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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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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. 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 sand. Using the observed results, such as accelerations of the tank and ground and displacements of the foundation, some practical hints for reasonable design of piled raft foundation for oil tanks on non-liquefiable sand are discussed. According to the results of this study, the main concern in the rational design of the foundation is piles' design and their punching effect on the raft, in case of PRF of oil tank on non-liquefiable sand.

Keywords:
Oil storage tank; Design of piled raft foundation; Centrifuge modeling

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. [1]. 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 [2-4]. 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 piled raft foundation cannot be extended to the civil engineering infrastructures.

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 [5], and some seismic design guidelines of the tank foundation allow relatively large total settlement, for example more than 3 inches [6], 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. [2, 7]). Some studies have been done on oil tank foundations [8-9]. However, a few researchers have considered PRF for the storage tanks. Sahraeian et al. [10-11] reported a dynamic centrifuge model study on the PRF of oil tanks and the behavior of tank was observed not only in the shaking direction but also in the transverse direction. Furthermore, they investigated the effect of pile installation method on the seismic behavior of tank [12]. 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 were performed to investigate the mechanical behavior of oil tank supported by PRFs on non-liquefiable dry sand. From the observed test results, such as accelerations of the ground and accelerations, rotation and settlement of the tank, special considerations for the rational design of PRF for oil tanks on non-liquefiable ground are described. Also some practical points for the application of PRF for oil storage tanks on non-liquefiable sand are presented.

2. The Difficulties in the Design of Piled Raft Foundation for Oil Storage Tanks

The most important difficulty in the design of PRF of oil tanks is the estimation of pile and raft load proportion especially in case of dynamic loading. As Figure (1a) indicates, the raft load proportion (RLP) and piles load proportion (PLP) during static loading

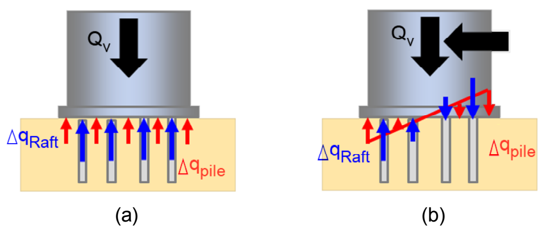


Figure 1. Piles and raft contribution during static and dynamic loading.

are $RLP = \int q_{raft} / Q_V$, $PLP = \sum q_{pile} / Q_V$ and the values range from 0 to 100 percent. However, during the seismic loading, the estimation is more complicated while the dynamic horizontal load (Q_d) cause some addition or reduction (Δ_q) in the raft or piles load (Figure 1b), which depends on the location of pile and the raft element (Equation 1).

$$\begin{aligned} q_{Raft}(dynamic) &= q_{Raft}(static) + \Delta q_{Raft} \\ q_{Pile}(dynamic) &= q_{Pile}(static) + \Delta q_{Pile} \end{aligned} \qquad (1)$$

Accordingly, determination of pile and raft design load is so complex due to the variability of *RLP* and *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.

On the other hand, type of piles (end bearing or friction pile) is another critical point in the concept of piled raft foundation. Because of a large tip resistance develops in the end bearing piles especially in the sand layers, enough structure settlement may not be afforded and the secure contact of raft and subsoil cannot be guaranteed. Therefore, utilizing of frictional piles is recommended to supply the reasonable performance of piled raft system.

In the continuation, 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 sand.

3. Dynamic Centrifuge Tests

3.1. 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 50 g centrifugal acceleration. For modelling of the ground, a laminar box consisted of 15 laminas and rubber membrane bag with inner dimensions of 600 mm in length, 250 mm in width and 438 mm in depth was used as in Figure (2c).

A simple uniform sandy ground with a moderate relative density was modelled beneath the tank, because the main purpose in this study was to model ground without liquefaction. As shown in Table (1), four model tests were performed. In Cases 1a and 1b, a slab foundation (*SF*) while in Cases 2a and 2b, piled raft foundation (*PRF*) was placed on the dry sand. 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. On the other hand, because Cases 1a and 2a were conducted prior to the other cases in a different period of time, the modeling dimensions and instrumentations details in these cases are slightly different from the others (Figure 2). Model dimension and instrumentation details are shown in Figures (2a) and (2b).

