Evolution Group 7 - Pile Design

Summary of UK Design for Pile Groups - Chris Raison

In the UK there are no specific requirements given in the National Annex covering design of pile groups. Particular issues are therefore to determine the ULS design actions for each individual pile to check bearing capacity, and to assess the SLS behaviour of the pile group.

For ULS bearing capacity checks, normal practice is to assume that the design resistance of a group of piles is equal to the sum of the individual pile resistances unless pile spacing is less than 3 x pile diameter. In this case, checks are normally carried out for shaft resistance based on the outer perimeter of the pile group. Experience suggests that the sum of the individual pile resistances is usually the worst case.

For routine situations, pile loads are usually determined by simple elastic methods assuming a rigid pile cap and the assumptions that vertical loads are shared equally by all piles, and moment loads are shared in proportion to their distance from the neutral axis using the following relationship:

$$PileLoad = \frac{\sum Load}{No of\ Piles} + \frac{\sum M_{yy}\, I_{xx} - \sum M_{xx}\, I_{xy}}{(I_{xx}\, I_{yy} - I_{xy}^{\,2})}\, x + \frac{\sum M_{xx}\, I_{yy} - \sum M_{yy}\, I_{xy}}{(I_{xx}\, I_{yy} - I_{xy}^{\,2})}\, y$$

Where it is necessary to determine pile group settlements and lateral movement under full 3D loading, pile group behaviour is usually modelled using the PIGLET software (based on the Randolph closed form solutions), or REPUTE program where the effect of soil layering or non linearity needs to be considered. Both programs allow raking piles to be analysed and give full details of loads for all piles.

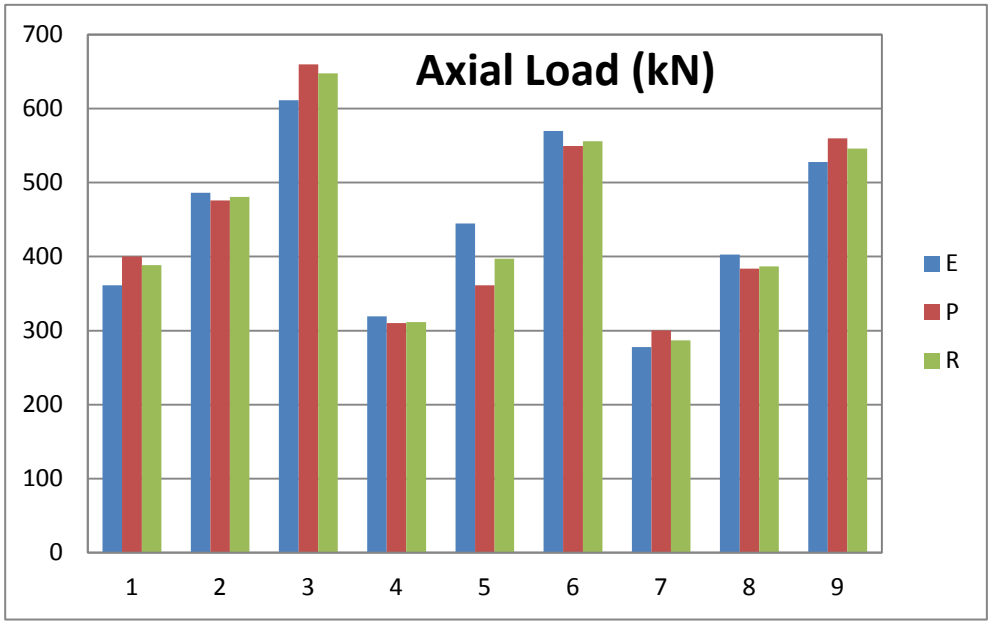
SLS checks for pile group settlement are more important for pile groups. Significant interaction between piles in a group can result in group settlements much greater than settlement for a single isolated pile determined either by calculation or static load test. In these cases, use of PIGLET or REPUTE is normal.

Examples of calculations based on all three methods are attached.

Hand calculations to determine pile group settlement can be carried out assuming an equivalent raft foundation located at about 2/3 depth of the piles for shaft friction piles, or close to the toe level for end bearing piles.

