Behaviour of Piled Rafts with Piles of Different Lengths and Diameters

J.C. Small
BSc(Eng), PhD, F.I.E. Aust
Associate Professor, The University of Sydney
H.H. Zhang
BE, ME, PhD
SMEC Australia Pty Ltd
H. Chow
BE, MES, MBA
Research Student, The University of Sydney

Summary: Piled rafts are an efficient means of supporting structures as the load is not only carried by the piles, but load is transferred to the soil by the raft. In cases where the raft is unevenly loaded, for instance by towers of different heights, longer piles or piles of larger diameter may be required beneath the more heavily loaded part of the raft to stop the foundation from rotation. For tall buildings, any rotation of the foundation can mean that the building will tilt, and this can mean large lateral movements at the top of the structure. In this paper, a finite layer approach is presented that may be used for analysis of piled rafts with different length or diameter piles. The soil may be horizontally layered, and loads on the raft may be vertical or horizontal.

INTRODUCTION

The design of piled raft foundations has been investigated by many researchers, and many different techniques have been developed for carrying out the analysis. The analytic techniques that have been used in the past can be classified into the following groups:

(1) Simple plate on springs approaches
These methods treat the piles as springs with the raft is treated as a plate, and include the methods of Clancy and Randolph (1993), Poulos (1994) and Viggiani (1998).

(2) Boundary element methods
These methods employ the technique described above and include solutions obtained by Butterfield and Banerjee (1971), Brown and Weisner (1975), Hain and Lee (1978), Kuwabara (1989) and Chow (1986).

(3) Finite Layer techniques
Ta and Small (1996) used finite layer techniques to compute the behaviour of piled rafts, where the piles were driven into layered soils. Cheung et al. (1988) had previously used series to analyse the behaviour of pile groups in layered soils, and the method can be extended to piled rafts. Zhang and Small (2000) have extended these techniques to horizontal loading of a piled raft.

(4) Simplified finite element or finite difference analyses
Analyses can be carried out by approximating the piles as a two dimensional or axisymmetric body and assigning 'smeared' material properties to the piles in order to approximate the actual three dimensional behaviour. That is, the solid continuous 'pile' in an axi-symmetric or 2-d analysis is given a lower modulus to make it compress the same amount as the actual individual piles. Analyses of this sort include those of Desai et al. (1974) and Hooper (1973). Lin et al. (1999) have used a finite difference technique to compute the behaviour of the soil beneath a piled raft, and applied the theory to piled rafts in Bangkok clay using a two-dimensional finite difference grid.

(5) Three-dimensional finite element analyses
As computer storage has increased, full 3-d analyses of piled rafts have been carried out and examples of this are given by Zhuang et al. (1991), Katzenbach and Reul (1997), Katzenbach et al. (1997), and Ottaviani (1975). However in all of these analyses apart from the finite element methods, it is not possible to analyse rafts supported by piles of different lengths and diameters. In this paper therefore, a technique is presented that allows such problems to be solved simply, without the need to use full 3-dimensional finite element methods.

FINITE LAYER ANALYSIS

Analysis of the piles and soil is carried out using the finite layer method. In this method, the layered soil is treated as a series of horizontal layers, each of which can have different properties. Loads can be applied to the surface of the layered soil system, or to the interfaces between each of the layers. For the piles, the continuous shear stress that is applied down the shaft of the piles can be approximated as a series of ring loads applied at the interfaces between the layers. If the number of these ring loads is large enough, the approximation to the continuous shear stress is sufficiently close to give accurate results for the pile behaviour.

The raft is analysed by using finite elements. These are assumed to be rectangular in shape as the contact stresses that are applied to the raft (and in an equal and opposite direction to the soil) are assumed to be uniform blocks of pressure. The finite layer method is capable of being used to compute the deflection of the soil under a uniform rectangular load, and so can be used for analysis of these contact stresses.

