DEVELOPMENT OF A TOTAL STATION WITH A CONCENTRIC CIRCLE RETICLE AND A NAVIGATION SYSTEM FOR PILE DRIVING

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ABSTRACT

In this research, we devised a measurement method using total stations (TSs) which have "the Baum" which is a concentric circle reticle, as substitute for crosshairs. The Baum owes its name to the similarity between the concentric circles and trees (Baum in German). By setting one circle on both of edges of cylinders, operators can set their sights on points on the center line of the cylinders, and also can measure positional coordinates of the points. Also, by measuring two different points on the center line, operators can measure the position and tilt of the axes of the cylinders. Furthermore, we developed a pile driving navigation system. Foundation piles are used for various structures, and their forms are generally cylindrical. Especially, although it is difficult to drive tilted pile foundations, their usage are expected to expand due to their high earthquake resistance. Yet, a method to accurately measure the tilts of piles has not been established. However, we proved that operators can obtain adequate accuracy to control foundation piles through the measurement experiment using this system. Using this system, the information of the pile is measured using a TS, transferred to a PDA, and displayed from the operator's view of the piling machine.

KEYWORDS

Total station, reticle, piling work, non-prism, cylindrical structure

INTRODUCTION

Research Background

In foundation construction of structures, pile foundations are widely used for deep bearing strata. There are two patterns to drive piles; vertically or obliquely to the ground. The shapes of the piles are normally cylindrical. Vertical pile foundations are employed as the foundations of many structures due to their high workability. But there is a problem, which is that this method does not bear measurement data as construction accuracies are visually checked. On the other hand, tilted pile foundation s are rarely employed because it is too difficult to ensure construction accuracy and because commonly used percussion methods brings noise and jolts when the piles are hit, while there are advantages that thinner piles are available ensuring earthquake-resistance as tilted piles curb horizontal displacements of structures which may be caused by earthquake ground motion. However, current strong requirements of cost reduction bring people's attentions to tilted pile foundations which can be driven reasonably and economically and much research of tilted piles has been carried out in order to improve their capacity. Also, a method of screwing piling has been developed which bears little noise and jolt. This method has solved tasks of workability and environmental burdens, and is becoming common. However, there is a necessity to develop a method to accurately measure the angles of piles' axes to drive piles into the ground from proper angles. Also, it is expected to find out a way to control construction information such as correction amount and construction record.

On the other hand, total stations (TSs) are commonly used for measuring structures. Lines to focus on targets (reticle) are placed in the focus of the eyepiece of an optical instrument. Normal TSs have crosshairs as a reticle, and surveyors align the crosshairs with the point to be measured. Also, TSs have a built-in computer to obtain and record the positional coordinates of measured points. However, if there is no mark showing the points to be measured, it is too difficult to align crosshairs with the points. For example, surveyors cannot accurately measure the center of cylindrical structures with crosshairs. That is why TSs are rarely used to control accuracy for constructions of foundation piles.

To solve these problems, we developed a total station in which the reticle with concentric circles is placed. These concentric circles enable TSs to be lined up with pointes on the center lines on cylindrical structures, and efficiently measure their radius.

This research shows operators can accurately measure the position and the tilt of the axes of the structures by measuring two points on the center line. Applying this technology, we also developed a system which aids constructions by passing the information about the pile angles which are obtained from measurements to the operator of the piling machine and by recording shift amounts in real time.

Tasks of Conventional Accuracy Control for Driving Foundation Piles

In the common method to measure verticality of piles for accuracy control of vertical pile foundations, workers position the pile tip at a predesignated position, set up two transits in two directions as shown in Figure 1, and align the vertical line of crosshairs of the transits with the pile. The use of two transits requires many man-hours as the transits needs an operator for each. Also, it is necessary to more frequently move the transits depending on the number of the piles to be driven, which required labor as well. Another problem is that measurement data is not retained because workers visually check the verticality.

