TABLE OF CONTENTS

Abstract ......................................................................................................................ii
Acknowledgements ....................................................................................................vi
Table of Contents .......................................................................................................viii
List of Figures ............................................................................................................xvi
List of Tables .............................................................................................................xxvi

Chapter 1
INTRODUCTION

1.1  GENERAL INTRODUCTION ......................................................................1
1.2  OBJECTIVES ..........................................................................................2
1.3  ORGANIZATION OF THESIS ...............................................................3

Chapter 2
BACKGROUND AND LITERATURE REVIEW

2.1  BACKGROUND ..........................................................................................5
2.2  COMPOSITE PILE BACKGROUND .........................................................5
  2.2.1  Types of composite piles .................................................................6
  2.2.1.1  Steel pipe core pile ......................................................................6
  2.2.1.2  Structurally reinforced plastic matrix pile ...................................8
  2.2.1.3  Concrete-filled FRP tube pile ....................................................9
2.3  LITERATURE REVIEW FOR THE COMPOSITE PILES SELECTED ....10
  2.3.1  Structural behavior ........................................................................10
    2.3.1.1  Concrete-filled FRP composite piles .......................................10
      2.3.1.1.1  Behavior under axial loading ...........................................11
      2.3.1.1.2  Flexural behavior ............................................................15
      2.3.1.1.3  Behavior under combined bending and axial loading .......17
    2.3.1.2  Steel reinforced recycled plastic composite piles .................19
2.3.2  Long-term durability behavior ............................................................20
  2.3.2.1  Concrete-filled FRP composite piles .......................................20
  2.3.2.2  Steel reinforced recycled plastic composite piles ..................22
2.3.3  Geotechnical behavior ......................................................................22
  2.3.3.1  Pile driveability .......................................................................22
  2.3.3.2  Lateral load capacity ...............................................................25
  2.3.3.3  Axial load capacity ...................................................................26
2.4  SUMMARY ..............................................................................................27
Chapter 3
EXPERIMENTAL STUDY OF INTERFACE BEHAVIOR BETWEEN COMPOSITE PILES AND TWO SANDS

3.1 INTRODUCTION .................................................................................................28
3.2 SOIL MATERIALS ...............................................................................................31
   3.2.1 Index properties ..................................................................................31
   3.2.2 Direct shear tests of sands ....................................................................33
3.3 PILE SURFACES ..............................................................................................38
   3.3.1 Introduction .........................................................................................38
   3.3.2 Surface topography characterization ....................................................38
   3.3.3 Interface hardness ................................................................................44
3.4 INTERFACE SHEAR TESTS............................................................................45
3.5 DISCUSSION OF RESULTS ............................................................................55
   3.5.1 Multiple linear regression for density sand tan \( \theta_{\text{peak}} \) values .............56
   3.5.2 Multiple linear regression for density sand tan \( \theta_{\text{cv}} \) values ...............57
   3.5.3 Multiple linear regression for model sand tan \( \theta_{\text{peak}} \) values ..........58
   3.5.4 Multiple linear regression for model sand tan \( \theta_{\text{cv}} \) values ..............59
   3.5.5 Observations from the linear regression analyses results .......................60
   3.5.6 Influence of angularity of sand ............................................................61
3.6 SUMMARY .......................................................................................................61

Chapter 4
EXPERIMENTAL DURABILITY STUDY OF FRP COMPOSITE PILES

4.1 INTRODUCTION .................................................................................................64
4.2 BACKGROUND ON DEGRADATION OF GLASS FRP COMPOSITES.64
4.3 LABORATORY STUDY OF DURABILITY .......................................................66
   4.3.1 Description of test specimens ...............................................................67
      4.3.1.1 Specimens from Lancaster Composites Inc. ..................................67
      4.3.1.2 Specimens from Hardcore Composites Inc. .................................69
   4.3.2 Test equipment and procedures ............................................................72
      4.3.2.1 Burnoff tests ...............................................................................72
      4.3.2.2 Axial tension tests ......................................................................73
      4.3.2.3 Hoop tension tests ....................................................................74
      4.3.2.4 Freeze-thaw testing ...................................................................75
   4.3.3 Baseline mechanical properties ............................................................77
      4.3.3.1 Longitudinal tension ..................................................................77
      4.3.3.2 Hoop tension ............................................................................78
5.7.1 Connection of piles with pile cap beam 144
5.8 SUMMARY AND CONCLUSIONS ............................................................148

