

A Study on Seismic Behavior of Piled Raft Foundation for Oil Storage Tanks using Centrifuge Model Tests

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ABSTRACT

Because of the performance of oil storage tanks during the huge previous earthquakes these infrastructures should be more considered especially against soil liquefaction. Piled Raft Foundation (PRF) seems to be a rational foundation system for these structures while some level of settlement is permitted for oil tanks. However, PRF has a complex interaction with soil if the tank rests on the liquefiable soil because of extreme change of the soil stiffness under the tank. In this paper some centrifuge tests were performed to investigate the mechanical behavior of oil tank supported by piled raft foundation on liquefiable sand. In this research two types of foundations were considered, one is slab foundation and another one is piled raft foundation. In the case of piled raft foundation two different methods of pile installation (Driven and non-Driven piles) were modelled and the result was compared. All the modelled piles are friction piles which are floating in the uniform sand. Using the observed results, such as excess pore water pressures of the ground, rotation and settlement of the tank, accelerations of the tank and the raft base pressures, dynamic and permanent displacement of the piled raft foundation are investigated and applicability of piled raft foundation for oil tanks on liquefiable ground is discussed.

Introduction

Majority of existing oil storage tanks in Japan were constructed before early 1970's when the soil liquefaction was first considered in the design of tank foundation. Since the 1995 Hyogoken-Nambu Earthquake, originally the 1964 Niigata earthquake and the 1978 Miyagiken-oki earthquake (Ishihara et al., 1980), 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 have received considerable attention in the recent years. 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 (Kakurai et al., 1987; Randolph, 1994; Horikoshi and Randolph, 1998; Horikoshi et al., 2003 and Poulos, 1994, 2001 and 2011). But, 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 piled raft foundation cannot be extended to the civil engineering structures. 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

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introduction of piled raft foundation is further hindered.

Another concern in the seismic design of piled raft foundation 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. While oil tanks can allow some level of settlement, as long as the differential settlement is below an allowable value, e.g., 1/500 for tilt of the tank and 1/300 for tank floor settlement along a radial line from the periphery to the tank center (BS 7777, 1993), and some seismic design guidelines of the tank foundation allow relatively large total settlement, for example more than 3 inches (Bachman et al., 2007), therefore the piled raft foundation is considered one of rational foundation systems for the oil tanks. To study the mechanical behavior of the piled raft foundation, centrifuge model tests have been conducted by some researchers both on static and dynamic conditions (e.g., Horikoshi et al., 2003a, 2003b). However, dynamic behavior of the piled raft foundation on liquefiable sand has not been well studied. Also the difference between the behavior of piled raft foundation with driven piles and non-driven piles during dynamic loading has not been investigated in spite of existence of some criteria in different guidelines for these pile installation methods.

In this study, a special setting was used to model a driven piled raft foundation for oil tanks in 50 g condition and dynamic centrifuge model tests were performed to investigate the mechanical behavior of oil tank supported by driven and non-driven piled raft foundations and also a slab foundation on liquefiable saturated sand. From the observed test results, such as excess pore water pressures of the ground, accelerations, rotation and settlement of the tank, typical dynamic and permanent displacements of tank are studied.

Dynamic Centrifuge Tests

Equipment, Model Foundations and Test Cases

Centrifuge tests were conducted using Tokyo Tech Mark III centrifuge and a newly developed medium size shaking table, under 50g centrifugal acceleration. For modelling of the ground a laminar box consisted of 15 laminas and rubber membrane bag with inner dimensions 600mm in length, 250mm in width and 438 mm in depth was used as in Figure 1(c).

As shown in Table 1, three model tests were performed. In Case 1 a slab foundation (SF) while in Case 2 and Case 3 piled raft foundation (PRF) was placed on the saturated sand. In Case 2 non-driven and in Case 3 driven pile installation process was modelled. The sensors were placed in two different sections, first section at the center line of the model in the shaking direction and the second in the transverse direction. Model dimension and instrumentation details are shown in Figures 1(a), (b).

