COMPARISON OF FOUR PILE GROUP ANALYSIS PROGRAMS

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Four computer programs CLAP, PIGLET, REPUTE and PLAXIS 3D, have been used for the analysis of pile groups subjected to applied loadings. The programs are briefly introduced and the basis of each program is described. The limitations of each program are discussed, together with the way in which the soil, piles and pile caps are modeled. The programs are first compared for the analysis of an idealized group of piles founded in a relatively simple geotechnical model. Loads applied to the model comprise vertical and horizontal forces, with longitudinal, transverse and torsion moment also being applied. Pile deflection, rotation and settlements under these loads were compared. Generally similar results are found using the four programs for this case, except for the axial loads predicted by PIGLET.

The programs have then been used for a real case history, a 151 storey super high-rise building in Songdo, Korea. The assessment of the geotechnical parameters is described and the same parameters have been used in all programs. The computed deflections, rotations and settlement for the real case are found to agree reasonably well, although there are some differences from the programs in which modeling of the real soil profile is necessarily simplified.

Keywords: Analysis, Incheon tower, Deep foundations, Piles, Deflection, Rotation, Settlement.

1. INTRODUCTION

Different methods can be used to predict a pile group behavior. Methods vary from hand calculations to more sophisticated software analysis. Usually the methods employed by the commercial software are the Boundary Element Analysis (BEM) and the Finite Element Method (FEM). Despite the availability of many different software packages, it seems that little effort has been made to compare the results of analyses carried out with alternative packages.

Therefore, in this paper the attention is focused in the comparison of four alternative computer software packages. The computer codes are briefly described and the comparisons are made between the results obtained from the four methods. The cases analyzed are listed below:

Advances in Foundation Engineering
Edited by K. K. Phoon, T. S. Chua, H. B. Yang and W. M. Cham

ISBN: 978-981-07-4623-0 :: doi:10.3850/978-981-07-4623-0_085

1. A simple hypothetical case involving a group of nine piles (3×3 configuration at centre-to-centre of 2 m in each direction) in a two soil layer ground model. 3D loading is applied to it.
2. The Incheon Tower Korea, one of the tallest towers in the world, currently awaiting recommencement of construction.

The main objective of this paper is to critically compare the above mentioned software so they can be used with more confidence when approaching a real case.

2. REVIEW OF FOUR ALTERNATIVE COMPUTER ANLYSES

2.1. *Program CLAP*

CLAP (**C**ombined **L**oad **A**nalysis of **P**iles) (Coffey, 2007) is a development of the program DEFPIG which uses a Boundary Element Analysis, for the analysis of axially and laterally loaded pile groups. It allows for simultaneous applications of lateral and moment loadings in two horizontal directions, as well as a torsional load, to the pile group. Different layer thicknesses along the pile shaft can be entered with different soil properties, and a number of different layers can be considered below the pile tip. Equivalent values of Young's modulus and ultimate end bearing capacity are estimated for the pile tip via the use of weighting factors down to the assumed depth of influence. The weighting factors reduce from unity at the pile tip to zero at the depth of influence, which is assessed by the user and is generally between 2 and 5, depending whether the layer increases its strength with depth (smaller value) or the softer layers are at some depth below the pile tip (larger value). The program allows also for the plastic behavior of the soil-pile interface. In addition, a more realistic estimation of the two-pile interaction factors can be made by allowing for the fact that the soil modulus depends on the strain level within the soil, so that the soil modulus between two piles will generally be greater than that at the pile-soil interface due to the lower strain level existing between the piles.

2.2. *Program PIGLET*

The software has been developed by Randolph (2004). PIGLET analyses the load deformation response both for a pile group and for a single pile. The interface is in EXCEL platform. The software uses a series of approximations to develop the response of the piles within the group under a 3D loading. The soil can only be modeled as linear elastic and the soil stiffness varies linearly with depth (Gibson soil).

