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Relationship between fracture behavior of RC pile foundation and maximum inertial force acting on the superstructure

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ABSTRACT: This study investigates the fracture behavior of reinforced concrete piles and the relationship between pile foundation damage and the dynamic response of the superstructure. The RC pile model had a diameter of 25 mm (prototype: 1.25 m) and consisted of mortar, four main reinforcements and a spiral hoop reinforcement. For the centrifuge shaking table test, we used a specimen consisting of the pile models, Toyoura dry sand with 60% relative density and a superstructure model. Shaking was conducted under 50 g field using seven Rinkai waves of different amplitudes. The test results showed plastic hinges occurring at the pile heads when the maximum input acceleration was 367 gal. Eventually, shear failure occurred at the pile heads and the inclined deformation of the superstructure increased at maximum shaking. This paper also examined the development of damage in the pile foundation and the maximum inertial force acting on the superstructure.

1 INTRODUCTION

After the massive earthquakes that struck Japan over the past few decades, such as the 1995 Southern Hyogo Prefecture Earthquake and the 2011 off the Pacific coast of Tohoku Earthquake, many pile members had been found to be damaged (Ohba & Hamakawa 1997, EC-RHAED 1998, Motosaka & Mitsuji 2012, Tokimatsu et al. 2012, JEC-RGEJED 2015). However, the mechanism behind the relationship between pile damage behavior under earthquakes and the maximum response acceleration of the superstructure is still unclear.

Few experimental studies are available on pile fracture behavior of the soil-pile-superstructure system under a strong earthquake. In particular, studies on large-diameter reinforced concrete (RC) piles are limited. Tamura studied the effect of damage in reinforced concrete piles (RC piles) under liquefied ground on the superstructure response using a large shaking table (Tamura et al. 2000). Kimura investigated the damage behavior and ultimate state of RC piles in dry sand under static horizontal loading in the centrifugal acceleration field (Kimura et al. 1998). Higuchi used the centrifuge shaking table test on large-diameter RC pile models and examined the vibration response when part of the reinforcing bar yielded (Higuchi et al. 2012).

On the other hand, we could not find experimental studies on the fracture behavior of large-diameter RC piles in dry sand and on the strong nonlinear seismic response of the superstructure when the pile foundation reaches the ultimate state. The authors verified the behavior of bending fracture of large diameter concrete piles and the ultimate response of the superstructure using a centrifuge test apparatus (Hayashi & Tamura 2017). This study investigates the shear fracture behavior of reinforced concrete piles and the relationship between pile foundation damage and the dynamic response of the superstructure.

2 PILE MODEL FOR CENTRIFUGE TEST

2.1 *Pile model cross section and material*

The experiment was carried out in a 50 g field using a centrifuge test apparatus located at the Disaster Prevention Research Institute, Kyoto University. In this paper, we used a simple mortar pile model which can reproduce, to some extent, the nonlinear elasto-plastic behavior of concrete piles and the degradation behavior after maximum strength is applied. Figure 1 shows the cross section of the pile model used in the experiment. Table 1 shows the pile model material characteristics. The diameter D of the pile model is 25 mm (D = 1.25 m in full scale). The pile model consisted of mortar (compressive strength of 6.0 MPa), four main reinforcements (1.2 mm diameter) and a spiral hoop reinforcement (0.8 mm diameter at intervals of 15 mm). The mortar was formulated with a water cement ratio of 0.85 and a cement sand ratio of 2.8, in order to increase the fluidity of the mortar to properly fill up the pile model cross section diameter of 25 mm. The main reinforcement ratio (p_r, Ratio of cross-sectional area of main reinforcement to cross-sectional area of pile) is 0.92%. Note that this value is slightly smaller than a full-size cross section example (D = 1800 mm, p_r = 1.13%) (AIJ 2004).

2.2 *Static loading test*

Figure 2a shows the outline of the static loading system for the pile model. In the figure, the lower end of the pile model is rigidly joined to a reaction force jig while the upper end is a cantilever connected to a horizontal loading device via a pin and vertical roller jig. The broken line shows the position of the critical cross section. A horizontal pushover loading protocol was used. At the pile model critical cross section, the ratio of active axial force $n = N/N_0 = 0.24$ (model scale values of member yielding axial force, i.e. summation of the product of mortar cross sectional area and compressive strength and the product of aluminum rod cross sectional area and yield stress, N_0 = 4652 N and acting axial force N = 1126 N), was adjusted. To measure displacement of the specimen, a laser displacement transducer in the horizontal direction was installed 200 mm above the critical section.

