Experimental Study on Lateral Load Capacity of RC Pile Group Foundation using a Centrifuge Model

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Abstract

In past earthquake disasters, the pile foundations of many buildings were damaged. However, few researchers have examined the strongly nonlinear behavior of soil-pile-superstructure interaction. Moreover, there are only a few studies related to large diameter RC piles, so the nonlinear behavior of RC pile foundations and their ultimate strength evaluation is unclear.

In this study, a static loading test was conducted under a 50G centrifuge field to investigate the ultimate strength of large diameter RC pile foundations. The centrifuge test model was composed of dry soil, RC pile models, footing, and superstructure. The footing was supported by four pile models in a vertical direction. The footing was connected to a horizontal static loading system and subjected to horizontal cyclic loading under a 50G field. The diameter of the pile model was 25mm (1.25m in full scale). The pile model consisted of mortar, four main reinforcement bars and a spiral hoop reinforcement. The diameter of the main reinforcement bars was 1.2mm, and the diameter of the hoop reinforcement was 0.8mm. The length of the pile model was 320mm (16m in full scale). The relative density of dry soil (Toyoura dry sand) was 60%. The mass of the superstructure was 7.45kg (931ton in full scale), and the mass of the footing was 1.77kg (221ton in full scale). The vertical load for one pile was 2.8MN in full scale. This value corresponds to a 10-floor RC building.

At the horizontal cyclic loading, bending failure occurred in all pile heads and in the middle portion of the pile models. The lateral strength of test model decreased after manifest the maximum value. This is because the pile models showed nonlinear strength deteriorating behavior. This behavior is the same as in a real RC structural member.

The authors also tried to evaluate the ultimate lateral strength (lateral loading capacity) of a pile foundation. The ultimate strength when a single pile breaks as bending failure mode can be calculated by the simple equation proposed by Broms. It is known that the strength of rear piles is smaller than piles at the front if the pile foundation is affected by pile group effect. Broms's simple equation targets the ultimate strength of a single pile and doesn't consider pile group effect. To evaluate the ultimate strength of RC pile foundations accurately, in this study the authors expanded Broms's simple equation. The evaluation value calculated by proposed equation was compared to the measured ultimate horizontal strength during the static loading test. The test results are mostly corresponded to the evaluated value for maximum strength.

Keywords: Static Loading Test, Dry Sand, Bending Failure, Nonlinear behavior, Strength Evaluation

1. Introduction

In the 2016 Kumamoto Earthquake (the main shock of the earthquake was measured at magnitude 7.3), it was reported that several pile foundations of building were damaged [1]. Mashiki city hall of a RC pile foundation structure was damaged and inclined by the earthquake. Through damage investigation after the earthquake, it was found that some piles were severe damaged. Therefore, the city hall was forced to be reconstructed. The relationship between damage of piles and dynamic response of superstructure has been unclear for the most part. Also, the evaluation method of ultimate lateral strength of pile group foundation has not been established.

To evaluate ultimate strength of pile foundation, Broms proposed theoretical method for single pile. The proposed equation considers the strongly nonliner behavior of pile member and ground [2]. However, few researchers have examined the strongly nonlinear behavior of soil-RC pile foundation structure interaction based on experiments. Kimura et al., conducted pushover loading and cyclic loading tests using a small diameter RC pile models on dry sand under a centrifuge field [3]. According to the test result of load - deformation relationship and observation of test specimen, the RC pile models had occurred the bending fracture. The evaluation method of ultimate strength hasn't been discussed. Higuchi et al., examined soil- large diameter RC pile interaction behavior until the main bar of pile models yielded, using a dynamic centrifuge test [4]. It indicates that the dynamic response of RC pile can be simulated at the FEM analysis considering the nonlinearity of soil and piles. Tamura conducted shaking table tests using a large scale laminar shear box [5]. It revealed the dynamic behavior and failure mechanisms of RC pile models during soil liquefaction. The diameter of RC pile models was 150 mm. Even among these studies, the strongly nonlinear behavior of soil - large diameter RC pile interaction hasn't been revealed. Also, pile group effect hasn't been considered to evaluate the ultimate strength of pile foundation in the previous study.

