Structural Engineering and Mechanics, *Vol. 52, No. 4 (2014) 843-855*
DOI: http://dx.doi.org/10.12989/sem.2014.52.4.843

Effects of infilled concrete and longitudinal rebar on flexural performance of composite PHC pile

Jin Wook Bang[1a], Bang Yeon Lee[2b], Byung Jae Lee[3c], Jung Hwan Hyun[1d] and Yun Yong Kim[*1]

[1]*Department of Civil Engineering, Chungnam National University, 99 Daehak-ro Yuseong-gu, Daejeon, 305-764, Republic of Korea*
[2]*School of Architecture, Chonnam National University, 300 Yongbong-dong, Buk-gu, Gwangju, 500-757, Republic of Korea*
[3]*R&D Center, JNTINC Co., Ltd., Hyundaikia-ro 830beon-Gil, Bibong-Myeon, Hwaseong-City, Gyeonggi-Do 445-842, Republic of Korea*

(Received May 9, 2014, Revised July 4, 2014, Accepted July 28, 2014)

Abstract. Concrete infill and reinforcement are one of the most well-known strengthening methods of structural elements. This study investigated flexural performance of concrete infill composite PHC pile (ICP pile) reinforced by infill concrete and longitudinal rebars in hollow PHC pile. A total four series of pile specimens were tested by four points bending method under simply supported conditions and investigated bending moment experimentally and analytically. From the test results, it was found that although reinforcement of infilled concrete on the pure bending moment of PHC pile was negligible, reinforcement of PHC pile using infilled concrete and longitudinal rebars increase the maximum bending moment with range from 1.95 to 2.31 times than that of conventional PHC pile. The error of bending moment between experimental results and predicted results by nonlinear sectional analysis on the basis of the conventional layered sectional approach was in the range of -2.54 % to 2.80 %. The axial compression and moment interaction analysis for ICP piles shows more significant strengthening effects of infilled concrete and longitudinal rebars.

Keywords: PHC pile; infilled concrete; longitudinal rebar; flexural performance

1. Introduction

Piles are important elements of constructions site placed into the ground to support axial and lateral loads. Piles such as steel, concrete and pre-tensioned spun high-strength concrete (PHC) piles are mainly used for foundations when the shallow foundation is not able to transfer the large structural loads to base of the deeper soil (Kim *et al*. 2009). Those are a type of deep foundations

∗Corresponding author, Professor, E-mail: yunkim@cnu.ac.kr
[a]Post-Doctor Researcher, E-mail: best6516@cnu.ac.kr
[b]Assistant Professor, E-mail: bylee@jnu.ac.kr
[c]Senior Researcher, E-mail: lbjae@hanmail.net
[d]Graduate Student, E-mail: mildface@cnu.ac.kr

http://www.techno-press.org/?journal=sem&subpage=8 ISSN: 1225-4568 (Print), 1598-6217 (Online)

which play an important role in securing stability of the structures (Meyerhof 1976, Iskander 1998, FHWA 2006). PHC piles and steel piles have been commonly used in infrastructure such as bridge, ports, and buildings (Li *et al*. 2014, Bhowmik *et al*. 2013). In particular in Korea, PHC piles have continuously made quantitative and qualitative growth, since it was firstly introduced in 1992 year from Japan. And more than 4 million tons of PHC have been applied to the construction sites in the early 2000's in Korea because of its low cost, homogeneous quality, high resistance to axial load and impact and corrosion resistance. At present, therefore, they account for 99.5% of the concrete based piles in Korea (Chun *et al*. 2010). The application of PHC piles, however, is constrained in the case of the structures subject to combined axial and lateral forces because the lateral force of PHC piles is 1/5 ~ 1/4 of that of steel piles, although they exhibited equivalent level of axial forces (Song 2008). In order to improve the lateral force of the PHC piles, various studies on combined steel and concrete composite piles such as hybrid composite pile (Lee *et al*. 2007), steel and PHC composite (Mha *et al*. 2012, Lee *et al*. 2009) where the upper part is manufactured using a steel pile with outstanding lateral force and the lower part is manufactured using a PHC pile with high axial compressive strength have been developed and applied in the on construction sites in Korea.

