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Optimum design of piled raft foundations

Dimensionnement optimum de fondations mixtes pieux-radier

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ABSTRACT: A design approach is presented for piled raft foundations, aimed at minimising differential settlements. The approach is based on the results of extensive parametric studies. Key non-dimensional parameters that govern the settlement response of piled rafts are presented and their effects discussed. The results show that piled rafts can be designed with negligible differential settlements using central pile support, and that the key parameters are (a) the ratio of pile group to raft stiffness, (b) the ratio of pile group area to the total raft area, and (c) the ratio of pile group capacity to the total applied load.

RESUME: Une étude des radiers bâtis sur pilotis est presentée, dans le but de minimiser les tassements différentiels. L'approche est fondée sur les résultats d'un plan d'expérience. Les paramètres adimentionnels clefs qui régissent la réponse en tassement d'un radier sont présentés et leurs effets sont discutés. Les résultats montrent que les radiers peuvent être modelisés avec des tassements différentiels négligeables utilisant le support du pieux central, et que les paramètres clefs sont les rapports (a) le groupe de pieux sur la rigidité du radier, (b) la surface du groupe de pieux sur la surface total du radier, et (c) la capacité du groupe de pieux sur la force total appliquée.

1 INTRODUCTION

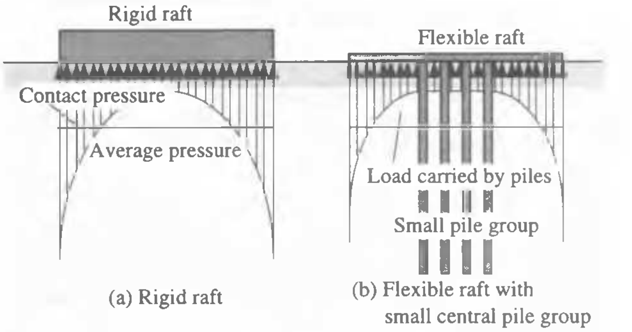
This paper describes a design approach for piled raft foundations that aims to minimise differential settlement. From an economic viewpoint, a simple raft foundation will generally be preferable to a piled foundation. However, even though the bearing capacity of the raft may be sufficient, additional pile support may be required to limit settlements. In most conventional designs, the required number of piles is decided assuming all load must be carried by the piles, ignoring any contribution from the raft or the pile cap. This assumption results in the installation of more piles than are necessary, and will often ensure that the overall magnitude of settlement well below the level that could be tolerated. Ideally, however, an optimum foundation design would include sufficient piles such that the average and differential settlements are limited to an acceptable level, but where the load-carrying capacity of the raft is taken into account. The concept of such 'settlement reducing piles', i.e. piles to control settlement rather than to carry the structure, was suggested by Burland et al (1977) and Padfield and Sharrock (1983). Yamashita et al (1994) reported the actual behaviour of a piled raft, showing good agreement between predicted and measured response.

Randolph (1994) suggested the possibility of minimising the differential settlement by installing a small pile group only beneath the central area of the raft. Subsequently, Horikoshi and Randolph (1996a) have verified the concept by means of centrifuge modelling. Figure 1 shows the concept, whereby a small central pile group is used to adjust the raft contact pressure distribution to mimic that associated with a rigid raft (with zero differential settlement).

As pointed out by Burland et al (1977), the key question becomes: 'How many piles are required to reduce the settlements to an acceptable level'; and also: 'Over which region of the raft should the piles be installed to minimise the differential settlement'. Horikoshi (1995) conducted extensive parametric study of piled rafts. This paper will present a simple framework to the above questions through the parametric study of various piled rafts using analysis developed by Clancy and Randolph (1993).

2 NON-DIMENSIONAL PARAMETERS

An important parameter controlling differential settlement is the raft-soil stiffness ratio, defined for a rectangular raft of width, B and length, L, $(B < L)$ as (Horikoshi and Randolph, 1996b):



(a) Rigid raft

(b) Flexible raft with small central pile group

Figure 1. Concept of settlement reducing piles

$$K_{rs} = 5.57 \frac{E_r(1-\nu_s^2)}{E_s(1-\nu_r^2)} \left(\frac{B}{L}\right)^{0.5} \left(\frac{t_r}{L}\right)^3 \qquad \text{(for rectangular rafts) (1)}$$

where E_r and E_s are Young's modulus of the raft and the soil respectively, ν_r and ν_s are Poisson's ratio of the raft and the soil, and t_r is the thickness of the raft. This definition is consistent with that for a circular raft with the same plan area and raft thickness, where the stiffness ratio is defined as (Clancy, 1993):

$$K_{rs} = \frac{E_r}{E_s} \frac{(1-\nu_s^2)}{(1-\nu_r^2)} \left(\frac{t_r}{a}\right)^3 \qquad \text{(for circular rafts)} \quad (2)$$

with the radius of the circular raft being denoted by 'a'.

