Pile Foundation Design Through the Increased Bearing Capacity of Extended End Pile

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Abstract

Pretensioned spun high strength concrete (PHC) piles are a commonly used type of pile, while approximately 60% of the pile's strength is only used in the design bearing capacity. Because of the limited support capacities of PHC piles, applying PHC piles to high-rise buildings or soft ground is inefficient. Extended end (EXT) piles are a new type of pile that can reduce the waste of pile strength and increase the ground bearing capacity. This study investigated the behavior of EXT piles through a field test and it was confirmed that the bearing capacity of the EXT pile is better than the PHC pile. The increased bearing capacity of EXT piles also influenced work duration and project cost.

Keywords: extended end pile; pile foundation design; end bearing capacity; skin friction force; pile load test

1. Introduction

The use of a pile foundation for basic reinforcement has increased due the building of structures that are larger and higher than before. A pile foundation is defined as the installation of a pile in the ground to transfer the load to solid bearing ground when the load of the upper structure is not able to be supported due to loose or soft soil. Piles are generally considered to be a reliable and time-saving method with easy installation in soil to reinforce existing geotechnical structures such as slopes, foundations, and excavations (Li *et al.*, 2014). Currently, PHC piles represent more than 90% of total pile production in South Korea: around 400 to 500 tons per year (Part *et al.*, 2008; Sin *et al.*, 2014). The quality and strength of PHC piles are generally reliable because they are prefabricated in factories. Due to economic considerations, PHC piles have been applied to most parts of civil structures (Shin *et al.*, 2014). However, PHC piles have weaknesses such as horizontal force and low bearing capacity (Cho, 2007; Jeong, 2013). Due to the limitation of the unit bearing capacity of the pile, the layout of the core part in buildings is not possible, which leads to an increase in construction cost and duration, especially in the case of a skyscraper (Lee and Song, 2010).

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To remedy the weaknesses of PHC piles, steel-PHC composite piles have been developed. These steel-PHC piles, also called hybrid composite piles, have been used as a viable replacement for steel piles and PHC piles because of their lower cost and excellent load bearing capacity (Shin *et al.*, 2014). The substructure of this type of pile is controlled by the PHC pile. Thus, it is difficult to obtain the benefits of the steel pipe pile, which is of sufficient strength. In general, composite piles are defined as piles consisting of two or more materials. The first composite piles were used in the United States in the 1980s as replacements for timber fender piles at the Port of Los Angeles (Heinz, 1993). Since the application of composite piles, several types of composite piles have been used in many construction sites. Fiber-reinforced polymer (FRP) piles are a different type of composite pile. Several researchers carried out a theoretical study on the buckling of FRP piles under driving impact and attempted to experimentally quantify the surface friction between FRP piles and sand (Frost and Han, 1999; Han and Frost, 1999; Mirmiran *et al.*, 2002; Fam and Rizkalla, 2002; Nehdi *et al.*, 2008). In addition, researchers have analyzed the flexural behavior and strain ductility of FRP piles, and have performed field tests (Mirmiran *et al.*, 1999; Mirmiran *et al.*, 2002; Moran and Pntelides, 2002; Li *et al.*, 2010). Concrete-filled steel tube (CFST) piles have been researched recently in order to identify the behavior of centrally loaded and axially loaded CFSTs, and their seismic behavior (Prion and Boehme, 1994; Schneider, 1998; Verma *et al.*, 2002; Sakino *et al.*, 2004; Huo *et al.*, 2009; Huo *et al.*, 2014).

Fig.1. shows a new type of composite pile called an "extended end" (EXT) pile. Several studies that are related to EXT piles have been performed, and these are related to material properties and bearing capacities, validity, effectiveness, and the method of construction (Cho, 2007; Kim, 2008; Lee and Song, 2010; Jeong *et al.*, 2013; Lim, 2014; Shin *et al.*, 2014). However most studies were conducted in terms of the material specification without actual experimentation. The objective of this study is to investigate the behavior of EXT piles that can bring efficiency to pile foundations with respect to time, cost, and workability.