On the other hand, other countries comparing with Korea have been focused on durability enhancement and maintenance by using fiber reinforced polymer (FRP) and plastic shell which can prevent concrete carbonation and corrosion caused by external environments as well as can improve the compressive strength of concrete piles rather than the composite action of the existing piles. Mirmiran *et al*. (1996), Guades *et al*. (2012) studied concrete-infilled FRP piles which are comprised of an FRP shell with unreinforced concrete infill. The FRP shell protects the concrete from severe environmental effects and infilled concrete improved the stiffness and axial loads of the piles. Iskander *et al*. (2002) reported steel pipe core piles which are consist of two layers, an inner steel layer and thick outer plastic shell. The inner layer provides the structural strength while the outer shell is used to protect the steel from corrosion. These piles, however, took place interface debonding and delamination problem.

This paper presents an experimental and analytical investigation on the flexural behavior of concrete infilled composite PHC piles (hereafter ICP pile) which were applied to new strengthening method by infilled concrete and longitudinal rebars (Bang *et al*. 2014, Hyun *et al*. 2012). A series of bending test was performed to investigate the effects of infilled concrete and longitudinal rebars on the flexural performance of ICP pile and then the numerical analysis to predict the nonlinear bending behavior and nominal axial compression and bending moment interaction of PHC and ICP was performed by a conventional layered sectional approach that considers the section of the PHC and ICP on concrete, prestressed high strength rebars, and reinforcing bars.

2. Experimental program

2.1 Material

Fig. 1 shows the sectional view of conventional PHC pile and ICP pile specimens respectively. The specifications of PHC pile used in this study are listed in Table 1. The PHC concrete with a compressive strength of 87.9 MPa was used. A total twelve high strength rebars (HSRs) with the nominal diameter of 8.3 mm and the tensile and yield strength of 1,450 MPa and 1,300 MPa were

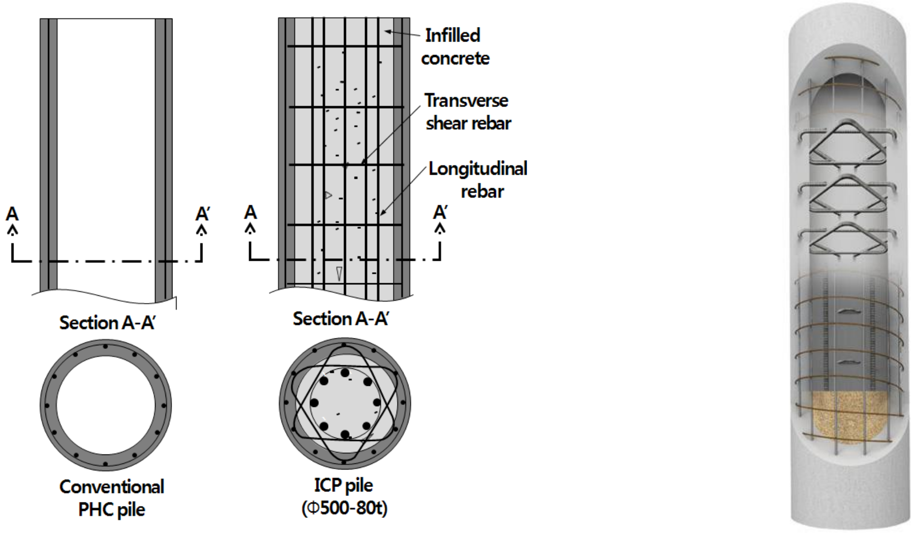


Fig. 1 Sectional view of ϕ500-80t series of PHC and ICP pile specimens

Table 1 Physical properties of PHC pile

PHC pile	Diameter (mm)	Thickness (mm)	Compressive strength (MPa)	Concrete area (mm^2)	Weight (t/m)
φ500-80t	500	80	87.9	105,600	0.274

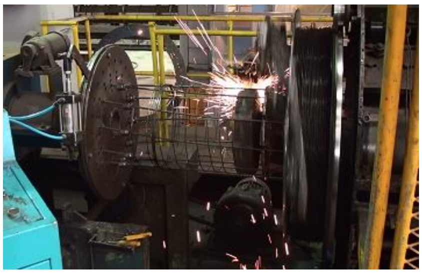
Table 2 Physical properties of infilled concrete

	Compressive Strength (MPa)	Slump (mm)	Maximum size of aggregate (mm)
Infilled concrete	28.4	150	20

