Geotechnical mapping using press-in piling data to estimate bearing layer

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Abstract

The fluctuation and inclination of the bearing layer have a negative impact on the reliability of pile foundations and embedded retaining walls. Since it is difficult to grasp spatial variation from the preliminary geotechnical investigation alone, it is necessary to confirm the bearing layer using data collected during construction, such as the blow count and penetration rate of prefabricated piles. There are few reports about how much the spatial variation of the depth of the bearing layer and the estimation error from piling data are. In this paper, the authors highlight the sources of error in the estimation of geotechnical properties using press-in piling data, estimate geotechnical information, and conduct the geotechnical mapping of two projects. Although one site's bearing layer depth changed greatly, the change in the N-value was clear and could easily be captured. At the other site, an observation of the middle layer was attempted; however, the change in the N-value was gradual, making it difficult. The spatial analysis indicated that the estimation seemed reasonable in view of the preliminary geotechnical investigations and the previous studies on the uncertainty of the ground. The spatial variability of the estimation was analyzed. These results will be helpful for the quality control of pile structures.

Keywords: Piling data, Bearing layer, Site investigation, Spatial analysis, Measurement error

1. Introduction

The fluctuation and inclination of the bearing layer are critical to the construction of pile foundations and embedded retaining walls. Recently in Japan, many pile foundation accidents have occurred, such as in apartment houses in Yokohama (2015) and Fukuoka (2020) and in a pedestrian bridge in Osaka (2020). The major causes were said to be gaps between the piles and the bearing layers. Suzuki et al. (2021b) pointed out that the same risk would cause rotational failures and large deformations even in steel pipe pile cantilever retaining walls embedded in stiff ground.

Design margins are one of the methods against the above issue (e.g., RTRI 2015), though they lead to unnecessary construction time and costs. Instead, piling data can be used to observe the boundary layer. However, there is little knowledge about how much the depth of the bearing layer changes and how reliably it can be estimated from the construction data.

In this paper, geotechnical information from the data of the rotary press-in piling was estimated in each pile and geotechnical mapping was conducted using all piles. Spatial analysis was also conducted to grasp the spatial characteristics of the support layer and the variation of the estimation. These results will be helpful for the management of the bearing layer of piles by using the data of press-in installation.

2. Literature Review

2.1 Geological investigations

Though new geotechnical technologies for exploration have been developed with more efficiency and cost effectiveness (Mayne, 2015), geotechnical uncertainties remain, such as inherent variability and measurement errors (Phoon and Kulhawy, 1999). On the reliability of ground investigation, ZENCHIREN (2017) reported that borehole soundings are accurate to within 10 cm and can be used for relatively hard ground while geophysical surveys are excellent for surface profile surveys and are accurate to within 2 m. Kakurai et al. (2009) reported the fluctuations of the ground itself: In Tokyo and Tenma layers, a maximum of 2–3 m of unconformity was observed at distances of 40 m or more. Assuming the variation followed an exponential autocorrelation function, the standard deviation (SD) was estimated to be 0.5–1.0 m.

2.2 Use of piling data

Ohki et al. (2005) reported the installation data of screw piles for 41 sites; however, they assumed that the estimations were true values and did not discuss measurement errors. Zhang and Dasaka (2010) estimated and compared static and as-built pile lengths of driven piles with three founding depth indicators: the depth of Grade-III bedrock, the depth of the standard penetration test 200 (SPT-200), and the depth of completely decomposed granite over the site. They reported that the length of the pile during construction correlates well with the SPT-200 profile, though they also noted that post-construction pile length can include human error due to unnecessarily cautious construction.

Other uses of piling data include the estimation of the bearing capacity for driven piles (Reddy and Stuedlein, 2013) and helical piles (Tang and Phoon, 2018), but there are few field reports. From the above mentioned studies and the general spacing of borehole logs, 30–300 m (e.g., Annex B in EN1997-2, 1997), an uncertainty of up to 2.0 m is unavoidable. This uncertainty can be critical for the retention of pile foundations and pile retaining walls. Confirmation of the state of the bearing layer using construction data effectively complements this.