Fig.1. Manufacturing Process of Extended End Piles

2. Research Methodology

This study was conducted on a real construction site to verify the economic feasibility of EXT piles and the selected construction site was an apartment building construction site in South Korea (Step 1). By using a real case study of a load test between the PHC pile and EXT pile, the bearing capacity was measured and strengths of the EXT pile were verified (Step 2). This study does not discuss seismic issues because the Korean peninsula is not located in an active seismic area. Additionally, to compare the number of EXT and PHC piles, a pile foundation design was carried out (Step 3). Finally, using the pile daily record at the construction site, the project work durations and pile quantities were measured (Step 4). Through these research steps, we determined whether the EXT pile foundation work in a construction project is more efficient in terms of time and costs (Fig.2.).

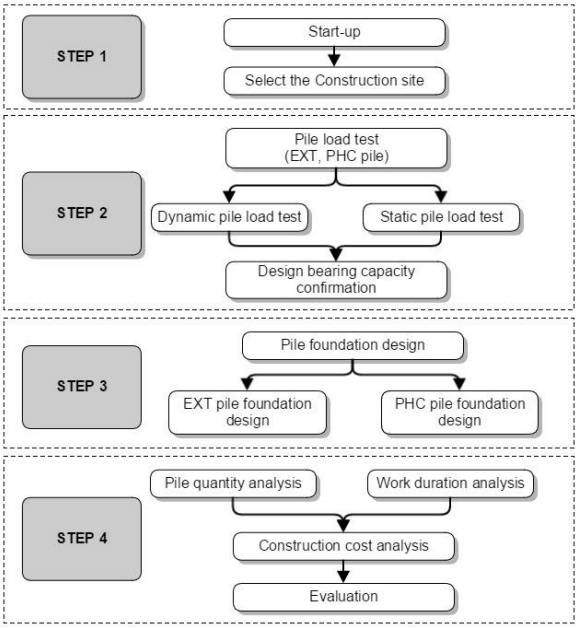

Fig.2. Research Procedure

3. Comparison between EXT Piles and PHC Piles

3.1 Allowable Bearing Capacity of a Pile

PHC piles are made in a circular pipe shape using pre-stressed steel bar, a reinforcement stirrup, and high strength concrete (Li *et al.*, 2014). Approximately 60% of the pile's strength is used in the design bearing capacity, and the rest is simply residing in the ground. To reduce waste of the pile strength, increasing the ground bearing capacity is a crucial point.

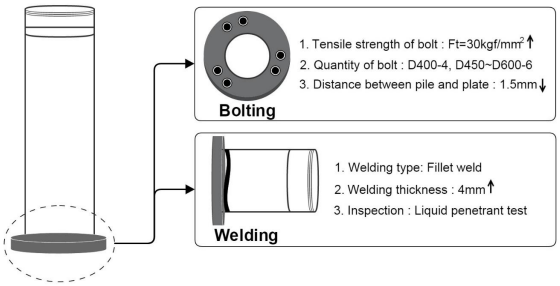

Fig.3. Connection Methods of the Extended Steel Plate

The EXT pile is an appropriate pile that can overcome the weakness of PHC piles. The EXT pile is a composite pile that is a PHC pile combined with an extended steel plate (SS400) on the bottom and the thickness of the extended end plate is 15 mm (Kim, 2008). As shown in Fig.3, an EXT pile is made by welding or bolting the extended steel plate to the bottom of a PHC pile, which overcomes the low bearing capacity of the PHC pile.

$$F_p = A \times \sigma \quad (1)$$

Fp: Allowable bearing capacity
A: Pile endpoint area
σ: Bearing capacity of ground

Equation (1) is the allowable bearing capacity calculation, where the endpoint area of the pile (A) is proportional to the allowable bearing capacity (Fp). Thus, because the EXT pile becomes the endpoint area, the value of Fp for the EXT pile is increased rather than that of the PHC pile. The pile shape is normally circular and the area is calculated using the square of the radius. Thus, a small expansion of the radius leads to a squared term in the area expansion, which strongly affects the value of Fp.