Chapter 6
FIELD LOAD TESTS AT THE ROUTE 351 BRIDGE

| 6.1  | INTRODUCTION .........................................................................................150 |
| 6.2  | DESCRIPTION OF THE BRIDGE ................................................................150 |
| 6.2.1 | The original bridge 150 |
| 6.2.2 | The new bridge 153 |
| 6.3  | DESCRIPTION OF TEST PILES .................................................................154 |
| 6.3.1 | Prestressed concrete test pile 155 |
| 6.3.2 | FRP composite test pile 156 |
| 6.3.3 | Polyethylene composite test pile 158 |
| 6.4  | SOIL CONDITIONS AT THE TEST SITE ..................................................161 |
| 6.4.1 | Geology 161 |
| 6.4.2 | Subsurface conditions 162 |
| 6.4.3 | Hampton River 163 |
| 6.5  | TEST PILE INSTRUMENTATION AND FABRICATION...............................165 |
| 6.5.1 | Test pile instrumentation 165 |
| 6.5.2 | Fabrication of prestressed concrete test pile 170 |
| 6.5.3 | Fabrication of FRP composite test pile 171 |
| 6.5.4 | Fabrication of plastic composite test pile 175 |
| 6.6  | PILE INSTALLATION AND DYNAMIC TESTING ....................................177 |
| 6.6.1 | Pile driving 177 |
| 6.6.2 | Dynamic testing 181 |
| 6.7  | PILE INTEGRITY TESTING OF TEST PILES .......................................184 |
| 6.8  | FIELD TESTING OF TEST PILES ............................................................189 |
| 6.8.1 | Axial load tests 189 |
| 6.8.1.1 | Residual stresses 192 |
| 6.8.1.2 | Load transfer 194 |
| 6.8.2 | Lateral load tests 197 |
| 6.9  | SUMMARY AND CONCLUSIONS ............................................................200 |
Chapter 7
ANALYSES OF THE AXIAL LOAD TESTS AT THE ROUTE 351 BRIDGE SITE

7.1 INTRODUCTION ........................................................................................................201

7.2 AXIAL PILE CAPACITY ............................................................................................201
  7.2.1 Methods to estimate axial load capacity of driven piles in sand 201
    7.2.1.1 Nordlund’s method 203
    7.2.1.2 API method 204
    7.2.1.3 LCPC method 207
    7.2.1.4 Imperial College method 208
  7.2.2 Predicted axial capacities 212
    7.2.2.1 Nordlund method predictions 213
    7.2.2.2 API method predictions 215
    7.2.2.3 LCPC method predictions 217
    7.2.2.4 Imperial College method predictions 218
  7.2.3 Summary of axial pile capacity predictions 219

7.3 LOAD SETTLEMENT BEHAVIOR OF AXIALLY LOADED SINGLE PILES .................................221
  7.3.1 Introduction 221
  7.3.2 Background of the load transfer method for pile settlement predictions 222
  7.3.3 Predictions using empirical load transfer curves 224
    7.3.3.1 Predictions using load transfer curves recommended by API (1993) 224
      7.3.3.1.1 Load transfer curves recommended by API (1993) 224
      7.3.3.1.2 Maximum shaft shear stress distributions recommended by API (1993) 225
      7.3.3.1.3 Prediction for the prestressed concrete test pile 226
      7.3.3.1.4 Prediction for the FRP test pile 227
      7.3.3.1.5 Prediction for plastic test pile 228
    7.3.3.2 Predictions using Vijayvergiya (1977) load transfer curves 229
      7.3.3.2.1 Load transfer curves recommended by Vijayvergiya (1997) 229
      7.3.3.2.2 Maximum shaft shear stress distributions 231
      7.3.3.2.3 Tip resistances 232
      7.3.3.2.4 Prediction for prestressed concrete test pile 233

xii
Chapter 9
LONG TERM MONITORING

9.1 INTRODUCTION .................................................................295
9.2 INSTRUMENTED PRODUCTION PILES .....................................296
  9.2.1 Prestressed concrete production pile 297
  9.2.2 FRP composite production pile 299
9.3 SOIL CONDITIONS AT THE INSTRUMENTED PRODUCTION PILES ..................................................................................303
9.4 PILE INSTALLATION AND DYNAMIC TESTING ............................306
  9.4.1 Pile driving ........................................................................306
  9.4.2 Dynamic testing ..................................................................307
9.5 PILE INTEGRITY TESTING OF TEST PILES ...............................309
9.6 MONITORING DATA GATHERED TO DATE ..................................312
9.7 SUMMARY .............................................................................316

Chapter 10
COST COMPARISON

10.1 INTRODUCTION ..................................................................318
10.2 COST INFORMATION FOR THE ROUTE 40 BRIDGE PROJECT ......318
10.3 COST INFORMATION FOR THE ROUTE 351 BRIDGE PROJECT ......319
  10.3.1 Hardcore FRP composite pile 319
  10.3.2 Plastic pile 319
  10.3.3 Prestressed concrete pile 320
  10.3.4 Summary of the Route 351 cost information 320
10.4 SUMMARY .............................................................................320
Chapter 11
SUMMARY AND CONCLUSIONS

11.1 INTRODUCTION .................................................................322

11.2 SUMMARY OF ACTIVITIES AND CONCLUSIONS .................324
   11.2.1 Literature review 324
   11.2.2 Interface study 324
   11.2.3 Durability study 326
   11.2.4 Field tests at the Route 40 Bridge 327
   11.2.5 Field tests at the Route 351 Bridge 328
   11.2.6 Axial analyses 329
   11.2.7 Lateral analyses 331
   11.2.8 Long term monitoring 332
   11.2.9 Cost information of composite piles 333

