



Single Piles and Pile Groups Under Lateral Loading

Lymon C. Reese
William F. Van Impe

Contents

PREFACE	XV
1 TECHNIQUES FOR DESIGN	1
1.1 Introduction	1
1.2 Occurrence of laterally loaded piles	2
1.3 Nature of the soil response	3
1.4 Response of a pile	7
1.4.1 Introduction	7
1.4.2 Static loading	7
1.4.3 Cyclic loading	7
1.4.4 Sustained loading	8
1.4.5 Dynamic loading	9
1.5 Models for use in analyses of a single pile	11
1.5.1 Elastic pile and elastic soil	11
1.5.2 Elastic pile and finite elements for soil	12
1.5.3 Rigid pile and plastic soil	12
1.5.4 Characteristic load method	13
1.5.5 Nonlinear pile and p - y model for soil	14
1.6 Models for groups of piles under lateral loading	16
1.7 Status of current state-of-the-art	18
2 DERIVATION OF EQUATIONS AND METHODS OF SOLUTION	21
2.1 Introduction	21
2.2 Derivation of the differential equation	21
2.2.1 Solution of Reduced Form of Differential Equation	25
2.2.2 Solution of the Differential Equation by Difference Equations	29
2.3 Solution for $E_{py} = k_{py}x$	35
2.3.1 Dimensional Analysis	36
2.3.2 Equations for $E_{py} = k_{py}x$	41
2.3.3 Example Solution	42
2.3.4 Discussion	46
2.4 Validity of the mechanics	47
3 MODELS FOR RESPONSE OF SOIL AND WEAK ROCK	49
3.1 Introduction	49
3.2 Mechanics concerning response of soil to lateral loading	50
3.2.1 Stress-deformation of soil	50
3.2.2 Proposed model for decay of E_s	50
3.2.3 Variation of stiffness of soil (E_s and G_s) with depth	51

VIII Contents

3.2.4	Initial stiffness and ultimate resistance of p - y curves from soil properties	53
3.2.5	Subgrade modulus related to piles under lateral loading	59
3.2.6	Theoretical solution by Skempton for subgrade modulus and for p - y curves for saturated clays	60
3.2.7	Practical use of Skempton's equations and values of subgrade modulus in analyzing a pile under lateral loading	62
3.3	Influence of diameter on p - y curves	64
3.3.1	Clay	64
3.3.2	Sand	64
3.4	Influence of cyclic loading	65
3.4.1	Clay	65
3.4.2	Sand	66
3.5	Experimental methods of obtaining p - y curves	67
3.5.1	Soil response from direct measurements	67
3.5.2	Soil response from experimental moment curves	67
3.5.3	Nondimensional methods for obtaining soil response	68
3.6	Early recommendations for computing p - y curves	68
3.6.1	Terzaghi	68
3.6.2	McClelland and Focht for clay (1958)	70
3.7	p - y curves for clay	70
3.7.1	Selection of stiffness of clay	70
3.7.2	Response of soft clay in the presence of free water	72
3.7.3	Response of stiff clay in the presence of free water	75
3.7.4	Response of stiff clay with no free water	82
3.8	p - y curves for sands above and below the water table	84
3.8.1	Detailed procedure	84
3.8.2	Recommended soil tests	87
3.8.3	Example curves	87
3.9	p - y curves for layered soils	87
3.9.1	Method of Georgiadis	88
3.9.2	Example p - y curves	89
3.10	p - y curves for soil with both cohesion and internal friction	91
3.10.1	Background	91
3.10.2	Recommendations for computing p - y curves	92
3.10.3	Discussion	96
3.11	Other recommendations for computing p - y curves	97
3.11.1	Clay	97
3.11.2	Sand	97
3.12	modifications to p - y curves for sloping ground	98
3.12.1	Introduction	98
3.12.2	Equations for ultimate resistance in clay	98
3.12.3	Equations for ultimate resistance in sand	99
3.13	Effect of batter	100
3.14	Shearing force at bottom of pile	101
3.15	p - y curves for weak rock	101
3.15.1	Introduction	101
3.15.2	Field tests	102
3.15.3	Interim recommendations	102
3.15.4	Comments on equations for predicting p - y curves for rock	106

