A Study on Development of the Automated Vertical Controllable Pilot-type Equipment for PHC Piles

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Abstract: This research is intended to develop a pilot type of automated pile verticality control equipment for PHC piles and motivated by a desire to address problems inherent in as-is verticality control exercise during pile driving. The paper provides understanding of the current verticality control methods and associated problems, design and manufacturing of the automated equipment pilot type, its testing and discussions of the results.

Keywords: PHC pile, vertical control, pile driver, automated equipment, servo system, pilot type

1. Introduction

1.1 Purpose & Background

Installation of Pre-tensioned Spun High Strength Concrete piles (hereinafter “PHC pile installation”) widely used in foundation work of architectural/civil structures such as apartment housing or hybrid commercial/residential building complex is broken down to setting the vertical center of a pile, pre-boring and pile driving, and pile cap removal.

If the verticality of pile is not maintained in pre-boring and pile driving, bending moment is applied to the pile and the pile is fractured or its load-bearing capacity is reduced if the bending moment exceeds the fracture limit of the pile material. Therefore, automated pile verticality control equipment that can maintain verticality of PHC piles in real time needs to be developed and this research intends to develop an initial pilot type of the aforementioned automated verticality control rig.

1.2 Scope & Methodology

PHC pile driving method is largely broken down to direct pile driving method and pre-boring & pile driving method, however, direct pile driving method is hardly used these days as it involves environmental nuisances such as noise, vibration or dust notably at construction sites located downtown. Therefore, the scope of this research has been limited to automated verticality measurement and control of pile drivers used in relation to concrete pile installation by pre-boring and pile driving method and the as-is verticality control process and associated issues were studied in a site investigation. In addition, relevant technical development cases were analyzed to identify key element technologies of the automated pile verticality control equipment to be developed and arrive at its conceptual design. A pilot type was developed and tested as a part of this research to provide references for further development of prototype.

2. Pile Verticality Measurement & Control

2.1 As-Is Verticality Control Process & Issues

A site trip was made to OO corporation plant located in Ulsan City, South Gyeongsang Province, where pile drivers and associated parts were manufactured to study characteristics of as-is pile verticality measurement & control rigs. A trip to 4 construction sites was made to identify as-is pre-boring and pile driving process.

Representative pile driver used in pre-boring pile driving method is as shown in Figure 1.

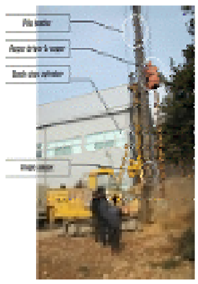

Figure 1. Pile driver used in pre-boring method

As indicated in **Figure 1,** the pile driver is consisted of main body where operator cabin and hydraulic power motor are located, auger and auger driver, pile leader that guides the auger in a track, back-stay cylinder controlling the pile leader movement and angle gauge attached to the side of the pile leader.

The site trip has found that the as-is pre-boring process comprises of following steps:

1. Site crew marks pile driving location with steel reinforcement bars and indicates pile leader location with hand signal;
2. Pile driver operator checks verticality with angle gauge and site engineer or experienced site crew measures pile leader verticality with plumb;
3. Bore a hole in the pile driving location with auger;
4. After the hole is completely bored, draw out screw attached to the auger and move pile to the hole;
5. Put pile in the bored hole;
6. Drive the pile to the required depth by free fall;
7. Once pile driving is completed, move on to the next pile driving location.

Pile verticality is measured 1) by operator preliminarily using angle gauge attached to pile driving system, 2) by assistant crew, measuring pile leader verticality with a water level ruler, 3) by assistant crew or a supervisor, checking verticality against pile leader with naked eyes, or 4) by assistant crew or a supervisor, comparing horizontality/verticality in reference to adjacent buildings with naked eyes.

Domestic standards require pile verticality to be maintained or pile verticality control rig to be used in pile driving, but, fall short of providing for specific criteria or methods for verticality measurement. As specific technical criteria for measuring and determining pile verticality is not available, verticality of pile foundation that is critical as it bears the load of structures tends to be dependent on skills of workers and failure of pile or reduction of load bearing capacity of pile resulting from human errors of site crews may lead to structural instability of buildings.

