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NON-LINEAR BENDING CHARACTERISTICS OF PHC PILES UNDER VARYING AXIAL LOAD

Toshihiko ASO[1] Fusanori MIURA[2] Takehiro INOUE[3] Masashi YAMAMOTO[4]

SUMMARY

This paper describes the bending characteristics of PHC piles up to ultimate state, when such piles are subjected to compressive and tensile axial forces. Monotonic loading tests of actual PHC piles were carried out for several levels of axial force. The relationship between moments-deflections and bending moments-curvatures are examined with respected to the axial forces.

Numerical analysis was conducted in order to simulate the pile's nonlinear bending behavior obtained from the test results. The results of the analysis agree well with the results of the loading tests. Earthquake response analyses of structures with pile foundations are performed. A comparison of the response analysis results, with and without consideration of varying axial load, demonstrates the need to include varying axial load within the analysis.

INTRODUCTION

During severe earthquakes, plastic deformations may develop not only in bridge piers but also in the pile foundations. Many types of pile foundations were severely damaged during the Hyogo-ken Nanbu earthquake, which occurred on January 17 1995. Since that time, much effort has gone toward improving the seismic resistance of pile foundations. The seismic design of Highway Bridge is shifting to the ultimate state design method, which considers the deformation ability. Ultimate state design method requires exact estimation of action forces and deformation characteristics of members under the earthquake.

Due to the difficulty of damage investigation and the prompt managements, securing the seismic safety of foundations is a serious problem. There are many types of foundations, however pile is the most popular foundation for bridges. Pre-stressed high strength concrete piles (PHC pile) are used at many sites due to its advantages of allowable stress, i.e. allowable stress of PHC piles is greater than RC piles. Hoshikuma [1] studied non-linear bending characteristics of a PHC pile. It proposed a method for defining the relationship between bending moment and curvature to consider non-linearity in dynamic analysis. On the other hand, a pile foundation is consists of a group of piles. In this case, due to a rotation of substructure

[1] Associate professor, Yamaguchi University, Ube, Japan. Email: aso@yamaguchi-u.ac.jp
[2] Professor, Yamaguchi University, Ube, Japan.
[3] Engineer, Kawada Industries, Inc., Osaka, Japan.
[4] Graduate student, Yamaguchi University, Ube, Japan.

of bridge, compressive force and tensile force acts to both sides of pile. Therefore, it is necessary to consider fluctuant axial force, when calculating a non-linear dynamic behavior of piles. There are few researches about non-linear bending characteristics of a PHC pile under tensile axial force.

This paper describes the bending characteristics of PHC pile under varying axial forces. Bending tests of real PHC pile under several axial forces were carried out to observe the bending behavior. Numerical simulation considering with the relationship between bending moment and curvature were performed. The results of the analysis agree well with the results of the bending tests. Earthquake response analysis of soil-pile-substructure system was also calculated. The results of response analysis clearly demonstrate the need to consider varying axial load in the analysis.

BENDING TEST OF A PHC PILE

Bending test of PHC piles with several axial forces ware performed. Diameters of test piles are 400mm, 600mm and 800mm. Table 1 shows dimensions of piles and conditions of bending tests. Loads at the central two points on the simple supported pile causes bending as shown in Fig. 1. Compression axial forces are installed as reaction of tension rod that was placed at inside the pile hollow and that was hauled by jack. On the other hand, tensile axial force was given by hauling of pile through tension rod attached at both ends of pile. In this case, the frame that was constructed around the pile supports the reactions of jacks. The monotonic step load was applied to a pile until the pile was broken.