Table 1. Endpoint Area and Design Load

Diameter (mm)	Internal force (A, tf)	PHC pile			EXT pile			Rate of increase (%)	
		Cross section (cm^2)	Design load (B, tonf)	Rate (B/A, %)	Cross section (cm^2)	Design load (C, tonf)	Rate (C/A, %)	Cross section	Rate
D400	112	684	60~80	54~71	1,210	95~105	85~94	77	23~31
D500	173	1,055	100~120	58~69	1,714	145~160	84~92	62	23~26
D600	236	1,442	120~140	51~59	2,242	190~210	81~89	55	30

3.2 Increase in End Bearing Capacity of EXT Piles

$$R = R_p + R_f$$
$$R_p = (25\sim30) \times N \times A_p \quad (2)$$
$$R_f = f_s \times A_b \times l$$

R_p : End bearing capacity
R_f : Sking friction force
A_p : Pile cross section
N : Standard penetration test (≤60)
f_s : Skin friction force unit
f_s (Cohesive soil) = 0.5 × qu (1.25N) = 0.65 × N
qu = Unconfirmed compressive strength
f_s (Sandy soil) = 0.2 × N
A_b : Pile principal plane length
l : Pile length

Equation (2) shows a commonly used bearing capacity formula. According to Eq. (2), the load on the head of a pile (R) is supported by the end bearing capacity (R_p), which is supported on the endpoint of the pile and by the skin friction force (R_f). From Eq. (2), R_p is applied to 25 to 30N by ground classification. This figure accounts for the construction situation in South Korea, because most of the piles are constructed with weathered rock layers and the average figure for load tests is in the range of 25 to 30N (Lee and Song, 2010). Also, the figure of standard penetration test (N) applies to upper value 60, this figure is the same as R_p. Finally, the value of R_f is applied to the decreasing figures around 20% to 30% to consider the uncertainty of each layer such as a gravel layer, or the velocity of a moving fluid layer (Lim, 2014).

Table 1. shows the rate of increase in the pile endpoint area and the design load with respect to the diameter of the piles. According to Table 1., the endpoint area of the EXT pile is higher than that of the PHC pile by around 55% to 77%, and the design load of the EXT pile is higher overall by 26% compared to the PHC pile. Thus, if the design load is determined to be 51% to 71% of the bearing capacity in the PHC pile, then the design load of the EXT pile is able to increase by 81% to 94% for the same diameter. The increased design load due to an increasing endpoint area leads to a similar change in bearing capacity between the EXT pile and the PHC pile that has a one level diameter higher than the EXT pile. The EXT pile, therefore, secures pile foundation stability by extending the end plate to the inside and outside of the pile, as shown in Fig.4.

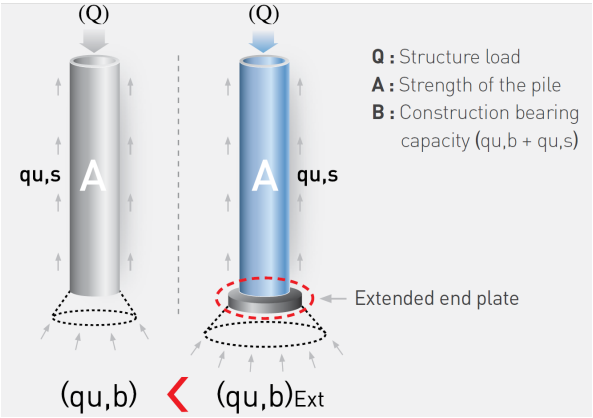

Fig.4. Principle of Increased Bearing Capacity

4. Case Study

4.1 Pile Load Test

A load test of the pile is used to design or verify the stability of the piles. This test is classified into two tests: a dynamic pile load test and a static pile load test. These load tests are highly reliable because they identify bearing capacity by applying a load to the actual pile. The dynamic pile load test can be used to suggest a standard of construction management that is more economical and safe by measuring the bearing capacity and settlement of piles through the use of a pile driving analyzer (PDA). The dynamic pile load test is classified as "end of initial driving (EOID) and restrike." The EOID is usually conducted after construction or during pile construction, to ensure construction management by a drivability analysis after measuring the driving stresses, impact energy, integrity, and end bearing capacity of the pile. The restrike test is conducted after a considerable length of time. Its goals are to verify the effects of changes in the ground (set-up, relaxation) over time, and the calculation of the allowable bearing capacity of a pile. The basic principle of the dynamic pile load test is shown in Fig.5.

