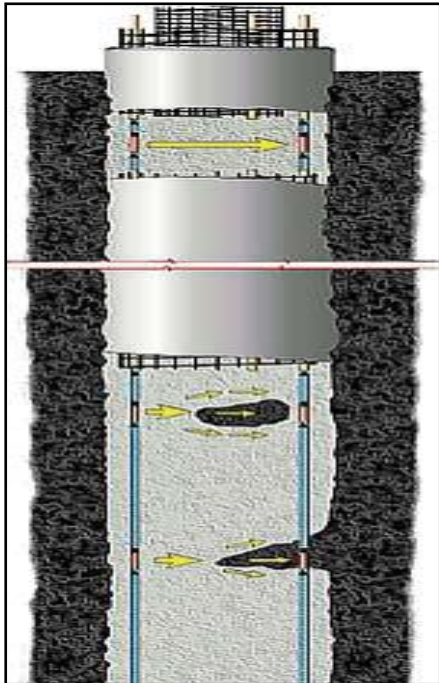

DRILLED SHAFT AXIAL CAPACITY

Effects Due to Anomalies

Publication No. FHWA-CFL/TD-08-008

September 2008



U.S. Department
of Transportation
**Federal Highway
Administration**



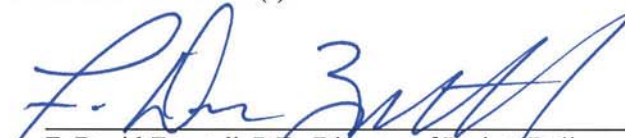
Central Federal Lands Highway Division
12300 West Dakota Avenue
Lakewood, CO 80228

FOREWORD

The Federal Lands Highway (FLH) of the Federal Highway Administration (FHWA) promotes development and deployment of applied research and technology applicable to solving transportation related issues on Federal Lands. The FLH provides technology delivery, innovative solutions, recommended best practices, and related information and knowledge sharing to Federal agencies, Tribal governments, and other offices within the FHWA.

The objective of this study was to produce guidelines for assessing the importance of defects on the drilled shaft capacity in different soils and also priority for remediation effort. The study included a literature search on earlier research, enhancement of a finite element code, PSI for use in this study, results of a comprehensive finite element analysis program with varying factors including defect location and sizes, soil types, and concrete strength. The following are the recommendations for the remediation guidelines:

- A proper construction quality monitoring program including sonic wave survey, tomographic imaging, and temperature, moisture, and density measurements are recommended for all critical drilled shafts,
- Once defects are located remediation measures must be implemented to fill the defect voids with concrete,
- If prioritization is necessary in fixing the defects, the shallow, non-concentric defects must receive first attention because of its experience of a higher pile loads than a deeper defects,
- The effects of soil types and strengths must be properly assessed from the pile load transfer and structural capacity curves to assess the critical nature of a defect(s).



F. David Zanetell, P.E., Director of Project Delivery
Federal Highway Administration
Central Federal Lands Highway Division

Notice

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The U.S. Government assumes no liability for the use of the information contained in this document. This report does not constitute a standard, specification, or regulation.

The U.S. Government does not endorse products or manufacturers. Trademarks or manufacturers' names appear in this report only because they are considered essential to the objective of the document.

Quality Assurance Statement

The FHWA provides high-quality information to serve Government, industry, and the public in a manner that promotes public understanding. Standards and policies are used to ensure and maximize the quality, objectivity, utility, and integrity of its information. FHWA periodically reviews quality issues and adjusts its programs and processes to ensure continuous quality improvement.