In this paper, the differential settlement of rectangular raft is defined as the difference between the raft centre and the mid-side point. Although the differential settlement between the centre and the corner will be larger, for most superstructures the raft corner is usually reinforced by the edge walls of the building. This will lead to the raft corner undergoing greater settlement than predicted by the simplified analyses, where the stiffening effect of the superstructure is not considered. Therefore, using the corner settlement as the basis for assessing differential settlement may lead to overly conservative design. Consequently, it was decided to use mid-side settlement in the definition. The differential settlement is normalised by the average settlement of the raft alone with the same K_{rs}. This normalised differential settlement is expressed as Δw^* in the following figures.

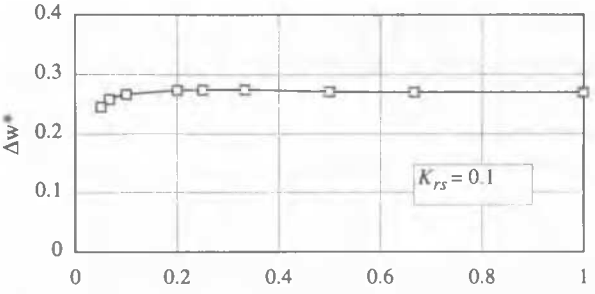


Figure 2. Normalised differential settlement for rectangular rafts with various aspect ratios

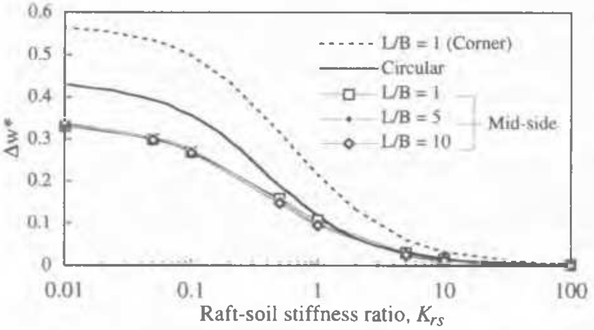


Figure 3. Variations of normalised differential settlement with raft-soil stiffness ratio, K_{rs}

It should be noted that the definition of raft-soil stiffness ratio in Equation (1) gives essentially the same magnitude of normalised differential settlement for a wide range of aspect ratio, B/L, as shown in Figure 2.

The variation of normalised differential settlement with the various K_{rs} is shown in Figure 3 for circular and rectangular rafts. The differential settlement between the centre and the corner of a square raft is also shown for comparison. The figure shows that Equation (1) gives the same pattern of the differential settlement for a wide range of K_{rs}.

The key non-dimensional parameters that govern the behaviour of piled rafts are summarised in Table 1, using the nomenclature defined in Figure 4. Here, p is the uniformly distributed pressure over the raft; A_g is the plan area of the pile group as a block; n is the number of piles; q_p is the ultimate bearing capacity of each pile; A_r is the area of the raft; k_p and k_r are the overall stiffnesses of the pile group and the raft in isolation. Among the parameters in Table 1, P_g* and P_t* can be calculated from the assumed geometry of the piled raft, and they are related to each other as $P_g^* = a_{gr}P_t^*$. The pile group stiffness, k_p, can be approximated by using the concept of the 'equivalent pier', which was introduced by Poulos and Davis (1980) and discussed by Randolph (1994). The raft stiffness. k_r, can also be approximated by assuming a fully rigid raft or a fully flexible raft (Poulos and Davis, 1974). It should be noted that, p_{gt} and m are generally unknown without some analysis. The pile length, L_p, is normalised by the radius of an equivalent circular raft, defined as $a_{eq} = \sqrt{(BL/\pi)}$.