11.3 RECOMMENDATIONS FOR FUTURE WORK .........................334

REFERENCES ...........................................................................337

APPENDIX A – INTERFACE TEST RESULTS ..................................355

APPENDIX B – MOISTURE DIFFUSION INTO A CYLINDRICAL FRP COMPOSITE .........................................................370

APPENDIX C – STRUCTURAL TEST RESULTS FROM COMPOSITE PILE CUTOFF SECTIONS FROM THE ROUTE 40 BRIDGE PROJECT ....375

APPENDIX D – GEOTECHNICAL FIELD INVESTIGATIONS AT THE ROUTE 351 BRIDGE TEST SITE ............................................380

VITA ..........................................................................................396
LIST OF FIGURES

Chapter 2

Figure 2.1 Degradation of conventional piles (Iskander and Hassan 1998) 5
Figure 2.2 Common types of composite piles 6
Figure 2.3 Confinement effect of FRP tube on concrete (Fam and Rizkalla 2001) 12
Figure 2.4 Experimental versus predicted load-strain behavior using Fam and Rizkalla model 15
Figure 2.5 Strip elements for sectional analysis (Mirmiran and Shahawy 1996) 16
Figure 2.6 Experimental versus analytical moment-curvature response (adapted from Fam and Rizkalla 2002) 17
Figure 2.7 Interaction diagrams for concrete-filled FRP tubes (Mirmiran 1999) 18
Figure 2.8 Illustration of the moisture absorption related durability model 21
Figure 2.9 Scanning electron microscope image showing evidence of damage in the FRP due to moisture absorption (McBagonluri et al. 2000) 21

Chapter 3

Figure 3.1 Influence of soil-pile interface friction on pile capacity 29
Figure 3.2 Grain size curves of test sands 32
Figure 3.3 Microscopic views of the test sands 32
Figure 3.4 Direct shear test results for Density sand (average $D_r=70\%$) 34
Figure 3.5 Direct shear test results for Density sand (average $D_r=100\%$) 35
Figure 3.6 Direct shear test results for Model sand (average $D_r=75\%$) 36
Figure 3.7 Stylus profilometer sketch (Johnson 2000) 39
Figure 3.8 Graphical representation of roughness parameters $R_t$, $S_m$, and $R_a$ 39
Figure 3.9 Surface characteristics of Lancaster FRP composite pile 40
Figure 3.10 Surface characteristics of Hardcore FRP composite pile 41
Figure 3.11 Surface characteristics of Hardcore FRP plate 41
Figure 3.12 Surface characteristics of Hardcore surface treated FRP plate 42
Figure 3.13 Surface characteristics of Plastic Piling plastic composite pile 42
Figure 3.14 Surface characteristics of prestressed concrete pile 43
Figure 3.15 Surface characteristics of steel sheet pile 43
Figure 3.16 Sketch of modified interface shear test setup 46
Figure 3.17 Typical interface shear test results for Density sand ($s_n^\prime \sim 100$ kPa) 49
Figure 3.18 Typical interface shear test results for Model sand ($s_n^\prime \sim 100$ kPa) 50
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.19</td>
<td>Interface shear strength envelopes for Lancaster Composite FRP shell</td>
</tr>
<tr>
<td>3.20</td>
<td>Interface shear strength envelopes for Hardcore Composite FRP shell</td>
</tr>
<tr>
<td>3.21</td>
<td>Interface shear strength envelopes for untreated Hardcore FRP plate</td>
</tr>
<tr>
<td>3.22</td>
<td>Interface shear strength envelopes for treated Hardcore FRP plate</td>
</tr>
<tr>
<td>3.23</td>
<td>Interface shear strength envelopes for PPI plastic</td>
</tr>
<tr>
<td>3.24</td>
<td>Interface shear strength envelopes for concrete</td>
</tr>
<tr>
<td>3.25</td>
<td>Interface shear strength envelopes for steel</td>
</tr>
<tr>
<td>3.26</td>
<td>Goodness of fit for multiple linear regression on Density sand tan $d_{peak}$ values</td>
</tr>
<tr>
<td>3.27</td>
<td>Goodness of fit for multiple linear regression on Density sand tan $d_{cv}$ values</td>
</tr>
<tr>
<td>3.28</td>
<td>Goodness of fit for multiple linear regression on Model sand tan $d_{peak}$ values</td>
</tr>
<tr>
<td>3.29</td>
<td>Goodness of fit for multiple linear regression on Model sand tan $d_{cv}$ values</td>
</tr>
</tbody>
</table>