For lateral loading of the piled raft, ring loads in the horizontal direction can be applied to the pile shaft to represent the continuous pressure applied by the soil in resisting lateral movement. The resisting force in shear between the raft and the soil can be treated as a series of rectangular shear stresses that are uniform over each element in the raft and applied over corresponding rectangular regions of the soil. Again solutions to the deflections of the soil due to these ring loads or rectangular shear loads can be found from finite layer theory. These ring and surface loads are shown in Figure 1, and a full explanation of the technique is presented in Zhang and Small (2000).

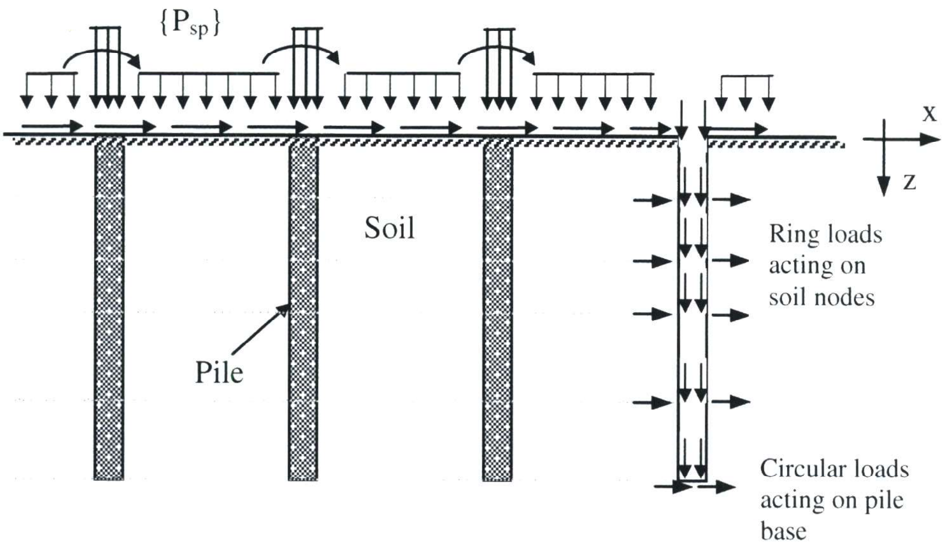

Figure 1: Ring loads acting along pile shafts and surface loads acting on the soil.

INTERACTION

In carrying out the analysis of a piled raft foundation, there are four different interactions that need to be computed. These are the interaction of one pile with another pile (i.e. the deflection of an unloaded pile caused by loading of a nearby pile), the interaction of a pile with the soil surface, the interaction of a loading on the soil surface with a pile, and the interaction of a loading on the soil surface with another point on the surface. All of these interactions can be computed for both vertical and lateral loadings.

As an example, two piles of different lengths were analysed, one being 50m long and having a diameter of 1m the other 25m long and having a diameter of 0.5m. The modulus of the soil was taken as 4MPa and of the piles as 30,000MPa. Figure 2 shows the interaction factors calculated when the long pile is loaded.

In the figure, the interaction factor α_v is plotted against the pile spacing to diameter ratio s/d. The vertical interaction factor is shown as calculated by a three-dimensional finite element program (FE) where the piles are treated as columns of stiff elements of square cross-section, and from finite layer calculations (FL). The interaction factors calculated by the computer program APRAF are also shown. The APRAF results are slightly different as the program is allowing for both vertical and horizontal movements. It may be seen that the finite layer results are slightly smaller than the finite element results, and this may be due to the fact that soil layers are of infinite lateral extent for the finite layer computations.