2.2. Tank, Pile, Raft and Ground Modeling

Characteristics of the tank, pile and raft for both the model and prototype scales are presented in Table (2). The tank model used in the tests (Figure 3a) was made by 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 with the slab/raft model made of aluminium disk with diameter of 150 mm and thickness of 10 mm (Figures (3b) and (3c). The raft model has 12 conical shape concave holes which are put on the pile heads (Figures 3c and 3d). Bottom surface of the raft model was glued with silica sand No. 8 (Table 3), which was also used for the model ground to create a rough surface. The piled raft foundation include 12 similar piles made of aluminium

Table 1. Tests Cases.

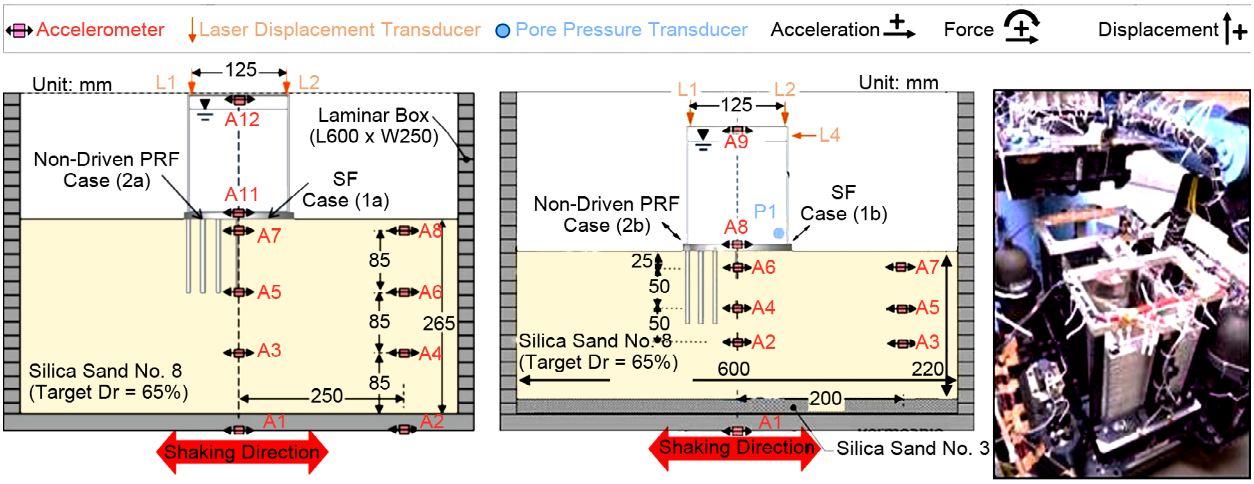
Test Code	Foundation	Ground
Case 1a	Slab	Dry Sand (Dr = 65%)
Case 1b	Slab	Dry Sand (Dr = 66%)
Case 2a	Piled Raft (12 Piles)	Dry Sand (Dr = 65%)
Case 2b	Piled Raft (12 Piles)	Dry Sand (Dr = 68%)

Table 2. Characteristics of tank, raft and pile used in model and prototype in 50 g.

		Model	Prototype
Tank	Material	Acrylic Cylinder	Steel
	Outer Diameter	140 mm	7.0 m
	Thickness	3 mm	
	Height	160 mm	8.0 m
	Weight (Liquid and Raft)	1.42 kN	3.6 MN
	Tank Average Pressure	81 kPa	81 kPa
Raft	Material	Aluminum	RC
	Diameter	150 mm	7.5 m
	Thickness	10 mm	0.5 m
	Base Surface	Rough	Rough
Pile	Material	Aluminum	RC
	Outer Diameter	6 mm (0.5 mm)	0.3 m
	Thickness	0.5 mm	25 mm
	Length	100 mm	5 mm
	Axial Rigidity: EA	596 kN	1.49GN
	Yielding Axial Load	0.6 kN	1.5 MN
	Bending Rigidity: EI	0.0023 kNm^2	14.2 kNm^2
	Shaft Surface	Rough	Rough

Table 3. Properties of silica sands.

