Continuum-Based Numerical Simulation of
Static and High-Strain Dynamic Pile Load
Testing Adopting Advanced Soil Models

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

DOCTOR OF PHILOSOPHY

School of Civil and Environmental Engineering
Faculty of Engineering and Information Technology
Feb 2019
Certificate of Original Authorship

I, **Mehdi Aghayarzadeh**, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis. This document has not been submitted for qualifications at any other academic institution. This Research is supported by the Australian Government Research Training Program.

**Production Note:**

**Signature:**  Signature removed prior to publication.

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## CONTENTS

**ACKNOWLEDGEMENT** iii  
**LIST OF RESEARCH PAPERS** iv  
**CONTENTS** v  
**LIST OF FIGURES** ix  
**LIST OF TABLES** xvi  
**NOTATIONS** xvii  
**ABSTRACT** xxiii

### CHAPTER 1  INTRODUCTION ................................................................. 1  
1.1 BACKGROUND AND PROBLEM STATEMENT .............................................. 1  
1.2 SCOPE AND OBJECTIVES ............................................................................. 5  
1.3 THESIS OUTLINE .......................................................................................... 6

### CHAPTER 2  LITERATURE REVIEW ...................................................... 9  
2.1 PILE LOAD TESTING OVERVIEW ............................................................. 10  
2.2 CLASSIFICATION OF PILES ........................................................................ 12  
2.3 STATIC PILE LOAD TESTING ...................................................................... 20  
  2.3.1 Static Pile Load Testing Procedure ....................................................... 23  
  2.3.2 Interpretation of Test Results ............................................................... 24  
2.4 DYNAMIC PILE LOAD TESTING ............................................................. 26  
  2.4.1 Proportionality Concept ....................................................................... 29  
  2.4.2 CAPWAP Background ................................................................. 30  
  2.4.3 CAPWAP Model ............................................................................... 36  
2.5 CONSTITUTIVE SOIL MODELS .............................................................. 39  
  2.5.1 Mohr-Coulomb Model (MC Model) .................................................. 39  
  2.5.2 Hardening Soil Model (HS Model) ...................................................... 42  
  2.5.3 Hardening Soil with Small Strain Stiffness Model (HS-Small Model) .... 43
2.5.4 Hypoplastic with Intergranular Strain Model (HP-IGS Model).......................... 45

2.6 REMARKABLE STUDIES ON PILE LOAD TESTING............................................ 48

2.6.1 Static Pile Load Testing: Numerical and Experimental Studies..................... 48

2.6.2 Dynamic pile load testing: numerical, experimental and analytical studies .... 55

2.7 GAP AND LIMITATIONS IN CURRENT LITERATURE ........................................ 68

CHAPTER 3 STATIC PILE LOAD TESTING: NUMERICAL SIMULATION OF SINGLE PILE AND PILES

GROUP BEHAVIOURS ................................................................................................. 70

3.1 SYNOPSIS ............................................................................................................ 70

3.2 INTRODUCTION .................................................................................................... 71

3.3 NUMERICAL SIMULATION PROCEDURE ............................................................ 73

3.4 SINGLE BORED PILE INTO DENSE AND LOOSE SAND DEPOSITS ..................... 75

3.4.1 Overview ........................................................................................................... 75

3.4.2 Results and Discussion ...................................................................................... 77

3.5 INTERACTION OF REACTION PILES ON TEST PILE ........................................... 83

3.5.1 Overview ........................................................................................................... 83

3.5.2 Results and Discussion ...................................................................................... 87

3.6 CONCRETE PILE GROUPS RESPONSE BORED IN CEMENTED SAND DEPOSIT .... 99

3.6.1 Overview ........................................................................................................... 99

3.6.2 Results and Discussion ...................................................................................... 105

3.7 SUMMARY .......................................................................................................... 114

CHAPTER 4 CASE METHOD AND ONE-DIMENSIONAL WAVE PROPAGATION INDUCED BY DYNAMIC

PILE LOAD TESTING: THEORY, CONCEPT, AND APPLICATION IN A REAL CASE PROJECT ........ 116

4.1 SYNOPSIS ............................................................................................................ 116

4.2 INTRODUCTION .................................................................................................... 117

4.3 BACKGROUND ...................................................................................................... 118

4.3.1 Total and Static Soil Resistance ................................................................. 119

4.3.2 CASE Damping Factor .................................................................................. 126
4.3.3 Pile Driving Stresses.......................................................................................................... 128
4.3.4 Hammer/Driving System .................................................................................................. 128
4.3.5 Total and Static Shaft Resistance ..................................................................................... 129
4.4 CASE STUDY................................................................................................................................... 131
4.5 SUMMARY..................................................................................................................................... 139

