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Analyses of vertical and horizontal load tests on piled raft models in dry sand

Analyses des essais en charge verticale et horizontale sur les modèles de radeau empilé en sable

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ABSTRACT
Analyses of the static centrifuge model test results of piled raft foundations subjected to vertical load and horizontal load are carried out using a simplified analysis method. The flexible raft is modelled as thin plates, the piles as elastic beams, and the soil is treated as springs. The interactions between structural members are taken into account for both vertical and horizontal forces. Good agreements between the calculated and the measured results are demonstrated, and the validity of the proposed analysis method is verified.

RÉSUMÉ
Les analyses de l'essai modèle centrifuge statique sur les bases de radeau empilées sujet aux charges verticales et horizontales au moyen d'une méthode analytique simplifiée sont rapportées. Le radeau flexible est modelé dans des plats minces tandis que les piles dans les faisceaux élastiques et le sol en ressorts. Les interactions parmi les pièces de charpente sont prises en considération des forces verticales et horizontales. Les résultats du calcul sont conformes à ceux de la mesure pendant les expériences et la méthode analytique proposée est vérifiée.

1 INTRODUCTION

Piled raft foundations have been widely recognized as one of the most economical methods of foundation systems since Burland *et al*. (1977) presented the concept of 'settlement reducers'. Although a number of research works on the settlement of piled raft foundations have been reported, the work that deals with the behaviour of piled rafts under horizontal loading seems to be very limited. In highly seismic areas such as Japan, establishments of a seismic design concept and a design tool for piled raft foundations are necessary.

With an aim to clarify this behaviour, Horikoshi *et al*. (2003a, 2003b) conducted a series of static and dynamic centrifuge model tests for piled raft foundation models on dry sand in a centrifugal field of 50g. An influence of the rigidity of the pile head connection on the horizontal behaviour of the foundation was investigated by designing two model piled rafts with two different pile head connections, i.e., rigidly fixed and hinged pile head connections. It was found that comparable behaviours of the piled rafts were obtained in the static and dynamic centrifuge model tests. These results support the idea of a traditional seismic design method of a foundation in which dynamic loads acting on the foundation are modelled by an equivalent static horizontal load.

Considering current trends toward the limit state design or performance based design in the area of foundation engineering, precise estimation of deformation of a pile foundation and of stresses of their structural members is a vital issue in the framework of this new design criteria. In the preliminary design stage, a number of alternative calculations are required, varying the number of piles, the pile length, the pile spacing, the locations of the piles, and so on. Hence, a feasible but reliable deformation analysis method of piled raft foundations would be useful. As a preliminary routine design tool of piled raft foundations subjected to vertical, horizontal and moment loads, a computer program PRAB (Piled Raft Analysis with Batter piles) has been developed by Kitiyodom & Matsumoto (2002, 2003).

In this work, in order to examine the applicability of the method, analyses of the static centrifuge model tests were carried out. The calculated results were compared with the static centrifuge test results.

2 CENTRIFUGE TEST RESULTS

Horikoshi *et al*. (2003a) has conducted a series of static vertical loading tests and horizontal loading tests of piled raft models on dry Toyoura sand by using a geotechnical centrifuge (Fig. 1). Principle findings from their study are:

1) The stiffness and the resistance of the single pile in piled raft foundations are different from those observed in the isolated single piles of the same size, due to the difference in the confining stress condition around the piles;
2) Piles play important roles in increasing horizontal ultimate resistance of piled raft foundations;
3) The initial horizontal stiffness of a piled raft is not always higher than that of a raft (alone) as the piles reduce the contact pressure between raft base and soil surface, and hence the stiffness of the upper soils;
4) Higher horizontal load is transferred to the piles in the piled raft with rigid pile head connection, which leads to higher initial horizontal stiffness compared with that in the piled raft with hinged connection;
5) The proportion of vertical load carried by the piles in a piled raft remains almost unchanged during horizontal loading, while the proportion of horizontal load carried by the piles increases as the horizontal displacement increases.