Table 1 Dimensions of test piles

No.	Diameter	Length	Thickness	PC Rods			Axial force
				Diameter	Number	Set radius	
	(mm)	(m)	(mm)	(mm)		(mm)	(kN)
1	400	8	65	10	6	335	-500
2							0
3							600
4							1180
5	600	8	90	10	19	520	-1000
6							0
7							1300
8							2600
9	800	10	110	10	34	700	0
10							2000
11							4000

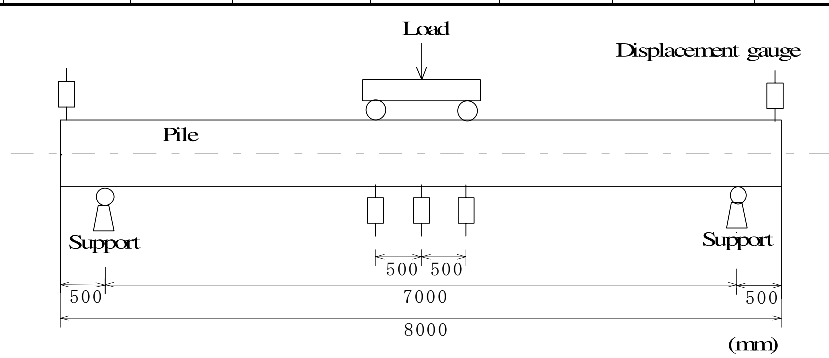
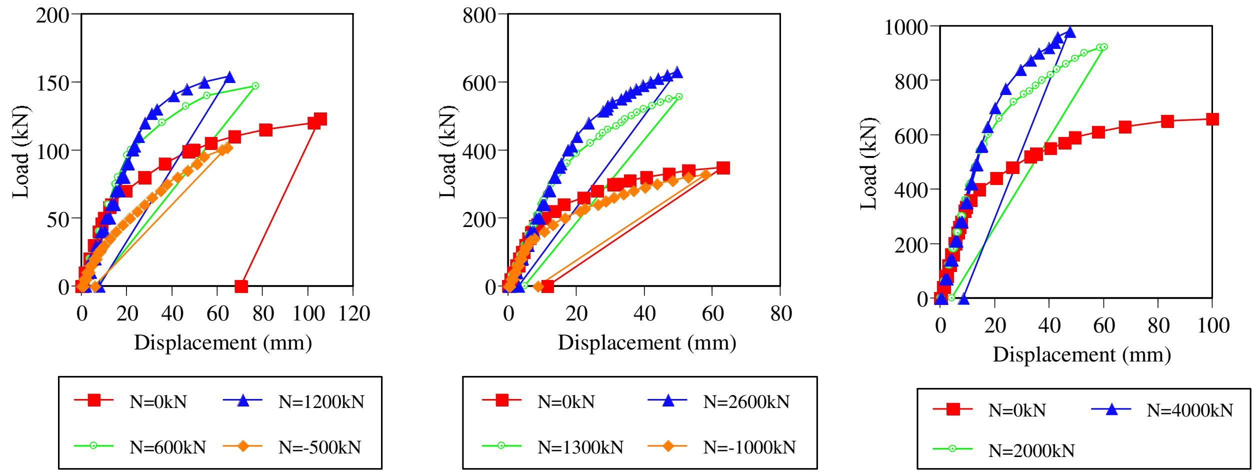


Fig.1 Bending test

The relationship between load magnitude and displacements at the center of pile were observed as shown in Fig. 2. In the case of pile diameter 400mm, the maximum deflection under tensile axial force is smaller than that with compression axial force. On the other hand, in the case of 600mm diameter pile, the maximum deflection under tensile axial force is larger than that with compression axial force. From these results, it could be confirmed that the axial force affects deformation ability of piles significantly.



(a) D=400mm (b) D=600mm (c) D=800mm

Fig.2 Relationship between displacement and load

RELATIONSHIP BETWEEN BENDING MOMENT AND CURVATURE OF PHC PILE

The following assumptions are considered in calculating the relationships between bending moment and curvature; refer to Oiwa [2].

(1) The section of a PHC pile holds a constant plane until destruction.

(2) Bending moment M_c corresponds to the cracking strain at the outermost tensile side of concrete.

(3) Bending moment M_y corresponds to the yield strain at the outermost tensile side PC rod.

(4) Bending moment M_u corresponds to the ultimate strain at the outermost compression side of concrete.

(5) Stress and strain relationships of concrete are shown in Fig.3 (a). That of PC rod is shown in Fig.3 (b).

(6) It is assumed that all cross sections of concrete are effective until M_c. After M_c, tensile stress of concrete is disregarded.

(7) At the neutral line, compression strain of concrete is zero.