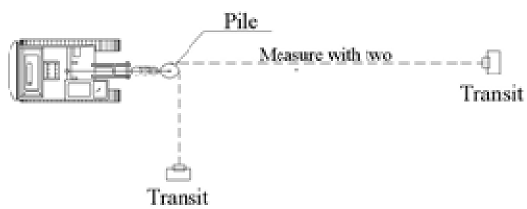

Figure 1 – Common method to drive foundation piles using two transits

Angles of tilted pile foundations are commonly measured using angle meters. A worker directly puts an angle meter on the pile to measure its verticality, which decreases the workability as it is necessary to halt the construction. Their method causes safety concerns because a worker needs to approach the pile. There is also a problem regarding accuracy. The position and the way to place an angle meter causes differences in the measurement results.

MEASURING CYLINDRICAL STRUCTURES

Overview

A TS with the Baum has concentric circles on their reticles as shown in Figure 2. The ratio of the space of each circle and the distance between the instrument and the object is 1:1000. The width of the target object can be calculated from the relation between the read concentric scale marks and the distance. By vertically or horizontally lining up one circle of the Baum on both of the edges of cylindrical structures, it is able to measure the center line of targets. For example, by lining up one circle on both edges of a cylindrical structure, points on the center line of the cylindrical structures can be measured. Also, its radius can be calculated. For example, when a cylindrical structure stands vertical, and is 10m away from a TS with the Baum, its radius is calculated from 10(m)*10/1000.

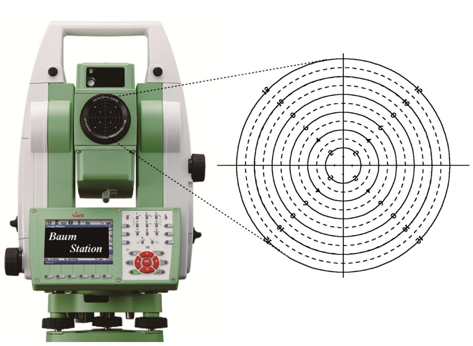

Figure 2 – A TS with the Baum

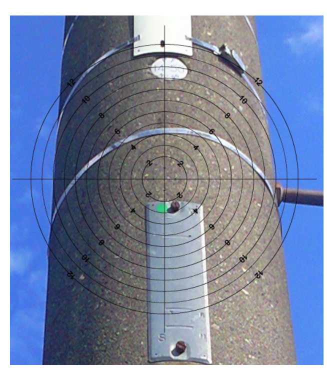

Figure 3 – Aligning with Baum

EXPERIMENT IN ALIGNING

Overview

When conducting measurements using TSs with the Baum, the widths between both of edges of the structures sometimes does not exactly fit on any circle of the Baum. In this case, operators need to presumptively read the space between two circles. For example in Figure 4, the edges of the structure are between the circles numbered 5 and 6 (Presumptively read value: 5.45). Also, as Figure 5 shows, the appearance of the pile in viewing field of the lens varies depending on the diameter of cylindrical structures and the distance between the target object and the TS. However, an experiment had not been carried out to estimate their effect on accuracy. Therefore, we conducted an experiment to estimate how much accuracy would vary depending on the concentric circles of TSs with the Baum to be aligned with piles.

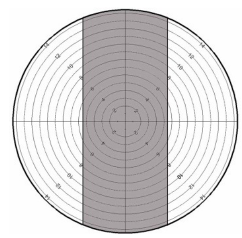

Figure 4 – Presumptive reading of the center (Read value: 5.45)

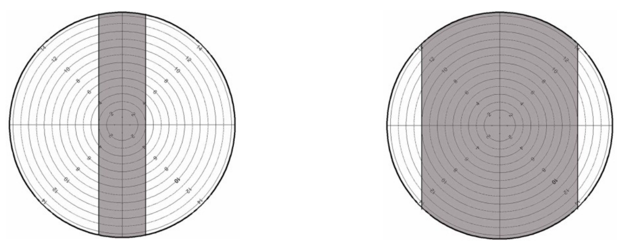

Figure 5 – Difference of piles' appearance in the viewing field.
(Used scale: 3 in left figure and 10 in right figure)

We used a TS11 from Leica in which the Baum had been mounted, and a vinyl chloride cylindrical pipe, which diameter was 60mm. We set the pipe at distances of 3m, 5m, 5.2m, 5.8m, 6m, and 10m from the TS. Each of the 3 operators (Denoted by Operator A to C) aligned the Baum with the points on the center of the pile 10 times, and we recorded the variation of horizontal angles. We conducted trials under the condition that the TS was mounted on a leveling plate around at the height of 1.4m, the instrument height was 1.5m, and the vertical angle was 90 degrees.