Tank, Pile, Raft and Ground Modelling

Characteristics of the tank, pile and raft for both the model and prototype scales are presented in Table 3.

The tank model used in the tests (Figure 2(a)) was made by an acrylic cylinder with 140mm outer diameter, 160mm height and 3mm thickness. It was glued with the slab/raft model made of aluminum disk with diameter of 150mm and thickness of 10mm (Figure 2(b, c)).

The raft model has 12 conical shape concave holes which are put on the pile heads (Figure 2(d)). Bottom surface of the raft model was glued with silica sand No.8 (Table 2) which was also used for the model ground to create a rough surface. Also five earth pressure cells are fixed inside the raft at the same level of raft surface to record the raft pressure (Figure 2(d)).

The piled raft foundation include 12 similar piles made of aluminum tube with outer diameter of 6mm, thickness of 0.5mm, and length of 100mm as shown in Figure 3. These piles were arranged symmetrically as shown in Figure 2(d). As mentioned before, the piles head was not fixed to the raft but simply capped by the convex hole, that allow free rotation like pinned connection (Figure 3). In this way the piles mostly were subjected to large axial and lateral forces and small moment at the connection point to the raft. This condition is closed to the actual situation of normal piled-foundation of oil tank (Ishimatsu et al., 2009). Also Piles surface was glued with silica No.8 to create rough shaft surface.

Table 1. Test cases

| Test code | Foundation | Ground |
|-----------|-----------------------|--|
| Case1 | Slab | Saturated sand ($D_r=65\%$), GWT $z=0$ |
| Case2 | Non-Driven Piled Raft | Saturated sand ($D_r=69\%$), GWT $z=0$ |
| Case3 | Driven Piled Raft | Saturated sand ($D_r=65\%$), GWT $z=0$ |

Table 2. Silica sand No. 8 properties

| | | |
|----------------------|---------------------|-------|
| Specific gravity | G_s | 2.65 |
| Mean grain size | $D_{50}(\text{mm})$ | 0.1 |
| Effective grain size | $D_{10}(\text{mm})$ | 0.041 |
| Max. void ratio | e_{\max} | 1.333 |
| Min. void ratio | e_{\min} | 0.703 |