Figure 2b shows the relationship between bending moment and deformation angle for the pushover converted to full scale. In the figure, the experimental result is indicated by the solid line. In addition, the calculated full plastic moment M_p (2.11 MN·m for the full scale model) is indicated by the dashed line. The pile model used in this study has a deformation capacity exhibiting the full plastic moment M_p, which turns into gentle deterioration after reaching the maximum bending strength. When the bending moment reached M_p, the compression strain of the critical cross section was 2,584μ. The pile model in Figure 1 can roughly reproduce the plastic deformation behavior of a large diameter RC pile of the predominant bending fracture. But strength deterioration by buckling of main reinforcement cannot be expressed. This is because the sectional area of one main reinforcement of the model is larger than the actual pile.

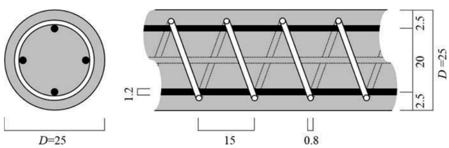
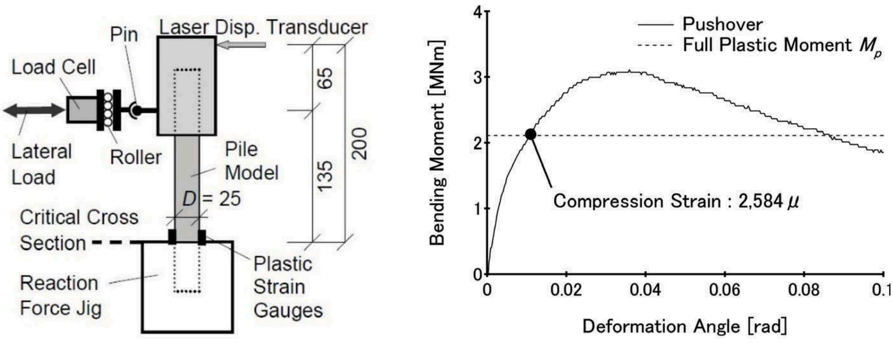


Figure 1. Cross section of the pile model. (unit: mm)

Table 1. Material characteristics.

Material	Young's Modulus	Comp. Strength, Yield Strength
Mortar	8.5 kN/mm^2	6.0 N/mm^2
Main reinforcement	205 kN/mm^2	374 N/mm^2
Hoop	205 kN/mm^2	432 N/mm^2



(a) Static loading system. (unit: mm) (b) Moment-deformation angle relation.

Figure 2. Static loading test of the pile model.

3 DYNAMIC CENTRIFUGAL MODEL TEST

3.1 *Experimental model*

Similar to the static loading test in the previous section, the experiment was conducted in a 50 g field using a centrifugal loading device at Kyoto University's Disaster Prevention Research Institute. The experimental model for the centrifuge shaking table test is shown in Figure 3 and the model specification is shown in Table 2. The footing is supported by four 200 mm long piles (Figure 1) with rigid connections at the pile head and bottom. The mass of the footing is 1.77 kg while the mass of the superstructure is 7.42 kg. The primary natural period of the superstructure is 0.013 seconds (0.63 seconds in full scale). The axial force ratio n of the pile model is about 0.24, which is roughly equivalent to the static loading experiment in the previous section. The primary natural period of the superstructure and the acting axial force of the pile are equivalent to a 10 story RC building (roughly a 35 m high building, with 5 to 6 m column spans).

The four piles have a center to center distance of 150 mm (6*D* with respect to the pile diameter, 7.5 m in full scale) in the shaking direction, and a center spacing of 62.5 mm (2.5*D*, 3.13 m in full scale) in the orthogonal direction. The soil consists of Toyoura dry sand with a relative density of 60% (slightly dense condition).

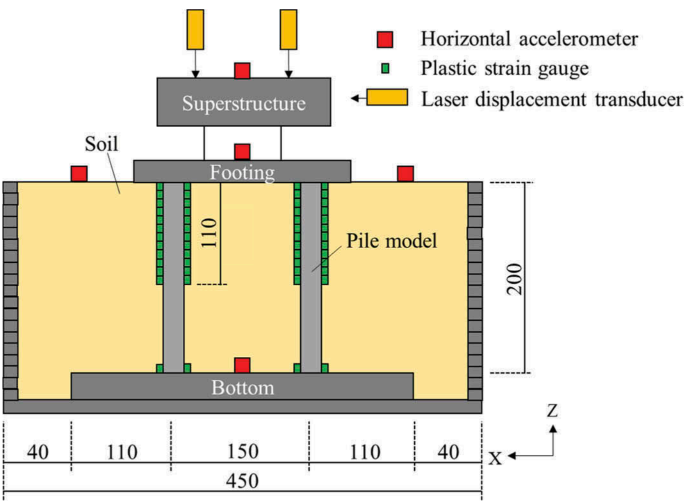


Figure 3. Experimental model for the centrifuge shaking table test. (unit: mm)

Table 2. Model specification for the centrifuge shaking table test.