Different value of shear modulus may be specified for vertical and lateral loading, although maintaining the same Poisson's ratio. The program doesn't allow for the overall stability of the piles which needs to be carried out separately.

Later versions of PIGLET allow for a limiting axial pile load, but the program is primarily used to compute the elastic response of the pile group.

2.3. *Program REPUTE*

Repute (Geocentrix, 2009) is based on a complete 3D BEM non-linear solution of the soil continuum which overcomes the approximations of Winkler models or interaction factors.

The analysis involves discretization of only the pile-soil interface into a number of elements and adopts the traditional Mindlin solution to perform a complete analysis of the group (i.e. the simultaneous influence of all the elements of all the piles within the group is considered). Non-linear response at the pile-soil interface is simulated by adopting a hyperbolic stress-strain model within a stepwise incremental procedure which ensures that the specified limiting stresses at the pile-soil interface are not exceeded. The soils installed in the program have been set up with a range of values so if a soil with different parameters has to be entered a new soil needs to be created. Square and rectangular pile layout are easy to enter but if a less conventional pile layout (i.e. not rectangular or not square layouts) has to be entered then a less immediate process must be followed. This involves entering the pile layout using a rectangular matrix with the desired number of piles and then changing the coordinates, if necessary, for each of the piles. Also a minimum distance $s/D \geq 2$ between piles needs to be maintained for the software to be able to run the analysis.

2.4. *Program PLAXIS 3D*

PLAXIS 3D FOUNDATION is a commercially available three-dimensional finite element program specifically developed by PLAXIS NL for the analysis of the interaction between foundation structures and the surrounding soil. The soil can be modeled and analyzed using different constitutive models. The piles can be represented as a series of solid elements, or as structural elements. The foundation can be modeled in stages to simulate stage of constructions and it is possible to see the effect of each loading case per each stage. The outputs are easily visualized by means of graphs.

3. COMPARISON OF SOLUTION FOR SIMPLE CASE

CLAP, PIGLET, REPUTE and PLAXIS 3D have been compared for the prediction of pile head settlement, deflection and rotation. Also Pile loads and bending moments have been compared by analysing a hypothetical problem of pile group shown in Figure 1.

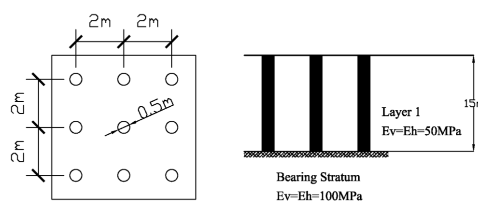

Figure 1. Pile Layout Plan – Simple Case.

A group of 9 piles (3 × 3 at centre to centre spacing 2 m in each direction) was analyzed. The piles are 15 m long, 0.5 m diameter, with a Young's modulus of 30 GPa, and are located in a 15 m layer of soil that is underlain by a stiffer bearing stratum. The first layer has a Young's modulus of 50 MPa for both vertical and lateral response, while the Young's Modulus of the bearing stratum is 100 MPa. Elastic ground behavior is assumed for this exercise. The pile group point loads and bending moments have been applied at the centre of the pile raft. Loads were as follow:

- Vertical Load = 9 MN
- Lateral Load (x-direction) = 0.9 MN
- Bending Moment (x-direction) = 3 MNm
- Lateral Load (y-direction) = 0.9 MN
- Bending Moment (y-direction) = 4.5 MNm
- Torsion = 1.5 MNm

Table 1. Comparison of solutions.