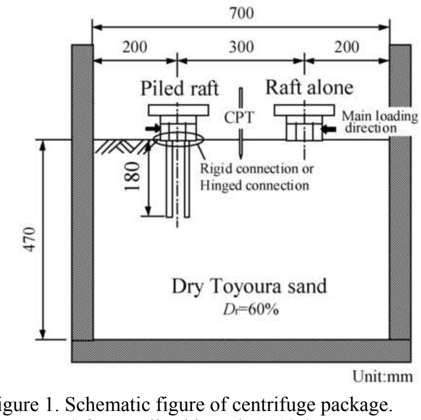


Figure 1. Schematic figure of centrifuge package. (after Horikoshi *et al*., 2003a)

3 METHOD OF ANALYSIS & ANALYSIS CONDITIONS

The back analyses of the static centrifuge model test results were carried out using the program PRAB which has been developed to estimate the deformation and load distribution of piled raft foundations subjected to vertical, horizontal, and moment loads. In this program, a hybrid model is employed in which the flexible raft is modelled as thin plates, the piles as elastic beams, and the soil is treated as springs (Fig. 2). Both the vertical and horizontal resistances of the piles as well as the raft base are incorporated into the model. The interactions between structural members, pile-soil-pile, pile-soil-raft and raft-soil-raft interactions are taken into account based on Mindlin's solutions for both vertical and horizontal forces. The considered soil profile may be homogeneous semi-infinite, arbitrarily layered and/or underlain by a rigid base stratum. The estimation of non-linear deformation of the foundations is calculated by employing the bi-linear (elastic-perfectly plastic) response of soil springs.

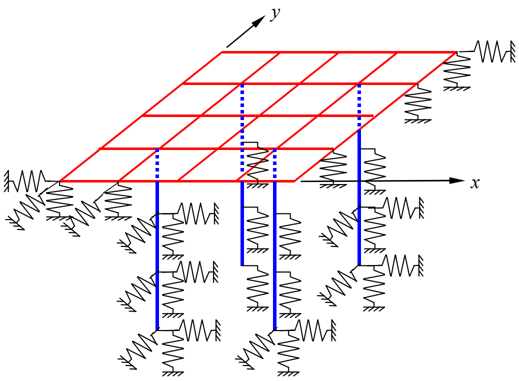


Figure 2. Plate-beam-spring modelling of a piled raft foundation.

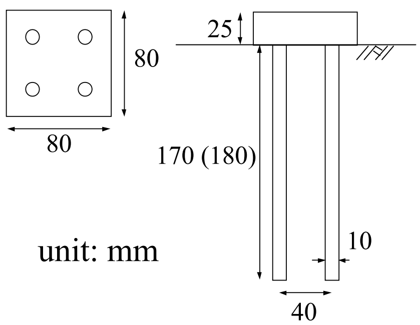


Figure 3. Configuration of piled raft.

Table 1. Analytical conditions.

	Loading direction	
	Vertical loading	Horizontal loading
Pile	Pile length = 170 mm	Pile length = 180 mm
	Outer diameter = 10 mm, Inner diameter = 8 mm Young's modulus = 70.6 GN/m^2 Poisson ratio = 0.16	
Raft	Mass = 0.90 kg	Mass = 4.69 kg
	Width = 80 mm, Breadth = 80 mm Thickness = 25 mm Young's modulus = 70.6 GN/m^2 Poisson ratio = 0.16	
Soil	Layer depth = 470 mm	Layer depth = 460 mm
	Density = 1.52 t/m^3, Internal friction angle = 35° Void ratio = 0.76, Poisson ratio = 0.3 Finite homogeneous layer	

Analyses of the centrifuge tests by Horikoshi *et al*. (2003a) were carried out using the geometrical and mechanical properties given in Fig. 3 and Table 1. The soil was treated as a finite homogeneous layer. Iwasaki & Tatsuoka (1977) suggested the relationship between the shear modulus of sand at the low strain, G_0, and the void ratio, e, as shown in Eq. (1).

$$G_0 = 850\frac{(2.17-e)^2}{1+e}p^{0.44} \qquad (\text{kgf/cm}^2) \tag{1}$$

Using the effective confined pressure, p (kgf/cm^2), at the depth equal to 2/3 of the pile length at 50g, the shear modulus of the model ground at the low strain, G_0, was calculated as 73.2 GN/m^2, resulting in the young modulus at the low strain, $E_0 = 2(1+\nu_s)G_0$ = 190.3 GN/m^2. Note that the coefficient of earth pressure at rest, K_0, was estimated by Jâky (1944) formula.

$$K_0 = 1 - \sin\phi' \tag{2}$$

In the analyses, the Young's modulus of the soil was obtained by fitting the measured load-displacement curves at the initial loading stage. And it was found that the values of the Young's modulus were 15 GN/m^2 and 17.4 GN/m^2 for model piled raft subjected to vertical and horizontal loading, respectively. These values are corresponding to the lower bound of the range $0.1E_0$ to $0.3E_0$ which is usually employed in the problem of pile foundation in practice (Yamashita *et al*., 1994).

