Final detailed design of an all-in-one attachment-based PHC pile head cutting robot and its structural stability analysis

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ABSTRACT
Conventional pretensioned spun, high-strength concrete (PHC), pile head cutting process is associated with safety, quality uniformity, and labor productivity problems. However, trend analysis has revealed that no technology has been developed to address these problems as these pertain to specific Korean construction site situations. This study aims to derive the final detailed design for an all-in-one attachment-based PHC pile head cutting robot, and analyzes its structural stability. To this end, the key functions of an all-in-one attachment-based PHC pile head cutting robot have been defined, and the related core element technologies have been analyzed. This has led to the presentation of two detailed design alternatives. Both of these were then subjected to an analytical hierarchical process (AHP) and trade-off analysis that led to the final selection of the diamond wheel saw-based detailed design. In a structural stability analysis of the final detailed design, all tested parts did not surpass the threshold yield strengths of 230 MPa (SS400) and 255 MPa (AL6061 T6). If a prototype is developed based on the final detailed design derived in this study, it is expected to have improved work safety, quality uniformity, and work efficiency characteristics compared with the conventional PHC pile head cutting process.

1. Introduction
A pretensioned spun high-strength concrete (PHC) pile has a compressive strength ≥ 78.5 N/mm² (Baek and Lee 2007), and is characterized by an excellent design support through its insertion at a required depth below ground level. The PHC pile installation operation was conducted based on the following order: (1) gauging and marking the PHC pile insertion position, (2) insertion of the PHC pile, and (3) cutting the PHC pile head (Yeom et al. 2017). The third step is an essential operation used to ensure a uniform transfer of the building load to the soil support layer by cutting the top part of the PHC piles exposed above ground to a uniform required height (Yeom et al. 2017).

The PHC pile head cutting operation is a construction step with a great safety hazard because it is performed by a worker with the use of a grinder. In a previous study (Yeom et al. 2018), the currently employed PHC pile head cutting method was reported to pose increased accident risks, such as injuries caused by cut-off fragments, or cutting equipment. Other problems associated with the PHC pile head cutting process is the varying quality of the PHC pile head cut-off surfaces and work productivity depending on the skills of the individual worker. Accordingly, the number of skilled workers engaged to perform PHC pile head cutting has been decreasing, and the safety hazard and productivity problem related to the PHC pile head cutting process are expected to be aggraved in line with the increasing level of difficulty owing to the increasing demand for large-diameter PHC piles.

Against this background, this study aims to derive detailed design alternatives for an all-in-one attachment-based PHC pile head cutting robot to improve labor safety, quality uniformity, and work productivity, followed by the selection of the final detailed design using the analytic hierarchical process (AHP) and trade-off analysis, and the verification of the structural validity of the final design. The final design derived in this study and its structural validity analysis results were reflected in the implementation of an all-in-one attachment-based PHC pile head cutting robot as a follow-up study. Upon completion of the performance assessment through field testing, all-in-one attachment-based PHC pile head cutting robots will be fabricated for practical use. The future construction sites equipped with the PHC pile head cutting robots developed in this study are expected to perform PHC pile head cutting operations with improved safety, quality uniformity, and work productivity compared with the conventional labor-centered PHC pile head cutting process.
2. PHC pile head cutting-related theoretical considerations

2.1. Characteristics of conventional PHC pile head cutting work

PHC pile head cutting is an operation that involves cutting PHC piles exposed above ground to a required height after driving the PHC piles based on the use of centrifugal forces to the designed depth. It is an essential operation in foundation works to ensure a uniform transfer of building loads down to the foundations (Yeom et al. 2017). PHC pile head cutting can be conducted with two different methods: the grinding-crushing method in which a grinder and a crusher are used to crush the upper part of the cut-off pile-head surface and connect the pile with the foundation with the steel rebar within the pile, and the one-cutting method in which the pile head is severed in one cut without steel rebar exposure. In this case, the cut-off surface is connected to the foundation with a steel rebar cap supporting the pile head. The one-cutting method was found to be advantageous over crushing-grinding method owing to uniform cut-off surfaces, working time, cost benefits, and labor efficiency, as well as the absence of dust and fly products. Consequently, according to our survey, most construction sites prefer the PHC pile-one-cutting method to the grinding-crushing method for its various advantages, including construction costs and duration reduction. Figure 1 shows the process of PHC pile head one-cutting.

