

# Contents

<i>Foreword</i>	vii
<i>Preface</i>	ix
1. Performance of Pile Foundations .....	1
1.1 Introduction .....	1
1.1.1 Axial capacity of a single pile .....	3
1.1.2 Pile capacity based on CPT testing .....	5
1.1.2.1 Pile base capacity .....	6
1.1.2.2 Shaft friction .....	7
1.2 Performance of Pile Foundations During Earthquake Loading .....	8
1.3 Soil Liquefaction and Lateral Spreading .....	11
1.4 Performance of Pile Foundations in Past Earthquakes .....	12
1.4.1 Showa bridge failure .....	14
1.4.2 Niigata Family Court House building .....	18
1.4.3 The Landing Bridge performance .....	21
1.4.4 The Harbour Master's Tower at Kandla Port .....	27
1.5 Modes of Pile Failure in Liquefiable Soils .....	31
1.5.1 Failure mechanisms for single piles .....	31
1.5.2 Failure mechanisms for pile groups .....	35
1.6 Summary .....	38
2. Inertial and Kinematic Loading .....	39
2.1 Pile Behaviour Under Earthquake Loading .....	39
2.1.1 Inertial loading .....	39
2.1.2 Kinematic loading in level ground .....	41
2.1.3 Kinematic loading in sloping ground .....	43
2.2 Analysis of Laterally Loaded Piles Under Static Conditions .....	43
2.2.1 Simplified soil profiles .....	44
2.2.2 Simplified analysis procedures for piles under static loading .....	46
2.3 Analysis of Laterally Loaded Piles Under Earthquake Loading .....	48

2.3.1	Variation in the action of inertial and kinematic loads with depth.....	48
2.3.2	Effective lengths of piles .....	49
2.3.3	Pile flexibility .....	50
2.4	Kinematic Response in Level Ground .....	51
2.5	Kinematic Loading in Laterally Spreading Soil .....	54
2.6	Inertial Response .....	56
2.6.1	Relative stiffness of pile-soil system .....	56
2.6.2	Damping coefficients .....	57
2.7	<i>p-y</i> Analysis of Piles .....	58
2.7.1	Static lateral loading .....	58
2.7.2	Cyclic lateral loading .....	62
2.7.3	<i>p-y</i> analysis under earthquake loading – level ground .....	63
2.7.4	<i>p-y</i> analysis under earthquake loading – sloping ground .....	64
2.8	Limit Equilibrium Analysis of Piles Subjected to Earthquake Loading .....	67
2.8.1	Limit equilibrium of piles in laterally spreading soils .....	68
2.8.2	Limit equilibrium analysis in the presence of nonliquefied crust.....	70
2.8.2.1	Stiff clay as a nonliquefiable layer .....	70
2.8.2.2	Dense sand as a nonliquefiable layer .....	74
2.9	Provisions in Eurocode 8 .....	76
2.9.1	Combination rules .....	77
2.9.2	Pile head fixity coefficients .....	77
2.9.3	Kinematic loading .....	78
2.10	Summary .....	79
3.	Accounting for Axial Loading in Level Ground .....	80
3.1	Liquefaction as a Foundation Hazard .....	80
3.1.1	Liquefaction .....	80
3.1.2	Determination of liquefaction susceptibility .....	82
3.2	Influence of Axial Loading on Pile Failure .....	84
3.3	Axial Load Transfer Due to Liquefaction .....	85
3.3.1	Liquefaction-induced (co-seismic) .....	85
3.3.2	Downdrag (post-earthquake) .....	88
3.4	Pile Settlement .....	88
3.4.1	Liquefaction-induced (co-seismic) .....	88
3.4.2	Downdrag (post-earthquake) .....	92
3.5	Guidelines for Designing Against Bearing Failure.....	95
3.6	Instability of Single Piles and Pile Groups .....	98
3.6.1	Rock-socketed piles .....	98
3.6.2	Floating piles .....	105
3.7	Bearing vs. Buckling Failure .....	108
3.7.1	Methodology .....	108
3.7.2	Sample analysis .....	110

3.7.3	Ultimate axial limiting states for piled foundations .....	111
3.7.4	Use of limiting states in pile sizing .....	114
3.8	Summary .....	115
4.	Lateral Spreading of Sloping Ground .....	116
4.1	Liquefaction-induced Lateral Spreading .....	116
4.1.1	Introduction .....	116
4.2	Simple Methods to Estimate the Extent of Lateral Spreading .....	120
4.3	Effects of Lateral Spreading on Pile Foundations .....	124
4.3.1	Presence of nonliquefiable crust .....	125
4.3.2	Lateral pressures generated on piles and pile caps.....	126
4.3.3	Current codal provisions .....	134
4.3.3.1	Specifications for Highway Bridges (JRA, 2002).....	134
4.3.3.2	Design Standard for Railway Facilities (RTRI 1999).....	134
4.3.3.3	Recommendations for Design of Building Foundations (AIJ 2001) .....	135
4.3.4	Recent experimental data vs codal provisions .....	135
4.4	Recommendations on Estimation of Lateral Loads for Pile Design .....	136
5.	Axial Loading on Piles in Laterally Spreading Ground .....	138
5.1	Introduction .....	138
5.2	Phasing of Loads .....	138
5.2.1	Inertial and kinematic loads .....	139
5.2.2	Presence of axial loads.....	142
5.3	Peak Lateral Response of Piled Foundations.....	143
5.4	Residual Lateral Response of Piled Foundations.....	147
5.4.1	Single piles .....	147
5.4.2	Pile groups (including axial load).....	149
5.4.3	Comparison of single pile and group pile behaviour .....	154
5.4.4	Insight into effects of axial load on group response.....	155
5.5	Validation of Effects of Axial Pile Load .....	157
5.6	Recommendations for Designing Piles in Laterally Spreading Ground .....	160
6.	Design Examples .....	165
6.1	Introduction .....	165
6.2	Design of Piles Under Static Loading .....	165
6.2.1	Example 1: Preliminary design of piles under static loading .....	166
6.2.1.1	End bearing.....	166
6.2.1.2	Shaft resistance .....	167
6.2.2	Example 2: Preliminary design of piles using CPT data.....	168
6.2.2.1	End bearing.....	168
6.2.2.2	Shaft resistance .....	168

6.3	Inertial and Kinematic Loading on Piles in Level Ground .....	171
6.3.1	Example 3: Soil stiffness and natural frequency .....	172
6.3.2	Example 4: Effective length and flexibility of the pile .....	175
6.3.2.1	Effective length of the pile.....	175
6.3.2.2	Flexibility of the pile .....	176
6.3.3	Example 5: Inertial loading on the pile.....	177
6.3.4	Example 6: Kinematic interaction.....	180
6.4	Design of Piles in Level Liquefiable Ground .....	182
6.4.1	Example 7: Determination of liquefaction potential from CPT data .....	182
6.4.2	Example 8: Pile sizing based on liquefaction considerations.....	187
6.4.3	Example 9: Inertial response in level liquefied ground.....	191
6.5	Design of Piles in Sloping Liquefiable Ground.....	192
6.5.1	Example 10: Pile group in two-layer soil profile subject to lateral spreading.....	192
6.5.1.1	Method 1.....	196
6.5.1.2	Method 2.....	196
6.5.1.3	Method 3.....	196
6.5.2	Example 11: Pile group in three-layer soil profile subject to lateral spreading.....	199
6.6	Summary of Inclusive Design Procedure .....	200
	<i>References</i> .....	203
	<i>Index</i> .....	211