		No.8	No.3
Specific Gravity	G_s	2.65	2.65
Mean Grain Size	D_{50} (mm)	0.1	1.47
Effective Grain Size	D_{10} (mm)	0.041	1.21
Maximum Void Ratio	e_{max}	1.333	0.971
Minimum Void Ratio	e_{min}	0.703	0.702



(a) Longitudinal Section (Cases 1a and 2a)   (b) Longitudinal Section (Cases 1b and 2b)   (c) Laminar Box

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

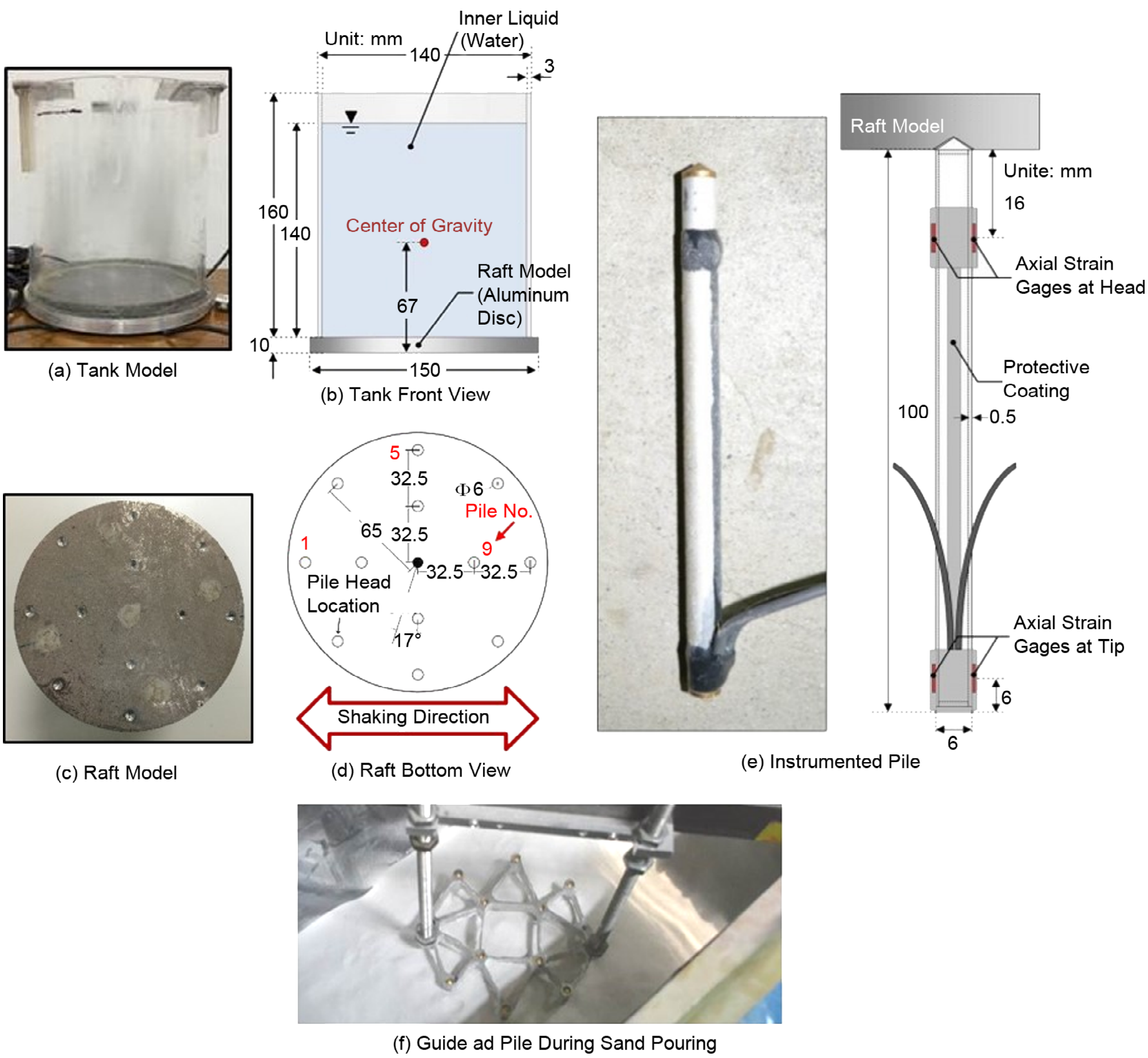


Figure 3. Tank, raft and pile model.

tube with outer diameter of 6 mm, thickness of 0.5 mm, and length of 100 mm as shown in Figure (3e). These piles were arranged symmetrically as shown in Figure (3d). 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 3e). In this way, the piles were mostly 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 [13]. Also piles surface was glued with silica No. 8 to create rough shaft surface.

The raft made by aluminium 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. Water was used as a liquid inside 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 (qv: total weight/raft base area) under 50 g centrifugal acceleration. In order to measure the pile axial load and shaft friction, the piles used in Cases 2a and 2b were instrumented by axial strain gages at the head and tip as shown in Figure (3e).

3. Model Preparation and Test Procedure

Fine sand (Silica sand No. 8) was used for the sand layer. Using air pluviation method, the sand layer with relative density of 65% was made but in some cases, the final relative density had a few deviations from the target value (Table 1). During the sand preparation, the sensors were placed at the prescribed locations as shown in Figure (2).