CHAPTER 5 DYNAMIC PILE LOAD TESTING: NUMERICAL SIMULATION, INTERPRETATION OF THE
RESULTS, AND ASSESSMENT OF GROUND VIBRATION INDUCED BY DYNAMIC TEST .................142

5.1 SYNOPSIS ................................................................................................................................... 142
5.2 INTRODUCTION ............................................................................................................................... 144
5.3 NUMERICAL SIMULATION PROCEDURE ..................................................................................... 149
5.4 CONCRETE PILE DRIVING IN SATURATED DENSE AND LOOSE SAND DEPOSITS ......................151
5.4.1 Overview...................................................................................................................................... 151
5.4.2 Results and Discussion ............................................................................................................ 152
5.5 ONE-DIMENSIONAL WAVE PROPAGATION IN FINITE ELEMENT PROGRAM ............................166
5.5.1 Overview...................................................................................................................................... 166
5.6 OPEN-ENDED STEEL PIPE PILE DRIVEN IN DENSE SAND DEPOSIT ....................................167
5.6.1 Overview...................................................................................................................................... 167
5.6.2 Results and Discussion............................................................................................................ 170
5.7 OPEN-ENDED STEEL PIPE PILE DRIVEN IN MULTILAYER SOIL ............................................176
5.7.1 Overview...................................................................................................................................... 176
5.7.2 Results and Discussion............................................................................................................ 183
5.7.3 Impact of Interface and Stiffness Degradation Parameters .....................................................196
5.8 GROUND VIBRATION INDUCED BY DYNAMIC PILE LOAD TESTING ........................................200
5.8.1 Overview...................................................................................................................................... 200
5.8.2 Allowable Ground Vibration ................................................................................................. 205
5.8.3 Results and Discussion............................................................................................................ 210
5.9 SUMMARY..................................................................................................................................... 215

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH ......................217
6.1 SUMMARY .......................................................................................................................................................... 217
6.2 CONCLUSIONS ...................................................................................................................................................... 219
  6.2.1 Static Pile Load Testing: Numerical Simulation of Single Pile and Piles Group Behaviour 219
  6.2.2 CASE Method: Theory, Concept and Application in a Real Case Project................................. 221
  6.2.3 Dynamic Pile Load Testing: Numerical Simulation, Interpretation of the Results, and
       Assessment of Ground Vibration Induced by Dynamic Testing...................................................... 221
6.3 RECOMMENDATIONS FOR FUTURE RESEARCH.............................................................................................. 223

REFERENCES .......................................................................................................................................................... 226

APPENDICES ......................................................................................................................................................... 243
LIST OF FIGURES

FIGURE 1.1 APPLICATION OF ADVANCED SOIL MODELS IN ACCURATE PREDICTION OF SOIL BEHAVIOUR DURING STATIC AND DYNAMIC PILE LOAD TESTING ...................................................................................................................... 4

FIGURE 2.1 CLASSIFICATION OF PILES BASED ON VARIOUS FACTORS ........................................................................................................... 12

FIGURE 2.2 CAST-IN-PLACE CONCRETE PILES (GARY PUNTMAN 2018) ........................................................................................................ 13

FIGURE 2.3 DRIVEN STEEL PIPE PILES AND THE MEASUREMENT OF SOIL PLUG LENGTH (AFTER FATTAH & AL-SOUDANI 2016) .......................................................................................................................................................... 15

FIGURE 2.4 DRIVING SHOE, WHICH IS WELDED AT THE PILE TOE (ESC GROUP 2018) ................................................................. 16

FIGURE 2.5 CLOSED-ENDED STEEL PIPE PILE (PILE BUCK 2018) ................................................................................................. 16

FIGURE 2.6 DIFFERENT STAGES OF SOIL PLUGGING: (A) UNPLUGGED (B) PARTIALLY PLUGGED AND (C) FULLY PLUGGED. X ILLUSTRATES THE PENETRATION DISTANCE OF THE PILE (AFTER KARLOWSKIS 2014) ............................................................................................................. 18

FIGURE 2.7 DIAGRAM OF COMPRESSION LOAD TEST SETUP USING KENTLEDGE SYSTEM (DUTCH INTERNATIONAL 2017) ..... 22

FIGURE 2.8 SCHEMATIC OF HYDRAULIC JACK ACTING AGAINST ANCHORED REACTION FRAME (AFTER ASTM INTERNATIONAL 2013) ................................................................................................................................................. 22

FIGURE 2.9 TYPICAL LOAD-DISPLACEMENT CURVE AND THE OFFSET LIMIT METHOD .............................................................. 25

FIGURE 2.10 (A) TYPICAL DYNAMIC PILE TEST SET-UP (B) DYNAMIC LOAD TESTING (APPLELIANLIAN 2013) ................. 28

FIGURE 2.11 FREE BODY DIAGRAM OF A SMALL SEGMENT OF A PILE (AFTER GARNIER 2001) ................................................................. 31

