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UIN:	ETOCRN126022086		
Title:	Geotechnical special publication.		
Publisher:	Reston, VA; American Society of Civil Engineers; 1998		
ISSN:	0895-0563		
Year:	2002	Part:	1
Issue:	116	Comments	
Pages:	441-458		
Author name(s):	Poulos, H. G.		
Article title words:	Simplified Design Procedure for Piled Raft Foundations		

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Simplified Design Procedure for Piled Raft Foundations

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Abstract

In situations where a raft foundation alone does not satisfy the design requirements, it may be possible to enhance the performance of the raft by the addition of piles. The use of a limited number of piles, strategically located, may improve both the ultimate load capacity and the settlement and differential settlement performance of the raft. This paper outlines the development of a simplified method of analysis which can provide a useful tool for preliminary design of piled raft foundations. It involves two phases:

1. The assessment of the overall foundation behavior;
2. The assessment of the behavior under individual column loads.

In both cases, use is made of simplified solutions to compute foundation stiffness and capacity characteristics. The selection of design geotechnical parameters is an essential component of both design stages, and some approximations for estimating the necessary parameters are summarized.

Typical applications to a case history of a piled raft and to model centrifuge tests are described, and it is found that the behavior predicted by the simplified analysis is broadly consistent with the measured behavior.

Introduction

It is now well-recognized that the behavior of a mat or raft foundation can be enhanced effectively by the addition of a limited number of piles. Such a piled raft foundation is particularly useful in circumstances where the raft provides significant bearing capacity and stiffness, but the computed settlements and/or differential settlements exceed allowable limits. A number of methods of analysis are available for analyzing the behavior of piled raft foundations (for example, Hain and Lee, (1978), Clancy and Randolph (1993), Franke et al. (1994), Poulos (1994a), Ta and Small (1996), van Impe and Lungu (1996), Poulos et al (1997), El-Mossallamy and Franke (1997), Russo and Viggiani (1998), Viggiani (1998), Yamashita et al. (1998), Anagnostopoulos and Georgiadis (1998), Katzenbach et al. (1998), Prakoso, W. and Kulhawy, F.H. (2001).

Most of the above methods involve the use of computer analyses, in some cases, quite complex ones, and as such are generally only suitable for detailed design. In addition, most of the analyses have focused on the behavior of uniformly loaded foundations, which represent a minority of cases in which such foundations are employed (for example, fluid storage structures). Most applications of piled rafts involve a series of column loadings, as well as patches of uniform loading. Some of the

design charts which have been developed for uniform loadings, while useful to give an indication of overall load-settlement behavior, cannot be used for detailed analysis of localized pile-raft interaction beneath column loadings.

This paper summarizes a relatively simple design procedure for piled rafts which considers two main aspects:

1. Overall load capacity and load-settlement behavior;
2. Localized load capacity and pile and raft behavior under individual column loadings.

The approach outlined is meant to be for preliminary design purposes, in particular, to provide a means of assessment of the feasibility of using a piled raft, and the pile and raft requirements. The calculations do not involve the use of complex numerical analyses, but can be programmed via spreadsheet or mathematical programs such as MATHCAD. Examples of the application of the approach to two cases are described briefly.

Design Issues

As with any foundation system, the design of a piled raft foundation requires the consideration of a number of issues, including:

1. Ultimate load capacity for vertical, lateral and moment loadings
2. Maximum settlement
3. Differential settlement
4. Raft moments and shears for the structural design of the raft
5. Pile loads and moments, for the structural design of the piles.

In much of the available literature, emphasis has been placed on the bearing capacity, settlement and differential settlement under vertical loads. These are generally the critical aspects, and are considered in this paper. However, the other issues must also be addressed, at least at the detailed design stage.

In assessing the feasibility of using a piled raft foundation, it is necessary first to assess the performance of a raft foundation without piles. Estimates of vertical and lateral bearing capacity, settlement and differential settlement may be made via conventional techniques. If the raft alone provides only a small proportion of the required load capacity, then it is likely that the foundation will need to be designed with the conventional philosophy in which the piles are designed to carry most of the load, so that the function of the raft is merely to reduce slightly the piling requirements. If however the raft alone has adequate or nearly adequate load capacity, but does not satisfy the settlement or differential settlement criteria, then it may be feasible to consider the use of piles as settlement reducers. (Burland, 1995; Randolph, 1994).

The most effective application of piled rafts occurs when the raft can provide adequate load capacity, but the settlement and/or differential settlements of the raft alone exceed the allowable values. This generally occurs when the near-surface soil profile contains relatively stiff clays or relatively dense sands. Conversely, considerable caution must be exercised when vertical ground movements are anticipated; these may adversely affect the settlement performance of the foundation (in the case of settlement) or induce unacceptable tensile forces in the piles (in the case of swelling movements).

The key design decisions which must be made for a piled raft include:

- The required raft thickness;

- The type of piles to be used;
- The required locations of the piles, and the pile diameter and length.

It should be emphasized that, in principle, different pile sizes can be used below the raft, depending on the design requirements. There should not be the expectation that all piles need to be of a similar size and length, or that they should extend to a strong bearing stratum. The pile requirements should be tailored to meet the design requirements, and this is the approach that will be followed in this paper.