2.2. Prior art and global technology development trend regarding a PHC pile head cutting robot

In this study, we examined prior art and technology development trends related to a PHC pile head cutting robot developed to address the problems of the conventional PHC pile head cutting method. As a result, we identified seven prior technologies related to a PHC pile head cutting robot filed and registered to-date, of which only four have been implemented.

To provide an overview of the analysis of the previous studies and technological developmental trends, the devices developed by Yeon (2005) and Shinhan Tech Co (2008) were based on the PHC pile head cutting method that combined manual installation of a guide rail on a PHC pile and automated head cutting. The remaining five devices were designed for automatic PHC pile-cutting operations by an excavator that moved along a rail, but were limited by the pre-and postcutting manual working processes, such as the estimations and markings of the cutting lines, and by the input of the construction equipment, such as lifting and transportation. Apart from these drawbacks, the method developed by Dustin (2016) was designed for concrete-filled square piles used in foreign countries, and was found to have limited applications in Korea where round PHC piles were used (Table 1).

3. Detailed design of an all-in-one attachment-based PHC pile head cutting robot

3.1. Key functions of an all-in-one attachment-based PHC pile head cutting robot

An all-in-one attachment-based PHC pile head cutting robot fulfills three functions, as defined below.

3.1.1. PHC pile-cutting position sensing function

The method of estimating and marking cutting lines currently used for PHC pile-head cutting has limitations as manual work, such as the measurement deviation in the height of the cut PHC piles and reduced work productivity through labor input at construction sites. To address these problems, we found that it is necessary to apply the PHC pile-cutting position sensing function to recognize the accurate cutting positions without performing the extra processes of the estimations and markings of the cutting lines, and the

Figure 1. Process of the PHC pile head one-cutting work (Yeom et al. 2017).
minimization of work errors compared with the conventional method.

### 3.1.2. PHC pile-cutting function

It has been noted that the conventional method of PHC pile cutting, wherein a worker cuts PHC pile heads with a grinder, has the disadvantages of irregular heights of the severed PHC pile heads and quality irregularities on the cut-off surfaces. It has also been reported that workers are at risk of electric shock and fall accidents while working at submerged or high water-level sites and that an extra work process is required when the cut-off surface is tilted, thus lowering the work productivity. It has also been shown that these problems can be addressed by applying the PHC pile cutting function to ensure precision of PHC pile-cutting without manual worker input.

### 3.1.3. PHC pile-handling function

The conventional method of pushing over, lifting, and transporting the severed (top) parts of PHC piles involves pushing them over using the excavator bucket, fastening each pile head pushed away with a rope for lifting, and transporting them with extra construction equipment. This process was found to have safety and quality implications threatened by collapse and collision of the severed PHC pile heads,
as well as work risks based on unsecure lifting and transporting operations. It was demonstrated that these problems can be addressed by developing and applying the PHC pile-handling function as one-stop input solution that enables the execution of the entire process by the input of one construction equipment.

### 3.2. Technical considerations for a detailed design of an all-in-one attachment-based PHC pile head cutting robot

We analyzed the technical considerations for the implementation of the three essential functions as defined above by conducting face-to-face interviews with field survey and PHC pile head cutting construction experts, and ten experts with experience in the design and manufacturing construction robots. The results of information collection and selection are summarized in Table 2.

### 3.3. Core element technology for the detailed design of an all-in-one attachment-based PHC pile head cutting robot

#### 3.3.1. Core element technology related to the PHC pile-cutting position-sensing function

Our review of the cutting position sensing function of an all-in-one attachment-based PHC pile head cutting robot led to the identification of three distinct sensing methods: (1) optical method, (2) wireless method, and (3) motion control method.

The optical method (Figure 2(a)) is most extensively used at construction sites where the conventional PHC pile head cutting is practiced. A laser leveler is positioned at the design work height and the cutting height is estimated with an optical receiver. The extensive use of the optical method at construction sites was attributed to its low cost and high usability for the implementation of core element technology. The technology used in the wireless method (Figure 2(b)) and motion control method (Figure 2(c)) is a positioning technology based on the excavator’s behavior information collected by motion sensors and roll-and-pitch sensors mounted on the excavator boom, arm, and bucket, initial coordinates, or coordinates based on the global navigation satellite system (GNSS). Even though the wireless method has the advantage of implementing the core element technology at a reasonable cost, it is prone to excavator bucket position recognition errors depending on the working environment and higher initial cost of installation compared with the optical method.