FIGURE 2.12 (A) REAL PILE AND DRIVING ACCESSORIES (B) SMITH PILE AND SOIL MODEL (C) CAPWAP MODEL (D) SMITH SOIL MODEL (AFTER NG 2011) ....................................................................................................................... 33

FIGURE 2.13 STRESS STRAIN (LOAD–DEFORMATION) DIAGRAM OF THE SOIL RESISTANCE AT A PILE POINT (AFTER NG 2011) .......................................................................................................................................................... 34

FIGURE 2.14 SIGNAL MATCHING ANALYSIS ALGORITHM IN CAPWAP (AFTER ROBINSON AND RAUSCHE 2000) ............... 38

FIGURE 2.15 TYPICAL OUTPUT OF CAPWAP MEASURED FORCE OR VELOCITY RESPONSE WITH TIME (A) RESULTS OF SIGNAL MATCHING ANALYSIS (MEASURED VERSUS COMPUTED FORCE) AND (B) FORCE AND VELOCITY TRACES RECORDED BY PDA MEASURED VERSUS TIME ............................................................................................................................................... 39

FIGURE 2.16 BASIC PRINCIPLE OF MC MODEL (AFTER WEHNERT & VERMEER 2004) .......................................................... 41

FIGURE 2.17 HYPERBOLIC STRESS–STRAIN RELATION IN PRIMARY LOADING FOR A STANDARD DRAINED TRIAXIAL TEST (AFTER BRINKGREVE, KUMARSWAMY & SWOLFS 2017) ......................................................................................................................... 44
FIGURE 2.18 Process of installation of CFA piles (Naturalzem 2019) ................................................................. 49
FIGURE 2.19 Comparison of calculated and measured load-settlement curves (after Hoikko & Stacho 2014) 50
FIGURE 2.20 Comparison of calculated and measured load distribution curves over the pile length (after Hoikko & Stacho 2014) .................................................................................................................. 50
FIGURE 2.21 Numerically established load-settlement curves for the single and pile groups (after Comodromos, Anagnostopoulos & Georgiadis 2003) ...................................................................................................... 51
FIGURE 2.22 Maintained load tests on square and circular cell foundations (after Yetginer, White & Bolton 2006) ........................................................................................................................................... 53
FIGURE 2.23 Comparison of single pile load-displacement and RATZ back-analysis (after Yetginer, White & Bolton 2006) ........................................................................................................................................... 54
FIGURE 2.24 Distribution of CAPWAP to SLT ratios for 226 piles (after Likins & Rausche 2004) .................. 56
FIGURE 2.25 Modes of wave propagation in the pile-plug system (after Paikowsky & Chernauskaus 2008).... 59
FIGURE 2.26 Apparent soil model proposed by Lee et al. (1988) ....................................................................... 63
FIGURE 2.27 A typical discretisation used in FEM (after Nath 1990) ................................................................... 65
FIGURE 2.28 Comparison of (a) pile resistance and (b) driving stress between wave equation and finite element methods (after Nath 1990) ........................................................................................................ 66
FIGURE 3.1 Simulated drained triaxial test sand applying Mohr-Coulomb and hardening soil models for (a) dense sand and (b) loose sand .................................................................................................................................. 77
FIGURE 3.2 Finite element model of the pile and the adjacent ground with the corresponding generated mesh .............................................................................................................................................. 78
FIGURE 3.3 Mesh size dependency of finite element models with (a) MC, (b) HS and (c) HP constitutive models .................................................................................................................................................. 79
FIGURE 3.4 Comparison of obtained load-displacement curves using different soil models in (a) dense and (b) loose sand soils .................................................................................................................................... 81
FIGURE 3.5 Influence of (a) critical state friction angle and (b) granular hardness on load-displacement curve of concrete bored pile in saturated sand ........................................................................... 84
FIGURE 3.6 Influence of (a) sensitivity of granular skeleton to change of pressure (b) critical void ratio at zero pressure on load-displacement curve of concrete bored pile in saturated sand ............... 85
FIGURE 3.7 Influence of (a) maximum void ratio at zero pressure (b) exponent describes the transition between peak and critical stress on load-displacement curve of concrete bored pile in saturated sand..................86

FIGURE 3.8 Influence of the exponent representing the change of stiffness at current density on load-displacement curve of concrete bored pile in saturated sand..........................................................87

FIGURE 3.9 Pile load testing – normalised intergranular strain tensor for (a) dense sand and (b) loose sand 88

FIGURE 3.10 Comparison of load-displacement curve of real static load test with simulated test using Mohr-Coulomb and hardening soil models............................................................90

FIGURE 3.11 Interpretation of load-settlement curve using Davison method .................................................................90

