Application of extended end composite pile design in pile foundation work

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Abstract

Pre-tensioned, spun, high-strength concrete (PHC) piles are the most commonly used type of pile in South Korea. Approximately 60% of the pile's strength is used in the design bearing capacity, and the rest is simply residing in the ground. Increasing the ground bearing capacity is crucial to reduce waste of the pile strength and to improve efficiency. Extended end (Ext) piles are a new kind of composite pile that can overcome the weakness of PHC piles. This study investigates the behaviour of Ext piles. Through field testing, it is confirmed that the bearing capacity of Ext piles is better than PHC piles by about 35% to 50%. Based on the study findings, the Ext pile design reduces the number of piles by around 38% compared to the PHC pile design through application in a selected construction site. The increased bearing capacity of Ext piles affects both work duration and project cost, which are 25% and 14% decreased, respectively.

1. Introduction

In recent decades, the use of piled foundations has increased due to the building of structures that are larger and higher than before. Pile foundations are principally used to transfer the loads from a superstructure, through weak, compressible strata or water onto stronger, more compact, less compressible and stiffer soil or rock at depth, increasing the effective size of a foundation and resisting horizontal loads (Tomlinson and Woodward, 2014). 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). In South Korea, reinforced concrete (RC) piles were mainly used from the 1960s to the early 1970s, and prestressed concrete (PC) piles were mainly used from the late 1970s until the early 1990s. However, owing to a growing awareness of safety, an increase in penetration and bearing capacity is required for foundation work. Therefore, pre-tensioned, spun, high-strength concrete (PHC) piles have been put to practical use, replacing the employment of PC piles. Currently, PHC piles represent more than 90% of the total pile production in South Korea: around 400 to 500 t/year (Park et al., 2008a; Sin et al., 2014). The quality and strength of PHC piles are generally reliable because they are prefabricated in factories. Economic considerations have meant that PHC piles have been applied to most parts of civil structures (Shin et al., 2014). However, PHC piles do have weaknesses, such as resistance to lateral loads and low bearing capacity (Cho, 2007; Jeong et al., 2013). Owing to the limited bearing capacity of PHC piles, the layout of the core part in buildings can become too congested, leading to increases in construction cost and duration, especially for skyscrapers (Lee and Song, 2010).

To address the weaknesses of PHC piles, steel–PHC composite piles, which have high resistance to horizontal forces and bending, 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 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 USA 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 and have been studied by a great number of researchers. Fibre-reinforced polymer (FRP) piles are another kind of composite pile. Several researchers have carried out theoretical studies on buckling of FRP piles under driving impact and have attempted to experimentally quantify the surface friction between FRP piles and sand (Fam and Rizkalla, 2002; Frost and Han, 1999; Han and Frost, 1999; Mirmiran et al., 2002; Nehdi et al., 2008). Moreover, researchers have analysed the flexural behaviour and strain ductility of FRP piles, and have performed field tests (Li et al., 2011; Mirmiran et al., 1999, 2002; Moran and Pntelides, 2002). Recently, concrete-filled steel tube (CFST) piles have been researched to identify the behaviour of centrally loaded and axially loaded CFSTs, as well as their seismic behaviour (Huo et al., 2009, 2014; Prion and Boehme, 1994; Sakino et al., 2004; Schneider, 1998; Varma et al., 2002).

There is a new type of composite pile called an 'extended end' (Ext) pile, as shown in Figure 1. However, investigations of Ext piles are rare. Only a few studies have been performed, and these have been related to material properties and bearing capacities, validity, effectiveness and the method of construction (Cho, 2007; Jeong et al., 2013; Kim, 2008; Lee and Song, 2010; Lim, 2014; Shin et al., 2014). In addition, most studies have used the material specification of the Ext pile without actual experimentation. However, Ext piles can bring efficiency to pile foundations with respect to time, cost and workability. The overall objective of the present study is to investigate the behaviour of Ext piles.

Figure 1. Ext composite pile: (a) extended steel plate; (b) pile dimension check; (c) welding connection; (d) Ext pile

2. Research methodology

To verify the economic feasibility of Ext piles, this study used a real construction site. The selected construction site is located in South Korea and is composed of ten apartment buildings with facilities. By using a real case study, various strengths of the Ext pile are demonstrated and compared with the PHC piles that are generally used. A load test was performed between the PHC pile and Ext pile, and the bearing capacity was measured, but seismic issues were not considered because the Korean peninsula is not located in an active seismic area. In addition, to compare the number of Ext and PHC piles, a pile foundation design was carried out. Also, using the pile daily record at the construction site, the project work durations were measured. Finally, this study determined whether the Ext pile foundation work in a construction project was more efficient in terms of time and cost (Figure 2).

3. Comparison of Ext pile with PHC pile

3.1 Allowable bearing capacity

Generally, a PHC pile is made in a circular pipe shape using pre-stressed steel bars, a reinforcement stirrup and highstrength concrete (Li et al., 2014). Approximately 60% of the pile's strength is used in the design bearing capacity, and the rest simply resides in the ground. Increasing the ground bearing capacity is crucial to reduce any waste of pile strength and to improve efficiency.

