

# An investigation on reasonable design of piled raft foundation for oil storage tanks using centrifuge modeling



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## ABSTRACT

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 behavior 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 PRF for oil tanks on non-liquefiable and liquefiable sand are discussed.

## RÉSUMÉ

Un certain niveau de tassement est autorisé dans la conception des réservoirs d'huile si le tassement irrégulier est contrôlé dans les limites des valeurs admissibles. Compte tenu de l'état critique de Piled Raft Foundation (PRF), c'est-à-dire un contact sûr de la base du radeau avec la surface du sol, le PRF est considéré comme l'une des fondations rationnelles des réservoirs d'huile. Cependant, le PRF a une interaction compliquée avec le sol sous chargement sismique horizontal, en particulier si le réservoir repose sur un sol liquéfiable qui peut provoquer un changement extrême de la rigidité du sol sous le réservoir. Compte tenu de cette complexité, la principale préoccupation dans l'utilisation du PRF pour les réservoirs d'huile est la conception appropriée de ce système de fondation. Dans cette étude, une série d'essais en centrifugeuse a été réalisée pour étudier le comportement mécanique des réservoirs d'huile soutenus par PRF sur du sable non liquéfiable et liquéfiable. En utilisant les résultats observés, tels que les accélérations du réservoir et du sol, les déplacements de la fondation et les pressions interstitielles excessives du sol, quelques conseils pratiques pour une conception raisonnable du PRF pour les réservoirs de pétrole sur du sable non liquéfiable et liquéfiable sont discutés.

## 1 INTRODUCTION

Piled raft foundations have received considerable attention in the recent years since the concept of piles as settlement reducers was introduced by Burland et al. (1977). This foundation system can decrease the construction expenses by reduction of the required number of piles. The raft in this foundation system has adequate bearing capacity and, therefore, the main objective of introducing these pile elements is to control or minimize the settlement, especially differential settlement, rather than to carry the major portion of the loads. Therefore, a major design question is how to design the piles optimally to control the settlement (Poulos, 2001). In spite of enormous studies on PRF for buildings, as the response of the piled raft during earthquake is a complex soil-structure interaction problem between "raft-ground-piles", optimal and rational design methods of PRF cannot be extended to the civil engineering infrastructures. In particular, if the piled raft resting on a liquefiable ground, the soil-foundation interaction becomes more complex. Because of this complexity and possible large settlement, the introduction of PRF is further hindered.

Another concern in the seismic design of PRF is to secure the contact of raft to the subsoil; otherwise the contribution of raft cannot be obtained against horizontal load. To achieve the secure contact, the foundation settlement should be greater than the ground settlement. In the design of oil tank foundation, the main concern regarding settlement is uneven settlement, rather than maximum settlement. For example, an allowable uneven settlement is 1/300 of tank diameter (FDMA, 1974), which implies that some level of tank foundation settlement is permitted if the uneven settlement is controlled below the allowable value. Therefore, this foundation system is considered as one of the rational foundations for oil storage tanks.

To study the mechanical behavior of the PRF, centrifuge model tests have been conducted by some researchers (Horikoshi et al. 2003). However, dynamic behavior of the PRF on liquefiable sand has not been well studied. Some studies have been done on oil tank foundations (Sento et al. 2004). But, a few researchers have considered PRF for the storage tanks. Sahraeian et al. (2019), (2018), (2015) and Sahraeian (2017) reported a dynamic centrifuge model study on the PRF of oil tanks and

the behavior of tank was observed in the shaking and transverse directions. Furthermore, they investigated the effect of pile installation method on the seismic behavior of tank (Sahraeian et al. 2017). Despite these previous studies, design procedure of PRF for oil storage tanks is still unclear.

In this study, a series of dynamic centrifuge model tests was performed to investigate the mechanical behavior of oil tank supported by PRFs on non-liquefiable dry sand and liquefiable saturated sand. From the observed test results, such as excess pore water pressures and accelerations of the ground and accelerations, rotation and settlement of the tank, special considerations for the rational design of PRF for oil tanks are described. Also some practical points for the application of PRF for oil storage tanks on non-liquefiable and liquefiable sand are presented.

## 2 ADVERSITIES IN THE DESIGN OF PILED RAFT FOUNDATION FOR OIL STORAGE TANKS

The most critical and difficult issue in the design of PRF of oil tanks is the estimation of pile and raft load proportion especially in the case of dynamic loading. The raft load proportion (RLP) and piles load proportion (PLP) are defined by Eq. (1) and these values range from 0 to 100 percent.

$$RLP = \int q_{raft}/Q_v \quad , \quad PLP = \sum q_{pile}/Q_v \quad [1]$$

where  $Q_v$  is total vertical load exerted from the tank and raft,  $q_{raft}$  the raft base contact stresses and  $q_{pile}$  the pile head axial load. In the static loading condition, both  $q_{raft}$  and  $q_{pile}$  are rather evenly distributed in axial symmetrical manner as shown in Fig.1(a). However, under the seismic loading condition the dynamic horizontal load ( $Q_d$ ) causes addition or reduction at the raft base and the piles load (Fig. 1(b)) depending on the location of pile and the raft element (Eq. (2)).

$$\begin{aligned} q_{Raft} (dynamic) &= q_{Raft} (static) + \Delta q_{Raft} \\ q_{pile} (dynamic) &= q_{pile} (static) + \Delta q_{pile} \end{aligned} \quad [2]$$

Table 1. Test cases: Conditions of foundation and ground.