		Symbol	Unit	Model	Full Scale
	Length	L	m	0.2	10
	Diameter	D	mm	25	1250
Pile	Yielding axial force	N_0	kN	4.65	11,630
Footing	Mass	M_f	kg	1.77	2.21×10^5
Superstructure	Mass	M_s	kg	7.42	9.28×10^5
	Natural period	T_s	s	0.013	0.63

3.2 *Shaking and measurement plan*

The centrifuge shaking table test was programmed to impose gradually progressive damage to the mortar pile model using gradually increasing amplitudes of horizontal unidirectional input waves. A total of seven Rinkai waves (JBDPA 1992) of different amplitudes were used. The maximum acceleration of each shaking ranged between 39 to 836 gal (from shaking I to VII).

As illustrated in Figure 3, we used accelerometers to measure the horizontal acceleration of the superstructure, footing, ground surface and bottom of the soil tank (input). Accelerometers capacity were 50G. Also, the vertical displacement and inclination angle of the superstructure and the horizontal displacement of the footing section were measured by laser displacement meters (on a fulcrum in the shaking table). Similar to the static loading experiment in the previous chapter, two plastic strain gauges were also attached to the surface of the pile models to measure axial strain at the pile heads.

3.3 *Test results*

Figures 4–6 show the main time history (0 to 50 s) of the horizontal acceleration of the superstructure, footing, ground surface and input (bottom of the soil tank), vertical displacement

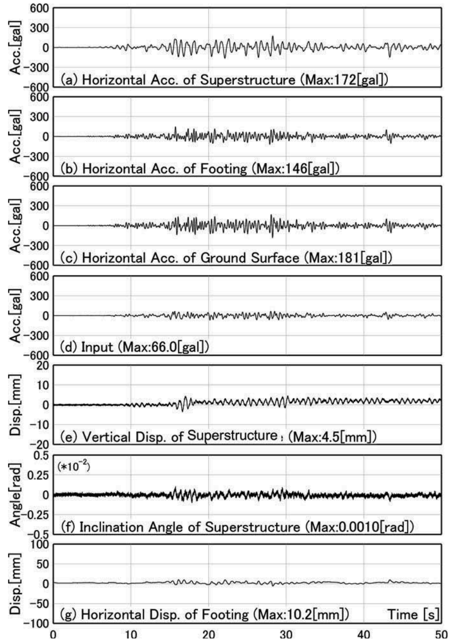


Figure 4. The main time history of shaking II.

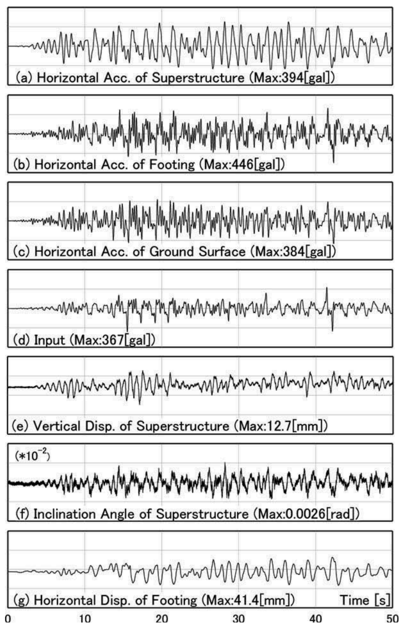


Figure 5. The main time history of shaking IV.

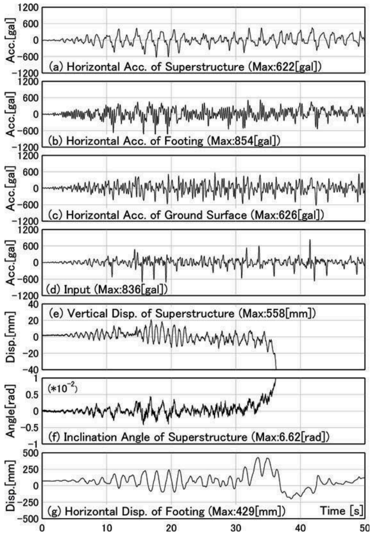


Figure 6. The main time history of shaking VII.