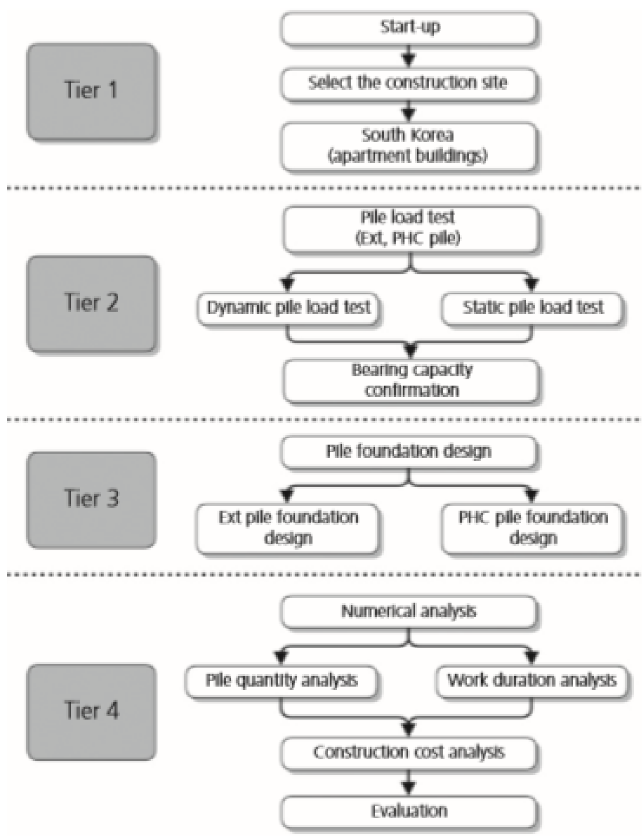

Figure 2. Research procedure

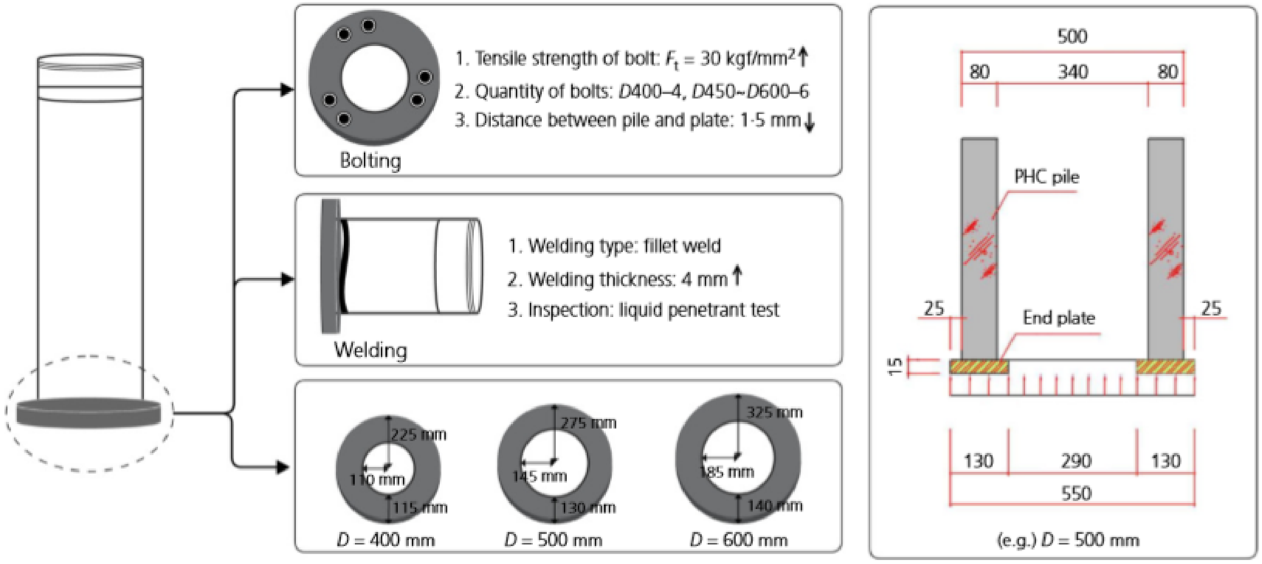

Figure 3. Connection methods and details of the Ext pile (dimensions: mm)

The Ext pile is capable of overcoming the issue of wasted pile strength that is seen in PHC piles. The Ext pile is a composite pile that combines a PHC pile with an extended steel plate (SS400) on the base. The thickness of the extended end plate is 15 mm (Kim, 2008). As shown in Figure 3, an Ext pile is made by welding or bolting the extended steel plate to the bottom of PHC pile. An Ext pile has the same skin friction but with increased end bearing capacity compared with a PHC pile of the same shaft diameter and length.

1. $Fp = A\sigma$

Equation 1 gives the allowable end bearing capacity, 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.

3.2 Increase in end bearing capacity

$$R = R_p + R_f$$
$$R_p = (25 \sim 30)NA_p$$
2. $$R_f = f_s A_b l$$
$$f_s(\text{cohesive soil}) = 0{\cdot}5q_u(q_u = 1{\cdot}25N) = 0{\cdot}625N$$
$$f_s(\text{sandy soil}) = 0{\cdot}2N$$

Equation 2 shows a bearing capacity formula commonly used in South Korea (Lee and Song, 2010; Lim, 2014; Park et al., 2008a, 2008b). According to Equation 2, the load on the head of a pile (R) is supported by the end bearing capacity (Rp) and by the skin friction (Rf). From Equation 2, Rp is applied to 25 to 30 multiples of N depending on the soil classification. This range of values covers the construction situation in South Korea, where most piles are constructed with weathered rock layers and the average figure for pile load tests correlates to a range of 25–30N (Lee and Song, 2010). To apply Equation 2 the area is input using units of m2, resulting in values of Rp and Rf in units of kN. Also, the magnitude of the standard penetration test (N) has an upper limit of 60. To determine, the value of Rf a reduction of around 20 to 30% is also applied in South Korea to consider the uncertainty of soil properties, such as the presence of a gravel layer or the velocity of a moving fluid layer (Lim, 2014).