For the pile installation in PRF cases (Cases 2a and 2b) a simple aluminium guide (Figure 3f) was used to fix the piles in the required location during the sand pluviation. Then, using the air pluviation method, sand was poured until reaching the required level. At this level, the piles tip with conical shape was just above the ground surface and could be put into the raft concave holes.

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 1 g condition. A detailed discussion on the preloading process and its reliability is presented in Sahraeian et al. [11].

After the preloading process, the whole setup 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 50 g. The input ground motion was applied to the model after confirming the steadiness of all sensors. The target input motion was EW component of the acceleration recorded at Kurikoma, Kurihara city in 2008 Iwate-Miyagi Nairiku earthquake (JMA, 2008) which is characterized as a vibration with a moderate duration.

The comparison of target acceleration and its Fourier spectrum with those of input motions in the tests are presented in the prototype scale in Figures (4a) and (4b). There were some differences in the magnitude of input acceleration, which can be clearly seen in the variation of Arias intensity (Ia) of the input accelerations in Figure (4c). Considering that Ia tends to exaggerate the difference in the acceleration by squaring the acceleration, the input motions except in Cases 1a and 2a, which had larger input motion, are nearly similar. In the discussion of the test results, the above-mentioned differences in the input motion are taken into consideration. For more information about the details of model preparation and the tests refer to Sahraeian et al. [11-12].

