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An investigation about seismic behavior of piled raft foundation for oil storage tanks using centrifuge modelling

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ABSTRACT

Some level of settlement is allowed in the design of oil tank if the uneven settlement can be controlled in an allowable value. Considering a critical condition of piled raft foundation (PRF), that is, secure contact of raft base to the ground surface, and the expected function of piles to impose additional resistance against the local settlement, PRF is considered as one of the rational foundation systems for the oil tanks. However, PRF has a complex interaction with soil under horizontal seismic loading, especially if the tank rests on a liquefiable soil, which may cause an extreme change of the soil stiffness underneath the tank. In this study, a series of centrifuge model tests was performed to investigate the mechanical behavior of oil tank supported by piled raft foundation on liquefiable saturated sand and non-liquefiable dry sand. In the tests, two types of foundation were modelled; a slab foundation, and a piled raft foundation. Using the observed results, such as accelerations of the tank and ground, dynamic and permanent displacement of the foundation, and excess pore water pressures of the ground, advantages and limitations of piled raft foundation for application to oil tanks on sandy soil are discussed.

1. Introduction

Majority of existing oil storage tanks in Japan were constructed before the early 1970's when soil liquefaction was first considered in the design of tank foundations. Since the 1964 Niigata earthquake, the 1978 Miyagiken-oki earthquake [1] and the 1995 Hyogoken-Nambu Earthquake, it has become an urgent matter for geotechnical engineers to assess the seismic stability of existing oil storage tanks and implement proper countermeasures against soil liquefaction.

Piled raft foundations (PRFs) have received considerable attention in the recent years, especially since Burland et al. [2] introduced the settlement reducer concept of PRF. The raft in this foundation system has adequate bearing capacity; therefore, the main objective of introducing the pile elements is to control or minimize the settlement, especially uneven settlement, rather than to carry the major portion of the vertical loads. Therefore, a major concern in the design of PRF is how to design the piles optimally to control the settlement [3–5]. Some researchers utilized finite element modelling (FEM) to study the effect of raft and pile dimension on the behavior of this foundation system [6,7]. Also, PRFs have been used for building design and some case studies of buildings have been reported. Field measurements were employed in these cases to estimate several parameters such as settlement, uneven settlement, load sharing between piles and the raft, and effective pile spacing [8,9]. Mechanical behavior of this foundation system under various loading conditions has been also studied by physical modelling. Static lateral loading tests were conducted in 1g condition to evaluate the application of pile groups and PRF, and discuss the optimized parameters, e.g. raft size, number of piles, piles spacing [10,11]. Furthermore, 1g experimental and analytical studies were performed for static lateral loading conditions to investigate the effects of pile head connection conditions between the raft and piles [12,13]. Similar researches were also made for dynamic loading conditions to investigate the performance of piled raft foundation [14,15]. In addition, some studies were accomplished about the performance of piled raft foundations, which experienced real earthquake loadings [9,16,17].

Centrifuge modelling is a prevalent approach for various studies in fields of geotechnical engineering, including soil liquefaction [18,19] and soil-structure-interaction problems [20,21]. To study the mechanical behavior of piled raft foundation as a complex soil-structure-interaction problem, centrifuge model tests have also been conducted under not only static loadings but also dynamic loadings. Horikoshi et al. [22] and Sawada and Takemura [23] used centrifuge modelling to compare the behavior of PRF with pile group and raft foundations under static horizontal loadings. On the other hand, Horikoshi et al. [14] and Nakai et al. [24] conducted dynamic centrifuge model tests to

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study the dynamic behavior of PRFs and pile group foundations, including the effect of pile head connection. Despite numerous studies on piled raft foundations, optimal and rational design methods of piled raft foundations have not been extended to the civil engineering infrastructures. This is partly due to the complex soil-structure interaction between raft, ground and piles during an earthquake. In particular, if the piled raft rests on a liquefiable ground, the soil-foundation interaction becomes more complex. Because of this complexity and possible large settlement, the practical implementation of piled raft foundation is further hindered.

Another concern in the seismic design of piled raft foundation is to secure the contact of the raft with the subsoil. Without the contact, the contribution of raft cannot be assured against the horizontal load. To ensure the secure contact, the foundation settlement should be greater than the ground settlement. In the design of oil tank foundations, uneven settlement is a greater concern than maximum settlement. For example, an allowable uneven settlement is 1/300 of tank diameter [25], implying that some level of tank foundation settlement is permitted as long as uneven settlement is maintained below the allowable value. Therefore, piled raft foundation is considered one of the rational foundation systems for the oil storage tanks. Some studies have been conducted about oil tank foundations. For example, performances of pile foundation of storage tanks were investigated in some case studies [26,27]. Sento et al. [28] reported case studies about oil tanks on liquefiable sandy soil using compaction method as the countermeasure. A few researchers have considered piled raft foundations for the oil tanks. A case study of oil storage tank with piled raft foundation was done by Liew et al. [29]. Chaudhary [30] utilized FEM to study the behavior of piled raft foundation for a huge storage tank. As few researches on PRF of oil tanks on the liquefiable sand, Imamura et al. [31] and Takemura et al. [32] investigated about the dynamic response of oil tank supported by PRF using centrifuge modelling. From these researches, dynamic and permanent behavior of foundations were well observed. However, the observations were made in the shaking direction only, not in the different directions.