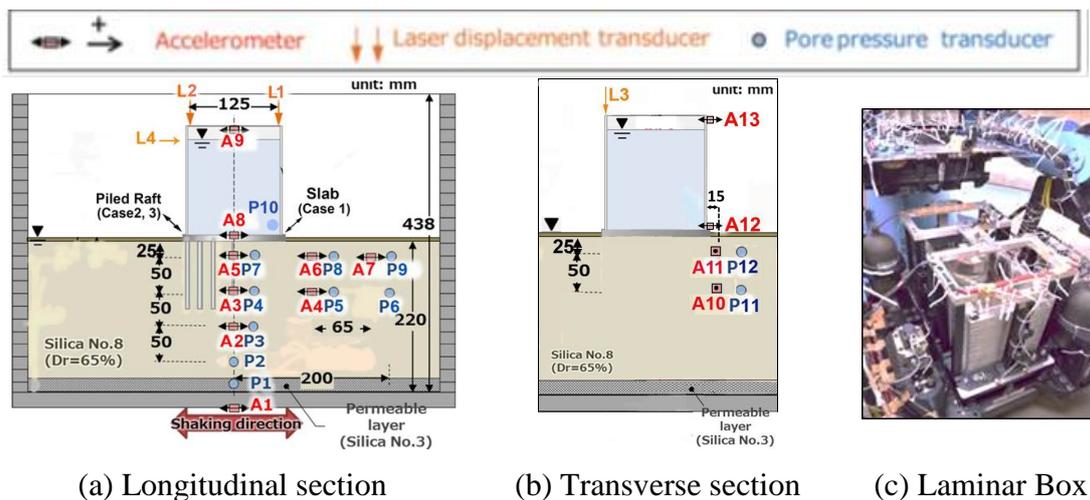


Figure 1. Model setup and laminar box used for the test

Table 3. Characteristics of tank, raft and pile model in 50g

| | Model | Prototype |
|------|-----------------------|-------------------------|
| Tank | Material | Acrylic cylinder |
| | Outer diameter | 140mm |
| | Thickness | 3mm |
| | Height | 160mm |
| | Mass (liquid & raft) | 2.7kg |
| | Tank average pressure | 76kPa |
| Raft | Material | Aluminum |
| | Diameter | 150mm |
| | Thickness | 10mm |
| | Base | rough |
| Pile | Material | Aluminum tube |
| | Outer diameter | 6mm (0.5mm) |
| | Thickness | 0.5mm |
| | Axial rigidity | 596 kN |
| | Bending rigidity | 0.0023 kNm ² |
| | Surface | Rough |

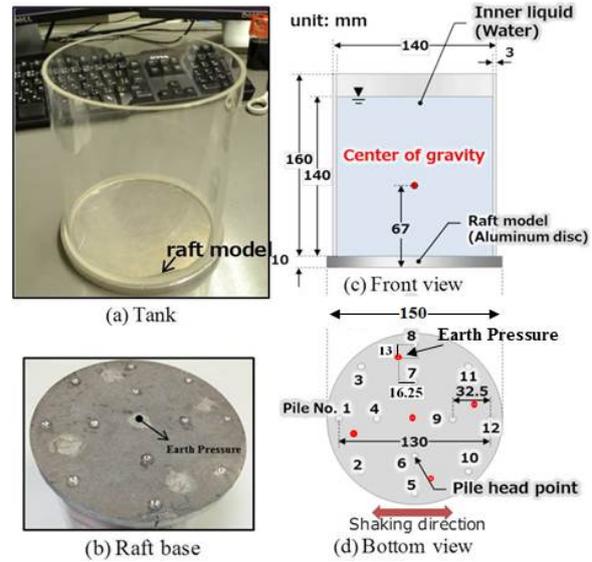


Figure 2. Tank and raft model

Model Preparation and Test Procedure

Fine sand (Silica sand No. 8) was used for the liquefiable sand layer and coarse silica sand (No.3) for the bottom drainage layer. The prototype permeability of silica sand No.8 is about 1.0×10^{-3} m/s in 50g centrifugal acceleration. Although this value is relatively high but it is low enough to accumulate excess pore water pressure during the input motion. Using air pluviation method, the sand layer with relative density of 65% was made. During the sand preparation, the sensors were placed at the prescribed locations as shown in Figure 1. In order to make saturated ground, after making of the sand layer, the sand sample was saturated in a vacuum tank by introducing de-aired water from the bottom of the container.

For the pile installation in non-driven PRF (case2) a simple aluminum guide was used to fix the piles in the required location during the sand pluviation but in case of driven PRF (case3) a more complicated procedure was employed. For this purpose, an acrylic guide was used to hold the piles during the pile installation at the center of the model ground, then in the first pile installation stage by exerting load (loading rate = 2 mm/min) with an electrical jack in 50g the piles were pushed to the sand (Figure 4(b)). The jack loading was stopped before the contact between the tank bottom and the guide. Then once the centrifuge was stopped the tank and guide were removed from the top of piles and the tank was put again on the top of piles (Figure 4(c), (d)). Again in 50g centrifugal acceleration, the jack load was exerted to the tank to drive the piles into the sand model and also to have a secure contact between the raft base and ground surface (Figure 4(f)).

After completion of the second stage of pile installation the centrifuge was stopped again and the whole setup was mounted to the shaking table and the centrifugal acceleration was increased up to 50g. The input ground motion was applied to the model after confirming the steadiness of all sensors. The target input motion is EW component of the acceleration recorded at Kurikoma, Kurihara city in 2008 Iwate-Miyagi Nairiku earthquake (JMA, 2008).

The comparison of target acceleration and its Fourier spectrum with those of input motions in

the tests are presented in Figure 5. As these graphs show the exerted input motions have proper compatibility in all cases. Detail of model preparation except of driven PRF is given by Takemura et al. (2014).

In the tests, accelerations, displacements, excess pore water pressures and earth pressures were measured and the results in the prototype scale are given in the following discussion.