Table 1 shows pile properties and illustrative end bearing calculation results for both PHC and Ext piles in three pile shaft diameter sizes. Equation 2 has been applied with an allowance for skin friction for a 3 m long pile in sandy soil. The Appendix also shows an example of how the design bearing capacity has been calculated and shows the factors of safety applied. The kN values used are 60 for the pile base and 50 for the skin friction.

Table 1 shows the increased endpoint area and design bearing capacity with respect to the shaft diameter of the PHC and Ext piles. The Ext pile end dimensions used are shown in Figure 3. Table 1 shows that the design bearing capacity of the three PHC piles utilises between 51 and 71% of the pile's proof stress. According to Table 1, the endpoint cross-section and wall thickness of the Ext pile is higher than that of the PHC pile by between 117 and 177%. The design bearing capacity of the Ext pile is able to increase proof stress utilisation to 81 to 94% for the same shaft diameter. The increased design load due to use of an Ext pile is approximately equivalent to using a PHC pile that is one diameter size greater. The Ext pile, therefore, secures pile foundation stability by extending the end plate to the inside and outside of the pile, as shown in Figure 4.

	PHC pile			Ext pile			Proportional increase
Diameter: mm	**Wall thickness: mm**	**Concrete cross-sectional area: m^2**	**Cross- sectional area: m^2**	**Thickness: mm**	**Ext cross-sectional area: m^2**	**Cross- sectional area: m^2**	**Cross- section and wall thickness: %**
*D*400	65	0·0684	0·1256	115	0·1210	0·159	127~177
*D*500	80	0·1055	0·1963	130	0·1714	0·2375	121~162
*D*600	90	0·1442	0·2826	140	0·2242	0·3317	117~155

		PHC pile		Ext pile		Increase
Diameter: mm	**Proof stress (allowable axial load): kN**	**Design bearing capacity: kN**	**Proof stress utilisation: %**	**Design bearing capacity: kN**	**Proof stress utilisation: %**	**Proof stress utilisation: %**
*D*400	1120	600~800	54~71	950~1050	85~94	23~31
*D*500	1730	1000~1200	58~69	1450~1600	84~92	23~26
*D*600	2360	1200~1400	51~59	1900~2100	81~89	30

Table 1. Increased endpoint area and design bearing capacity of the Ext pile

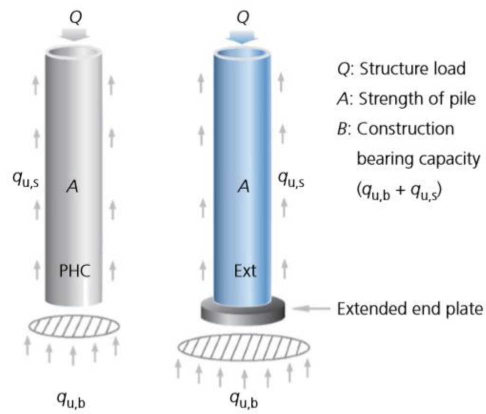

Figure 4. Principle of increased bearing capacity

4. Field test

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 types: 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 analyser (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 by a driveability analysis after measures 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 pile. The basic principle of the dynamic pile load test is shown in Figure 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 Figure 6. Also, through this system, axial load–settlement (P–S) curves were obtained.

4.2 Test results

The construction site for case study is located in South Korea and comprises seven apartment buildings, neighbourhood public facility and common service facilities. The land area and building area of this site are 52 183 000 m2 and 8 929 873 m2, respectively. To verify detailed soil conditions about the testing site, a standard penetration test was conducted, with selected results shown in Figure 7, and pile installation was conducted based on the test results. Around 18 661 617 m2 of the land area was required piling for foundations owing to the insufficient bearing capacity of the soil determined through field load testing. The standard pile size used on this construction site was D=500 mm, a shaft wall thickness of 80 mm and concrete compressive strength was 78·5 N/mm2 (800 kg/cm2). Drop-4·0 t hammers were used for the pile driving load test. The design bearing capacity of these areas is 1200 kN in the PHC pile and 1600 kN in the Ext pile per unit.