In the shaking tests, the ground and tank

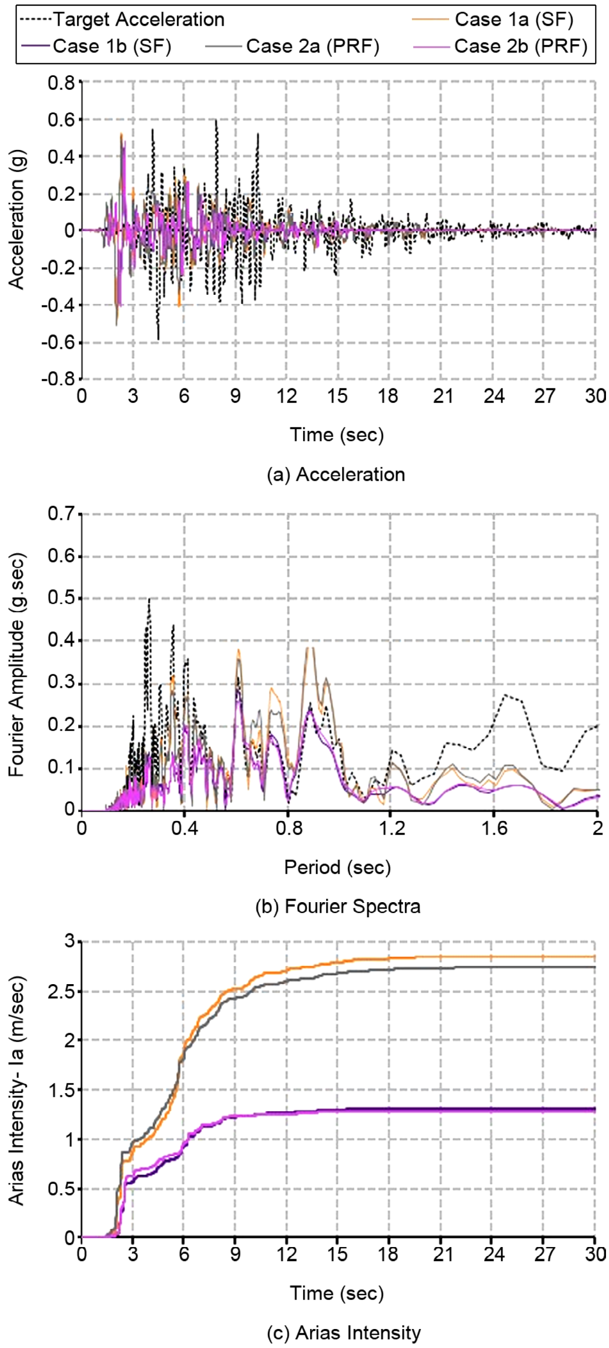


Figure 4. Input motions.

accelerations, the displacements of the tank and the piles loads were measured as shown in Figure (2). From those test results, special considerations for the rational design of piled raft foundation for oil tanks are described. Also some practical points for the application of piled raft foundation for oil storage tanks on non-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

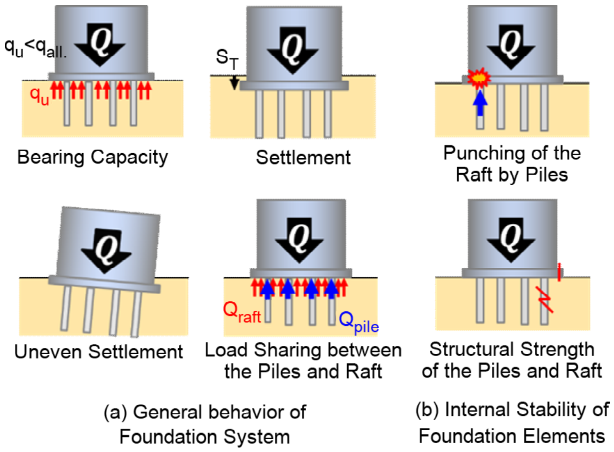


Figure 5. Key issues in the design of PRF for oil tanks.