The purpose of a static pile load test is to determine the bearing capacity of a pile by using a load test that is conducted with an axial pile load. In this research, the plate load test (PLT) system used around the piles was performed as shown in Fig.6. Also, through this system, pressure-settlement (p-s) curves were obtained.

4.2 Test Results

The construction site for our case study is located in South Korea and is comprised of ten apartment buildings, and neighborhood public facility and common service facilities. The bearing capacity was

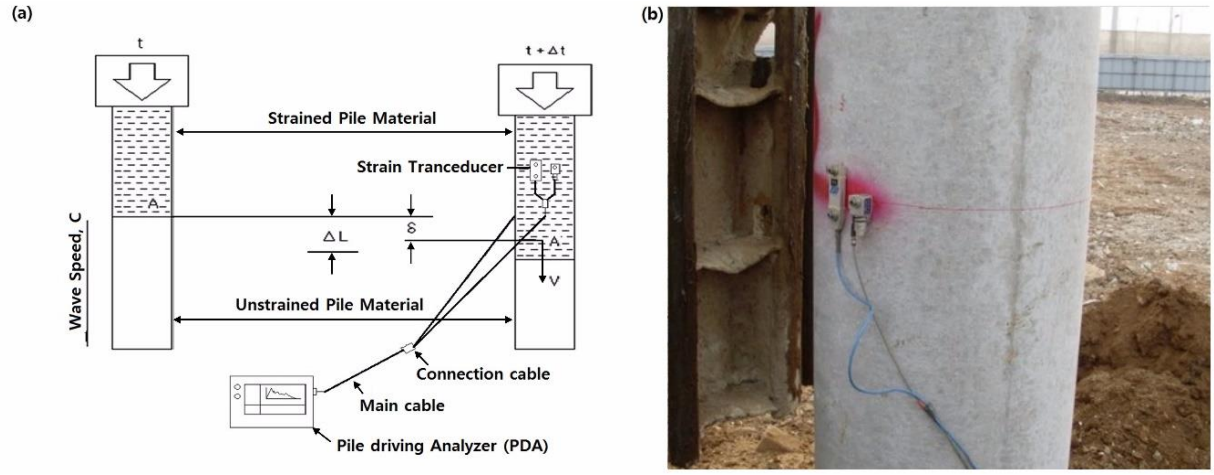

Fig.5. Dynamic Pile Load System: (a) Schematic Diagram, (b) Installation

measured through a field-loading test. Only the area not satisfied with the demanded bearing capacity in 250 kPa (25 tonf/m^2) is determined to construct piles. The pile standard of this construction site is D=500 mm, a thickness of 80 mm, and a compressive strength of 800 kg/cm^2. Also, DROP-5.0 and 6.0-ton hammers were used for the driving pile load test. The design bearing capacity of these areas is 1200 kPa (122.37 tonf) in the PHC pile and 1600 kPa (163.15 tonf) in the EXT pile per unit.

As shown in Table 2., the test results of the allowable bearing capacity of the EXT pile are 199.6, 196.08, 190.84, 197.92, 179.52, and 175.52 tonf/each (ea), respectively. Thus, the overall value is 189.92 tonf/ea. The PHC pile results are 152.84, 159.28, 127.72, 141.12, 168.08, and 168.08 tonf/ea. Thus, we obtained an overall value of 152.94 tonf/ea. Based on the test result, it was determined that the allowable bearing capacity of the EXT pile is around 24% higher than that of the PHC pile. The static pile load test requires 225% of the maximum possible load design. Therefore, 367.10 tonf was determined to be the maximum load, and the loading test was conducted after eight load steps.