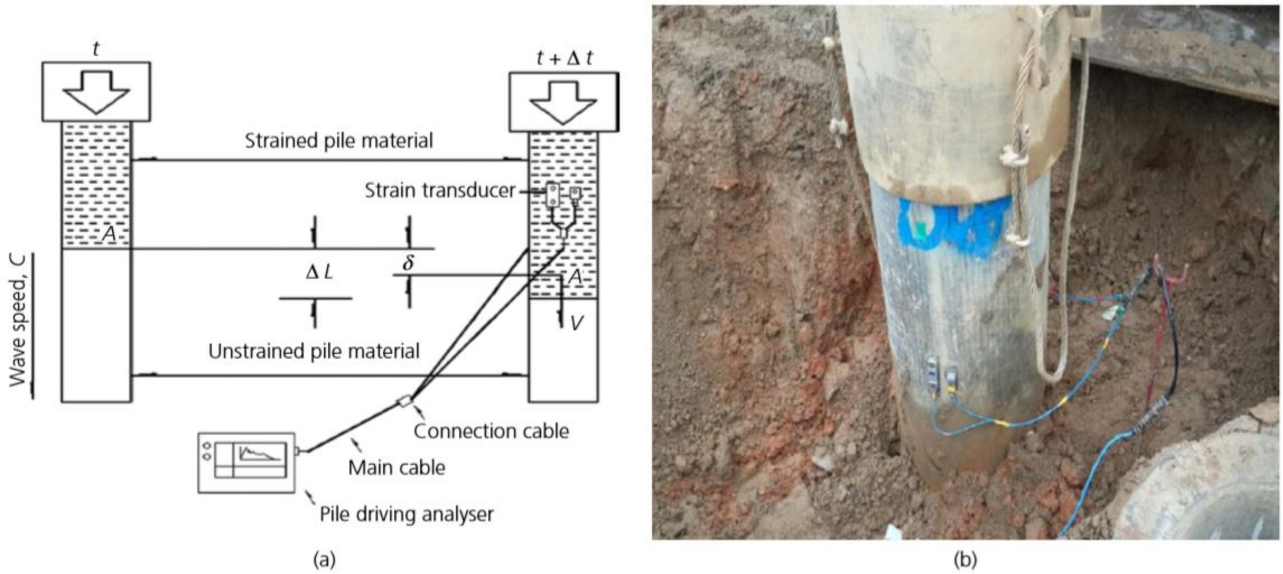

Figure 5. Dynamic pile load system: (a) schematic diagram; (b) installation

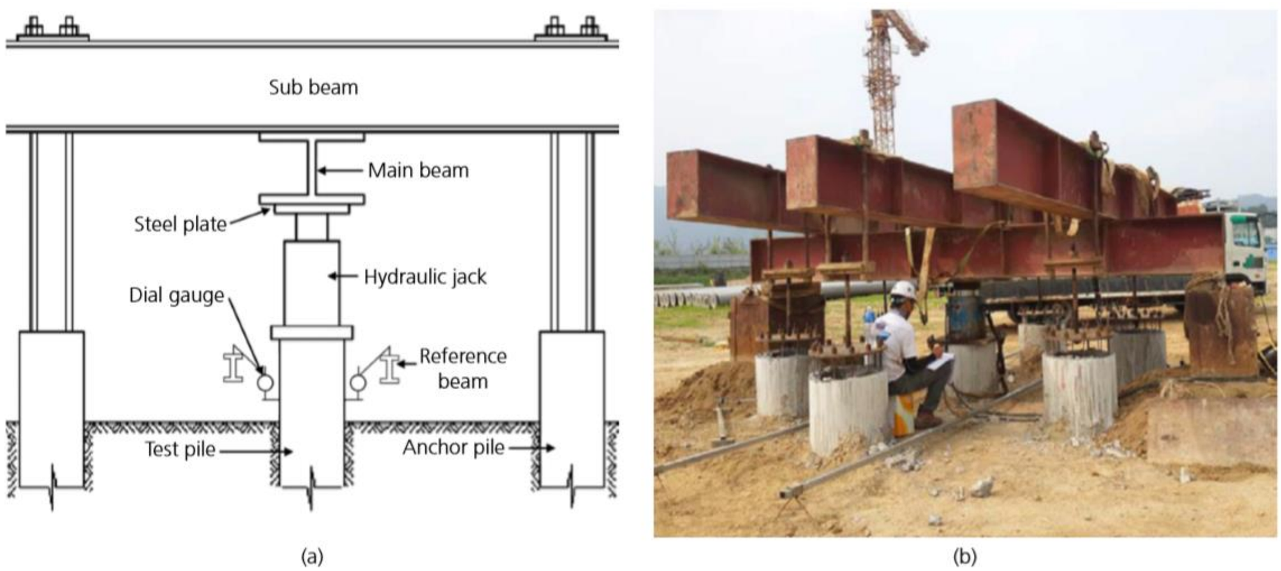

Figure 6. Plate load test system used around piles: (a) schematic diagram; (b) installation

The test piles, both Ext and PHC, were constructed using the separated doughnut auger (SDA) method and a driving procedure has been added in Figure 8. The SDA piling method is to drill the ground with the upper continuous flight auger and the lower casing, rotating counter to each other, and to rotate and push or drive lightly after a pre-cast pile is inserted. The SDA piling method is a solution to the low bearing capacity of the pile and the stress relaxation, which are common problems in other piling methods (Chai, 2000; Hong and Chai, 2003). As shown in Figure 8, Ext piles were reinforced by cement milk grouting around in increased installation diameter comprising the extended end plate. Therefore, the end plate does not disturb the soil during pile installation. Also, to avoid overstress and damage to the pile, the weight of hammer applied was determined as shown in Figure 9.

