSMFE: *International Society for Soil Mechanics and Foundation Engineering*.
- King, G.J.W., Dickin, E.A., and Lyndon, A. (1984). The development of a medium size centrifugal testing facilities. *Proceedings of The Application of Centrifuge Modeling to Geotechnical Design, Manchester, England*, 24-46.
- Kitiyodom P., Matsumoto T., Kawaguchi K. (2005). A simplified analysis method for piled raft foundations subjected to ground movements induced by tunneling. *Int. J. Numer. Anal. Meth. Geomech.*, 29 (15) (2005), pp. 1485–1507 ISSN 1096-9853
- Komiya, K., Soga, K., Akagi, H., Hagiwara, T., Bolton, M.D. (1999). Finite element modelling of excavation and advancement process of a shield tunnelling machine. *Soils and Foundation*. 39(3): 37-52.
- Kulhawy, F. H. (1984). Limiting tip and side resistance: fact or fallacy. *In Analysis and Design of Pile Foundations*: (pp. 80-98). ASCE.
- Lake, L. M., Rankin, W. J., and Hawley, J. (1992). Prediction and effects of ground movements caused by tunneling in soft ground beneath urban areas. CIRIA Project Rep. 30, *Construction Industry Research and Information Association*, London.
- Latha, G.M., Dash, S.K. and Rajagopal, K. (2010). Numerical Simulation of the Behavior of Geocell Reinforced Sand in Foundations. *International Journal of Geomechanics*. 9(4),143–152.
- Leca, E. (1996). Modelling and prediction for bored tunnels. *International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground*, 15-17 April, London. 27-41.
- Lee, C. J., Jacobsz, S. W. (2006). The influence of tunnelling on adjacent piled foundations. *Tunnelling and Underground Space Technology* 21(3):430-430.
- Lee, C.J., and Chiang, K.H., (2007). Responses of single piles to tunnelling-induced soil movements in sandy ground. *Canadian Geotechnical Journal*, 44(10), 1224-1241.
- Lee, C.J., Chiang, K.H., Kuo, C.M. (2004). Ground movements and tunnel stability when tunnelling in sandy ground, *Journal of the Chinese Institute of Engineers*. 27(7): 1021-1032.

- Lee, C.J., Wu, B.R., Chen, H.T., Chiang, K.H. (2006). Tunnelling stability and arching effects during tunnelling in soft clayey soil. *Tunnelling and Underground Space Technology*. 21(2): 119–132.
- Lee, G.T.K. and Ng, W.W.C. (2005). Effects of advancing open face tunnelling on an existing loaded pile, *Journal of Geotechnical and Geoenvironmental Engineering*. ASCE, Vol. 131(2), 193 – 201.
- Lee, G.T.K., Ng, C.W.W. (2002). Three-dimensional analysis of ground settlements due to tunnelling: Role of K_0 and stiffness anisotropy. *Proceeding of the International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground*. Lyon, Specifique. 617-622.
- Lee, K.M., and Rowe, R.K. (1989). Deformations caused by surface loading and tunnelling: the role of elastic anisotropy. *Geotechnique*. 39(1): 125-140.
- Lee, K.M., Rowe, R.K., and Lo, K.Y. (1992). Subsidence owing to tunnelling. I: estimating the gap parameter. *Canadian Geotechnical Journal*. 29: 929-940.
- Lee, R. G., Turner, A. J., & Whitworth, L. J. (1994). Deformations caused by tunnelling beneath a piled structure. *In proceedings of the international conference on soil mechanics and foundation engineering-international society for soil mechanics and foundation engineering* (vol. 3, pp. 873-873).
- Lee, S.W., Choy, C.K.M., Cheang, W.W.L., Swolfs, W., and Brinkgreve, R. (2010). Modelling of tunnelling beneath a building supported by friction bored piles. *The 17th Southeast Asian Geotechnical Conference*, 215-218.
- Lee, Y. J., and Bassett, R. H. (2007). Influence zones for 2D pile–soil-tunnelling interaction based on model test and numerical analysis. *Tunnelling and underground space technology*, 22(3), 325-342.
- Litwiniszyn, J. (1956). Application of the Equation of Stochastic Processes to Mechanics of Loose Bodies. *Arch. Mech. Stosow*. 8: 393-411.
- Liu, B., and Han, Y. (2006). A *FLAC*^{3D}-based subway tunneling-induced ground settlement prediction system developed in China. *4th International FLAC Symposium on Numerical Modeling in Geomechanics*.
- Liu, H.Y., Small, J.C. and Carter, J.P. (2008), “Full 3D modelling for effects of tunnelling on existing support systems in the Sydney region”, *Tunnelling and Underground Space Technology* 23, 399-420.