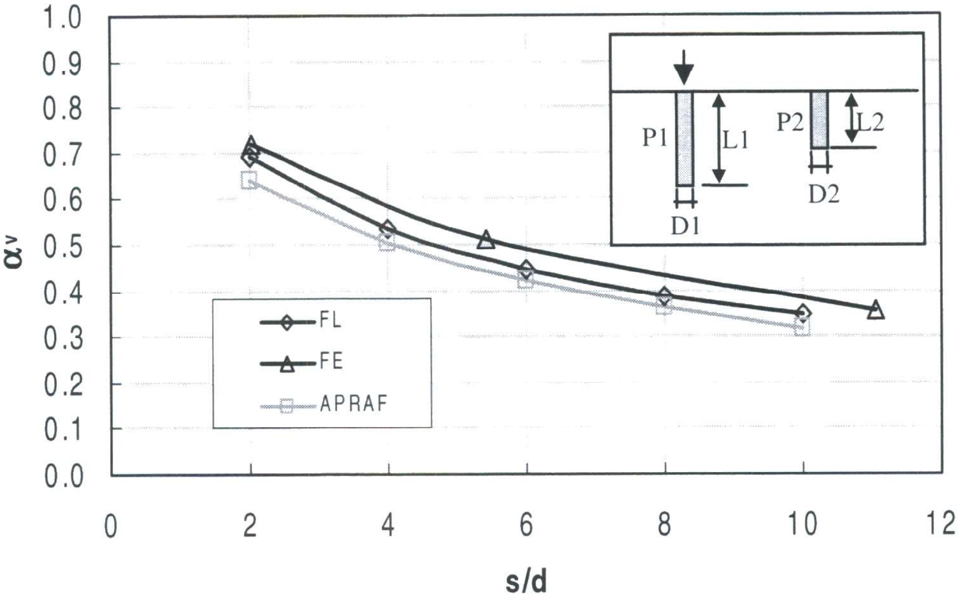

Figure 2: Pile-pile interaction for vertical load and piles of different lengths and diameters. (L_1=50m, D_1=1.0m, L_2=25m, D_2=0.5m. d=D_1).

The interaction factors are different for piles of different dimensions depending on which pile is loaded. For example, for two piles of different diameters and lengths (and soil properties as for the first example), the interaction caused by loading pile 1 is different than that caused by loading pile 2. This is shown in Figure 3 where loading the longer pile may be seen to cause more settlement of pile 2 than in the reverse case where pile 2 is loaded causing pile1 to settle.

This is also true of horizontal loading. As can be seen from the plot of Figure 4, loading pile 1 laterally causes the short pile (Pile 2) to deflect more than when the reverse occurs and pile 2 is loaded causing pile 1 to deflect horizontally. In Figure 4 the soil and pile moduli used were 4MPa and 30,000MPa respectively.

Although these examples have been for piles in homogeneous soils, there is no restriction on the piles being in soils that are horizontally layered.

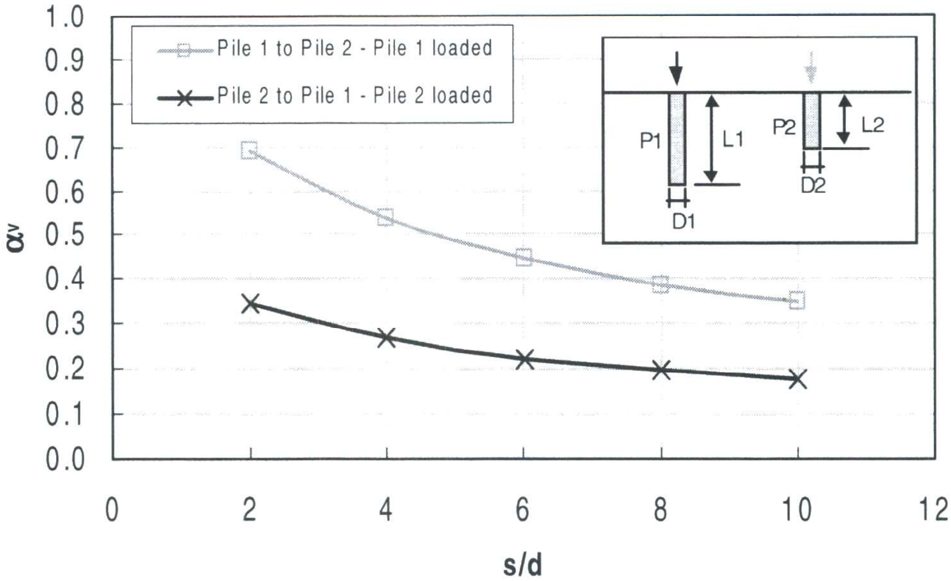

Figure 3: Vertical interaction factors for piles of different lengths and diameters. (L_1=50m, D_1=1.0m, L_2=25m, D_2=0.5m. d=D_1).