As shown in Table 2, the test results of the allowable bearing capacity of the Ext pile are 1956·08, 1921·58, 1870·23 and 1939·62 kN, respectively. Thus, the overall value is 1921·88 kN. The PHC pile results are 1497·83, 1560·94, 1251·66 and 1382·98 kN. Thus, this study obtained an overall value of 1423·35 kN. Based on the test result, it was determined that the allowable bearing capacity of the Ext pile is on average 35% higher than that of the PHC pile. The static pile load test requires 225% of the maximum possible load design. Therefore, 3600 kN was determined to be the maximum load, and the loading test was conducted after eight load steps. Moreover, 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. Figure 10 shows the results of the static pile load test. As shown in Figure 10(a), the P–S curve of the Ext pile shows that the settlement regularly increased in each step until 3600 kN. Thus, the allowable bearing capacity of the Ext pile with a safety factor of 2·0 was determined to be 1800 kN ". In the case of the PHC pile, the designed load test was also applied until 2700 kN, which is 225% of the maximum possible load design of 1200 kN. As a result, the allowable bearing capacity was found to be 1350 kN " (137·66 tf) after applying a safety factor of 2·0.

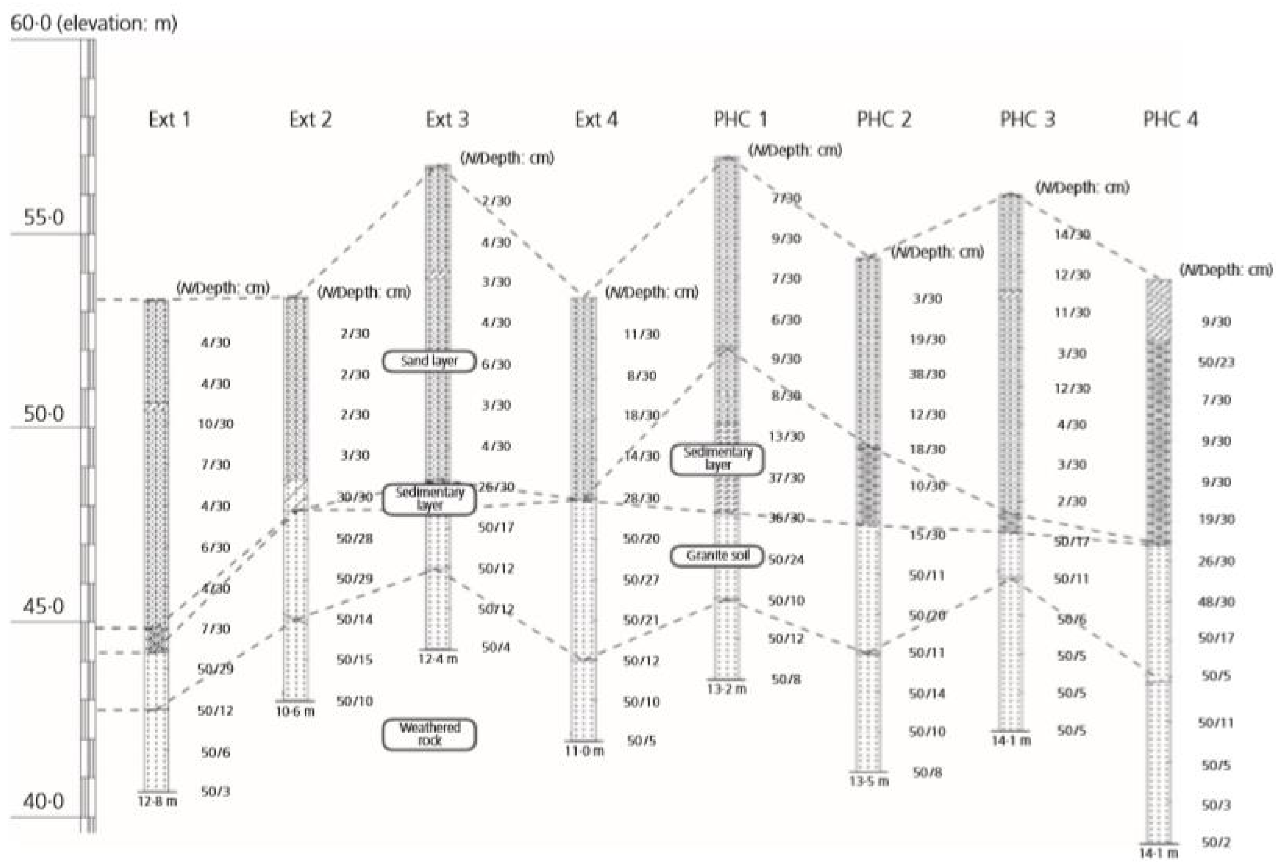

Figure 7. Standard penetration test at selected locations of the site

5. Cost analysis
5.1 Pile quantities

Through the pile load test, it was confirmed that the bearing capacity of the Ext pile is better than the PHC pile. Thus, it is possible to increase the design load in the pile design step. Next, this study compared the number of piles between the Ext piles and PHC piles through the design of the pile foundation. The load is delivered by the wall to the piles through the foundation, and the piles transfer the load to the ground. Therefore, a low bearing capacity is required to a quantity of many piles, but a high bearing capacity leads to the opposite result. Using this principle and the pile load test results, a pile foundation design carried out.

