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# Centrifuge model tests on piled raft foundation in sand subjected to lateral and moment loads

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**Abstract**

Piled raft foundation has been widely recognized as a rational and economical foundation system with the combined effects of raft and piles. However, the behavior of laterally loaded piled raft foundation has not been well understood due to the complicated interaction of raft–ground–piles. A series of static horizontal loading tests were carried out on three types of foundation models, i.e., piled raft, pile group and raft alone models, on sand using a geotechnical centrifuge. In this paper, the influences of relatively large moment load and rotation on the overall performance of laterally loaded piled raft foundation were examined. From the centrifuge model tests, it is found that the vertical displacement due to horizontal loads is different between piled raft and pile group foundation, and this vertical displacement has significant influences on the performance of laterally loaded piled raft foundation. The horizontal resistance of the pile part in the piled raft foundation is higher than those observed in the pile group foundation due to raft base contact pressure. The vertical displacement of the foundation due to the horizontal loads affects the vertical resistances of piles, which results in the different mobilization of moment resistances between the piled raft and pile group foundations.


*Keywords:* Piled raft; Pile group; Raft; Sand; Centrifuge model; Lateral load; Moment load

## 1. Introduction

The piled raft foundation has been recognized as an economical and rational foundation system since Burland et al. (1977) presented the concept of settlement reducers. Some design concepts have been reported (Kakurai et al., 1987; Randolph, 1994; Horikoshi and Randolph, 1998). Furthermore, a design code of the piled raft foundations has also been published in Japan (Architectural Institute of Japan, 2001). The design concept of piled raft foundation is to take the advantage of the bearing capacity of the raft and to reduce the settlement of foundations to an acceptable level by installing a few piles. Piles in the piled raft foundation play the roles of reducing the settlement and transferring a part of the load to the deep ground. In Japan, piled raft foundations have been applied to building designs, and several observations have been reported on actual buildings (Yamashita et al., 1993; Yamashita et al., 2011; Yamashita, 2012), while the behavior of the piled raft foundation under seismic load has not been well clarified. This is partly due to the uncertainty in the complicated behavior of the piled raft foundation when it is subjected to seismic and horizontal loads. In order to clarify the complicated behavior of the piled raft foundation, accumulation of

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Table 1
Summary of previous researches on piled raft foundation subjected to static horizontal load and this study.

| | Test condition ($g$) | Pile length (mm) | $h/S$[a] | RVLP[b](%) | Observed load–disp. curve[c] | Foundation type tested[d] |
|---|---|---|---|---|---|---|
| Hamada et al. (2012) | 1 | 700 | 0 | 58–82 | $P_L$–$\delta$ | PG, PR, SP, R |
| Matsumoto et al. (2004a) | 1 | 170 | 1.23–4.69 | 9.6–42.8 | $P_L$–$\delta$ | PR |
| Pastsakorn et al. (2002) | 1 | 200 | 0.07–0.13 | 8.7–42.4 | $P_L$–$\delta$ | PR, PG |
| Horikoshi et al. (2003a) | 50 | 180 | 0.63 | 60 | $P_L$–$\delta$ | PR, SP, R |
| Mano et al. (2002a) | 30 | 180 | 0.24 | 75 | $P_L$–$\delta$ | PR, R |
| This study | 50 | 160 | 1, 1.8 | 27 | $P_L$–$\delta$, $M_L$–$\theta$ | PR, PG, R |

[a] $h$ is loading height from raft base; and $S$ is pile spacing.
[b] Proportion of vertical load carried by raft.
[c] $P_L$ is the horizontal load; $M_L$ is the moment load; $\delta$ is the horizontal displacement; and $\theta$ is the rotation of foundation.
[d] PR is the piled raft; PG is the pile group; SP is the single pile; and R is the raft.

the observed data under seismic and horizontal loading is crucial. However, comparing the researches of vertically loaded piled raft foundations (e.g., Thaher, 1991; Horikoshi and Randolph, 1994, 1996; Poulos, 2001), research on the behavior of horizontally loaded piled raft foundations is relatively limited. In particular, the observed data on piled raft foundations subjected to seismic loading is very limited. To the best of the authors' knowledge, the behavior of piled raft foundations recorded during the Hyogoken-Nambu Earthquake (Yamada et al., 2001) and the 2011 off the Pacific coast of Tohoku Earthquake (Yamashita et al., 2012) are very rare case records.

Since it is difficult to record the actual field data of the foundation during an earthquake, physical models can play an important role in the study of piled raft foundations under seismic loading. Table 1 summarizes the research on the piled raft foundations subjected to a static horizontal load. A series of horizontal loading tests on pile group models and piled raft models in the 1 g condition was conducted by Pastsakorn et al. (2002), in which a horizontal load was applied at a low height to restrain the rotation of foundation. Hamada et al. (2012) carried out a relatively large scale horizontal loading tests on a piled raft foundation in a field. In their study, the rotation of the foundation was prevented by means of outer and inner frames. In the above research, the influences of moment load and the rotation of the foundation were not taken into account. Matsumoto et al. (2004a, 2004b) carried out static and dynamic horizontal loading tests on a piled raft in 1 g to study the influences of loading height and the condition of the pile head fixity on the behavior of the piled raft. However, the detailed behavior of piled raft foundations subjected to horizontal and moment loads has yet to be well clarified. This could be because of the difficulty of using 1 g small scale models in modeling the complicated raft–soil–piles interactions, including the raft base contact pressure which varies during the loading.

Centrifuge model can satisfy crucial similitude in a small scale model and therefore has advantages in modeling the complicated raft–soil–piles interaction. Horikoshi et al. (2003a, 2003b) investigated the behavior of horizontally loaded piled raft foundations in loose sand by static and dynamic centrifuge model tests done at 50$g$ centrifugal acceleration. In the tests, piled raft foundations with different pile head fixities, i.e., rigid and hinged connections, a raft foundation model and a single pile were modeled and the horizontal stiffness of the foundation system and the proportion of the load carried by raft and piles were carefully studied. Mano et al. (2002a, 2002b) also carried out static and dynamic loading tests on piled raft models and raft models in dense dry sand at 30$g$ centrifugal acceleration. In the static loading of the above mentioned centrifuge tests, horizontal displacement was applied at relatively low heights, as shown in Table 1. From the above literature review, it can be said that the research on the laterally loaded piled raft foundations were mostly carried out under conditions in which rotation and moment load might not be a main concern. However, for the relatively small size raft foundation supporting tall superstructures, such as viaducts, the rotation of the foundation becomes large, and the distribution of contact pressure beneath the raft base varies during the loading, resulting in more complicated interactions among the raft base, ground and piles. The authors are aware that it is essential to clarify the mechanical behavior of the piled raft foundation subjected to relatively large rotation and the moment load for its seismic design.

In this study, a series of static horizontal loading tests was conducted for three types of model foundations, namely, raft, pile group and piled raft foundations on sand. These foundations have a relatively small raft with four displacement piles in a square arrangement with pile spacing and a diameter ratio ($S/D$) of 5. Before the horizontal loading tests, the model foundations experienced a vertical loading process which determined the initial condition of the foundation. In the horizontal loading tests, a load was applied at two different heights from the raft base ($h$) with $h/S=1$ and 1.8 ($S$ is the pile spacing) to investigate the influence of the complicated interaction of raft–ground–piles on the performance of horizontally loaded piled raft foundations under a relatively large moment load and rotation.

## 2. Model foundation and test procedures

### 2.1. Centrifuge package

The geotechnical centrifuge used in this study was Tokyo Tech Mark III centrifuge which was described in detail by