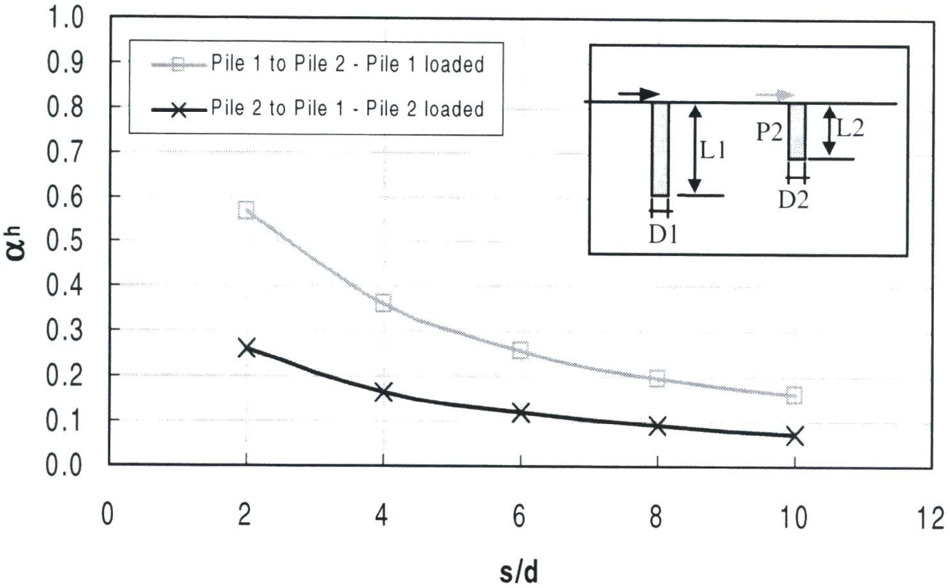

Figure 4: Horizontal interaction factors for piles of different lengths and diameters. (L_1=50m, D_1=1.0m, L_2=25m, D_2=0.5m. d=D_1).

ANALYSIS OF PILED RAFTS

The finite layer theory was used to analyse a foundation where the piles were longer on one side of the pile cap than the other. The problem was firstly analysed using the finite difference program FLAC^{3D}, and then using the finite layer method. The pile layout can be seen in the plot of the finite difference grid shown in Figure 5. As can be seen, in this case the raft was clear of the ground. All of the properties used in the analysis are given in Table 1.

For the FLAC^{3D} analysis it was convenient to make the piles square in cross-section, and so the pile cross-sectional area was made equal to that of the circular piles of the Finite Layer analyses. The piles were either of uniform length (16m CASE 2 and 22m CASE 3) or were made 16m long (beneath the ground level) under the left half of the raft and 22m long under the right hand side of the raft (CASE 1).