Result

Table 1 shows averages of values each 3 operators obtained from 10 trials, and the average and mean square error of all trials according to distances denoted by L between the TS and the surface of the cylindrical structure. Also, the table shows the values of distances into which have been translated from measured angles. We calculated the error values which were translated from angle into distance, denoted by *e* from $e = L\tan\theta$, in which θ means the angle which was calculated from mean square errors. We conclude that the variety of errors is very small from the fact the greatest error in each trial was 5 seconds. Additionally, there was a lot of variation when the distance was 5.47m. We assume that this variation was caused by the presumptive readings skills of individuals, because the edges of the structure were almost in the middle of circles numbered 5 and 6, which was read as 5.45. We also found that operators can accurately measure the centers of cylindrical structures by presumptive reading as there was not a lot of variation when the distance was 5.175m and 5.770m. The errors which are translated from angle to distance increase in proportion to the distance to the target object while the accuracy in horizontal angles does not nearly vary. Therefore, we found that the more accurately we can conduct measurements, the shorter the distance becomes from these facts. From this result, we can calculate that the error is 1.25(mm) when we measure a pile with the diameter of 600mm from the distance of 100m (L=100m).

Table 1 – Trials for accuracy

L(m)	2.971	4.969	5.175	5.47	5.77	5.974	10
Baum's Scale (Theoretical value)	10.00	6.00	5.77	5.45	5.17	5.00	3.00
Operator A	172°30:21	171°53:50	172°00:34	171°54:25	171°57:08	171°54:24	171°59:05
Operator B	172°30:20	171°53:50	172°00:33	171°54:24	171°57:06	171°54:23	171°59:06
Operator C	172°30:22	171°53:51	172°00:29	171°54:15	171°57:06	171°54:18	171°59:03
Average Value	172°30:21	171°53:50	172°00:32	171°54:21	171°57:07	171°54:21	171°59:05
Mean Square Error	0°00:03	0°00:02	0°00:03	0°00:05	0°00:03	0°00:04	0°00:03
Translated Error (mm)	0.039	0.049	0.079	0.143	0.074	0.108	0.125

MEASURING THE COORDINATES OF THE AXIS

The distance which total stations can measure is only to the surface of objects. That is, it is impossible to directly measure the axes of structures using total stations. Therefore, we need to calculate the positional coordinates of the axes from those of the surface of the cylindrical structures. As shown in Figure 6, we measure two points on the center line on the surface, which are denoted by A and B in Figure 6, and then we calculate $\overrightarrow{AB}$. Finally, we can calculate the axis of the structure denoted by A'B' by moving $\overrightarrow{AB}$ toward the axis (which is vertical to the line AB on the plane OAB) by the length of the radius of the structure.

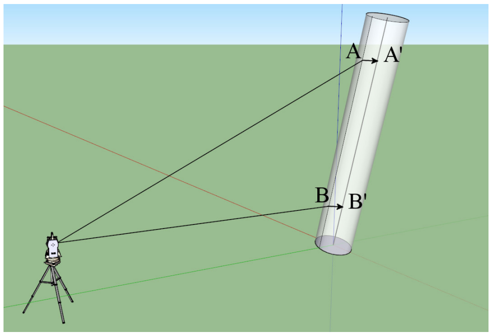

Figure 6 – How to measure the axis

APPLICATION TO PILE DRIVING SYSTEM

Applying center measurements of cylindrical structures using TSs with the Baum, we developed a system for accuracy control of driving structural foundation piles. TSs with the Baum perform high workability as we can measure the axes of piles from any directions using just one TS with the Baum, and we do not move two instruments to measure other piles which is usually done in the common method. The measurement results are recorded as numerical values. Moreover workers' safety is ensured as it is not necessary to move two transits to measure other piles. That is why, the workability is high and the safety of workers is ensured. This allows us to ensure workers' safety.

