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Centrifuge Model Test on the Dynamic Buckling Behavior of RC Slender Pile in Saturated Ground

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Abstract

In the current Japanese design code for pile foundations, the buckling behavior of pile members is not taken into account. This is because the surrounding ground restrains buckling of pile members. However, when the ground liquefies, the stiffening force for horizontal deformation of the pile weakens, and when a slender pile is subjected to high axial compression forces as a result of increased vertical loads that occur at the overturning moment of superstructure under a strong earthquake, flexural buckling may occur in pile members in soft ground. The buckling behavior of steel piles in liquefied ground has been studied previously. This study investigated the dynamic buckling behavior of reinforced concrete (RC) piles using a centrifuge model.

In this study, the diameter of the RC pile model was 13 mm (prototype scale: 0.52 m). The pile model consisted of mortar (16.2 MPa in compressive strength), 4 main reinforcements (1.2 mm in diameter), and a spiral hoop reinforcement (0.8 mm in diameter at intervals of 8 mm). In a shaking table test under a 40 G field, the specimens used RC pile models, saturated soil (Toyoura sand) with a relative density of 30%, footing, and a superstructure model with a natural period of 0.027 sec (prototype scale: 1.10 sec). Shaking was a Rinkai wave with a maximum acceleration of 738 gal. The lateral displacement of the pile foundation was fully restrained so that the only the vertical load (the sum of the sustained load of the superstructure and the temporary load at the overturning moment) acted on the piles.

Buckling failure occurred in the pile members of the centrifugal model after the ground was liquefied. All pile members formed three plastic hinges at the pile head, lower side, and middle position. After the pile buckled, the footing sank, and the seismic response of the superstructure decreased. The measured buckling strength of the RC pile model was evaluated by extending the tangent modulus theory (Engesser and Schanley). Because concrete (mortar) is a non-linear material, the tangential stiffness changes according to the acting axial force. Also, even if the ground liquefies, the stiffening force for horizontal deformation of the pile members does not become zero. Therefore, in order to evaluate the buckling strength of RC pile members in liquefied ground, it is necessary to consider the influence of the non-linearity of concrete and the decrease in the stiffening force of the surrounding ground.

Keywords: Liquefied ground, Reinforced Concrete, Tangent Modulus Theory, Nonlinear, Strength Evaluation

1. Introduction

In the current Japanese design code for pile foundations [1], the buckling behavior of pile members is not taken into account. This is because the surrounding ground restrains buckling of the pile members. However, when the ground liquefies, the stiffening force for horizontal deformation of the pile weakens. Therefore, when a slender pile is subjected to high axial compression forces as a result of increased vertical loads at the overturning moment of superstructure, as under a strong earthquake, flexural buckling may occur in pile members in soft ground.

The buckling behavior of steel piles in liquefied ground has been studied previously. Kimura et al. [2, 3, 4] examined the dynamic buckling behavior of steel piles experimentally and proposed a formula for evaluating buckling strength. However, the buckling behavior of reinforced concrete (RC) piles in liquefied ground has not been studied. This study investigated the dynamic buckling behavior of RC piles using a centrifuge model and proposes a method for evaluating the buckling strength of RC piles in liquefied ground.

2. Dynamic Centrifugal Test

2.1 Experimental model

The experiment was carried out in a 40 g field using centrifuge test apparatus located at the Disaster Prevention Research Institute, Kyoto University [5]. The soil-pile-superstructure interaction model for the centrifuge shaking table test is shown in Fig. 1 and the model specification is shown in Table 1. The footing was supported by four 260 mm slender piles with rigid connections at the pile head and bottom. The soil consists of Toyoura saturated sand with a relative density D_r = 30%.

Fig. 2 shows the cross section of the RC pile model used in the experiment. The diameter D of the pile model was 13 mm (D = 0.52 m in full scale). The pile model consisted of mortar (compressive strength of 16.2 MPa), four main reinforcements (1.2 mm diameter) and a spiral hoop reinforcement (0.8 mm diameter at intervals of 15 mm).

The mass of the footing was 1.32 kg while the mass of the superstructure was 7.45 kg. The footing and the superstructure were connected by two leaf springs. The primary natural period of the superstructure was 0.027 seconds (1.10 seconds in full scale). The primary natural period of the superstructure was equivalent to a 20 story RC building. The lateral displacement of the footing was fully restrained so that the only the vertical load (the sum of the sustained load of the superstructure and the temporary load by overturning moment) acted on the piles. In this experiment, buckling failure occurred in the pile members by applying the large varying axial force due at the overturning moment of superstructure.