Technical Report Documentation Page

1. Report No. FHWA-CFL/TD-08-008	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle <i>Drilled Shaft Axial Capacities Effects Due to Anomalies</i>		5. Report Date September 2008	
		6. Performing Organization Code	
7. Author(s) Nien-Yin Chang, Ph.D., P.E., Principal Investigator (P.I.) Hien Nghiem, Research Assistant (R.A.)		8. Performing Organization Report No. CGES 001-08	
9. Performing Organization Name and Address Center for Geotechnical Engineering Science, University of Colorado, Denver, 1200 Larimer Street, Denver, CO 80217-3364		10. Work Unit No. (TRAVIS)	
		11. Contract or Grant No. DTFH68-06-X-00033	
12. Sponsoring Agency Name and Address Federal Highway Administration Central Federal Lands Highway Division 12300 West Dakota Avenue, Suite 210 Lakewood, CO 80228		13. Type of Report and Period Covered Final Report August 2006 – April 2008	
		14. Sponsoring Agency Code HFTS-16.4	
15. Supplementary Notes COTR: Khamis Y. Haramy, FHWA-CFLHD. Advisory Panel Members: Roger Surdahl, FHWA-CFLHD; Scott Anderson and Barry Siel, FHWA-RC; and Matt Greer, FHWA-CO Division. This project was funded under the FHWA Federal Lands Highway Technology Deployment Initiatives and Partnership Program (TDIPP).			
16. Abstract Drilled shafts are increasingly being used in supporting critical structures, mainly because of their high-load supporting capacities, relatively low construction noise, and technological advancement in detecting drilled shaft anomalies created during construction. The critical importance of drilled shafts as foundations makes it mandatory to detect the size and location of anomalies and assess their potential effect on drilled shaft capacity. Numerical analysis was conducted using Pile-Soil Interaction (PSI), a finite element analysis program to assess the effect of different anomalies on the axial load capacities of drilled shafts in soils ranging from soft to extremely stiff clay and loose to very dense sand. The investigation included the affect of anomalies of various sizes and lengths on both structural and geotechnical capacities. The analysis results indicate that the drilled shaft capacity is affected by the size and location of the anomaly and the strength of the surrounding soil. Also, nonconcentric anomalies significantly decrease the structural capacity of a drilled shaft under axial load. The resulting drilled shaft capacity then equals the smaller one of the two capacities: structural or geotechnical.			
17. Key Words DRILLED SHAFTS, GEOTECHNICAL, STRUCTURAL, DRILLED SHAFT CAPACITIES, ANOMALIES, FINITE ELEMENT ANALYSIS, PSI		18. Distribution Statement No restriction. This document is available to the public from the sponsoring agency at their website http://www.cflhd.gov .	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 148	22. Price

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in ²	square inches	645.2	square millimeters	mm ²
ft ²	square feet	0.093	square meters	m ²
yd ²	square yard	0.836	square meters	m ²
ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	square kilometers	km ²
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft ³	cubic feet	0.028	cubic meters	m ³
yd ³	cubic yards	0.765	cubic meters	m ³
NOTE: volumes greater than 1000 L shall be shown in m ³				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm ²	square millimeters	0.0016	square inches	in ²
m ²	square meters	10.764	square feet	ft ²
m ²	square meters	1.195	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.386	square miles	mi ²
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m ³	cubic meters	35.314	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

TABLE OF CONTENTS

CHAPTER 1 - INTRODUCTION.....	1
CHAPTER 2 - LITERATURE REVIEW.....	3
2.1 LITERATURE REVIEW OF CAPACITY OF DRILLED SHAFTS WITH ANOMALIES	3
2.2. DESIGN METHOD FOR AXIAL CAPACITY.....	11
2.2.1 Design for axial capacity in cohesive soil.....	11
2.2.1.1 <i>Side resistance in cohesive soils</i>	11
2.2.1.2 <i>End bearing in cohesive soils</i>	13
2.2.2 Design for axial capacity in cohesionless soil.....	13
2.2.2.1 <i>Side resistance in cohesionless soil</i>	13
2.2.2.2 <i>End bearing in cohesionless soil</i>	18
2.3. LOAD TRANSFER CURVES.....	19
2.3.1 Theoretical load transfer curve.....	19
2.3.1.1 <i>Elasto-perfect plastic model</i>	19
2.3.1.2 <i>Hyperbolic mode</i>	20
2.3.1.3 <i>Determination of parameters for nonlinear spring</i>	22
2.3.1.3.1 Initial shear modulus.....	22
2.3.1.3.2 Spring stiffness.....	23
2.3.1.3.3 Ultimate force.....	24
2.3.2 Load transfer curves from field test studies.....	25
CHAPTER 3 - STRUCTURAL CAPACITY OF DRILLED SHAFTS.....	31
3.1 AXIAL LOAD.....	31
3.2 AXIAL LOAD AND BENDING MOMENT.....	31
CHAPTER 4 - PILE-SOIL INTERACTION (PSI) FINITE ELEMENT CODE.....	35
4.1 INTRODUCTION.....	35
4.2 FINITE ELEMENTS.....	35
4.3 ELASTO-PLASTIC RATE INTEGRATION OF DIFFERENTIAL PLASTIC MODELS.....	36
4.4 CONSTITUTIVE MODELS OF SOILS.....	37
4.4.1 Mohr-Coulomb Model.....	37
4.4.2 Cap Model.....	38
4.5 ELASTO-PERFECT PLASTIC MODEL FOR BAR ELEMENT.....	40
4.6 CONVERGENCE CRITERIA.....	40
4.7 PSI CALIBRATION AND VALIDATION.....	41
4.7.1 Case histories for calibration.....	41
4.7.2 Comparative study between PSI and LS-DYNA codes.....	49
CHAPTER 5 - CAPACITIES OF DRILLED SHAFTS WITH ANOMALIES.....	57
5.1. STRUCTURAL CAPACITY OF DRILLED SHAFTS.....	57
5.1.1 Concrete.....	57
5.1.2 Structural capacity of drilled shafts without anomalies via ACI Code.....	58