**Chapter 4**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Burnoff testing</td>
</tr>
<tr>
<td>4.2</td>
<td>Typical tension test setup</td>
</tr>
<tr>
<td>4.3</td>
<td>Typical split disk test setup</td>
</tr>
<tr>
<td>4.4</td>
<td>Freeze-thaw chamber</td>
</tr>
<tr>
<td>4.5</td>
<td>Freeze-thaw fixture</td>
</tr>
<tr>
<td>4.6</td>
<td>Average freeze-thaw cycle undergone by FRP samples</td>
</tr>
<tr>
<td>4.7</td>
<td>Representative baseline longitudinal tension stress-strain curves</td>
</tr>
<tr>
<td>4.8</td>
<td>Representative baseline hoop tension stress-strain curves</td>
</tr>
<tr>
<td>4.9</td>
<td>Absorption curves for Lancaster 12-inch FRP tube</td>
</tr>
<tr>
<td>4.10</td>
<td>Absorption curves for Lancaster 24-inch FRP tube</td>
</tr>
<tr>
<td>4.11</td>
<td>Absorption curves for Hardcore 12-inch FRP tube</td>
</tr>
<tr>
<td>4.12</td>
<td>Absorption curves for Hardcore 24-inch FRP tube</td>
</tr>
<tr>
<td>4.13</td>
<td>Selected diffusion analyses for Lancaster 12-inch FRP samples</td>
</tr>
<tr>
<td>4.14</td>
<td>Selected diffusion analyses for Lancaster 24-inch FRP samples</td>
</tr>
<tr>
<td>4.15</td>
<td>Selected diffusion analyses for Hardcore 12-inch FRP samples</td>
</tr>
<tr>
<td>4.16</td>
<td>Selected diffusion analyses for Hardcore 24-inch FRP samples</td>
</tr>
</tbody>
</table>
Figure 4.17 Longitudinal tensile properties versus submergence time for Lancaster 24-inch FRP tube
Figure 4.18 Hoop tensile properties versus submergence time for Lancaster 24-inch FRP tube
Figure 4.19 Longitudinal tensile properties versus submergence time for Lancaster 12-inch FRP tube
Figure 4.20 Hoop tensile properties versus submergence time for Lancaster 12-inch FRP tube
Figure 4.21 Longitudinal tensile properties versus moisture content for Lancaster 12-inch FRP tube
Figure 4.22 Hoop tensile properties versus moisture content for Lancaster 12-in FRP tube
Figure 4.23 Longitudinal tensile properties versus submergence time for Hardcor 24-inch FRP tube
Figure 4.24 Longitudinal tensile properties versus moisture content for Hardcor 24-inch FRP tube
Figure 4.25 Longitudinal tensile properties versus submergence time for Hardcor 12-inch FRP tube
Figure 4.26 Hoop tensile properties versus submergence time for Hardcor 12-inch FRP tube
Figure 4.27 Longitudinal tensile properties versus moisture content for Hardcor 12-inch FRP tube
Figure 4.28 Hoop tensile properties versus moisture content for Hardcor 12-inch FRP tube
Figure 4.29 Influence of freeze-thaw cycles on the longitudinal tensile properties for the Lancaster 24-inch FRP tube
Figure 4.30 Influence of freeze-thaw cycles on the longitudinal tensile properties for the Lancaster 12-inch FRP tube
Figure 4.31 Influence of freeze-thaw cycles on the longitudinal tensile properties for the Hardcor 24-inch FRP tube
Figure 4.32 Influence of freeze-thaw cycles on the longitudinal tensile properties for the Hardcor 12-inch FRP tube
Figure 4.33 SEM images for Lancaster 24-inch FRP tube
Figure 4.34 SEM images for Lancaster 12-inch FRP tube
Figure 4.35 SEM images for Hardcor 24-inch FRP tube
Figure 4.36 SEM images for Hardcor 12-inch FRP tube
Figure 4.37 Estimated long-term axial capacity of the 12-inch Lancaster pile 108
Figure 4.38 Estimated long-term flexural capacity of the 12-inch Lancaster pile 109

Chapter 5

Figure 5.1 Location map of the Route 40 Bridge Project in Sussex County, Virginia (Fam et al. 2003) 114
Figure 5.2 Former Route 40 bridge 114
Figure 5.3 Signs of deterioration of the former Route 40 bridge (Fam et al. 2003) 115
Figure 5.4 Schematic of the new Route 40 bridge 116
Figure 5.5 Concrete-filled FRP tubular piles 118
Figure 5.6 Stress-strain response of concrete used in the composite pile 119
Figure 5.7 Reinforcement details of prestressed concrete pile 120
Figure 5.8 Simplified soil stratigraphy near test pile area 121
Figure 5.9 Fabrication of prestressed concrete pile 122
Figure 5.10 Fabrication of concrete-filled FRP piles 123
Figure 5.11 Driving of test piles 124
Figure 5.12 Driving records for test piles 125
Figure 5.13 End-of-driving PDA recordings 127
Figure 5.14 Test pile instrumentation 130
Figure 5.15 Axial load test setup using the Statnamic device 131
Figure 5.16 Pile head displacement versus equivalent axial static load 132
Figure 5.17 Axial load – axial strain behavior of test piles 133
Figure 5.18 Variation of axial strain along pile length for 3 Statnamic load cycles 133
Figure 5.19 Lateral Statnamic setup at the Route 40 project 135
Figure 5.20 Displacement time histories at the loading point for both piles (Brown et al. 2003) 136
Figure 5.21 Peak lateral displacement profiles for both test piles at different cycles of Statnamic load 137
Figure 5.22 Calculated static and dynamic (static+damping) resistances for both test piles 141
Figure 5.23 Moment-curvature responses for composite and prestressed concrete piles 143
Figure 5.24 Computed and measure lateral load-displacement response for both test piles (Brown et al. 2002) 144
Figure 5.25 Details of pile head showing the bars used to connect the pile to cap beam 146
| Figure 5.26 | Connection of composite piles to cap beam at Pier No. 2 | 146 |
| Figure 5.27 | Pier No. 2 including the composite piles and reinforced concrete cap beam | 147 |
| Figure 5.28 | The new Route 40 bridge over the Nottoway River in Virginia | 147 |