Our research group investigated the fracture behavior of large diameter RC piles and the relationship between damage of pile member and dynamic response of superstructure [6]. The shaking table test of soil - large diameter RC pile - superstructure interaction system under the centrifuge field was conducted. The shear failure occurred at the pile heads and caused the large inclined deformation of the superstructure by strong input motions. When shear failure occurs, the interaction system exhibited a deteriorating behavior, and the inertial force acting on the superstructure decreased.

The authors aim to evaluate ultimate strength of large diameter RC pile group foundation considering the pile group effect when the bending failure occurred. In this study, static loading test was conducted on a soil-RC pile foundation interaction system under a 50G centrifuge field. Also, the authors expanded Broms's equation and proposed an evaluation formula considering pile group effect. The evaluated strength was compared with the test result.

2. RC pile model for centrifuge test

2.1 RC pile model

The experiment was conducted under a 50G field using the centrifuge test system of the Disaster Prevention Research Institute at Kyoto University. A RC pile model (hereinafter called 'the pile model') that could reproduce the elasto - plastic behavior was used to conduct the experiment. Figure 1 shows the details of the pile model. The pile model was designed to reproduce the elasto-plastic behaviour of concrete piles. It consisted of mortar, 4-main reinforcement bars (diameter: 1.2mm, yield strength:374N/mm^2), and a spiral hoop reinforcement bar at intervals of 7.5mm (diameter: 0.8mm, yield strength:432N/mm^2). The diameter of the pile model was 25mm (full scale: 1.25m). Table 1 shows a comparison of pile cross sections: the main reinforcement ratio and the hoop reinforcement ratio of the pile model almost correspond to the example cross section suggested by design examples of foundation structures in Japan [7]

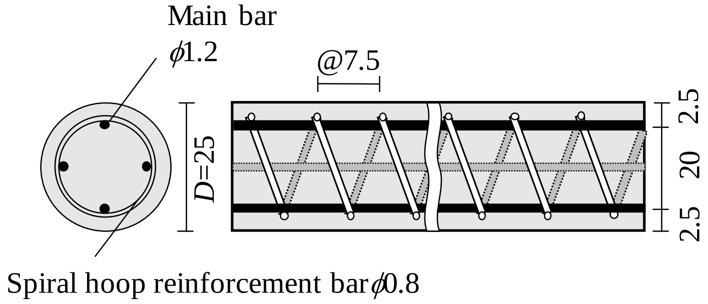


Fig. 1: Cross section of RC pile model (mm)

Table 1: Comparison of pile cross section

		Pile Model (Model scale)	Example cross-section (Real scale)
Diameter		25mm	1800mm
Main reinforcement bar	Rebar	4-ϕ1.2	45-D29
	Ratio	0.92%	1.13%
Hoop reinforcement bar	Rebar	ϕ0.8@7.5	D13@150
	Ratio	0.27%	0.26%

2.2 Bending and compression loading test

The bending and compression loading test was conducted to evaluate the performance of the pile model. Figures 2 shows the loading system of the test. The bottom of the pile model was rigidly jointed to a reaction force jig, and the top was connected to a horizontal loading device by a pin jig and a vertical roller jig. The horizontal deformation was measured by a laser displacement transducer. The horizontal cyclic loading was input to 47.5mm (shear span ratio=1.9*D*, full scale: 2.375m) above the critical section, and the loading device was controlled according to rotation angles of 0.005, 0.01, 0.02, 0.04, 0.06, 0.08, 0.1, and 0.15 rad. The rotation angle of the pile model was calculated using the distance between the laser displacement transducer and the critical section (47.5mm). The compressive strength of the mortar of pile model was 14.8 Mpa. The axial force for the pile model was 1,126N (full scale: 2.8MN). It was same value as the axial force for each pile model of the static loading test, which is described later. The ultimate strength(loading capacity) of the pile model in this test is calculated as equation (1)

$$Q_u = \frac{M_u}{L} \tag{1}$$

where M_u is the full plastic moment of the pile model, and L is the shear span (47.5mm).

Figure 3 shows the relationship between load and rotation angle in full scale. The red line indicates the calculated ultimate strength(loading capacity, full scale: Q_u= 1.2MN). The RC pile model used in this study performed degradation behaviour after reached ultimate strength. This behaviour reproduced to a real RC member.