Table 3 Physical properties of rebars

	Nominal diameter (mm)	Nominal section area (mm^2)	Tensile strength (MPa)	Yield strength (MPa)
D10	9.53	71.33	618	505
D19	19.1	286.5	601	483
D25	25.4	506.7	607	492

used. The twelve HSRs were prestressed until 70% of the tensile strength and the prestressing forces applied to the PHC concrete. To avoid shear failure and delamination of specimens, two D10 deformed rebars with a shape of opposite triangle were installed in a star shape as transverse shear rebars before placing the concrete in the PHC pile manufacturing process for manufacturing the ICP pile. The infilled concrete and longitudinal rebars were reinforced in hollow section of the PHC pile installed transverse shear rebars for the purpose of improvement the flexural strength. The infilled concrete with compressive strength of 28.4 MPa was used as shown in Table 2. Eight D19 and D25 deformed rebars were used for the longitudinal reinforcement, respectively, and their physical properties are listed in Table 3.


(a) Preparation of cage


(b) Installation of transverse shear rebars


(c) Concrete placement


(d) Prestressing


(e) Centrifugal casting


(f) Curing


(g) Demolding


(h) Preparation of piles


(i) Infilled concrete placement


(j) Infilled concrete curing

Fig. 2 Manufacturing process of PHC and ICP pile specimens

Table 4 Specimens of piles

Specimens	Type	Length (mm)	Compressive Strength of infilled concrete (MPa)	Longitudinal rebar (f_y=400 MPa)
PHC-500	ϕ500-80t	8,000	-	-
ICP-24-D0			24	-
ICP-24-D19				8ea -D19
ICP-24-D25				8ea -D25

Fig. 3 Setup for bending test

2.2 Manufacture of specimens

In order to evaluate the flexural performance of conventional PHC and ICP piles reinforced with infilled concrete and longitudinal rebars, a series of specimens were manufactured. Fig. 2 shows the manufacturing process of the piles specimens. The HSRs cage was manufactured by welding to spiral wire. And the cage was fastened and fixed at the steel mold. Then, the pile concrete was placed in the steel mold. For ICP piles, a shape of opposite triangular transverse shear rebars was installed by hand before the concrete placement. The spacing between the transverse shear rebars was 200 mm. After the concrete placement, the remaining processes such as prestressing, centrifugal casting, curing, demoldings are identical to the process of PHC pile (Fig. 2 (d) ~ (g)) (Bang *et al*. 2013). Steel mold was demolded after 12 hours steam curing period. After manufactured the PHC pile, in order to manufacture the ICP piles, eight longitudinal rebars were inserted into the hollow section of the PHC pile and placing the infilled concrete. Two conventional PHC piles without the transverse shear rebars and a total of six ICP piles were manufactured according to the reinforcement of longitudinal rebars as shown in Table 4. After curing the infilled concrete for 28-days under air dry condition, bending test was performed.

2.3 Test program

In order to evaluate improvement of the flexural strength in accordance with reinforcement, all the specimens were tested by four points bending method under simply supported conditions as shown in Fig. 3 (KS F 4306 2003). Vertical load without axial force on the piles was applied through the actuator with a capacity 1,500 kN according to the load-controlled loading sequence.

The pure bending span length of the each specimen between two loading points was 1,000 mm. The deflection at the midspan of each specimen was measured using linear variable differential transducers (LVDTs) with a capacity of 100 mm. The bending test was finished when the vertical load reached the maximum load.