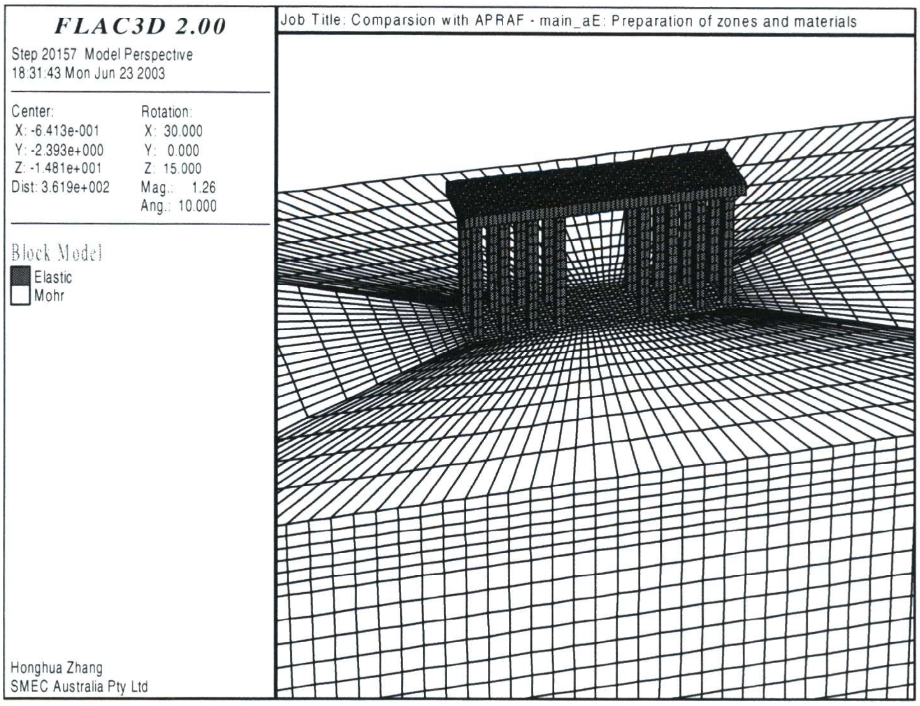

Figure 5: Finite difference grid used in FLAC^{3D} analysis.

Two point loads of equal magnitude (10500kN) were placed at the centres of the 8 piles to the left and to the right of the raft (see Figure 5). This would be expected to cause the raft to tilt in the direction of the shorter piles.

Figure 6 shows the vertical displacement along the centre line of the front row of the pile group. Where the two pile lengths are equal, the raft deflects uniformly (CASES 2 and 3). Where the pile lengths are different, the raft tilts towards the direction of shorter pile lengths (CASE 1). The FLAC^{3D} solution for CASE1 is shown in the figure and it can be seen to be of the same shape, but of less magnitude than the APRAF (Finite Layer solution).

Table 1: Properties used in the analysis of the piled raft.

Quantity	Value
Modulus of soil (MPa)	Variable (see Table 2)
Poisson's ratio of soil	Variable (see Table 2)
Modulus of raft (MPa)	25000
Thickness of raft (m)	1.0
Plan dimensions of raft (length x width) (m)	22.5 x 6.0
Poisson's ratio of raft	0.15
Diameter of piles (m)	0.846 (0.75 x 0.75 FLAC^{3D})
Modulus of piles (MPa)	25000
Pile spacing (centre to centre) (m)	2.25

Table 2: Layered soil properties

Depth (m)	Soil modulus (MPa)	Poisson's Ratio
0-4	5	0.30
4-6	7	0.35
6-10	60	0.20
10-20	100	0.15
20-22	10	0.30
22-25	800	0.25
25-50	2000	0.20

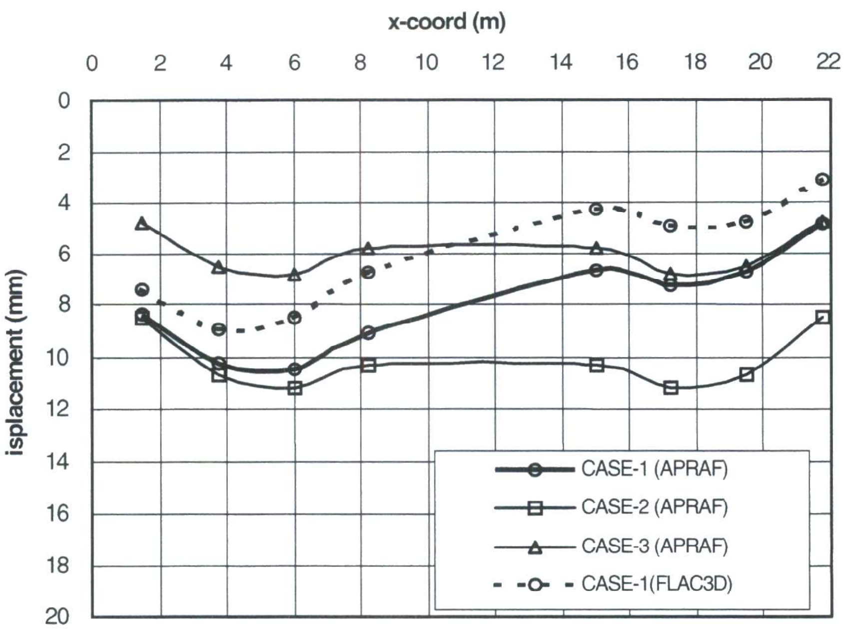

Figure 6: Vertical displacement of raft along the front row of piles from FLAC^{3D} and Finite Layer Analyses.

