Pile cap effects on lateral response of pile groups and piled rafts

H. Chow, J.C. Small & H.G. Poulos
Coffey Geotechnics, Sydney, NSW, Australia

ABSTRACT
Pile groups subjected to lateral loadings have in the past been treated as a group of piles that resist lateral loading due to the lateral pressure acting on the pile shaft. The effect of the cap or raft in resisting the lateral loading has often been neglected although cohesive or friction forces may be acting across the base of the cap. In this paper therefore, the effect of the forces acting on the base of the cap is considered in the analysis. The performance of pile groups is assessed with the cap resistance acting, and without the cap resistance acting so as to allow some quantification of the effect of not considering the cap resistance.

RÉSUMÉ
Dans le passé, on considérait que les groupes de pieux soumis aux chargements latéraux ne résistaient que par l'action de la pression latérale s'exerçant sur le fût. Le rôle joué par le chapiteau ou le radier dans la résistance au chargement latéral a souvent été négligé bien que des forces cohésives ou de frottement à la base du radier puissent entrer en jeu. Dans cet article, l'effet de ces forces est pris en compte dans l'analyse. Le comportement des groupes de pieux est étudié avec, puis sans la résistance du radier afin d'en quantifier l'effet.

1 INTRODUCTION

Early analysis of the deflection of piles and pile groups under lateral loading was carried out by Poulos (1971a) (see also Poulos & Davis (1980)) for simple cases where the piles were considered to be constructed in uniform elastic soil layers i.e. where the soil was treated as a continuum. The importance of interaction among the piles when piles were used in groups was recognised and charts were presented for interaction factors that quantified the effect of the lateral movement of one pile on the movement of another pile in the group (Poulos 1971b).

Bannerjee and Davies (1978) presented solutions for the case where the soil was non-homogeneous, and Small & Zhang (2002) extended the solutions to pile groups in layered soils and for pile groups with a flexible cap.

Another popular method for estimating lateral movements of piles involved the p-y methods of Matlock and Reese (1960) and Reese (1984) where the soil was treated as a series of non-linear springs. Interaction between the springs and between piles is one of the limitations of this method, but it is of practical use for single piles.

More recent work on the effect of a pile cap on the lateral deflection of a pile group has been carried out by Rollins and Sparks (2002) for static loading and Rollins and Cole (2006) for cyclic loading. These authors performed large scale tests on pile groups with a cap by jacking the group into a fill that provided lateral resistance against the cap. The weight of the cap was also considered to generate frictional resistance on the base of the cap.

2 METHOD OF ANALYSIS

The method of analysis for laterally loaded pile groups is based on the Finite Layer Method (Small and Booker 1986). The method is capable of analysing the behaviour of horizontally layered elastic soils and loads can be placed on the surface of the layered soil or at the interfaces between the layers.

For piled rafts, It may be assumed that the contact stresses between the raft and the soil are uniform blocks of pressure (in the vertical direction) and uniform shear loads (in each of the two horizontal directions). The skin friction acting along the shafts of the piles can be assumed to be ring loads acting both vertically and laterally at discrete points down the shaft, while the pressure on the base of the pile can be assumed to be a uniform circular vertical load or a uniform circular shear load. Such loads can be applied to the soil using the Finite Layer Method, and this has the advantage that layered soils can be used. The only restriction is that the various soil layers need to be horizontal and cannot change in thickness (or have properties change) in the lateral direction.

Equal and opposite loads are applied to the piles and raft as shown in Figure 1. The number of ring loads used down the pile shaft will affect the accuracy of solution as will the number of blocks of uniform pressure that represent the contact stresses. The deflection of the piles and the raft under the action of the ring loads or the uniform blocks of pressure is calculated using finite element methods. The piles are discretised into beam bending elements and the ring loads applied at the nodes. The raft is divided into plate bending elements (here 8 node isoparametric elements were used) and the blocks of contact pressure (that are the same size as the element) applied as a uniform pressure acting either vertically or laterally on the element.