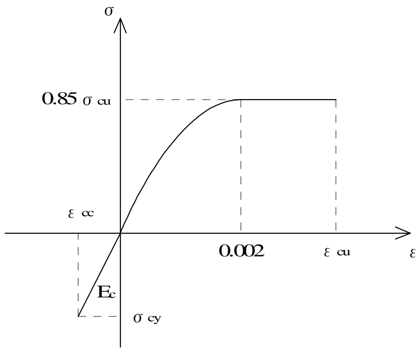
(8) PC rods are substituted as equivalent thin-wall steel pipe.

Bending moment M_c and curvature ϕ_c are expressed with following formula.

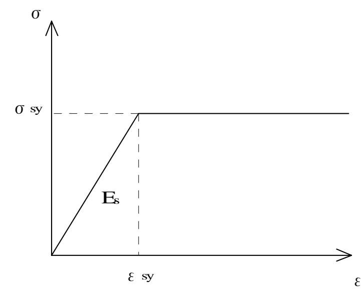
$$M_c = \frac{I_e}{r_0}\left(\sigma_{ce} + \sigma_{bt} + \frac{N}{A_e}\right) \qquad \phi_c = \frac{M_c}{E_c I_e} \quad (1)$$

Where, I_e : equivalent moment of inertia, r_0 : radius to centerline of thickness, σ_{ce} : effective pre-stress, σ_{bt} : bending tensile strength of concrete, N : axial force, A_e : equivalent cross sectional are.

The position of neutral line after M_c must be decided by numerical calculation. Referring to Fig.4, compression force $C(i)$ and bending moment $M(i)$ of concrete with assumed arbitrary neutral axis position are expressed by Eq.(2) and Eq.(3).



(a) Concrete



(b) PC

Fig.3 Stress and strain relationships

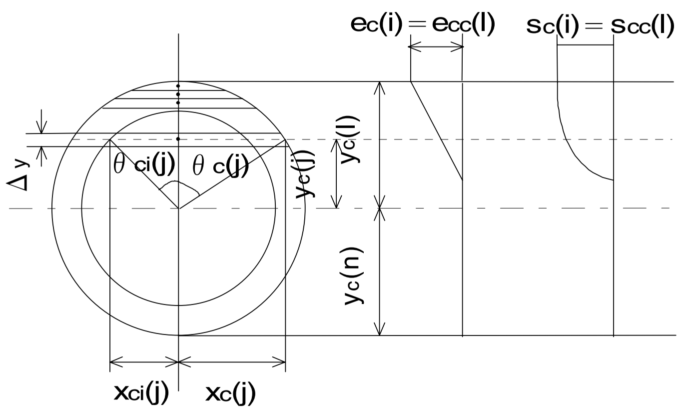


Fig.4 Analytical model

$$C(i) = \frac{4D}{n} \sum \sigma_{cc}(j) \{D \sin\theta_c(j) - d \sin\theta_{ci}(j)\} \qquad (2)$$

$$M_c(i) = \frac{4D^2}{n} \sum \cos\theta_c(j) \sigma_{cc}(j) \{D \sin\theta_c(j) - d \sin\theta_{ci}(j)\} \qquad (3)$$

Where, D: diameter of pile, d: internal diameter of pile, n: number of elements, $\sigma_{cc}(j)$: compressive stress of j th element, $\theta_c(j)$: center angle of outside circle of j th element.

Tensile force $T(i)$ and bending moment $M_P(i)$ of PC rod with assumed arbitrary neutral axis position are expressed by Eq. (4) and Eq. (5).

$$T(i) = (A_P/m) \sum \sigma_P(k) \qquad (4)$$

$$M_P(i) = (A_P/m) \sum \sigma_P(k) \cdot \cos\theta_P(k) \qquad (5)$$

Where, A_P: total cross sectional area of PC rods, m: number of division of equivalent thin-wall steel pipe, $\sigma_P(k)$: tensile stress of k th element, $\theta_P(k)$: center angle of thin-wall steel pipe of k th element.

The position of neutral line is decided from according to the following condition.

$N^*(i) = C(i) - T(i)$ (6)

Here, bending moment and curvature are obtained by equations (7) and (8), respectively.