3 PARAMETRIC STUDY

3.1 *Method of analyses*

Clancy and Randolph (1993) developed a method of piled raft analysis (HyPR: Hybrid Piled Raft analysis) based on the hybrid approach of Chow (1986). A piled raft on a homogeneous soil layer of finite depth can be analysed with full allowance for interaction between the various foundation components. Slip between pile and soil is accounted for in the analysis, which is an important consideration since piles may be loaded close to their full capacity, even under working conditions.

Table 1. Non-dimensional parameters used for piled raft design

Ratio of pile area load to pile capacity	$P_g^* = p\,A_g\,/\,(nq_p)$
Ratio of total applied load to pile capacity	$P_t^* = pA_r\,/\,(nq_p)$
Pile group-raft stiffness ratio	$K_{pr} = k_p\,/k_r$
Proportion of load carried by piles	$p_{gt} = P_g\,/\,(pA_r)$
Ratio of pile load to pile capacity	$m = P_g\,/\,(nq_p)$

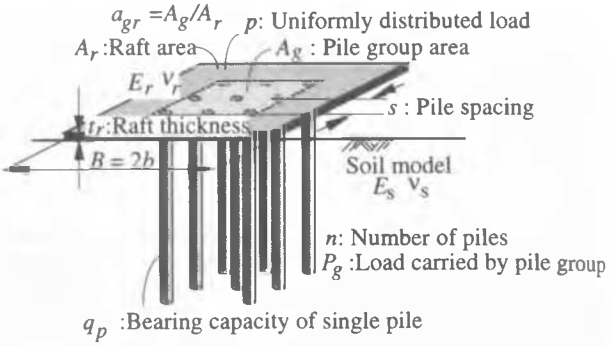


Figure 4. Piled raft model analysed in parametric study

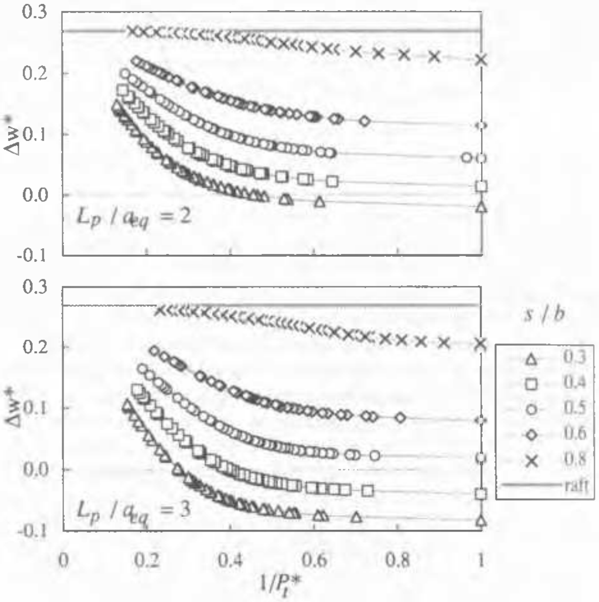


Figure 5. Effects of pile spacing and length on differential settlement

3.2 *Effects of pile group area*

Table 2 shows the basic parameters adopted for the analyses. In the table, d_p and E_p are the diameter and Young's modulus of the pile respectively, and h is the thickness of the soil. Only 9 piles have been modelled in the analyses, since it was considered that the 'equivalent pier' concept can be applied to any piled raft with more piles, replacing subgroups of piles by an equivalent pier.

The effect of pile spacing (s) and pile length (L_p) are explored first. Note that s and a_{gr} are related by $a_{gr} = (s/b)^2$. In the analyses, the square raft was divided into 49 plate bending elements, and each pile was divided into 15 rod elements. The base resistance of each pile is assumed to be $q_b = 9s_u = 9\,(G_s\,/500)$, where s_u and G_s are the undrained shear strength and shear modulus of the soil respectively. The ultimate shaft friction, τ_s, was assumed to be

Table 2. Basic parameters used for parametric study

Pile	Square raft	Soil
$n = 9$	$L = B = 13.3$ m	$h = \infty$
$d_p = 0.3$ m	$E_r = 35$ GPa	$E_s = 35$ MPa
$E_p = 35$ GPa	$\nu_r = 0.16$	$\nu_s = 0.5$