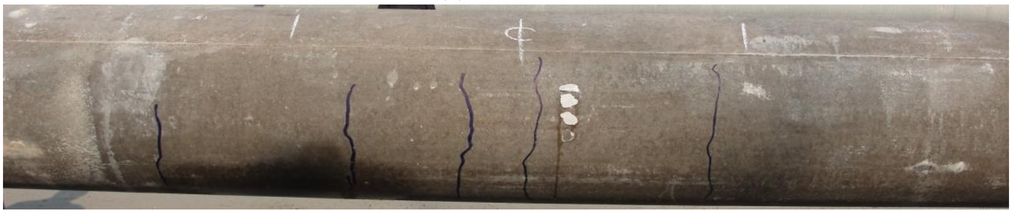
3. Test results and discussions

3.1 Cracking and failure pattern

The crack pattern the all reference specimens are shown in Fig. 4. In the case of specimen PHC-500, initially the crack was appeared in the tensile zone of the concrete at a load of 133 kN, loading further, the number of flexural crack has increased and the crack width has increased with the increase in the load. However the cracks were occurred at the midspan of the pile only in addition the there is no crack was observed near the support. Finally the specimen failed by yielding of steel cum crushing of concrete occurred in the tension zone of the pile in addition favorable enhancement in ductility was observed. In the case of PHC pile filled with concrete alone ICP-24-D0, the initial crack of concrete observed at the load of 139 kN, which is equal to the load at which the crack observed in PHC-500, finally the specimen failed by steel yielding cum crushing of concrete occurred at the load of 212 kN, which is equal to the ultimate load of PHC-500. As like as PHC-500, the increase in ductility performance was also observed. However, it was expected that the infilled concrete increase the flexural behavior of PHC pile, nevertheless the behavior of specimen ICP-24-D0 very similar to the specimen PHC-500, in addition, the ultimate flexural strength was also same. From the observation, it can be confirmed that the infilling of plain concrete in PHC pile does not have any influence on the flexural behavior of PHC pile. The reason is attributed to, during bending the top and bottom zone of the pile subjected to compression and bending respectively, and the neutral axis of the pile coupled in the infilled concrete. So that the influence of infilled concrete become unidentified.

In the case of concrete filled PHC pile with 19 mm rebars, the initial cracking of concrete observed at the load of 167 kN, which is 20.1%, higher than that of PHC-500. Loading further the increase in number of cracks was observed in addition the crack was observed throughout the length of the pile occurred at the bottom. The introduction of 19 mm rebar increases the stiffness of the piles, and provide the restraint effect against deflection as a result, the formation of crack, extended from midspan of the pile to the support. Finally, the specimen has failed due to the crushing of concrete occurred in the tension zone of the pile, in addition the ductility behavior of the pile was got reduced. The crushing of concrete failure is attributed to the increase in the number of rebars. The increase in the number of rebars, make the pile as an over reinforced section, as a result the concrete has reached the maximum strain value earlier. The above similar behavior was observed in the case of infilled PHC pile with 25 mm rebars (ICP-24-D25), however the flexural strength was high. In above all infilld pile, there was no separation of pile and infilled concrete was observed. This is a result of the fact that the introduction of transverse shear rebars effectively bonds the PHC pile concrete and infilled concrete and increase the composite action between the both as a result the delamination of two elements have been eliminated. On the whole, it was concluded that the introduction of longitudinal rebars, effectively control the crack formation of the pile and enhance the flexural strength, however, the rebars has a profound effect on the ductility behavior of the pile.

(a) PHC-500



(b) ICP-24-D0

(c) ICP-24-D19

(d) ICP-24-D25

Fig. 4 Cracking and failure patterns of specimens

3.2 Load and deflection

Fig. 5 shows the each load versus midspan deflection curve of the eight pile specimens until maximum load. The average maximum load of specimens PHC-500, ICP-24-D0, ICP-24-D19 and ICP-24-D25 were 203 kN, 211 kN, 408 kN and 491 kN respectively. The maximum load of the ICP-24-D0, ICP-24-D19 and ICP-24-D25 were 1.04, 2.01 and 2.41 times higher that of PHC-500 specimen, respectively. The load bearing capacity and the stiffness before first cracking were increased by reinforcing hollow PHC pile with longitudinal rebars and infilled concrete. On the other hand, the average deflections of specimens ICP-24-D0, ICP-24-D19 and ICP-24-D25 corresponding to the maximum load were 65.5 mm, 60.0 mm and 49.5 mm, which were 0.94, 0.86 and 0.71 times that of the PHC-500 specimen. This is attributed to the higher reinforcement of longitudinal rebars. As shown in Fig. 5 and Fig. 6, however, the specimen of PHC-500 and ICP-24-D0 showed similar flexural behavior. Because the tensile strength of infilled concrete is approximately 2.0 times lower than that of PHC body concrete (Oluokun 1991) and the infilled concrete located in the center of section close to the neutral axis, the infilled concrete did not