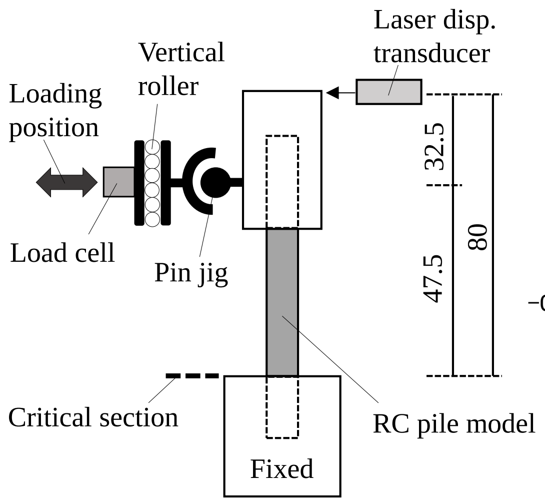


Fig. 2: System of the test (mm)

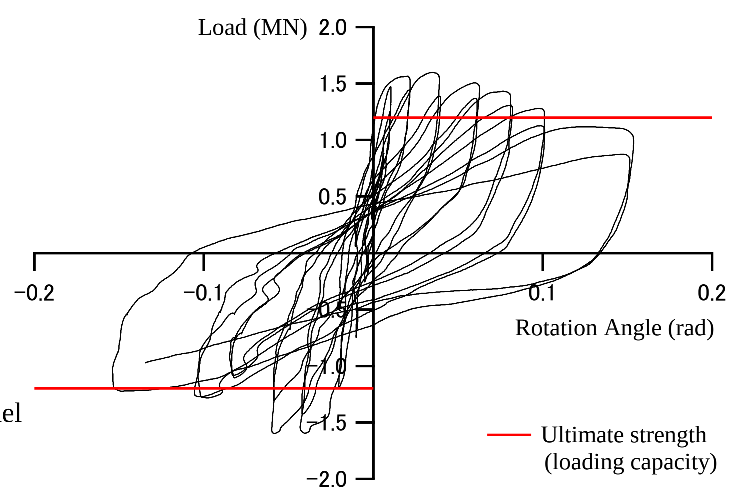


Fig. 3: Test result

3. Static loading test of dry soil - RC pile foundation interaction

3.1 Specimen of the loading test

The static loading test was conducted under a 50 G field to investigate the dry soil-RC pile foundation interaction. Figure 4 shows the specimen for the centrifuge test and Table 2 shows its properties. The specimen was composed of dry soil, RC pile models, footing, and superstructure. The footing was supported by four pile models in a vertical direction. The distance of the pile models were 100mm (full scale : 4*D*, 5m) for *X* direction, and 50mm (full scale : 2*D*, 2.5m) for *Y* direction. The footing was connected to a horizontal static loading system by a pin jig and a vertical roller jig. The length of the pile model was 320mm (full scale: 16m). They were set in a box filled with Toyoura dry sand. The relative density of the dry soil was 60%. The mass of the footing was 1.77kg and the mass of the superstructure was 7.42kg. Therefore, the total mass was 4,503N (full scale: 11.3MN) and the axial force for each pile model was 1,126N (full scale: 2.8MN).