Moreover, there is another advantage that measurement data are recorded as numerical values and the history of driving piles is also recorded. However, there are also some issues to be improved; collected information does not contain the direction the piling machine faces, and there are few ways to transfer the information from the operator of the TS with the Baum to the operator of the piling machine. Therefore, we developed a system to promptly and accurately transfer the information of the piling process to the operator of the piling machine.

Figure 7 illustrates the outline of the pile navigation system. As it shows, the information of the pile (the positional coordinates of the pile surface) go through the following steps; the information is collected by using a TS with the Baum, transmitted from the transmitter mounted on the TS to the repeater device, and transformed into Bluetooth, and sent to the (PDA) which are in the operation room for the piling machine.

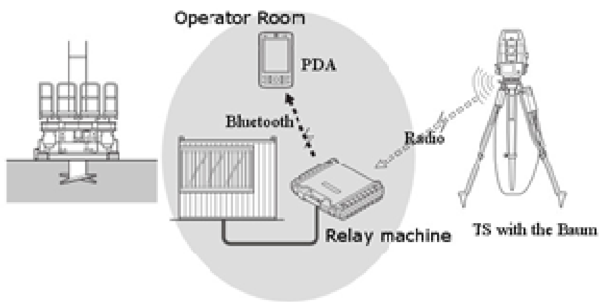

Figure 7 – Outline of the pile navigation system

The program in the PDA immediately calculates deviations and tilts of the pile at the planned height of the pile top, and correction amounts to planned position. Also, when an operator know how much a point is apart from the pile bottom, by measuring the point as the first measurement point, it is able to calculate the present depth of the pile bottom, and the gap between the present and planned height of the pile top which are based on the height which should be achieved when driving is completed. The information of these is displayed from the view of the operator of the piling machine on the screen of the PDA (Figure 8). Correction amounts are shown as numerical values, which helps operators to accurately correct deviations and record the process history by accumulating measurement results.

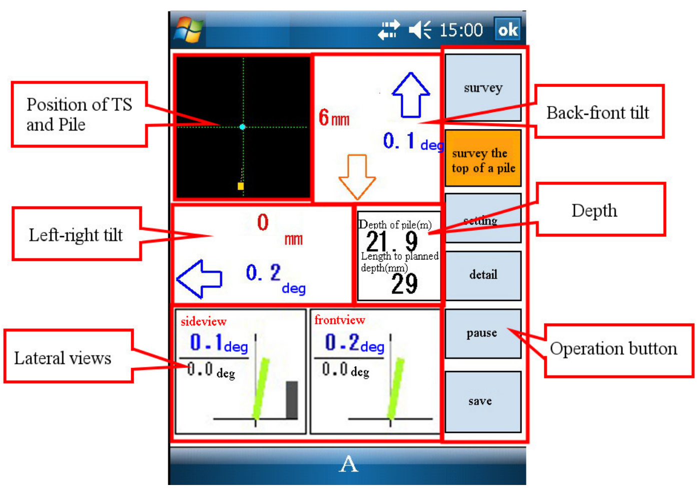

Figure 8 – Driving pile navigation's screen displaying a measurement result.

MEASUREMENT EXPERIMENT

Overview of the Experiment

We conducted an experiment to figure out measurement efficacy in the actual pile driving using a TS with the Baum. We employed vertical pile foundation and screwing piling method in this experiment and three steel pipes of 11.5 long and 800mm diameter welded into a pile foundation. We welded the piles at site. In piling, when the length between the ground and the tip of the first pile was 3.74 m the second pile was jointed to the first one. Then, when the length between the ground and the tip of the jointed pile was 4.14m the third pile was jointed. When the depth of the driven pile was 26m, we stopped driving the piles. The verticality was measured and corrected in the conventional method and compared with the results from the measurement using a TS with the Baum. We did not make a correction for the pile based on the measurement results from a TS with the Baum.

As the conventional method, we took measurements of the verticality using two transits from two right-angle directions. We took measurements before the first pile was driven, when the second and third piles were jointed, and piling was stopped. The verticality correction was also made before the first pile was driven, when the second and third piles were jointed.

