Experimental Study on Fracture Behavior of RC Piles and Superstructure Dynamic Response Using Centrifuge Model

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***Abstract*— In past earthquake disasters, many pile foundations of building were damaged. Although many researchers have examined the relationships related to soil-pile-superstructure interaction, few studies have been conducted to examine the damage of piles based on experiment. This study investigated the relationship between the pile fracture and dynamic response of a superstructure when the footing is embedded. Also, we tried evaluating the ultimate shear strength of a pile foundation when the pile was shear fractured. The shaking table test under a centrifuge field was conducted to investigate the behavior of the RC pile foundation. The diameter of the pile model is 25mm (1.25m in prototype scale). This pile model consists of mortar, four main reinforcement bars and a hoop reinforcement bar. The experimental model was set in a laminar shear box filled with Toyoura dry sand. The density of the soil was 60%. In the shaking table test, 11 different amplitude Rinkai waves were input under a 50G field. In the result of the experiment, the heads of the pile models were shear fractured. It caused the reduction of vibration transmissibility between the superstructure and the ground surface. The maximum inertial force of the superstructure mostly corresponded to the total value of the ultimate shear strength calculated using the shear strength of the pile model, the coefficient of pile group effect, and the resistance force of footing.**

***Index Terms*— centrifuge test, reinforced concrete pile, dry sand, maximum inertial force, failure behavior, embedded footing**

I. Introduction

It is reported that many pile foundations of buildings were damaged by the 1995 Hyogo-ken Nanbu Earthquake [1] and the 2011 Tohoku-chihou Pacific Offshore Earthquake [2], also large piles whose diameter were over 1m were damaged. Little is known about the relationship between the damage of piles and the maximum response acceleration of superstructure under these massive earthquakes.

Many researchers have examined the damage of piles related to soil-pail-superstructure interaction based on numerical analysis. Ross [3] evaluated the Winkler foundation analysis method for analyzing seismic soil-pile-structure interaction through the results of a series of dynamic centrifuge model tests. Chau [4] tested a soil–pile–superstructure model on a shaking table, and carried out nonlinear finite element method (FEM) analyses. Cai [5] studied three-dimensional nonlinear interactive finite element subsystem methodology to investigate seismic soil-pail-superstructure interaction effects more precisely. However, few studies have been conducted to examine the damage of piles based on experiment. The experiments conducted in these few studies used a dynamic centrifuge test apparatus and a large shaking table. Most of them were conducted with pile models using small diameter steel pipes, meaning that not many experiments were conducted with reinforced concrete (RC) piles.

Kimura [6] conducted static loading tests and studied the damage behavior and final state of RC piles in dry soil under a centrifuge field. Higuchi [7] conducted centrifuge tests related to a large diameter RC pile model in dry soil and studied the shaking response when the steel bar yielded. Even among them, the behavior of pile foundation and the superstructure, in which the footing is embedded, has never been focused on. Also, the behavior and effects of shear fractured piles have never been studied. The objectives of this study are to clarify the change of seismic response of superstructure caused by pile fracture, and to verify the relationship between the maximum inertial force of superstructure and pile fracture behavior.

II. Pile Model for Centrifuge Test

A. *Design of Pile Model*

The experiment was conducted under a 50G field using the centrifuge test apparatus of Disaster Prevention Research Institute in Kyoto University. For conducting the centrifuge experiment, we proposed a simple mortar pile model.