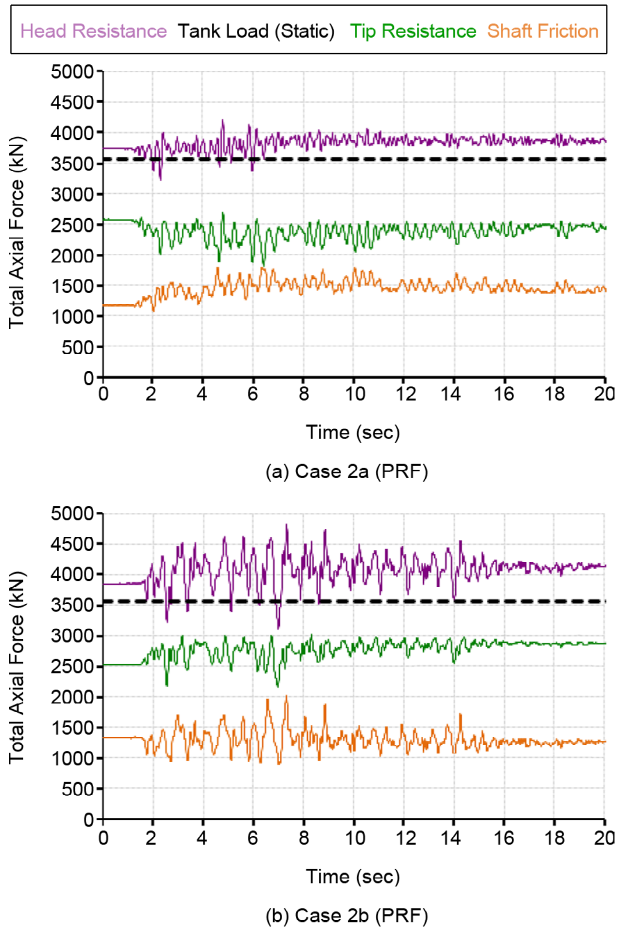


Figure 6. Total axial forces carried by piles.

Figure (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 and the load sharing between the foundation elements (i.e. piles and raft). The second one is the internal stability of foundation elements e. g. punching of the raft by piles and structural strength of the piles and raft. All of these significant criteria should be evaluated during a rational design of PRF for oil tanks resting on non-liquefiable and liquefiable sand.

5. Piled Raft Foundation of Oil Tank on Non-Liquefiable (Dry) Sand

According to the previous studies by the authors [11, 14], piled raft foundation of oil tanks on non-liquefiable sand has acceptable performance in reducing the settlement and uneven settlement of the superstructure. Thus, the main concern in the rational design of foundation is design of structural components (piles and raft).

6. Structural Components of the Foundation (Piles and Raft)

Piles head resistance, tip resistance and shaft friction along with tank total load in static condition is presented in Figure (6) for Cases 2a and 2b (*PRF* on dry sand). It should be noted that due to the interference of the moment strain to the axial strain measurement near the pile top, the measured total pile load was overestimated, which could be seen in the static and dynamic components. Namely, the measured pile loads were larger than the tank load in static condition and during the shaking, though the shaking motion was applied in the horizontal direction, not vertical direction. As this figure indicates in case that piled raft of oil tank located on non-liquefiable sand with sufficient resistance of soil, the main part of loads is transferred to the piles. In the other words, the pile load proportion (*PLP*) is large at the beginning before the start of shaking and even it increases slightly after the shaking. On the other hand, considering the less number and the smaller length of piles in piled raft systems in comparison to pile foundations, larger static and dynamic load may develop in the pile group. In this condition, more caution is essential for the design of piles while they have the main contribution against the loads.

The dynamic part of piles head load, tip resistance and shaft friction in Cases 2a and 2b (PRF on dry sand) during the dynamic loading are presented in Figure (7) for pile No. 1 at outer edge of the raft in shaking direction, pile No. 5 at outer edge of the raft in transverse direction and pile No. 9 at the central