Overall Vertical Load Capacity

For assessing vertical bearing capacity, the ultimate load capacity can generally be taken as the lesser of the following two values:

- The sum of the ultimate capacities of the raft plus all the piles
- The ultimate capacity of a block containing the piles and the raft, plus that of the portion of the raft outside the periphery of the piles.

Figure 1 illustrates the general problem, involving a layered soil profile and a typical building column layout. In assessing the ultimate load capacity of the piled raft system, the following issues need to be addressed:

1. The assessment of the bearing capacity of the raft on a layered soil deposit requires engineering judgment, as there are few well-established simple techniques available. Two approaches can be considered:

- Use of average *strength parameters* within the depth of influence of the raft (typically 1.5 times the smaller dimension of the raft);
- Use of the average *bearing capacity* of the individual layers.

If the first approach is adopted, then, as pointed out by Briaud et al (2000), the assumed distribution of strength with depth can have an important effect on the computed bearing capacity. The author tends to adopt the second approach because of the difficulties of assigning average parameters to a profile consisting of both clays and sands.

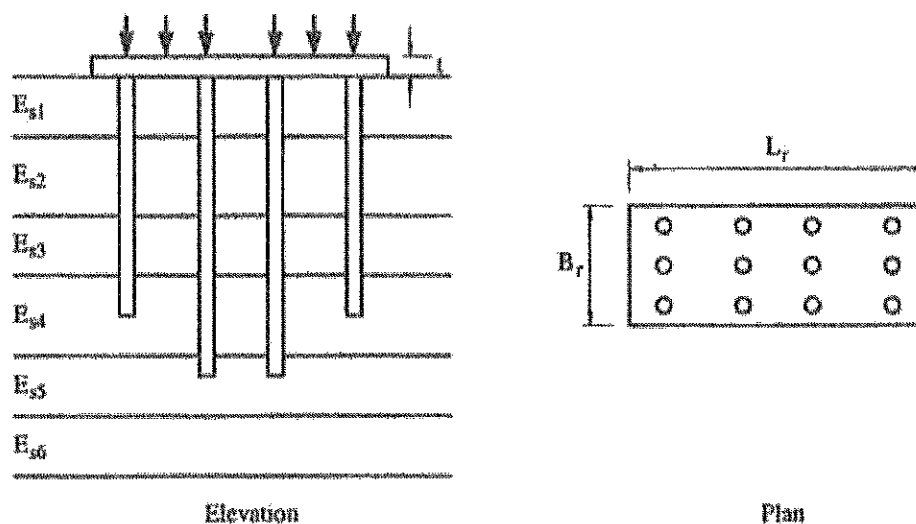


Figure 1. General problem of piled raft on layered soil profile.

2. In the assessment of pile capacity, the influence of layering below the pile tips need to be considered carefully (Meyerhof and Sastry, 1978). The block end bearing capacity is more likely to be affected by soft underlying layers than is the end capacity of the individual piles.

A useful outcome of the analysis is a plot of ultimate capacity versus number of piles, in order to assess the maximum number of piles which could usefully be employed.

Overall Load-Settlement Behavior

For estimating the load-settlement behavior, an approach described by Poulos (2001) can be adopted. This involves an extension of the method proposed by Poulos and Davis (1980), using the simple method of estimating the load sharing between the raft and the piles outlined by Randolph (1994). The definition of the pile problem considered by Randolph is shown in Figure 2. Using his approach, the stiffness of the piled raft foundation can be estimated as follows:

$$K_{pr} = (K_p + K_r(1 - \alpha_{cp})) / (1 - \alpha_{cp}^2 K_r / K_p) \quad (1)$$

where K_{pr} = stiffness of piled raft; K_p = stiffness of the pile group; K_r = stiffness of the raft alone; α_{cp} = raft - pile interaction factor.

The raft stiffness K_r (for the center of the raft) can be estimated via elastic theory, for example using the solutions of Fraser and Wardle (1976) or Mayne and Poulos (1999). The pile group stiffness can also be estimated from elastic theory, using approaches such as those described by Poulos and Davis (1980), Fleming et al (1992) or Poulos (1989). In the latter cases, the single pile stiffness is computed from elastic theory, and then multiplied by a group stiffness efficiency factor which is estimated approximately from elastic solutions, i.e. $K_p = K_1 \cdot n^w$ where K_1 = stiffness of single pile, n = number of piles, w = group exponent, typically in the range 0.3-0.5, but varying with spacing.