Figure 2. Verticality Measurement with Angle Gauge

2.2 Needs for Automated Verticality Control Rig & Analysis of Its Feasibility

A 5-minute rating was used in this research to measure productivity. Pile verticality was measured across the entire range of piling work including pile driving location designation, leader verticality measurement, pre-boring, moving pile to location, pile lowering, pile driving and piling area clearing and major measurement targets were one backhoe operator, one pile driver operator and one assistant crew. The pile driving sequence involved 10 piles in total and 1 pile driving cycle took 11 minutes and 20 seconds on average.

As indicated in **Table 1**, productivity was measured in the order of backhoe operator (100%), pile driver operator (77%) and assistant crew (15%), which indicates that the assistant crew was responsible only for measuring verticality when marking piling location in the initial phase of the observed piling sequence, remaining idle for the rest of the process and showing relatively low productivity level in turn. It is also to be noted that the accuracy of verticality measurement to be factored in work quality was largely dependent on the skills of a worker without any objective measurement and control methodology in use.

Moreover, the assistant crew had to wait for more than 10 minutes at idle to perform verticality measurement that took only 5 seconds.

Table 1. Productivity Assessment by 5-Minute Rating

Classification	No. of Rating (A)	No. of Works (B)	Productivity (B/A *100)
Backhoe Operator	52	52	100
Pile Driver Operator	52	40	77
Assistant Crew	52	8	15
Total	156	100	64

When analyzing the role of the assistant crew in reference to the flow of the entire work process, following observations were made in regard to the time spent by him and his interface to other work sequences.

First of all, the sequence for which he was responsible required far less time than the other sequences, which indicates that the job of assistant crew is not critical to piling work and his productivity is bound to be low as he is not actively involved in most of the work process.

In terms of his interface to pre-boring sequence, most of his job did not have any significant influence on the main part of the piling exercise and his step is rather likely to lower the overall productivity of piling sequence.

In short, it is concluded that verticality must be secured to ensure accuracy of work and expedite the overall work sequence of piling and automation is required to reduce inefficient work elements involved.

2.3 Current Technical Trends in Korea

2.3.1 Technology Development in Korea

Technologies available at home in regard to pile behavior and pile driver control can be summarized as in **Table 2**.

Table 2. Domestic Technologies Regarding Pile Driver & Pile Driving

Regarding Pile Driver Verticality	Regarding Pile Behavior	Regarding Pile Driver
1. Removable axle verticality measurement & control device 2. Boring machine verticality guiding device 3. Auger machine verticality control device	- Pile displacement measurement during driving with high speed line scan camera	- Pile driver over-turning prevention device

Firstly, removable axle verticality measurement and control equipment is a device that can be attached to machines to measure and control verticality of axle quickly and accurately. Secondly, boring machine verticality guiding equipment is used in small pile drivers to maintain verticality of its head guide by supporting the lower body of the head guide with removable device to prevent head guide from shaking and fix it in location. Thirdly, auger machine verticality control equipment was developed to be mounted on a crane modified from backhoe and maintain leader to be vertical in reference to the ground during boring to improve work efficiency. In addition, pile displacement measurement during driving and pile driver over-turning prevention equipment may be considered in the context of this research.

2.3.2 Technology Development Abroad

As for applicable technologies available abroad, firstly, automatic vertical controlling device for pile driver that was developed to prevent momentary derailment of control system at the start of work and secure stability of vehicles by reducing acceleration of cylinder rod when pushed ahead by the leader. Secondly, a vibratory equipment designed to prevent vibration of vibratory equipment used in crushing, excavation and stone destruction by supporting both vibration prevention device and bracket has been developed in Japan. The support device is intended to prevent failure of the equipment resulting from vertical vibration and reduction of work efficiency of the operator.

As studied so far, the technologies currently available either use ancillary devices attached to the pile driver to fix pile driver leader position or control pile driver position with analogue mechanism before boring or pile driving starts, failing to monitor and control pile displacement consistently while piling is in progress.

2.4 Criteria for Automation

Automation priority was analyzed in a matrix (**Figure 3**) of work tasks and consideration items to identify elements to be considered in development of automated verticality measurement & control technology. Safety hazard, limitation of manual measurement/control and cost impact were selected as items for consideration in determination of automation-qualified tasks and priority ratings of piling tasks were analyzed in 4 site visits and following discussions.