The differences of the basic designs between the PHC pile and Ext pile are shown in Figure 11. With PHC piles, the pile design should 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 Figure 11(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 Figure 11(d). Therefore, the pile design between PHC and Ext piles is totally different. 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 Figures 11(c) and 11(d). For an isolated foundation, five PHC piles must be constructed per location, while only three Ext piles can withstand the same load as shown in Figures 11(a) and 11(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 2337 PHC piles were used whereas the Ext pile design used only 1683 piles. Therefore, the Ext pile design reduced the number of piles by around 38% compared to the PHC pile design.

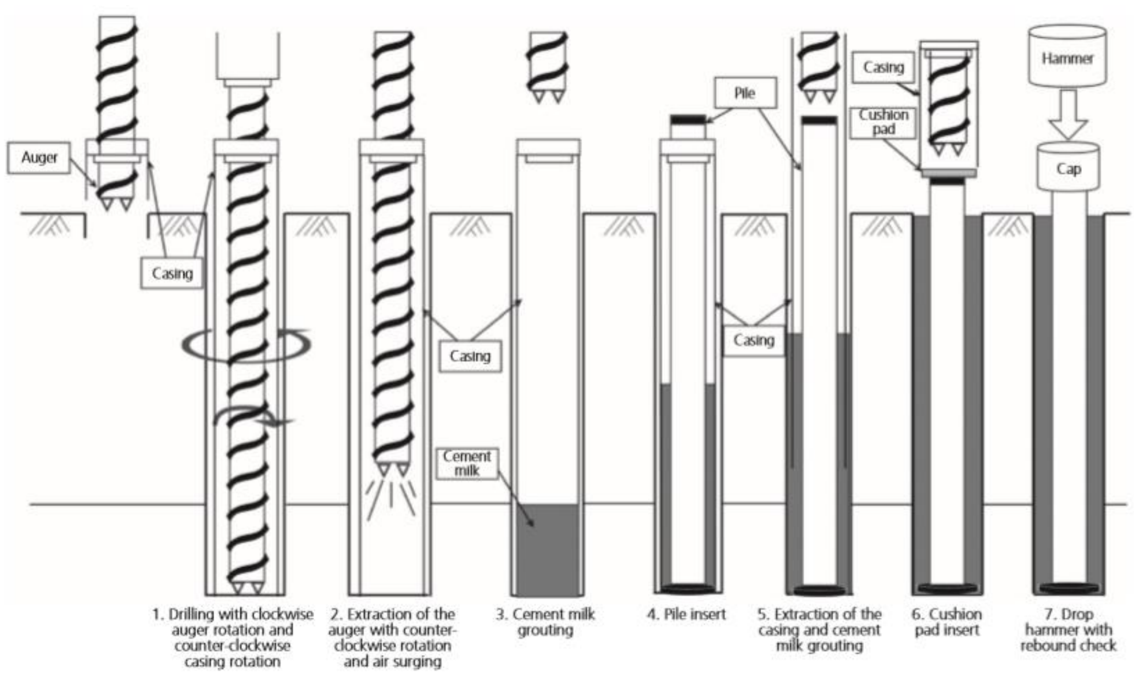

Figure 8. SDA procedure

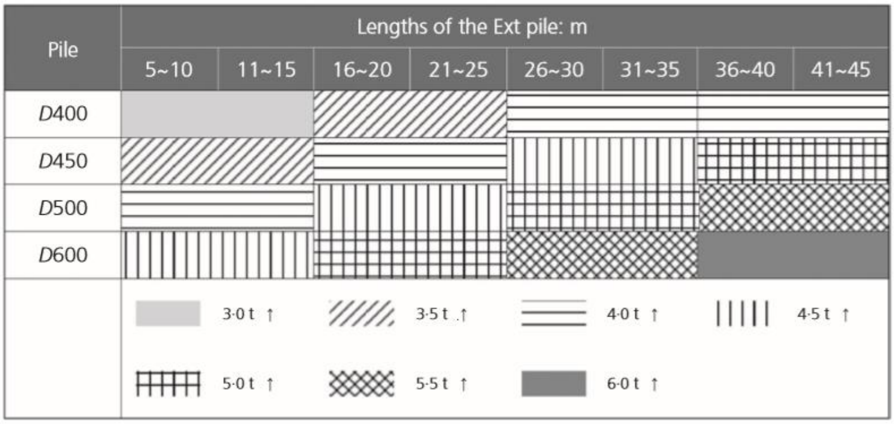

Figure 9. Hammer standards

5.2 Work duration

Through the comparison of the Ext and PHC pile foundation designs, this study determined that one advantage of the Ext pile is the decreased number of piles required. However, there is another advantage of the Ext pile in terms of the project's duration. Normally, 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 pile foundation work. To evaluate this effect, a duration assessment of the pile foundation work was conducted by calculating the quantity of Ext and PHC piles. Using the pile daily record of the Ext pile in the selected construction site, the duration was calculated to be 57 d using two pile-driving machines. Therefore, it is confirmed that an average of 15 piles can be constructed per day using one piledriving machine to drive 1683 piles. Using this calculation method, the pile foundation work duration of the PHC pile was also measured.