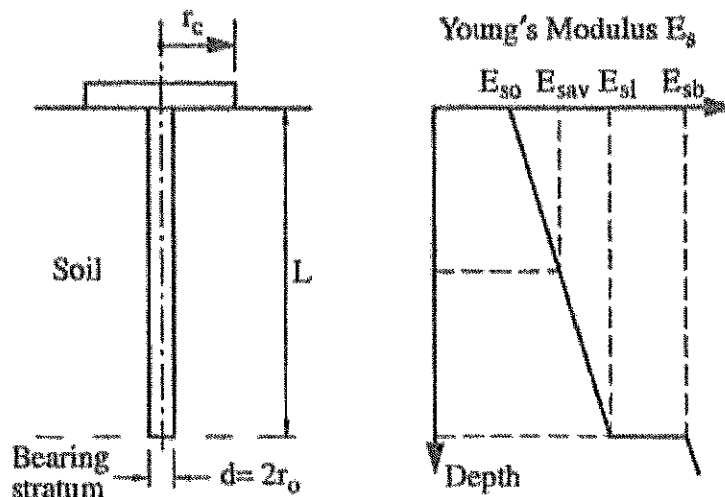


Figure 2. Simplified representation of pile-raft unit.

The proportion of the total applied load carried by the raft is:

$$P_r / P_t = K_r (1 - \alpha_{cp}) / (K_p + K_r (1 - \alpha_{cp})) = X \quad (2)$$

where P_r = load carried by the raft; P_t = total applied load.

The raft - pile interaction factor α_{cp} can be estimated as follows:

$$\alpha_{cp} = 1 - \ln (r_c / r_0) / \zeta \quad (3)$$

where r_c = average radius of pile cap, (corresponding to an area equal to the raft area divided by number of piles); r_0 = radius of pile; $\zeta = \ln (r_m / r_0)$; $r_m = (0.25 + \xi [2.5 \rho (1 - \nu) - 0.25]) * L$; $\xi = E_{st} / E_{sb}$; $\rho = E_{sav} / E_{st}$; ν = Poisson's ratio of soil; L = pile length; E_{st} = soil Young's modulus at level of pile tip; E_{sb} = soil Young's modulus of bearing stratum below pile tip; E_{sav} = average soil Young's modulus along pile shaft.

The above equations can be used to develop a tri-linear load-settlement curve as shown in Figure 3. First, the stiffness of the piled raft is computed from equation (1) for the number of piles being considered. This stiffness will remain operative until the pile capacity is fully mobilized. Making the simplifying assumption that the pile load mobilization occurs simultaneously, the total applied load, P_1 , at which the pile capacity is reached is given by:

$$P_1 = P_{up} / (1 - X) \quad (4)$$

where P_{up} = ultimate load capacity of the piles in the group; X = proportion of load carried by the raft (equation 2).

Beyond that point (Point A in Figure 3), the stiffness of the foundation system is that of the raft alone (K_r), and this holds until the ultimate load capacity of the piled raft foundation system is reached (Point B in Figure 3). At that stage, the load-settlement relationship becomes horizontal.

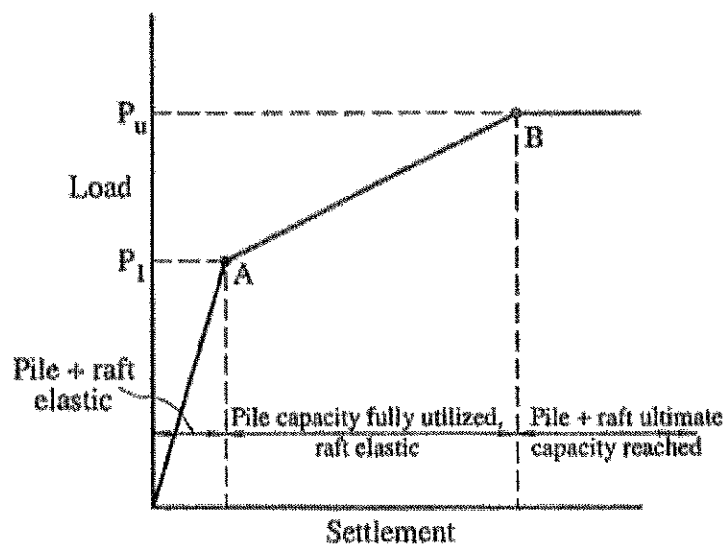


Figure 3. Simplified load-settlement curve for preliminary analysis.

The load – settlement curves for a raft with various numbers of piles can be computed with the aid of a computer spreadsheet or a mathematical program such as MATHCAD. In this way, it is simple to compute the relationship between the number of piles and the average settlement of the foundation.

A key requirement of using the equations developed by Randolph is that the actual soil profile has to be simplified such that it is represented by a profile whose stiffness increases linearly with depth, and in which there is a uniform bearing stratum. In practice, it is usually adequate to compute a mean weighted soil modulus along the pile shaft length, and to adopt a mean stiffness and bearing capacity for the pile tip, based on the weighted values within an effective depth of 2 to 3 diameters of the tip (Poulos, 1994b).

Despite the simple and approximate nature of the above approach, it has been shown to provide load-settlement curves which are in good agreement with those from more sophisticated numerical analyses (Poulos, 2000). An example of a comparison with the program GARP (Poulos, 1994a) is shown in Figure 4. A similar measure of agreement has also been obtained with results from the program FLAC 3D.

Estimation of Overall Differential Settlements

Most analyses of pile group settlement make one of the two following extreme assumptions:

1. The pile cap is perfectly rigid so that all piles settle equally (under centric load) and hence there is no differential settlement.
2. The pile cap is flexible, so that the distribution of load onto the piles is known; in this case, the differential settlements within the group can be computed, ignoring the effect of the raft.