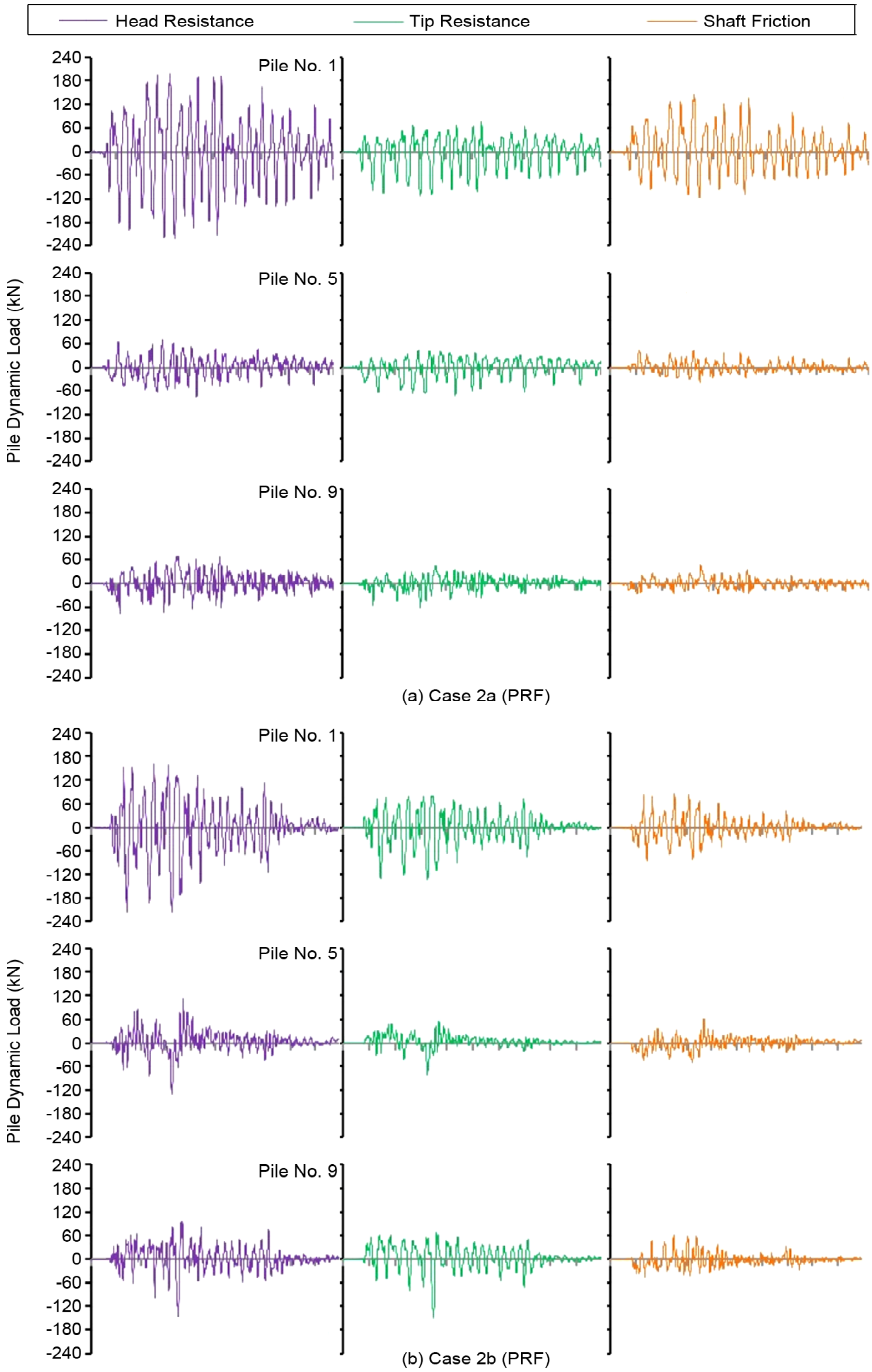


Figure 7. Dynamic portion of piles No. 1, 5 and 9 loads during the shaking.

part of the raft (Figure 3d). These loads are calculated by subtracting the static part of load during the shaking from the total one. As this figure indicates, pile No. 1 at the raft outer edge in shaking direction has higher resistance (amplitude) during dynamic loading in comparison to piles No. 5 at transverse direction and No. 9 at central part of the raft. Obviously, during the shaking, higher piles load is expected due to the contribution of piles against dynamic loads. The average of amplitudes of piles dynamic load during the shaking along with maximum total load of piles for both Cases 2a and 2b are shown in Figures (8a) and (8b). As Figure (8a) indicates, the distribution of dynamic part of load depends on the piles location while the piles at the raft perimeter have larger resistance against dynamic loads in comparison to the piles at the raft center. Almost similar trend can be observed in the maximum total loads of piles (Figure 8-b). Another concern in the rational design of PRF for oil tank is punching of the raft by the piles while the piles has considerable load share especially during the dynamic loading. 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 that includes rational design loads and factor of safety is inevitable in case that oil tank with *PRF* is located on dry sand.

