Pile Driving and Drilling Monitoring Survey Technology Using a Total Station

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ABSTRACT

Maintaining correct pile's verticality or inclination during installation, while ascertaining the safety of laborers and cost-effectiveness, is a key factor for construction survey. Traditional methods involve a significant amount of manual work, carried out using measurement rods and transits. Therefore, as more laborers are required, safety hazards also increase. Traditional Total Stations (TSs) have cross-hair reticles and are used for calculating coordinates and locations. Traditional cross-hair reticles in TSs are inadequate to measure structures that have pointed shapes, acute angles or no clearly identifiable center. Moreover, two laborers are required to take measurements when a prism is needed to indicate distances and angles. To solve these problems, a new reticle fashioned with concentric circles, was developed and incorporated to TSs. Moreover, new TS releases eliminate the need of prisms by developing a one-man operated device and incorporating the non-prismatic function. Baum Stations operation principle is based on aligning one of the circles in the Baum reticle to both sides of a pile. Measurements can be performed without centerline identifiers and at any inclination. Measurements can be performed even when there is insufficient distance to capture both sides of the pile, by capturing one point on the side of the pile.

Key words: *Cylindrical Structure, Total Station, Reticle, Central Coordinates, Concentric Circles, Pile, Piling*

1. Introduction

1.1. Background

Piles are frequently used as a foundation system in which structural loads are transferred to bearing strata. Their main objectives are avoiding uplifts, distributing loads and preventing excessive settlement of the structure they support (Gue & Chow, 2009).

There are two main pile classifications depending on the installation method: piles can be driven or drilled. Combination of these two methods is also common, such as the case of pre-bored piles. Driven piles are pre-fabricated piles that are installed directly on the soil, either by hammering or pressing until the desired depth is achieved. There is a wide variety of materials to build prefabricated piles; they can be made of concrete, steel or timber. Drilled piles or shafts, on the other hand, are constructed on-site. First, a deep excavation is made to the bearing stratum, followed by a steel reinforcement cage and a concrete mixture filling (Pile Driving Contractors Association).

Further concerns on performance and cost-effectiveness have led to an increased interest in the use of tilted piles, also known as batter piles (Kavazanjian, 2006).

Tilted piles have a higher resistance to lateral loads. These loads, aside from the seismic kind, also include winds and blasts, earth lateral pressure and displacement, and impacts from waves or currents. Nevertheless, they are seldom used due to difficulties in ascertaining and maintaining correct inclinations during installation.

Lately, a preference on using driven piles has been increasing. Since installed piles are mainly pre-fabricated, they have added advantages, such as faster installation, fairly consistent performance and uniformity in composition.

1.2. On-site pile monitoring practice

Frequent concerns are related to pile's integrity and stress conditions during driving. Therefore, various technologies, such as the Pile Driving Analyzer (PDA), developed by GRL Engineers, Inc., have been developed to help address these concerns. This technology can monitor the pile capacity, integrity, hammer performance and driving stresses in real time (GRL Engineers, Inc.).

Another example of dynamic testing technology is the Pile Driving Monitor (PDM); idea conceived by Dr. Julian Seidel of AFT (Advanced Foundation Technologies). This technology, similar to the PDA, focuses on pile's capacity and condition monitoring (Advanced Foundation Technologies, 2015).

Nevertheless, methods regarding positioning of piles on-site and to ascertain verticality or correct incline; are not frequently improved. A high level of trust is put on pile leads to maintain the correct position of the pile while driving; yet, this method does not provide records of pile's position changes during driving nor ensures that the pile was driven at the correct angle.

Modern practices, used mostly for piles driven on waterbodies, involve use of several instruments, such as total stations, inclinometers and markings over the structure (Fierro Jr., 2012).

In Japan, common practice during pile driving to ascertain verticality and position is carried out manually by two steps process (Nakaniwa, Yabuki, Kitayama & Makizumi, 2012). The pile's position can change after each hammer hit or during drilling, therefore constant position change monitoring is needed. The first step consists of position monitoring. The position is determined and maintained using measuring rods. In this step, pile deviations from design can occur easily as the position of the pile is maintained in relation to the handheld rod's length and position. Safety hazards are also elevated as laborers need to stay close to the pile during the installation process.