Test code	Foundation	Ground	Details
Case 1a	Slab	Dry sand ( $H_s=265\text{mm}$ , $Dr=65\%$ )	Slab w/o E.P.s
Case 1b	Slab	Dry sand ( $H_s=220\text{mm}$ , $Dr=66\%$ )	Slab w/o E.P.s
Case 2a	Non-Driven PRF (12 piles)	Dry sand ( $H_s=265\text{mm}$ , $Dr=65\%$ )	Inst. piles & raft w/o E.P.s
Case 2b	Non-Driven PRF (12 piles)	Dry sand ( $H_s=220\text{mm}$ , $Dr=68\%$ )	Inst. piles & raft w/o E.P.s
Case 3a	Slab	Saturated sand ( $H_s=220\text{mm}$ , $Dr=65\%$ )	Slab with 5 non-built-in E.P.s
Case 3b	Slab	Saturated sand ( $H_s=220\text{mm}$ , $Dr=68\%$ )	Slab with 5 built-in E.P.s
Case 4a	Non-Driven PRF (12 piles)	Saturated sand ( $H_s=220\text{mm}$ , $Dr=65\%$ )	Inst. piles & raft w/o E.P.s
Case 4b	Non-Driven PRF (12 piles)	Saturated sand ( $H_s=220\text{mm}$ , $Dr=69\%$ )	Non-inst. piles & raft with 5 non-built-in E.P.s
Case 5	Driven PRF (12 piles)	Saturated sand ( $H_s=220\text{mm}$ , $Dr=70\%$ )	Non-inst. piles & raft with 5 built-in E.P.s
Case 6	Driven PRF (24 piles)	Saturated sand ( $H_s=220\text{mm}$ , $Dr=65\%$ )	Non-inst. piles & raft with 5 built-in E.P.s

Accordingly, determination of pile and raft design load is so complex due to the variability of RLP and PLP during the dynamic loads. For the rational design of PRF for oil storage tanks, critical conditions of these proportion should be identified and considered, and appropriate countermeasures should be applied if necessary.

On the other hand, type of piles (end bearing or friction pile) is another critical point in the concept of PRF. Because of a large tip resistance develops in the end bearing piles especially in the sand layers, the raft settlement may not be more or equal to the soil settlement and the secure contact of raft and subsoil could not be guaranteed. Therefore, the concept of frictional pile with less pile tip resistance is recommended to secure the raft load proportion in the piled raft system.

## 3 DYNAMIC CENTRIFUGE TESTS

### 3.1 Equipment, Model Foundations and Test Cases

Centrifuge tests were conducted using Tokyo Tech Mark III centrifuge and a medium size shaking table in 50g centrifugal acceleration. For modelling of the ground a laminar box with inner dimensions 600mm in length, 250mm in width and 438 mm in depth was used as in Fig. 2(c).

Because the main objective in this study 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. Figs. 2(a) and (b) show the typical model setup, with instrumentation. In Cases 1a and 1b, a slab foundation (SF) was placed on dry sand and a non-driven piled raft foundation (ND-PRF) including 12 piles was modeled on dry sand in Cases 2a and 2b. The SF and PRF were also modelled for saturated sand. In Case 3a, a slab foundation (SF) was placed on the saturated sand. Case 3b was conducted in almost same conditions as Case 3a. The non-driven PRF was modeled in Cases 4a and 4b for saturated sand. To compare the behavior of oil tanks supported by PRFs with non-driven and driven piles, a driven piled raft foundation (D-PRF) with 12 piles was modeled on saturated sand in Case 5. The driven PRF with larger piles number (24piles) was modeled

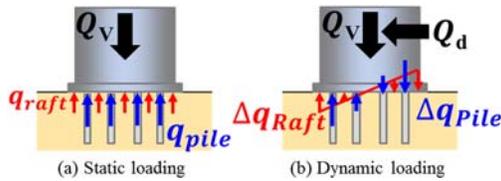


Figure 1. Piles and raft contribution during static and dynamic loading (Sahraeian et al. 2020).