3. Methods

3.1 Estimating the N-value with piling data

For the estimation of the N-value by rotary press-in piling as proposed by Ishihara et al. (2015), the required measurement data are the press-in axial force and torque at the pile head, the vertical position of the pile, and the transition of the length of the soil column in the pipe. These are constantly measured by the press-in machine at 9Hz. As for other inputs, the internal friction angle of the ground is assumed from geotechnical investigations, the rotational speed is converted from the torque, and the size of the pile is used.

However, since the projects studied in this paper did not require piles to have the vertical bearing capacity, there were no specific observations of the bearing layer or transitions of the length of the soil column in the pipe. Therefore, the final filling ratio (FFR) is used in this paper instead of the incremental filling ratio (IFR), and the FFR is assumed to be 0.5. It should be noted that in some projects, N-values are estimated to be smaller than that of the SPT. These could be improved by measuring the length of soil in the pipe and referring to the test piles installed at the SPT location.

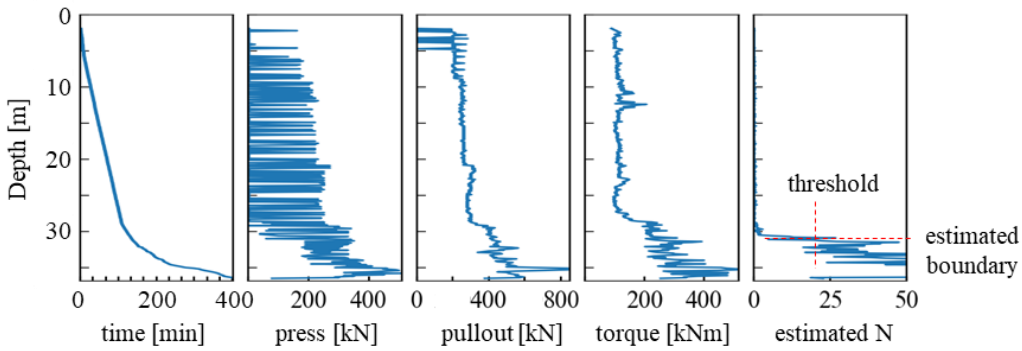

Figure 1: Illustration of piling data and estimated N-value (Project ID=t15022, pile no=3)

In this paper, the N-value was estimated per 10 cm, which is around the net penetration length in repetitive up and down motion. The depth of the piles was based on the completed construction, as the top heights of the piles were aligned after the piling.

3.2 Average length

Ishihara et al. (2015) stated that the energy consumed at the pile tip during rotary cutting and press-in is a function of the press-in force and rotary torque at the pile tip, which is proportional to the SPT-N-value. Strictly speaking, since the diameter of the steel pipe pile is larger than that of the SPT, the press-in resistance could depend on the average N-value near the pile base, instead of that of the point. The average depth may be from 3B to 6B, where B is the pile diameter (Zhang and Chen, 2012; Otake and Honjo, 2012).

Theoretically, a sequence of original N-values can be acquired progressively if the moving average is observed at equal intervals with awareness of the initial values and the size of the moving window. However, this may not be appropriate as the initial estimation error would continue to accumulate thereafter.

With this in mind, the estimated N-value was used as is in this paper, although it was a weighted average that took into account the ratio of torque to the press-in force.

3.3 Judging the boundary

The boundary of the layer was determined to be the depth at which the median of 30 cm above and below became larger than a threshold (Figure 1). It should be noted that the threshold is generally derived from the result of the pilot test, but in this paper, it was derived from the results of all piles in the projects. Naturally, the estimation error depends on the threshold.

3.4 Estimation errors

Table 1 lists the sources of the estimation errors. When compared with the sources of the measurement errors of the SPT shown in Appendix A of Kulhawy and Mayne (1990), it can be observed that machine measurement may resolve some of the human errors, such as careless blow count, but some will remain. Also, the estimation error measured in this paper is repeatability not reproducibility. Thus, the estimation errors marked with [S] in Table 1 may be measured.