FIGURE 1 shows the cross section of the pile model used in the experiment. This pile model was designed by scaling law so that the pile model could reproduce the elasto - plastic behavior of concrete piles and degradation behavior. The diameter of the pile model is 25mm which is 1.25m in prototype scale. This pile model consists of mortar, four main reinforcement bars and a hoop

Manuscript received December 14, 2018; revised April 21, 2019.

doi: 10.18178/ijscer.8.3.234-239

reinforcement bar. The diameter of the main reinforcement bars was 1.2 mm, also the diameter of the hoop reinforcement bar was 0.8mm. Table I shows the comparison of pile cross - sections. As it shows, the main reinforcement ratio and the hoop reinforcement ratio of this pile model corresponds to the example cross – section suggested by Design problems in foundation engineering [8]. The intervals of the hoop reinforcement bar are 15mm. The compressive strength of mortar is 14.8MPa. The mortar was designed using a water cement ratio of 0.8 and a cement sand ratio of 1.5.

B. Static Loading Test of Pile Model

The static loading test was carried out to evaluate the characteristics of this pile model. Fig. 2 shows the system of the static loading test. The lower part of pile model was rigidly joined to a reaction force jig and the upper part was joined as a cantilever type that was connected to a horizontal loading device by a pin jig and a vertical roller jig. The horizontal cyclic load was inputted to the pile model. The point of loading was 85mm above the critical section. The deformation was measured by a laser displacement transducer at 117.5mm above the critical section, and the loading was measured by load cell. The loading history comprised pile rotation angles of 0.005, 0.01, 0.02, 0.04, 0.06, 0.08, 0.10, and 0.15 rad. The pile head rotation angle was calculated using the distance between the laser displacement transducer and the critical section (117.5mm). The axial force for the pile model was 2814kN in prototype scale. It was same value as the axial force for each pile model of the shaking table test which is described later.

Fig. 3 shows the bending moment – deformation angle of this test in prototype scale. Red line indicates the calculated full plastic moment of this pile model. The full plastic moment was 2.86MNm.

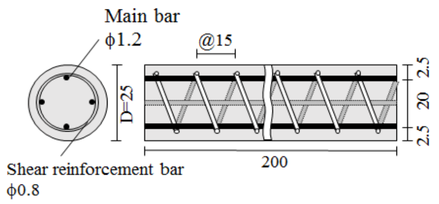


Figure 1. Cross section of Pile model

As it shows, this pile model demonstrated the elasto – plastic condition. The flexural strength of the pile model reached over full plastic moment. After that, it performed degradation behavior. The behavior of this pile model reproduces to a real reinforced concrete member.

III. Dynamic Centrifugal Model Test

Table II and Figure 4 show the experimental model of shaking table test and its dimensions. The superstructure and the footing were supported by the four pile models which had the same characteristics as in the static loading test. The length of each pile model was 200mm which was 10m in prototype scale. The space of pile models for shaking direction was 150mm which was six times the diameter of the pile model, and the space for the cross angle of shaking direction was 62.5mm which was 2.5times the diameter. The mass of superstructure was 7.42kg which was 928ton in prototype scale, and the mass of footing was 1.77kg which was 221ton in prototype scale. The superstructure corresponds to an 11 floor prototype building where the height of each floor is 3m. The fundamental natural period of this prototype building is 0.66sec in prototype scale. In the prototype building, the axial force for each pile is 2750kN. According to the scaling law, the axial force for each pile model was designed to 2814kN in prototype scale which corresponds to 102% of the axial force for each prototype building pile. It was same axial force as the static loading test. The superstructure was connected to the footing by a metal plate spring. The natural period of the superstructure was 0.625s in prototype scale which corresponds to the fundamental natural period of the prototype building.

TABLE I. Comparison of Pile Cross – Sections

		Pile Model (Prototype scale)	Example cross-section
Diameter		25mm	1800mm
Main reinforcement bar	Rebar	4-ϕ1.2	45-D29
	Ratio	0.92%	1.13%
Hoop reinforcement bar	Rebar	ϕ0.8@15	D13@150
	Ratio	0.27%	0.26%

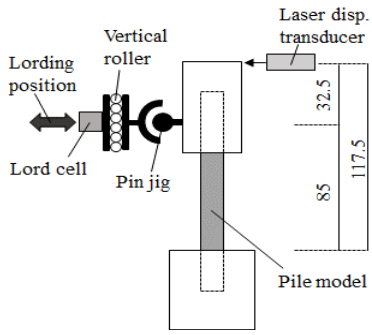


Figure 2. The static loading test (mm)