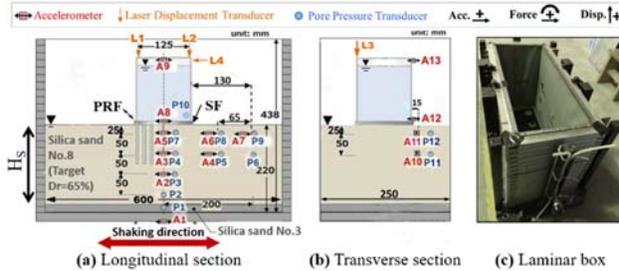


Figure 2. Model setup, instrumentation and laminar box used for the tests.

in Case 6. During the ground preparation, the sensors were placed in two different cross sections, the first section at the center line of the model in the shaking direction and the second section in the transverse direction (Figs. 2(a) & 2(b)).

### 3.2 Tank, Pile, Raft and Ground Modeling

The tank model is made of an acrylic cylinder with 140mm outer diameter, 160mm height and 3mm 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 models made of an aluminum disk with a diameter of 150mm and thickness of 10mm. The raft model has 12 (Cases 2a, 2b, 4a, 4b & 5) and 24 (Case 6) conical shape concave holes which are put on the pile heads. Silica sand No.8 was glued on the bottom surface of the raft model to create a rough surface condition. Water was used as a liquid inside the tank with a height of 140mm.

The piled raft foundation had 12 or 24 identical piles, made of an aluminum tube with outer diameter of 6mm, a thickness of 0.5mm, and length of 100mm as shown in. The pile heads were not rigidly fixed to the raft, but simply capped by the concave hole, which allows partially free rotation like pinned connection.

In Cases 2a, 2b and 4a the pile axial load and shaft friction were measured by axial strain gages at the head and tip. While in Cases 4b, 5 and 6, non-instrumented piles were substituted and the contact pressures at the raft base were measured by five earth pressure (EP) cells. With non-instrumented piles, external (non-built-in) cells were glued on the raft base in Case 4b, while in Case 5 and Case 6 new raft models with 5 built-in earth-pressure cells covered by thin silicon rubber were employed to improve the reliability of earth pressure measurements by eliminating the stress concentration on the attached EP cells (Sahraeian et al. 2018).

### 3.3 Model Preparations and Test Procedures

Fine silica sand (No. 8) was used for the loose sand layer by air pluviation method and coarse silica sand (No. 3) for the bottom drainage layer. In the model, de-aired water was used as pore fluid of the sand. The sand layer with a relative density of 65% was aimed as target density, but in some cases, the final relative density had a few deviations from the aimed value as shown in Table 1.

In case of non-driven PRF (Cases 2a, 2b, 4a and 4b), the piles were fixed at the center of the modeling box by an aluminum guide during pouring the sand. Then, using the air pluviation method, sand was poured until reaching the required level. During the sand preparation, the accelerometers and pore water pressure transducers (PPTs) were placed at the prescribed locations as shown in Fig. 2. Having made the model ground, in saturated cases, the saturation process was applied (Sahraeian et al. 2018).

In slab cases (1a, 1b, 3a and 3b) and non-driven PRF cases (2a, 2b, 4a and 4b) after completion of the model ground preparation, the model tank was placed on the ground. There was inevitable unevenness at the ground surface especially for the case with piles, which created non-uniform contact condition of raft base to the ground surface, such as local gaps. To reduce the effects of the local bedding error and secure the contact, small vertical displacement (preloading) was imposed by an electrical jack in 1g condition.

In order to model in-flight installation of the driven piles in Case 5 and Case 6, a 20mm thick acrylic guide plate with 6.5mm holes at the pile locations was used to hold the piles and tank during the pile installation at the center of the saturated model ground. For more details about the modeling, installation process and the reliability of preloading in all cases refer to Sahraeian et al. (2017 and 2018).

After the preloading process, the whole model was mounted on the shaking table on the swing platform of the centrifuge. The displacement sensors (LDTs) were set on the model and filling the tank with water, the centrifugal acceleration was increased up to 50g. The shaking tests were conducted after confirming the steadiness of all sensors output. The target input wave of the main shock used in the tests is the EW component of the acceleration recorded at Kurikoma, Kurihara city during the 2008 Iwate-Miyagi Nairiku earthquake (JMA, 2008), which is characterized as a vibration with a moderate duration. Two shakings were input to the model. Confirming all measured values became constant after the first shake, the second shake with about fifteen percent higher amplitude was applied to the model. In Cases 1a, 2a and 4a, only the first shake was applied on the model. The comparison of target acceleration and its Fourier spectrum with those of input motions in the tests are presented in the prototype scale in Fig. 3. There were some differences in the magnitude of input acceleration, which can be clearly seen in the variation of Arias intensity ( $I_a$ ) of the input accelerations in Fig. 4. Considering that  $I_a$  tends to exaggerate the difference in the acceleration by squaring the acceleration, the input motions of all cases in Shake 1 except Cases 1a, 2a, 3a and 4a which had larger input motion, are nearly

similar. In shake 2, a larger  $I_a$  level was obtained in Cases 3a and 3b than the other cases, which had almost the similar input motion levels.