In each load step, the load was maintained until the rate of settlement was 0.25 mm/h or under, and for less than 2 h. Table 3., and Fig.7. show the results of the static pile load test. As shown in Fig.7.a., the p-s curve of the EXT pile shows that the settlement regularly increased in each step until 367.10 tonf. Thus, the allowable bearing capacity of the EXT pile with a safety factor of 2.0 was determined to be upper 183.55 tonf/ea. In the case of the PHC pile, the designed load test was also applied until 275.32 tonf, which is 225% of the maximum possible load design of 122.37 tonf/ea. As a result, the allowable bearing capacity was found to be upper 137.66 tonf/ea after applying a safety factor of 2.0.

5. Time and Cost Analysis

5.1 Analysis of Pile Quantities

The pile load test shows that the bearing capacity of the EXT pile is better than the PHC pile. Through the pile load test result, the pile foundation design carried out and the number of piles between the EXT piles and PHC piles were compared. The differences of the basic designs between the PHC pile and EXT pile are shown in Fig.8. With PHC piles, the pile design should

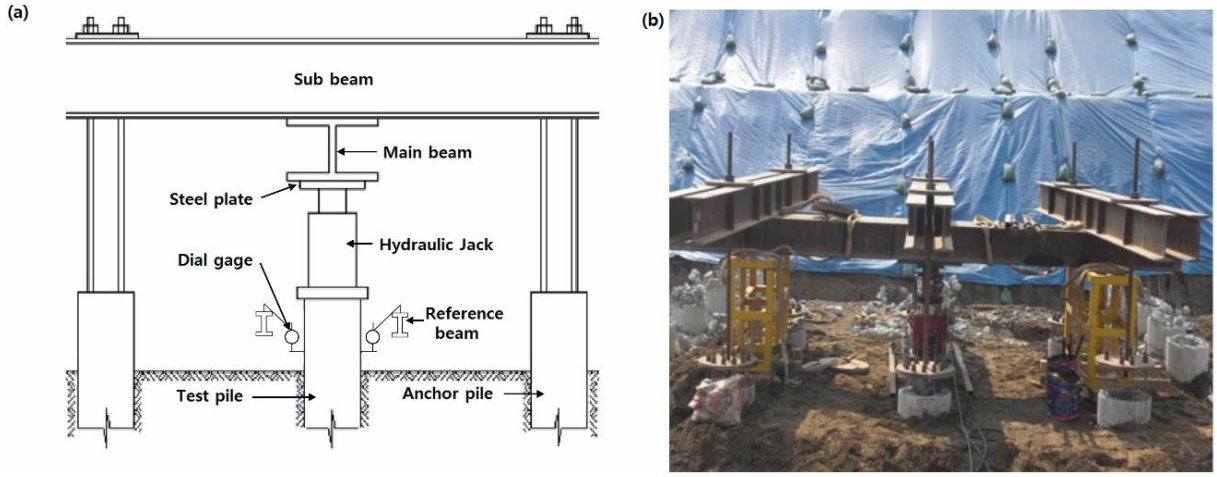

Fig.6. Plate Load Test System Used Around Piles: (a) Schematic Diagram, (b) Installation