### Chapter 6

| Figure 6.1 | Location map of the Route 351 bridge in Hampton, Virginia | 151 |
| Figure 6.2 | Aerial view of the Route 351 bridge in Hampton, Virginia | 151 |
| Figure 6.3 | Wide angle views of the original Route 351 bridge | 152 |
| Figure 6.4 | Signs of deterioration of the original Route 351 bridge | 153 |
| Figure 6.5 | Schematic of the new Route 351 bridge | 154 |
| Figure 6.6 | Test pile cross section details | 155 |
| Figure 6.7 | Test pile material properties | 157 |
| Figure 6.8 | Axial load – axial strain behavior of test piles | 158 |
| Figure 6.9 | Flexural characteristics for the three test piles | 160 |
| Figure 6.10 | Location of test pile site at the Route 351 bridge | 161 |
| Figure 6.11 | Simplified soil stratigraphy near test pile area | 163 |
| Figure 6.12 | Pile load test layout | 164 |
| Figure 6.13 | Instrumentation layout for prestressed concrete test pile | 166 |
| Figure 6.14 | Instrumentation layout for FRP composite test pile | 168 |
| Figure 6.15 | Instrumentation layout for plastic composite test pile | 169 |
| Figure 6.16 | Fabrication of prestressed concrete test pile | 170 |
| Figure 6.17 | Fabrication of concrete-filled FRP piles | 172 |
| Figure 6.18 | Setup used for concrete filling of FRP composite piles | 173 |
| Figure 6.19 | Concrete filling of FRP composite piles | 174 |
| Figure 6.20 | Rebar cage of the plastic composite test pile | 175 |
| Figure 6.21 | Photos of manufacturing process for the plastic composite test pile | 176 |
| Figure 6.22 | Driving records for test piles | 177 |
| Figure 6.23 | Installation of prestressed concrete test pile | 178 |
| Figure 6.24 | Installation of FRP composite test pile | 179 |
| Figure 6.25 | Installation of plastic composite test pile | 180 |
| Figure 6.26 | PDA recordings during restrike | 182 |
| Figure 6.27 | Selected photos of PIT tests on test piles | 185 |
| Figure 6.28 | PIT sounding on the prestressed concrete test pile before installation | 186 |
| Figure 6.29 | PIT sounding on the prestressed concrete test pile after installation | 186 |
| Figure 6.30 | PIT sounding on the FRP composite test pile before installation | 187 |
| Figure 6.31 | PIT sounding on the FRP composite test pile after installation | 187 |
Figure 6.32  PIT sounding on the plastic composite test pile before installation 188
Figure 6.33  PIT sounding on the plastic composite test pile after installation 188
Figure 6.34  Photos of axial load test of prestressed concrete pile 190
Figure 6.35  Axial load test results 191
Figure 6.36  Distribution of residual loads 193
Figure 6.37  Distribution of residual stresses 193
Figure 6.38  Load distribution for the three test piles at the Davisson failure loads 194
Figure 6.39  Mobilized average unit shaft resistance – toe resistance relationships for the three test piles 196
Figure 6.40  Apparent strength gain with time measured in the three test piles 197
Figure 6.41  Deformed shapes of piles at different lateral loads 198
Figure 6.42  Measured lateral deflections at ground surface for the three test piles 199