$M(i) = M_C(i) - M_P(i)$ (7)

$$\phi(i) = \frac{\varepsilon_c(i) - \varepsilon_t}{2r_0} \quad (8)$$

Where, $\varepsilon_c(i)$: strain of the outermost compressive side of the pile, ε_t : strain of the outermost tensile side of the pile.

COMPARISON OF ANALYSIS AND BENDING TEST

The relationships of bending moment and curvature are calculated. Geometrical conditions and physical characteristics of the piles are shown in Table 2. Figure 5 shows the comparison of test results and calculated value. These figures indicate that the crack moment, yield moment and ultimate moment strength increase with the axial force. In the case when tensile axial force acts, the curvature increases. When high compression axial force acts in piles of diameter 600mm and 800mm, M_y becomes greater than M_u. This shows that compression side concrete is in an ultimate state before PC rods yield. Comparisons of analysis and test results are shown in Fig.6 and Fig.7. In this figure, circle marks indicate results of analysis and solid line is results of bending test. Analytical results and test results shows good correlation in all axial forces. Thus, validity of the analysis was confirmed.

Table 2 Geometrical conditions and physical characteristics of the pile

Outside diameter (mm)	D	200	300	400
Inside diameter (mm)	d	135	210	290
PC rods set radius (mm)	r_0	167.5	255	350
Number of PC rods	n	6	19	34
Angle of PC rods (rad)	θ_i	1.05	0.33	0.18
Elastic modukus of concrete (N/mm^2)	E_c	37736		
Elastic modukus of PC rod (N/mm^2)	E_s	201000		
Cross sectional area pf concrete (mm^2)	A_c	67937	142707	235777
Cross sectional area of PC rods (mm^2)	A_s	471	1492	2670
Pre-stress (N/mm^2)	σ_{ce}	7.845		
Crack strain of concrete	ε_{cc}	0.000125		
Yield strain pf PC rod	ε_{sy}	0.007158		
Ultimate strain of concrete	ε_{cu}	0.002450		