FIGURE 3.12 Three-dimensional finite element model used in simulation: (a) plan view (b) three-dimensional view ...................................................................................................................................................93

FIGURE 3.13 Plan view of a simulated static load test with (a) two reaction piles and (b) four reaction piles 94

FIGURE 3.14 Comparison of interaction of two and four reaction piles with the test pile \( D_{\text{TEST PILE}} = D_{\text{REACTION PILE}} \) and \( L_{\text{TEST PILE}} = L_{\text{REACTION PILE}} \) ........................................................................................................................ 94

FIGURE 3.15 Comparison of load-displacement curve of test pile in different distances of reaction piles \( D_{\text{TEST PILE}} = D_{\text{REACTION PILE}} \) and \( L_{\text{TEST PILE}} = L_{\text{REACTION PILE}} \) ...................................................................................................................................................95

FIGURE 3.16 Effect of reaction pile length on the test pile with a length of 9.5 m \( D_{\text{TEST PILE}} = D_{\text{REACTION PILE}} \) .... 96

FIGURE 3.17 Effect of reaction pile diameter on test pile with a diameter of 1.3 m \( L_{\text{TEST PILE}} = L_{\text{REACTION PILE}} \) ...... 97

FIGURE 3.18 Effect of different reaction piles (a) concrete pile, (b) steel pipe pile with fully unplugged behaviour and (c) steel pipe pile with partially plugged behaviour on test pile with a diameter of 1.3 m \( L_{\text{TEST PILE}} = L_{\text{REACTION PILE}} \) .............................................................................................................................98

FIGURE 3.19 Effect of steel pipe pile as the reaction pile on the test pile ........................................................................ 98

FIGURE 3.20 Summary of soil condition and cap dimension.................................................................................................................101

FIGURE 3.21 Plan view of (a) Group A and (b) Group B (after Ismael 2001)................................................................. 103

FIGURE 3.22 Finite element model of pile group and adjacent soil .........................................................................................104

FIGURE 3.23 Pile group layout for different analyses .................................................................................................................. 105

FIGURE 3.24 (a) Measured and predicted load-displacement curves for Group A (b) Group B .................................106

FIGURE 3.25 Comparison of measured and predicted axial load distribution along the central pile in Group A ........................................................................................................................................110
FIGURE 3.26 PREDICTED AND AVERAGED LOAD – DISPLACEMENT OF PILE GROUP B VERSUS THE SINGLE PILE .......... 110
FIGURE 3.27 GROUP SETTLEMENT RATIO VERSUS PILE GROUP SETTLEMENT ...................................................... 111
FIGURE 3.28 TOP (T.) AND BASE (B.) LOAD IN CENTRAL PILE IN PILE GROUP ......................................................... 112
FIGURE 3.29 RATIO OF THE INDIVIDUAL PILE LOAD TO THE AVERAGE INDIVIDUAL LOAD ............................ 113
FIGURE 3.30 INDIVIDUAL PILE LOAD-DISPLACEMENT CURVE FOR PILE GROUP B ................................................. 113
FIGURE 4.1 FREE PILE TOP FORCE AND VELOCITY UNDER ACTION OF SUDDENLY APPLIED CONSTANT FORCE (AFTER RAUSCHE, Goble & Likins 1985) ........................................................................................................................ 120
FIGURE 4.2 FREE PILE TOP VELOCITY UNDER ACTION OF SOIL RESISTING FORCE ........................................... 123
FIGURE 4.3 INDUCED AND REFLECTED WAVES DUE TO THE HAMMER IMPACT OVER THE PILE HEAD ............ 130
FIGURE 4.4 (A) STRATIGRAPHY OF SITE AT THE LOCATION OF PILE ISU5 (B) CROSS SECTION OF THE STEEL H-PILE (AFTER NG ET AL. 2011) ........................................................................................................................ 133
FIGURE 4.5 SIGNALS MEASURED AT (A) END OF DRIVING (B) SIXTH RESTRIKE TEST (AFTER NG ET AL. 2011) ..... 134
FIGURE 4.6 COMPARISON OF TOTAL SOIL RESISTANCE (RTL) BETWEEN PDA AND THE MATLAB CODE .............. 135
FIGURE 4.7 COMPARISON OF MAXIMUM STATIC SOIL RESISTANCE (RMX) BETWEEN PDA AND THE DEVELOPED CODE USING MATLAB ........................................................................................................ 136
FIGURE 4.8 COMPARISON OF MAXIMUM COMPRESSIVE STRESS (CSX) BETWEEN PDA AND THE MATLAB CODE ........ 136
FIGURE 4.9 COMPARISON OF MAXIMUM ENERGY TRANSFERRED TO THE PILE (EMX) BETWEEN PDA AND THE MATLAB CODE ............................................................................................................. 137
FIGURE 4.10 THE EFFECT OF CASE DAMPING FACTOR ON THE MAXIMUM STATIC SOIL RESISTANCE IN BOTH CONDITIONS END OF DRIVING (EOD) AND BEGINNING OF RESTRIKE (BOR) ............................................................. 137
FIGURE 4.11 INCREASING OF MAXIMUM STATIC SOIL RESISTANCE (RMX) WITH TIME USING DIFFERENT CASE DAMPING FACTOR ............................................................................................................. 138
FIGURE 4.12 THE AMOUNT OF MAXIMUM STATIC SOIL RESISTANCE (RMX) RELATIVE CHANGES WHEN CASE DAMPING FACTOR CHANGES FROM 0.7 TO 1 ..................................................................................... 138
FIGURE 5.2 Variation of shear stress in soil at different distances from pile shaft, (a) dense sand, and (b) loose sand (Hardening Soil model) ................................................................. 154