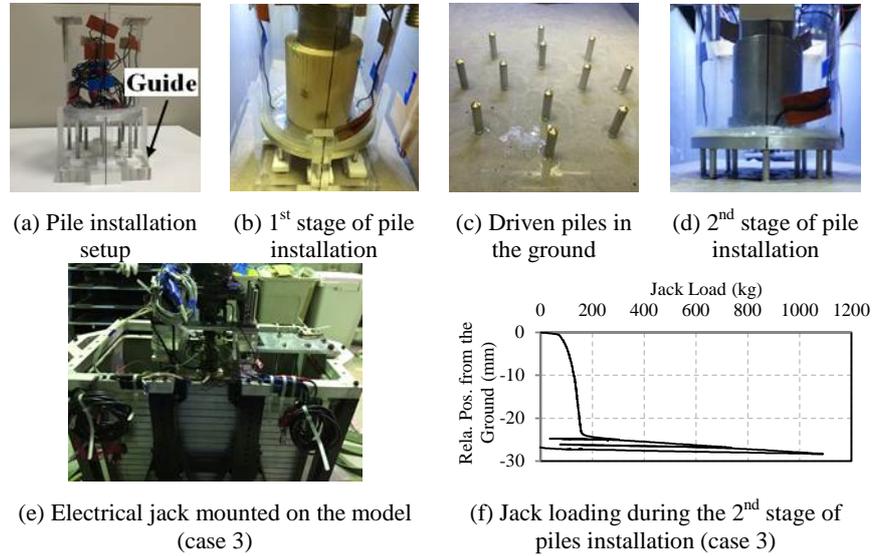
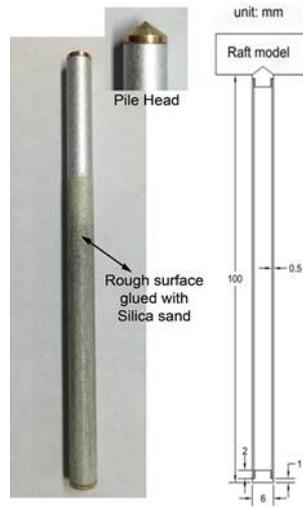


Figure 3. Pile model

Figure 4. Pile installation

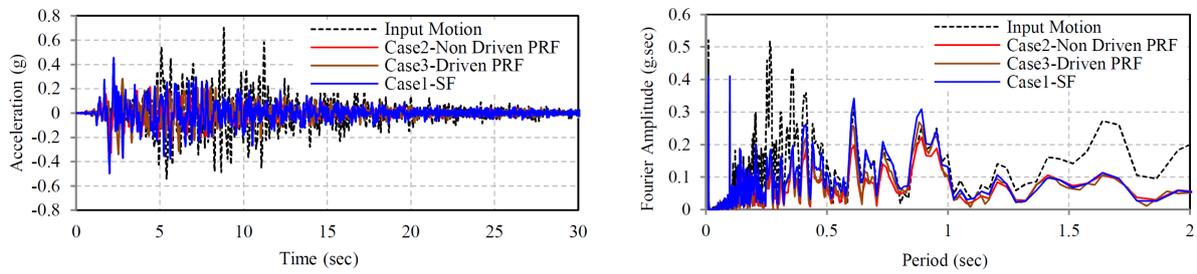


Figure 5. Input Acceleration and Fourier Spectrum (A1)