In the shaking tests, the ground and tank accelerations, the displacements of the tank, the piles and raft loads and the excess pore water pressures in the ground were measured as shown in Fig. 2. From those test results, special considerations for the rational design of PRF for oil tanks are described. Also some practical points for the application of PRF for oil storage tanks on non-liquefiable and liquefiable sand are presented.

#### 4 KEY ISSUES IN THE DESIGN OF PILED RAFT FOUNDATION OF OIL TANKS

Some critical issues which should be considered in the design of PRF for oil tanks are shown in Fig. 5. As the figure indicates, these issues are categorized into two groups. The first group is general behavior of foundation system which includes bearing capacity, settlement and uneven settlement of the foundation, the load sharing between the foundation elements (i.e. piles and raft) and tank response to dynamic loading e.g. tank rocking motion and accelerations. The second one is the internal stability of structural component of the foundation e. g. punching of the raft by piles and structural strength of the piles and raft. All of these issues should be examined in a rational design of PRF for oil tanks resting on non-liquefiable and liquefiable sand with appropriate criteria.

##### 4.1 Structural Components of the Foundation (Piles and Raft)

Pile load proportion (PLP) and raft load proportion (RLP) in PRF cases for dry (Cases 2a & 2b) and saturated cases (Cases 4a, 4b, 5 & 6) during Shake 1 are drawn in Figs. 6(a) and (b) respectively. PLP is the ratio of loads carried by the piles to the tank total load while RLP is the ratio of loads carried by the raft to the tank total load. The PLP in dry cases is calculated employing head resistance

of piles measured by strain gages attached at the piles head. In these cases, the RLP is determined by subtracting the PLP from the tank total load. On the other hand, PLP is calculated by subtracting the average raft load estimated by the recorded earth pressures from tank total load in Cases 4b, 5 and 6. In Case 4a this value is calculated directly by recorded piles load. In Case 4b the calculated PLP is negative in some duration of shaking. The reason is overestimation of average raft load estimated by non-built-in earth pressure cells which caused some stress concentration on the sensors (Sahraeian et al. 2017).

In dry cases due to the interference of the moment strain to the axial strain measurement near the pile top, the measured total pile load was overestimated. Namely, the calculated PLP was more than 100% in static condition and during the shaking, though the shaking motion was applied in the horizontal direction, not vertical direction. As can be confirmed in Fig. 6, for PRFs on non-liquefiable sand with sufficient resistance of soil, the main part of loads is transferred to the piles. The PLP is large from the beginning of shaking and increased slightly after the shaking. Fig. 7(b) shows the measured maximum pile head load during the shaking. Due to the less pile number in the piled raft systems than common pile foundations, the larger static and dynamic load could develop in the pile group especially near the perimeter of the raft in the shaking direction as seen in Fig.7(a). Because of the considerable load share during the dynamic loading in the PRF on dry sand, another concern in the rational design of PRF for oil tank is punching of the raft by the piles. The raft punching may develop rupture in the tank shell and cause the leakage of the hazardous liquid inside the tank. In such a complicated situation, in order to have enough structural strength and factor of safety against failure, the design of piles and raft is a critical issue. Therefore, precise pile and raft design procedure which includes rational design loads and factor of safety is inevitable in case that oil tank with PRF is located on dry sand. As critical loads in the piles design, it may be suggested to estimate piles design load

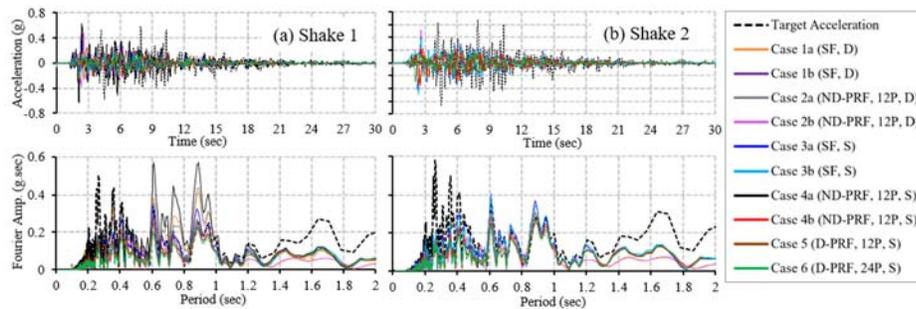


Figure 3. Input accelerations and their Fourier spectra.

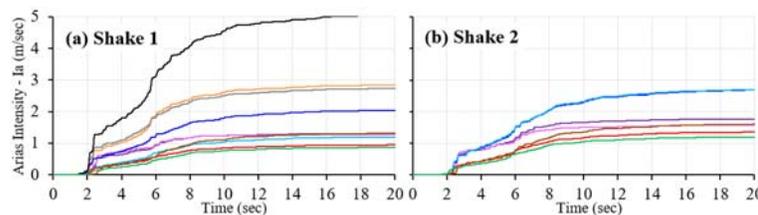


Figure 4. Arias intensity of input motions.