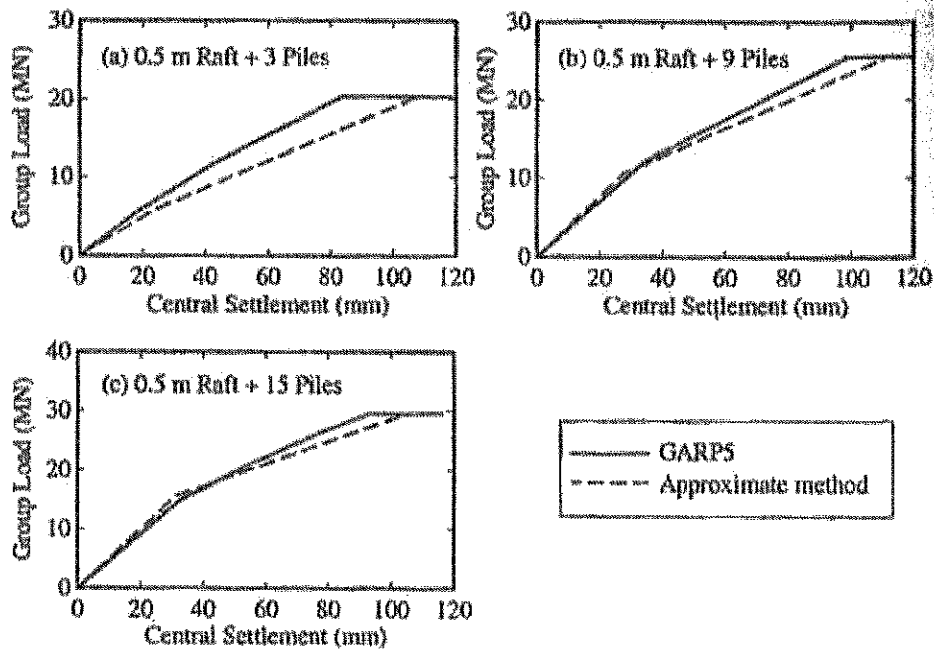


Figure 4. Comparison between GARP5 and approximate method (Poulos, 2000).

In reality, the situation is usually between these two extremes. Randolph (1994) has developed useful design guidelines for assessing the differential settlement within a uniformly loaded pile group. For a flexible pile cap, Randolph has related the ratio of differential settlement ΔS to the average group settlement, S_{av} , to a ratio R , as follows:

$$\Delta S/S_{av} = fR / 4 \quad \text{for } R \leq 4 \quad (5a)$$

$$\Delta S/S_{av} = f \quad \text{for } R > 4 \quad (5b)$$

where $f = 0.3$ for center-to-midside, and 0.5 for center-to-corner;

$$R = (ns/L)^{0.5} \quad (5c)$$

n = number of piles; s = pile center-to-center spacing; L = pile length.

For pile caps with a finite rigidity, the differential settlements will reduce from the above values (which are for perfectly flexible pile caps), and Randolph suggests that the approach developed by Randolph and Clancy (1993) be adopted. This approach relates the normalized differential settlement to the relative stiffness of the pile cap (considered as a raft). Mayne and Poulos (1999) have developed a closed-form approximation for the ratio of corner to center settlement of a rectangular foundation, and from this approximation, a rigidity correction factor, f_R can be derived:

$$f_R = 1 / (1 + 2.17 K_P) \quad (6a)$$

$$\text{where } K_P = (E_c/E_{soil}) (2t/d)^3 \quad (6b)$$

f_R = foundation flexibility factor; E_c = Young's modulus of pile cap; E_{soil} = representative soil Young's modulus beneath the cap (typically within a depth of about half the equivalent diameter of the cap); t = thickness of pile cap; d = equivalent diameter of pile cap (to give equal area with the actual cap).

The factor f_R from equation is then applied to the maximum differential settlement estimated from equations (5).

Design For Localized Behavior Under Individual Columns

Introduction

This section presents an approach which allows for an assessment of the maximum column loadings which may be supported by the raft without a pile below the column, and also the requirements for raft thickness and reinforcement.

A typical column on a raft is shown in Figure 5. There are at least four circumstances in which a pile may be needed below the column:

- * If the maximum moment in the raft below the column exceeds the allowable value for the raft
- * If the maximum shear in the raft below the column exceeds the allowable value for the raft