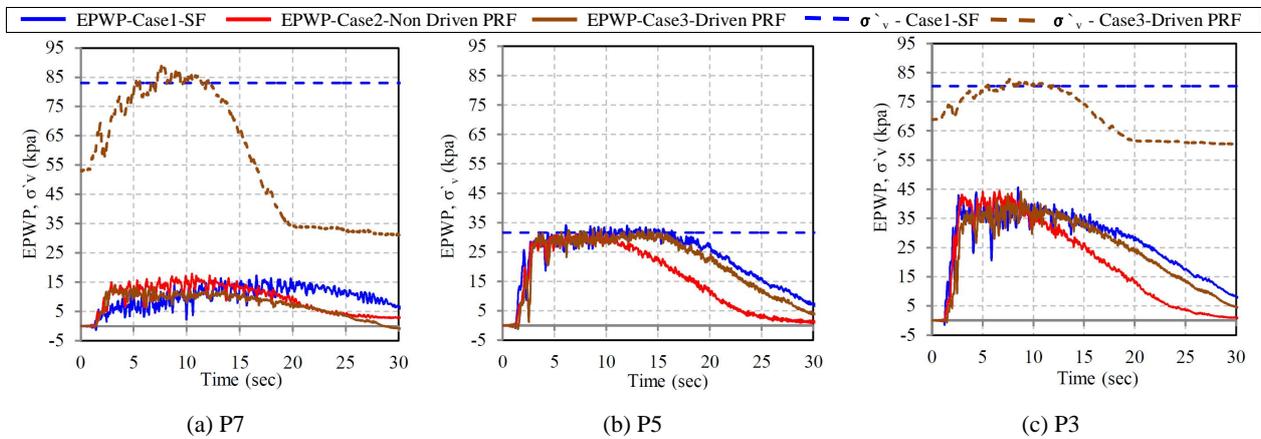


Figure 6. Excess pore water pressure and effective vertical stress (σ'_v) under the tank

Results and Discussion

Excess Pore Water Pressure

Excess Pore Water Pressure (EPWPs) measured below the tank (P3, P5, P7) during the shaking are presented in Figure 6. Also effective vertical stresses (σ'_v) which is total vertical stress minus hydrostatic water pressure, at the depth of the pore water pressure transducers are shown in the figure. Using the elastic stress distribution of raft load which is estimated by earth pressures data in piled raft cases (Figure 7), the total vertical stress increments below the tank are calculated.

Although at P5, EPWPs reached to σ'_v rapidly ($t=1-3\text{sec}$), confirming a clear liquefaction below the free field but as shown in Figure 6, EPWPs under the tank were all less than effective stress because of the confinement effect. However under the tank also EPWPs increased quickly in the same time and caused rapid reduction in the effective stress in this area. With increase of the depth, the differences between EPWP and σ'_v decrease. This implies more significant decrease of stiffness and strength at the deep part below the pile tip (P3) comparing to the shallow depth inside the pile group (P7).