FIGURE 5.3 Pile head displacement (a) dense sand and (b) loose sand ............................................................... 156

FIGURE 5.4 Impedance × Velocity variation with time, recorded at the gauge location for (a) dense sand, and (b) loose sand ........................................................................................................... 158

FIGURE 5.5 Velocity × Impedance and force traces, recorded at the gauge location using Hardening Soil model for dense sand by applying harmonic loading with a frequency of 50 Hz ......................... 159

FIGURE 5.6 Applied harmonic load with a frequency of 250 Hz ........................................................................ 159

FIGURE 5.7 Velocity × Impedance and force traces, recorded at the gauge location using Hardening Soil model for dense sand by applying a harmonic load with a frequency of 250 Hz ...................................................... 160

FIGURE 5.8 Influence of hypoplastic model parameters on the measured pile head displacement during the pile driving in dense sand (a) critical friction angle, and (b) granular hardness ........................................... 163

FIGURE 5.9 Influence of intergranular strain parameters defined in hypoplastic model on the measured pile head displacement during the pile driving in dense sand (a) $\beta r$ and (b) $\chi$ ........................................ 164

FIGURE 5.10 Concrete pile driving — normalised intergranular strain tensor for (a) dense sand, and (b) loose sand ........................................................................................................................................ 165

FIGURE 5.11 Rod with two different tip conditions (a) fixed-end (b) elastic support and (c) the applied harmonic load (After Masouleh & Fakhrarian 2008) ................................................................. 168

FIGURE 5.12 (a) Comparison of numerical results reported by Masouleh and Fakhrarian (2008) using FLAC 2D with PLAXIS 2D predictions conducted in this study: (a) fixed-end rod and (b) rod on elastic support ($E = 10$ MPa) ........................................................................................................................................ 169

FIGURE 5.13 Cone penetrometer results for the site at Shenton Park (After Byrne 1995) ............................................ 171

FIGURE 5.14 Finite element model of the pile and the adjacent ground with the corresponding generated mesh ............................................................................................................................... 172

FIGURE 5.15 Measured force with time and numerical predictions, (a) the effect of different parameters on signal matching and (b) the best match obtained .......................................................... 174

FIGURE 5.16 Computed displacement at the pile head .......................................................................................... 175

FIGURE 5.17 Maximum compressive (a) and tensile stresses (b) distribution along the pile shaft ............... 175
FIGURE 5.18 COMPARISON OF MEASURED AND PREDICTED PILE LOAD-DISPLACEMENT VARIATION DURING STATIC LOAD TESTING ................................................................. 176

FIGURE 5.19 (A) CONSTRAINED MODULUS OBTAINED THROUGH CPT, CPTu AND SDMT TESTS (B) SOIL STRATIGRAPHY AT THE LOCATION OF PILE 11B IN TERMS OF SOIL TYPE, AND (C) SOIL STRATIGRAPHY AT THE LOCATION OF PILE 11B IN TERMS OF SOIL ORIGIN ................................................................. 180

FIGURE 5.20 SHEAR MODULUS OBTAINED FROM SDMT TESTS .................................................. 181

FIGURE 5.21 STRESS-STRAIN GRAPHS OBTAINED FROM TRIAXIAL TESTS CONDUCTED ON SAMPLES TAKEN FROM DIFFERENT DEPTHS .............................................................. 182

FIGURE 5.22 STIFFNESS DEGRADATION CURVE OBTAINED FOR DIFFERENT SOIL LAYERS ................................................................. 183

FIGURE 5.23 (A) SCHEMATIC DIAGRAM OF THE SIMULATED MODEL, AND (B) GEOMETRY OF THE PILE ALONE ..................... 185

FIGURE 5.24 AN AXISYMMETRIC FINITE ELEMENT MODEL OF THE PILE AND ADJACENT GROUND WITH THE CORRESPONDING GENERATED MESH ................................................................. 186