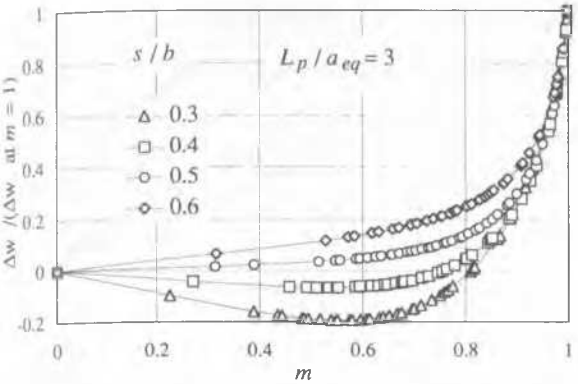


Figure 6. Degree of mobilisation of pile capacity

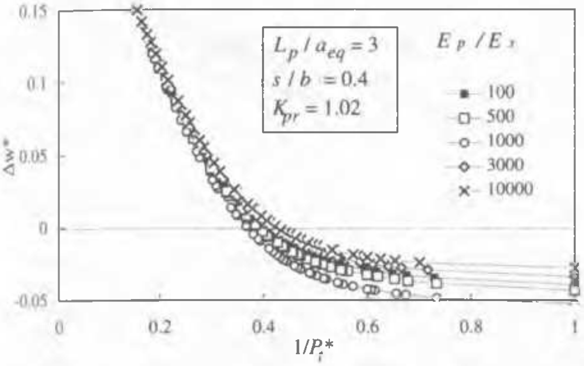


Figure 7. Effects of E_p/E_s on differential settlement

equal to s_u. However, as discussed by Horikoshi (1995), the results shown below are not affected by the chosen G_s/s_u ratio.

Figure 5 shows the results for the cases $K_{rs} = 0.1$, $L_p/a_{eq} = 2$ and 3. In the figures, the horizontal axis is $1/P_t^*$, so that the left hand side of the plots correspond to high values of load applied to the raft. The normalised differential settlement, Δw*, for the raft alone has also been calculated by HyPR, and is independent of P_t^* since the raft behaviour is treated as elastic. The figures show that the differential settlements are strongly affected by the pile group area a_{gr}. The average settlements of the piled rafts were found to be almost the same for the given K_{rs} and L_p/a_{eq} conditions, although the results are not shown here. As the applied load increases, the normalised differential settlement of the piled raft approaches that of the raft alone (since the piles reach their ultimate load and have reducing effect). Even if Δw* is close to zero during the initial stage of loading, this cannot be maintained as the pile capacity is mobilised (for example, see the case $L_p/a_{eq} = 3$, $s/b = 0.5$). This suggests that the initial elastic differential settlement of piled rafts should be slightly negative, with the mid-side point settling slightly more than the raft centre, rather than zero.

Figure 6 shows the variation of differential settlement with '*m*' (the degree of mobilisation of pile capacity). In the figure, the differential settlement is normalised by that at $m = 1$ (full mobilisation of the pile capacity). This figure shows that the differential settlement increases significantly when $m > 0.8$, implying that the value of '*m*' should be controlled below 0.8.

It should be noted that the case of $L_p/a_{eq} = 3$, $s/b = 0.4$ ($a_{gr} = 0.16$) corresponds to a marginally negative differential settlement at low load levels, and essentially zero differential settlement when $1/P_t^*$ is between 0.3 and 0.4. This may be considered close to an optimum design, and was chosen as the basic case from which to explore the effect of other parameter changes.

During the study, it was found that pile group-raft stiffness ratio K_{pr} is the most critical among the parameters shown in Table 1, and that optimum conditions correspond to K_{pr} close to unity. Note that K_{pr} is calculated as 1.02 for the basic case.