In the matrix analysis of potential candidates for automation, automation of body horizontal measurement was rated lower in terms of safety hazard and cost impact while automation of body horizontal control was also rated lower in reference to the same items as quoted in the above.

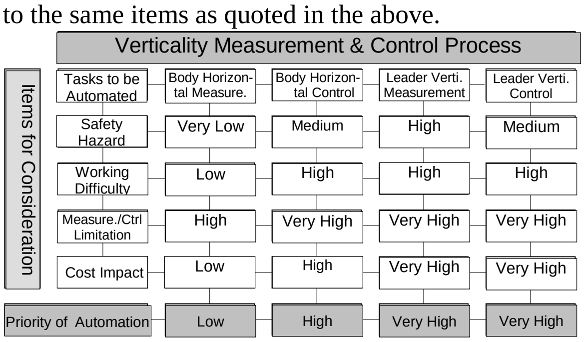

Figure 3. Matrix Analysis of Automation Priorities

2.5 Design Factors

Technological elements considered to develop automated equipment capable of performing two target tasks described in 2.4 are as follows:

1) Select a digital position sensor that can determine verticality of pile driver leader in reference to gravity direction; 2) Develop a digital hydraulic valve that can control hydraulic cylinder of as-is pile driver automatically; 3) Develop a system that can control the digital hydraulic valve with interface to the selected position sensor; 4) Configure the system to be actively responsive to displacement triggered by increase in leader elevation; 5) Develop an automated system that can work independently without the help of assistant crew and measure/Contr ol verticality in a clear and objective manner without relying on subjective judgment of the operator.

3. Pilot Type Development

3.1 System Configuration & Conceptual Design

Four alternatives applicable to development of automated pilot type equipment intended to resolve the issues in the as-is verticality control arrangement described in the above and provide four key functions selected to be automated were presented and optimum concept was selected through various analysis to provide a basis for conceptual design. (See **Figure 4**)

3.1.1 Comparison among Alternatives & Key Functions of Pilot Type

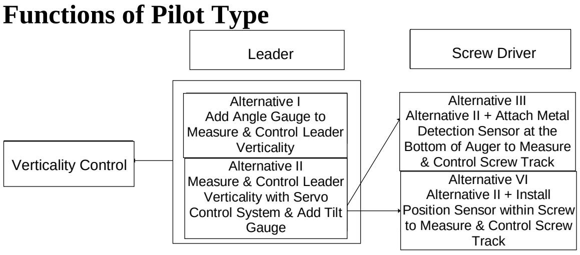

Figure 4. Description of Alternatives

Alternative 1 proposes that additional angle gauge be attached and hydraulic pump controller installed onboard respond to leader behavior measured by two angle gauges. Alternative 2 assumes that servo system is installed in back-stay cylinder to measure linear behavior of back-stay cylinder in real time with interface to hydraulic pump controller to control leader verticality automatically. In Alternative 2, displacement of bending behavior measured by tilt gauge is reflected on back-stay cylinder control to reduce error in vertical control. Alternative 3 is based on Alternative 2 plus metal detection sensor mounted on the bottom of auger driver to measure screw track in real time. Alternative 4 employs Alternative 2 plus position sensor attached to the joint between screw drivers to detect boring defect caused by bending moment of screw driver in advance.

3.1.2 Determination of Optimum Alternative

To determine optimum conceptual design, the aforementioned alternatives were assessed in terms of technical feasibility, durability, user convenience and economic viability as a part of this research. Alternative 2 was favored in terms of accuracy and technical feasibility over Alternative 1 that used analogue approach to analyzing bending moment of leader and controlling back-stay cylinder. The former was also assessed to be the most practical as it conceptualized a system measuring and responding to back-stay cylinder displacement. Alternatives 3 and 4 were found to be limited from both economic and technical perspectives given the level of technologies available at the moment. Given the outcome of assessment described in the above, conceptual design was developed based on Alternative 2.

3.1.3 Conceptual Design

The conceptual design requires servo valve and linear transducer to be installed in back-stay cylinder of pile driver to measure/control linear behavior of the back-stay cylinder and each tilt gauge to be attached to the top and the bottom of leader respectively to measure/control leader displacement and deformation by bending behavior automatically.