FIGURE 5.25 FORCE (F) AND VELOCITY TIMES IMPEDANCE (Zv) TRACES MEASURED BY PDA ........................................ 187

FIGURE 5.26 COMPARISON OF (A) REAL PILE, (B) CAPWAP, AND (C) SIMULATED PILE IN NUMERICAL MODELLING .......... 188

FIGURE 5.27 COMPARISON OF MEASURED AND PREDICTED VELOCITIES .............................................................. 189

FIGURE 5.28 COMPARISON OF MEASURED AND PREDICTED DISPLACEMENTS .............................................................. 189

FIGURE 5.29 PILE RESISTANCE TRACES: (A) TOTAL RESISTANCE, AND (B) STATIC RESISTANCE ........................................ 190

FIGURE 5.30 CORRELATION OF PREDICTED AND MEASURED DATA (A) DOWNWARD, AND (B) UPWARD TRAVELLING WAVES 193

FIGURE 5.31 PREDICTED AND MEASURED APPLIED ENERGIES VERSUS TIME .............................................................. 194

FIGURE 5.32 COMPARISON OF LOAD-SETTLEMENT CURVE OBTAINED BY CAPWAP AND THE FINITE ELEMENT PROGRAM ... 195

FIGURE 5.33 INFLUENCE OF THE PILE-SOIL STRENGTH AND DEFORMATION PROPERTIES ON THE PILE HEAD VELOCITY ....... 197

FIGURE 5.34 INFLUENCE OF THE PILE-SOIL STRENGTH AND DEFORMATION PROPERTIES ON THE MAXIMUM STATIC PILE RESISTANCE (RMX) .............................................................. 198

FIGURE 5.35 NEW STIFFNESS DEGRADATION CURVE FOR SILTY SAND LAYER BY CHANGING THE REFERENCE SHEAR STRAIN... 199

FIGURE 5.36 COMPARISON OF MEASURED AND PREDICTED DISPLACEMENTS BETWEEN CAPWAP AND THE CONTINUUM NUMERICAL MODEL BY ASSIGNING THE REFERENCE SHEAR STRAIN EQUAL TO $10^{-4}$ TO ALL SOIL LAYERS ............ 199

FIGURE 5.37 WAVES GENERATED FROM PILE DRIVING AND DYNAMIC LOAD TESTING OPERATIONS (AFTER DUNGCA ET AL. 2016) .............................................................. 203
FIGURE 5.38 Measuring ground vibration using seismograph ................................................................. 204

FIGURE 5.39 Ground vibrations induced by dynamic load testing, (A) three different boreholes defined in the model, (B) three-dimensional simulated model, and (C) plan view and the locations of vibration measurement .................................................................................................................. 206

FIGURE 5.40 The variations of vertical particle velocities in different distances from source of vibration... 212

FIGURE 5.41 The variations of particle velocities in different distances in three different orthogonal direction, (a) 5 m, (b) 10 m, (c) 20 m, (d) 30 m and (e) 40 m ................................................................................................................................. 213

FIGURE 5.42 The variations of peak vertical particle velocities in different distances from the source of vibration ........................................................................................................................................... 214

FIGURE 5.43 Response of the building and inhabitants in a vicinity of pile driving site ......................... 214
LIST OF TABLES

Table 2.1 Summary of suggested dynamic soil parameters (after Ng & Sritaran 2013) ........................................ 36
Table 2.2 Required parameters for Mohr-Coulomb model (after Brinkgreve, Kumarswamy & Swolfs 2017) 41
Table 2.3 Required parameters for Hardening Soil model (after Brinkgreve, Kumarswamy & Swolfs 2017). 45
Table 2.4 Required parameters of granular material for Hypoplastic model (after Dung 2009) ............... 47
Table 2.5 Defined parameters in intergranular strain concept (after Dung 2009) ........................................ 48
Table 3.1 Baskarp sand properties (after Dung 2009) ......................................................................................... 76
Table 3.2 Mohr-Coulomb model properties for Baskarp sand ................................................................. 76
Table 3.3 Interface parameters of different soil models defined in numerical modelling .................. 78
Table 3.4 Adopted soil parameters in the numerical modelling (after Wehnert & Vermeer 2004) .......... 89
Table 3.5 Ultimate capacity of the test pile using Davisson method .......................................................... 91
Table 4.1 Summary of CASE damping factors (after Hannigan et al. 1998) ................................................. 127
Table 4.2 Schedule of restrike tests based on the elapsed time after end of driving (after Ng et al. 2011) ... 134
Table 5.1 Properties of the circular rod used in the model ............................................................................. 166
Table 5.2 Properties of dense sand in Shenton Park .................................................................................... 171
Table 5.3 Hardening Soil with Small Strain Stiffness model soil properties .............................................. 184
Table 5.4 Comparison of shaft resistance between different methods ....................................................... 191
Table 5.5 Comparison of pile resistance obtained by CAPWAP and PLAXIS ............................................. 192
Table 5.6 Capability of correlation of dynamic and static behaviour of pile in the numerical model ... 194
Table 5.7 Displacement of pile head and toe due to the SLS loading ......................................................... 196
Table 5.8 Typical range of structural responses to the pile driving (after British Standard 1990) .......... 208
Table 5.9 Transient vibrations guide values for cosmetic damage (after British Standard 1993) .......... 209
Table 5.10 Guidelines values for transient vibration on structures (after German Standard 1999) .... 209
NOTATIONS

