# Panel discussion: Some observations on piled raft (mat) foundation analyses

## Débat de spécialistes: Quelques observations sur l'étude de fondation par radier sur pieux

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## 1 INTRODUCTION AND DESIGN APPROACHES

Shallow raft (mat) foundations, enhanced with deep foundation elements (driven piles, drilled shafts, etc.), have received a fair amount of attention in recent years (e.g. Poulos 1994, Randolph 1994, Burland 1995). This attention has focused on newer and/or different ways of utilizing or designing this type of "floating" foundation (herein called piled raft for brevity). In this paper, some key issues of piled raft behavior are noted, and the role of optimization in design is explored with a simple example.

In designing piled rafts, two basic approaches have evolved. In the first or traditional approach, the foundation is designed essentially as a pile group with "normal" pile factors of safety. Pile spacing is more-or-less uniform under the entire raft, which is assumed to carry 10-20% of the loading.

In the second approach, the piles are utilized mainly to reduce the vertical displacement of the raft. The piles are spaced locally for displacement control, and their depths are varied for further displacement control. The piles are designed to operate at high mobilization levels or "creep limits" (typically 70-80% or more of ultimate axial capacity), and they are allowed to move plastically relative to the soil. Therefore, the foundation is designed essentially as a raft with pile enhancement. This design approach assumes no significant post-peak reductions in pile capacity. The remainder of this paper focuses on this second approach.

## 2 CURRENT UNDERSTANDING

Foundation design consists of providing a structural transition between the loaded structure and the supporting soil. Regardless of the design assumption, the basic system behavior is depicted in Figure 1. A forcing function (normally dead and live loads in foundation design) is applied to an assumed system, and a measurable response occurs. Between the forcing function and the system response is the model invoked to describe the system behavior, coupled with the properties needed for this particular model. The overall usefulness of this system behavior depends on measured system responses (case histories) and back-calculations or "calibrations" to test the assumed model and properties.

For piled rafts, the "calibration loop" has been limited to date, and details of differential and total displacements, raft bending moments, contact pressures, and pile loads, with corresponding property data, are sparse. Table 1 lists our current understanding of some key issues for piled rafts under vertical loading. This list is not necessarily exhaustive.

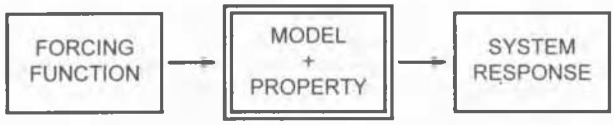

Figure 1. Components of geotechnical prediction

### 2.1 *Issues that are understood conceptually*

System geometry is the only issue that has been researched in some depth. The general influence of each geometric element is relatively understood, at least for elastic models. However, further work is needed for nonlinear soil models and for the latter two categories in Table 1.

Table 1. Behavior issues for floating piled rafts

| Current understanding | Issues |
|---|---|
| Conceptually understood, but more refinements needed | • System geometry<br>- Raft thickness (stiffness)<br>- Piled area<br>- Pile depth<br>- Pile spacing<br>- Pile diameter<br>• Nonlinearity |
| Limited understanding | • Non-uniform loading<br>• Non-uniform system geometry<br>• Non-homogeneity<br>• Construction effects<br>- Pile installation<br>- Deep excavation<br>- Raft concreting |
| Not explored to date | • Soil consolidation<br>• Stress and property anisotropy<br>• Non-vertical loading |

It appears that nonlinearity should be incorporated in these analyses (e.g. Bilotta et al. 1991), because only a small number of piles are used and they are loaded at high mobilization levels. However, this observation does not necessarily mean that simpler linear models are of no use. For example, simple models can be used for parametric studies. Also, Burland and Kalra (1986) have shown that when the piles are assumed to be "fully" mobilized, they can be represented simply by vertical forces.

### 2.2 *Issues of limited understanding*

Most of the analytical studies to date have assumed uniform raft loading. However, structures often generate non-uniform loading (e.g. Hooper 1973, Kishida 1991). Consider, for example, a structure with load-bearing exterior walls and relatively few interior columns so that the loading would be primarily along the raft outer edges. For this case, the displacement profile would be an upward dish and therefore, to minimize differential displacement, piles should be placed primarily along the edges. This strategy is exactly the opposite of the results for uniform loading.

Non-uniform system geometry has been evaluated for a few tall structures, and their performance has been quite satisfactory. Similarly, soil non-homogeneity has been examined in only a few case histories. Parametric studies of both issues are needed.

Construction effects need to be explored in more detail. The effect of each separate construction stage generally is understood. However, the coupled effects are complex. Stresses developed from pile installation, raft excavation, and subsequent raft and structure placement are all important components that will influence the piled raft behavior.

