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SOME CONTRIBUTION TO RATIONAL DESIGN OF PILED RAFT FOUNDATION FOR OIL STORAGE TANKS ON NON-LIQUEFIABLE GROUND: APPLICATION OF DYNAMIC CENTRIFUGE MODELING

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Some level of settlement is allowed in the design of oil tanks if uneven settlement is controlled within allowable values. Considering the critical condition of Piled Raft Foundation (PRF), that is, secure contact of raft base to the ground surface, PRF is considered as one of the rational foundations for the oil tanks. However, PRF has a complicated 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 under the tank. Regarding this complexity, the main concern in use of PRF for oil tanks is proper design of this foundation system. In this study, a series of centrifuge tests were performed to investigate the mechanical behaviour of oil tanks supported by PRF on non-liquefiable and liquefiable sand. Using the observed results, such as accelerations of the tank and ground, displacements of the foundation and excess pore water pressures of the ground, some practical hints for reasonable design of piled raft foundation for oil tanks on non-liquefiable and liquefiable sand are discussed.

The traditional capacity-based design approach of piled rafts, similar to the design of group piles determines the dimensions (diameter and length) and number of piles to carry the vertical structural load by the piles with an appropriate safety factor against bearing capacity failure. In this way, the piles are uniformly located beneath the raft at an adequate spacing, and the main concern for design is the pile group design to sustain the structure's weight, neglecting the contribution of the raft. In other words, in this approach, neglecting the raft contribution, the minimum number of piles with adequate safety factor is determined and settlement is estimated to check the design sufficiency. Some previous studies indicated how over-conservative is this concept and showed that total and uneven settlement of foundation in most cases are unnecessarily very small.

In the innovative design approach, the raft bearing capacity is not neglected and the load sharing between the piles and the raft is a basic parameter that should be estimated properly. In this concept, the designer should determine the required piles needed to gain an acceptable performance of the foundation. In other words, if the bearing capacity of raft is adequate with a reasonable safety factor against the total load, but the total or uneven settlement of the raft is larger than allowable values, the optimum design solution should determine the minimum number, cross sectional area and length of piles to control the settlements within the allowable values. Although, thanks to innovative design procedure the construction cost will be decreased by reduction of required piles number and length, providing general criteria for the optimum design of PRFs is so complicated because the conditions that PRF is prioritized to the raft foundation are various. On the other hand, estimation of loads carried by the foundation elements (piles and raft), which depends on the sophisticated interaction between the soil and those components and also ground conditions, structure and loading types is a tough work.

Accordingly, determination of pile and raft design load is so complex due to the variability of raft load proportion (RLP) and pile load proportion (PLP) during the dynamic loads. Because of this complexity, to design piled raft foundation for oil storage tanks properly, critical conditions in the application of this foundation system for oil tanks should be determined and the adoption of appropriate countermeasures is a necessity.

In this study, using the results of a series of dynamic centrifuge model tests conducted to model piled raft foundation for oil tank, some practical hints for rational design of piled raft foundation system for oil storage tanks are discussed in cases that tank is located on non-liquefiable dry and liquefiable saturated sand.

Using Tokyo Tech Mark III centrifuge and a shaking table, centrifuge tests were conducted under 50g centrifugal acceleration. A laminar box and rubber membrane bag was used for making the model setups.

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, ten model tests were performed as shown in Table 1.

Table 1. Test cases.

Test Code	Foundation	Ground
Case 1a	Slab	Dry sand (Dr = 65%)
Case 1b	Slab	Dry sand (Dr = 66%)
Case 2a	Non-Driven Piled Raft (12 piles)	Dry sand (Dr = 65%)
Case 2b	Non-Driven Piled Raft (12 piles)	Dry sand (Dr = 68%)
Case 3a	Slab	Saturated sand (Dr = 65%)
Case 3b	Slab	Saturated sand (Dr = 68%)
Case 4a	Non-Driven Piled Raft (12 piles)	Saturated sand (Dr = 65%)
Case 4b	Non-Driven Piled Raft (12 piles)	Saturated sand (Dr = 69%)
Case 5	Driven Piled Raft (12 piles)	Saturated sand (Dr = 70%)
Case 6	Driven Piled Raft (24 piles)	Saturated sand (Dr = 65%)

From the dynamic centrifuge model tests, some practical points about application and rational design of PRF for oil tanks were concluded as below:

1. Due to the significant contribution of piles in carrying of loads and large piles load proportion (PLP) during the static and dynamic loading in case of PRF of oil tank on non-liquefiable sand, the main concerns in the rational design of the foundation are piles design and their punching effect on the raft.
2. In the PRF of oil tank on liquefiable (saturated) sand, the raft load proportion (RLP) increased by the reduction of pile loads due to the liquefaction, but by the recovery of effective stresses of the soil due to the dissipation of EPWP the raft load decreased, and the pile load was regained gradually. Therefore, during liquefaction period, the bearing capacity of the piles was seriously affected, i.e. reduced partially or even completely diminished by the increase of EPWP. Accordingly, the bearing capacity of piles cannot be taken into account for the design of foundation system, and the slab alone should satisfy the bearing capacity criteria.
3. Unlike the dry cases, the piles design load and their punching effect on the raft, are not the main concern in the rational design of piled raft foundation for oil tank on liquefiable sand. On the other hand, the main critical issue is the diminishing piles bearing capacity during the liquefaction that strongly affects the performance of piled raft foundation. This may cause some instability in the superstructure and significant settlement and uneven settlement may happen.
4. The PRF of oil tank on liquefiable sand in comparison to slab foundation could not have a better performance for reducing the tank settlement and uneven settlement except in the early stage before start of liquefaction. In this period (EPWP build-up stage) the settlement and uneven settlement of PRFs were smaller than or equal to those of slab foundation.
5. If the ground condition and design seismic motion of a given site result in a site liquefaction potential value (PL) less than 10, a better performance for piled raft foundation of oil tank on liquefiable sand can be expected.