The second step involves the use of two transits to monitor pile's verticality, as shown in **Fig. 1**. In this step, the transits need to be adjusted every time the pile is hit by the hammer or during drilling. This may cause a significant increase in the hand labor required. Moreover, accuracy levels can drop as measurements and records are mostly manually taken. It can also reflect in increased cost for hand labor and security hazards.

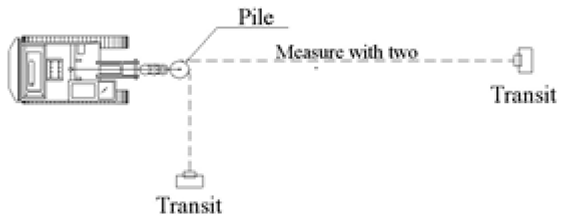

Fig. 1 Manual method of pile monitoring, using two or more transits

Recent approaches include the SINDS_Pile Management System, developed by Inoue Sokuryo, which uses auto tracking TS, and a specially developed system to monitor the pile driving process. With this system, the operator is able to control the pile's position via a monitor located in a vehicle. Nevertheless, several devices need to be used, such as communication units and in-vehicle computer (Inoue Sokuryo, 2012).

Another example is the "Kuimoni" system, developed by TAIYU Co., Ltd. This system consists of a device that monitors pile's position by attaching the devise directly to the pile's surface while driving. However, it requires the devise to be attached directly to the pile, which can prove to be troublesome when driving several piles (TAIYU Co., Ltd., 2012).

GPS-based systems for monitoring drilled piles are being developed and used increasingly by European contractors, although not as frequently by North American countries. Examples of systems, which use

GPS for horizontal positioning, are the “B-APS Assistant Positioning System integrated in the B-Tronic System” by Bauer and the “Drilling Mate System” by Soilmec North America. Improvements to piling equipment are also made, such as attaching inclinometers to the drill masts which allow for remote monitoring, nevertheless there is still the need to verify verticality by using levels. (Hertlein *et al*., 2016).

TS is a surveying instrument used to measure and record distances, elevations and angles. A typical TS is equipped with s cross-hair reticle, which center is aligned to the centerline on the structure when carrying out measurements. However, it is very difficult to align a TS’s cross-hair reticle to the centerline of a cylindrical structure, such as most piles, when not clearly indicated. Therefore, TSs have not been used frequently for pile installation works.

New TS has a non-prism function which eliminates the need for a prism, therefore no extra laborer is needed to carry the prism in order to carry out measurements. This improvements with cost-effectiveness and reduces safety hazards by eliminating unnecessary hand labor. However, the difficulty in measuring structures with cylindrical, pointed or sharp corner shapes still remains if using a cross-hair reticle.

1.3. TS with a built-in “Baum”

1.3.1. Overview

To solve the issue of measuring cylindrical structures, a new reticle was developed. It is fashioned with a unique scale, which has a concentric circle pattern. It was named “Baum”. In German, the word “Baum” means tree. Tree annual rings are shaped in concentric circles; therefore the reason for naming the new reticle “Baum”, the new reticle resembles a tree’s annual rings.

When using a Baum Station, measurements are carried out by aligning one of the circles in the reticle to the outer sides of the object to be measured. By installing the Baum reticle on a TS with non-prismatic function, required hand labor is reduced to the device operator. Safety hazards are reduced as well by eliminating the need to go near the installation site for measuring. Data accuracy increases as measurements are taken and recorded simultaneously with the driving process by using the TS. Most importantly, cylindrical, pointed and sharp corner shaped structures can be measured efficiently.

1.3.2. Baum reticle

The Baum reticle consists of a gauge numbered from 1 to 14. The gauge numbered 1 is represented as marks in the reticle, therefore there are 13 concentric circles drawn. Even values are represented by a solid lined circumference while odd values are represented with a dashed lined circumference, shown in **Fig. 2**, to reduce reading mistakes.