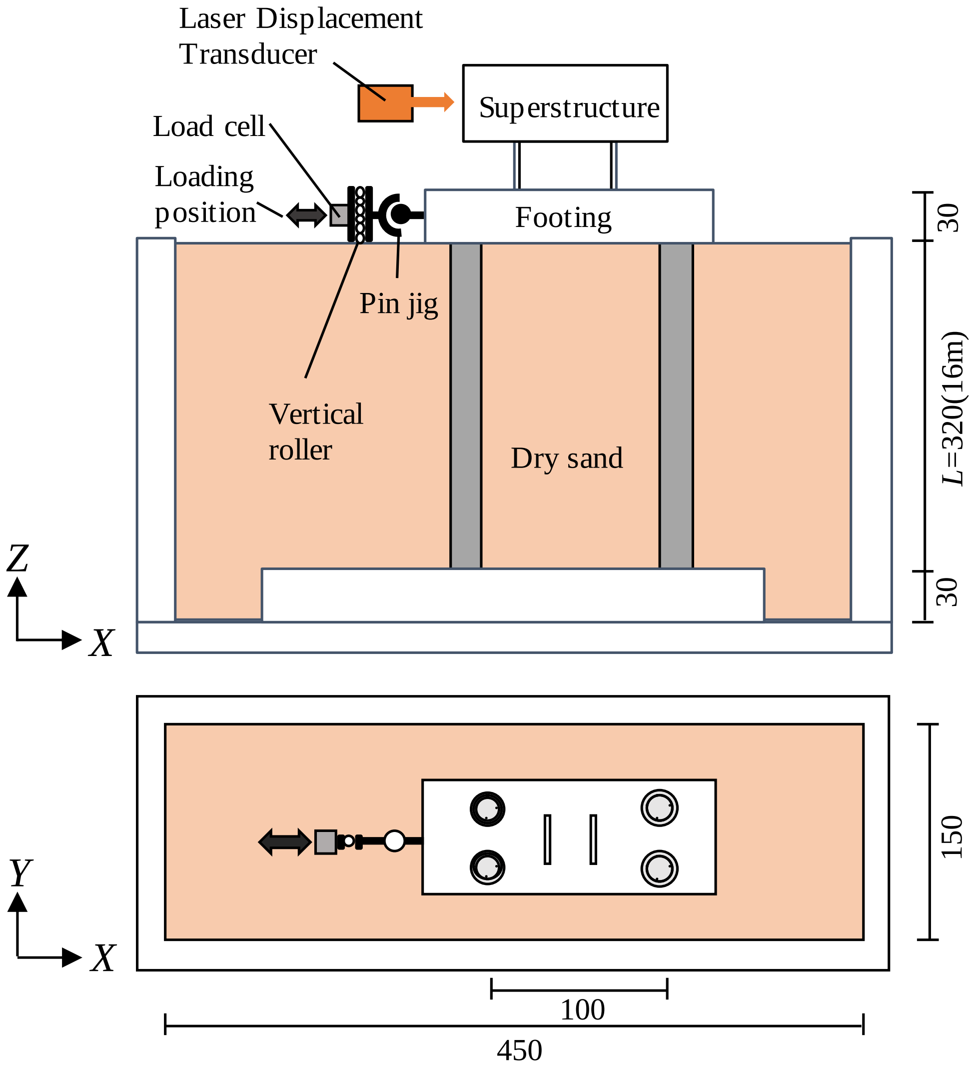


Fig. 4: The specimen of static loading test (mm)

Table 2: Properties of the specimen

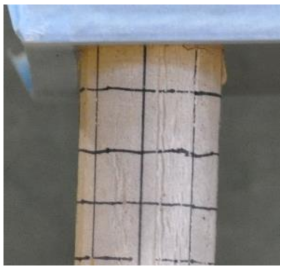
			Scaling Law	Unit	Full Scale	Model Scale
Piles	Length		$1/\lambda$	m	16	0.32
	Diameter		$1/\lambda$	mm	1250	25
	moment of inertia of area		$1/\lambda^4$	cm^4	1.29×10^7	2.08
	Yield stress of mortar		1	N/mm^2	8.31	8.31
	Main bar	Diameter	$1/\lambda$	mm	60	1.2
		Yeild stress	1	N/mm^2	374	374
	Shear reinforcement bar	Diameter	$1/\lambda$	mm	40	0.8
		Pitch	$1/\lambda$	mm	375	7.5
		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

3.2 Loading protocol and measurement plan

The horizontal cyclic loading was input to the footing. The loading protocol was controlled according to displacement of the superstructure (and the footing), at 0.625, 1.25, 1.875, 2.5, 3.75, 5.0 and 7.5mm. The deformation was measured by a laser displacement transducer.

3.3 Test result

Figure 5 shows the specimen after centrifuge loading test. Bending failure (plastic hinge) occured at the head and middle portion of the pile models. The 2 plastic hinge mode was formed on the pile models.



(b) Head of pile model

(a)Specime

(c) Middle portion of pile

Fig. 5: Specimen after the loading test

Figure 6 shows the relationship between load and displacement of the footing in the static loading test result. The vertical axis indicates the loading measured by load cell. The horizontal axis indicates dimensionless displacement of the footing. It was obtained by displacement of the footing divided by diameter of the pile model. Maximum strength of test result was 6.41MN (in full scale) when the dimensionless displacement of the footing was 0.2. After the pile model performed the maximum strength, the loading decreased gradually. This degradation behaviour indicates that the pile models fractured when bending.