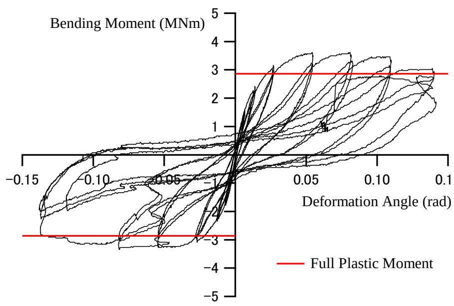


Figure 3. The bending moment-Deformation angle

The experimental model was set in a laminar shear box filled with Toyoura dry sand (Specific gravity Gs = 2.635, Maximum void ratio emax = 0.966, Minimum void ratio emin = 0.600, D50 = 0.18 mm with no fines content under 75tim [9]). The footing was embedded for 30mm which was 1.5m in prototype scale. The density of soil was 60%. Below, they are shown at full scale unless otherwise stated.

The horizontal acceleration of the bottom of the model, ground surface, footing and superstructure were measured by acceleration sensors. The horizontal displacement, the vertical displacement and the rotation angle of the superstructure were measured by laser displacement transducers. A total of 11 plastic strain gauges were installed on the surface of the pile models to evaluate the curvature distribution in the vertical direction.

TABLE III shows the list of excitations. During the shaking table test under the 50G field, 11 different amplitude Rinkai waves (JBDPA, 1992) were input. The maximum acceleration of the 1st excitation was 46.4gal in prototype scale. The amplitude of input waves was becoming strong. The maximum acceleration of final excitation was 751gal. The last two excitations were the same amplitude.

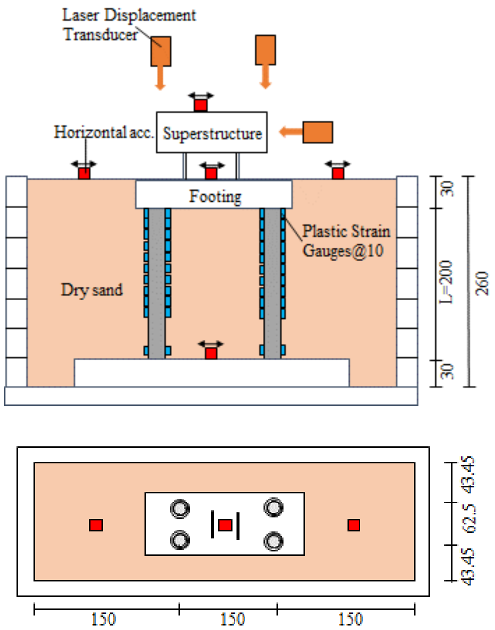


Figure 4. The Experimental Model (mm)

TABLE II. DIMENSIONS OF THE MODEL

			Scaling Law	Unit	Prototype Scale	Model Scale
Piles	Length		1/λ	m	10	0.2
	Diameter		1/λ	mm	1250	25
	moment of inertia of area		$1/\lambda^4$	cm^4	1.29×10^7	2.08
	Yield stress of mortar		1	N/mm^2	14.81	14.81
	Main bar	Diameter	1/λ	mm	60	1.2
		Yeild stress	1	N/mm^2	374	374
	Shear reinforcement bar	Diameter	1/λ	mm	40	0.8
		Pitch	1/λ	mm	750	1.5
		Yeild stress	1	N/mm^2	432	432
Footing	Mass		$1/\lambda^3$	kg	221250	1.77
Superstructure	Mass		$1/\lambda^3$	kg	927500	7.42
Soil	Density		1	%	60	60

IV. THE RESULT OF SHAKING TABLE TEST

A. Main Time History

Figs. 5 to 7 show the main time history (0s to 50s) of horizontal acceleration at superstructure, footing, ground surface and input (the bottom of the model), also settlement and rotation angle of superstructure during input No.2 (elastic condition), No. 4 (plastic hinges occurred) and No.11 (final excitation) excitations.