Pile no.	Depth of penetration: m	Capwap capacity: kN Skin friction force	End bearing capacity	Whole supporting force	Allowable bearing capacity: kN Capwap (FS = 2·5)	Davisson (FS = 2·0)	Final allowable bearing capacity: kN	Division
PHC 1	13·2	8·82	3662·26	3671·08	1468·432	1836·52	—	EOID
		401·8	3342·78	3744·58	1497·832	1870·82	1497·83	Restrike
PHC 2	13·5	251·86	3560·34	3812·2	1524·88	1804·18	—	EOID
		674·24	3230·08	3902·36	1560·944	1841·42	1560·94	Restrike
PHC 3	14·1	0·98	3004·68	3005·66	1202·264	986·37	—	EOID
		595·84	2480·38	3135·02	1251·656	1151·01	1251·66	Restrike
PHC 4	14·1	61·74	3149·72	3211·46	1284·584	1301·93	—	EOID
		709·52	2747·92	3457·44	1382·976	1422·47	1382·98	Restrike
Ext 1	12·8	413·56	4118·94	4118·94	1647·576	2059·47	—	EOID
		988·82	3901·38	4890·2	1956·08	2444·12	1956·08	Restrike
Ext 2	10·6	88·2	4174·8	4263	1705·2	2448·04	—	EOID
		855·54	3948·42	4803·96	1921·584	2411·78	1921·58	Restrike
Ext 3	12·4	89·18	4362·96	4452·14	1780·856	2093·28	—	EOID
		645·82	4028·78	4675·58	1870·232	2101·218	1870·23	Restrike
Ext 4	11·0	237·16	4095·42	4332·58	1733·032	2071·72	—	EOID
		463·54	4384·52	4849·04	1939·616	2059·764	1939·62	Restrike

Table 2. Dynamic pile load test result

Through the field test, this study verified that the construction of an average of 15 piles is possible per day using one piledriving machine at the selected construction site. Therefore, a work duration of 2337 PHC piles requires around 156 d when using one pile-driving machine, and this will be reduced by half (to around 78 d) when two pile-driving machines are used. According to the test results, the Ext pile has a time advantage in that its use can decrease the required construction time by 36% in pile foundation work in comparison with the PHC pile. However, at the selected construction site, two pile-driving machines were used in view of the scale of the construction site and process planning. Thus, the duration of pile foundation work between the Ext and PHC piles is 57 and 78 d, respectively, as shown in Table 3. Through this test result, it can be seen that the increased bearing capacity of the Ext pile leads to a reduction in the number of piles and the duration of work. From this study, it is anticipated that these effects will be greater for a large-scale construction site or in adverse soil conditions.

5.3 Construction costs

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 analysed 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 testing. Therefore, a comparison between the Ext pile and the PHC pile was carried out to in order to understand the cost benefits.

As shown in Table 4, the pile cutting work cost was observed to be the biggest reduction, with around a decrease of around 28%. Moreover, the pile-driving work and material cost also decreased by around 27% and 9·3%, respectively. Therefore, this study confirmed that Ext pile construction can decrease the cost of pile foundation work by approximately 15·4% compared with PHC pile construction.

6. Conclusions

In this study, a new composite pile called the ‘Ext pile’ was proposed for pile foundation work in a real construction project. 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 piles. Then, the study confirmed that the bearing capacity of the Ext pile was better than that of the PHC piles by, on average, 35%. Based on these test results, the pile foundation design saved a significant number of piles by using Ext piles in place of PHC piles. Finally, this study confirmed that the Ext pile is efficient in terms of time and cost. On the basis of these findings, the following conclusions are drawn.