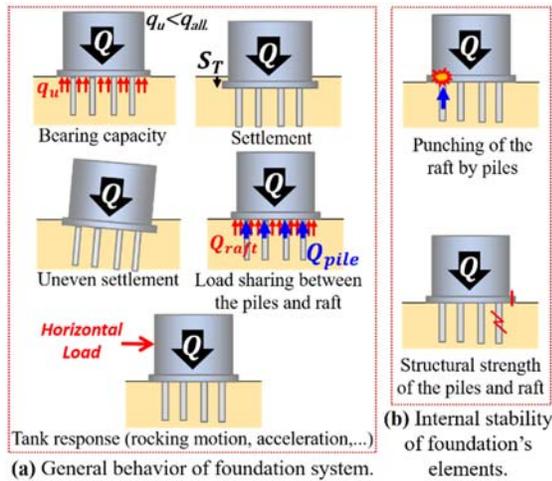


Figure 5. Key issues in the design of PRF for oil tanks.

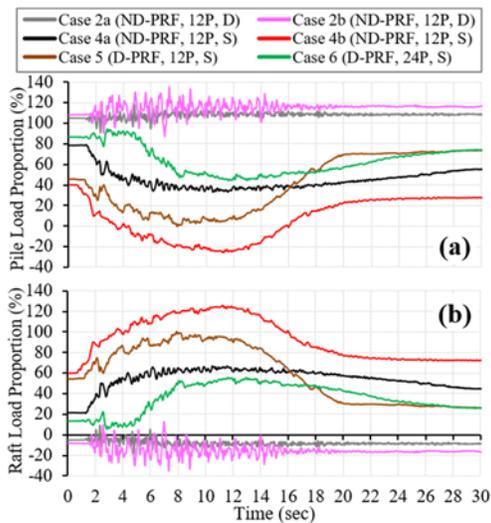


Figure 6. Variation of (a) PLP & (b) RLP in Shake 1.

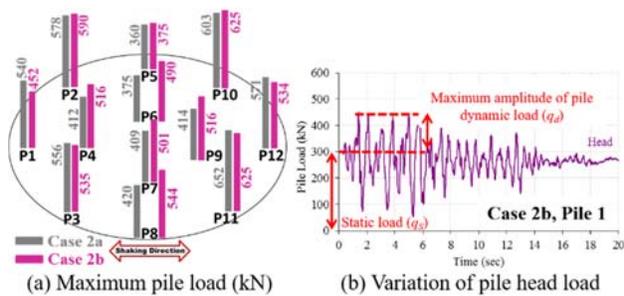


Figure 7. Piles head load during shaking in dry sand (Cases 2a & 2b).

by the assumption of RLP equal to zero, but the ultimate pile bearing capacity as the maximum applied pile head load with a proper load factor.

The load-displacement relationships in the 2<sup>nd</sup> installation stage and preloading process in Cases 5 and 6 are presented in terms of total and per-pile load in Figs. 8(a) and (b) respectively. Though some differences are

seen in the load settlement curves of the two cases, the critical pile resistances, over which the pile settles without the significant increase of pile load, can be estimated, around 350 kN and 500 kN for before and after preloading, which are considered as the ultimate pile bearing capacity in non-displacement and displacement piles. From the saturated condition in the ground of Cases 5 and 6, these ultimate values in the dry sand could increase to up 560 kN and 800 kN. Considering the condition of dynamic loading and overestimation of the pile head load due to the bending moment interference, the observed maximum pile head resistances in Cases 2a and 2b of about 620-650kN (Fig. 7(a)) are considered very close to the ultimate load.

The average raft pressures (ARP) in Shake 1 and Shake 2 for four PRF models on saturated sand are shown together with EPWP at the PPT just beneath the tank (P7 or P8 (Case 4a)) and the vertical load intensity ( $q_v$ ) in Fig. 9. In Case 4a, the data is not recorded for Shake 2. The average raft pressure (ARP) is the average of the pressures recorded by five EP cells in Cases 4b, 5 and 6, while in Case 4a, it is calculated from the measured pile head loads. In the figure,  $t_1$ , the end of rapid increase of EPWP (build-up period),  $t_2$ , the end of liquefaction period or start of EPWP dissipation and  $t_3$ , the end of dissipation of EPWP (dissipation period) are also indicated (Sahraeian et al. 2018).

By comparing Fig. 6 and Fig.9, a clear trend can be confirmed, that is, the raft load proportion increased by the reduction of pile loads due to the liquefaction, but with the recovery of effective stresses of the soil due to the dissipation of EPWPs, the pile load was regained and the raft load decreased gradually. Figs. 6 and 9 indicate that due to the increase of excess pore water pressure, the bearing capacity of piles is reduced partially or even completely diminished (Cases 4b and 5) during the liquefaction period. Accordingly, in case of PRF of oil tank on saturated sand, the bearing capacity of piles cannot be taken into account for design of foundation system and the slab alone should satisfy the bearing capacity criteria.