Table 2. Dynamic Pile Load Test Result

Pile no.	CAPWAP Capacity (tonf/ea)			Allowable bearing capacity (tonf/ea)		Final allowable bearing capacity (tonf/ea)	Division
	Skin friction force	End bearing capacity	Whole supporting force	CAPWAP (FS=2.5)	Davisson (FS=2.0)		
PHC. 1	0.9	373.7	374.6	149.84	187.40	-	E.O.I.D
	41.0	341.1	382.1	152.84	190.90	152.84	Restrike
PHC. 2	25.7	363.3	389.0	155.60	184.10	-	E.O.I.D
	68.8	329.6	398.2	159.28	187.90	159.28	Restrike
PHC. 3	0.1	306.6	306.7	122.68	100.65	-	E.O.I.D
	60.8	253.1	319.9	127.72	117.45	127.72	Restrike
PHC. 4	6.3	321.4	327.7	131.08	132.85	-	E.O.I.D
	72.4	280.4	352.8	141.12	145.15	141.12	Restrike
PHC. 5	38.7	367.9	406.6	162.64	107.25	-	E.O.I.D
	39.0	381.2	420.2	168.08	120.75	168.08	Restrike
PHC. 6	38.7	367.9	406.6	162.64	107.25	-	E.O.I.D
	39.0	381.2	420.2	168.08	120.75	168.08	Restrike
EXT. 1	42.2	420.3	420.3	168.12	210.15	-	E.O.I.D
	100.9	398.1	499.0	199.60	249.40	199.60	Restrike
EXT. 2	9.0	426.0	435.0	174.00	249.80	-	E.O.I.D
	87.3	402.9	490.2	196.08	246.10	196.08	Restrike
EXT. 3	9.1	445.2	454.3	181.72	213.60	-	E.O.I.D
	65.9	411.1	477.1	190.84	214.41	190.84	Restrike
EXT. 4	24.2	417.9	442.1	176.84	211.40	-	E.O.I.D
	47.3	447.4	494.8	197.92	210.18	197.92	Restrike
EXT. 5	14.2	405.0	419.2	167.68	182.55	-	E.O.I.D
	62.7	386.1	448.8	179.52	200.90	179.52	Restrike
EXT. 6	7.3	423.6	430.9	172.36	205.80	-	E.O.I.D
	80.9	357.9	438.8	175.52	199.90	175.52	Restrike

Table 3. Plate Load Test Result

		P-S	log P–log S	S-logT	P-ds/ d(logT)	Davisson's	Pile no.	DMX (0.1D (60mm))	DFN (0.025D (15mm))	Allowable load (tonf/ea)
PHC	Maximum load (tonf/ea)	367.10↑	367.10↑	367.10↑	367.10↑	367.10↑	1	11.45mm	1.47mm	183.55↑
	Safety factor	2.0	2.0	2.0	2.0	2.0	2	17.19mm	5.54mm	183.55↑
	Allowable load (tonf/ea)	183.55↑	183.55↑	183.55↑	183.55↑	183.55↑	3	11.05mm	1.43mm	183.55↑
EXT	Maximum load (tonf/ea)	367.10↑	367.10↑	367.10↑	367.10↑	367.10↑	1	4.62mm	2.43mm	183.55↑
	Safety factor	2.0	2.0	2.0	2.0	2.0	2	4.72mm	3.55mm	183.55↑
	Allowable load (tonf/ea)	183.55↑	183.55↑	183.55↑	183.55↑	183.55↑	3	5.03mm	2.53mm	183.55↑

be arranged in two columns in order to support the load of the building because a large number of piles should be arranged within a limited space as shown in Fig.8.c. In contrast, an EXT pile is able to arrange one column on the lower part of a vertical wall because the pile quantities are decreased as shown in Fig.8.d. In the case of a wall foundation, four PHC piles should be constructed to endure the load of a structure, but only two EXT piles can withstand the same load of the four PHC piles as shown in Fig.8.c,d. For an isolated foundation, five PHC piles must be constructed per location, while only three EXT piles can withstand