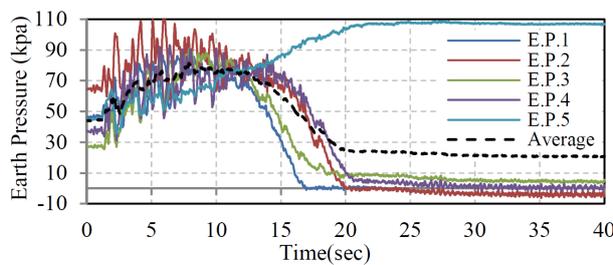


Figure 7. Earth pressure under the tank in case 3

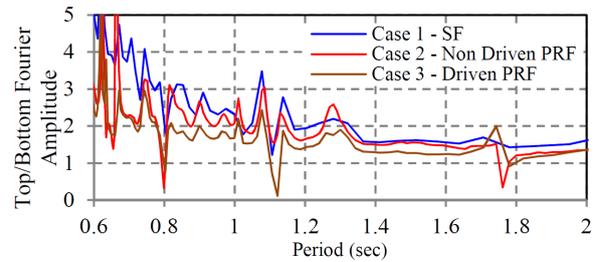
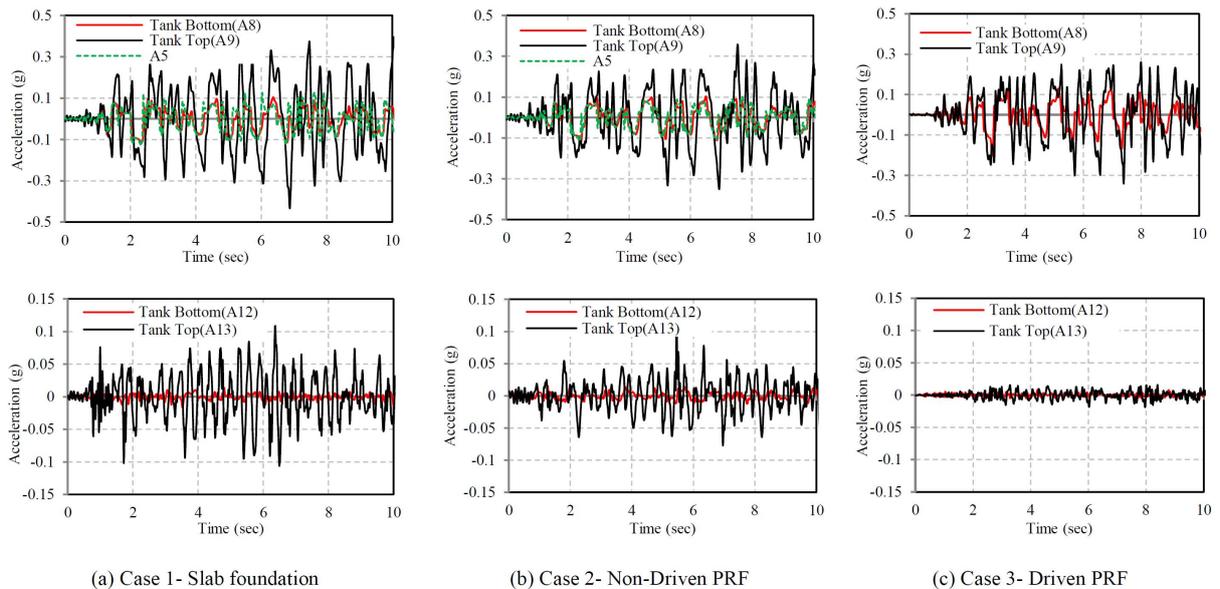


Figure 9. Tank top and bottom Fourier amplitude Ratio



(a) Case 1- Slab foundation

(b) Case 2- Non-Driven PRF

(c) Case 3- Driven PRF

Figure 8. Tank response acceleration at shaking and transverse directions

In the build-up period (rapid increase of EPWPs), increase of EPWP is slower in Case 1 in the shallow part (P7) because of more load from the slab in this case. However after the shake, EPWPs dissipated more rapid in piled raft cases (Cases 2 and 3) especially in the shallow part (P7) where piles located. Obviously the reason is more confinement effect by the pile group in these cases. The reason for faster EPWP dissipation in case 2 is unintentional higher soil relative density (about 4%) during making the ground model.

Tank Response, Settlement and Rotation

Accelerations at top and bottom of the tank in shaking direction (A8, A9), transverse direction (A12, A13) and in the ground just beneath the tank (A5) are shown in Figure 8. In Case 3, A5 was not recorded. After rapid increase of EPWP, a large difference between the tank top and bottom accelerations was appeared especially in Case 1 with slab foundation. The main reason is reduction in foundation stiffness while the water pressure fluctuation in the tank is negligible based on P10 result. The ratio of Fourier amplitude at tank top and bottom is presented in Figure 9. As Figures 8 and 9 shows, the piled raft foundation is effective in reducing the rocking motion not only in the shaking direction but also in the transverse direction especially in Case 3 with driven piled raft foundation.

The tank settlements derived by the three laser displacement transducers are presented in Figure 10. Also the settlements at the tank center are compared for three cases in Figure 11. In this figure, the average of LDT1 and LDT2 is considered as the tank center settlement. The settlement increases gradually during the shaking in contrast to EPWPs behavior. In case of the slab foundation, settlement is significantly larger than settlement in the piled raft foundation cases. Non-driven PRF has more settlement at LDT3 comparing to the center settlement. The settlement in driven PRF is smaller than non-driven PRF at the EPWP build-up duration (Figure 11) but the final settlement after shaking is more in this case.

Tank maximum rotation calculated by three LDTs data is shown in Figure 12. The rotation increased in all cases at the beginning of shaking because of the rapid increase of EPWPs. After this stage, the trends in three cases became different. In Case 1, the rotation decreases but in Case 2 and Case 3, it increases gradually.