Quantity	CLAP	PIGLET	REPUTE	PLAXIS 3D
Central Settlement mm	7.43	9.1	8.8	14.1
Lateral Deflection (x) mm	3.1	2.0	3.3	4.7
Lateral Deflection (y) mm	3.2	2.2	2.3	4.2
Rotation (x) rad	0.0004	0.0015	0.0002	0.0032
Rotation (y) rad	0.0005	0.0001	0.0006	0.0019
Torsional Rotation rad	0.0004	0.0004	0.0005	–
Maximum Axial Load MN	1.9	3.4	1.8	1.8
Maximum Lateral Load (x) MN	0.17	0.18	0.25	0.27
Maximum Lateral Load (y) MN	0.17	0.18	0.25	0.26
Maximum Moment (x) MNm	0.12	0.25	0.18	0.32
Maximum Moment (y) MNm	0.11	0.24	0.14	0.31
Maximum Torsion Moment (x) MNm	0.01	0.01	0.01	–

Table 1 summarizes the results of the CLAP, PIGLET, REPUTE and PLAXIS 3D analysis for the group and shows the computed forces and moment due to the applied loads for the most heavily loaded pile. The results shown in the table reveals a generally reasonable agreement given the different underlying assumptions in the four programs adopted. The exception is the maximum axial load given by PIGLET, which is much greater than that from the other programs.

All the values shown on the above table refer to those piles located within the corner of the pile raft, except for the settlements.

4. APLLICATION TO THE INCHEON TOWER

4.1. *Foundation Layout*

A pile raft foundation was designed to support the tower superstructure, consisting of 172 concrete bored pile of 2.5 m diameter supported by a 5.5 m thick raft. Their length varied from 46.1 m to 76.1 m depending on the local ground conditions. A detailed foundation description of the foundation design is available in *Abdelrazaq et al. (2011)*. The pile layout is shown in Fig 2. Architectural rendering of the 151 storey Incheon Tower is shown in Fig. 3.

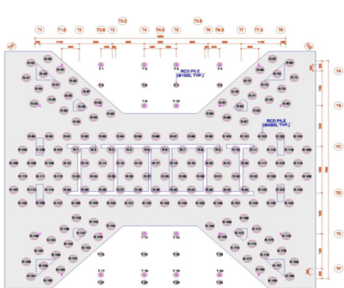

Figure 2. Pile Layout Plan Incheon Tower (Adopted from *Ahmad Abdelrazaq et al., 2011*).

Figure 3. 151 Storey Incheon Tower (Architectural Rendering (Adopted from *Ahmad Abdelrazaq et al., 2011*).

4.2. *Ground Investigation*

From the available borehole data it was assessed that the geological profile is very heterogeneous. The site lies entirely within an area of reclamation, which is understood to comprise of a thick layer of approximately 8 meters of loose sand and sandy silt, over approximately 20 meters of soft to firm marine silty clay, referred to as the Upper Marine Deposits (UMD). These deposits are underlain by approximately 2 m of medium dense to dense silty sand, referred to as the Lower Marine Deposits (LMD), which overlie residual soil and a profile of weathered rock. The rock materials found within about 50 meters have experienced weathering which is understood to have reduced their strength to a very weak rock or a soil-like material. A detailed interpretation of the ground conditions based on the comprehensive ground investigation (Halla 2008) was developed by *Poulos et al. (2011)*. A diagrammatic geological model is presented in Figure 4.

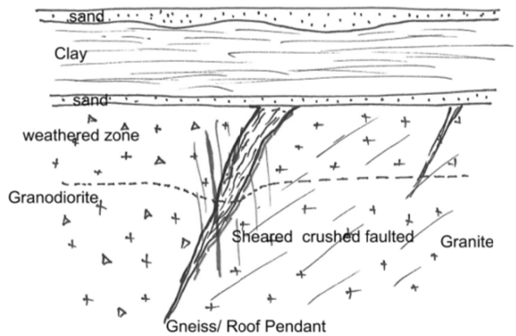

Figure 4. Diagrammatic Geological Model (Adopted from *Ahmad Abdelrazaq et al., 2011)*.

4.3. *Geotechnical Model*

The tower's footprint was divided into eight zones which were considered to be representative of the variation of both ground and geotechnical conditions, and a geotechnical model was developed for each zone. Appropriate geotechnical parameters for the various strata were adopted using the available field and laboratory data, including pressuremeter and geophysical data. Further details of the development of geotechnical parameters are given by Abdelrazaq et al. (2011) and Poulos et al. (2011). Typical geotechnical parameters for one of the zones adopted for this analysis are shown in Table 2.