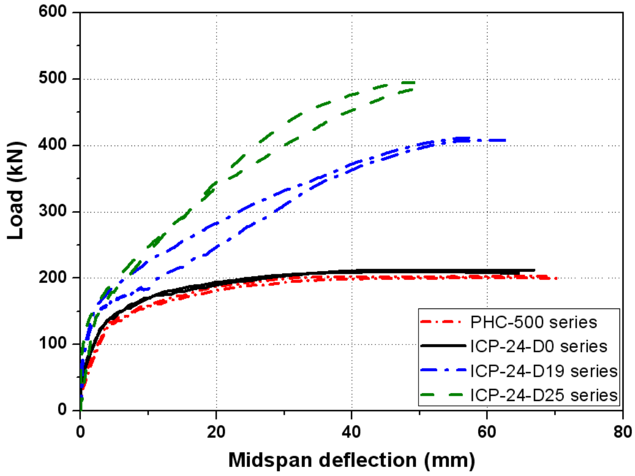


Fig. 5 Load-deflection curve of specimens at midspan

Table 5 Test results of each specimen (average values)

specimens	First cracking			Maximum load	
	Load (kN)	Deflection (mm)	Stiffness (kN/mm)	Load (kN)	Deflection (mm)
PHC-500	132	4.54	29.1	203	69.5
ICP-24-D0	138	4.20	31.5	212	65.5
ICP-24-D19	167	3.97	44.8	408	60.0
ICP-24-D25	174	3.84	45.3	497	49.5

significantly affect the flexural strength of specimen. The average values of load, deflection, and stiffness of each two specimens are listed in Table 5.

4. Analysis model of specimens

4.1 Nonlinear sectional analysis

A numerical analysis to predict the nonlinear bending behavior of PHC and ICP has been performed by a conventional layered sectional approach that considers the section of the PHC and ICP on concrete, HSRs bars, and reinforcing bars as shown in Fig. 6. The initial prestressing was taken into account in the analysis. In this study, the theoretical stress-strain relationships of concrete, HSRs bar, and reinforcing bar are shown in Fig. 7, which shows the stress-strain relationship of the materials. The material properties of concrete, HSRs bar and reinforcing bar used in the nonlinear analysis are based on the experimental results as shown in Table 1, Table 2, and Table 3 respectively. The analysis was stopped at reaching a compressive strain in a concrete layer to the ultimate strain of 0.003, the crush of concrete.

4.2 Comparison between experimental and predicted results

Table 6 compares the maximum bending moment between the experimental results and

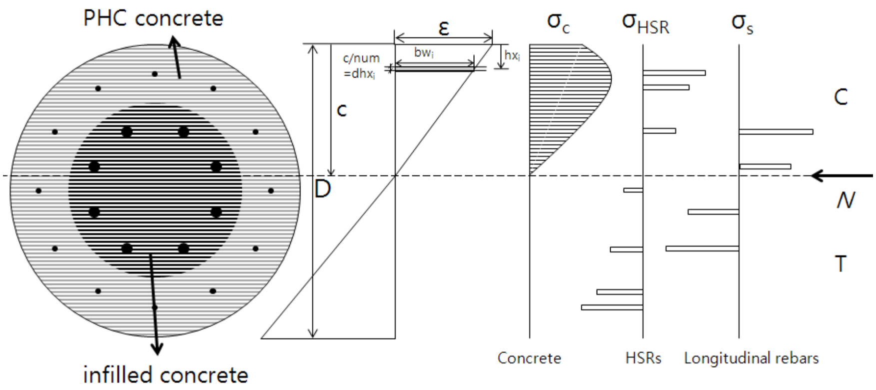
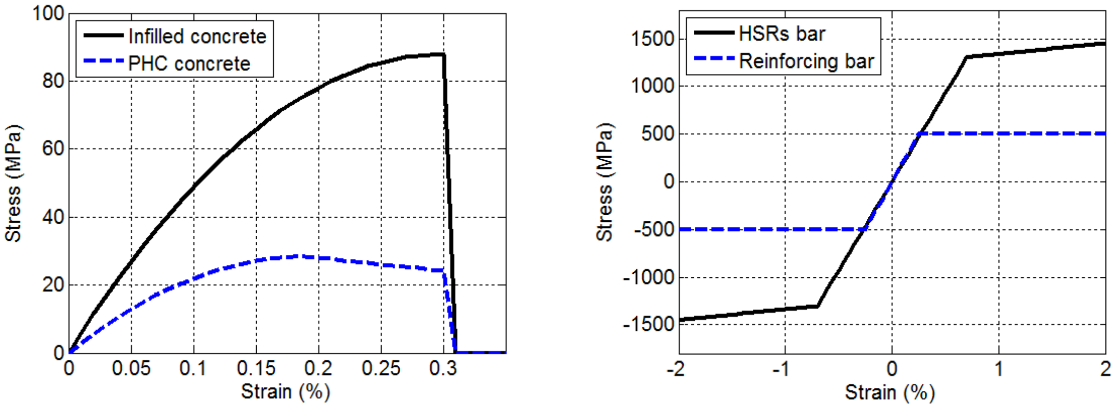