The problem then reduces to one of finding the magnitudes of the ring loads and surface blocks of pressure so that the displacements of the piles and raft are equal at selected points. If there are *N* ring loads, pile base loads and contact pressures, then displacement matching between the soil and the structure must be

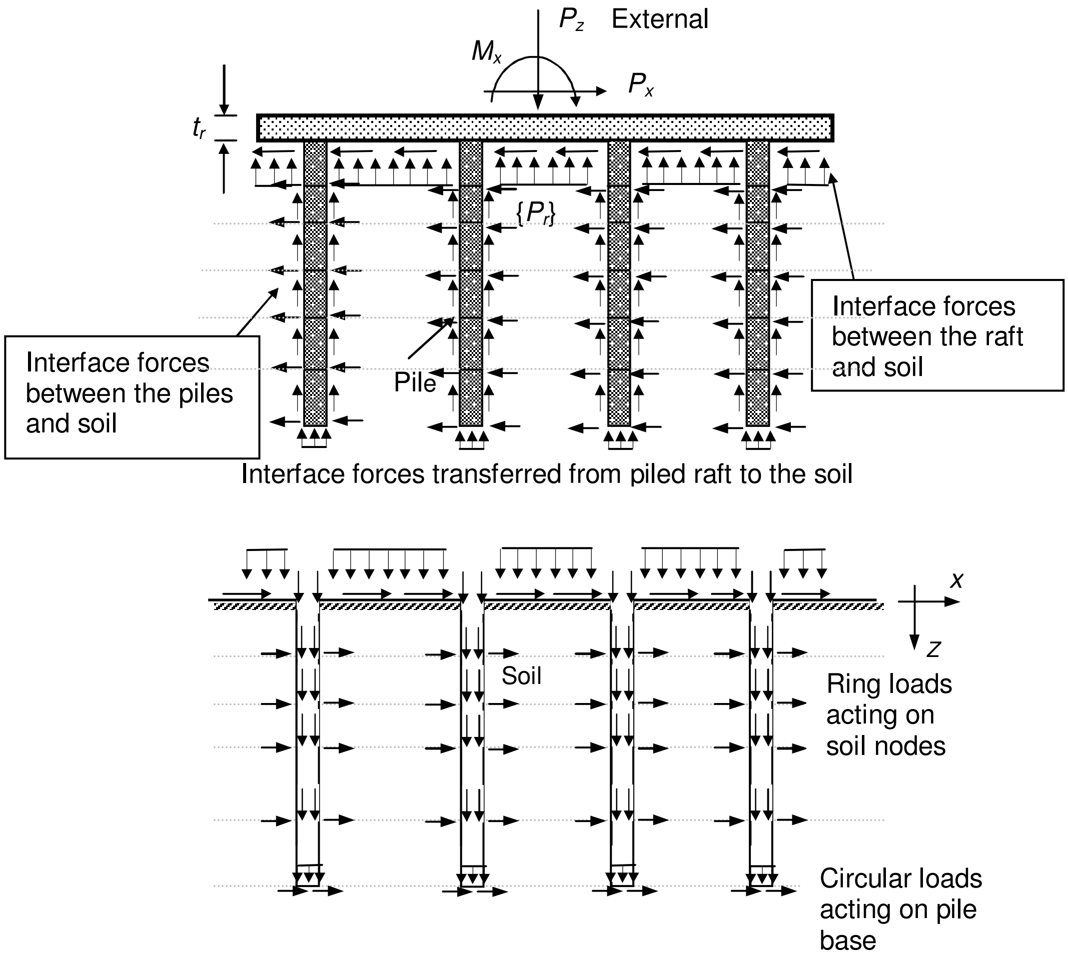

Figure 1. Forces acting on the piled raft

performed at N points. Here the matching is carried out at the centre of each raft element or at the nodes of the pile elements.

Equilibrium of the system must also be maintained, and so there must be force balance in each of the three axis directions, and moment equilibrium about the x, y and z axes. This leads to an extra 6 equations, and so there will be a set of $N + 6$ equations to solve.

Non-linearity can then be introduced into the system by allowing the ring loads or blocks of contact pressure to be limited to a maximum value. For lateral loading, the ring load is limited to a value equal to P_x in the x-direction where

$$P_x = p_x . d . \delta\ell$$

and p_x is the limit pressure, d is the pile diameter and $\delta\ell$ is the length of pile shaft over which the ring load is considered to act. Similar limiting values can be placed on ring loads in the y-direction and the shear forces between the raft and the soil for each of the blocks of shear stress in both the x and y directions as well as in the vertical z direction. Once the equations of compatibility are altered by limiting the pressure, the displacement of the structure and the soil are no longer equal at the point of displacement matching, and so "slip" of the raft or pile shaft occurs.