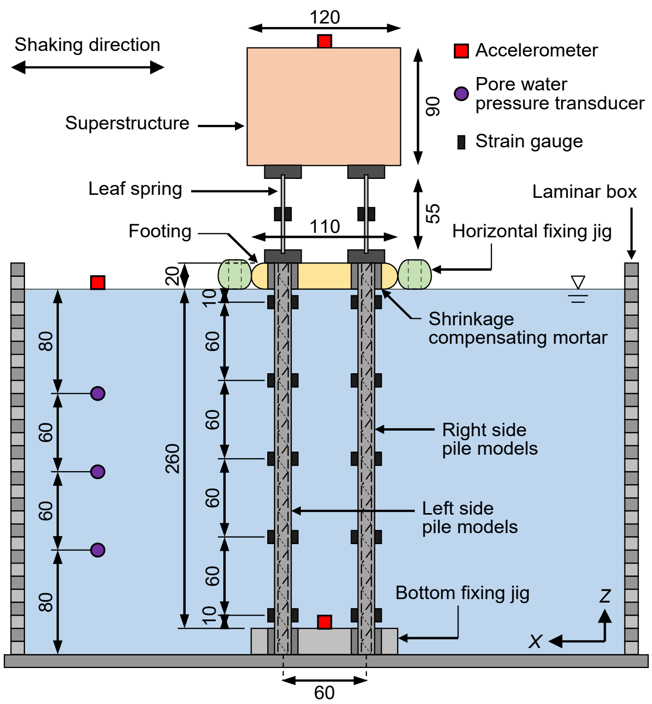


Fig. 1 – Shaking test model (Unit: mm)

Table 1 – Details of shaking test model.

		Sym.	Unit	Model	Prototype
Pile model	Length	L	m	0.26	10.4
	Diameter	D	mm	13	520
Footing	Mass	M_f	Kg	1.32	8.45×10^4
Super structure	Mass	M_s	Kg	7.45	4.77×10^5
	Natural period	T_s	sec.	0.0274	1.10

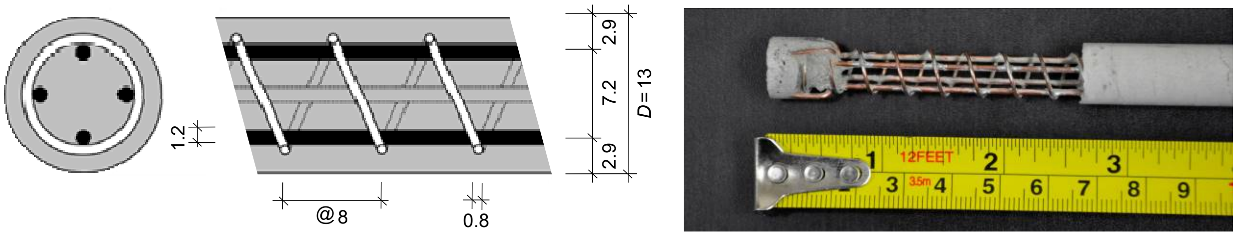


Fig. 2 – RC pile model (Unit: mm)

2.2 Shaking and measurement plan

In the centrifuge shaking table test, a horizontal unidirectional input wave (Rinkai wave [6]) was used. The maximum acceleration was 738 gal. Accelerometers were used to measure the horizontal acceleration of the superstructure, ground surface and bottom of the soil tank (input), as shown in Fig. 1. The pore water pressure transducers were placed at a depth of 80 mm, 140 mm and 200 mm in saturated sandy ground (3.2 m, 5.6 m and 8.0 m in full scale). Plastic strain gauges were also attached to the surface of the pile models to measure axial strain, and strain gauges were attached to the surface of the leaf spring to measure the varying axial force due to overturning moment of the superstructure (shown at full scale below unless otherwise stated).