Chris Raison - 6th November 2012

Pile Group Load Assessment



Elastic Method

Pile	V
	kN
1	361
2	486
3	611
4	319
5	444
6	569
7	278
8	403
9	528

PIGLET Method

Pile	V	Hx	Myz	Hy	Mxz	Txy
	kN	kN	kNm	kN	kNm	kNm
1	400	12	-20	36	-4	0
2	476	11	-18	32	-3	0
3	660	12	-20	36	-4	0
4	310	11	-18	32	-3	0
5	361	9	-16	28	-2	0
6	549	11	-18	32	-3	0
7	300	12	-20	36	-4	0
8	384	11	-18	32	-3	0
9	560	12	-20	36	-4	0

V	Hx	Myz	Hy	Mxz	Txy
kN	kN	kNm	kN	kNm	kNm
4000	100	1000	300	3000	0
mm	mm	10^{-3} rad	mm	10^{-3} rad	10^{-3} rad
3.58	0.70	0.08417	1.76	0.21826	0.00000

REPUTE Method

Pile	V	Hy	Mx	Hx	My
	kN	kN	kNm	kN	kNm
1	388	3	-26	44	-2
2	481	9	-25	43	-4
3	647	22	-27	46	-11
4	312	2	-20	32	-1
5	397	7	-18	28	-3
6	556	22	-20	32	-10
7	287	4	-18	28	-2
8	387	9	-16	23	-4
9	546	22	-17	26	-10

V	Hy	Mx	Hx	My
kN	kN	kNm	kN	kNm
4000	100	1000	300	3000
mm	mm	10^{-3} rad	mm	10^{-3} rad
4.00	0.93	0.08800	2.13	0.19900

Abutment Pile Cap - EC7 Design Actions - Factor Set A2 to BS EN 1997

	Pile Cap Loads						Computed Pile Loads		
	Vz	My	Mx	Hx	Hy	Tz	Minimum	Maximum	Horizontal
	kN	kNm	kNm	kN	kN	kNm	kN	kN	kN
Load Case 1	4000	3000	1000	100	300	0	278	611	35

Pile	X	Y	Xi	Yi	Xi2	Yi2	XiYi	P/n	MX/sumX	MY/sumY	Pmax
1	-4.000	4.000	-4.000	4.000	16.000	16.000	-16.000	444	-125	42	361
2	0.000	4.000	0.000	4.000	0.000	16.000	0.000	444	0	42	486
3	4.000	4.000	4.000	4.000	16.000	16.000	16.000	444	125	42	611
4	-4.000	0.000	-4.000	0.000	16.000	0.000	0.000	444	-125	0	319
5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	444	0	0	444
6	4.000	0.000	4.000	0.000	16.000	0.000	0.000	444	125	0	569
7	-4.000	-4.000	-4.000	-4.000	16.000	16.000	16.000	444	-125	-42	278
8	0.000	-4.000	0.000	-4.000	0.000	16.000	0.000	444	0	-42	403
9	4.000	-4.000	4.000	-4.000	16.000	16.000	-16.000	444	125	-42	528

Total	xc	yc
9	0.000	0.000

SumX2	SumY2	SumXY
96.000	96.000	0.000

Min	278
Max	611

Pile	X	Y	Li	Li2	MzX/sumL	MzY/sumL	H tor	Hx/n	Hy/n	H horiz	H total
1	-4.000	4.000	5.657	32.000	0	0	0	11	33	35	35
2	0.000	4.000	4.000	16.000	0	0	0	11	33	35	35
3	4.000	4.000	5.657	32.000	0	0	0	11	33	35	35
4	-4.000	0.000	4.000	16.000	0	0	0	11	33	35	35
5	0.000	0.000	0.000	0.000	0	0	0	11	33	35	35
6	4.000	0.000	4.000	16.000	0	0	0	11	33	35	35
7	-4.000	-4.000	5.657	32.000	0	0	0	11	33	35	35
8	0.000	-4.000	4.000	16.000	0	0	0	11	33	35	35
9	4.000	-4.000	5.657	32.000	0	0	0	11	33	35	35

SumLi2
192.000

Min	35
Max	35

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**                                                                            **
**                                                                            **
**    PPPPPPP     IIIIII      GGGGGG     LL          EEEEEEEE    TTTTTTTT    **
**    PP    PP      II       GG    GG    LL          EE             TT       **
**    PP    PP      II       GG          LL          EE             TT       **
**    PPPPPPP       II       GG   GG     LL          EEEEE          TT       **
**    PP            II       GG    GG    LL          EE             TT       **
**    PP            II       GG    GG    LL          EE             TT       **
**    PP          IIIIII      GGGGGG     LLLLLLLL    EEEEEEEE       TT       **
**                                                                            **
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Evolution Group 7 - Pile Group Example - EC7 Factor Set A2 Chris Raison Associates (UK)

Pile group analysis for 9 piles under general loading conditions

Pile details are

Embedded length = 1.250E+01
Freestanding length = 0.000E+00

Equivalent Youngs modulus of embedded section of piles:

Axial : 2.000E+07 , Lateral : 2.000E+07

Piles are assumed to be fixed into the pile cap

Pile layout details are:

Pile no.	Radius	Base radius	X co-ord	Y co-ord	Rake psi(x)	Rake psi(y)
1	1.750E-01	1.750E-01	-4.000E+00	4.000E+00	0.000E+00	0.000E+00
2	1.750E-01	1.750E-01	0.000E+00	4.000E+00	0.000E+00	0.000E+00
3	1.750E-01	1.750E-01	4.000E+00	4.000E+00	0.000E+00	0.000E+00
4	1.750E-01	1.750E-01	-4.000E+00	0.000E+00	0.000E+00	0.000E+00
5	1.750E-01	1.750E-01	0.000E+00	0.000E+00	0.000E+00	0.000E+00
6	1.750E-01	1.750E-01	4.000E+00	0.000E+00	0.000E+00	0.000E+00
7	1.750E-01	1.750E-01	-4.000E+00	-4.000E+00	0.000E+00	0.000E+00
8	1.750E-01	1.750E-01	0.000E+00	-4.000E+00	0.000E+00	0.000E+00
9	1.750E-01	1.750E-01	4.000E+00	-4.000E+00	0.000E+00	0.000E+00

Soil properties are:

Axial load-deformation - G(0) = 8.000E+03
dG/dz = 6.300E+02
G(b) = 1.600E+05
Nu = 0.200

Lateral load-deformation - G(0) = 8.000E+03
dG/dz = 6.300E+02
Nu = 0.200

Parameters for axial load-deformation behaviour are:

Shear modulus at level of pile bases is G(L) = 1.588E+04
Rho = G(L/2)/G(L) = 7.520E-01
Shear modulus below pile bases is G(b) = 1.600E+05
Xi = G(L)/G(b) = 9.922E-02
Poissons ratio is nu = 0.200
Rm = (0.25+xi*(2.5*rho*(1-nu)-0.25))*L + 4.514E+00 = 9.194E+00
Pile stiffness ratio is Epa/G(L) = 1.260E+03
Axial flexibility of pile no. 1 (isolated, at mudline) = 4.993E-06

Parameters for lateral load-deformation behaviour are:

Gc = (G(0)+(Lc/2)*Gm*(1.+0.75nu) = 1.030E+04
Rhoc=G(Lc/4)/G(Lc/2) = 9.465E-01
Critical slenderness ratio is Sc = 1.740E+01
Critical depth is Lc = 3.045E+00
Lateral flexibilities (isolated, at mudline) of first pile are:
u/H = 5.365E-05
th/H or u/M = 3.916E-05
th/M = 6.673E-05

Parameters for torsional load-deformation behaviour are:

Gc = G(0)+Lc*Gm = 1.093E+04
Rhoc = G(Lc/2)/Gc = 8.661E-01
Critical slenderness ratio is Sc = 2.653E+01
Critical depth is Lc = 4.644E+00
Torsional flexibility (at mudline) of first pile = 1.674E-04

The following pages of output give the load deformation behaviour of the pile group under general loading

Load case no. 1 out of 1

Pile loads and deformations

Vertical load	Horizontal load (x)	Moment (x to z)	Horizontal load (y)	Moment (y to z)	Torque (x to y)
4.0000E+03	1.0000E+02	3.0000E+03	3.0000E+02	1.0000E+03	0.0000E+00

Vertical deflection	Horizontal defn (x)	Rotation (x to z)	Horizontal defn (y)	Rotation (y to z)	Torsion (x to y)
3.5824E-03	6.9949E-04	2.1826E-04	1.7560E-03	8.4166E-05	1.3541E-12

Pile no.	Axial loads	Lateral loads (x)	Moments (x to z)	Lateral loads (y)	Moments (y to z)	Torques (x to y)
1	4.0024E+02	1.1994E+01	-3.8911E+00	3.5929E+01	-2.0182E+01	8.0905E-09
2	4.7592E+02	1.0605E+01	-3.1381E+00	3.2410E+01	-1.8194E+01	8.0905E-09
3	6.5956E+02	1.1994E+01	-3.8911E+00	3.5929E+01	-2.0182E+01	8.0905E-09
4	3.1032E+02	1.0804E+01	-3.2197E+00	3.1865E+01	-1.7974E+01	8.0905E-09
5	3.6110E+02	9.2070E+00	-2.3491E+00	2.7731E+01	-1.5640E+01	8.0905E-09
6	5.4934E+02	1.0804E+01	-3.2197E+00	3.1865E+01	-1.7974E+01	8.0905E-09
7	3.0024E+02	1.1994E+01	-3.8911E+00	3.5929E+01	-2.0182E+01	8.0905E-09
8	3.8374E+02	1.0605E+01	-3.1381E+00	3.2410E+01	-1.8194E+01	8.0905E-09
9	5.5956E+02	1.1994E+01	-3.8911E+00	3.5929E+01	-2.0182E+01	8.0905E-09

EG7 Piling Example

Project

Property	Value
Name	EG7 Piling Example
Description	Three x Three Pile Group Bridge Abutment
Project number	EG7/PG1
Revision	-
Made by	Chris Raison
Date	2012-11-05
Client	
Company	