Chapter 7
Figure 7.1  Load transfer in an axially loaded pile 202
Figure 7.2  Interpreted average CPT and SPT design profiles for Route 351 test site 212
Figure 7.3  Accuracy of Nordlund method predictions using d values from Nordlund’s charts 213
Figure 7.4  Accuracy of Nordlund method predictions using d values from interface shear tests 214
Figure 7.5  Accuracy of API method predictions using d values from Table 7.1 215
Figure 7.6  Accuracy of API method predictions using d values from interface shear tests 216
Figure 7.7  Accuracy of LCPC method predictions using “steel pile” assumption 217
Figure 7.8  Accuracy of LCPC method predictions using “concrete pile” assumption 218
Figure 7.9  Accuracy of IC method predictions using d values from interface shear tests 219
Figure 7.10  Idealized model used in T-Z load transfer analyses 223
Figure 7.11  Pile tip load – pile tip displacement curve (Q-Z) (API 1993) 225
Figure 7.12  Maximum shear stress distribution along pile shaft, according to API (1993) 226
Figure 7.13  Settlement predictions for the prestressed concrete pile using API (1993) 227
Figure 7.14 Settlement predictions for the FRP pile using API (1993) 228
Figure 7.15 Settlement predictions for the plastic pile using API (1993) 229
Figure 7.16 Normalized T-Z curves according to API (1993) and Vijayvergiya (1977) 230
Figure 7.17 Normalized Q-Z curves according to Vijayvergiya (1997) and API (1993) 231
Figure 7.18 Maximum shear stress distributions used in predictions using Vijayvergiya (1977) 232
Figure 7.19 Settlement predictions for the concrete pile using Vijayvergiya (1977) 233
Figure 7.20 Settlement predictions for the FRP pile using Vijayvergiya (1977) 234
Figure 7.21 Settlement predictions for the plastic pile using Vijayvergiya (1977) 235
Figure 7.22 Concentric cylinder model for settlement analysis of axially loaded piles (adapted from Randolph and Wroth 1978) 237
Figure 7.23 Linear T-Z curve obtained using Randolph and Wroth (1978) 240
Figure 7.24 Linear $Q_b$-Z curve obtained using Boussinesq’s theory 241
Figure 7.25 Hyperbolic T-Z curve based on Randolph and Wroth (1978) 246
Figure 7.26 Variation of secant shear modulus for different hyperbolic-type models 247
Figure 7.27 Theoretically derived T-Z curve using concentric cylinders and the modified hyperbola from Fahey and Carter (1992) 249
Figure 7.28 Theoretically derived $Q$-$Z$ curve using Boussinesq’s theory and the modified hyperbola from Fahey and Carter (1992) 250
Figure 7.29 Route 351 initial shear modulus profile from CPT correlations 251
Figure 7.30 Settlement predictions for the concrete pile using theoretically derived transfer curves 253
Figure 7.31 Settlement predictions for the FRP pile using theoretically derived transfer curves 254
Figure 7.32 Settlement predictions for the plastic pile using theoretically derived transfer curves 255
Chapter 8

Table of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 8.1</td>
<td>Laterally loaded pile problem</td>
<td>260</td>
</tr>
<tr>
<td>Figure 8.2</td>
<td>Distribution of stresses against a pile before and after lateral loading (adapted from Reese and Van Impe 2001)</td>
<td>266</td>
</tr>
<tr>
<td>Figure 8.3</td>
<td>Typical p-y curve and resulting p-y modulus (Reese and Van Impe 2001)</td>
<td>267</td>
</tr>
<tr>
<td>Figure 8.4</td>
<td>Schematic showing the influence of shape of cross section of pile on the soil reaction p (adapted from Reese and Van Impe 2001)</td>
<td>269</td>
</tr>
<tr>
<td>Figure 8.5</td>
<td>Elements of a characteristic p-y curve for sand based on recommendations by Reese et al. (1974)</td>
<td>270</td>
</tr>
<tr>
<td>Figure 8.6</td>
<td>Schematic showing p-y model used for analysis of laterally loaded piles</td>
<td>272</td>
</tr>
<tr>
<td>Figure 8.7</td>
<td>In situ test data for the upper soils in the northern end of the test pile site</td>
<td>275</td>
</tr>
<tr>
<td>Figure 8.8</td>
<td>In situ test data for the upper soils in the southern end of the test pile site</td>
<td>275</td>
</tr>
<tr>
<td>Figure 8.9</td>
<td>Initial p-y modulus profile used to define default p-y curves for LPILE analyses on the prestressed concrete pile</td>
<td>278</td>
</tr>
<tr>
<td>Figure 8.10</td>
<td>Predicted versus measured lateral displacement profile for prestressed concrete pile (Lateral loads 51.2 and 97.3 kN)</td>
<td>278</td>
</tr>
<tr>
<td>Figure 8.11</td>
<td>Predicted versus measured lateral displacement profile for prestressed concrete pile (Lateral loads 141.2 and 186.4 kN)</td>
<td>279</td>
</tr>
<tr>
<td>Figure 8.12</td>
<td>Predicted versus measured lateral displacement profile for prestressed concrete pile (Lateral loads 228 and 247.7 kN)</td>
<td>279</td>
</tr>
<tr>
<td>Figure 8.13</td>
<td>Calculated load-deflection curve for the prestressed concrete pile</td>
<td>280</td>
</tr>
<tr>
<td>Figure 8.14</td>
<td>Calculated load-slope curve for the prestressed concrete pile</td>
<td>281</td>
</tr>
<tr>
<td>Figure 8.15</td>
<td>Initial p-y modulus profile used to define default p-y curves for LPILE analyses on the FRP pile</td>
<td>283</td>
</tr>
<tr>
<td>Figure 8.16</td>
<td>Predicted versus measured lateral displacement profile for FRP pile (Lateral loads 51.6 and 96 kN)</td>
<td>283</td>
</tr>
<tr>
<td>Figure 8.17</td>
<td>Predicted versus measured lateral displacement profile for FRP pile (Lateral loads 144.8 and 186.1 kN)</td>
<td>284</td>
</tr>
<tr>
<td>Figure 8.18</td>
<td>Predicted versus measured lateral displacement profile for FRP pile (Lateral loads 230.1 and 270.5 kN)</td>
<td>284</td>
</tr>
<tr>
<td>Figure 8.19</td>
<td>Calculated load-deflection curve for the FRP pile</td>
<td>285</td>
</tr>
<tr>
<td>Figure 8.20</td>
<td>Calculated load-slope curve for the FRP pile</td>
<td>286</td>
</tr>
<tr>
<td>Figure 8.21</td>
<td>Initial p-y modulus profile used to define default p-y curves for LPILE analyses on the plastic pile</td>
<td>288</td>
</tr>
<tr>
<td>Figure 8.22</td>
<td>Predicted versus measured lateral displacement profile for plastic pile (Lateral loads 48.1 and 102.4 kN)</td>
<td>288</td>
</tr>
<tr>
<td>Figure 8.23</td>
<td>Predicted versus measured lateral displacement profile for plastic pile (Lateral loads 140.1 and 183.1 kN)</td>
<td>289</td>
</tr>
<tr>
<td>Figure 8.24</td>
<td>Predicted versus measured lateral displacement profile for plastic pile (Lateral loads 230.8 and 275.3 kN)</td>
<td>289</td>
</tr>
<tr>
<td>Figure 8.25</td>
<td>Calculated load-deflection curve for the plastic pile</td>
<td>290</td>
</tr>
<tr>
<td>Figure 8.26</td>
<td>Calculated load-slope curve for the plastic pile</td>
<td>291</td>
</tr>
</tbody>
</table>
Chapter 9