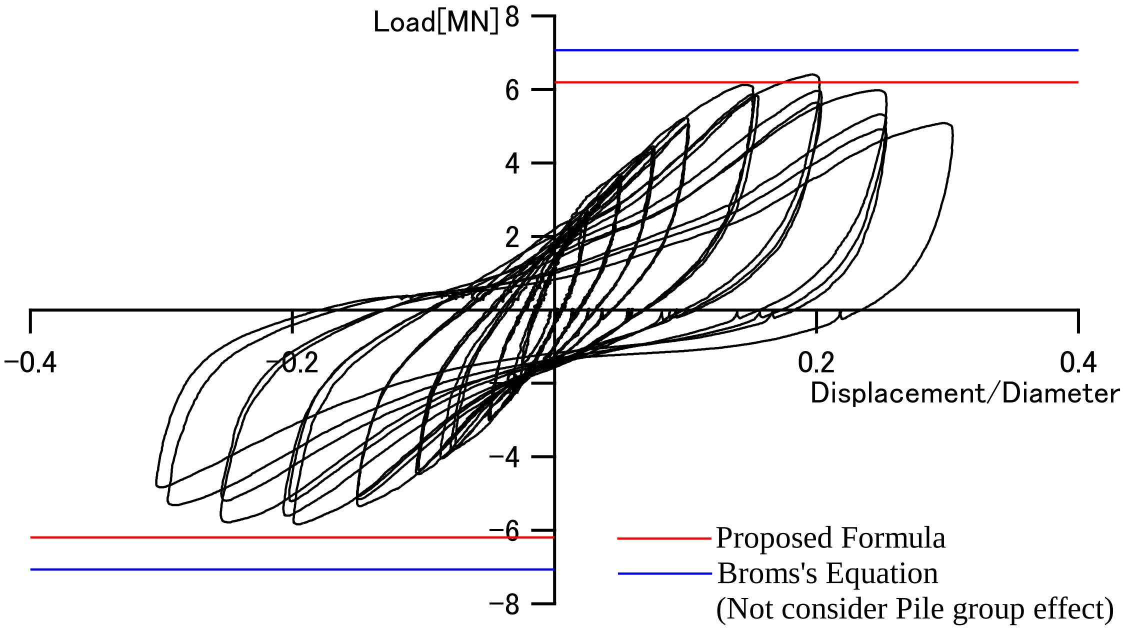


Fig. 6: Test result and evaluation value

4. Evaluation formula of ultimate lateral strength

4.1 Broms's equation

Broms proposed an equation to evaluate the ultimate lateral resistance [2]. The equation assumes that lateral reactions of soil are distributed in a triangle shape. When the pile forms 2 hinge mode as shown in Figure 7, the ultimate lateral resistance P can be determined from equations (2) and (3):

$$2M_u = P\left(\frac{2}{3}D_y\right) \tag{2}$$

$$D_y = \sqrt{\frac{2P}{3K_p\gamma B}} \tag{3}$$

where M_u is the full plastic moment of pile, K_p is the coefficient of passive earth pressure, γ is the unit weight of soil, B is the diameter of the pile, and D_y is the distance between 2 hinges.

The ultimate lateral resistance P can be calculated from equation (4) by combining above equation.

$$P = 2.38\left(\frac{M_u}{K_p\gamma B^4}\right)^{\frac{2}{3}} K_p\gamma B^3 \tag{4}$$