In this study, dynamic centrifuge model tests were performed to investigate the mechanical behavior of oil tank supported by piled raft foundation on liquefiable saturated sand and non-liquefiable dry sand. In the tests, two types of foundations were modelled for oil storage tanks, namely, slab foundation (SF) and piled raft foundation (PRF). From the observed behavior, such as excess pore water pressures and accelerations of the ground, and accelerations, rotation and settlement of the tank, typical dynamic behavior and permanent displacements of the tank with PRF were studied and compared with those of the slab foundation not only in the shaking direction but also in the transverse direction. From these investigations and comparisons, the advantages and limitations of piled raft foundation for the application to oil tanks on sandy soil are discussed.

2. Dynamic centrifuge tests

2.1. Equipment, model foundations and test cases

The centrifuge tests were conducted using Tokyo Tech Mark III centrifuge and a shaking table [33], under 50 g centrifugal acceleration. For modelling of the ground, a laminar box consisted of 15 laminas and rubber membrane bag with inner dimensions 600 mm in length, 250 mm in width and 438 mm in depth was used as shown in Fig. 1.

Because the main objective in the current research was to model ground without liquefaction and with complete liquefaction, a simple uniform sandy ground with a moderate relative density was modelled beneath the tank. To this end, five model tests were performed (Table 1). In Case 1 and Case 2, a slab foundation (SF) and a piled raft foundation (PRF) were placed on dry sand, respectively. The SF and PRF were also modelled in Cases 3a and 3b and Case 4 for saturated sand. Case 3b was conducted in almost same conditions as Case 3a. The sensors were placed in two different sections; one section at the center line of the model in the shaking direction; and the other, in the transverse direction. Model dimensions and instrumentation details are shown in Fig. 1(a), (b) and (c).

2.2. Tank, pile, raft and ground modelling

Characteristics of the tank, pile and raft model used for the tests are presented in both the model and prototype scales in Table 2 (for more details about scaling factors in geotechnical centrifuge modelling refer to Garnier et al. [34]). The tank model (Fig. 2(a)) is made of an acrylic cylinder with 140 mm outer diameter, 160 mm height and 3 mm thickness. These dimensions were selected to model a small size tank considering the capacity of the model box. It was glued to the slab/raft model made of an aluminum disk with 150 mm diameter and 10 mm thickness (Fig. 2(a) and (c)). The raft model has 12 conical shape concave holes which are put onto the pile heads (Fig. 2(d) and Fig. 3). Silica sand No.8 (Table 3), which was used for the model ground, was glued to the bottom surface of the model raft to create a rough surface condition. Water was used as a liquid in the tank with a height of 140 mm. The total weight of the water, tank and raft (2.9 kg), created 1.42 kN of weight and 81 kPa of the average raft base pressure under 50 g centrifugal acceleration.

The piled raft foundation has 12 identical piles, made of an aluminum tube with outer diameter of 6 mm, a thickness of 0.5 mm, and length of 100 mm as shown in Fig. 3. The rough piles shaft surface was also made by gluing silica sand No.8. These piles were arranged symmetrically as shown in Fig. 2(d). Utilizing this number and configuration of piles, the spacing/diameter ratio of piles (s/d) for most of the piles is 5.4. Friction angle of sand (φ') with relatively medium condition (Dr = 65%) is about 40° [35]. The calculated vertical bearing capacities of the raft, assuming the full mobilization and partial mobilization ($\tan \varphi^* = 2/3 \tan \varphi'$ [36], $\varphi^* = 30°$) of the friction angle of the sand, range from 29 to 147 MN and 18 to 92 MN for dry and saturated sand, respectively, in prototype scale. The vertical bearing capacity of one pile for these friction angles ranges from 0.32 to 1.7 MN and 0.19–1.1 MN for dry and saturated sand, respectively, in prototype scale. The total load of tank, including the tank and raft, is about 3.6 MN, which is much smaller than the bearing capacity of the raft alone, but almost larger than the total bearing capacities of the 12 piles. From these calculations, the expected function of piles as a settlement reducer which is the major objective of piles in PRF, can be confirmed. The pile heads were not rigidly fixed onto the raft, but simply capped by the concave hole, which allows free rotation like pinned connection (Fig. 3). In this way, the piles were subjected mostly to large axial and lateral forces and a small bending moment at the connection point to the raft. This condition is close to the actual situation of normal piled-foundation of oil tank [37]. In the model pile design, flexural rigidity and axial stiffness of concrete piles were targeted, but not failure of piles. As confirmed in Table 2, the axial load causing yield of the pile material is larger than the most of expected pile bearing capacity, shown above, and also much higher than the total load divided by pile number, i.e., 0.3 MN (= 3.6/12). The raft made by aluminum can be considered as a rigid plate which corresponds to a small diameter tank foundation. These conditions of structure components were made to focus on the effects of soil failure rather than the structural failures.

In order to measure the pile axial load and shaft friction, the piles used in Case 2 were instrumented by axial strain gages at the head and tip as shown in Fig. 3. However, in Case 4, to prevent the non-uniformity of the ground made by sand pouring due to the wires connected to the piles, non-instrumented piles were substituted while 5 external (non-built-in) earth pressure cells (E.P.s) were glued on the raft base to measure the raft contact pressure (Fig. 2(d)). The raft model with non-built-in E.P.s was also used in Case 3a. To improve the reliability of earth pressure measurement by eliminating the stress concentration on the attached E.P.s, a new raft model with 5 built-in E.P.s covered by