The final maximum rotation (uneven settlement) in Case 1 when the sand in the surrounding area was liquefied is less than two other cases which implies that in liquefied condition, the effect of piled raft foundation for reducing uneven settlement could not be confirmed. This trend is also visible in Figure 13 which shows the tank center settlement against the tank maximum rotation. These results predicate more effectiveness of driven PRF in reducing maximum rotation of the tank comparing to non-driven PRF. Figure 14 shows θ , the angle between shaking direction and the direction of maximum rotation. This figure shows that in the EPWP build-up period, the maximum tank rotation occurred in the shaking direction. But once the surrounding ground was liquefied, the direction of maximum rotation could be diverted from the shaking direction, which probably depends on the heterogeneity of the ground conditions and unintentional structural unevenness.

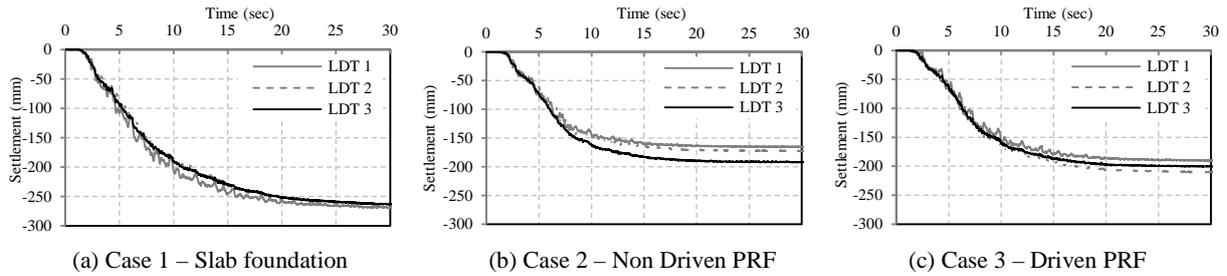


Figure 10. Tank Settlement

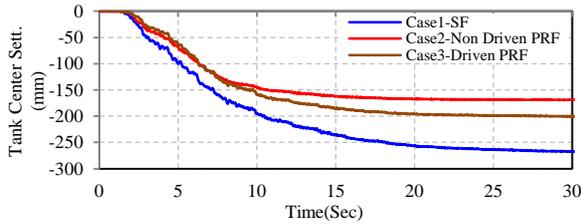


Figure 11. Tank center settlement

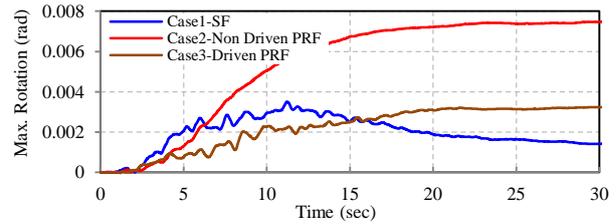


Figure 12. Tank maximum rotation

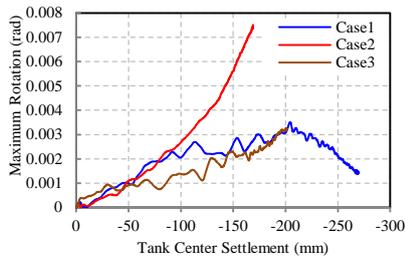


Figure 13. Tank max. rotation vs tank center settlement

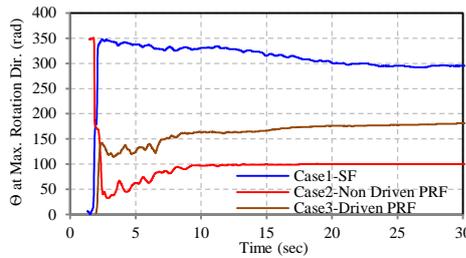


Figure 14. θ at maximum rotation direction

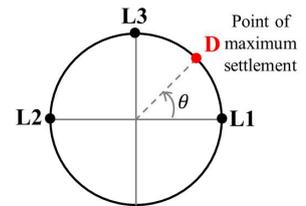


Figure 15. Tank top view and θ direction

Conclusions

From the dynamic centrifuge model tests on slab and piled raft foundation of oil storage tank resting on thick loose saturated sand, the following conclusions were derived.