3.16	Selection of p-y curves	106
3.16.1	Introduction	106
3.16.2	Factors to be considered	106
3.16.3	Specific suggestions	107
4	STRUCTURAL CHARACTERISTICS OF PILES	109
4.1	Introduction	109
4.2	Computation of an equivalent diameter of a pile with a noncircular cross section	109
4.3	Mechanics for computation of m_{ult} and e_{pi} as a function of bending moment and axial load	111
4.4	Stress-strain curves for normal-weight concrete and structural steel	114
4.5	Implementation of the method for a steel h-section	116
4.6	Implementation of the method for a steel pipe	118
4.7	Implementation of the method for a reinforced-concrete section	119
4.7.1	Example computations for a square shape	119
4.7.2	Example computations for a circular shape	121
4.8	Approximation of moment of inertia for a reinforced-concrete section	121
5	ANALYSIS OF GROUPS OF PILES SUBJECTED TO INCLINED AND ECCENTRIC LOADING	125
5.1	Introduction	125
5.2	Approach to analysis of groups of piles	126
5.3	Review of theories for the response of groups of piles to inclined and eccentric loads	126
5.4	Rational equations for the response of a group of piles under generalized loading	129
5.4.1	Introduction	129
5.4.2	Equations for a two-dimensional group of piles	132
5.5	Laterally loaded piles	136
5.5.1	Movement of pile head due to applied loading	136
5.5.2	Effect of batter	136
5.6	Axially loaded piles	137
5.6.1	Introduction	137
5.6.2	Relevant parameters concerning deformation of soil	137
5.6.3	Influence of method of installation on soil characteristics	139
5.6.4	Methods of formulating axial-stiffness curves	140
5.6.5	Differential equation for solution of finite-difference equation for axially loaded piles.	142
5.6.6	Finite difference equation	145
5.6.7	Load-transfer curves	145
5.7	Closely-spaced piles under lateral loading	151
5.7.1	Modification of load-transfer curves for closely spaced piles	151
5.7.2	Concept of interaction under lateral loading	152
5.7.3	Proposals for solving for influence coefficients for closely-spaced piles under lateral loading	152
5.7.4	Description and analysis of experiments with closely-spaced piles installed in-line and side-by-side	155
5.7.5	Prediction equations for closely-spaced piles installed in-line and side-by-side	158

X Contents

5.7.6	Use of modified prediction equations in developing p - y curves for analyzing results of experiments with full-scale groups	160
5.7.7	Discussion of the method of predicting the interaction of closely-spaced piles under lateral loading	173
5.8	Proposals for solving for influence coefficients for closely-spaced piles under axial loading	173
5.8.1	Introduction	173
5.8.2	Concept of interaction under axial loading	174
5.8.3	Review of relevant literature	174
5.8.4	Interim recommendations for computing the efficiency of groups of piles under axial loading	177
5.9	Analysis of an experiment with batter piles	178
5.9.1	Description of the testing arrangement	178
5.9.2	Properties of the sand	179
5.9.3	Properties of the pipe piles	181
5.9.4	Pile group	181
5.9.5	Experimental curve of axial load versus settlement for single pile	182
5.9.6	Results from experiment and from analysis	183
5.9.7	Comments on analytical method	185
6	ANALYSIS OF SINGLE PILES AND GROUPS OF PILES SUBJECTED TO ACTIVE AND PASSIVE LOADING	187
6.1	Nature of lateral loading	187
6.2	Active loading	187
6.2.1	Wind loading	187
6.2.2	Wave loading	189
6.2.3	Current loading	194
6.2.4	Scour	195
6.2.5	Ice loading	197
6.2.6	Ship impact	198
6.2.7	Loads from miscellaneous sources	198
6.3	Single piles or groups of piles subjected to active loading	199
6.3.1	Overhead sign	199
6.3.2	Breasting dolphin	203
6.3.3	Pile for anchoring a ship in soft soil	207
6.3.4	Offshore platform	213
6.4	Passive loading	223
6.4.1	Earth pressures	223
6.4.2	Moving soil	224
6.4.3	Thrusts from dead loading of structures	226
6.5	Single piles or groups of piles subjected to passive loading	226
6.5.1	Pile-supported retaining wall	226
6.5.2	Anchored bulkhead	231
6.5.3	Pile-supported mat at the Pyramid Building	237
6.5.4	Piles for stabilizing a slope	245
6.5.5	Piles in a settling fill in a sloping valley	251
7	CASE STUDIES	259
7.1	Introduction	259
7.2	Piles installed into cohesive soil with no free water	260
7.2.1	Bagnolet	260