DRILLED SHAFT AXIAL CAPACITY, EFFECTS DUE TO ANOMALIES - TABLE OF CONTENTS

5.2. STRUCTURAL CAPACITY OF DRILLED SHAFTS WITH ANOMALIES59
 5.2.1 Size, location, and properties of anomalies59
 5.2.2 Structure capacity of drilled shafts with anomalies63
5.3. SOIL PROPERTIES64
5.4. SHAFT MODEL.....67
5.5. DEFINE THE EFFECT OF ANOMALIES68
5.6. CAPACITIES OF DRILLED SHAFTS IN COHESIVE SOILS69
5.7. CAPACITIES OF DRILLED SHAFTS IN COHESIONLESS SOILS81
5.8. CAPACITIES OF DRILLED SHAFTS IN COHESIVE SOIL WITH
 BEDROCK AT SHAFT TIP90

CHAPTER 6 - SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS93
 6.1. SUMMARY93
 6.2. CONCLUSIONS.....93
 6.3. RECOMMENDATIONS FOR REMEDIATION94
 6.4. FUTURE STUDY95

APPENDIX A – FIGURES97

REFERENCES131

LIST OF FIGURES

Figure 1. Defective drilled shaft with multiple types of anomalies (DiMaggio, 2008).....1

Figure 2. Drilled shaft profile in varved clay and legend for planned and predicted anomalies (Iskander, et al., 2003)4

Figure 3. Planned and predicted anomalies in Shaft #2 (Iskander, et al., 2003).....4

Figure 4. Planned and predicted anomalies in Shaft #4 (Iskander, et al., 2003).....5

Figure 5. Parameter of void flaws (after O’Neill, et al., 2003).....7

Figure 6. Moment deflection curves for flexural tests (after O’Neill, et al., 2003).....7

Figure 7. Moment deflection curves for combined loading tests (after O’Neill, et al., 2003)8

Figure 8. Asymmetric anomaly (Jung, et al., 2006).....9

Figure 9. Normalized axial stress across defective section (Jung, et al., 2006).....9

Figure 10. Typical cylindrical anomaly in a drilled shaft (Haramy, 2006)10

Figure 11. Variation of α with c_u/p_a (Kulhawy and Jackson, 1989)12

Figure 12. Back-calculated lateral earth pressure coefficient K versus depth for load tests along with boundaries for $(K_0)_{NC}$ and K_p (Rollins, et al., 2005)15

Figure 13. Back-calculated β versus depth from load tests in (Rollins, et al., 2005)16

Figure 14. Predicted and actual f_s values for sands, sand gravels, and gravels (Harraz, et al., 2005).....16

Figure 15. Back-calculated Horizontal stress to Vertical stress ratio, K , vs. % Gravel (Harraz, et al., 2005).....17

Figure 16. Back-calculated Horizontal stress to Vertical stress ratio, K , vs. Depth to Mid-layer (Harraz, et al., 2005)17

Figure 17. Initial empirical model (Harraz, et al., 2005)18

Figure 18. Predicted and actual f_s values for sands, sand gravels, and gravels using the initial empirical model (Harraz, et al., 2005)18

Figure 19. Numerical model of an axially loaded shaft and load transfer curve19

Figure 20. Elasto-perfect plastic model20

Figure 21. Hyperbolic model20

Figure 22. Variation of tangent shear modulus for hyperbolic and modified hyperbolic models22

Figure 23. Shearing of concentric cylinders (Kraft, et al., 1981)23

Figure 24. Shaft base load and shaft base displacement curve (API 1993).....25

Figure 25. Normalized side load transfer for drilled shafts in cohesive soil (after O’Neill and Reese, 1999)27