- Liu, J., Qi, T., Wu, Z. (2012). Analysis of ground movement due to metro station driven with enlarging shield tunnels under building and its parameter sensitivity analysis. *Tunnelling and Underground Space Technology*, 28: 287–296.
- Lizzi, F. (1982). The static restoration of monuments. International Society for Micropiles & *The International Association of Foundation Drilling*.
- Loganathan, N., and Poulos, H. G. (1998). Analytical prediction for tunneling-induced ground movements in clays. *Journal of Geotechnical and Geoenvironmental Engineering*, 124(9), 846-856.
- Loganathan, N., Poulos, H.G., Stewart, D.P., (2000). Centrifuge model testing of tunnelling-induced ground and pile deformations. *Geotechnique*, 50(3), 283-294.
- Mair, R.J., Taylor, R.N., Bracegirdle, A. (1993). Subsurface settlement profiles above tunnels in clays. *Geotechnique*. 43(2): 315–320.
- Mair, RJ and Williamson, MG (2014). The influence of tunnelling and deep excavation on piled foundations. Geotechnical Aspects of Underground Construction in Soft Ground - Proceedings of the 8th Int. *Symposium on Geotechnical Aspects of Underground Construction in Soft Ground*, TC204 ISSMGE - IS-SEOUL 2014. pp. 21-30.
- Marshall, A.M. and Haji, T. (2015). "An analytical study of tunnel-pile interaction." *Tunnelling and Underground Space Technology*, vol. 45, pp. 43-51.
- Marshall, A.M., (2012). Tunnel-pile interaction analysis using cavity expansion methods *Journal of Geotechnical and Geoenvironmental Engineering*. 138(10), 1237–1246
- Marshall, A.M., (2013). Closure to tunnel–pile interaction analysis using cavity expansion methods by Alec M. Marshall, *ASCE J. Geotech. Geoenviron. Eng.*, 139 (11) (2013), pp. 2002–2004
- McClelland, B. (1974). Design of deep penetration piles for ocean structures. *J. Geotech. Eng. Div., Am. Soc. Civ. Eng.*; (United States), 100.
- Meguid, M. A., Saada, O., Nunes, M. A., Mattar, J. (2008). Physical modeling of tunnels in soft ground: A review. *Tunnelling and Underground Space Technology*. 23: 185–198.
- Meguid, M.A. and Mattar J. (2009) An investigation of tunnel-soil-pile interaction in cohesive soils. *ASCE's Journal of Geotechnical and Geoenvironmental Engineering*, 135(7), 973-979

- Meguid, M.A., Mattar, J., Nunes, M. Saxe, S. (2009). On the physical modelling of tunnels in soft ground. *59th Canadian Geotechnical Conference*, Vancouver, British Columbia.
- Meng, C. W. (2016). Singapore Case Histories on Performance of Piles Subjected to Tunnelling-Induced Soil Movement.
- Meyerhof, G. G., & Hanna, A. M. (1978). Ultimate bearing capacity of foundations on layered soils under inclined load. *Canadian Geotechnical Journal*, 15(4), 565-572.
- Moghaddas Tafreshi, S.N. and Dawson, a. R. (2012). A comparison of static and cyclic loading responses of foundations on geocell-reinforced sand. *Geotextiles and Geomembranes*. 32,55–68.
- Mohamad, H., Soga, K., Pellew, A., and Bennett, P. J. (2011). Performance monitoring of a secant-piled wall using distributed fiber optic strain sensing. *Journal of Geotechnical and Geoenvironmental Engineering*, 137(12), 1236-1243.
- Mohamad, H. (2012). Assessment of building performance under ground movement due to tunnel construction. (Doctoral dissertation, PhD Thesis, Universiti Teknologi Malaysia).
- Möller, S.C. and Vermeer, P.A. (2008). On numerical simulation of tunnel installation. *Tunnelling and Underground Space Technology*. 23: 461–475.
- Möller, S.C., Vermeer, P.A., Bonnier, P.G. (2003). A fast 3D tunnel analysis. Proceeding of 2nd MIT Conference on Computational Fluid and Solid Mechanics. 17-20 June. The Netherlands, Amsterdam. 486–489.
- Morton, J. D., and King, K. H. (1979). Effects of tunneling on the bearing capacity and settlement of piled foundations. *In Proc. Tunnelling*, Vol. 79, pp. 57-58.
- Mroueh, H., and Shahrour, I. (2002). 3D finite element analysis of the interaction between tunneling and pile foundations. *International Journal for Numerical and Analytical Methods in Geomechanics*. 26: 217-230
- Mroueh, H., and Shahrour, I. (2008). A simplified 3D model for tunnel construction using tunnel boring machines. *Tunnelling and Underground Space Technology*. 23: 38–45.
- Namazi, E., and Mohamad, H. (2012). Potential damage assessment in buildings undergoing tilt. *Proceedings of the ICE - Geotechnical Engineering*.