During the No. 2 excitation, the maximum curvature was 3.98×10-5mm-1 among both front pile model and back pile model. According to Bernoulli-Euler theory, the bending moment was calculated as 1.13MNm when the pile model reached that curvature. It is 39.4% of the full plastic moment (Mu=2.86MNm). From this result, the pile model seems to be still in elastic condition. The maximum response of ground surface acceleration was amplified 2.21 times as much as input acceleration. The response acceleration of the superstructure was 1.38 times as much as ground surface acceleration. On the other hand, the response acceleration of footing was 0.69 times as much as ground surface acceleration. The maximum rotation angle was 1.97×10-3rad. After input No. 2 excitation, residual settlement was 2.21mm, and residual rotation angle was 4.22×10-4 rad.

During the No. 4 excitation, plastic hinge was considered to have occurred on the pile head according to the value of the strain gauges. The maximum response of ground surface acceleration was amplified 1.62 times as much as input acceleration. The response acceleration of the superstructure was 1.03 times as much as ground surface acceleration. The response acceleration of the footing was 0.73 times as much as ground surface acceleration. The response of acceleration between the footing and the ground surface seems not to be big different, but between the superstructure and the ground surface it was reduced compared to the No.2 excitation. It indicates that the vibration transmissibility of the superstructure decreases if the plastic hinge was created in the pile. The maximum rotation angle was 1.35×10-2 rad. After input of No. 4 excitation, residual settlement was 10.4mm, and residual rotation angle was 14.1×10-4 rad. It shows that the residual settlement and residual rotation were still very small even though the plastic hinge occurred. Hence, there is a possibility that the pile is flexure fractured after a massive earthquake although the building seems not to be settled or rotated.

During the final excitation, No.11, The maximum response of ground surface acceleration was amplified 0.92 times as much as the input acceleration. The response acceleration of the superstructure was 1.05 times as much as ground surface acceleration.

TABLE III. LIST OF EXCITATIONS

Excitation number	1	2	3	4	5	6
Max Acceleration (gal)	46.4	78.1	199.6	318.8	490.0	589.3
Excitation number	7	8	9	10	11	
Max Acceleration (gal)	631.1	681.0	727.2	755.7	750.5	

The response acceleration of the footing was 1.00 times as much as ground surface acceleration. The maximum rotation angle was 3.19×10-2 rad. After inputting the final excitation, residual settlement was 18.0mm, and residual rotation angle was 155×10-4 rad. Also, the pile model was shear fractured. This residual settlement and rotation were much bigger than that after the No.4 excitation. In the No.4 excitation, flexure fracture occurred, but the residual settlement and rotation were still small. However, in the final excitation, shear fracture occurred, and caused significant residual settlement and rotation

Fig. 8 are pictures after finishing the experiment. As it shows, the head of the pile model was shear fractured. Settlement and rotation of the superstructure were caused by this fracture behavior. The footing was exposed through excitation. The embedment depth of the footing was reduced 1.5m to 0.55m during excitations.