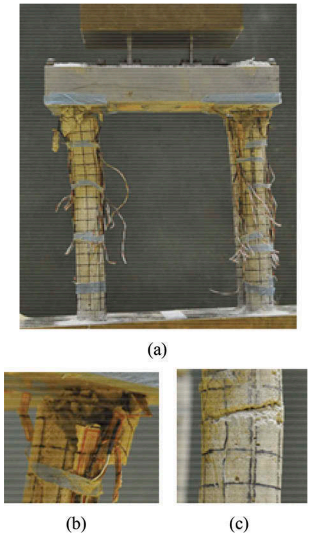


Figure 7. Pile member damage.

and inclination angle of the superstructure, and horizontal displacement of the footing for shaking II, IV and VII respectively. Figure 7 shows the damage on pile models after the centrifuge test.

According to the strain gauge measurements, the maximum compression strain exceeded 2584μ during shaking IV, which means that plastic hinges occurred at the pile heads. However, there was no significant residual deformation in the superstructure. This result shows that mild damage to the piles does not necessarily manifest as a visible change in the superstructure. During shaking VII, damage to the pile model further progressed and the inclined deformation of the superstructure rapidly increased. A survey after all shakings were over revealed that shear failure occurred at the pile heads and both the superstructure and footing leaned over, as shown in Figure 7. This means that the shear failure of the pile models occurred during shaking VII.

During shaking II (with maximum acceleration at 18% of that from shaking IV) where plastic hinges did not form, the maximum acceleration of the superstructure was 261% of the input acceleration. On the other hand, during shaking IV, the maximum acceleration of the superstructure was 107% of the input. Furthermore, during shaking VII, superstructure acceleration was only 74% of the input.

3.4 *Damage on pile members and maximum inertial force acting on the superstructure*

Figure 8 shows the maximum inertial force for each shaking, with the horizontal axis indicating maximum horizontal displacement of the footing and the vertical axis indicating maximum inertial force of the superstructure and footing. The dotted lines show elastic stiffness based on the results of shaking I. Until shaking III where plastic hinges did not form, the experimental model maintained a linear elastic curve.

After a plastic hinge formed at a pile head (during shaking IV), the maximum inertial force against the maximum displacement relation became nonlinear. This relationship does not show negative slope until shaking VI.

The maximum inertial force dramatically declined during shaking VII, when shear failure occurred at the pile heads. The soil-pile-superstructure system exhibited a deteriorating behavior, with increasing horizontal displacement of the footing and decreasing inertial force acting on the superstructure, when shear failure occurs at the pile members.

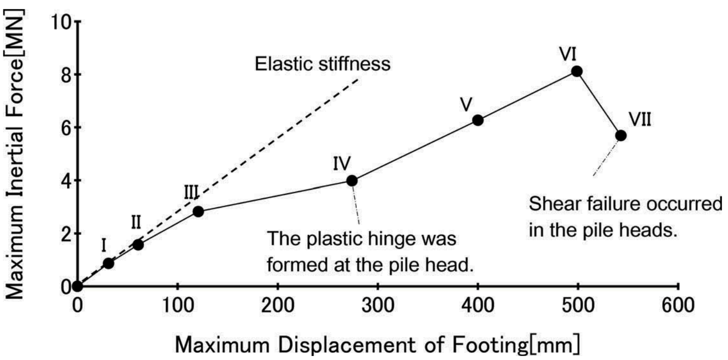


Figure 8. Maximum inertial force at each shaking.

4 CONCLUSIONS

This paper investigated the relationship between damage in large cross section RC piles and the dynamic response of the superstructure using a centrifuge test apparatus. In the centrifuge shaking table test, shaking was conducted under a 50 g field using a total of seven Rinkai waves of different amplitudes. Results showed that shear failure occurred at the pile heads and the inclined deformation of the superstructure rapidly increased in the experimental model of the soil-pile-superstructure system.

The following results were obtained from the tests.

1. After a plastic hinge formed at a pile head, the maximum inertial force of the superstructure against the maximum displacement of the footing relation became nonlinear. This relationship does not show negative slope until shear failure occurred at the pile head.
2. There was no significant residual settlement and inclination in the superstructure until shear failure occurred. This result shows that bending fracture of the pile members does not necessarily manifest as a visible change in the superstructure.
3. When shear failure occurs at the pile members, the system exhibits a deteriorating behavior, with the horizontal displacement and inclined deformation of the footing rapidly increasing while, conversely, the inertial force acting on the superstructure decreases.

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