Fig. 6 Nonlinear bending analysis by a layered section approach



(a) PHC concrete and infilled concrete (b) HSRs bar and reinforcing bar

Fig. 7 Materials model

theoretical predictions. The experimental maximum bending moment of each specimen were obtained from the Eq. (1) and maximum load in Table 5

$$M = \frac{(W_{PHC}+W_{con})L}{40} + \frac{P_v}{4}\left(\frac{3}{5}L - 1\right) \tag{1}$$

where, W_{PHC} is the weight of PHC pile, W_{con} is the weight of infilled concrete with a specific weight assumed to be 2,300 kg/m^3. L and P_v were length of the specimen and maximum load respectively.

The predicted bending moment of four specimens showed approximately ranges from -2.54 % to 2.80 % compared to experimental results obtained from bending test. The bending moment of ICP-24-D0 specimen reinforced with only infilled concrete was predicted almost same value compared to PHC-500 specimens. The test results also showed similar tendency compared to the predicted values and the relation made between the predicted and measured bending moment is shown in Figure 8. In case of reinforcement with infilled concrete and longitudinal rebars, however, the predicted bending moment of ICP-24-D19 and ICP-24-D25 showed approximately 1.90 times and 2.38 times higher than that of the PHC-500 specimens. The experimental results showed that the bending moment of ICP-24-D19 and ICP-24-D25 increased 1.95 times and 2.31

Table 6 Comparison between experimental and predicted results

Specimens	Experimental maximum bending moment		Predicted maximum bending moment		Error*
	Moment (kN·m)	Increase (times)	Moment (kN·m)	Increase (times)	Moment (%)
PHC-500	199	1.00	200	1.00	0.24
ICP-24-D0	204	1.02	200	1.00	-1.70
ICP-24-D19	390	1.95	380	1.90	-2.54
ICP-24-D25	463	2.31	476	2.38	2.80

* Predicted maximum moment compared to experimental maximum moment

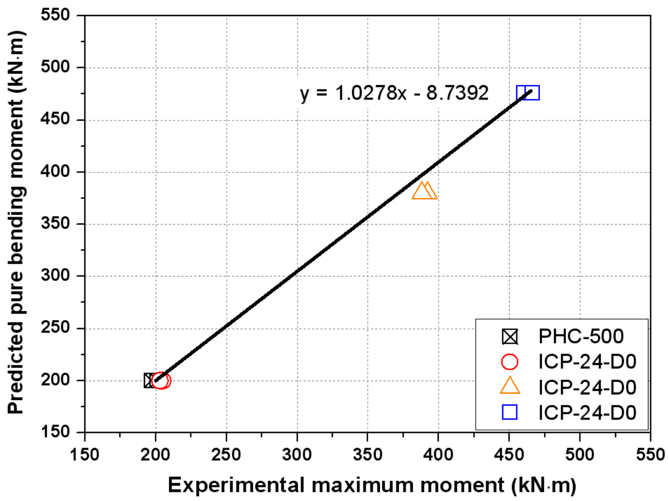


Fig. 8 Relation of the predicted and measured bending moment

times compared to that of the PHC-500 specimens. The relative errors between predicted results and experimental results of ICP-24-D19 and ICP-24-D25 specimens were -2.54 % and 2.80 % respectively.

4.3 Axial compression and bending moment interaction analysis

Slender piles including PHC piles, steel pipe piles, and concrete and steel composite piles are structural elements used primarily to support axial compressive loads. The ultimate compressive axial load is influenced by slenderness, which also produced additional bending moment because of transverse deformation. In this study, the numerical analysis to predict the nominal axial load and bending moment interaction (hereafter, P-M interaction) and investigate the effect of infilled concrete and longitudinal rebars on the performance of ICP piles have been performed by the conventional layered sectional approach same to that of section 4.1. Fig. 9 presents the calculating procedures of P-M interaction for the pile specimens. Fig. 10 shows the calculated nominal P-M interaction results of PHC and ICP piles. As can be seen in Fig. 10, the infilled concrete and longitudinal rebars increase the load bearing capacity of PHC pile subject to axial compression as well as bending moment, although the reinforcement of infilled concrete on the pure bending moment of PHC pile was negligible. From these analysis results, the load bearing capacity of PHC