Figure 26. Normalized base load transfer for drilled shafts in cohesive soil (after O’Neill and Reese, 1999)27

Figure 27. Shaft Normalized side load transfer for drilled shafts in cohesionless soil (after O’Neill and Reese, 1999)28

Figure 28. Normalized base load transfer for drilled shafts in cohesionless soil (after O’Neill and Reese, 1999)28

Figure 29. Normalized base load transfer for drilled shafts in cohesionless soil (after Rollins, et al., 2005)29

Figure 30. Strain distributions corresponding to point on the P-M interaction diagram (McGregor and Wight, 2005)32

DRILLED SHAFT AXIAL CAPACITY, EFFECTS DUE TO ANOMALIES - TABLE OF CONTENTS

Figure 31. Nonconcentric anomaly.....	32
Figure 32. Stress strain curve for concrete (O'Neill and Reese, 1999)	33
Figure 33. Stress strain curve for steel (O'Neill and Reese, 1999).....	34
Figure 34. Finite strips of cross section	34
Figure 35. Finite element types.....	35
Figure 36. Mohr-Coulomb failure criteria	38
Figure 37. Yield surface for cap model (Desai and Siriwardane, 1984).....	39
Figure 38. Nonlinear model of bar element.....	40
Figure 39. Side view and 3D view of finite element mesh.....	42
Figure 40. Comparison the result between PSI, PLAXIS, BEM, and test results	42
Figure 41. Effect of finite element mesh	43
Figure 42. Side view and 3D view of finite element mesh.....	44
Figure 43. Comparison of the result between PSI, ABAQUS, and test data.....	45
Figure 44. Socketed shaft (Brown, et al., 2001)	46
Figure 45. Comparison of shaft head displacement for single socketed shaft.....	46
Figure 46. C_u and K_0 profiles (Wang and Sita, 2004).....	47
Figure 47. Comparison of the result between PSI, OPENSEES, and test data.....	48
Figure 48. Schematics of numerical shaft-load test.....	50
Figure 49. Finite element mesh for the numerical shaft-load test (axisymmetric condition).....	50
Figure 50. Numerical unconfined compression test for concrete	52
Figure 51. Numerical triaxial compression tests of sand used in the comparative study	53
Figure 52. Numerical static shaft-load test comparison between LS-DYNA and PSI with perfect shaft and without contact interface.....	53
Figure 53. Location of anomaly near the shaft top.....	54
Figure 54. Numerical static shaft-load test comparison between LS-DYNA and PSI with anomaly at top of shaft and without contact interface.....	54
Figure 55. Numerical static shaft-load test comparison between LS-DYNA and PSI with contact interface between shaft and soil	55
Figure 56. Stress strain curves for concrete cylinders	57
Figure 57. Load-displacement curves of four concrete drilled shafts.....	59
Figure 58. Anomaly locations.....	61
Figure 59. Anomaly sizes and shapes (shaded areas are anomaly zones)	62
Figure 60. Structural capacity and interaction diagram of nonconcentric anomaly section.....	64
Figure 61. Dilatancy angles for sands (Bolton, 1986)	66
Figure 62. Plane and 3-D views of a drilled shaft with symmetric anomaly.....	67
Figure 63. Plane and 3-D views of a drilled shaft with nonconcentric anomaly	67
Figure 64. Effect definition of anomaly.....	68
Figure 65. Load-settlement curves for 1-m diameter drilled shaft in clay, various stiffness	70
Figure 66. Load-settlement curves for 2-m diameter drilled shaft in clay, various stiffness	70
Figure 67. Shaft-load transfer and structural capacity curves for 1-m drilled shafts with 3,000 psi concrete constructed in clay	71
Figure 68. Shaft-load transfer and structural capacity curves for 1-m drilled shafts with 4,500 psi concrete constructed in clay	71
Figure 69. Shaft-load transfer and structural capacity curves for 2-m drilled shafts with 3,000 psi concrete constructed in clay.....	72