The first gauge value is 0.226 mm, and circles are spaced at a 0.226 mm interval as well. Calculations are automatically done by knowing this value and the Baum’s reading value. The spacing of 0.226 mm was obtained after calculations and experimental tests. This value also proved to increase precision of measurement for Leica Geosystem’s TS, considering a proportion of 1:1000, width to distance, in experimental tests (Nakaniwa, Yabuki, Nishi & Dzianis, 2016).

1.3.3. Dedicated software

In conjunction to the Baum reticle, a dedicated software was released to automatically execute the calculations related to the new reticle. This software was named “Trinos”.

The software interface is installed on every Baum Station. It consists of several functions, which are: “Radius Offset”, “Sphere Offset”, “Line Offset”, “Point Offset”, “Plane Offset” and “Pile Offset”. These functions are described in more depth in section **2**.

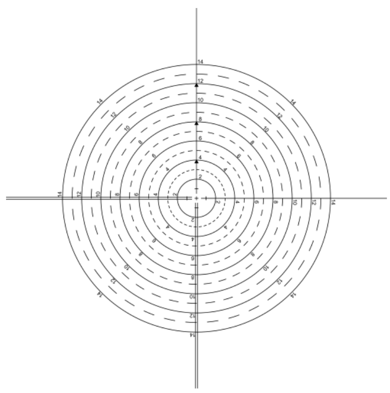

Fig. 2 Baum reticle

2. Baum implementation options

2.1. Measuring cylindrical structures

The measurement of cylindrical structures was previously almost impossible to carry out without placing centerline identifiers on the object. It has become now possible by using a Baum reticle, which additionally makes the process straightforward.

Measurement, when using a Baum Station, is carried out by aligning two points on the circumference of one circle of the Baum reticle to parallel outer sides of the object to be measured, as shown in **Fig. 3**. The resulting reading value is indicated by the gauge numbers on the Baum reticle.

When both sides of the structure fall within two circles on the Baum scale; the gauge value must be presumed. Experimental results have shown that the experience of the TS operator can be considered irrelevant to Baum reticle's gauge readings. The impact of Baum Station operators on the readings was calculated through experimental tests. The error calculated in these tests, considering TS operators with different years of experience, was shown to be 1 mm at 10 m away (Nakaniwa, *et al.*, 2012).

Additionally, when measuring pile positions, regardless of whether they are to be driven vertically or tilted, the Baum reticle can adjust to varied tilts and measure successfully, as shown in **Fig. 4**.

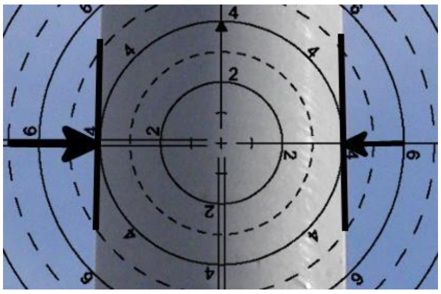

Fig. 3 Baum measuring alignment for cylindrical structures

Fig. 4 Cylindrical structures can be measured at any inclination

2.2. Measurement of central axis coordinates

The basic method of using the Baum reticle relies on aligning both outer sides of piles to one circle on the Baum reticle. The "Trinos" software includes several functions, which are selected depending on the object to be measured.

When using the "Radius Offset" function, both sides of the structure are aligned with a circle on the Baum reticle, shown in **Fig. 5**, which makes it possible to locate the center of the object. After the measurements are taken, the center's coordinates are automatically calculated in the "Trinos" software. The calculation principle is based on the assumption that measured object's cross sectional shape is a true circle. Therefore, central coordinates are obtained by offsetting the radius value from the measured point.

Additionally, when the radius value of the pile is known, it can be used directly for calculations. Otherwise the Baum Station can measure the radius when the values are unknown.

With same principle as previously described, thorough the "Sphere Offset" function, it is possible to calculate the center of a sphere by only capturing one point on its surface.