1. Although the EPWP beneath the tank were much less than the initial effective stress, it rapidly increased and became constant values. The time of getting the constant value is almost same as the time in which sand in the surrounding area became liquefied.
2. Piled raft foundation was effective in reducing not only total settlement but also rocking motion. The driven PRF has better operation in reducing the rocking motion furthermore it could reduce the maximum rotation of tank comparing to non-driven PRF.
3. In the EPWP build-up period, the PRF could have better performance in reducing the uneven settlement compared to the slab foundation, especially for the foundation with driven piles. However, once the sand in the surrounding area was liquefied, the effect of PRF in reducing the uneven settlement could not be confirmed.
4. In the early stage of shaking during the pore pressure build-up period, the maximum tank rotation occurred in the shaking direction. But once the surrounding ground was liquefied, it's direction could be diverted from the shaking direction, which probably depends on

the heterogeneity of the ground conditions and unenviable structural unevenness. The number of piles in the piled raft model was relatively less compared to the actual tank foundation. Besides the ground condition in the centrifuge model was so loose against the input shaking motion. Therefore the piled raft model with more piles and higher liquefaction resistance of the ground can be main concerns for the further study.

References

- Bachman R, Nyman D, Bhushan K, Leyendecker E V, Lister L. *Seismic design guidelines and data submittal requirements for LNG facilities*. Federal Energy Regulatory Commission: Washington D.C, 2007.
- BS 7777. *Flat-bottomed, vertical, cylindrical storage tanks for low temperature service*. **1**, 1993.
- Horikoshi K, Randolph M F. A contribution to optimum design of piled rafts. *Geotechnique* 1998; **48** (3): 301-317.
- Horikoshi K, Matsumoto T, Hashizume Y, Watanabe T, Fukuyama H. Performance of piled raft foundations subjected to static horizontal loads. *Int. Jour. of Physical Modelling in Geotechnics* 2003a; **3**(2): 37-50.
- Horikoshi K, Matsumoto T, Hashizume Y, Watanabe T, Performance of piled raft foundations subjected to dynamic loading. *Int. Jour. of Physical Modelling in Geotechnics* 2003b; **3**(2): 51-62.
- Ishihara S, Kawase Y, Nakajima M. Liquefaction characteristics of sand deposits at an oil tank site during the 1978 Miyagiken-oki Earthquake. *Soils and Foundations* 1980; **20** (2): 97-111.
- Ishimatsu S, Yagi T, Yoshimi T, Takemura J. Field observation of pile behavior during the liquid level variation in an oil tank. *Kisoko* 2009, **37** (10):76-79.
- JMA (Japan Meteorological Agency (2008)). http://www.seisvol.kishou.go.jp/eq/kyoshin/jishin/080614_iwate-miyagi/index.html.
- Kakurai M, Yamashita K, Tomono M. Settlement behavior of piled raft foundation on soft ground. *Proc. 8th ARCSMFE* 1987; **1**: 373-376.
- Poulos H G, Alternative design strategies for piled raft foundation. *Proc. 3rd International Conference Deep Foundation Practice* 1994; 239-244.
- Poulos H G, Piled raft foundations: design and applications. *Geotechnique* 2001;**51**(2):95-113.
- Poulos H G, Small J C, Chow H. Piled raft foundations for tall building. *Geotechnical Engineering Journal of the SEAGS & AGSSEA* 2011;**42**(2): 78-84.
- Randolph M F. Design methods for pile groups and piled rafts. *Proc. 13th ICSMGE* 1994; **5**: 61-82.
- Takemura J, Yamada M, Seki S. Dynamic response and settlement behavior of piled raft foundation of oil storage tank. *Proc. 8th inter. con. on physical modelling in Geotechnique* 2014; **1**: 613-619.