3. Buckling Strength Evaluation Formula for an RC Pile in Liquefied Ground

3.1 Buckling strength for RC member

According to the ACI-318 building code [7], the Euler buckling strength of RC slender columns can be evaluated by the following equation.

$$P_{cr} = \frac{\pi^2 EI}{l_k^2} \qquad (1)$$

$$EI = 0.2 E_c I_c + E_s I_s$$

where

E_c is the Young's modulus of the concrete;
I_c is the moment of inertia of the concrete;
E_s is the Young's modulus of the steel rebar;
I_s is the moment of inertia of the steel rebar;
l_k is the effective length of an RC column.

In addition, concrete is a non-linear material, and the tangential stiffness changes according to the acting axial force. Considering the nonlinearity of the concrete material, the buckling curve of the RC column can be evaluated by the following equation based on the tangent modulus theory (Engesser and Schanley).

$$\frac{\sigma_{cr}}{\sigma_0}=\frac{P_{cr}}{N_0}=\frac{\sqrt{4\Lambda^4(1-r)+1}-1}{2\Lambda^4(1-r)} \quad (2)$$

$$\Lambda=l_k\Big/\sqrt{\frac{\pi^2 E_t I}{N_0}},\quad N_0=\sigma_B A_c+\sigma_y A_s,\quad A=A_c+A_s,\quad \sigma_{cr}=P_{cr}/A,\quad \sigma_0=N_0/A$$

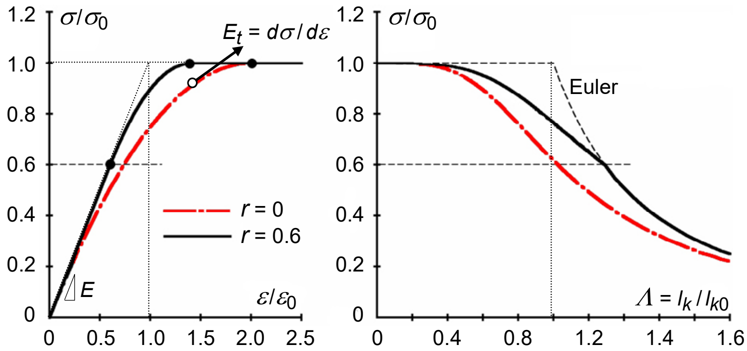
where

σ_B is the compressive strength of the concrete;
A_c is the area of the concrete;
σ_y is the yield strain of the steel rebar;
A_s is the area of the steel rebar;
r is the limit of proportionality on the stress-strain relationship (shown in Fig. 3 (a)) .

Assuming that the RC member's stress-strain relationship is parabolic, as shown in Fig. 3 (a) and equation (3), the buckling curve can be calculated explicitly, as shown in Fig. 3 (b). In this paper, the limit of proportionality $r = 0$ was adopted.

$$\frac{\sigma}{\sigma_0}=\begin{cases}\varepsilon/\varepsilon_0 & \varepsilon/\varepsilon_0\le r\\ \dfrac{1}{4(1-r)}\left[\dfrac{\varepsilon}{\varepsilon_0}\left(4-2r-\dfrac{\varepsilon}{\varepsilon_0}\right)-r\right] & \varepsilon/\varepsilon_0>r\end{cases} \quad (3)$$

$$\frac{E_t}{E}=\begin{cases}1 & \varepsilon/\varepsilon_0\le r\\ \dfrac{1}{2(1-r)}\left(2-r-\dfrac{\varepsilon}{\varepsilon_0}\right) & \varepsilon/\varepsilon_0>r\end{cases} \quad (4)$$



(a) stress-strain relationship (b) buckling curve

Fig. 3 – Parabola model

3.2 Buckling strength of an RC member in liquefied ground

Even if the ground liquefies, the stiffening force for horizontal deformation of the pile members does not become zero. Therefore, in order to evaluate the buckling strength of RC pile members in liquefied ground, it is necessary to consider the influence of the non-linearity of concrete and the decrease in the stiffening force of the surrounding ground. Kimura et al. proposed a formula to evaluate the buckling strength of steel piles in liquefied ground [4]. As authors are considering the nonlinear stiffness of concrete members, the buckling strength evaluation formula in [4] was expanded as follows.