**Latin Letters**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Cross section of pile</td>
</tr>
<tr>
<td>$c$</td>
<td>Wave propagation speed</td>
</tr>
<tr>
<td>$c$</td>
<td>Soil cohesion</td>
</tr>
<tr>
<td>$D$</td>
<td>Pile diameter</td>
</tr>
<tr>
<td>$D_r$</td>
<td>Relative density</td>
</tr>
<tr>
<td>$e_{c0}$</td>
<td>Critical void ratio at zero pressure</td>
</tr>
<tr>
<td>$e_{d0}$</td>
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<tr>
<td>$e_{l0}$</td>
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<td>$E$</td>
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<td>$E_{50}$</td>
<td>Secant elastic modulus for a mobilization of 50% of the maximum shear strength</td>
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<tr>
<td>$E_{50}^{ref}$</td>
<td>Secant stiffness in standard drained triaxial test</td>
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<td>$E_M$</td>
<td>Menard modulus</td>
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<td>Tangent stiffness for primary oedometer loading</td>
</tr>
<tr>
<td>$E_{ur}^{ref}$</td>
<td>Unloading / reloading stiffness</td>
</tr>
<tr>
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<td>$F_c$</td>
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</tr>
<tr>
<td>$F_m(t^*)$</td>
<td>Measured force at any time at the gauge location</td>
</tr>
<tr>
<td>$F_T(t)$</td>
<td>Force measured at the pile head</td>
</tr>
<tr>
<td>$h_s$</td>
<td>Granular hardness</td>
</tr>
<tr>
<td>$J$</td>
<td>Damping factor</td>
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</table>
\( J_c \) CASE damping factor

\( k_0^{nc} \) \( k_0 \) for normal consolidation

\( L \) Length of pile

\( L_c \) Length of stress wave

\( M \) The total mass of a pile

\( m \) Power for stress level dependency of stiffness

\( m \) Maximum steps

\( m_R \) Stiffness increase for a 180 degree reversal

\( m_T \) Stiffness increase for a 90 degree change of strain path direction

\( n \) Sensitivity of granular skeleton to change of pressure

\( n \) Number of sub-steps

\( P_s \) The mean particle pressure

\( p^{ref} \) Reference stress for stiffness

\( Q_{ave} \) Average individual pile head load

\( q \) Soil quake

\( R \) Radius of elastic range

\( R_d \) Dynamic soil resistance

\( R_{int} \) Interface strength reduction factor

\( R_f \) Failure ratio

\( R_s \) Group settlement ratio

\( R_s \) Static soil resistance

\( R_{toe} \) Static toe resistance
\( S \) Settlement without the influence of reaction piles

\( S_m \) Settlement considering the influence of reaction piles

\( t_{\text{max}} \) The time of impact

\( t^* \) Time corresponding to measured force and velocity (any time)

\( t_1 \) Impact time (time corresponding to first peak in force and velocity traces)

\( t_2 \) Time corresponding to wave reflection from pile toe

\( v \) Velocity measured at the gauge location

\( v_b \) Velocity of the pile toe

\( v_m(t^*) \) Measured velocity at the gauge location

\( v_R(t) \) The particle velocities of the generated waves due to the resistance

\( v_T(t) \) Velocity at the pile head

\( v_T^D(t) \) Pile top velocity due to the downward travelling wave caused by soil resistance

\( v_T^U(t) \) Pile top velocity due to the upward travelling wave caused by soil resistance