#### 3.3.2. Core element technology related to PHC pile-cutting function

Our review of core element technology related to the cutting function of an all-in-one attachment-based PHC pile head cutting robot led to the identification of three distinct methods: (1) diamond wire saw, (2) diamond wheel saw, and (3) diamond chain saw.

(1) A diamond wheel saw is a cutting tool mainly used in PHC pile head cutting work sites; it cuts a PHC pile by high-speed rotation of a round saw blade. It has the advantages of relatively rapid cutting operation, excellent cut-off surface quality, and inexpensive replacement of maintenance, repair, and operation (MRO) materials. Additionally, it has been shown to require particular attention to safety hazards owing to the possibility of damage to the diamond wheel saw in the event of excessive workload (Figure 3(a)). (2) A diamond wire saw cuts a PHC pile by high-speed rotation of a high-strength wire. This method is advantageous in that it can cut any object regardless of shape or size by maintaining the replacement cost of the MRO materials at relatively low levels. Its disadvantages are the large amount of sludge generated by the thick wire during the cutting operation, and the possibility of wire breakage when subjected to excessive workloads that requires a thorough safety assurance (Figure 3(b)). (3) A diamond chain saw cuts a pile based on the friction induced by the high-speed rotation of high-strength chains. It can cut objects of any size by adjusting the length of the diamond chain saw, but its MRO materials need to be replaced frequently and the replacement cost is higher than other core element technologies (Figure 3(c)).

#### 3.3.3. Core element technology related to the PHC pile-handling function

Our review of the core element technology related to the handling function of an all-in-one attachment-based PHC pile head cutting robot led to the identification of three distinct methods: (1) orange grapple, (2) rotary multigrab, and (3) demolition grab.

(1) An orange grapple was found unsuitable for the performance of the complex process of sensing and cutting operations because it lifts and moves a pile by grabbing it vertically that makes secure grabbing and

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**Table 2. Technical consideration for PHC pile-cutting machine.**

| Essential function | Technical consideration |
|--------------------|-------------------------|
| Sensing            | - Ease of use of sensing device |
|                    | - Speed and accuracy of the cutting position recognition |
|                    | - Cost-effective equipment construction |
|                    | - Ability to perform work in various working environments |
|                    | - Possibility of precision control |
| Cutting            | - Superiority of durability and stiffness |
|                    | - Cost-effective replacement period and replacement cost |
|                    | - Low probability of safety accident |
|                    | - Superiority of surface quality |
| Handling           | - Ability to transport heavy load piles |
|                    | - Ease of clamping between equipment and piles |
|                    | - Superior clamping force between equipment and piles |
|                    | - Ease of rotation, transportation, load for piles |
lifting a considerable challenge (Figure 4(a)). (2) Rotary multigrab was found to be best-suited for the execution of the handling function of an all-in-one attachment-based PHC pile head-cutting robot because it allows the rotation of the connecting unit, executes complex processes, such as sensing and cutting operations, and can easily transport vertical and horizontal parts (Figure 4(b)). (3) A demolition grab can rotate the connecting unit and easily transport vertical and horizontal parts, and can a rotary multigrab. These capabilities make it a popular tool for the crushing and transportation of light objects, but the form of its edges makes it unsuitable for lifting and transporting the PHC pile (Figure 4(c)).

3.4. Proposal of detailed design alternatives of all-in-one attachment-based PHC pile head cutting robot

Using the results of core element technology analysis performed in Section 3.3 above, we derived two alternative designs for the current all-in-one attachment-based PHC pile head cutting robot.