DRILLED SHAFT AXIAL CAPACITY, EFFECTS DUE TO ANOMALIES - TABLE OF CONTENTS

Figure 70. Shaft-load transfer and structural capacity curves for 2-m drilled shafts with 4,5000 psi concrete constructed in clay	72
Figure 71. Neck-in anomaly Type 1 and cylindrical anomaly at 1-m depth, D = 2 m	74
Figure 72. Neck-in anomaly Type 1 and cylindrical anomaly at 11-m depth, D = 2 m	74
Figure 73. Comparison of short and long anomalies	75
Figure 74. Load-settlement curves for drilled shafts of 1-m diameter in sand	82
Figure 75. Load-settlement curves for drilled shafts of 2-m diameter in sand	82
Figure 76. Shaft-load transfer curves for drilled shafts of 1-m diameter in sand	83
Figure 77. Shaft-load transfer curves for drilled shafts of 1-m diameter in sand	83
Figure 78. Shaft-load transfer curves for drilled shafts of 2-m diameter in sand	84
Figure 79. Shaft-load transfer curves for drilled shafts of 2-m diameter in sand	84
Figure 80. Load-settlement curves for drilled shafts of 1-m diameter in clay (Concrete strength 3000 psi, 1-m length cylindrical anomaly at 1-m depth)	97
Figure 81. Load-settlement curves for drilled shafts of 1-m diameter in clay (Concrete strength 4500 psi, 1-m length cylindrical anomaly at 1-m depth)	97
Figure 82. Load-settlement curves for drilled shafts of 1-m diameter in clay (Concrete strength 4500 psi, 1-m length cylindrical anomaly at 11-m depth)	98
Figure 83. Load-settlement curves for drilled shafts of 1-m diameter in clay (Concrete strength 4500 psi, 1-m length cylindrical anomaly at 11-m depth)	98
Figure 84. Load-settlement curves for drilled shafts of 1-m diameter in clay (Concrete strength 4500 psi, 1.2-m length cylindrical anomaly at 19-m depth)	99
Figure 85. Load-settlement curves for drilled shafts of 1-m diameter in clay (Concrete strength 4500 psi, 1.2-m length cylindrical anomaly at 19-m depth)	99
Figure 86. Load-settlement curves for drilled shafts of 1-m diameter in clay (Concrete strength 3000 psi, 1-m length neck-in anomaly type 2 at 1-m depth)	100
Figure 87. Load-settlement curves for drilled shafts of 1-m diameter in clay (Concrete strength 4500 psi, 1-m length neck-in anomaly type 2 at 1-m depth)	100
Figure 88. Load-settlement curves for drilled shafts of 1-m diameter in clay (Concrete strength 3000 psi, 1-m length neck-in anomaly type 2 at 11-m depth)	101
Figure 89. Load-settlement curves for drilled shafts of 1-m diameter in clay (Concrete strength 4500 psi, 1-m length neck-in anomaly type 2 at 11-m depth)	101
Figure 90. Load-settlement curves for drilled shafts of 1-m diameter in clay (Concrete strength 3000 psi, 1-m length neck-in anomaly type 3 at 1-m depth)	102
Figure 91. Load-settlement curves for drilled shafts of 1-m diameter in clay (Concrete strength 4500 psi, 1-m length neck-in anomaly type 3 at 1-m depth)	102
Figure 92. Load-settlement curves for drilled shafts of 1-m diameter in clay (Concrete strength 3000 psi, 1-m length neck-in anomaly type 3 at 11-m depth)	103
Figure 93. Load-settlement curves for drilled shafts of 1-m diameter in clay (Concrete strength 4500 psi, 1-m length neck-in anomaly type 3 at 11-m depth)	103
Figure 94. Load-settlement curves for drilled shafts of 1-m diameter in clay (Concrete strength 3000 psi, 1-m length neck-in anomaly type 3 at 19-m depth)	104
Figure 95. Load-settlement curves for drilled shafts of 1-m diameter in clay (Concrete strength 4500 psi, 1-m length neck-in anomaly type 3 at 19-m depth)	104
Figure 96. Load-settlement curves for drilled shafts of 2-m diameter in clay (Concrete strength 3000 psi, 1-m length neck-in anomaly type 2 at 1-m depth)	105
Figure 97. Load-settlement curves for drilled shafts of 2-m diameter in clay	