- Namazi, E., and Mohamad, H. (2012). Assessment of building damage induced by three-dimensional ground movements. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE. Accepted Manuscript.
- Ng, C. W. W., Lu, H., & Peng, S. Y. (2013). 3D centrifuge modelling of the effects of twin tunnelling on an existing pile. *Tunnelling and Underground Space Technology*, 35, 189-199.
- Ng, C. W. W., Soomro, M. A., & Hong, Y. (2014). 3D centrifuge modelling of pile group responses to side-by-side twin tunnelling. *Tunnelling and Underground Space Technology*, 43, 350-361.
- Ng, C. W. W., Soomro, M. A., & Hong, Y. (2014). 3D centrifuge modelling of pile group responses to side-by-side twin tunnelling. *Tunnelling and Underground Space Technology*, 43, 350-361.
- Ng, C. W. W., Yau, T. L. Y., Li, J. H. M., and Tang, W. H. (2001). "New failure load criterion for large diameter bored piles in weathered geomaterials". *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 127 (6): 488-498.
- Ng, C.W. (2014). The state-of-the-art centrifuge modelling of geotechnical problems at HKUST. *Journal of Zhejiang University SCIENCE A*, 15(1), 1-21.
- Ng, C.W. (2014). The state-of-the-art centrifuge modelling of geotechnical problems at HKUST. *Journal of Zhejiang University SCIENCE A*, 15(1), 1-21.
- Ng, C.W.W., Lu, H., and Peng, S.Y. (2013). 3D centrifuge modelling of the effects of twin tunnelling on an existing pile. *Tunnelling and Underground Space Technology*, 35, 189-199.
- Ng, C.W.W., Lu, H., Peng, S.Y., (2013). Three-dimensional centrifuge modelling of the effects of twin tunnelling on an existing pile. *Tunnelling and Underground Space Technology*, 35, 189-199.
- Ng, C.W.W., Yau, T.L.Y., Li, J.H.M., Tang, W.H., (2001). New failure load criterion for large diameter bored piles in weathered geomaterials. *J. Geotech. Geoenviron. Eng.*, ASCE 127 (6), 488-498.
- Ng, C.W.W., Yau, T.L.Y., Li, J.H.M., Tang, W.H., (2001a). New failure load criterion for large diameter bored piles in weathered geomaterials. *J. Geotech. Geoenviron. Eng.*, ASCE 127, 488-498.

- Nomoto, T., Imamura, S., Hagiwara, T., Kusakabe, O., Fujii, N., (1999). Shield tunnel construction in centrifuge. *Journal of geotechnical and geoenvironmental engineering*, 125(4), 289-300.
- Nomoto, T., Mito, K., Imamura, S., Ueno, K. & Kusakabe, O. (1994). A miniature shield tunnelling machine for a centrifuge. *Centrifuge '94*, 699–704.
- O'Neill, M. W. and L. C. Reese. (1999). *Drilled Shafts: Construction Procedures and Design*
- O'Reilly, M.P., and New, B.M. (1982). Settlements above tunnels in the united kingdom- their magnitude and prediction. *Proceeding of tunnelling 82*. The institution of mining and metallurgy, London. 173-181.
- Oblozinsky P, Kuwano J (2004). Centrifuge experiments on stability of tunnel face. *Slovak J Civil Eng* 3:23–29.
- Ong, C. W. , Leung, C. F. , Yong, K. Y. , and Chow, Y. K. (2007). “Performance of pile due to tunneling-induced soil movements.” Proc., *33rd ITA–AITES World Tunnel Congress—Underground Space—4th Dimension of Metropolises*, Vol. 1 ,CRC Press, Boca Raton, FL, 619–624.
- Ong, C.W., Leung, C.F., Yong, K.Y., Chow, Y.K., (2006). Pile responses due to tunnelling in clay. *Physical Modelling in Geotechnics-6th ICPMG*, London, pp. 1177-1182.
- Ovesen, N.K. (1981) : Centrifuge tests of the uplift capacity of anchors. 10th ICSMFE, Stockholm, pp. 717 – 722.
- Park, K. H. (2005). Elastic Analytical Solution for Tunnelling-Induced Ground Movement in Clays. *Tunnelling and Underground Space Technology*. 20: 249-261.
- Park, K.H. (2004). Elastic solution for tunnelling-induced ground movements in clays. *International Journal of Geomechanics, ASCE*. 4(4): 310-318.
- Park, S.H., Adachi, T., (2002). Laboratory model tests and FE analyses on tunneling in the unconsolidated ground with inclined layers. *Tunnelling and underground space technology*, 17(2), 181-193.
- Peck, R. B. (1969). Deep excavations and tunnelling in soft ground. Pages 225-290 of proc of the 7th int. Conference on soil mechanics and foundation engineering. State of the art volume. *Sociaded Mexician de Mecanica de Suelos*, A. C.