4 ANALYSIS RESULTS

4.1 *Model foundations subjected to vertical loading*

For the analysis of the vertically loaded piled raft, in order to take into account the non-linear response, the value of the uniform ultimate pile shaft resistance and the pile base bearing capacity were set as 100 kN/m^2 and 10000 kN/m^2, respectively. These values were obtained from the measured axial force distribution of piles in the piled raft at the settlement of 5 to 6 mm. Note that for the case of the centrifuge model test on sand, the modulus of the model sand ground significantly increases with the depth. Consequently, the pile in the piled raft didn't act purely like a friction pile (Watanabe *et al*., 2001). In this analysis, an average value of the shaft resistance was employed. In addition, it was assumed that there is no failure occurred at the raft base.

Fig. 4 shows the comparisons between the load-settlement behaviour of the model piled raft calculated using PRAB and those obtained from the centrifuge modelling. The load-settlement behaviour of the four piles in the piled raft is also shown in the figure. Fig. 5 shows the proportions of the vertical load carried by the raft and the four piles. It can be seen from the figures that there are good agreements between the calculated results using the simplified method and the measured results.

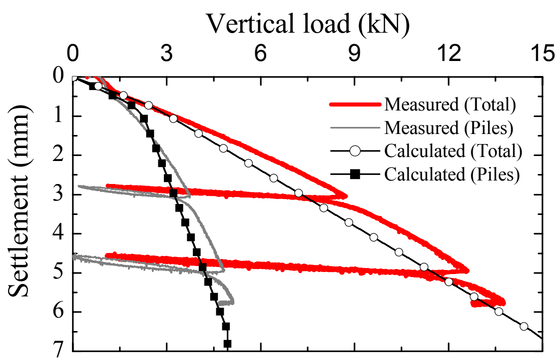


Figure 4. Load-settlement relationship.

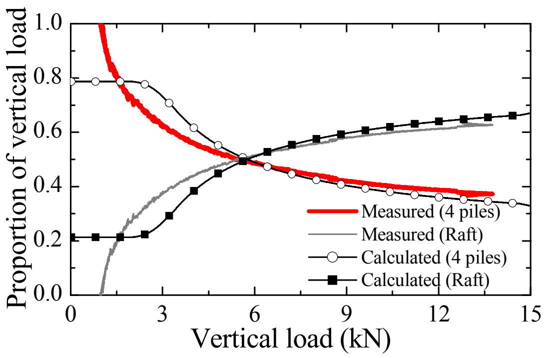


Figure 5. Proportions of vertical loads carried by raft and piles.

4.2 *Model foundations subjected to horizontal loading*

Although cyclic horizontal loads were applied to the model piled raft in the centrifuge tests, the horizontal load is applied in one direction in the analysis as shown in Fig. 6. The analysis is conducted for only horizontal loading stage. However, the vertical load carried by the raft before the horizontal loading was taken into account as the initial condition in the calculation. The vertical load carried by the raft base just before the centrifuge horizontal load test (57% the raft weight of 2300 N) was assumed to distribute uniformly over the raft base. The friction coefficient at the raft base of 0.42 was obtained from the horizontal load test of the raft alone (Fig. 7). In the estimation of the limit horizontal pressure of the piles located just beneath the raft in cohesionless soils, the effect of the increase in the vertical stress of the soil due to the vertical load transferred through the raft should be taken into account by using Eq. (3).

$$p_{\mathrm{u}} = K_{\mathrm{p}}\sigma'_{\mathrm{v}} = K_{\mathrm{p}}\left(\sigma'_{\mathrm{v0}} + \Delta\sigma'_{\mathrm{v}}\right) \tag{3}$$

where K_p is the Rankine passive pressure coefficient, σ'_v is the total effective overburden pressure, σ'_{v0} is the initial effective overburden pressure and $\Delta\sigma'_v$ is the increase in the vertical stress of the soil beneath the raft and may be approximately estimated as follows:

$$\Delta\sigma'_{\mathrm{v}} = \frac{q_z \times B_{\mathrm{r}} \times L_{\mathrm{r}}}{\left(B_{\mathrm{r}} + z\right)\left(L_{\mathrm{r}} + z\right)} \tag{4}$$

where q_z is the load per unit area, B_r and L_r are the breadth and the length of the raft, and z is the depth of the considered point below the raft. Note that Eq. (4) is based on the assumption that the stress from the raft spreads out along lines with a 2 vertical to 1 horizontal slope. The distribution of the limit soil pressures with depth is shown in Fig. 8.