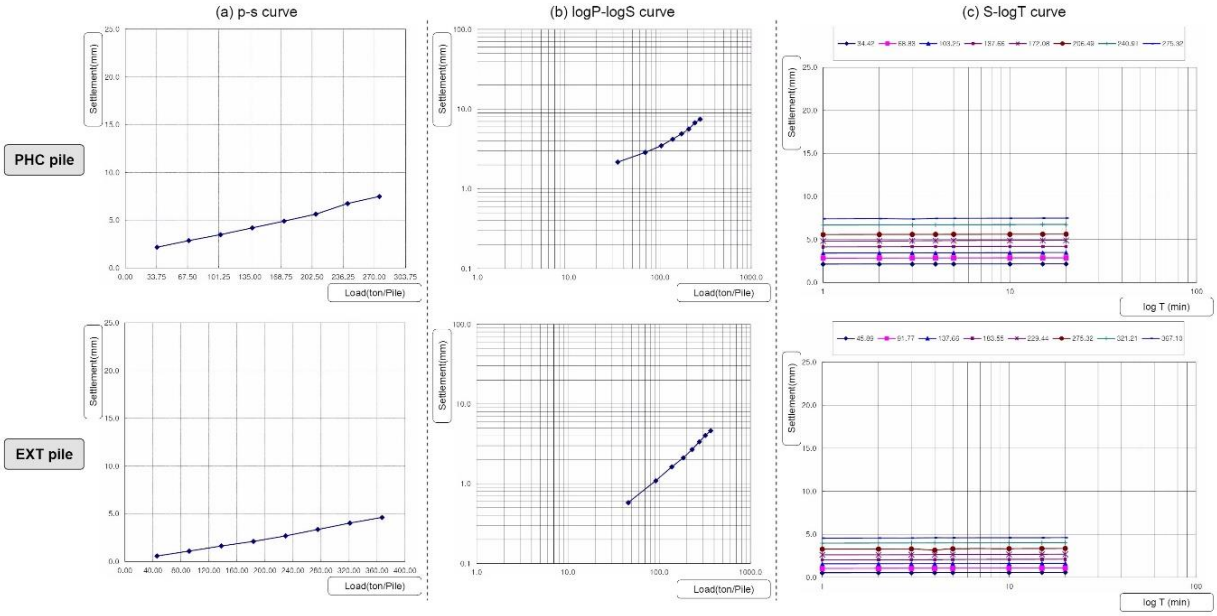

Fig.7. Pile Load Tests: (a) p-s Curve, (b) logP-logS Curve, (c) S-logT Curve

Table 4. Comparison of Work Duration

Pile	Pile quantity	Driving pile machine	Working days	Shortening days
PHC	2,592 ea	2 ea	93	-
EXT	2,004 ea	2 ea	72	21

the same load as shown in Fig.8.a,b. These pile foundation designs were carried out based on structural calculations. Through this basic design, pile foundation design was conducted for the applied construction site. When PHC piles were used for the pile foundation design, a total of 2,592 PHC piles were used whereas the EXT pile design used only 2,004 piles. Therefore, the EXT pile design reduced the number of piles by around 23% compared to the PHC pile design.

5.2 Analysis of Work Duration

The duration of the pile foundation work is influenced by the number of piles. Thus, the reduction of the pile quantity results in a reduction in the project duration, especially in the pile foundation work. To verify this effect, a duration assessment of the pile foundation work was conducted by calculating the pile daily record of the EXT pile in the selected construction site, the duration was calculated to be 72 days using two-pile driving machines. Therefore, it is confirmed that an average of 14 piles can be constructed per day using one pile driving machine to drive 2,004 piles. Using this calculation method, the pile foundation work duration of the PHC pile was also measured.

Through the field test, we verified that, a work duration of 2,592 PHC piles requires around 186 days when using one pile driving machine, and this will be reduced by half (to around 93 days) when two pile driving machines are used. According to the test results, the EXT pile has the time advantage that is able to decrease the required construction time by 30% in pile foundation work in comparison to the PHC pile. At the selected construction site, two driving pile machines were used because of the scale of construction site and process planning. Thus, the duration of pile foundation work between the EXT and PHC piles are 72 and 93 days, respectively, as shown in Table 4.

Through this test result, the increased bearing capacity of the EXT pile leads to the reduction of piles and work duration. We anticipate that these effects will be higher in a large-scale construction site or in adverse soil conditions.

Table 5. Comparison of Work Costs

Cost types	PHC pile (D500)			EXT pile (D500)			Difference ($)	Reduction (%)
	Quantity	Unit ($)	Total ($)	Quantity	Unit ($)	Total ($)		
Materials[a]	2,592 ea (28,124m)	27	759,348	2,004 ea (21,744m)	34	739,296	-20,052	-2.6
Construction[b]	93 days	2,210*2[c]	411,060	72 days	2,210*2[c]	318,240	-92,820	-22.6
Pile head cutting	2,592 ea	7.3	18,922	2,004	7.3	14,630	-4,292	-22.7
			1,189,330			1,072,166	-117,164	-9.85

[a] Materials: Piles
[b] Construction: Pile driver, Backhoe, Silo, Payloader, Generator, Labors
[c] 2: Two pile drivers