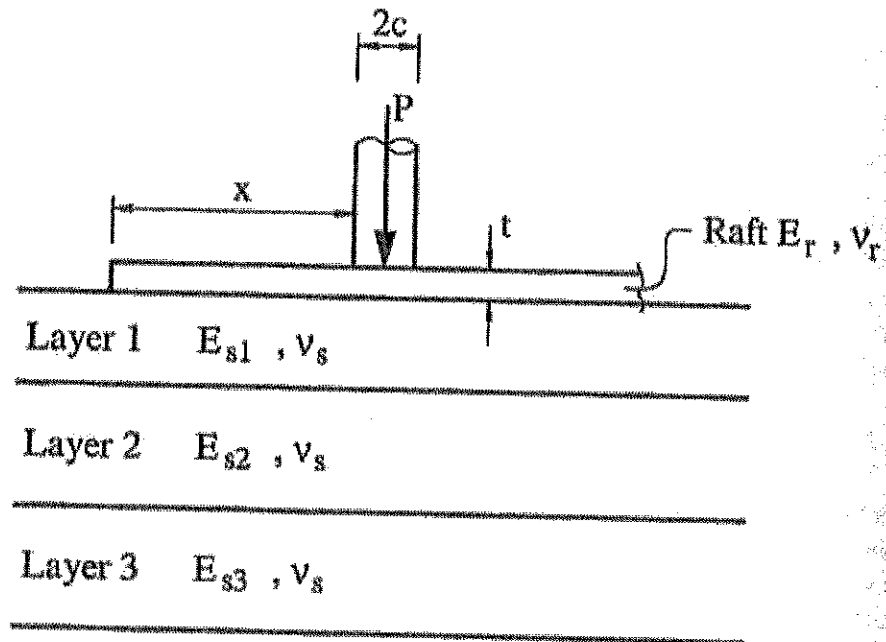


Figure 5. Individual column load-raft on layered soil profile.

- If the maximum contact pressure below the raft exceeds the allowable design value for the soil
- If the local settlement below the column exceeds the allowable value.

To estimate the maximum moment, shear, contact pressure and local settlement caused by column loading on the raft, use can be made of the approach described by Poulos (2001), who utilizes the elastic solutions summarized by Selvadurai (1979). These are for the ideal case of a single concentrated load on a semi-infinite elastic raft supported by a homogeneous elastic layer of great depth, but they do at least provide a rational basis for design, provided that the equivalent soil modulus and bearing values are chosen appropriately, as described below.

Soil profile idealization for local design

It is necessary to transform approximately the layered soil profile into an equivalent homogeneous soil layer by using the approach described by Fraser and Wardle (1976). Referring to Figure 5, for the assessment of the equivalent modulus to be used for column loading, the average value within the effective depth below the raft should be considered. As an approximation, the effective depth can be taken to be $3a$, where a = characteristic length of raft, defined as follows:

$$a = t \cdot [E_r \cdot (1 - \nu_s^2) / 6 \cdot E_s \cdot (1 - \nu_r^2)]^{1/3} \quad (7)$$

where t = raft thickness; E_r = raft Young's modulus; E_s = soil Young's modulus; ν_r = raft Poisson's ratio; ν_s = soil Poisson's ratio.

It should be noted that this will generally be different from the value used for the assessment of overall raft stiffness K_r in equations 1 to 4. The estimation of the average value of soil modulus and the characteristic length a will generally be an iterative procedure, as E_s and a are inter-related via equation 7.

Similarly, for the estimation of the local bearing capacity of raft under a column, the average strength parameters or bearing capacity values within a depth equal to $3a$ should be used for the raft.

Maximum moment criterion

The maximum moments M_x and M_y below a column of radius c acting on a semi-infinite raft are given by the following approximations:

$$M_x = A_x \cdot P \quad (8a)$$

$$M_y = B_y \cdot P \quad (8b)$$

where $A_x = [A - 0.0928 (\ln (c / a))]$; $B_y = [B - 0.0928 (\ln (c / a))]$; A , B = coefficients depending on x/a ; x = distance of the column center line from the raft edge; a = characteristic length of raft, as defined in equation 7.

The coefficients A and B are tabulated in Table 1 for the limiting cases of interior and edge columns.

Table 1
Factors for Local Raft Behavior Below Column

Factor	Central Columns	Edge Columns
A	0.59	-0.15
B	0.59	0.15
C_q	1.00	1.64
\bar{q}	0.20	1.11
ω	0.41	0.66

The maximum column load, P_{cl} , that can be carried by the raft without exceeding the allowable moment is then given by:

$$P_{cl} = M_d / (\text{larger of } A_x \text{ and } B_y) \quad (9)$$

where M_d = design moment capacity of raft.

Maximum shear criterion

The maximum shear V_{max} below a column can be expressed as:

$$V_{max} = (P - q \pi c^2) \cdot C_q / 2\pi c \quad (10)$$

where q = contact pressure below raft; c = column radius; C_q = shear factor, as given in Table 1.

Thus, if the design shear capacity of the raft is V_d , the maximum column load, P_{c2} , which can be applied to the raft is:

$$P_{c2} = V_d \cdot 2\pi c / C_q + q_d \pi c^2 \quad (11)$$

where q_d = design allowable bearing pressure below raft.

Maximum contact pressure criterion

The maximum contact pressure on the base of the raft, q_{max} , can be estimated as follows:

$$q_{max} = \bar{q} \cdot P / a^2 \quad (12)$$

where \bar{q} = factor, given in Table 1 for interior and edge columns; a = characteristic length defined in equation 7.

The maximum column load, P_{c3} , which can be applied without exceeding the allowable contact pressure is then :

$$P_{c3} = q_u a^2 / (F_s \cdot \bar{q}) \quad (13)$$

where q_u = ultimate bearing capacity of soil below raft; F_s = factor of safety for contact pressure.