### 2.3 *Issues essentially not explored to date*

Soil consolidation has been modeled roughly by varying the soil

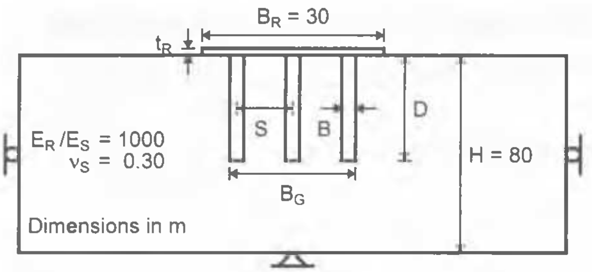

Figure 2. System geometry of problem analyzed (not to scale)

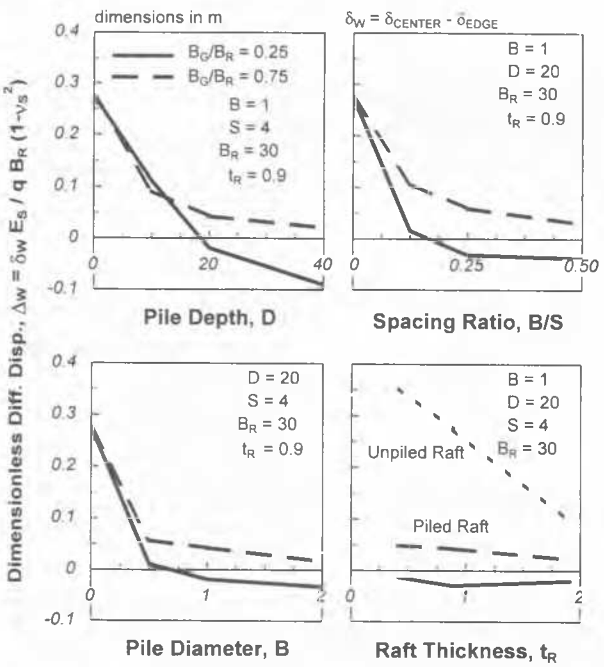

Figure 3. Influence of geometry on differential displacement

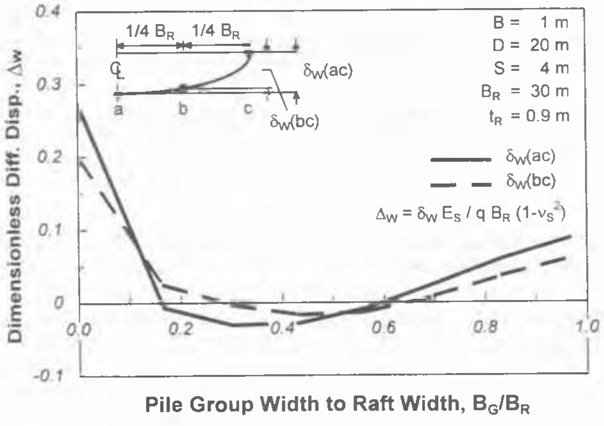

Figure 4. Influence of $B_G/B_R$ on differential displacement

Poisson's ratio. However, this modeling does not really represent what is truly occurring in the field. For example, consider a piled raft for a tall structure with several basement levels. The complex process of unloading and loading obviously cannot be modeled by varying Poisson's ratio. Proper models are needed.

In-situ stress and soil property anisotropy also are important parameters that have not been addressed. Only isotropic values have been assumed to date.

Non-vertical loading (lateral, inclined, moment) is perhaps the most important parameter yet to be explored. This issue could be quite important when relatively few piles are used over a small portion of the raft. Then, with a large overturning moment, tension can develop under the raft and, as a result, loss of raft contact might occur in the unpiled areas. This situation certainly can cause unsatisfactory foundation performance. This type of influence of non-vertical loading needs to be examined carefully.

## 3 OPTIMIZATION PROCESS

An optimization process certainly needs to be performed for piled rafts to achieve an efficient design. This process could be more important when considering non-uniform system geometry and, perhaps, non-vertical loading.

The following example is intended to show the importance of optimization in designing piled rafts. Figure 2 shows the system geometry of the uniformly-loaded, square, piled raft analyzed. The variable chosen to be minimized is the dimensionless differential displacement, $\Delta_W$ [ $= \delta_W E_S / q B_R (1-\nu_S^2)$], in which is $\delta_W$ = differential displacement, $E_S$ = soil modulus, q = applied stress, $B_R$ = raft width, and $\nu_S$ = soil Poisson's ratio. A simple, linear, elastic, plane-strain finite element model was used, and the piles were represented by the simplification of Desai et al. (1974).

Figure 3 shows the dimensionless differential displacement $\Delta_W$ between the center and edge of the raft for two pile group sizes ($B_G/B_R$ = 0.25 and 0.75) and representative pile and raft geometries. Both group sizes show essentially the same trends, and each component of the pile group geometry shows its optimal value. For this particular case, the optimum system geometry would be D = 15-20 m, B = 0.7-1.0 m, and S = 4-6 m. Beyond these values, the reduction in $\Delta_W$ is relatively small. Note also that the effect of raft thickness on $\Delta_W$ is minimal once the piles are placed optimally beneath the raft. However, the behavior of the unpiled raft is very dependent on raft thickness.

Figure 4 shows the influence of $B_G/B_R$ on $\Delta_W$. The two curves shown are the dimensionless differential displacements between the center and edge of the raft $\Delta_W$(ac) and between the quarter point and edge of the raft $\Delta_W$(bc). Note that $\Delta_W$(ac) is not always larger than $\Delta_W$(bc), indicating that the displacement profile is not always a downward smooth dish and the values of $\Delta_W$ could be negative, indicating upward dishing. The trends of both curves are essentially the same. The value of $\Delta_W$ decreases, levels out, and then increases as $B_G/B_R$ increases. This behavior indicates that, once the optimum ratio is achieved, more piles do not necessarily mean better performance. For this example, the optimum $B_G/B_R$ is about 0.3-0.6.

## 4 CONCLUSIONS

Current understanding of the behavior of piled rafts is still incomplete. Many issues must be researched, as discussed herein, and relatively simple design guidelines will need to evolve from this research. Perhaps the most important issue yet to be explored is the influence of non-vertical loading. In any case, an optimization process should be performed when designing piled rafts.

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