Piles

Pile	Length		Diameter			Coordinates		Rake		Young's modulus	
	Embedded	Free	Shaft	Internal	Base	X	Y	XZ	YZ	Axial	Lateral
1	12.500 m	0.0 m	0.350 m	0.0 m	0.350 m	-4.000 m	4.000 m	0.0 deg	0.0 deg	20.000 GPa	20.000 GPa
2	12.500 m	0.0 m	0.350 m	0.0 m	0.350 m	0.0 m	4.000 m	0.0 deg	0.0 deg	20.000 GPa	20.000 GPa
3	12.500 m	0.0 m	0.350 m	0.0 m	0.350 m	4.000 m	4.000 m	0.0 deg	0.0 deg	20.000 GPa	20.000 GPa
4	12.500 m	0.0 m	0.350 m	0.0 m	0.350 m	-4.000 m	0.0 m	0.0 deg	0.0 deg	20.000 GPa	20.000 GPa
5	12.500 m	0.0 m	0.350 m	0.0 m	0.350 m	0.0 m	0.0 m	0.0 deg	0.0 deg	20.000 GPa	20.000 GPa
6	12.500 m	0.0 m	0.350 m	0.0 m	0.350 m	4.000 m	0.0 m	0.0 deg	0.0 deg	20.000 GPa	20.000 GPa
7	12.500 m	0.0 m	0.350 m	0.0 m	0.350 m	-4.000 m	-4.000 m	0.0 deg	0.0 deg	20.000 GPa	20.000 GPa
8	12.500 m	0.0 m	0.350 m	0.0 m	0.350 m	0.0 m	-4.000 m	0.0 deg	0.0 deg	20.000 GPa	20.000 GPa
9	12.500 m	0.0 m	0.350 m	0.0 m	0.350 m	4.000 m	-4.000 m	0.0 deg	0.0 deg	20.000 GPa	20.000 GPa

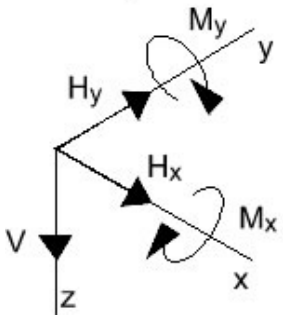
Layers

Layer	Type	Thickness	Axial soil modulus		Lateral soil modulus		Poisson's ratio	Below water table
			At top	Gradient	At top	Gradient		
1	Drained Layer	12.500 m	19.200 MPa	1.512 MN/m³	19.200 MPa	1.512 MN/m³	0.200	yes
2	Drained Layer	5.000 m	384.000 MPa	0.0 MN/m³	384.000 MPa	0.0 MN/m³	0.200	yes

Loads

Load Case	Vertical Axis	Horizontal X-Axis		Horizontal Y-Axis
	Force V	X Position	Y Position	

				Force H_x	Moment M_x	Force H_y	Moment M_y
1	4.000 MN	0.0 m	0.0 m	0.100 MN	1.000 MNm	0.300 MN	3.000 MNm



Options

Parameter	Value
Analysis	3-dimensional/linear
No of load increments	1
No of elements per pile	18

EG7 Piling Example

Key results

Pile cap	Vertical Z-Axis		Horizontal X-Axis				Horizontal Y-Axis			
	Force/Displacement		Force/Displacement		Moment/Rotation		Force/Displacement		Moment/Rotation	
Action	4000.000	kN	100.000	kN	1000.000	kNm	300.000	kN	3000.000	kNm
Effect	3.999	mm	0.934	mm	0.088	x10 $^{-3}$rad	2.132	mm	0.199	x10 $^{-3}$rad

Pile	Vertical Z-Axis		Horizontal X-Axis				Horizontal Y-Axis			
	Force at head		Force at head		Moment at head		Force at head		Moment at head	
1	388.300	kN	3.417	kN	-26.050	kNm	43.850	kN	-1.791	kNm
2	480.700	kN	8.939	kN	-25.100	kNm	42.710	kN	-4.480	kNm
3	647.300	kN	22.490	kN	-27.050	kNm	46.310	kN	-10.760	kNm
4	311.600	kN	1.675	kN	-19.980	kNm	31.580	kN	-0.883	kNm
5	397.100	kN	6.989	kN	-17.820	kNm	27.730	kN	-3.477	kNm
6	555.800	kN	21.640	kN	-19.980	kNm	31.580	kN	-10.250	kNm
7	286.800	kN	4.159	kN	-18.390	kNm	27.970	kN	-2.097	kNm
8	386.700	kN	8.939	kN	-15.730	kNm	22.740	kN	-4.480	kNm
9	545.800	kN	21.750	kN	-17.380	kNm	25.520	kN	-10.460	kNm