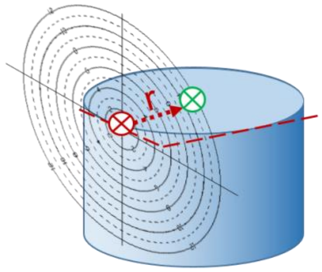

Fig. 5 "Radius Offset" measurement principle

Finally, for specific use with pile installations, the "Pile Offset" function is available. With this function it is possible to measure the position and tilt of the pile or any other cylindrical object by measuring two points on the centerline of the pile. It is also possible to obtain unknown pile coordinates as well as any point along the centerline of the "offset line".

2.3. Measuring pointed shapes or sharp corners

The exact point on sharp corners or pointed shapes cannot be measured using the conventional cross-hairs reticle equipped with TS because its laser beam would pass a corner or a point that is to be measured, thus yielding errors in measurement results.

The Baum reticle can be used to carry out measurements for these geometries by two different methods depending on the object. The final coordinates are obtained by offset calculations.

When measuring an object with a pointed geometry, such as telecommunication antennas, the "Point Offset" function is used. As shown in **Fig. 6**, the intersection of the cross-hairs is aligned to the last measurable point on the object, red point. Next, a circle on the Baum scale is used to offset the distance from the center of the cross-hair reticle to the tip of the object, green point on **Fig. 6**.

Furthermore, with the "Line Offset" function, it is possible to measure non visible values along the centerline of the pile by offsetting the values from last visible points. It is also possible to obtain unknown pile coordinates as well as any point along the centerline of the "offset line".

In the case of sharp corners, the "Plane Offset" function is used. Measurable points along the vertical and horizontal line of the wall in which the corner is located are measured. Simultaneously, the Baum's reticle is used to offset the distance from those points to the exact point located on the perimeter corresponding to each measurement point on the structure. Afterwards, the offset vertical and horizontal perimeter lines are extended and the resulting intersecting point, which corresponds to the corner's value, can be located, as shown in **Fig. 7**.

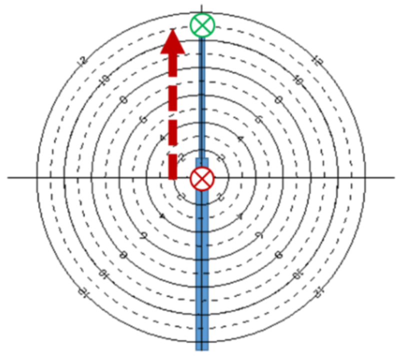

Fig. 6 "Point Offset" measurement principle

3. Method developed for implementing Baum Stations in pile installation projects

3.1. Overview

As discussed in the previous section, the unique configuration of the Baum Station's reticle makes it possible to measure cylindrical structures at any inclination. As projects that use piles as their foundation structure increase, so does the demand for technologies and methods for controlling accuracy of pile installation.

Therefore, a method for measuring piles' position during installation was developed, which employs the Baum station. This method was named PM (Piling-Measurement) Method.

In addition to the PM method, improvements were also made to the basic "Trinos" software. The new software was named "Trinos+". Main improvements to the "Trinos" software are related to pile installation and are based in the "Radius Offset" function and are applied in the new "Pile Driving Function".

Improvements on the "Trinos+" software include the capacity to upload pile design files, automatic calculations of position deviations and incline deviation from the design data and addition of pile measurement options of "One Side" or "2 Side" measurement. These improvements are described in more detail in section **3.3.**

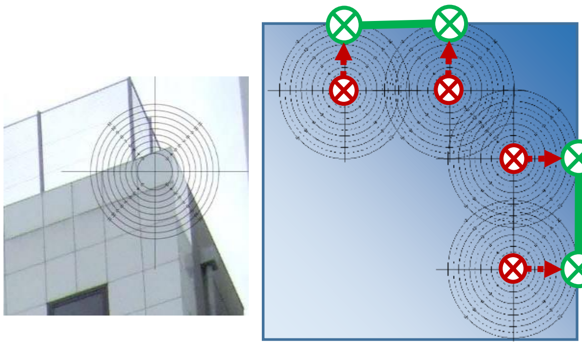

Fig. 7 "Plane Offset" measurement principle

3.2. PM (Piling-Measurement) Method

The Baum Station's PM method was developed mainly for pre-bored pile installations. It consists of a "survey results sheet", in which mandatory coordinate measurements are specified for the boring and pile installation processes. Measurements taken during the boring and pile installation are filled into the "PM Survey Results Sheets"; screenshots of the measuring results from the TS's screen, are added and handed over as survey results.