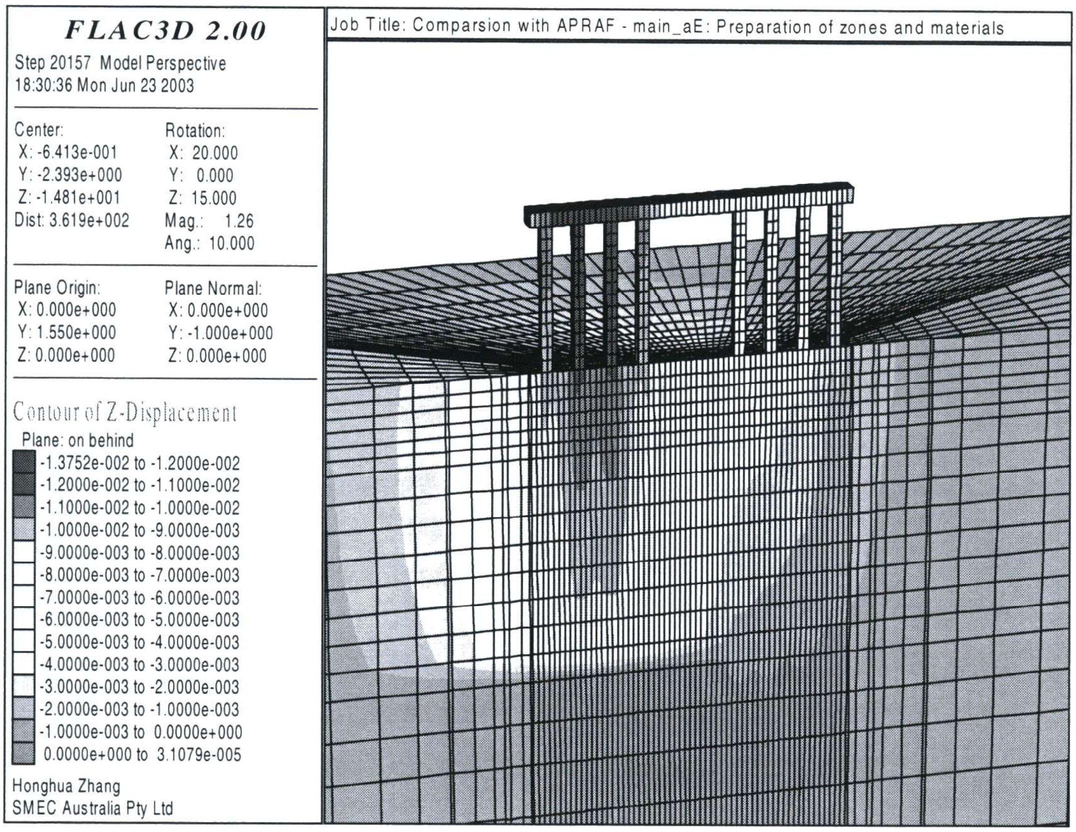

Figure 7: Contours of vertical displacement for CASE 1

CONCLUSIONS

The Finite Layer Method may be used to analyse piled rafts where the length and diameter of the piles may be different, and to obtain reasonably accurate solutions for such problems. The method is fairly efficient, and is simpler and easier to use than full three-dimensional analyses such as the FLAC^{3D} analyses presented here as check solutions.

Piled rafts that are loaded either vertically or horizontally may be analysed with the technique, and layered soils and soils of finite depth, present no particular difficulty in the analysis.