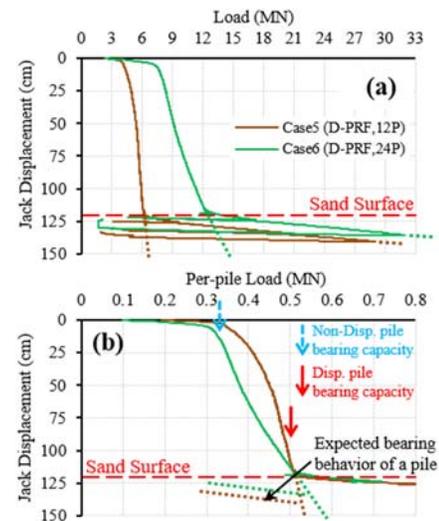


Figure 8. Jack loading in Cases 5 & 6 during 2<sup>nd</sup> stage of piles installation and preloading; (a) Total load, (b) Per-pile load before contact.

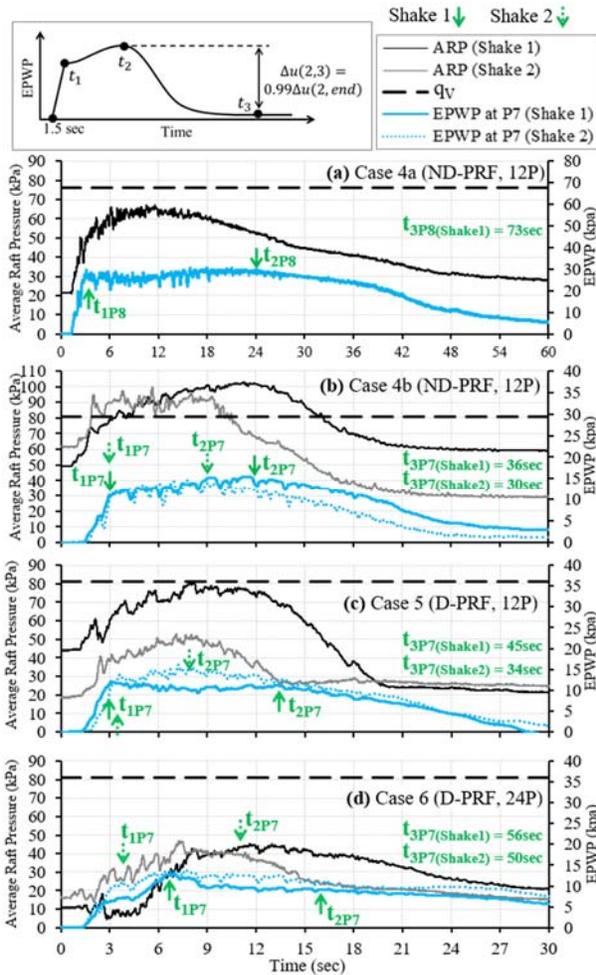


Figure 9. Variation of average raft pressure and excess pore water pressure beneath the tank during the shakings.

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 PRF 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 PRF. This may cause some instability in the superstructure and significant settlement and uneven settlement may happen as discussed in the following section.

In this study, the piles of PRF was modeled as frictional piles (floating piles) to avoid developing a gap between the raft and subsoil due to the unequal settlement of the foundation and subsoil. But, another critical condition may happen when the tank is located on a ground with liquefiable sand overlaying a stiff layer. If the piles of PRF reach to the stiff layer, a group of end-bearing piles develop beneath the foundation. Then, in case of occurrence of liquefaction in the upper liquefiable layer, due to reduction of raft load proportion (RLP) by loosening of the layer, significant load concentration might develop at the piles tip and cause local pile failure. This situation could be observed in Shake 1 of Case 6 with large number of piles and large effects of pile penetration (Fig. 9(d)). RLP in Shake 1 of Case 6 did not increase, even slightly

decreased in the early stage of loading, though EPWP increased, which implying the chance of pile load for the partial liquefaction conditions, especially the pile embedded in less liquefiable layer at the deeper depth.

#### 4.2 Settlement and Uneven Settlement of Tank

The tank center settlement which is the average of L1 and L2 in two edges of the tank in the shaking direction, are compared for the dry and saturated cases in Fig. 10(a) and (b) respectively. In Case 2b, the settlement at L1 is plotted in Fig. 10(a) because the settlement could not be measured by L2 due to the dislocation of the laser from the target plate. Considering the fact that Cases 1a and 2a were conducted by different conditions (sand thickness and input motion) from Cases 1b and 2b as indicated in Table 1 and Figs. 3 and 4, it can be confirmed from Fig. 10(a) that in the case of dry sand, the settlements of PRF (Case 2a & 2b) are much smaller than those of SF (1a & 1b), which is a good evidence of settlement reducer function of the piles.