This method provides standardized steps, in which coordinates of the pile and drilling machine are constantly taken and recorded. Results are delivered into the "PM Survey Results Sheets" during four different stages. The stages are illustrated from **Fig. 8** to **Fig. 11** and described below.

Stage 1: Before Excavation

- Start drilling location is checked to ascertain correct design location coordinates before excavation, **Fig. 8**.
- Construction errors can be decreased.

Stage 2: During Excavation:

- Piling rod's coordinates can be monitored and recorded during excavation, **Fig. 9**.
- Coordinates recordings are available for all the excavation process.

Fig. 8 PM Method, Stage 1, before excavation

Fig. 9 PM Method, Stage 2, during excavation

Stage 3: During Pile Installation

- Pile cap coordinates are measured before final pile's settlement, **Fig. 10**.
- Read values are compared to design values, further increasing accuracy.
- Pile position coordinate records are available.

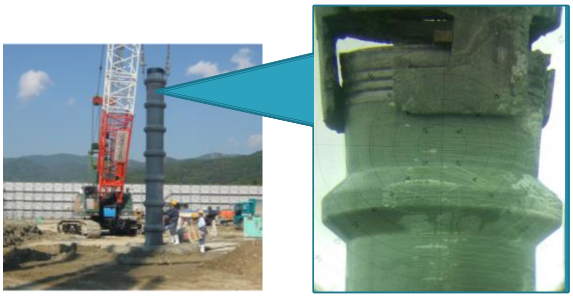

Fig. 10 PM Method, Stage 3, during pile installation

Stage 4: Before Final Pile Settlement

- Connection point between the pile driver and the pile is measured as the pile cap is no longer visible, **Fig. 11**.
- Read coordinates are compared to design values to verify correct position.

Stage 5: After Final Pile Settlement

- Optional Step.
- After completing installation, the center point of the pile can be measured once more to verify correct positioning.

Fig. 11 PM Method, Stage 4, before final pile settlement

Improvement studies in of the PM method to traditional methods were carried out, obtaining monetary improvements of 43.7%, mainly due to unnecessary handlabor reduction. Hand labor is reduced from 4 laborers to 1, only requiring the Baum Station operator. The improvement calculations were based on a project in which 10 piles of 1m diameter and 20m long were installed. Only the measurement section of pile installation was taken into account for the comparisons. Calculations were based on comparison of machinery and labor costs.

Table 1. Improvement Percentage Calculation

	PM Method	Traditional Method	Improvement
Cost	334,500 JPY	594,500 JPY	43.73%

3.3. "Pile Driving Function"

The "Pile Driving Function" was developed to assist in the surveying of prefabricated pile installations within the PM method. The new modifications to the basic "Radius Offset Function" were made to specifically support pile installation by comparing design data with on-site data, through the "Trinos+" software.

The "Pile Driving Function" consists of two interface settings; the first is "2 Sides", which is used when both sides of the object are visible. The second setting is "1 Side", which is used when only one side of the object is visible due to site restrictions. These interface settings were developed based on the "Radius Offset Function".

Other benefit of using the Baum Station is that by using the screenshot function on the TS, it is possible to record the device's work screen with the final measurement data and create detailed survey reports.

In **Fig. 12**, measurement interface for the "Radius Offset Function" is shown. In **Fig. 13**, the improvements made, included in "Trinos+" software version, to the "Radius Offset Function" interface is shown.

By uploading the project's design data into the TS with the each pile's design position coordinates, differences between design values and actual measurement values can be calculated and displayed for reference or corrections. By selecting the "Coordinate" option from the "Guide Method" menu, X and Y coordinate deviations are displayed as numerical values, which can be used by the operator to control pile positions for a more efficient driving processes.