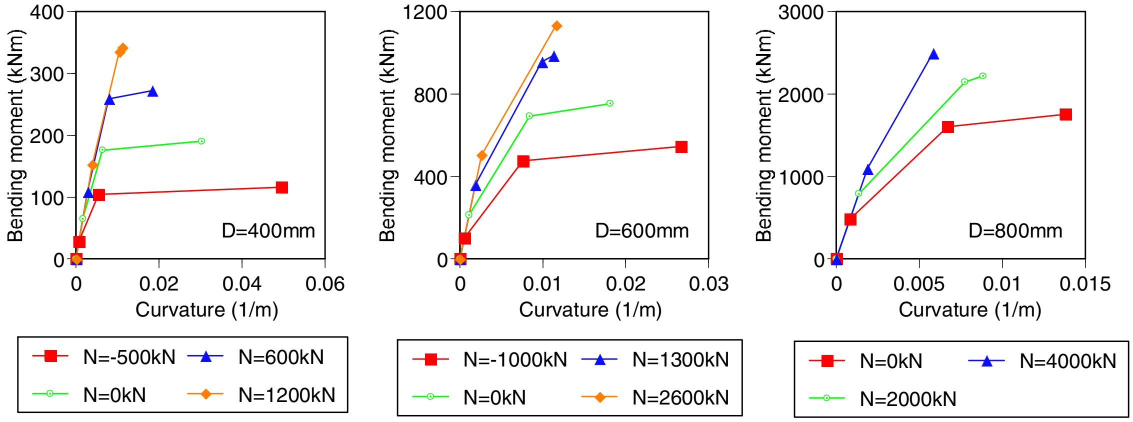


Fig.5 Relationship between bending moment and curvature

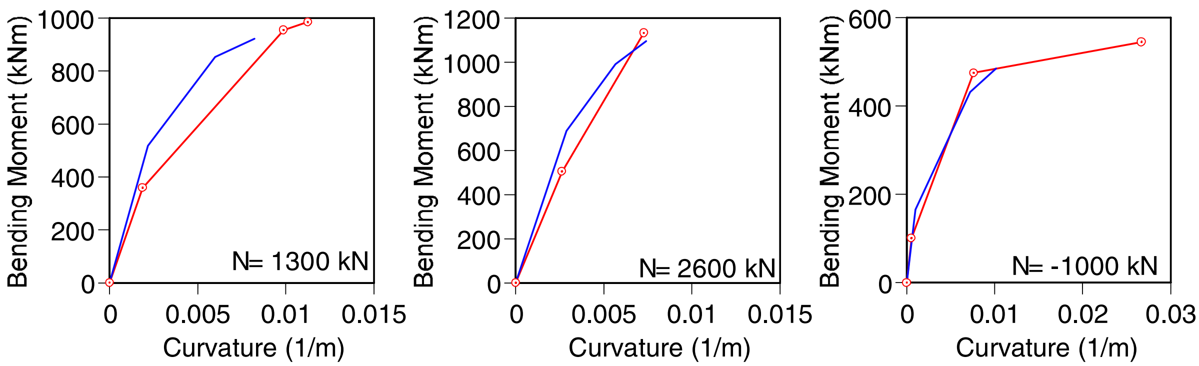


Fig.6 Comparison of moment-curvature relationships (D=600mm)

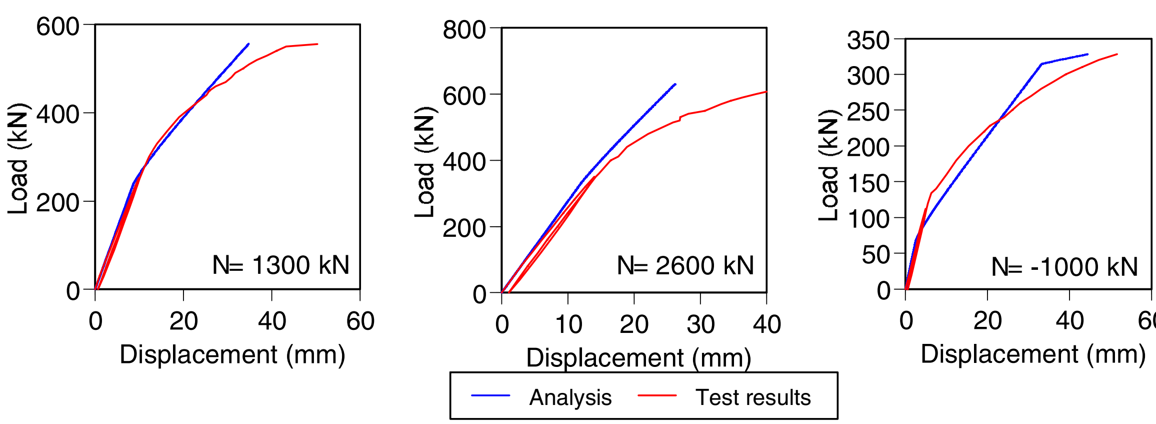


Fig.7 Comparison of load-displacement relationships (D=600mm)

EARTHQUAKE RESPONSE ANALYSIS

Earthquake response analysis in consideration of fluctuant axial force is performed using the $M-\phi$ relationships that are obtained in this research. In the analysis, it carries out about the model of the bridge pier - foundation - ground system as shown in Fig. 8. Figure 9 shows the soil property and Fig.10 is the sketch of pier and foundation. The bottom of the ground was set as a fixed boundary, and the sides have viscous boundary in order to consider the energy dissipation. The Hardin-Drnevich model was used for the nonlinearity of the ground. A nonlinearity of pile bending is taken as bi-linear defined by its crack and ultimate point. On the other hand, when considering the fluctuant axial force into nonlinearity of pile, the relationship between axial force and bending moment were set as shown in Fig.11. The damping ratio of ground was 20% and that of structures is 2%. The input seismic wave is sown in Fig. 12. This is generated based on the standard seismic wave described in Highway Specifications in Japan and the soil properties. The standard wave was JR Takatori, which was recorded in Hyougoken Nanbu earthquake. Time histories of axial force that was observed at pile No.1 and No.3 are shown in Fig.13. Large fluctuant axial force acts in pile No.1, however, axial force on No.3 contains initial axial force only. This is caused by rotation of footing. Figure 14 displays distribution of maximum bending moment along the pile No.3. Difference of maximum bending moment appears at upper part of pile. Most of the points show that the bending moment under M-N-f is greater than that of M-N. Relationship between bending moment and curvature at the point 0.3m below pile top is displayed in Fig.15. From this figure, hysteresis loop is appeared when fluctuant axial force was considered. This suggests that fluctuant axial forces must be considered in earthquake response analysis.