Local settlement criterion

The settlement below a column (considered as a concentrated load) is given by:

$$S = \omega (1 - \nu_s^2) P / (E_s \cdot a) \quad (14)$$

where ω = settlement factor given in Table 1.

It should be recognized that this expression does not allow for the effects of adjacent columns on the settlement of the column being considered, and so is a local settlement which is superimposed on a more general settlement "bowl".

If the allowable local settlement is S_a , then the maximum column load, P_{c4} , so as not to exceed this value is then:

$$P_{c4} = S_a E_s a / (\omega (1 - \nu_s^2)) \quad (15)$$

Assessment of pile requirements for a column location

If the actual design column load at a particular location is P_c , then a pile will be required if P_c exceeds the least value of the above four criteria, that is, if:

$$P_c > P_{crit} \quad (16)$$

where $P_{crit} =$ minimum of P_{c1} , P_{c2} , P_{c3} , or P_{c4} .

If the critical criterion is maximum moment, shear or contact pressure (i.e. P_{crit} is P_{c1} , P_{c2} or P_{c3}), then the pile should be designed to provide the deficiency in load capacity. Burland (1995) has suggested that only about 90% of the ultimate pile load capacity should be considered as being mobilized below a piled raft system. On this basis, the ultimate pile load capacity, P_{ud} , at the column location is then given by:

$$P_{ud} = 1.11 F_p [P_c - P_{crit}] \quad (17)$$

where $F_p =$ factor of safety for piles.

When designing the piles as settlement reducers, F_p can be taken as unity.

If the critical criterion is local settlement, then the pile should be designed to provide an appropriate additional stiffness. For a maximum local settlement of S_a , the target stiffness, K_{cd} , of the foundation below the column is:

$$K_{cd} = P_c / S_a \quad (18)$$

As a first approximation, using equation 1, the required pile stiffness K_p to achieve this target stiffness can be obtained by solving the following quadratic equation:

$$K_p^2 + K_p [K_r (1 - 2\alpha_{cp}) - K_{cd}] + \alpha_{cp}^2 \cdot K_r \cdot K_{cd} = 0 \quad (19)$$

where $\alpha_{cp} =$ raft-pile interaction factor; $K_r =$ stiffness of raft around the column.

α_{cp} can be computed from equation 3, while the raft stiffness K_r can be estimated as the stiffness of a circular foundation having a radius equal to the characteristic length a (provided that this does not lead to a total raft area which exceeds the actual area of the raft).

Ultimate bearing capacity of raft and pile below a column

It may be required to demonstrate that the foundation at each column has an adequate factor of safety against bearing capacity failure. This may be assessed by adding the ultimate capacity of the pile(s) to that of the effective area of the raft contributing to the load sharing. As a first approximation, this effective area may be assumed to have a radius a , where a is defined in equation 7. Thus, the ultimate bearing capacity P_{uc} below a column is:

$$P_{uc} = P_{up} + p_{ult} \cdot \pi a^2 \quad (20)$$

where $P_{up} =$ sum of ultimate capacity of pile(s) below column; $p_{ult} =$ local bearing capacity of raft below column (see Section 5.2); $a =$ characteristic length of raft.

Geotechnical Parameter Assessment

The design of a piled raft foundation requires an assessment of a number of geotechnical and performance parameters, including:

- Raft bearing capacity

- Pile capacity
- Soil modulus for raft stiffness assessment
- Soil modulus for pile stiffness.

While there are a number of laboratory and in-situ procedures available for the assessment of these parameters, it is common for at least initial assessments to be based on the results of simple in-situ tests such as the Standard Penetration Test (SPT) and the Static Cone Penetration Test (CPT). Typical of the correlations are the following which the author has employed frequently are those based on the work of Decourt (1989, 1995) using the SPT:

$$\text{Raft ultimate bearing capacity: } p_{ur} = K_1 \cdot N_r \text{ kPa} \quad (21)$$

$$\text{Pile ultimate shaft resistance: } f_s = a_f \cdot [2.8 N_s + 10] \text{ kPa} \quad (22)$$

$$\text{Pile ultimate base resistance: } f_b = K_2 \cdot N_b \text{ kPa} \quad (23)$$

$$\text{Soil Young's modulus below raft: } E_{sr} = 2N \text{ MPa} \quad (24)$$

$$\text{Young's modulus along and below pile: } E_s = 3N \text{ MPa} \quad (25)$$