In the stability assessment of tank foundation, the uneven settlement is a critical concern. For the relatively small diameter tank supported by a rigid slab or raft, the uneven settlement is equivalent to the rotation of the foundation. The tank maximum rotation for dry and saturated cases is shown in Figs. 11(a) and (b) respectively. The maximum rotation of tank is calculated using equation of flat plane in geometry and the recorded data of three LDTs at top of the tank (L1, L2 and L3) (Sahraeian et al. 2018). The maximum rotation of tank in the direction from tank center to point D was calculated. In Cases 1a, 1b, 2a and 2b, as L3 was not recorded (Fig. 2(b)) the rotation shown in the figure is in the shaking (L1-L2) direction. From Fig. 11(a) it can be also confirmed that the PRF on dry sand could effectively reduce the tank rotation, indicating rotation reducer function of the piles.

The tank center settlement and maximum rotation for the foundations on saturated sand are shown in Figs. 10(b) and 11(b) respectively. In Case 4a as L3 is not recorded, the rotation in the shaking direction is shown in Fig. 11(b). The time variations of settlement and rotation are shown along with the marks at the time of EPWP buildup ( $t_1$ ) and liquefaction stage ( $t_2$ ) obtained from the location of P8 or P9 (Case 4a & Case 6 (P8 was not recorded)) at the shallow depth beside the tank. These times are considered as indicators of the period of partial liquefaction and complete liquefaction. Although the relationships are very different for the various cases, as an overall trend of the relations, it can be inferred that the settlement and uneven settlement of PRF of tank resting on the liquefiable sand is considerable. Also, no clear positive effect of large pile numbers can be confirmed in Case 6, which showed relatively large settlement and rotation. As discussed on Fig. 9(d), due to installation of large number of driven piles in Case 6, at the beginning of first shake most of the load was carried by the piles and the secure contact between the raft and the subsoil could not be developed. However, as the piles bearing capacity was diminished by the liquefaction and the raft load increased, the large settlement and uneven settlement happened due the poor initial contact. Therefore, enough and uniform contact condition between the raft and subsoil should be secured

during the construction. On the other hand, regarding these graphs the majority of the settlement and rotation took place in the liquefaction stage ( $t_1$ - $t_2$ ). Furthermore, the PRFs (Cases 4a, 4b, 5 and 6) in comparison to slab cases (Cases 3a and 3b) could not have a better performance for reducing the tank settlement and uneven settlement except in the early stage until  $t_1$ . In this period (EPWP build-up stage) the settlements and rotations of PRFs except for Case 4a, were smaller than or equal to those of slab foundations (Cases 3a and 3b). The larger rotation of Case 6 during the build-up stage could be attributed to the poor raft contact condition as discussed above. For Case 4a, the extremely larger input motion exerted (Fig. 4) might cause the larger rotation during the build-up period in comparison to SF cases. Regarding the results of this study, a key sketch about the main design concerns in the design of PRF for oil storage tanks on non-liquefiable and liquefiable ground is presented in Fig. 12.

Considering the complex performance of PRF of oil tanks on liquefiable sand, some criteria below which the PRF of oil tanks on liquefiable sand could keep a preferable behavior is discussed in the following. As the integrity of the foundation pertains on the liquefaction intensity, the

ground liquefaction level should be assessed. To this end, the authors employed PL value introduced by Iwasaki (1986), specified by Eq. (3) to approximate the liquefaction intensity at a given site for a seismic motion.

$$P_L = \int_0^{20} F \cdot W(z) dz \quad [3]$$

where  $F=1-FL$  for  $FL \leq 1$ ,  $F=0$  for  $FL > 1$  and  $w(z)=10-0.5z$  ( $z$ : depth in m).  $FL$  is liquefaction resistance factor, an ability to resist the liquefaction of a soil element at an arbitrary depth. When  $FL$  at a certain soil is less than 1, the soil will be liquefied during earthquakes. The  $w(z)$  function is a weight function of the depth and gives a bigger weight to the shallow portion. Iwasaki calculated  $PL$  value for many liquefied and non-liquefied sites observed in previous earthquakes and proposed a simple method for determining soil liquefaction potential in terms of  $PL$ . Regarding his recommended criteria if  $PL = 0$ : liquefaction risk is very low, if  $0 < PL \leq 5$ : liquefaction risk is low, if  $5 < PL \leq 15$  Liquefaction risk is high and if  $PL > 15$ : Liquefaction risk is very high.