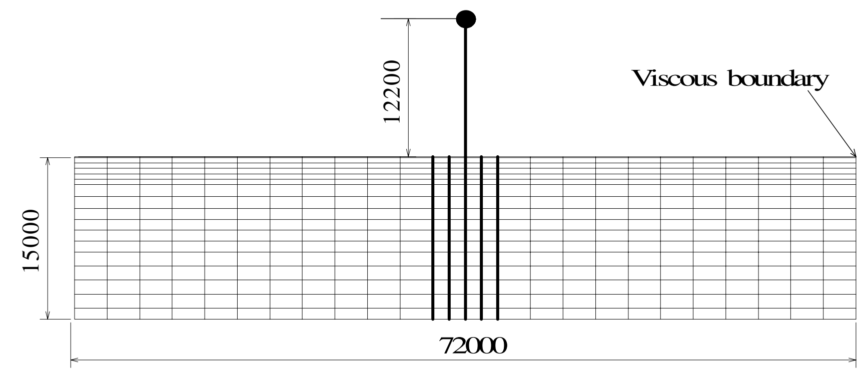
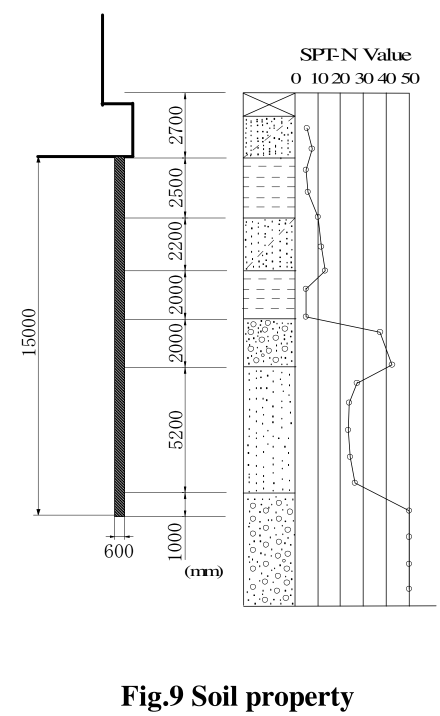