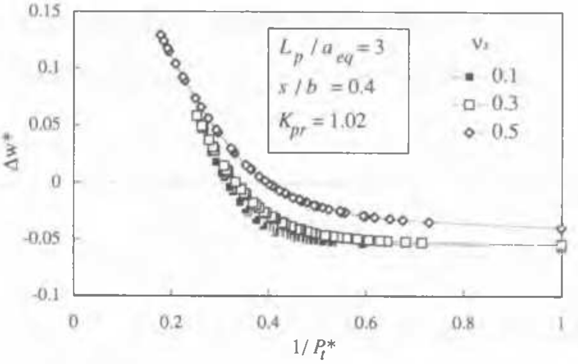


Figure 8. Effects of Poisson's ratio of soil on differential settlement

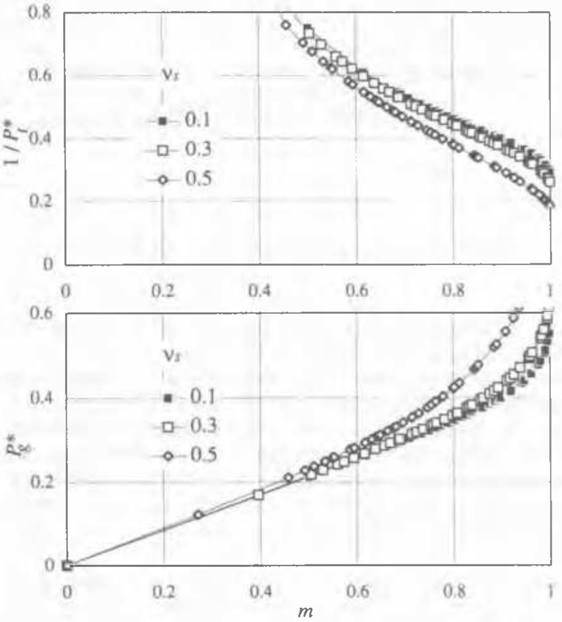


Figure 9. *m* and $1/P_t^*$, *m* and P_g^* relationships (effects of ν_s)

3.3 *Effects of pile compressibility, E_p/E_s*

Pile compressibility, E_p/E_s, was changed, keeping $K_{pr} = 1.02$ by changing the pile radius. The ratio G_s/τ_s was kept at 500, as for the basic case, so that the pile capacity varied according to the adjusted pile radius. Other conditions were kept constant. Figure 7 shows that the differential settlement stays small when $1/P_t^*$ is between 0.3 and 0.4. The figure shows that the differential settlement is essentially independent of pile compressibility, provided the pile group-raft stiffness ratio, K_{pr}, remains the same.

3.4 *Effects of Poisson's ratio of soil, ν_s*

Poisson's ratio of the soil was changed, keeping $K_{pr} = 1.02$ and $E_p/G_s = 3000$, but varying the pile radius and E_p. Figure 8 shows the results of the analyses, which indicates no significant difference for ν_s in the range 0.1 - 0.5, although there is a tendency for the differential settlement to become more negative as ν_s reduces.

The variations of $1/P_t^*$ and P_g^* with *m* are shown in Figure 9. For ν_s less than 0.5, P_g^* is between 0.3 and 0.4 when *m* equals 0.8. The corresponding $1/P_t^*$ is slightly larger than that for fully undrained conditions.

3.5 *Optimum K_{pr} value*

In addition to the above results, it was found that, even if the pile length or the soil thickness is varied, the differential settlement

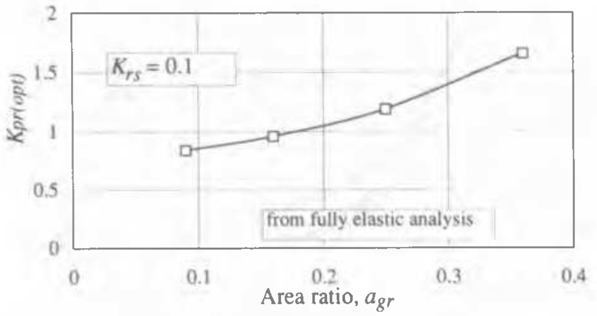


Figure 10. Optimum K_{pr} from fully elastic analyses

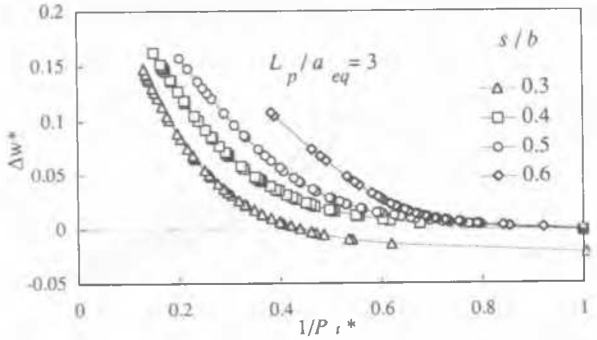


Figure 11. Non-linear analyses by using $K_{pr(opt)}$ in Figure 10

behaviour is essentially the same so long as the pile group-raft stiffness ratio, K_{pr}, is maintained constant.