Figure 9.1 Location of instrumented production piles at the Route 351 bridge 296
Figure 9.2 Load transfer instrumentation layout for prestressed concrete production pile 298
Figure 9.3 Instrumentation layout for FRP composite production pile 301
Figure 9.4 Layout of external durability instrumentation used in the FRP composite production pile 302
Figure 9.5 Simplified stratigraphy along the Route 351 bridge alignment 303
Figure 9.6 Simplified stratigraphy in the vicinity of the instrumented prestressed concrete pile installed at Pier 10 304
Figure 9.7 Simplified stratigraphy in the vicinity of the instrumented FRP composite pile installed at Pier 11 305
Figure 9.8 Driving records for instrumented production piles 306
Figure 9.9 PDA recordings during restrike (Spiro and Pais 2002b) 308
Figure 9.10 PIT sounding on the prestressed concrete production pile before installation 310
Figure 9.11 PIT sounding on the prestressed concrete production pile after installation and restrike 310
Figure 9.12 PIT sounding on the FRP composite production pile before installation 311
Figure 9.13 PIT sounding on the FRP composite production pile before installation 311
Figure 9.14 Photo of Route 351 bridge under construction on December 30, 2002 313
Figure 9.15 Load distributions on November 7, 2002 and December 30, 2002 for the prestressed concrete production pile at Pier 10 314
Figure 9.16 Load distributions on November 7, 2002 and December 30, 2002 for the FRP composite production pile at Pier 11 315

Appendix A

Figure A.1 Interface shear test results Density Sand-to-Lancaster FRP shell interface 356
Figure A.2 Interface shear test results Density Sand-to-Hardcore FRP shell interface 357
Figure A.3 Interface shear test results Density Sand-to-HC FRP plate (untreated) interface 358
Figure A.4 Interface shear test results Density Sand-to-Treated FRP plate interface 359
Figure A.5 Interface shear test results Density Sand-to-Plastic interface 360
Figure A.6 Interface shear test results Density Sand-to-Concrete interface 361
Figure A.7 Interface shear test results Density Sand-to-Steel interface 362
Figure A.8 Interface shear test results Model Sand-to-Lancaster FRP shell interface 363
Figure A.9 Interface shear test results Model Sand-to-Hardcore FRP
| Figure A.10 | Interface shear test results Model Sand-to-HC FRP plate (untreated) interface |
| Figure A.11 | Interface shear test results Model Sand-to-Treated FRP plate interface |
| Figure A.12 | Interface shear test results Model Sand-to-Plastic interface |
| Figure A.13 | Interface shear test results Model Sand-to-Concrete interface |
| Figure A.14 | Interface shear test results Model Sand-to-Steel interface |

**Appendix B**

| Figure B.1   | Moisture concentration profile for the case in which the inner radius of the FRP is dry and the outer radius of the FRP is saturated |
| Figure B.2   | Moisture concentration profile for the case in which the inner and outer radii of the FRP are saturated |

**Appendix C**

| Figure C.1   | VTRC pushout test setup |
| Figure C.2   | VT pushout test setup |
| Figure C.3   | Creep bending test setup |
| Figure C.4   | Creep deflection test results |