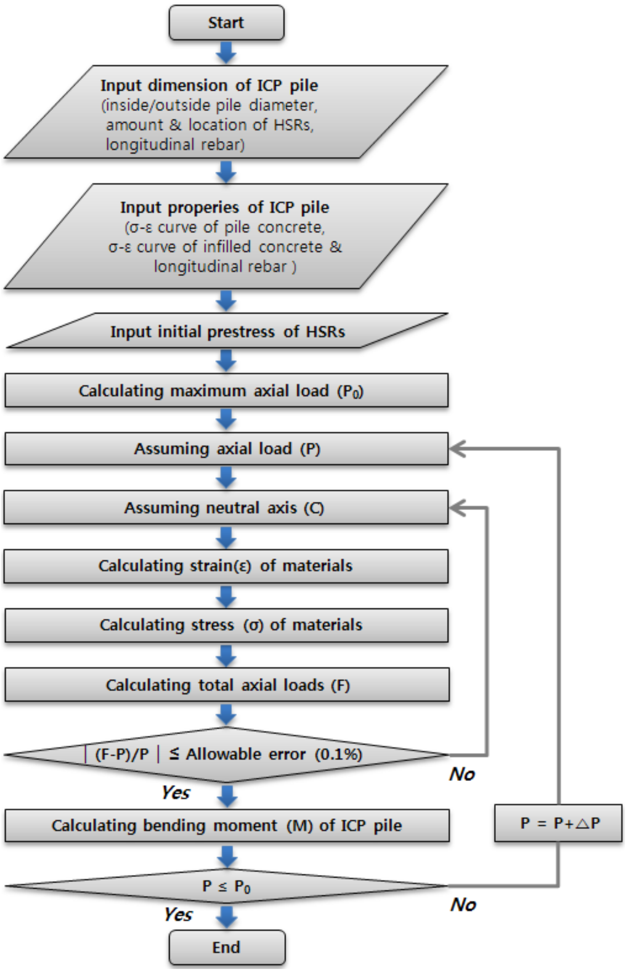


Fig. 9 Calculating procedures of P-M interaction for the PHC and ICP pile specimens

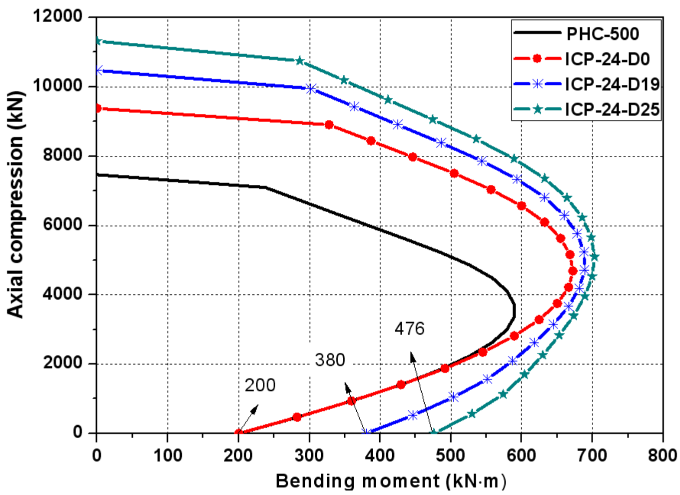


Fig. 10 Axial compression and bending moment interaction of each specimen

pile can be increased by using infilled concrete and longitudinal rebars regardless of the level of axial compression. The longitudinal reinforcing rebars is necessary to improve the load bearing capacity of PHC pile when the axial compression acting on PHC pile is lower than that corresponding to maximum bending moment.

5. Conclusions

This paper investigates experimental and numerical analysis studies on the flexural behavior of ICP piles reinforced with infilled concrete, longitudinal rebars and transverse shear rebars comparing to conventional PHC piles. A series of bending specimens with PHC piles and ICP piles were manufactured and four point bending test as well as nonlinear sectional analysis was performed to evaluate the effect of infilled concrete and longitudinal rebars on the load bearing capacity of hollow PHC piles. The following conclusions and findings are drawn;

(1) From the bending test results, it was verified that the reinforcement of PHC using infilled concrete and longitudinal rebars increase the maximum bending moment with a range from 1.95 to 2.31 times higher than that of conventional PHC piles specimens under the condition in this study. However, the reinforcement of infilled concrete on the pure bending moment of PHC pile was negligible.