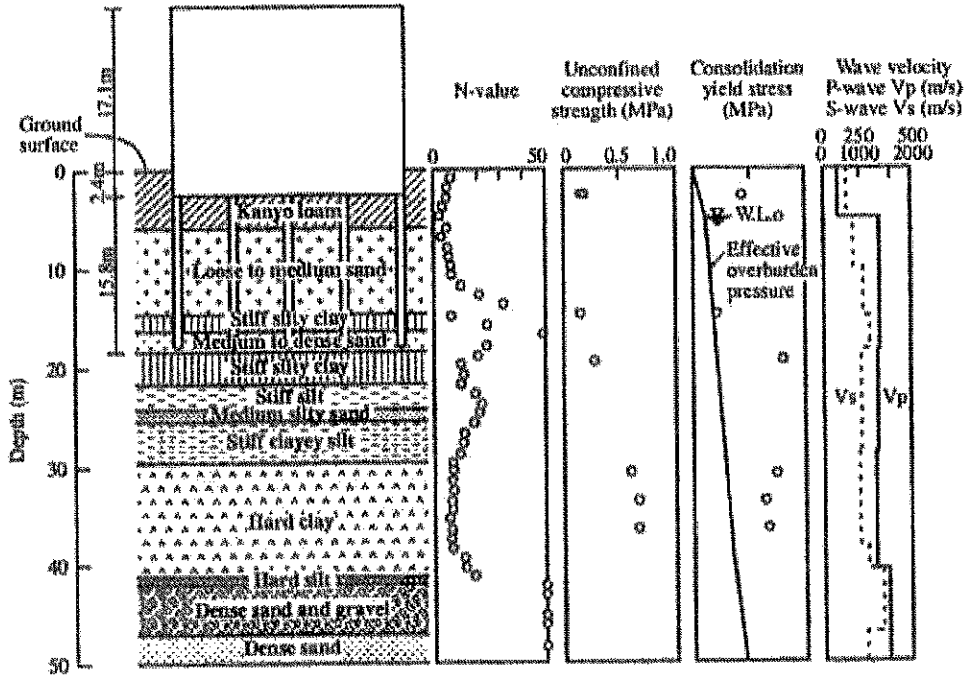
where N_r = average SPT*(N_{60}) value within depth of one-half of the raft width; N_s = SPT value along pile shaft; N_b = average SPT value close to pile tip; K_1 , K_2 = factors shown in Table 2; a_f = 1 for displacement piles in all soils and non-displacement piles in clays, and a_f = 0.5 – 0.6 for non-displacement piles in granular soils.

Table 2
Correlation factors K_1 and K_2

Soil Type	K_1 (Raft)	K_2 Displacement Piles	K_2 Non-Displacement Piles
Sand	90	325	165
Sandy silt	80	205	115
Clayey silt	80	165	100
Clay	65	100	80

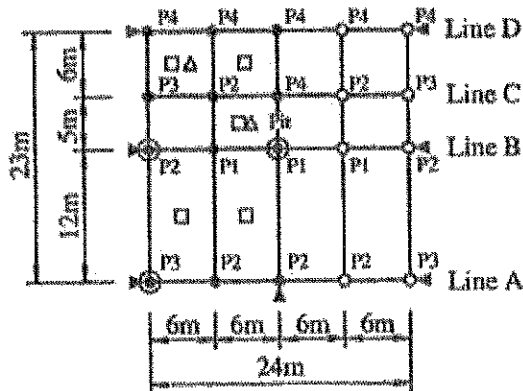
Application To Case History

Yamashita et al (1994, 1998) have described a well-instrumented and documented case of a piled raft foundation for a 5-story building on stiff clay in Japan. Figure 6 illustrates the geotechnical conditions, the basic parameters obtained from laboratory and field testing, and the building footprint which was rectangular, with sides 24 m by 23 m. The foundation consisted of a raft (inferred to be 0.3 m thick) with 20 piles, one under each column. The piles were bored concrete piles, either 0.8 or 0.7 m in diameter, with a central steel H-pile inserted. The pile diameter and steel pile size depended on the column load, which ranged between 1.02 MN and 3.95 MN.



(a) Elevation of building and summary of soil investigation

Pile No.	Borehole dia. (m)	Size of steel-H (mm)
P1	0.80	414 x 405 x 18 x 28
P2	0.80	400 x 400 x 13 x 21
P3	0.70	350 x 350 x 12 x 19
P4	0.70	300 x 300 x 10 x 15



(b) Foundation plan

Figure 6. Five-story building in Japan (Yamashita et al; 1994).

The simplified analysis described above was used to analyze this case, using the values of soil Young's modulus reported by Yamashita et al. The analysis was programmed via MATHCAD, which allows ready calculation of the effects of varying the raft and pile characteristics, and plotting of the results in a practically-useable form. The computed average settlement was 13mm while the measured settlement values across the raft ranged between about 18 mm and 7 mm. Assuming the total load of 47.5 MN to be uniformly distributed, the maximum differential settlement (center-to-corner) was computed to be about 5 mm, while the center-to-mid-side differential settlement was about 3mm. The loads were certainly not uniformly distributed, but the measured differential settlements were of a similar order.

Considering the local behavior, the simplified analysis indicated that the maximum loads which could be sustained by the raft without pile support were 1.23 MN for interior columns. The actual interior column loads were between 1.58 MN and 3.95 MN, and all had a pile supporting the column, so that the actual design was consistent with the indications from the analysis. For the edge columns, the analysis indicated that the maximum load which could be sustained without pile support was 0.76 MN. The actual edge column loads ranged between 0.96 MN (at the corner) to 3.09 MN. Thus, again the simple analysis confirmed that piles were required for all columns around the edge of the raft, and hence, it would appear that it would have provided appropriate guidance in the selection of locations for the piles required for the foundation.