3.4.1. A detailed design of a PHC pile head cutting robot based on diamond wire saw

The PHC pile head cutting robot that is based on a diamond wire saw is designed to use an optical method to perform the PHC pile-cutting position-sensing function, a diamond wire saw to perform the PHC pile-cutting function, and a rotary multigrab to perform the PHC pile-handling function. The clamp of the diamond wire saw-based detailed design was equipped with a number of protruding contacts to increase the frictional force between the PHC pile, and the contact surface, thus maximizing the stable fastening of the PHC pile. In addition, it is designed as an integral frame-cover structure connected to the excavator connecting unit and cutting base frame by a pair of clamp shafts (Figure 5).

The driving frame of the diamond wire saw-based detailed design was placed on the base plate of the cutting base frame, and was connected to the driving rail by being meshed with the main roller among the driving rollers of the upper part. This triggered the driving frame that was connected to the driving rail to be operated by five driving rollers and the timing belt to rotate along the driving rail, putting the driving
3.4.2. A detailed design of a PHC pile head cutting robot based on a diamond wire saw

A diamond wheel saw-based PHC pile head cutting robot is designed to use an optical method to perform the PHC pile cutting position sensing function, a diamond wheel saw to perform the PHC pile-cutting function, and a rotary multigrab used to perform the PHC pile handling function. The clamp of the diamond wheel saw-based design was vertically connected to the assistant plate along the core to facilitate the maintenance of the vertical arrangement between the PHC pile and the clamp, and the structures of the receiving loads in the front direction, unlike the diamond wire saw, was compensated by the used claw. Further, the claw was designed to respond to the PHC piles of various sizes by connecting them with a pin junction through the claw shaft to allow the required degree-of-freedom (Figure 8).

The diamond wheel saw-based detailed design was designed to operate based on the movement of the driving frame along the driving rail meshed with the main roller, in conjunction with the concurrent operations of seven driving rollers and the concurrent rotation of the timing belt. The driving frame was positioned on the base plate of the cutting base frame, and was connected to the main roller among the driving rail in a serrated manner. In addition, the diamond wheel saw connected to the ring gear was designed to operate stably by the rotation of the maintenance roller and the swing belt so that the pinion roller connected to the maintenance roller rotated and the ring gear meshed with the pinion roller rotated along the guide roller (Figure 9).

The detailed diamond wheel saw-based design executes the PHC pile cutting as follows: (a) backward movement of the driving frame mounted on the base plate of the cutting base frame along the driving rail to prepare for the cutting operation, (b) cutting while the driving frame advanced forward, and (c) 140° rotation of the diamond wheel saw connected to the driving frame. These three steps thus allowed the cutting of the PHC pile (Figure 10).
3.5. Selection of the final detailed design based on AHP analysis

3.5.1. Selection of evaluation parameters and weight calculation for the detailed design alternatives

For the selection of the final detailed design for the all-in-one attachment-based PHC pile head cutting robot, we set the following evaluation parameters by taking into account the problem solving and utility aspects of the conventional PHC pile head cutting method: accuracy, safety, work facility, and economic feasibility (Table 3).

To calculate the weight of the evaluation parameters, we conducted a questionnaire survey with 37 construction and mechanical engineering experts and field experts with PHC pile head cutting work experience. We also conducted a pairwise comparison using the AHP analysis technique on the survey results, and derived the weights of the evaluation parameters with the use of the analyzed results of the 34 questionnaires after the exclusion of three questionnaires with a consistency ratio (CR) that exceeded 0.2 (Table 4).

3.5.2. Selection of the final detailed design using a trade-off analysis

We calculated the mean score of each detailed design alternative based on a questionnaire survey with 37 construction and mechanical engineering experts and field experts with PHC pile-head cutting work experience. The evaluation scores were collected based on a 5-point Likert
In trade-off analysis, the total score for each detailed design alternative was calculated using the weight and the mean score that each detailed design alternative gains in four evaluation criteria ($W_1$ ~ $W_4$) derived for selecting the final detailed design of the all-in-one attachment-based PHC pile head cutting robot. Its detailed...
As a result of the trade-off analysis, the diamond wheel saw-based detailed design was thus selected as the final detailed design by outscoring the diamond wire saw-based detailed design (3.585 vs. 3.318) (Table 5).