The load is incremented onto the raft in stages and if the total pressure acting exceeds the allowable the increment is set so that the pressure reaches its maximum. On subsequent load increments the change in the limiting pressure is set to zero.

It may be noted that the system is a coupled system whereby a horizontal loading on the pile group will cause not only lateral deflections but vertical deflections and a vertical load will cause both vertical and lateral deflection of the piles and raft.

3 EXAMPLES

The effect that the cap has on the lateral deflection of a group of piles is examined in the following examples. The first example is one of a group of 9 piles loaded laterally in the x-axis direction by a uniformly applied lateral load as shown in Figure 2. The piles are 0.4m in diameter, 8m long and spaced at 1.25m centre to centre. The raft is 3.5m square and 0.4m thick so that it is relatively rigid. The soil is assumed to be uniform and to have an elastic modulus of 15MPa and a Poisson's ratio of 0.48. A uniform shear load of q_h is applied to the top of the raft in the x-direction and applied in increments.

The finite element mesh for the raft is shown in Figure 2 and consists of 196 isoparametric 8 noded shell elements while the piles are modelled with 3 node beam bending elements. The raft is assumed to have a modulus of 30000MPa and a Poisson's ratio of 0.2.

Initially the raft was assumed to be in contact with the soil and that there was no limit on the pressures acting on the piles and raft, so that the solution was a purely elastic solution. Subsequent solutions were obtained with the undrained shear strength s_u of the soil being a uniform 20kPa for the full length of the pile. The limit pressure against the pile shaft was chosen to be $9s_u$ (i.e. 180kPa). Three cases were run, with different limiting shear stresses p_s between the raft and the soil where p_s = 0kPa (i.e. raft not in contact) 10kPa, 20kPa.

It should be emphasised that for a buried raft, there would be passive soil pressures acting against one face of the raft, however these forces have not been taken into account here i.e. the cap is assumed to be above ground level.

The load-deflection behaviour of the raft obtained for these cases is shown in Figure 3, where the effect that the raft has on the lateral deflection of the pile group may be seen. If the load levels are low, then obviously the soil will not yield against the piles or slip beneath the raft, and so the deflections are similar in all cases, but at higher load levels, there is a large difference in the deflections obtained. The higher the resistance to slip of the raft, the smaller the deflection of the pile group as may be expected. The "no yield" case shown in Figure 3 is the purely elastic solution where the soil is assumed not to fail against the piles or beneath the raft.

The effect of the pile diameter on the raft behaviour was examined by keeping the interface shear strength on the base of the raft at 20kPa and the undrained shear strength of the soil at 20kPa, but changing the size of the pile diameter. The load-deflection curves for this case is shown in Figure 4 for three pile diameters 0.3, 0.35 and 0.4m and where all other parameters are the same as in the previous problem. The ultimate load that the piled raft group can carry can be seen to be much more sensitive to the pile diameter than to the adhesion at the base of the raft (cf. Figure 3).

The effect of the raft resistance not only has an effect on the pile displacements, but also the moments and shear forces in the piles. A plot of the moment distribution over the length of the centre pile is shown in Figure 5 for a load of 2450kN applied to the raft. It can be seen that as the resistance to sliding on the base of the raft increases, the maximum moment in the pile shaft reduces, but that for this example, the moment at the pile head is not much affected.

Shears in the piles for the different adhesions on the base of the raft are shown in Figure 6, again for a lateral load of 2450kN acting on the raft. The shear stress distribution is linear over the upper part of the piles (when yield is allowed) showing that there has been yield of the soil in this region. There is also a jump in the shear force diagram at about 3m depth that can be seen to reduce in magnitude as the adhesive force on the base of the pile cap increases.

4 CONCLUSIONS

The effect of the raft or cap on a pile group that is loaded laterally is to reduce the lateral deflections and as the raft carries part of the load, the lateral bearing capacity of the piled raft increases.