Fig. 9 shows the comparisons between the load-displacement behaviour of horizontally loaded model piled raft with the rigid pile head connection calculated using PRAB and those obtained from the centrifuge test. The horizontal load-displacement behaviour of the raft in the piled raft is also shown in the figure. Fig. 9(a) shows the calculated results where the value of the limit horizontal pressure of the piles was estimated considering the effect of the increase in the soil stress beneath the raft, while the calculated results where the effect of the increase in the soil stress beneath the raft was neglected are shown in Fig. 9(b). The calculated results that considered the effect of the increase in the soil stress beneath the raft overestimate the measured total horizontal resistance, because of the overestimation of the horizontal pile resistance. This was thought to be due to the configuration of the model piled raft employed in this study. The raft breadth is relatively narrow compared to the pile length (Fig. 6). Hence, the effect of the increase in the soil stresses due to the raft load on the value of the limit horizontal pressure of the pile is small. Consequently, the calculated results that neglected the effect of the increase in the soil stress beneath the raft are closer to the measured values (Fig. 9(b)). Note that the analysis results hereafter were calculated using the limit soil pressure value without the effect of the increase in the soil stress beneath the raft.

The influence of the rigidity of the pile head connection on the horizontal behaviour of the piled raft foundation was also investigated in the centrifuge tests. The analysis of the horizontally loaded piled raft with the hinged pile head connection was also carried out. Analysis parameters were set to be the same as the previous analysis of the piled raft with the rigid pile head connection. Fig. 10 shows the comparisons between the load-displacement behaviour of horizontally loaded model piled raft with the hinged pile head connection calculated using PRAB and those obtained from the centrifuge test. Good agreements were found between these two results. Comparing the results in Fig. 10 with those in Fig. 9 (b), it can be seen from both the calculated results and the centrifuge results that the piles in the piled raft with the hinged pile head connection carry smaller amount of the horizontal load than those in the piled raft with the rigid pile head connection, while the amount of the horizontal load carried by the raft is almost the same.

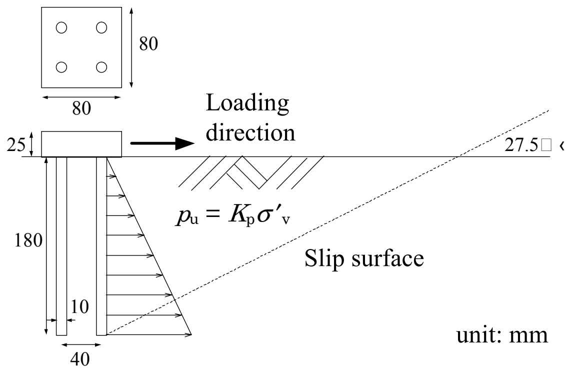


Figure 6. Problem analyzed (horizontal loading).

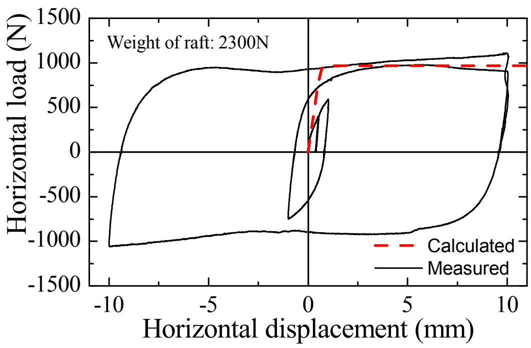


Figure 7. Horizontal load-displacement curves (raft alone).