(2) The error between experimental results and predicted results by nonlinear sectional analysis on the basis of the conventional layered sectional approach were in the range of -2.54 % to 2.80 %. From these results, it was verified that the maximum bending moment of ICP can be predicted accurately by nonlinear sectional analysis.

(3) P-M interaction analysis showed more significant strengthening effects of infilled concrete and longitudinal rebars on the load bearing capacity of PHC subject to axial compression as well as bending moment.

Acknowledgements

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (No. 2011-0024924)

References

Bang, J.W., Hyun, J.H., Lee, B.Y. and Kim, Y.Y. (2014), “Cyclic behavior of connection between footing and concrete-infilled composite PHC pile”, *Struct. Eng. Mech*, **50**(6), 603-617.

Bhowmik, D., Baidya, D.K. and Dasgupta, S.P. (2013). “A numerical and experimental study of hollow steel pile in layered soil subjected to lateral dynamic loading”, *J. Soil Dyn. Earthq. Eng.*, **53**, 119-129.

Chun, Y.S., Park, J.B. and Sim, Y.J. (2010), “Mechanical properties of PHC pile head connection with foundation slab and field application”, *Mag. Korea Concrete Inst.*, **22**(5), 71-77.

Gary, L.H. (2006), *Behavior of Fiber-Reinforced Polymer Composite Piles Under Vertical Loads*, Federal Highway Administration, Mclean, VA, USA.

Guades, E., Aravinthan, T., Islam, M. and Manalo, A. (2012), “A review on the driving performance of FRP composite piles”, *Compos. Struct.*, **94**(6), 1932-1942.

Hyun, J.H., Bang, J.W., Lee, S.S. and Kim, Y.Y. (2012) "Shear strength enhancement of hollow PHC pile reinforced with ininfilled concrete and shear reinforcement", *J. Korea Concrete Inst.*, **24**(1), 71-78.

Iskander, M. and Hassan, M. (1998) "State of the practice review in FRP composite piling", *J. Compos. Construct.*, ASCE, **2**(3), 116-120.

Kim, Y.S., Lee, J.B., Kim, S.K. and Lee, J.H. (2009), "Development of an automated machine for PHC pile head grinding and crushing work", *Autom. Const.*, **18**, 737-750.

Korean agency for Technology and Standards F 4306 (2003), "Pretensioned spun high strength concrete piles", 1-16.

Lee, J.D. and Lee, H. (2007), "The performance evaluation of hybrid composite pile connections", *Mag. Korea Concrete Inst.*, **19**(3), 51-56.

Lee, K.Y., Park, Y.D., Chung, W.Y., Choi, Y.D. and Kim, H.S. (2009), "Evaluation of structural performance and field application in composite pile", *Proceeding of the Korean society for Railway*, 2173-2180.

Li, G.W., Pei, H.F., Yin, J.H., Lu, X.C. and Teng, J. (2014). "Monitoring and analysis of PHC pipe piles under hydraulic jacking using FBG sensing technology", *Measurement*, **49**, 358-367.

Meyerhof, G.G. (1976), "Bearing capacity and settlement of pile foundations", *J. Geotech. Eng. Div.*, ASCE, **102**(3), 195-228.

Mha, H.S., Won, J.H. and Cho, H.S. (2012), "A study on flexural behavior of composite PHC pile with CT structural steel", *J. Korean Soc. Steel Constr.*, **24**(2), 233-243.

Mirmiran, A. and Shahawy, M. (1996), "A new concrete-filled hollow FRP composite column", *Compos. Part B*, **27**(1), 263-268.

Mirmiran, A., Shao, Y. and Shahawy, M. (2002), "Analysis and field tests on the performance of composite tubes under pile driving impact", *Compos. Struct.*, **55**(2), 127-135.

Oluokun, F. (1991) "Prediction of concrete tensile strength from its compressive strength: evaluation of existing relations for normal weight concrete", *J. ACI Mater.*, **88**(3), 302-309.

Song, T.E. (2008), "Decision procedure in applying PHC piles instead of steel plies", *Mag. Ssangyong Eng. Const.*, **48**, 32-36.

CC