Fig.8 FEM model



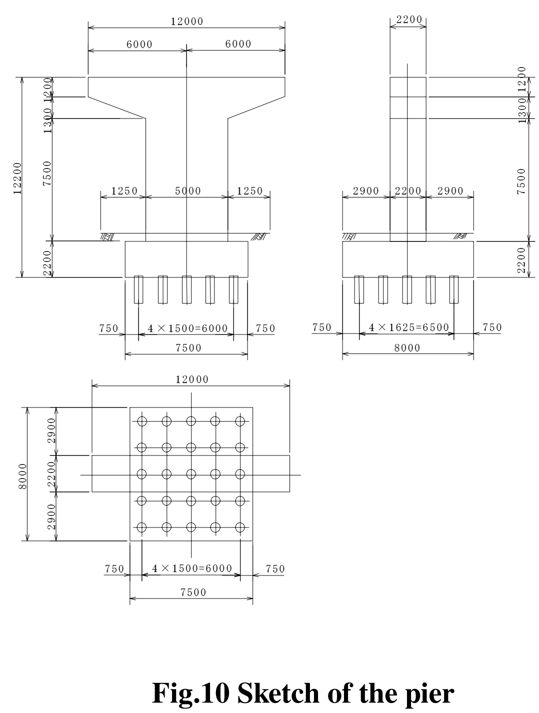


Fig.9 Soil property

Fig.10 Sketch of the pier

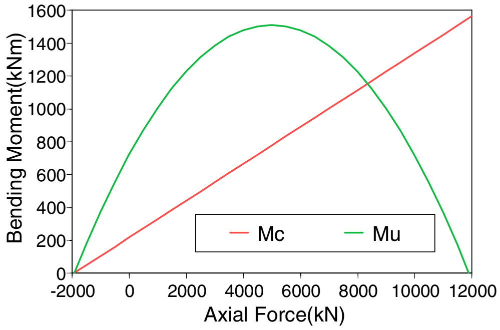


Fig.11 M-N relationships

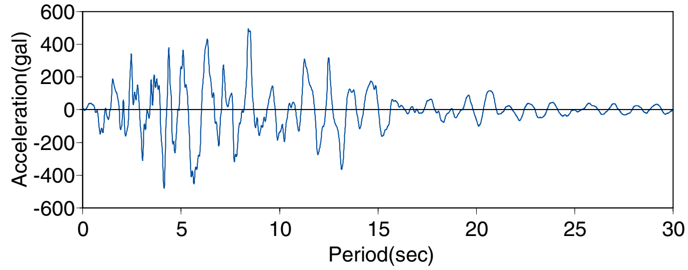


Fig.12 Input seismic wave

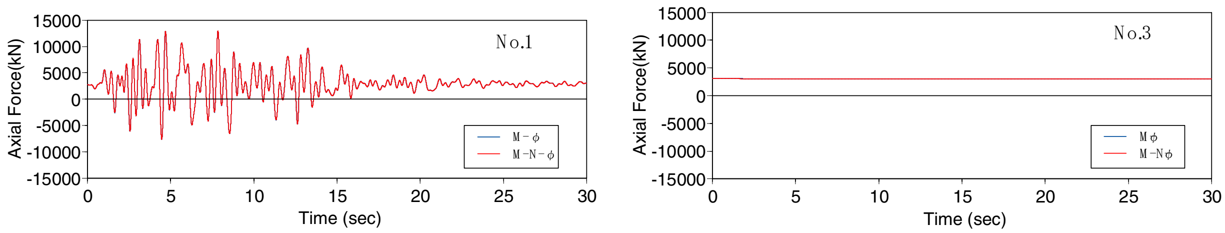


Fig.13 Axial forces

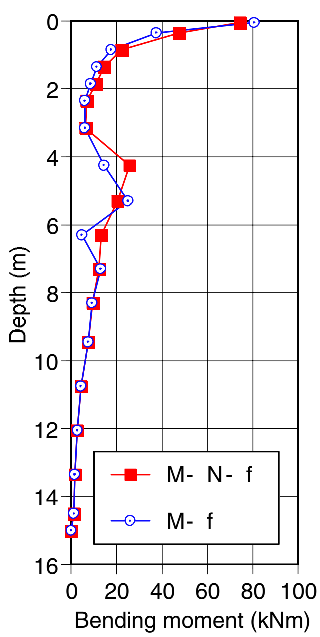


Fig.14 Distribution of Bending moment

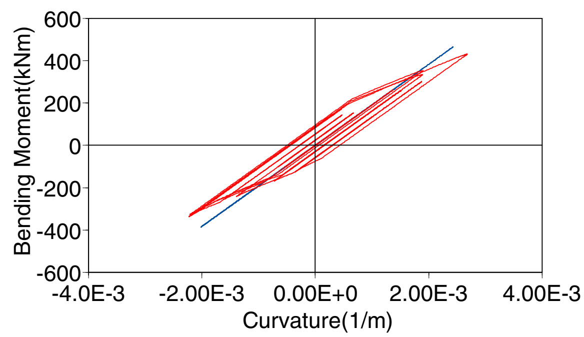


Fig.15 Moment-curvature relationships

CONCLUSION

This study presented the bending moment – curvature curve of PHC pile under fluctuant axial forces based on bending test results of actual piles acted by tensile axial forces. Results revealed that the analytic results showed good correlation with test results. The bending moment – curvature curves and load – displacement relationships under bending load of both were similar, thus, bending behavior was well simulated. Furthermore, this paper suggest the consideration of fluctuant axial forces in seismic design since it was confirmed that due to fluctuant axial forces, bending behavior of piles changes significantly.

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