4. Structural stability analysis of the detailed design for an all-in-one attachment-based PHC pile head cutting robot

4.1. Material setup for structural stability analysis

The selected design for an all-in-one attachment-based PHC pile head cutting robot was divided into two structural components: (1) upper structure and (2) understructure. The upper structure consisted of a clamp, cylinder bracket supporting the hydraulic cylinder of the clamp, clamp base that connected and supported the clamp and clamp shaft, and the claw that could be replaced by attaching it to and detaching it from the clamp with a pin (Figure 11). Regarding the material for the upper structure, rolled steel for general
structure (SS400) was used for all the components. The understructure consists of a hydraulic motor bracket that is connected to the ring gear to support the hydraulic motor. All the understructural components were made of SS400 except for the hydraulic motor bracket which was made of AL6061 T6 (Figure 12).

4.2. Structural stability analysis

Structural stability of the final detailed design was analyzed with the CATIA V5 program, which is typically used in the field of mechanical design. Specifically, structural analysis was conducted on the clamp, cylinder bracket, clamp base, claw, and hydraulic motor bracket that will likely exhibit weak structural responses. The loads applied on the clamp, cylinder bracket, clamp base, and claw were set as the forces generated when the maximum pressure of the hydraulic cylinder was used, and the load applied on the hydraulic motor bracket was estimated by applying the force generated at the highest torque value of the geared motor.

The structural analysis yielded the following maximum stress levels: 47.9 MPa for clamp, 59.97 MPa for cylinder bracket, 22.45 MPa for clamp base, 19 MPa for claw, and 126 MPa for hydraulic motor bracket, i.e., stress levels that were smaller by 50% relative to the yield strength, thus confirming that the final detailed design has a high-structural stability (Figure 13).

Likewise, as a result of structural analysis of deformation, the maximum deformation was analyzed to be in a stable range with 0.021 mm for the clamp, 0.0126 mm for the cylinder bracket, 0.012 mm for clamp base, 0.0078 mm for claw, and 0.6 mm for hydraulic motor bracket. The stress generated at the maximum deformation point was 0.2 MPa for clamp, 4.79 MPa for cylinder bracket, 0.5 MPa for clamp base, 0.58 MPa for claw, and 8 MPa for the hydraulic motor bracket (Figure 14).

Figure 15 shows the snapshots of the performance assessment testing of the prototype of the all-in-one attachment-based PHC pile head cutting robot designed and fabricated based on the results of the detailed design derived in this study and its structural stability analysis.

The authors plan to develop a practical model of the all-in-one attachment-based PHC pile head cutting robot by taking into account the considerations for improvements derived based on its performance assessment outcomes and use of the model at construction sites.

5. Conclusions

In this study, we presented detailed design alternatives based on the results of the core element technology analysis for an all-in-one attachment-based PHC pile
head cutting robot, selected the final detailed design based on the results of AHP and trade-off analyses, and verified its structural validity based on structural analyses. The conclusions of this study are as follows.

(1) As a result of the essential function and core element technology analyses conducted to derive detailed designs of an all-in-one attachment-based PHC pile head cutting robot, essential functions were defined as the PHC pile-cutting position sensing function, PHC pile-cutting function, and PHC pile-handling function. Accordingly, core element technologies selected as optical methods for the sensing function, diamond wire saw, and
diamond wheel saw for the cutting function, and the rotary multigrab for the handling function.

(2) On the basis of the core element technologies selected above, two detailed design alternatives were derived: diamond wire saw-based and diamond wheel saw-based designs. The latter was finally selected based on the results of AHP and trade-off analyses by outscoring the former (3.585 vs. 3.318).

(3) A structural analysis of the final detailed design yielded the following maximum stress levels: 47.9 MPa for clamp, 59.97 MPa for cylinder bracket, 22.45 MPa for clamp base, 19 MPa for claw, and 126 MPa for the hydraulic motor bracket, i.e., it yielded stress levels that were 50% smaller than the yield strength, and the maximum deformation was estimated at 0.021 mm for clamp, 0.0126 mm for cylinder bracket, 0.012 mm for the clamp base, 0.0078 mm for claw, and 0.6 mm for the hydraulic motor bracket, thus demonstrating the structural stability of the final detailed design.

If a prototype is developed based on the final design of an all-in-one attachment-based PHC pile head cutting robot derived in this study, it is expected to have improved work safety, quality uniformity, and work efficiency compared with the conventional PHC pile head cutting process.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

**Funding**

This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2020R1A2C2008616).

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