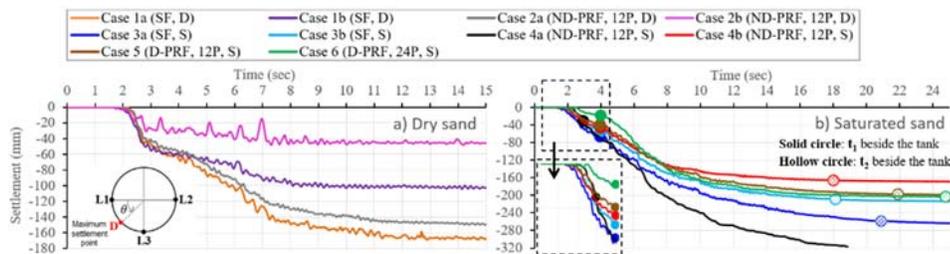


Figure 10. Tank settlement in Shake 1; (a) dry sand, (b) saturated sand.

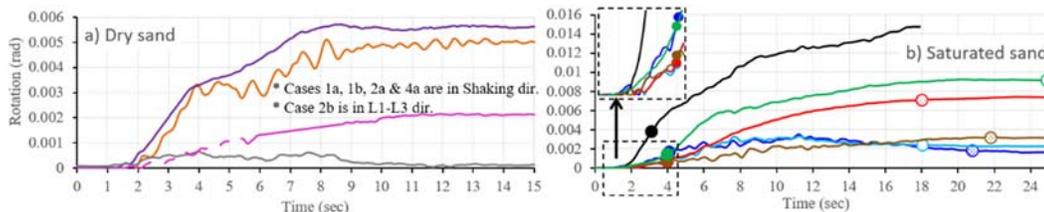


Figure 11. Tank rotation in Shake 1; (a) dry sand, (b) saturated sand.

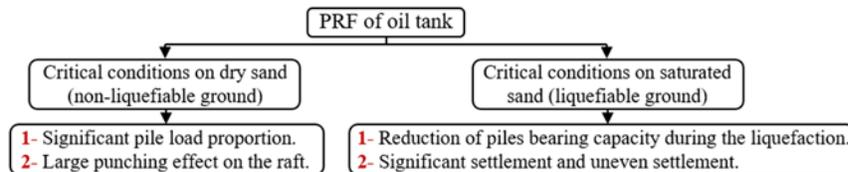


Figure 12. Main design concerns in the design of PRF for oil tanks.

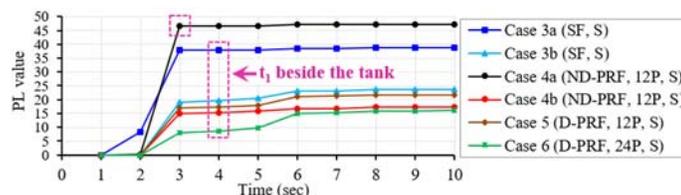


Figure 13.  $P_L$  value during Shake 1.

The PL value for the cases of tank on liquefiable sand during Shake 1 is shown in Fig. 13. In this calculation, FL value is estimated using the simplified method explained by Annaki et al. (1977) and Yoshimi (1980). Based on the previous discussion (Figs. 10 and 11), PRF of oil tank could control the settlement and uneven settlement of tank in comparison to slab foundation (Cases 3a and 3b) at the beginning of shake before  $t_1$  (start of liquefaction stage). While  $t_1$  is 4sec for all cases except Case 4a with  $t_1 = 3$ sec, the PL value for the corresponding time is 9 for Case 6, 15 for Case 4, 17 for Case 5 and 47 for Case 4a (Fig. 13). Considering these results, it seems that if the ground condition and design seismic motion of a given site confine the PL value to 10, a better performance for PRF of tank on liquefiable sand might be expected.

## 5 CONCLUSION

From the dynamic centrifuge model tests on slab and piled raft foundation of oil storage tank resting on non-liquefiable dry sand and liquefiable saturated sand, some practical points about the application and rational design of PRF for oil tanks were concluded as below:

1. In cases that oil tank resting on dry sand because the PLP is significant, the main concern for reasonable design of PRF is piles design load and their punching effect on the raft. To reduce the risk of piles failure and raft punching failure, it may be suggested to estimate piles design load with the assumption of RLP equal zero.
2. In case of PRF of storage tanks on liquefiable sand, during liquefaction the bearing capacity of the piles is seriously affected by the increase of excess pore water pressure. Therefore, the bearing capacity of piles is reduced partially or even completely diminished during the liquefaction period. Hence, in these cases, the slab should satisfy the bearing capacity criteria while the bearing capacity of piles cannot be taken into account.
3. Although, the settlement and uneven settlement reducer function of PRF on dry sand can be certified, the settlement and uneven settlement are real concerns where oil tank PRF is located on liquefiable ground. The main reason for this trend is the diminishing piles bearing capacity during the liquefaction stage that may initiate significant settlement and rotation in the superstructure.
4. PL value can be employed to introduce the status in which PRF of oil tank on liquefiable ground has a better performance. Considering this concept, the application of PRF system for oil tanks on liquefiable sand might be more efficient if seismic motion level and ground condition of a site generate a site liquefaction potential value (PL) less than 10.

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