Table 2. Typical Geotechnical Design Parameters.

Stratum	E_v (MPa)	E_h (MPa)	f_s (kPa)	fb (MPa)
UMD	7–15	5–11	29–48	–
LMD	30	21	50	–
Weathered Soil	60	42	75	–
Weathered Rock	200	140	500	5
Soft Rock (above EL-50m)	300	210	750	12
Soft Rock (below EL-50m)	1700	1190	750	12

Note: E_v = Vertical Modulus; f_s = Ultimate shaft friction; E_h = Horizontal Modulus; fb = Ultimate end bearing.

4.4. *Procedure, Analysis and Comparison of Results for the Pile Group Foundation*

A single load case was applied to the respective models in each of the software adopted for this study. The loads considered are listed below:

- Vertical Load = 6560.4 MN
- Lateral Load (x-direction) = 149 MN
- Bending Moment (x-direction) = 21600 MNm
- Lateral Load (y-direction) = 114.6 MN
- Bending Moment (y-direction) = 12710 MNm
- Torsion =1996 MNm

The loads were applied at the centre of the Incheon Tower pile group model for the following programs:

- CLAP
- PIGLET
- REPUTE

In PLAXIS 3D, moment and torsional load cannot be applied directly, and so these loads were applied as point loads as discussed in Pile Raft Foundation for Tall Buildings, Poulos et al. (2011). The results of the analyses are shown in Table 3.

Table 3. Comparison of solutions for Incheon Tower.

Quantity	CLAP	PIGLET	REPUTE	PLAXIS 3D
Central Settlement mm	53.0	57.6	55	56
Lateral Deflection (x) mm	18.5	19.5	21	18.7
Lateral Deflection (y) mm	14.92	16.1	18	15
Rotation (x) rad	0.0002	0.0003	0.0002	0.0002
Rotation (y) rad	0.0002	0.0002	0.0000	0.0002
Torsional Rotation rad	0.0004	0.074	0.0003	0.0003
Maximum Axial Load MN	84.6	158	84.8	83.0
Maximum Lateral Load (x) MN	2.711	4.25	3	2.5
Maximum Lateral Load (y) MN	2.607	3.7	2.8	2.2
Maximum Moment (x) MNm	22.87	16.5	21.4	20
Maximum Moment (y) MNm	22.9	12	18.5	21
Maximum Torsion Moment (x) MNm	3.68	0.00	1.00	2.50

All the values shown on the above table refer to those piles located within the corner of the pile raft, except for the settlements. The agreement between the four programs is again quite reasonable, except again for the maximum axial load given by PIGLET, which is much greater than the other three programs.

5. CONCLUSIONS

Four different computer programs were adopted for the analysis of a pile group. The programs were CLAP, REPUTE, PIGLET and PLAXIS 3D. These programs have been described briefly, and then compared for the analysis of a simple problem. The results generally agree reasonably well and the small differences can be considered as the result of the different approach that the software adopt to model the pile-soil interaction. The exception is the maximum axial load computed by PIGLET, which appears to be considerably larger than that from the other programs.

The same software packages have also been used to estimate pile group (172 piles) behavior of the 151 storey Incheon Tower, Korea. The estimated pile head settlement, deflection, rotation, pile loads and bending moments seem to converge reasonably well. Again, the maximum axial load from PIGLET is larger than from the other programs.

It will be interesting to compare these predictions with measured data, but at this stage no data are available as the construction of the Incheon Tower is currently suspended.

ACKNOWLEDGMENTS

The authors gratefully acknowledges the contributions of Professor John Small for his technical support regarding CLAP and PIGLET, Dr Francesco Basile for his continuous support with REPUTE and Dr Helen Chow in relation to the PLAXIS 3D analysis for the tower described in this paper.

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