DRILLED SHAFT AXIAL CAPACITY, EFFECTS DUE TO ANOMALIES - TABLE OF CONTENTS

(Concrete strength 4500 psi, 1-m length neck-in anomaly type 2 at 1-m depth)	105
Figure 98. Load-settlement curves for drilled shafts of 2-m diameter in clay	
(Concrete strength 3000 psi, 1-m length neck-in anomaly type 2 at 11-m depth)	106
Figure 99. Load-settlement curves for drilled shafts of 2-m diameter in clay	
(Concrete strength 4500 psi, 1-m length neck-in anomaly type 2 at 11-m depth)	106
Figure 100. Load-settlement curves for drilled shafts of 2-m diameter in clay	
(Concrete strength 3000 psi, 1.2-m length neck-in anomaly type 2 at 19-m depth)	107
Figure 101. Load-settlement curves for drilled shafts of 2-m diameter in clay	
(Concrete strength 4500 psi, 1.2-m length neck-in anomaly type 2 at 19-m depth)	107
Figure 102. Load-settlement curves for drilled shafts of 2-m diameter in clay	
(Concrete strength 3000 psi, 1-m length neck-in anomaly type 3 at 1-m depth)	108
Figure 103. Load-settlement curves for drilled shafts of 2-m diameter in clay	
(Concrete strength 4500 psi, 1-m length neck-in anomaly type 3 at 1-m depth)	108
Figure 104. Load-settlement curves for drilled shafts of 2-m diameter in clay	
(Concrete strength 3000 psi, 1-m length neck-in anomaly type 3 at 11-m depth)	109
Figure 105. Load-settlement curves for drilled shafts of 2-m diameter in clay	
(Concrete strength 4500 psi, 1-m length neck-in anomaly type 3 at 11-m depth)	109
Figure 106. Load-settlement curves for drilled shafts of 2-m diameter in clay	
(Concrete strength 3000 psi, 1.2-m length neck-in anomaly type 3 at 19-m depth)	110
Figure 107. Load-settlement curves for drilled shafts of 2-m diameter in clay	
(Concrete strength 4500 psi, 1.2-m length neck-in anomaly type 3 at 19-m depth)	110
Figure 108. Load-settlement curves for drilled shafts of 1-m diameter in sand	
(Concrete strength 3000 psi, 1-m length cylindrical anomaly at 1-m depth)	111
Figure 109. Load-settlement curves for drilled shafts of 1-m diameter in sand	
(Concrete strength 4500 psi, 1-m length cylindrical anomaly at 1-m depth)	111
Figure 110. Load-settlement curves for drilled shafts of 1-m diameter in sand	
(Concrete strength 3000 psi, 1-m length cylindrical anomaly at 11-m depth)	112
Figure 111. Load-settlement curves for drilled shafts of 1-m diameter in sand	
(Concrete strength 4500 psi, 1-m length cylindrical anomaly at 11-m depth)	112
Figure 112. Load-settlement curves for drilled shafts of 1-m diameter in sand	
(Concrete strength 3000 psi, 1-m length cylindrical anomaly at 11-m depth)	113
Figure 113. Load-settlement curves for drilled shafts of 1-m diameter in sand	
(Concrete strength 4500 psi, 1-m length cylindrical anomaly at 11-m depth)	113
Figure 114. Load-settlement curves for drilled shafts of 1-m diameter in sand	
(Concrete strength 3000 psi, 1.2-m length cylindrical anomaly at 191-m depth)	114
Figure 115. Load-settlement curves for drilled shafts of 1-m diameter in sand	
(Concrete strength 4500 psi, 1.2-m length cylindrical anomaly at 19-m depth)	114
Figure 116. Load-settlement curves for drilled shafts of 1-m diameter in sand	
(Concrete strength 3000 psi, 1-m length neck-in anomaly type 2 at 1-m depth)	115
Figure 117. Load-settlement curves for drilled shafts of 1-m diameter in sand	
(Concrete strength 4500 psi, 1-m length neck-in anomaly type 2 at 1-m depth)	115
Figure 118. Load-settlement curves for drilled shafts of 1-m diameter in sand	
(Concrete strength 3000 psi, 1-m length neck-in anomaly type 2 at 11-m depth)	116
Figure 119. Load-settlement curves for drilled shafts of 1-m diameter in sand	
(Concrete strength 4500 psi, 1-m length neck-in anomaly type 2 at 11-m depth)	116
Figure 120. Load-settlement curves for drilled shafts of 1-m diameter in sand	