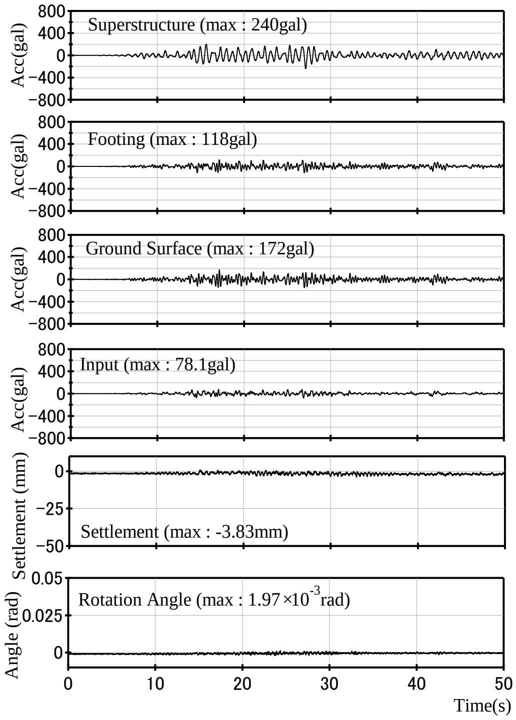


Figure 5. The main time history of excitation No.2

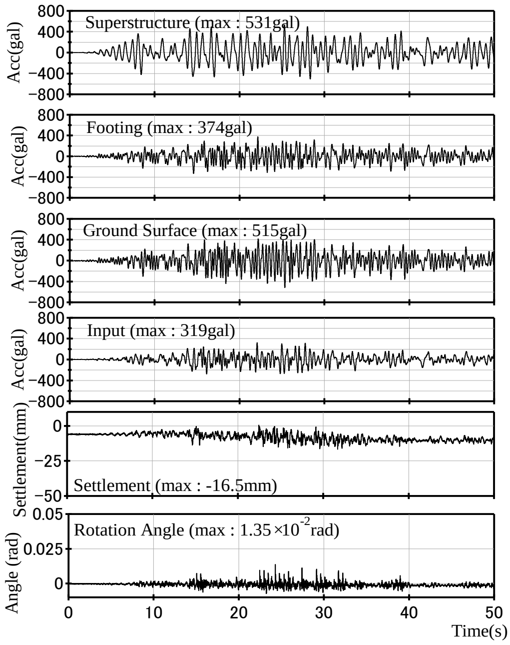


Figure 6. The main time history of excitation No.4

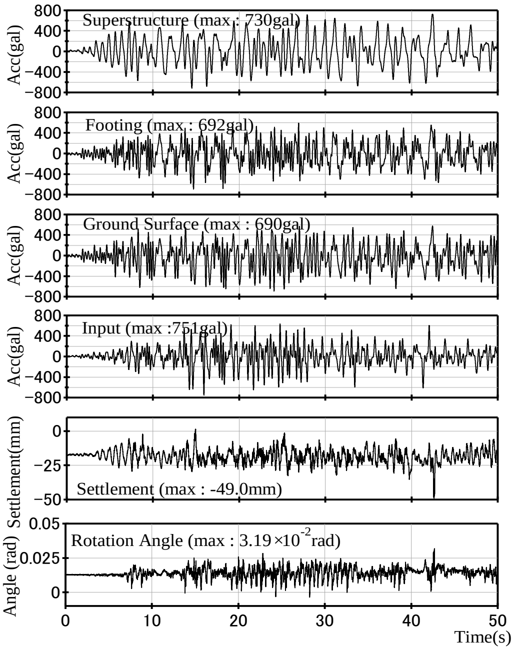
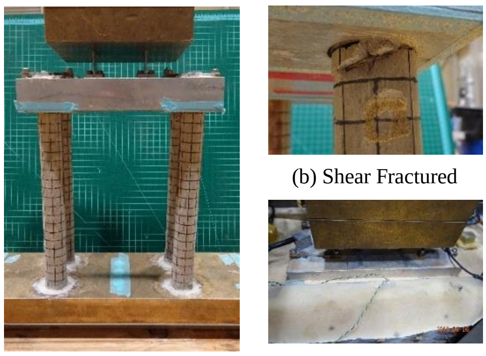