The distance from the TS to the pile was approximately 40m. We employed an arbitrary coordinate system, with which errors of front-back direction from the pile are shown on X-axis, and errors of left-right direction are shown on Y-axis. We started the measurements when the pile depth was about 1m, and took a measurement every further 1m of the depth. We collected 27 measurement data of the pile during the screwing piling, and 4 when the pile was still.

Experiment Result

Table 2 shows mean square error of deviation amount and angles in the method using a TS with the Baum, and Figure 8 shows plotted deviation of the pile in 31 trials. In Figure 9, horizontal axis shows deviations in the x direction, and vertical axis shows deviations in the y direction. The results are under the condition that the planned height of pile top, z=0. The plots were made on a map with the origin (0,0), and circles with of which radius are respectably 10mm, 20mm, 30mm, 40mm, 50mm, which were guide lines to plot.

Table 2 – Errors in measuring a foundation pile

	Trials (Time)	Deviation (mm)				Angle (°)	
		x		y		Average	Means Square Error
		Average	Means Square Error	Average	Means Square Error		
Total	21	3.4	8.7	2.4	9.5	0.19	0.22
Screwing	27	4.3	9.0	3.0	10.1	0.21	0.23
Still	4	-2.5	6.6	-1.5	2.2	0.10	0.10

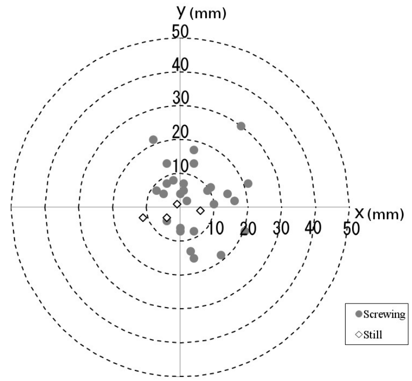

Figure 9 – Plot map of error on a horizontal plane

We found that we can take measurements within this accuracy; deviations of piles are up to about 30mm, and mean square errors of measurement eccentricities are up to about 10mm on both x and y axes. Also, we found that mean square errors of angles were 0.1° when the pile was still and 0.2° when the pile was screwing. The deviation and tilt of piles when the piles were still were smaller than those when the piles were screwing. These differences are considered to be brought when the pile wobbled by the length as much as 2 scales of the Baum which is about 0.008(m) in left-right direction, which is calculated from 2x40(m)x1/1000. The pile bottom wobbled less than its top. Also, we compared screwing piles, and the errors of still piles deviation in the y axis were smaller than that of the x axis. The Y direction is left-right direction from the TS. We attribute this result to the pile's wobble taken over while it was measured.

SUMMARY

The following are the findings in this research.

- We developed a TS with which the Baum is equipped as a reticle instead of the conventional crosshairs.
- We had an experiment of measuring cylindrical structures, and found that the more accurately we can conduct measurements the closer the distance between the TS with the Baum and the target cylindrical structure gets.
- By measuring two points on the center line of the cylindrical structures, their axes can be calculated.
- Applying the Baum technology to pile construction, we developed a navigation system which assists driving piles, showing the horizontal position and tilt of the pile and correction amount from the view of the operator of the pile driving machine.
- This system requires just one person to measure the piles' verticality, deviation, and depth. Then, this system transfers the measurement results to the operator in an easy-to-understand way and in real time. As this system saves measurement data in chronological order, it will be a big help for pile foundation managements.
- The results of the measuring experiment in driving vertical foundations show that the error on a vertical plane when the pile was screwing was greater by 2mm in back and front direction, by 8mm in left and right direction, and by 0.1° than the error when the pile was still.
- We can measure vertical and tilted piles in the same way using this system, we can use this system to control tilted pile foundations which had until now been too difficult.
- We expect that this system will contribute to popularize tilted pile foundations.
- We aim to develop a system which can take measurements more easily and accurately by accumulating and analyzing the data. Especially, we aim to reveal errors of driving tilted foundations to increase the applicability of the system to titled pile foundations.

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