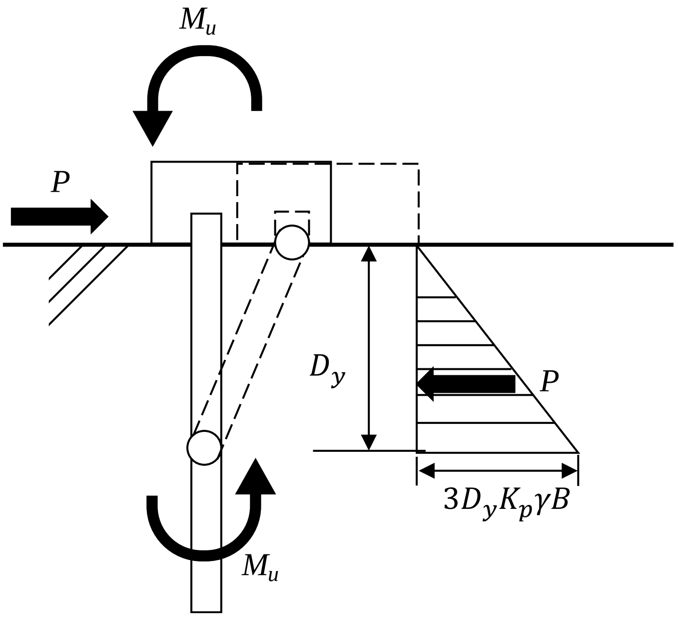


Fig. 7: Distribution of soil reactions

4.2 Pile group effect

It is known that the strength of piles at the rear of a building is smaller than piles at the front if the pile foundation is affected by pile group effect. In case of dry soil ground, horizontal plastic ground reaction coefficient (pile group effect) κ is defined as less than 3. For single pile, κ is determined as 3. Pile group effect κ is determined from equation (5) [8]:

$$\kappa = \left\{ a\left(\frac{R}{B} - 1.0\right) + 0.4 \right\} \leq 3 \tag{5}$$

$$a = 0.55 - 0.007\phi$$

where R is the distance between front and rear piles (100mm).

Internal friction angle ϕ is caluculated by equation (6) [9]:

$$\phi = 32.5 - 20.6\frac{D_r - 40}{100} \tag{6}$$

where D_r is the relative density of soil.

4.3 Proposed evaluation formula of ultimate lateral strength

To evaluate the ultimate lateral strength of both front and rear piles accurately, pile group effect κ is combined with Broms's equation. In equation (3), 3 is replaced by κ, and an equation (7) is created for determining the distance between hinges considering pile group effect:

$$D_y = \sqrt{\frac{2P}{\kappa K_p \gamma D}} \tag{7}$$

Equation (7) is inserted into equation (2) to determine the ultimate lateral strength *P* giving the proposed evaluation formula (8):

$$2M_u = P\left(\frac{2}{3}\sqrt{\frac{2P}{\kappa K_p \gamma D}}\right)$$

$$P = \frac{2M_u}{0.67\left(\frac{2P}{\kappa K_p \gamma D}\right)^{1/2}}$$

$$P = 1.65\left(\frac{M_u}{\kappa K_p \gamma B^4}\right)^{\frac{2}{3}} \kappa K_p \gamma B^3 \qquad (8)$$

In the case of a single pile, κ=3 is inerted into the proposed formula (8), then the equation is the same as equation (4).

4.4 Comparison between static loading test result and evaluation value

In Figure 6, a red line indicates the evaluation value culacaluted by the proposed formula (8), and a blue line indicates the Broms's equation (4). To evaluate by Broms's equation, the strength of single pile model was calculated by equation (4) and multiplied by 4. Maximum strength of the test result was 6.41MN(full scale), and the evaluated value using the proposed formula (8) wad 6.19MN(full scale). The evaluation value using the proposed formula was 96.6% of the test result. It shows that the evaluation value calculated using the proposed formula mostly corresponds to the test result. The evaluated value by Brom's equation was 7.07MN (full scale). The evaluated value by Brom's equation was overestimated. This was because the Broms's equation didn't consider the pile group effect.

5. Conclusion

This paper conducted a static loading test of the dry soil-RC pile foundation interaction using the centrifuge models. In addition, the author tried to evaluate ultimate lateral strength of pile foundation with surrounding ground. The following results were obtained.

1) A RC pile model was proposed for this study. According to the result of the bending and compression loading test, the pile model strength reached the full plastic moment and then performed degradation behaviour. This behaviour reproduced to a real RC pile member.

2) Static loading test of the dry soil - RC pile foundation interaction was conducted. Bending failure (plastic hinge) occured at the head and middle portion of the pile models.

3) The author expanded Brom's equation to evaluate ultimate lateral strength for pile group foundation. The proposed formula considers the pile group effect. The evaluation strength mostly corresponded to the test result.

6. Acknowledgments

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7. References

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