Figure 7. The main time history of excitation No.11



(a) Shaking table test model (b) Shear Fractured (c) Embedment of Footing

Figure 8. Damage of the pile model

In this experiment, the pile model was shear fractured. Thereby, the vibration transmissibility between the superstructure and the ground surface was reduced (excitation [2]: 1.38, [4]: 1.03, [11]: 1.05times) compared to when the pile model was not fractured. However, the vibration transmissibility between the footing and the ground surface was slightly increased throughout the excitations (excitation [2]: 0.69, [4]: 0.73, [11]: 1.00times). It may be because the embedment depth of the footing was reduced, which caused the reduction of horizontal resistant pressure of soil for footing. Moreover, the vibration transmissibility between the ground surface and the input was reduced (excitation [2]: 2.21, [4]: 1.62, [11]: 0.92times). It may be because of the nonlinearization of the ground.

B. *Curvature of Pile Model*

FIGURE 9 shows the curvature distribution in the vertical direction of pile models according to strain gauges during maximum footing displacement in each excitation. The vertical axis shows the depth from the ground surface, and horizontal axis shows the curvature.

The bending moment distributions were larger at the head and middle portion of pile models. The plastic hinge was created during the No. 4 excitation at the pile head. The depth of the largest curvature in the middle portion of the front pile model was 2.86m, and in the back pile model it was 3.88m. This result indicates that the bending behavior of these pile models were double curvature bending mode as shown FIGURE 10.

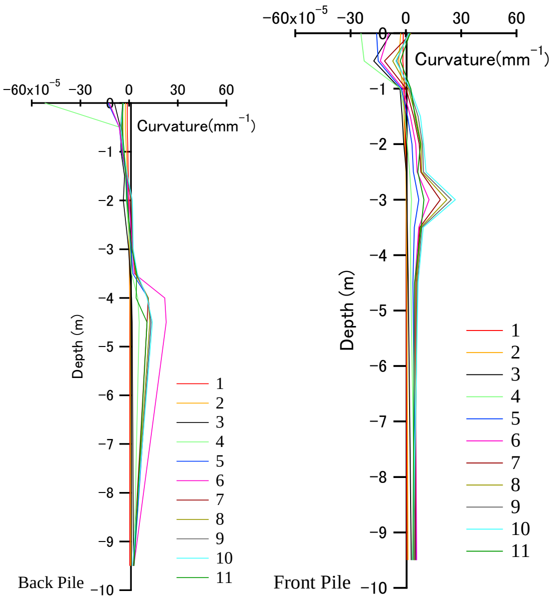


Figure 9. Curvature of the Front and the Back pile

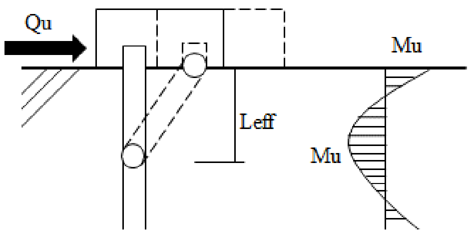


Figure 10. Double curvature bending mode

C. Ultimate Shear Strength of RC Pile Foundation

Fig. 11 shows the maximum inertial force at each excitation. The vertical axis shows the maximum inertial force and horizontal axis shows the maximum displacement of footing.

The horizontal line indicates the ultimate shear strength. The depth of the largest curvature in the middle portion of pile model L_{eff} (front pile: 2.86m, back pile: 3.88m) affects to calculate ultimate share strength. Shear span ratio is required to calculate ultimate shear strength, and is calculated by formula (1) if we presume that inflection point is half of L_{eff}.

$$\frac{M}{QD} = \frac{L_{eff}/2}{D} \tag{1}$$

The shear span ratio of front pile is 1.14, and the back pile is 1.55. To calculate the ultimate shear strength, AIJ Standard for Structural Calculation of Reinforced Concrete Structures [10] suggests formula (2).

$$Q_s = \left\{ \frac{0.115 k_u k_p \left(180 + F_c\right)}{M/QD + 0.12} + 2.7\sqrt{p_w \cdot {}_s\sigma_y} \right\} bj \tag{2}$$

In this formula, k_p is effective depth, k_u is collection coefficient, F_c is yield stress of mortar which is 14.8MPa in this experiment, P_w is reinforcement ratio, ${}_s\sigma_y$ is yield stress of reinforcement bar, σ_0 is axis direction unit stress, b is width of equivalent square cross section and j is stress center distance.