REFERENCES

Brown, P.T. and Weisner, T.J. (1975). "The behaviour of uniformly loaded piled strip footings," *Soils and Foundations*. Vol.15, No.4, pp.13-21.

Butterfield, R. and Banerjee, P.K. (1971). "The elastic analysis of compressible piles and pile groups," *Géotechnique*, Vol.21,No.1, pp.43-60.

Cheung, Y.K. and Nag, D.K. (1968). "Plates and beams on elastic foundations- linear and non-linear behaviour," *Géotechnique*, Vol.18, pp.250-260.

Chow, Y.K. (1986). "Analysis of vertically loaded pile groups," *Int. Jl. For Numerical and Analytical Methods in Geomechanics*, Vol.10, pp.59-72.

Clancy, P. & Randolph, M.F. (1993). "An approximate analysis procedure for piled raft foundations," *Int Jl. for Numerical and Analytical Methods in Geomechanics*, Vol.17, No.12, pp.849-869.

Desai, C.S., Johnson, L.D. & Hargett, C.M. (1974). "Analysis of pile supported gravity lock," *Jl. Geotechnical Division, ASCE,* Vol.100, GT9, pp.1009-1029.

Hain, S. & Lee, I.K. (1978). "The analysis of flexible raft-pile systems," *Géotechnique,* Vol.28, No.1, pp.65-83.

Hooper, J.A. (1973). "Observations on the Behaviour of a Piled-Raft Foundation on London Clay," *Proc. Instn. Civil Engineers,* Vol.55, No.2, pp.855-877. (Discussion 1974 Vol.57, No.2, pp.547-552).

Katzenbach, R. and Reul, O. (1997). "Design and performance of piled rafts," *Proceedings of the 14th Int. Conf. on Soil Mechs. and Found Eng., Hamburg,* Vol.4, pp.2253-2256.

Katzenbach, R., Arslan, U., Gutwald, J. and Holzhäuser, J. (1997). "Soil-structure-interaction of the 300m high Commerzbank tower in Frankfurt am Main. Measurements and numerical studies," *Proceedings of the 14th Int. Conf. on Soil Mechs. and Found Eng., Hamburg,* Vol.2, pp.1081-1084.

Kuwabara, F. (1989). "An elastic analysis for piled raft foundations in a homogeneous soil," *Soils and Foundations,* Vol.29, No.1, pp.82-92.

Lin, D.G., Bergado, D.T. and Balasubramanium, A.S. (1999). "Soil-structure interaction of piled raft foundation in Bangkok subsoil,". *Eleventh Asian Regional Conf. on Soil Mech. Found. Eng.*, Hong et al. Eds., pp.183-187.

Ottaviani, M. (1975). "Three-dimensional finite element analysis of vertically loaded pile groups," *Géotechnique,* Vol.25, No.2, pp.159-174.

Poulos, H.G. (1994). "An approximate numerical analysis of pile-raft interaction," *Int. Jl. for Numerical and Analytical Methods in Geomechanics,* Vol.18, No.2, pp.73-92.

Ta, L.D. and Small, J.C. (1996). "Analysis of piled raft systems in layered soils," *Int. Jl. for Numerical and Analytical Methods in Geomechanics*, Vol.20, pp.57-72.

Viggiani, C. (1998). "Pile groups and piled raft behaviour," *Deep Foundations on Bored and Augered Piles, BAP III*, van Impe and Haegman (eds.), Balkema, Rotterdam, pp.77-90.

Zhang, H.H. and Small, J.C. (2000). "Analysis of capped pile groups subjected to horizontal and vertical loads," *Computers and Geotechnics*, Vol.26, No.1, pp.1-21.

Zhuang, G.M., Lee, I.K. and Zhao, X.H. (1991). "Interactive analysis of behaviour of raft-pile foundations," *Proceedings of the Int. Conf. on Geotech. Eng. for Coastal Development – Theory and Practice on Soft Ground - GEO-COAST '91. 3-6 Sept Yokohama*. Vol.1, pp.759-764.