DRILLED SHAFT AXIAL CAPACITY, EFFECTS DUE TO ANOMALIES - TABLE OF CONTENTS

(Concrete strength 3000 psi, 1.2-m length neck-in anomaly type 2 at 19-m depth)	117
Figure 121. Load-settlement curves for drilled shafts of 1-m diameter in sand	
(Concrete strength 4500 psi, 1.2-m length neck-in anomaly type 2 at 19-m depth)	117
Figure 122. Load-settlement curves for drilled shafts of 1-m diameter in sand	
(Concrete strength 3000 psi, 1-m length neck-in anomaly type 3 at 1-m depth)	118
Figure 123. Load-settlement curves for drilled shafts of 1-m diameter in sand	
(Concrete strength 4500 psi, 1-m length neck-in anomaly type 3 at 1-m depth)	118
Figure 124. Load-settlement curves for drilled shafts of 1-m diameter in sand	
(Concrete strength 3000 psi, 1-m length neck-in anomaly type 3 at 11-m depth)	119
Figure 125. Load-settlement curves for drilled shafts of 1-m diameter in sand	
(Concrete strength 4500 psi, 1-m length neck-in anomaly type 3 at 11-m depth)	119
Figure 126. Load-settlement curves for drilled shafts of 1-m diameter in sand	
(Concrete strength 3000 psi, 1.2-m length neck-in anomaly type 3 at 19-m depth)	120
Figure 127. Load-settlement curves for drilled shafts of 1-m diameter in sand	
(Concrete strength 4500 psi, 1.2-m length neck-in anomaly type 3 at 19-m depth)	120
Figure 128. Load-settlement curves for drilled shafts of 2-m diameter in sand	
(Concrete strength 3000 psi, 1-m length cylindrical anomaly at 1-m depth)	121
Figure 129. Load-settlement curves for drilled shafts of 2-m diameter in sand	
(Concrete strength 4500 psi, 1-m length cylindrical anomaly at 1-m depth)	121
Figure 130. Load-settlement curves for drilled shafts of 2-m diameter in sand	
(Concrete strength 3000 psi, 1-m length cylindrical anomaly at 11-m depth)	122
Figure 131. Load-settlement curves for drilled shafts of 2-m diameter in sand	
(Concrete strength 4500 psi, 1-m length cylindrical anomaly at 11-m depth)	122
Figure 132. Load-settlement curves for drilled shafts of 2-m diameter in sand	
(Concrete strength 3000 psi, 1.2-m length cylindrical anomaly at 19-m depth)	123
Figure 133. Load-settlement curves for drilled shafts of 2-m diameter in sand	
(Concrete strength 4500 psi, 1.2-m length cylindrical anomaly at 19-m depth)	123
Figure 134. Load-settlement curves for drilled shafts of 2-m diameter in sand	
(Concrete strength 3000 psi, 1-m length neck-in anomaly type 2 at 1-m depth)	124
Figure 135. Load-settlement curves for drilled shafts of 2-m diameter in sand	
(Concrete strength 4500 psi, 1-m length neck-in anomaly type 2 at 1-m depth)	124
Figure 136. Load-settlement curves for drilled shafts of 2-m diameter in sand	
(Concrete strength 3000 psi, 1-m length neck-in anomaly type 2 at 11-m depth)	125
Figure 137. Load-settlement curves for drilled shafts of 2-m diameter in sand	
(Concrete strength 4500 psi, 1-m length neck-in anomaly type 2 at 11-m depth)	125
Figure 138. Load-settlement curves for drilled shafts of 2-m diameter in sand	
(Concrete strength 3000 psi, 1-m length neck-in anomaly type 2 at 19-m depth)	126
Figure 139. Load-settlement curves for drilled shafts of 2-m diameter in sand	
(Concrete strength 4500 psi, 1-m length neck-in anomaly type 2 at 19-m depth)	126
Figure 140. Load-settlement curves for drilled shafts of 2-m diameter in sand	
(Concrete strength 3000 psi, 1-m length neck-in anomaly type 3 at 1-m depth)	127
Figure 141. Load-settlement curves for drilled shafts of 2-m diameter in sand	
(Concrete strength 4500 psi, 1-m length neck-in anomaly type 3 at 1-m depth)	127
Figure 142. Load-settlement curves for drilled shafts of 2-m diameter in sand	
(Concrete strength 3000 psi, 1-m length neck-in anomaly type 3 at 11-m depth)	128

DRILLED SHAFT AXIAL CAPACITY, EFFECTS DUE TO ANOMALIES - TABLE OF CONTENTS

Figure 143. Load-settlement curves for drilled shafts of 2-m diameter in sand (Concrete strength 4500 psi, 1-m length neck-in anomaly type 3 at 11-m depth)	128
Figure 144. Load-settlement curves for drilled shafts of 2-m diameter in sand (Concrete strength 3000 psi, 1-m length neck-in anomaly type 3 at 19-m depth)	129
Figure 145. Load-settlement curves for drilled shafts of 2-m diameter in sand (Concrete strength 4500 psi, 1-m length neck-in anomaly type 3 at 19-m depth)	129