As shown in **Fig. 14**, by changing the "Guide Method" to "Line", the differences of X and Y values from the design values are shown as position arrows from the operator's point of view. This option is useful for pile position corrections on site. The option to choose known or unknown radius was removed since the radius of pre-manufactured piles is always known. Measurement results are saved with a new file name automatically. Moreover, it is possible to select subsequent piles from the uploaded file to continue the driving process without having to set up the TS all over again. Data is saved in chronological order for each measurement, with corresponding X, Y and Z coordinate values.

Design, measurement and result data are recorded, used and compared throughout the survey; all relevant data are recorded in a single screen.

Moreover, it proves to be an efficient way to create records for pile construction and management. Since data such as pile number, radius, design coordinates, measured coordinates, eccentricity, measuring time, etc. are contained in the same display screen, by creating screenshots; reports can be easily created. Transcript errors and work time are also reduced, as the need to rewrite and digitize on-site hand-written data is eliminated.

3.4. Baum Station additional accessories: "Pile Navi"

This system was developed as an addition to Baum equipped TS mainly for installing tilted piles. This system enables precise pile driving and comprehensible process as all navigation is performed from the operator's point of view and in real time.

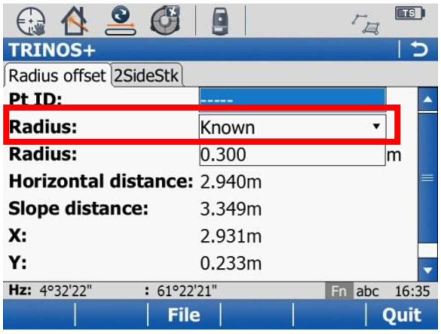

Fig. 12 Basic Baum Station work interface

The application's system quantifies the tilt and depth of the pile, as well as the correction amount for the driving position. It allows the operator to clearly view the correct position.

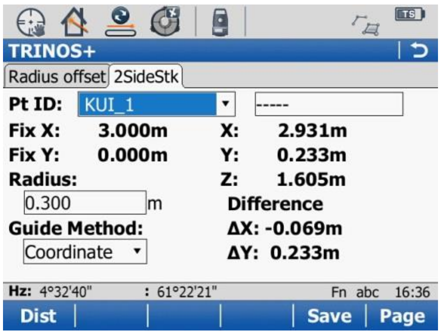

Fig. 13 Improved Baum Station work interface for pile installation, "Coordinate Guide Mode"

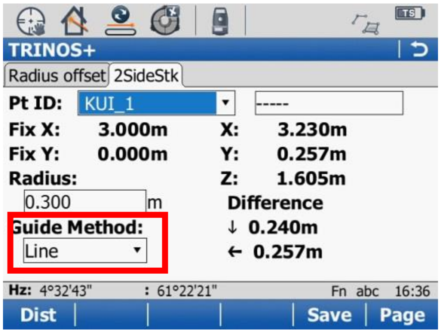

Fig. 14 Improved Baum Station work interface for pile installation, "Line Guide Mode"

Therefore, during the process of pile driving, as tilt and depth values are simultaneously calculated and displayed, immediate pile position corrections are possible. This enables to achieve a higher accuracy level as data is measured and recorded immediately.

First, measurements are performed by the Baum Station, then, measurement records are transferred directly to a Portable Digital Assistant (PDA) through the developed program, which performs the tilt and depth calculations as well. **Fig. 15** shows the navigation interface of the "Pile Navi" accessory.

This system works as an additional accessory to the Baum station and is most useful when monitoring the installation of tilted piles.

4. Baum Station use cases

4.1. Overview

Since its release, the Baum Station has been used in a variety of projects. The Baum Station has been employed for pile installations of projects in urban areas as well as in large scale projects in mountainous areas. Due to its high accuracy for monitoring pile installation, it is used more frequently in projects where the pile's final position is of utmost importance. Below are some examples of projects in which the Baum Station was utilized for high accuracy pile installation.