The effect of the cap depends on the load level, and becomes more pronounced as load increases. In the example shown in this paper, a limiting shear stress of 20kPa at the raft-soil contact interface would reduce the

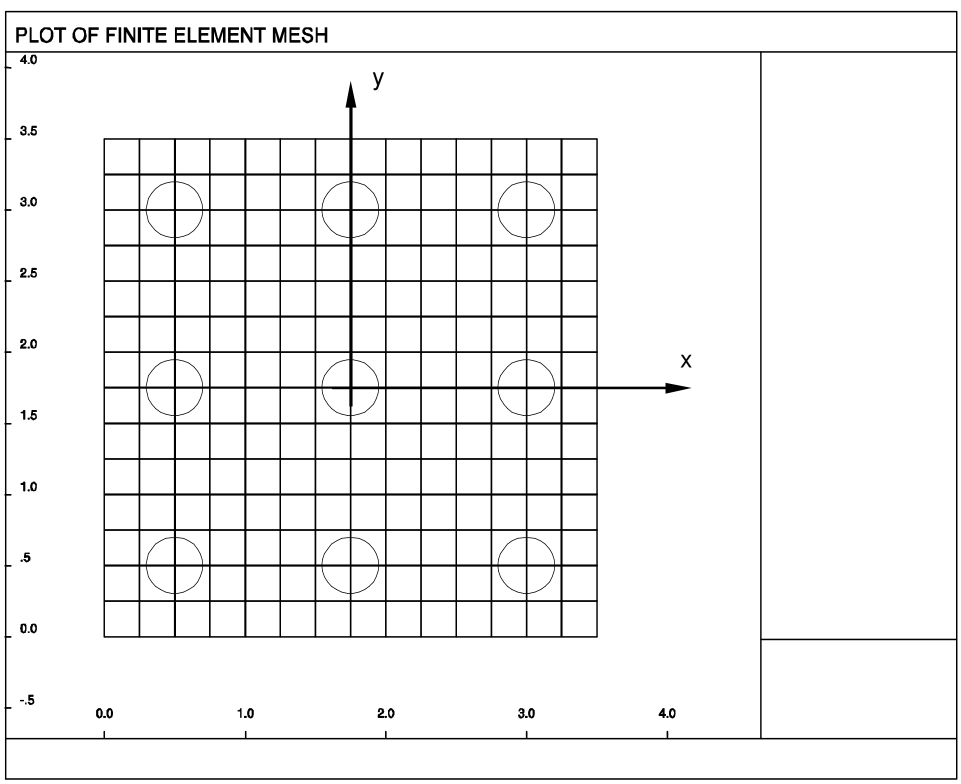

Figure 2. Layout of piles beneath raft.