$$P_{cr} = \frac{\pi^2 E_t I}{l^2}\alpha \tag{5}$$

$$\alpha = 4 + \frac{3}{4}\left(\frac{l}{\pi}\right)^4 \frac{K_c}{E_t I} \qquad \left(l \le 2\pi \sqrt[4]{\frac{E_t I}{3K_c}} \right)$$

$$\alpha = \left[8\left(1-\frac{1}{\sqrt{3}}\right) + 2\left(\frac{l}{\pi}\right)^2 \sqrt{\frac{K_c}{E_t I}} \right]\left[\frac{3}{4} + 2\left(\frac{\pi}{l}\right)^2 \sqrt{\frac{E_t I}{K_c}} \right] \qquad \left(l > 2\pi \sqrt[4]{\frac{E_t I}{3K_c}} \right)$$

$$K_c = k_{h1} D, \quad k_{h1} = 80 E_r \overline{D}^{-3/4}, \quad E_r = (1-r_u) E_0 \ge 0.01 E_0$$

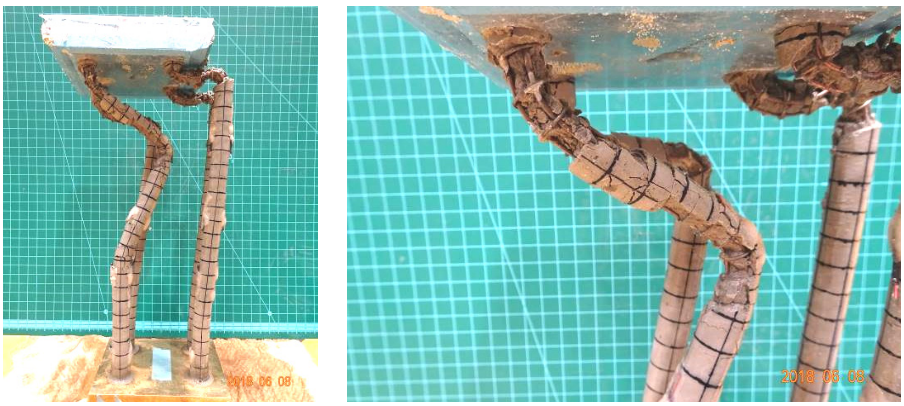
where

E_0 is the deformation modulus of Toyoura dry sand (in the case of D_r = 30%, E_0 = 3.50MN/m^3 [5]);
r_u is the excess pore water pressure ratio;
l is the pile length.

4. Test Results

Fig. 4 shows the damage to pile models after shaking. Buckling failure occurred in the pile members of the centrifugal model after the ground was liquefied. All pile members formed three plastic hinges at the pile head, lower side, and middle position. After the pile buckled, the footing sank into the liquefied ground.

Fig. 5 shows the main time history (0s to 25s) of shaking table test. Figs. 5(a) to (c) show the results of horizontal acceleration on the superstructure, ground surface and input (bottom of the soil tank). Fig. 5(d) shows underground excess pore water pressures. Figs. 5(e) and (f) show the varying axial force on the pile models. Fig. 5(g) shows the axial strain on the pile heads. The excess pore water pressure rose sharply after 6 seconds so the soil was liquefied. Fig. 5 (e) and (f), show the large varying axial force that occurred in the pile models. However, after 18 seconds, the variation amount of the axial force decreased. Hereafter, the amplitude of the response acceleration of the superstructure also decreased, and the axial strain on the pile head became unstable (shown in Fig. 5(a) and (g)).The buckling failure of the pile model presumably occurred after 18 seconds.