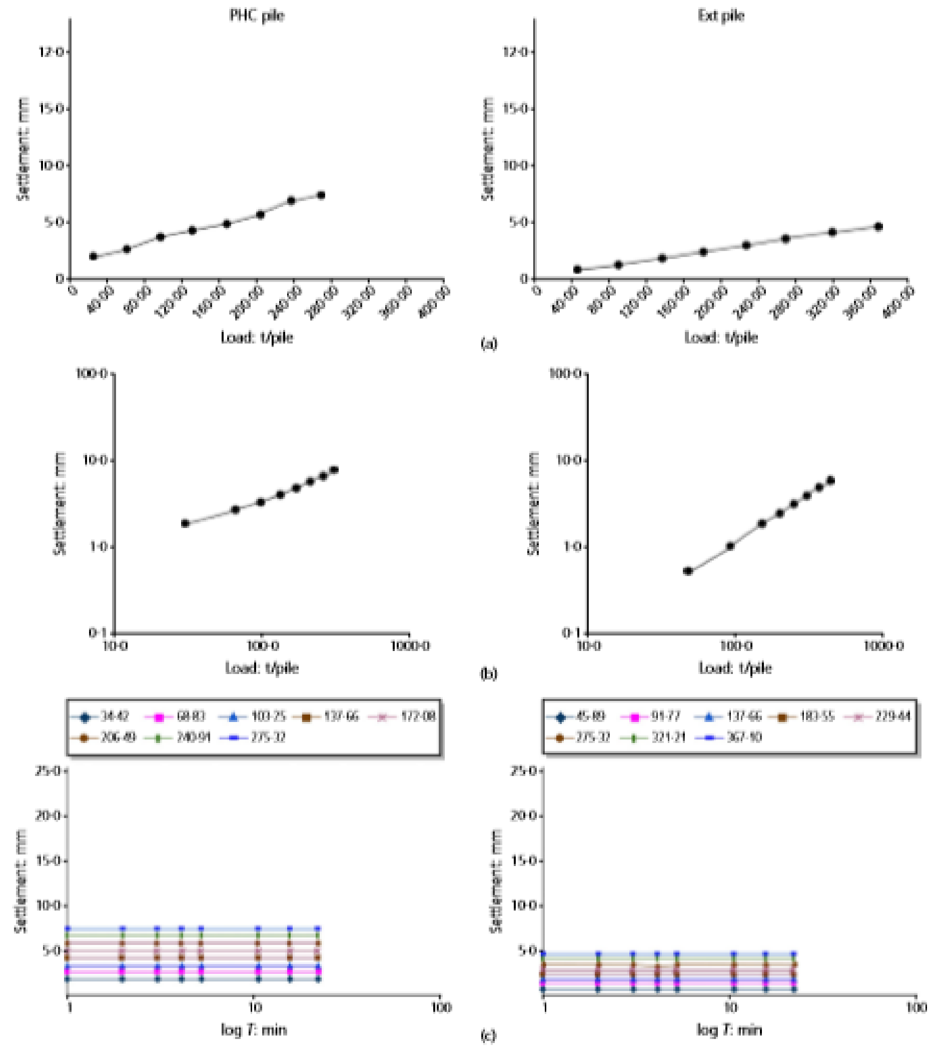

Figure 10. Pile load tests: (a) P–S curve; (b) logP–logS curve; (c) S–logT curve

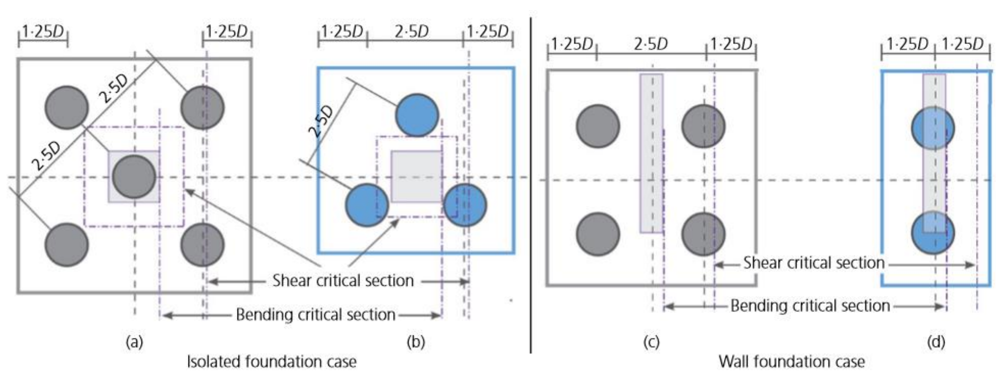

Figure 11. Comparison of pile foundation designs: isolated foundation case for (a) PHC pile; (b) Ext pile; and wall foundation case for (c) PHC pile; (d) Ext pile

(a) Ext piles can be used more effectively in congested areas because of the increased bearing capacity per unit due to the extended steel end plate. In this study, a reduction of piles of approximately 38% was confirmed at an actual construction site.

Pile types	Pile diameter: mm	Design bearing capacity: kN	Pile quantity: ea	Total pile length: m	Pile-driving machine: ea	Working duration: d	Duration shortened by: d
PHC	500	1200	2337	25 357	2	78	—
Ext	500	1600	1683	18 258	2	57	21

ea, each number

Table 3. Comparison of work duration

	PHC pile (D500)			Ext pile (D500)				
Cost types	Quantity	Unit: US$	Total: US$	Quantity	Unit: US$	Total: US$	Difference: US$	Reduction: %
Materials[a]	2337 ea (25 357 m)	27	684 640	1683 ea (18 258 m)	34	620 772	−63 868	−9·3
Construction[b]	78 d	2210 × 2[c]	344 760	57 d	2210 × 2[c]	251 940	−92 820	−27
Pile head cutting	2337 ea	7·3	17 060	1683	7·3	12 286	−4774	−28
		1 046 460			884 998		−161 462	−15·4

[a]Materials: piles
[b]Construction: pile driver, backhoe, silo, pay loader, generator, labour
[c]2: two pile drivers

Table 4. Comparison of work costs

Pile		PHC pile	Ext pile
Diameter: mm		500	500
Cross-sectional area (A_p): m^2		0·1963	0·2375
Pile principal plane length (A_b): m		3·14	3·454
Pile length (l): m		3	3
End bearing capacity (R_p): kN	$25 \times N \times A_p$ ($N = 60$)	2885·61	3491·25
Skin friction (R_f): kN	$f_s \times A_b \times l$ $f_s = 0{\cdot}2 \times N$ (sandy soil) ($N = 50$)	923·16	1015·476
Safety factor, n		3	3
Design bearing capacity: kN	$\frac{1}{n} \times (R_p + R_f)$	1269·59	1502·24

Table 5. Example design bearing capacity calculation using Equation 2

(b) The reduced number of piles also leads to a reduction in work duration. At the field site, it was determined that the pile foundation work using the Ext piles required 57 d, whereas using the PHC piles required 78 d. Thus the use of Ext piles reduced the work duration by a total of 21 d. The effect of this reduction in work duration will be higher at a large-scale construction site or under adverse soil conditions.

(c) The advantage of the Ext pile also manifested in terms of the construction cost. Based on the results of the study site, using Ext piles reduced the cost of the foundation work by approximately 15·4% compared to the use of PHC piles.

Appendix

See Table 5 for an example of the design bearing capacity calculation.

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