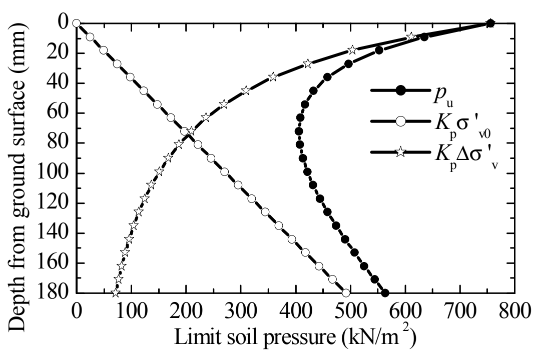
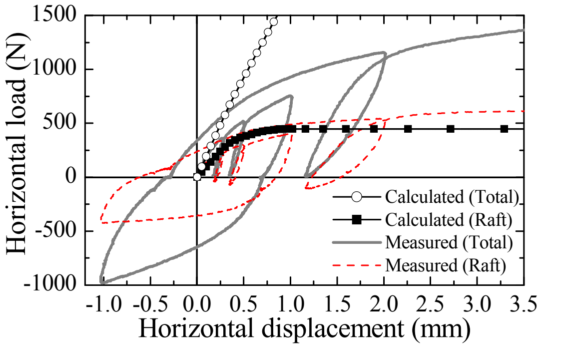
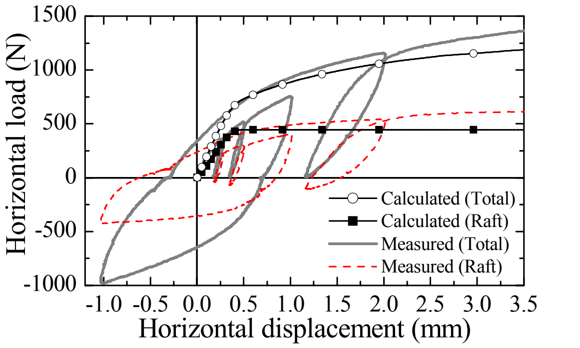


Figure 8. Recommend limit horizontal pressure of a pile in piled raft.



(a) With consideration of increase in the soil stress due to the raft load



(b) Without consideration of increase in the soil stress due to the raft load

Figure 9. Horizontal load-displacement curves (rigid pile head connection).

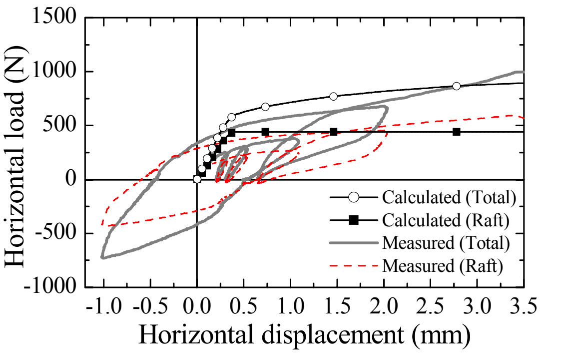


Figure 10. Horizontal load-displacement curves (hinged pile head connection).

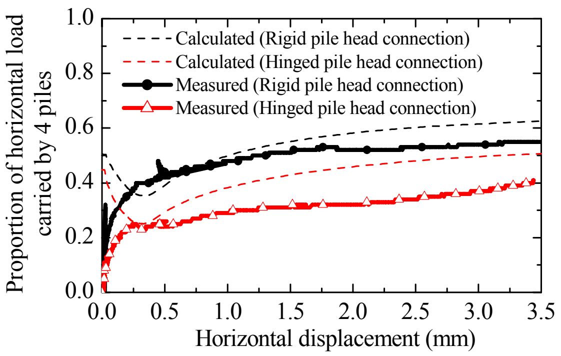


Figure 11. Proportion of horizontal load carried by piles.

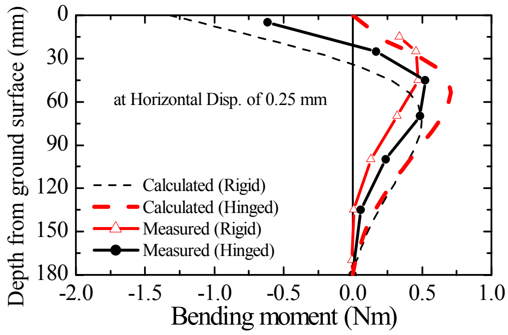


Figure 12. Distributions of bending moment.

Fig. 11 shows the comparisons between the proportions of the horizontal load carried by four piles calculated using PRAB and those obtained from the centrifuge tests. The higher proportion of the horizontal load carried by the piles is shown in the case of the piled raft with the rigid pile head connection. The bending moment profiles at a horizontal displacement of 0.25 mm calculated using PRAB are compared with the centrifuge results in Fig. 12. It was found from the figure that the values of the bending moments calculated using PRAB are a little bit higher than those of the measured values, and the points where maximum bending moment occurred are deeper in the calculation results. However, as a whole, the analysis results match well with the measured values obtained from the centrifuge tests.

5 CONCLUDING REMARKS

The applicability of a computer program PRAB was examined through the analyses of the static centrifuge model test results. Good agreements between the calculated results and the measured values were demonstrated. It can be stated that even though the proposed method is simple, the method can be used with a confident as a design tool for piled raft foundations subjected to vertical loads as well as horizontal loads.

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