LIST OF TABLES

Table 1. The comparison capacity of Shafts #2 and #4	5
Table 2. Values of I_r and N_c^* (Reese, et al., 2006).....	13
Table 3. β for Gravelly sands and gravels (Rollins, et al., 2005).....	15
Table 4. Exponent M for shear modulus (Hardin and Drnevich, 1972)	23
Table 5. Empirical load transfer curves	26
Table 6. Material parameter for soil data (Brinkgreve, 2004)	41
Table 7. Soil parameters from triaxial test results	42
Table 8. Adjusted soil parameter for match case.....	43
Table 9. Material parameter for soil data (Brown, et al., 2001)	46
Table 10. Material parameters used in the comparative study.....	51
Table 11. Concrete material.....	57
Table 12. Structural capacity of concrete without reduction	58
Table 13. Structural capacity of drilled shafts with 2% reinforcement	58
Table 14. Anomaly sizes.....	60
Table 15. Anomaly locations	60
Table 16. Structural capacities of drilled shafts with anomalies	63
Table 17. Strength properties of soil.....	65
Table 18. Geotechnical capacity of drilled shafts in cohesive soil.....	69
Table 19. Drilled shaft capacity reduction for the case of concrete strength 3000 psi, shaft in clay, shaft diameter D = 1 m, anomaly length 1-1.2 m.....	76
Table 20. Drilled shaft capacity reduction for the case of concrete strength 4500 psi, shaft in clay, shaft diameter D = 1 m, anomaly length 1-1.2 m.....	77
Table 21. Drilled shaft capacity reduction for the case of concrete strength 3000 psi, shaft in clay, shaft diameter D = 2 m, anomaly length 1-1.2 m.....	78
Table 22. Drilled shaft capacity reduction for the case of concrete strength 4500 psi, shaft in clay, shaft diameter D = 2 m, anomaly length 1-1.2 m.....	79
Table 23. Drilled shaft capacity reduction for nonconcentric anomaly, concrete strength 3000 psi, diameter D = 2 m, shaft in clay, anomaly length 1-1.2 m	80
Table 24. Drilled shaft capacity reduction for nonconcentric anomaly, concrete strength 4500 psi, diameter D = 2 m, shaft in clay, anomaly length 1-1.2 m	80
Table 25. Capacity of drilled shafts in sandy soil.....	81
Table 26. Drilled shaft capacity reduction for the case of concrete strength 3000 psi, shaft in sand, shaft diameter D = 1 m, anomaly length 1-1.2 m	85
Table 27. Drilled shaft capacity reduction for the case of concrete strength 4500 psi, shaft in sand, shaft diameter D = 1 m, anomaly length 1-1.2 m	86
Table 28. Drilled shaft capacity reduction for the case of concrete strength 3000 psi, shaft in sand, shaft diameter D = 2 m, anomaly length 1-1.2 m	87
Table 29. Drilled shaft capacity reduction for the case of concrete strength 4500 psi, shaft in sand, shaft diameter D = 2 m, anomaly length 1-1.2 m	88
Table 30. Drilled shaft capacity reduction for nonconcentric anomaly, concrete strength 3000 psi, diameter D = 2 m, soil in sand, anomaly length 1-1.2 m.....	89
Table 31. Drilled shaft capacity reduction for nonconcentric anomaly, concrete strength 4500 psi, diameter D = 2 m, soil in sand, anomaly length 1-1.2 m.....	89

DRILLED SHAFT AXIAL CAPACITY, EFFECTS DUE TO ANOMALIES - TABLE OF CONTENTS

- Table 32. Drilled shaft capacity reduction for the case of concrete strength 3000 psi,
shaft in clay with bedrock at shaft tip, shaft diameter $D = 1$ m, anomaly length 1-1.2 m.90
- Table 33. Drilled shaft capacity reduction for the case of concrete strength 4500 psi,
shaft in clay with bedrock at shaft tip, shaft diameter $D = 1$ m, anomaly length 1-1.2 m.91
- Table 34. Drilled shaft capacity reduction for the case of concrete strength 3000 psi,
shaft in clay with bedrock at shaft tip, shaft diameter $D = 2$ m, anomaly length 1-1.2 m.91
- Table 35. Drilled shaft capacity reduction for the case of concrete strength 4500 psi,
shaft in clay with bedrock at shaft tip, shaft diameter $D = 2$ m, anomaly length 1-1.2 m.92