Interfacing leader displacement by bending moment measured by two tilt gauges to linear transducer measuring back-stay cylinder displacement can reduce the range of verticality control error. **Figure 5** shows interaction between change in leader behavior measured by the tilt gauge and linear transducer in back-stay cylinder.

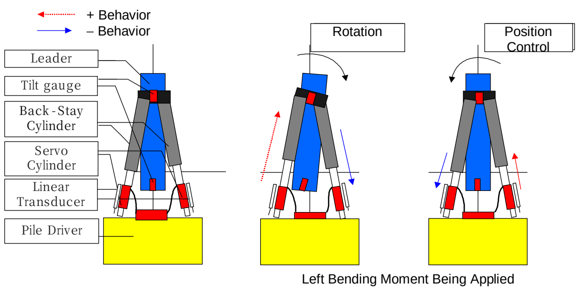

Figure 5. Conceptual Design of Pilot Type Adopting Servo System

3.2 Manufacturing & Assessment of Pilot Type

3.2.1 Detailed Design

The pilot type developed in this research is a 1:20 scale model that adopts a servo system as opposed to hydraulic system found in conventional pile drivers for more precision in control and uses linear transducers attached to both sides of cylinder to enable automated control in response to feedback on cylinder rod position. (See **Figure 6**)

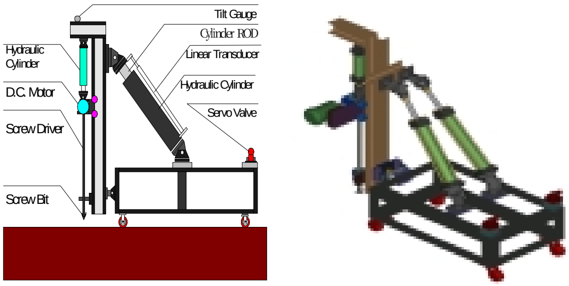

Figure 6. Equipment Configuration & 3D Image

Specifications of the pilot type is as described in **Table 3**.

3.2.2 Test Results & Performance Evaluation

Performance test of the pilot type was conducted three times in the 1st year. The performance test consisted of discrete function test of each configuration element (1st & 2nd tests) and system operation test (3rd test).

Description and result of each test is as follows:

Table 3. Specifications of Pilot Type

Height				1.73 m
Width				0.60 m
Length				1.50 m
Hardware	Cylinder	Cylinder type		Hydraulic servo cylinder
		Cylinder size	Bore	38 mm
			Stroke	400 mm
		Cylinder speed		10 m/sec
		Hydraulic pressure	Min.	20 kg/cm2
			Max.	210 kg/cm2
		Hydraulic volume		30 L/min
	Servo valve	Hydraulic pressure available		210 kg/cm2
		Hydraulic volume available		30 L/min
		Frequency		15 Mhz
	Tilt gauge	Measurement Limit		+/- 5 degree
		Sensor sensitivity		0.1 ms
	Feedback mechanism	Linear transducer	Voltage measurement	+/- 10 V
	Controller	CPU type		Intel CPM8401
Software	Control Program			C

1) The 1st Function Test

The 1st test was designed to determine whether the servo valve would operate as intended on hydraulic pressure from hydraulic pressure supplier.

The system comprises of hydraulic pressure supplier, servo valve, linear transducer and controller. First of all, the hydraulic pressure supplier can supply hydraulic oil from 20kg/cm^2 to 220kg/cm^2 in terms of pressure and at 30L/min in terms of volume. The supplying capacity was set to 70kg/cm^2, 30L/min in the 1st test. The Servo valve opens proportionally at analogue signal from the controller. The signal is from 0 to 40mA and the valve opening control at signal was confirmed. Stroke of the cylinder was from 0-400mm and the linear transducer generated voltage difference from 0-10V. During the test, it was confirmed by measuring change in linear transducer length that the servo valve controlled hydraulic pressure properly to operate the cylinder back and forth as intended at the command from the controller.

2) The 2nd Function Test

The 2nd test was intended to find out whether the servo valve controlled leader position in reference to tilt gauge measurement. In other words, the test objective was to verify whether the servo system would respond to cylinder control signal from the tilt gauge. The tilt gauge applied to the test could measure tilting angle in +/- 5 degree and had angle sensor that generated up to +/- 5V voltage in proportion to change in slope to measure tilting angle in two directions (X—Y direction).