**Appendix D**

| Figure D.1   | Location of field tests |
| Figure D.2   | Boring B-1 (SPT-1) |
| Figure D.3   | Boring B-2 (SPT-2) |
| Figure D.4   | CPT-1 |
| Figure D.5   | CPT-2 |
| Figure D.6   | CPT033 |
| Figure D.7   | CPT034 |
| Figure D.8   | DMT |
LIST OF TABLES

Chapter 2
Table 2.1 Selected projects involving installation of composite piles 7
Table 2.2 Expressions for the strength of confined concrete and maximum axial strain (adapted from Shehata et al. 2002) 11
Table 2.3 Available structural information for steel reinforced plastic piles by Plastic Pilings, Inc. 19
Table 2.4 Comparison of pile impedance 24

Chapter 3
Table 3.1 Interface behavior test matrix 30
Table 3.2 Index parameter values of the sands used in this study 31
Table 3.3 Internal friction angles obtained from direct shear tests 33
Table 3.4 Summary of surface roughness measurements 44
Table 3.5 Surface hardness 45
Table 3.6 Summary of interface shear test results on Density sand 47
Table 3.7 Summary of interface shear test results on Model sand 48
Table 3.8 Summary of interface friction angles 54
Table 3.9 Multiple linear regression result for tan \( \delta_{\text{peak}} \) of Density sand 56
Table 3.10 Multiple linear regression result for tan \( \delta_{\text{cv}} \) of Density sand 57
Table 3.11 Multiple linear regression result for tan \( \delta_{\text{peak}} \) of Model sand 58
Table 3.12 Multiple linear regression result for tan \( \delta_{\text{cv}} \) of Model sand 59

Chapter 4
Table 4.1 Characterization data for Lancaster Composites, Inc. 12-inch FRP tube 68
Table 4.2 Characterization data for Lancaster Composites, Inc. 24-inch FRP tube 68
Table 4.3 Characterization data for Hardcore Composites, Inc. 12-inch FRP tube 70
Table 4.4 Characterization data for Hardcore Composites, Inc. 24-inch FRP tube 71
Table 4.5 As-received longitudinal tensile properties 77
Table 4.6 As-received hoop tensile properties 78
Table 4.7 Fickian diffusion parameters for the Lancaster 12-inch FRP 88
Table 4.8 Fickian diffusion parameters for the Lancaster 24-inch FRP 88
Table 4.9 Fickian diffusion parameters for the Hardcore 12-inch FRP 89
Table 4.10 Fickian diffusion parameters for the Hardcore 24-inch FRP 89
Chapter 5
Table 5.1  Mechanical properties of FRP shell of composite pile 119
Table 5.2  Pile driving measurements for the prestressed and composite pile 127
Table 5.3  Summary of signal matching analyses at end-of-driving (from Muchard et al. 1999) 128

Chapter 6
Table 6.1  Summary of pile driving measurement for the prestressed and composite piles (after Spiro and Pais 2002) 183
Table 6.2  Summary of CASE and CAPWAP analyses results (Spiro and Pais 2002) 184
Table 6.3  Test dates for the test pile program at the Route 351 bridge project 189
Table 6.4  Comparison of failure loads for the three test piles 192
Table 6.5  Load distributions from static load tests at the Davisson failure loads 195
Table 6.6  Unit shaft and toe resistances from static axial load tests 195

Chapter 7
Table 7.1  API recommendations for side friction in siliceous soil (API 1993) 205
Table 7.2  API recommendations for tip resistance in siliceous soil (API 1993) 206
Table 7.3  LCPC friction coefficient a for sands (Bustamente and Gianeselli 1982) 207
Table 7.4  LCPC bearing capacity factors for driven piles in sands (after Bustamente and Gianeselli 1982) 208
Table 7.5  Predicted axial capacities for the test piles at Route 351 220

Chapter 8
Table 8.1  Relationships commonly used for elastic piles in flexion 259
Table 8.2  Recommended criteria for p-y curves in different soils (adapted from Reese and Isenhower, 1997) 268
Table 8.3  Properties of test piles 273
Table 8.4  Parameters used to define default p-y curves in LPILE for the prestressed concrete pile 277
Table 8.5  Parameters used to define default p-y curves in LPILE for the FRP pile 282
Table 8.6  Parameters used to define default p-y curves in LPILE for the plastic pile 287
Chapter 9
Table 9.1 Summary of pile driving measurements for the prestressed and FRP production piles (after Spiro and Pais 2002b) 308
Table 9.2 Summary of CASE and CAPWAP analyses results (Spiro and Pais 2002b) 309
Table 9.3 Test dates for the instrumented production pile program at the Route 351 bridge project 312
Table 9.4 Monitoring dates for prestressed concrete pile at the Route 351 bridge 312
Table 9.5 Monitoring dates for FRP composite pile at the Route 351 bridge 312

Chapter 11
Table 11.1 Project objectives 323

Appendix A
Table A.1 Organization of the figures in Appendix A 355

Appendix C
Table C.1 Summary of pushout test results 377