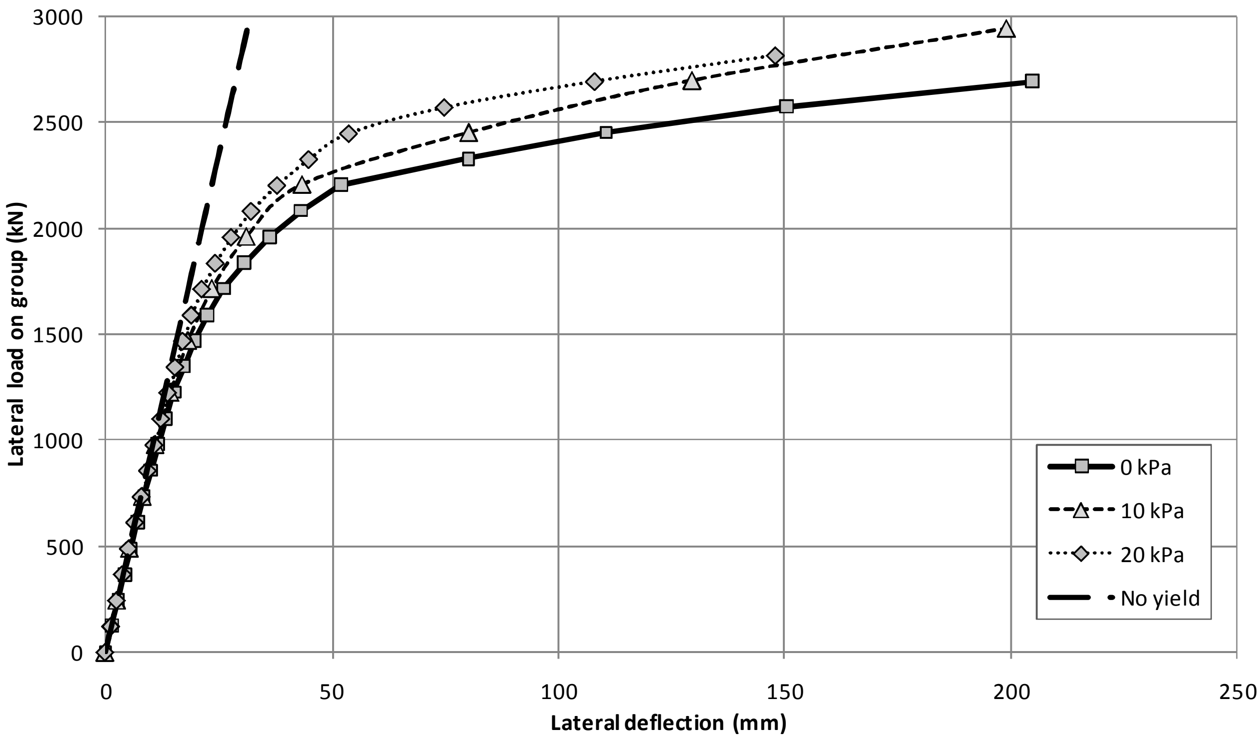

Figure 3. Load-deflection curves for piled raft with different allowable shear resistances under raft.

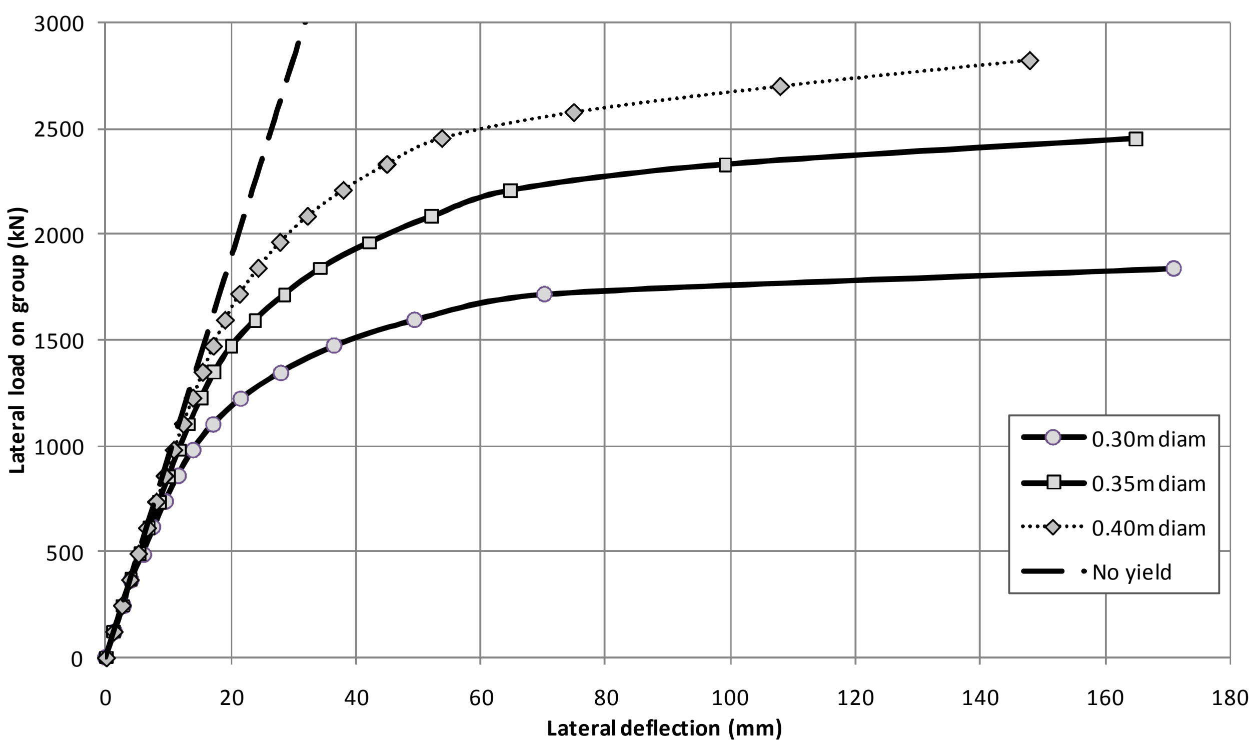

Figure 4. Effect of pile diameter on piled raft lateral deflection (20kPa adhesion on raft).

lateral deflection of the raft by about 50% at a load level that would cause failure of a pile group with no cap in contact with the ground.

Moments and shear forces in the piles in the group are also reduced by the resistance to lateral movement provided by the cap. This has the implication that if the resistance of the pile cap is not taken into account, then more reinforcing would be used in the pile when it may not be needed.