The tilt gauge was attached to the top of the pilot type leader and control algorithm designed to operate cylinder in real time in opposite direction to the one in which the sensor was tilted. (**Figure 7**) The sensor sensitivity was set to 0.1ms and the cylinder speed less than 10mm/sec to prevent unintended movement of the pilot type when the cylinder was operated abruptly.

3) System Operation Test

Figure 7. Tilt Gauge & Servo Valve Function Test

Objective of the 3rd test was to find how the servo system adopting the control algorithm applied up to the 2nd test with interface to tilt gauge would measure and control leader behavior automatically while a pile hole was being bored by auger to which the 2nd test algorithm is applied. Unlike the foregoing functional tests, the pile driving rig was controlled purely by the servo system without human interference in the 3rd test.

Figure 8. Pilot Type Operation Test

A series of tasks that the tilt gauge detected leader verticality error and sent command to the servo valve to control leader verticality was performed automatically. **(Figure 8)** Hydraulic pressure was applied at 210kg/cm^2 which was equal to the one used in actual working environment.

3.3 Derivation of Prototype Design Parameters

During the 3 rounds of laboratory tests, the following prototype design parameters were derived.

In terms of hardware, it seems sensible to set the bore of cylinder to 100mm and its stroke to 120mm given that the cylinder is mounted on pile driver. The hydraulic volume to be applied seems sensible at 50L/min and the hydraulic pressure at 210kg/cm^2. The pilot type adopted linear transducer as cylinder sensor, but, it would be better for the prototype to use feedback from tilt gauge rather than linear transducer that might have durability problem when mounted on actual pile drivers.

The tilt gauge to be applied should be capable of measuring tilting angle in +/-5 degree, but the actual operational range would be in +/-3 degree and analogue output of +/- 5V as default, considering that if the leader is tilted at an angle beyond +/-3 degree, pile driver would be prone to overturning.

Table 4. Comparison between Pilot Type & Proto Type

Equipment				Pilot type	Prototype
Hardware	Cylinder	Cylinder type		Hydraulic servo cylinder	Hydraulic servo cylinder
		Cylinder size	Bore	38 mm	100 mm
			Stroke	400 mm	120 mm
		Cylinder speed		10 m/sec	10 m/sec
		Hydraulic pressure	Min.	20 kg/cm2	20 kg/cm2
			Max.	210 kg/cm2	210 kg/cm2
		Hydraulic volume		30 L/min	50 L/min
	Servo valve	Hydraulic pressure available		210 kg/cm2	210 kg/cm2
		Hydraulic volume available		30 L/min	50 L/min
		Frequency		15 Mhz	15 Mhz
	Tilt gauge	Measurement Limit		+/– 5 degree	+/– 3 degree
		Sensor sensitivity		0.1 ms	0.1 ms
	Feedback mechanism	Linear transducer	Voltage measurement	+/– 10 V	Feedback from Tilt gauge
	Controller	CPU type		Intel CPM8401	Intel 8051
Software	Equipment control			C	C

Servo valve rated at 50L/min, 210kg/cm^2 and operational frequency of 15Hz (when phase delay is less than 5%) seems desirable given the cylinder volume.

In terms of software, it was found in the test that the industrial computer applied to the pilot type could be applied to the prototype as well, however, Intel 8051 series CPU Chip is deemed to be more desirable to reduce size/weight of the entire system. It seems also sensible to develop a custom control application with C language.

4. Summary & Further Researches

Conclusions of this research and tasks to be followed in the future are:

(1) This research developed pilot type automated verticality measurement/control equipment for PHC piles. To that end, as-is verticality measurement/cont rol arrangement status was investigated, applicable technologies available in Korea and abroad were analyzed, conceptual design was proposed, pilot type was designed and performance test was conducted.

(2) This research analyzed technical feasibility of the proposed system by developing & testing its pilot type as the 1st year assignment in a 3-year R&D program. As a result, technical feasibility of servo system and advanced sensing technology applied to as-is pile drivers to measure and control verticality automatically was proven.

(3) This research plans to develop a prototype based on design parameters identified in pilot type performance test. All technical elements adopted by the prototype to be developed will be applied to as-is pile drivers to test technical feasibility in field environment and economic viability of the proposed equipment will be analyzed as well.

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