- Peck, R.B. (1969). Deep excavations and tunnelling in soft ground. *Proceedings of the 7th international conference on soil mechanics and foundation engineering*. State of the art volume. Mexico City. 225-290.
- Petrukhin V.P., Shuljatjev, O. V., Mozgacheva, O. A (2006). Vertical geotechnical barrier erected by compensation grouting. *Geotechnica aspects of underground construction in soft ground*, Bakker et al, London, ISBN 0414391245.
- Pickhaver, J. A. (2006). Numerical modelling of building response to tunnelling. University of Oxford.
- Pinto, F. and Whittle, A. J. (2006). Discussion of elastic solution for tunnelling-induced Ground movements in clays by K. H. Park. *International Journal of Geomechanics, ASCE*. 72-76.
- PN-83/B-02482, Foundationsc (1983). Bearing capacity of piles and pile foundations., *Polish Committee for Standardization*.
- Potts, D.M., and Zdravkovic, L. (1999). *Finite element analysis in geotechnical engineering application*. London: Thomas Telford.
- Reese, L. C., & O'Neill, M. W. (1989). New design method for drilled shafts from common soil and rock tests. In *Foundation Engineering: Current principles and practices* (pp. 1026-1039). ASCE.
- Rowe, R. K., and Kack, G. J. (1983). A Theoretical Examination of the Settlements Induced by Tunnelling: Four Case Histories. *Canadian Geotechnical Journal*. 20: 229-314.
- Sagaseta, C. (1987). Analysis of Undrained Soil Deformations Due to Ground Loss. *Geotechnique*. 37(3): 301-320.
- Sagaseta, C. (1987). Analysis of Undrained Soil Deformations Due to Ground Loss. *Geotechnique*. 37(3): 301-320.
- Schanz, T., & Vermeer, P. A. (1998). On the stiffness of sands. *Géotechnique*, 48, 383-387.
- Li J. (2008) Case study of movement and damage to a residential building founded on expansive clays. *Geotechnical Engineering for Disaster Mitigation and Rehabilitation: Proc. 2nd Int. Conf., GEDMAR 08, Nanjing, China, 2008*, pp. 659–694.
- Schikora, K., Ostermeier, B. (1988). Two-dimensional calculation model in tunnelling- Verification by measurement results and by spatial calculation.

- Proceeding of 6th International Conference on Numerical Methods in Geomechanics*, Innsbruck. 1499-1503.
- Schmidt, B. (1969). Settlements and ground movements associated with tunnelling in soil. Ph.D. thesis, University of Illinois.
- Schuller, H., Schweiger, H.F. (2002). Application of a multilaminate model to simulation of shear band formation in NATM-tunnelling. *Computers and Geotechnics*. 29: 501–52.
- Selemetas, D., Standing, J. R., & Mair, R. J. (2005). The response of full-scale piles to tunnelling. In Proc. of the Fifth Int. *Symposium on Geotechnical Aspects of Underground Construction in Soft Ground*, Amsterdam.
- Sitharam, T. G. and Sireesh, S. (2012) “Behavior of Embedded Footings Supported on Geogrid Cell Reinforced Foundation Beds. *Geotechnical Testing Journal*. 28(5), 1–12.
- Stallebrass, S.E. and Taylor, R.N. (1997). Prediction of ground movements in over consolidated clay. *Geotechnique*. 47(2): 235–253.
- Stallebrass, S.E., Jovicic, V. and Taylor, R.N. (1994). The influence of recent stress history on ground movements around tunnels. *Prefailure Deformation of Geomaterials*, Balkema. 1: 612-620.
- Standing, J.R, and Burland J.B. (2006). Unexpected tunnelling volume losses in the Westminster area, London. *GEOTECHNIQUE*. 56: 11-26.
- Strack, O.E. and Verruijt, A. (2002). A complex variable solution for a deforming buoyant tunnel in a heavy elastic half-plane. *International Journal for Numerical and Analytical Methods in Geomechanics*. 26: 1235-1252.
- Sun, J., Liu, J., (2014). Visualization of tunnelling-induced ground movement in transparent sand. *Tunnelling and Underground Space Technology*, 40, 236-240.
- Swoboda, G. (1979). Finite Element Analysis of the New Austrian Tunnelling Method (NATM). *Proceeding of 3rd International Conference on Numerical Methods in Geomechanics*. Aachen. 2: 581-586.
- Tan, T. S., Setiaji, R. R., and Hight, D. W. (2005). Numerical analyses using commercial software– A black box. *Proceedings of Underground Singapore*. pp. 250-258.
- Tang, D.K.W., Lee, K.M., Ng, C.W.W. (2000). Stress paths around a 3-D numerically simulated NATM tunnel in stiff clay. *Proceeding of the International*