The above case was also analyzed by Poulos (2001) using the computer program GARP. The settlements computed by GARP were in reasonable agreement with, although generally a little larger than, the measured values, and of a similar order to those predicted herein. Thus, the simplified approach appears to be a useful tool for the preliminary design of piled raft foundations. In particular, it offers a rapid means of assessing the feasibility of using relatively thin rafts with piles to economize on foundation costs.

Application To Centrifuge Tests

Horikoshi (1995) has described a series of centrifuge tests on piled raft model foundations, to investigate the effects of the number and configuration of piles on foundation performance. Tests were carried out on a raft only, and a raft with 9, 21 and 69 piles. In prototype scale, the raft was circular, 14 m in diameter and 45 mm thick, while the piles were 15m long and 0.315 m in diameter. The soil used for the tests was a reconstituted clay, whose undrained shear strength s_u increased approximately linearly with depth, according to the expression: $s_u = 33 + 1.2z_p$, where z_p = depth below surface, on the prototype scale. This distribution of strength was adopted for the estimation of the raft and pile capacities, while the Young's modulus of the soil was taken to be about $800 s_u$, following the suggestions of Horikoshi (1995).

Calculations were carried out to estimate the stiffness of the piled raft with various numbers of piles, and the calculations were compared with the experimental centrifuge data. The pile group stiffness was computed from the simplified expression given below equation 1, assuming a value of $w = 0.45$ for pile spacings of 3 diameters, with a correction applied for other spacings, as per Fleming et al (1992).

Figure 7 compares the computed variation of piled raft central stiffness with number of piles with the measured values from the centrifuge tests, for an applied

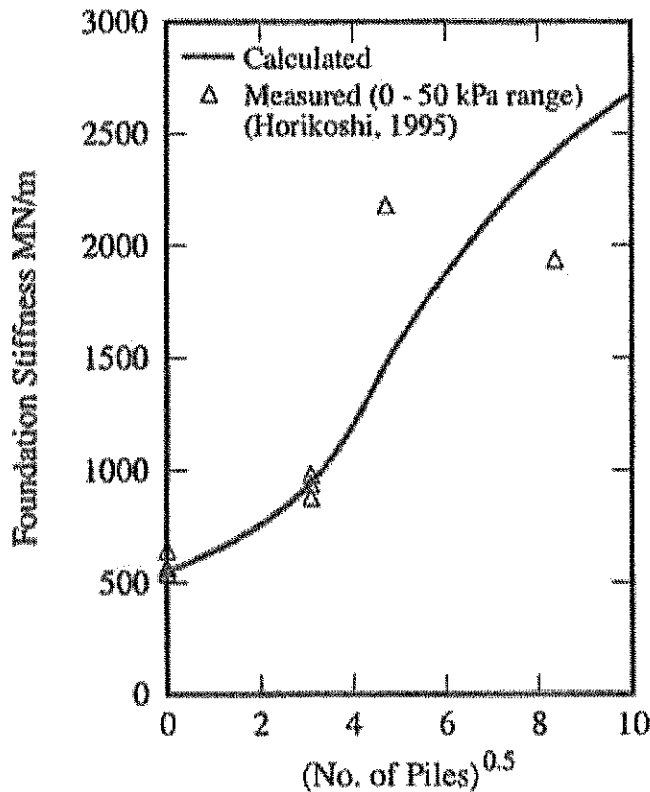


Figure 7. Calculated versus measured central stiffness of piled rafts from centrifuge tests.

pressure range of 0 – 50 kPa. There is reasonable agreement between the measured and computed values, although there is some variability in the measured values for the larger numbers of piles. Nevertheless, it would appear that, discretely used, the simple approach can provide reasonable first estimates of piled raft settlement performance.

Conclusions

This paper has outlined a simplified method of carrying out a preliminary feasibility study and design of a piled raft foundation system. It employs closed form or approximate solutions for raft and pile stiffness, and for the estimation of the combined foundation stiffness, taking raft-pile interaction into account. By using simple solutions for an elastic plate subjected to concentrated loadings, it is also possible to estimate the maximum column loads which can be sustained by a raft without piles. An attractive feature of the analysis is that it can be programmed either via a spreadsheet program or a mathematical program such as MATHCAD.

Application of the approach to a case history and to a series of centrifuge tests indicate that it can give a reasonable estimate of the order of magnitude of settlement and differential settlement of the foundation.

It should be emphasized that the piled raft foundation solution is not suitable for every circumstance. It is unlikely to be very effective if soft clays or loose sands exist near the surface, and it is generally not a suitable option if ground movements are likely to occur below the raft. However, in cases where the soil conditions allow the raft to develop adequate capacity and stiffness, the piled raft solution may be very suitable, and the simplified approach offers a rapid means of preliminary design in such cases, provided that, as always, appropriate parameters can be assessed for the geotechnical and foundation models.

Acknowledgments

The author is grateful to Dr. John Small of the University of Sydney, for many fruitful discussions on methods of analysis.

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