Figure 10 shows optimum K_{pr} values, giving zero differential settlement for fully elastic conditions. As the pile group area ratio increases, the optimum K_{pr} value increases slightly. However, overall, a K_{pr} value of about unity may be suitable when piles are installed beneath the central area of the raft. Horikoshi (1995) has suggested that area ratios, a_{gr}, in the range 0.16 to 0.25 are optimal to minimise the raft bending moment as well as differential settlement.

Figure 11 shows the results of non-linear analyses, adopting the optimum K_{pr} from fully elastic analysis (Figure 10). The initial (elastic) differential settlements are therefore nearly zero. As noted by Horikoshi (1995), K_{pr} values approximately 5 % larger than those shown in Figure 10 should be applied to minimise the differential settlement after moderate mobilisation of pile capacity.

Figure 12 shows the variations of $1/P_t^*$ and P_g^* with m. When m is 0.8, the corresponding P_g^* is about 0.5 for $s/b = 0.4$ to 0.6, which is larger than the value of 0.4 shown in Figure 9. A slightly higher K_{pr} value reduces P_g^* to close to 0.4, and the corresponding P_t^* then varies from 2.5 to 1.6 as the area ratio, a_{gr}, increases from 0.16 to 0.25.

Horikoshi and Randolph (1996c) have proposed that a raft-soil stiffness ratio of $K_{rs} = 0.1$ may be suitable for rafts of moderate size. However, as the raft size increases, the appropriate K_{rs} must reduce unless the raft becomes very thick. As such, K_{rs} may reduce to less than 0.01, and the optimum pile group will change, increasing the area ratio and reducing the relative pile length, in order to avoid any local maximum settlements just outside the piled area.

4 CONCLUSIONS

A parametric study of piled raft behaviour was performed to establish a framework for optimum design in terms of differential settlement. Although the cases considered in this paper are still limited, the following guidelines for optimum design are proposed:

For an optimum design:

(1) Piles should be distributed over the central 16 to 25 % of the raft area.

(2) The pile group (or equivalent pier) stiffness should be approximately equal to the stiffness of the raft alone ($K_{pr} \approx 1$).

(3) Total pile capacity should be designed for between 40 and 70 % of the design load, depending on the pile group area ratio and Poisson's ratio for the soil.

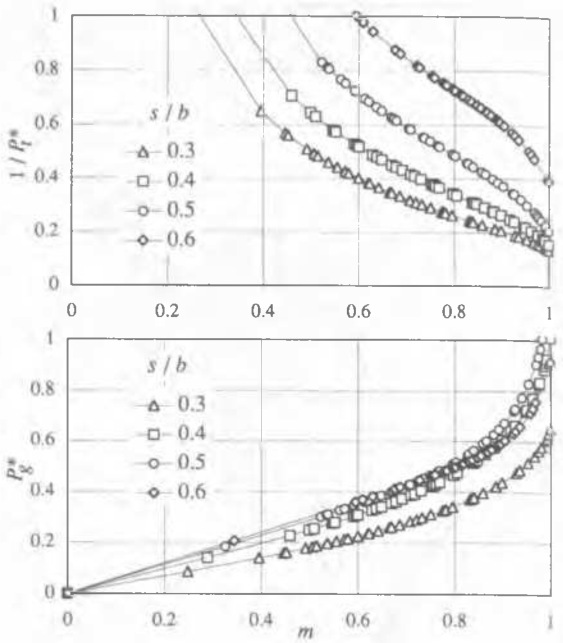


Figure 12. m and $1/P_t^*$, m and P_g^* relationships (effects of s/b)

The pile group-raft stiffness ratio is the most critical parameter that governs the settlement behaviour of piled rafts. The degree of mobilisation of pile capacity, m, should be less than or equal to 0.8, to avoid significant increases in differential settlement. For m in the region of 0.8, optimum pile support corresponds to a total pile capacity of between 2.5 and 3 times the load applied over the region of the pile group, but only 40 to 70 % of the total applied load over the full raft.

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