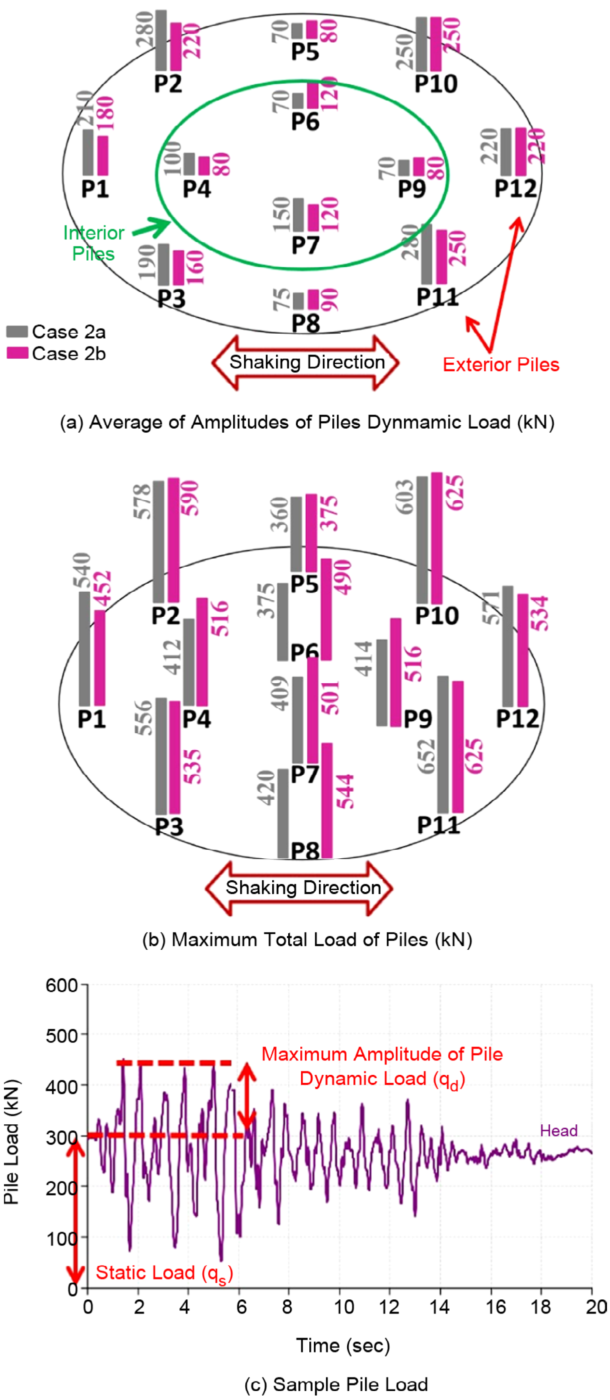


Figure 8. Piles dynamic load.

Considering these critical issues, to reduce the risk of piles failure, some remedies can be recommended. In order to reasonably estimate piles design loads, it may be suggested to estimate piles design load with assumption of raft load proportion equal to zero (*RLP* ≈ 0). Also, a designer can use different factor of safety for the interior and exterior piles; a larger one for the outer piles and a smaller one for the inner piles. Furthermore, the piles in the interior and perimeter zones can be designed for a design load equal to the summation of static load (q_s) plus maximum of amplitudes of the dynamic loads in the related zone (q_d) (piles design $load = q_s + q_d$) as shown in Figure (8b). Using this approach, the raft thickness should be estimated by checking the punching effect of the perimeter piles with larger pile load, bending moment and shear load of the raft.

7. Conclusion

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

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.

To reduce the risk of piles failure in *PRF* of oil tank on non-liquefiable sand, some remedies might be recommended. In order to reasonably estimate piles design load, it can be suggested to estimate piles design load with assumption of raft load proportion equal to zero (*RLP* ≈ 0). Also, a designer can use different factor of safety for the interior and exterior piles; a larger one for the outer piles and a smaller one for the inner piles because the piles located in the perimeter of raft have more contribution against dynamic load. Furthermore, the piles located in the two zones (interior and perimeter) can be designed for a design load equal to the summation of static load (q_s) plus the maximum amplitude of the dynamic loads in the piles of the respective zone (q_d). Using this approach, the punching effect of the perimeter piles should be checked for the design of raft thickness.

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