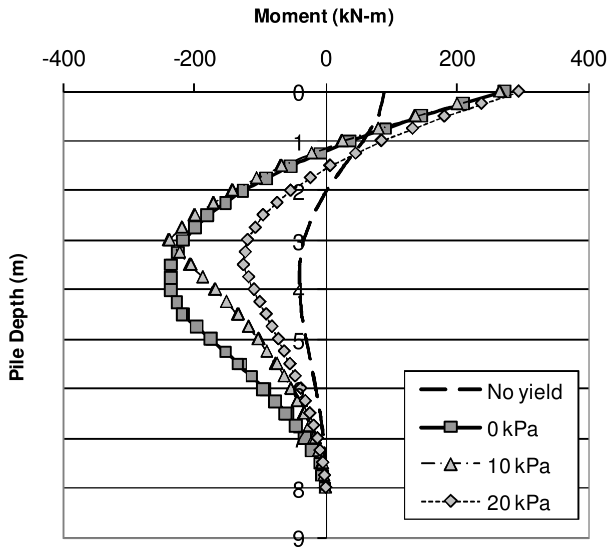

Figure 5. Moments in the pile for different raft-soil adhesions.

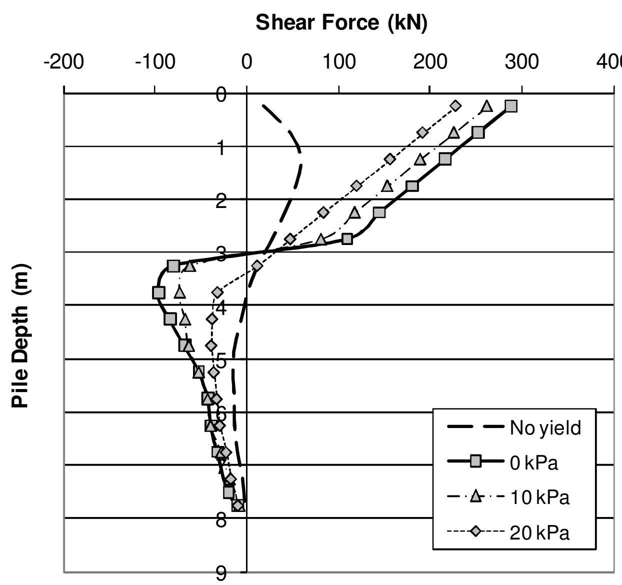

Figure 6. Shear forces in the pile for different raft-soil adhesions.

REFERENCES

Bannerjee, P.K., and Davies, T.G. 1978. Behaviour of axially and laterally loaded single piles embedded in nonhomogeneous soils, *Géotechnique*, 28 (3): 309-326.

Cole, R.T. and Rollins, K.M. (2006) Passive Earth Pressure Mobilisation During Cyclic Loading. J. Geotech. and Geoenv. Eng., ASCE, 132(9): 1143-1153.

Matlock,H. And Reese, L.C. 1960. Generalized Solutions for Laterally Loaded Piles, *J. Soil Mechs. and Found. Div.* ASCE, 86 (5): 63-91.

Poulos, H.G. 1971a. Behaviour of Laterally Loaded Piles, I: single piles. *J. Soil Mech. and Found. Div.* ASCE, 97 (SM5): 711-731.

Poulos, HG (1971b) Behaviour of Laterally Loaded Piles: II- Pile Groups *J. Soil Mech. and Found. Div.* ASCE., 97(SM5): 733-751.

Poulos, H.G. and Davis, E.H. 1980 *Pile Foundation Analysis and Design*, John Wiley and Sons, New York.

Reese, L.C. 1984. Handbook on Design of Piles and Drilled Shafts Under Lateral Load. FHWA-IP-84-11, *Fed Highway Admin., US Dept. Of Transp.,* Washington, D.C.

Rollins, K.M. and Sparks, A. 2002. Lateral Resistance of Full Scale Pile Cap with Gravel Backfill. *J. Geotech. and Geoenv. Eng.*, ASCE, 128 (9): 711-723.

Small, J.C. and Booker, J.R. 1986. Finite Layer Analysis of Layered Elastic Materials Using a Flexibility Approach Part 2 - Circular and Rectangular Loadings, *International Journal for Numerical Methods in Engineering*, 23: 959-978.

Small, J.C. and H.H. Zhang, H.H. 2002. Behaviour of Piled Raft Foundations under Lateral and Vertical Loading, *International Journal of Geomechanics*, 2 (1): 29-45.