(a) Panorama (b) Pile head

Fig. 4 – Pile models at the after shaking

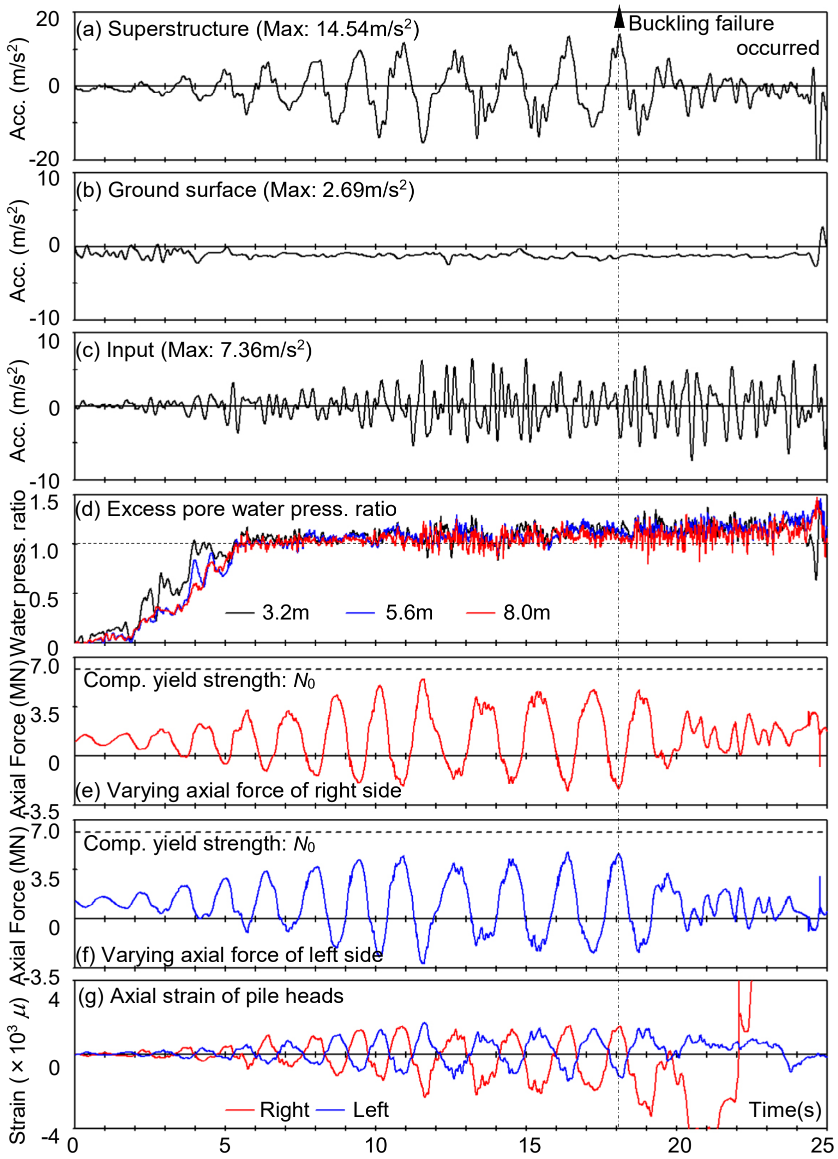


Fig. 5 – Time histories (0-25s)

Fig. 6 shows a comparison between the shaking table test result and the buckling curve based on the proposed evaluation formula (5). The vertical axis is the axial force ratio P_{cr} / N_0. The horizontal axis is the dimensionless slenderness ratio $\overline{\Lambda}$ expressed by the following equation:

$$\overline{\Lambda} = l \Big/ \sqrt{\frac{\alpha \pi^2 E_t I}{N_0}} \quad (6)$$

The maximum acting axial force of the pile models indicated by black circle and white circle in the fig. 6 correspond to the buckling strength evaluation formula (5).

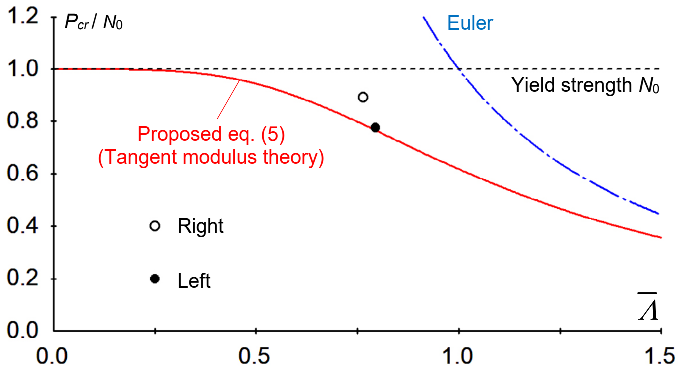


Fig. 6 – Test result and buckling curve

5. Conclusions

This paper investigated the dynamic buckling behavior of reinforced concrete piles using centrifuge test apparatus. In the centrifuge shaking table test, shaking was conducted under 40 g.

The following results were obtained:

1) Buckling failure occurred in the pile members of the centrifugal model after the ground was liquefied. All pile members formed three plastic hinges at the pile head, lower side, and middle position.

2) The measured buckling strength of the reinforced concrete pile model of the centrifuge model was evaluated by extending the tangent modulus theory (Engesser and Schanley). In order to evaluate the buckling strength of RC pile members in liquefied ground, it is necessary to consider the influence of the non-linearity of concrete and the decrease in the stiffening force of the surrounding ground.

6. Acknowledgements

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