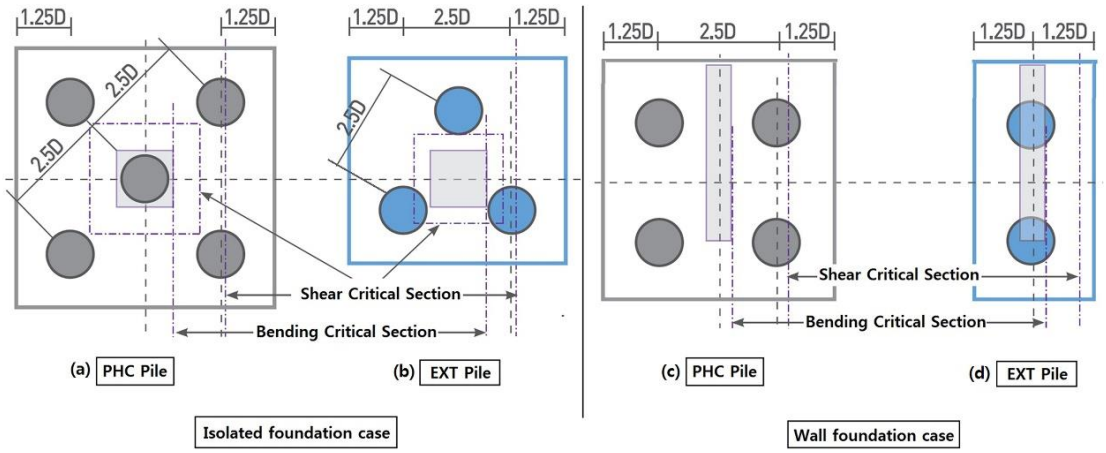

Fig.8. Comparison of Pile Foundation Designs

5.3 Analysis of Construction Cost

The advantage of EXT pile construction is closely related to the construction cost. To verify this, the pile foundation costs of the selected construction site were analyzed through the related construction costs. The cost of pile foundation work is normally based on the materials used, pile driving work, pile cutting work, and the static and dynamic pile load test. Therefore, a comparison between the EXT pile and PHC pile was carried out in order to understand the cost benefits.

As shown in Table 5., the pile cutting work cost was seen as the biggest drop with around a 22.7% decrease. Moreover, the pile driving work and material cost also decreased by around 22.6% and 2.6%, respectively. Therefore, we confirmed that EXT pile construction can decrease the pile foundation work cost by approximately 10% compared to the PHC pile construction.

6. Conclusion

The EXT pile method was applied to a construction site to determine its various effects. First, a pile load test was conducted at a selected construction site in order to determine the bearing capacity of the EXT pile. Then, we confirmed that the bearing capacity of the EXT pile is better than that of the PHC pile by around 24%. Based on these test results, the pile foundation design carried out the verification of saving piles numbers between the PHC pile and EXT pile. Finally, we confirmed that the EXT pile is efficient in terms of time and cost. On the basis of these findings, the following conclusions are drawn:

(1) The EXT pile shows that an effective arrangement of piles is possible rather than a PHC pile of the same specification because it can increase the bearing capacity per unit area by using an extended steel plate on the bottom. Therefore, the EXT pile system can provide effective delivery of the weight of the structure to the ground in pile design work. In this study, the reduction of piles of approximately 23% was confirmed at an actual construction site.

(2) The reduced number of piles also leads to the reduction of work duration. Through our field test, it was confirmed that the pile foundation work with the EXT pile required 72 days, and with PHC pile required 93 days. Thus, the EXT pile was reduced by a total of 21 days. This test result shows that increased bearing capacity of the EXT pile leads to pile reduction, and the effect of work duration will be higher at a large scale construction site or under adverse soil conditions.

(3) The advantage of the EXT pile also appeared in the construction cost. The analysis was conducted through the related costs of the pile foundation work. We confirmed that the EXT pile is more efficient than the PHC pile in construction work. Based on the results of the numerical analysis, the cost of EXT pile foundation work can be reduced by approximately 10% compared to the PHC pile.

Acknowledgements

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