7.2.2	Houston	263
7.2.3	Brent Cross	264
7.2.4	Japan	267
7.3	Piles installed into cohesive soil with free water above ground surface	269
7.3.1	Lake Austin	269
7.3.2	Sabine	272
7.3.3	Manor	273
7.4	Piles installed in cohesionless soil	276
7.4.1	Mustang Island	276
7.4.2	Garston	277
7.4.3	Arkansas River	278
7.5	Piles installed into layered soil	283
7.5.1	Talisheek	283
7.5.2	Alcácer do Sol	286
7.5.3	Florida	288
7.5.4	Apapa	288
7.6	Piles installed in $c-\phi$ soil	290
7.6.1	Kuwait	290
7.6.2	Los Angeles	291
7.7	Piles installed in weak rock	293
7.7.1	Islamorada	293
7.7.2	San Francisco	295
7.8	Analysis of results of case studies	298
7.9	Comments on case studies	299
8	TESTING OF FULL-SIZED PILES	303
8.1	Introduction	303
8.1.1	Scope of presentation	303
8.1.2	Summary of method of analysis	303
8.1.3	Classification of tests	303
8.1.4	Features unique to testing of piles under lateral loading	304
8.2	Designing the test program	304
8.2.1	Planning for the testing	304
8.2.2	Selection of test pile and test site	305
8.3	Subsurface investigation	306
8.4	Installation of test pile	309
8.5	Testing techniques loading arrangements and instrumentation at the pile head	310
8.6	Loading arrangements and instrumentation at the pile head	311
8.6.1	Loading arrangements	311
8.6.2	Instrumentation	313
8.7	Testing for design of production piles	317
8.7.1	Introduction	317
8.7.2	Interpretation of data	317
8.7.3	Example Computation	317
8.8	Testing for obtaining details on response of soil	319
8.8.1	Introduction	319
8.8.2	Preparation of test piles	319
8.8.3	Test setup and loading equipment	321
8.8.4	Instrumentation	322
8.8.5	Calibration of test piles	325
8.8.6	Soil borings and laboratory tests	328

XII Contents

8.8.7	Installation of test piles	332
8.8.8	Test procedures and details of loading	334
8.8.9	Penetrometer tests	335
8.8.10	Ground settlement due to pile driving	338
8.8.11	Ground settlement due to lateral loading	339
8.8.12	Recalibration of test piles	339
8.8.13	Graphical presentation of curves showing bending moment	340
8.8.14	Interpretation of bending moment curves to obtain p - y curves	341
8.9	Summary	346
9	IMPLEMENTATION OF FACTORS OF SAFETY	347
9.1	Introduction	347
9.2	Limit states	347
9.3	Consequences of a failure	348
9.4	Philosophy concerning safety coefficient	350
9.5	Influence of nature of structure	351
9.6	Special problem in characterizing soil	351
9.6.1	Introduction	351
9.6.2	Characteristic value of soil parameters	352
9.7	Level of quality control	353
9.8	Two general approaches to selecting the factor of safety	353
9.9	Global approach	354
9.9.1	Introductory comments	354
9.9.2	Recommendations of the American Petroleum Institute	355
9.10	Method of partial safety factors (psf)	356
9.10.1	Introduction	356
9.10.2	Suggested values for partial factors for design of laterally loaded piles	356
9.10.3	Example computations	358
9.11	Method of load and resistance factors (LRFD)	358
9.11.1	Introduction	358
9.11.2	Loads addressed by the LRFD specifications	359
9.11.3	Resistances addressed by the LRFD specifications	359
9.11.4	Design of piles by the LRFD specifications	360
9.12	Concluding comments	360
10	SUGGESTIONS FOR DESIGN	363
10.1	Introduction	363
10.2	Range of factors to be considered in design	363
10.3	Validation of results from computations for single pile	364
10.3.1	Introduction	364
10.3.2	Solution of example problems	364
10.3.3	Check of echo print of input data	364
10.3.4	Investigation of length of word employed in internal computations	365
10.3.5	Selection of tolerance and length of increment	365
10.3.6	Check of soil resistance	365
10.3.7	Check of mechanics	366
10.3.8	Use of nondimensional curves	366
10.4	Validation of results from computations for pile group	366
10.5	Additional steps in design	367
10.5.1	Risk management	367
10.5.2	Peer review	367

10.5.3 Technical contributions	367
10.5.4 The design team	368
APPENDICES	
A Broms method for analysis of single piles under lateral loading	369
B Nondimensional coefficients for piles with finite length, no axial load, constant $E_p I_p$, and constant E_s	385
C Difference equations for solving the problem of step-tapered beams on foundations having variable stiffness	395
D Instructions for use of student versions of computer programs LPILE and GROUP	405
E Nondimensional curves for piles under lateral loading for case where $E_{py} = K_{py}x$	409
F Tables of values of efficiency measured in tests of groups of piles under lateral loading	419
G Horizontal stresses in soil near shaft during installation of a pile	423
H Use of data from uninstrumented piles under lateral loading to obtain soil response	429
I Eurocode principles related to geotechnical design	435
J Discussion of factor of safety related to piles under axial load	439
REFERENCES	443
AUTHOR INDEX	457
SUBJECT INDEX	461