Symposium on Geotechnical Aspects of Underground Construction in Soft Ground. Rotterdam, Balkema. 443-449.

- Tatlisoz, N., Edil, T.B. and Benson, C.H. (1998). Interaction between reinforcing geosynthetics and soil–tire chip mixtures. *Journal of Geotechnical and Geoenvironmental Engineering*. 124 (11), 1109–1119.
- Terzaghi, K. (1942). Discussion of the progress report of the committee on the bearing value of pile foundations. *In Proceedings of the American Society of Civil Engineers* (Vol. 68, No. 2, pp. 311-323).
- Tham, K. S., and M. S. Deutscher. "Tunnelling Under Woodleigh Workers' Quarters on Contract 705." ZHAO J, SHIRLAW JN, KRISHNAN R. *Tunnels and Underground Structures*. Rotterdam: Balkema AA (2000): 241-248.
- Theinat, A. K. (2015). 3D numerical modelling of micropiles interaction with soil & rock.
- Timoshenko, S.P., and Goodier, J.N. (1997). *Theory of Elasticity*. McGraw-Hill, New York, NY.
- Uriel, A.O, and Sagasetta C. (1989). Selection on design parameters for underground construction. *Proc. of the 12th international congress on soil mechanics*, Riode Janeiro, Vol. 9. Rotterdam: A.A. Balkema. 2521–2551.
- Vermeer, P.A., Bonnier, P.G., Möller, S.C. (2002). On a smart use of 3D-FEM in tunnelling. *Proceedings of the 8th international symposium on numerical models in geomechanics*. Rotterdam, Balkema. 361-366.
- Verruijt, A, and Booker, J. R. (1996). Surface Settlement Due to Deformation of a Tunnel in an Elastic Half Plane. *Geotechnique*. 46(4): 753-756.
- Wang, Z., Wong, R.C.K., Li, S., and Qiao, L. (2012). Finite element analysis of long-term surface settlement above a shallow tunnel in soft ground. *Tunnelling and Underground Space Technology*. 30: 85-92.
- Williamson, M.G. (2014). Tunnelling effects on bored piles in clay, Ph.D. thesis, University of Cambridge, UK.
- Wong, K.S., Ng, C.W.W., Chen, Y.M., Bian, X.C., (2012). Centrifuge and numerical investigation of passive failure of tunnel face in sand. *Tunnelling and Underground Space Technology*, 28, 297-303.
- Wood, D. M. (2004). Geotechnical modelling. Vol. 2. CRC Press.

- Wu, B.R., Lee, C.J., (2003). Ground movements and collapse mechanisms induced by tunneling in clayey soil. *International Journal of Physical Modelling in Geotechnics*, 3(4), 15-29.
- Yang, J.S., Liu, B.C., and Wang, M.C. (2004). Modeling of tunneling-induced ground surface movements using stochastic medium theory. *Tunnelling and Underground Space Technology*. 19: 113–123.
- Yao, G., Li, J., and Chu, F. (2009). Numerical Analysis for the Influence of Bored Piles on Adjacent Tunnels. *Contemporary Topics in In Situ Testing, Analysis, and Reliability of Foundations*: pp. 143-150.
- Zhang J.R., Zhang, J., Lok, T.M., and Lyu, M.R. (2007). A hybrid particle swarm optimization–back-propagation algorithm for feedforward neural network training. *Applied Mathematics and Computation*. 185: 1026–1037.
- Zidan, A. and Ramadan, O. (2015). Three dimensional numerical analysis of the effects of tunnelling near piled structures. *KSCE Journal of Civil Engineering*, 10.1007/s12205-014-0741-6, 917-928.