4.2. R&D (Research and Development) Center construction

- Piles Installed: 44 in total
- Pile Diameter: between 400mm and 600mm
- Installation Requirements: maximum allowable displacement of 50mm

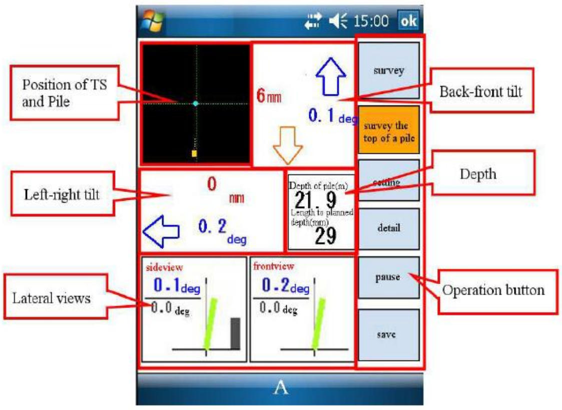

Fig. 15 "Pile Navi" system interface

- Special Site Conditions: steel structure constructed directly over installed piles, therefore the need to keep piles deviations from design data at a minimum.
- Accuracy Achieved: all except 2 piles were driven with accuracies between 6mm and 47mm, which fall within the accuracy required. Only piles #42, with a deviation of 79mm and pile #43 with a deviation of 114mm were outside the margin of acceptable displacement.

4.3. Application of new civil engineering construction methods

- Piles Installed: 14
- Installation Requirements: high level of accuracy for management.
- Pile Diameter:800mm
- Special Site Conditions: Mountainous area with construction of highway piers, sloped ground, and hard strata with a fine sand layer.
- Accuracy Achieved: level between 13mm and 75mm.

4.4. Residential building development

- Piles Installed: 26
- Installation Requirements: deep piles installation to prevent slippage of the building
- Pile Diameter: 600mm to 700mm
- Special Site Conditions: real time quantitative monitoring required due to high traffic area, large number of obstacles and city center construction
- Accuracy Achieved: between 10mm and 70mm

4.5. Industrial building construction

- Piles Installed: 60
- Installation Requirements: vertical accuracy needed for driving short piles, length of 10m
- Pile Diameter: 400mm to 900mm
- Special Site Conditions: marked difference between soil's soft layer and hard layer, which increases the risk of piles driving or drilling out of alignment
- Accuracy Achieved: between 7mm and 99mm

4.6. Summary

Presented from section **4.2.** to **4.5.**, were some successful projects in which the PM Method in conjunction with the Baum Station was used to achieve high level of pile position accuracy. The Baum Station has been successfully used to minimize pile deviations in projects, such as the case of the Daiken Industry's R&D Center, in which deviations from design positions can affect the project negatively.

The PM Method in conjunction with the Baum Station also provides a good monitoring system for difficult installations, such as the case of short piles, presented in section point **4.5.**, which can drive out of alignment easily. Another example was presented in section **4.4.**, which was a project carried out in an urbanized area, therefore, there was a lot of interference from automobiles, pedestrians and buildings. In this case, the "1 Side" function from the PM method, developed for the Baum Station, proved to be helpful due to the limited construction space on the project.

Finally, the Baum Station can also be used for large scale civil engineering projects, as described in section **4.3.** It was used successfully for the installation of larger diameter piles in a mountainous area.

5. Concluding remarks

As discussed previously, some of the merits of using the Baum station when pile driving are listed below:

- Higher measurement accuracy compared to the widely used manual methods.
- Real time corrections can be made during pile installation.
- By using the Piling-Measurement Method, cost can be reduced by 43%.

- Necessary manual labor is reduced comparing to traditional methods from 4 to 1.
- Survey result errors are reduced as screenshots of measuring results can be used directly, eliminating the need for hand calculations with results automatically displayed on the Baum Station screen.
- Tilted piles incline can be monitored accurately and corrected accordingly when using the "Pile Navi" accessory.
- No extra hand labor required as only the TS operator is needed for survey works.
- As the pile driving process is recorded from start to finish, extensive monitoring data is created.
- The drilling rod's position during excavation is also recorded and verified.
- Pile's position from start to finish is recorded and verified.
- Records are created and delivered in a standard format by using the PM Method for vertical pre-bored piles and the "Trinos+" software for calculation results.

6. Acknowledgements

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