The shear strength of back pile is calculated using the shear strength of front pile. It is known that the load for back pile is smaller than the load for the front pile if the pile foundation has a group pile effect. The coefficient of pile group effect κ is calculated by formula (3), (4), and (5) [11].

$$\kappa = \left\{ a\left(\frac{R}{B} - 1.0\right) + 0.4 \right\} \tag{3}$$

$$a = 0.55 - 0.007\phi \tag{4}$$

$$\phi = 32.5 - 20.6\frac{D_r - 40}{100} \tag{5}$$

In these formulas, R is the space of pile models for shaking direction, so it is 7.5m in this experimental model. B is the diameter of the pile model and D_r is the density of soil.

In addition, horizontal resistance force of the embedded footing is calculated by formula (6)

$$Q_f = \frac{3}{2} K_p \gamma B l^2 \tag{6}$$

In this formula, K_p is the passive earth pressure coefficient, γ is unit weight of soil, l is the height of the footing.

From these formulas, ultimate shear strength was evaluated. Red line is the ultimate shear strength which combined the front pile shear strength, the back pile shear strength, and the resistance force of the embedded footing. It shows a case where the embedment of the footing is 0.55m. The one front pile strength was 2.47MN, the one back pile strength was 1.54MN, and the resistance force of footing was 0.14MN. Hence, the ultimate shear strength of the pile footing was 8.15MN. From this result, the maximum inertial force mostly corresponded to the evaluated ultimate shear strength, but it is a bit small. It may be because the coefficient of group pile effect was not evaluated suitably.

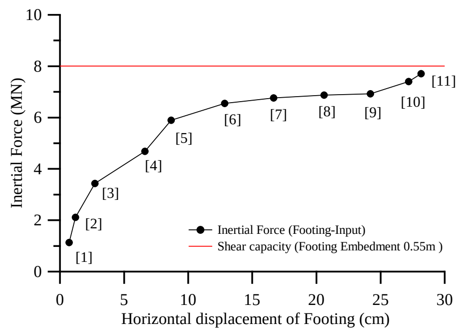


Figure 11. The maximum inertial force

V. Conclusion

This paper investigated the relationship between the damage of reinforced concrete pile and the response of the superstructure, also investigated the effects of embedded footing for the shear strength using a centrifuge shaking table. Based on these studies, the following results were obtained.

1) We used a pile model in this thesis. The flexural strength of the pile model reached over the full plastic moment. After that, it performed degradation behavior. The behavior of this pile model reproduced to a real reinforced concrete member.
2) The 11-different amplitude Rinkai waves were input under a 50G field in the shaking table test. The shear fracture occurred in the head of the pile model. In this soil-pile-superstructure interaction, the response of the superstructure was reduced when the fracture occurred in the pile.
3) The residual settlement and rotation angle were still small even though flexure fracture occurred. However, the residual rotation angle was very big after shear fracture occurred. Hence, there is a possibility that the pile is flexure fractured after a massive earthquake although the building seems not to be settled or rotated.
4) The maximum inertial force mostly corresponded to the evaluated ultimate shear strength. A future task is to propose an appropriate evaluation method of the pile group effect.

In future work, we will conduct other shaking table tests which are different parameters (ex. density of soil, dimension and strength of RC piles, pile spacing). Then, organize these results and clarify the relationships of pile fracture and dynamic response of a superstructure.

Acknowledgment

This paper reports a continuing research supported in part by the Obayashi Federation (Number: 2018-35, Principal Investigator: Kazuhiro Hayashi).

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