\( W_D \) Downward travelling wave

\( W_U \) Upward travelling wave

\( Z \) Pile impedance
**Greek Letters**

\( \alpha \) Exponent describes the transition between peak and critical stress

\( \alpha \) Influence of mass in the damping

\( \beta \) Exponent represents the change of stiffness at current density

\( \beta \) Influence of stiffness in the damping

\( \beta_R \) Material constant

\( \gamma_{0,7} \) Threshold shear strain

\( \Delta t \) Duration of dynamic loading

\( \delta t \) Time step used in dynamic calculations

\( \sigma_c \) Compressive stress

\( \sigma_T \) Tensile stress

\( \nu_{ur} \) Poisson ratio for unloading-reloading

\( \phi_c \) Critical state friction angle

\( \chi \) Material constant represents stiffness degradation

**Acronyms**

BOR Beginning of restrike

CAPWAP CAse Pile Wave Analyses Program

CL Centre line

CSX Maximum compressive stress
$DSX$  Maximum displacement of pile

$EMX$  Maximum transferred energy at gauge location

$EOD$  End of driving

$HP$  Hypoplastic

$HS$  Hardening Soil

$HS-$Small  Hardening Soil with Small Strain Stiffness

$IGS$  Intergranular Strain

$LE$  Linear elastic

$MC$  Mohr-Coulomb

$PDA$  Pile driving analyser

$PPV$  Peak particle velocity

$RMX$  Maximum static soil resistance

$RTL$  Maximum total resistance

$RX0$  Maximum static soil resistance with CASE damping factor zero

$SDMT$  Seismic dilatometer test

$SET$  Permanent displacement of pile

$SFR$  Static shaft resistance
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>SFT</td>
<td>Total shaft resistance</td>
</tr>
<tr>
<td>TC</td>
<td>Temporary compression</td>
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<tr>
<td>WEAP</td>
<td>Wave equation analysis program</td>
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</table>
ABSTRACT

Piles are generally used to carry structural loads when the soil at the ground surface is low in strength or the loads are substantial. It is very common to conduct pile load testing to assess whether the piles will behave as predicted in the design stage. Static load testing (SLT) is considered to be the benchmark for assessing the performance of piles since it is known the most fundamental way of pile load testing. However, this kind of test is time consuming and expensive, and in cases such as offshore operations, SLT is generally not possible for many cases. In spite of this, powerful computer programs for pile testing simulation have been revolutionised and are available. Of these different methods, the dynamic load testing (DLT) method for assessing the static bearing capacity of piles is of major interest and importance. A dynamic pile test is based on the signal matching technique in which the pile-soil system is modelled using the CAse Pile Wave Analyses Program (CAPWAP). This program tries to calculate the tip and side resistance of embedded piles and produces a force versus time signal which matches the measured data. The signal matching analysis uses a one-dimensional wave equation analysis of piles based on the Smith model to differentiate between toe and shaft resistance, to ascertain the distribution of frictional resistance along the pile shaft to determine the tensile and compressive stresses during pile driving. However, this technique uses a mass–spring–dashpot system to model the soil media surrounding and below the toe which imposes some restrictions such as being user-dependant process and using constant uncommon soil parameters such as quake along the pile length, regardless of soil strata, which can be layered or uniform. Furthermore, using CAPWAP to analyse pile driving interrupts the continuity of different stages of pile modelling from simulating pile driving, quality control, and investigating settlement. GRLWEAP or CAPWAP generally should be used
with a second software package such as PLAXIS in order to investigate any subsequent settlement or interaction.

In order to overcome the aforementioned limitations and assess pile behaviour during load testing in more detail, so-called continuum numerical models using the finite element program PLAXIS are established. In these numerical models, wave propagation, the static and dynamic response of piles during load testing for solid concrete piles and open-ended tubular steel piles are evaluated. In fact, the numerical simulations in this study are a remarkable improvement compared to the previous numerical studies because when simulating pile load testing, different soil models such as the Mohr-Coulomb, hardening soil, hardening soil with small strain stiffness and hypoplastic with intergranular strain are utilised to carry out a more rigorous deformation analysis.

To investigate the capability of the numerical model, the dynamic and static responses of a driven steel pipe pile monitored as part of a highway bridge construction project in New South Wales, Australia is simulated and numerically analysed using the finite element method. During these dynamic and static load testing simulations, a hardening soil model with small strain stiffness is used to obtain the best correlation between the large and small strains, while the pile is under a static load and being driven. The numerical predictions obtained using two-dimensional continuum finite element simulations are then compared with the corresponding predictions obtained from the CASE method and CAPWAP program to evaluate the predictions. Moreover, the total and static soil resistances as well as displacement and velocity traces obtained from numerical model are compared with the existing data acquired from the field measurements. The results indicate that the hardening soil model with small strain stiffness exhibits a reasonable correlation with the field measurements during static and dynamic loading.
Evaluation of static and dynamic pile load testing based on the continuum based finite element model has many advantages for geotechnical engineers dealing with pile design, because an established continuum numerical model can assess pile testing under more realistic conditions. This model can also be used to evaluate the performance of piles under different loading conditions on a single pile or group of piles, and piles built close to existing structures. Furthermore, this method retains the continuity of different stages of modelling from simulating pile driving, quality control, and investigating settlement, while all these analyses are carried out using one appropriate finite element based software.