Item	Cause	How to accommodate
N-value		
Measurement error		
	Estimated N-value may be the average of the N-value in a range, as mentioned in Section 3.2.	In general, the pile capacity is important for quality control; the embedment of the pile into the bearing layer may not be critical.
	Calibration error in hydraulic measurement of construction machinery.	Periodic inspection and calibration may be required.
	Loss of significance, e.g., the axial force is stored in units of 10 kN. [S]	-
	Difficulty in measuring piling resistance in soft ground where the pile sinks under the weight of the machine and the pile.* [S]	The scope of application to soft ground should be noted.
Transformation error		
	Some assumptions involve uncertainty: ・Conversion of resistance from the pile top to the pile tip. ・Conversion from the energy to the SPT N-value.	Prior geotechnical investigations are helpful. Statistical evaluations are needed, e.g., Akca (2003).
Human error or others		
	Adjacent piling may affect the ground around the next pile. [S]	The boundary after construction is highly important but it is not discussed.
	Lack of input data as mentioned in Section 3.1.* [S]	It depends on the purpose of the estimation.
	Some piling conditions may differ such as the amount of water discharged, its direction, and the rest time. [S]	The construction records need to be recorded and stored.
	Damage may occur in the pile and the attachments such as bits installed at the pile. [S]	Observe sound and vibration during piling.
Boundary		
Measurement error		
	Cumulative error of measuring depth by sensor of the hydraulic cylinder.* [S]	New technology such as that introduced by Ishihara and Yasuoka (2022) can help with verification.
Transformation error		
	The error of deciding the boundary such as the threshold * [S]	Prior geotechnical investigations are helpful.
	It is more difficult to estimate the boundary when no clear boundary is apparent, such as when the N-value increases slowly.* [S]	Some automatic calculation methods have been proposed (e.g., Yoshida et al., 2019).

Note: Since the estimated boundary depends on the estimated N-value, the sources of error when estimating the N-value include that of the boundary. * indicates what were thought to be the major causes of error in this study. [S] indicates the error which varies in the same site.

Table 1: Major sources of error in the estimation using piling data

3.5 Spatial statistical analysis

Ground variation is assumed to consist of a long-term trend, a short-term trend, and white noise. The long-term trend in this paper was approximated by a polynomial function using the least squares method, and the residuals were fitted with Gaussian process regression (GPR: Kriging) using kernels of the Gaussian function (a.k.a. squared-exponential, radial basis function: RBF). The hyperparameters of the kernel (i.e., the autocorrelation distance and variance and the variance of white noise) were determined from maximum likelihood methods. It should be noted that Stein (1999) recommended using the Matérn covariance function for interpolating, but the Matérn function may sometimes overfit observations and underestimate the variance of white noise. Therefore, Gaussian function was used in this paper to estimate the measurement errors. Although it is difficult to strictly separate long- and short-term trends, their influence on the interpolation was believed to be sufficiently small. Since lateral spacing of the observations was less than the scale of fluctuation (SOF) of the general ground (1–3 m vs. 20–200 m), the interpolation was assumed to be true value, and the residuals became the estimation error itself.

4. Case studies

4.1 Project t15001

The first project aimed to raise a seawall, and 160 steel pipe piles of 800 mm diameter were contiguously installed for about 450 m. Figure 2 draws the boundary layer based on 13 borehole logs and the SPT. The bearing layer was tuff with CL-CM class based on CRIEPI rock-mass classification (Saito and Arata, 1992), and the depth of the bearing layer (shown with a black solid line) was about 5–20 m over the section. The depth at which the SPT N-value was more than 50 was about 1 m under the bearing layer.

Figure 2 shows that for piles No. 90–130 the boundary layer was almost constant at a depth of 20 m. Figure 3 illustrates the geotechnical map using the estimated N-values. When compared, the estimated depth ranges from the boundary layer investigated by the borehole to the layer with an N-value that became more than 50, excluding the piles around No. 130–150. The estimated depth changed by up to 3 m within the range, and it is believed that this area was difficult to investigate before construction. There were a few areas where the estimated N-values were large and differed from those of the adjacent piles. This is considered to be an estimation error due to the difference in the degree of the FFR.

Figure 4 shows the geometric mean of the estimated N-values for the lower 1.0 m of the bearing layer with a 95% confidence interval. The averaged N-value was well fitted to the log-normal distribution. The SOF of 31 m was within the range of previous studies, indicating that the estimation was reasonable. The coefficient of variation (COV) of the short-trend and white noise were 13% and 15%, respectively, and the estimation error was minimal.

The horizontal SOF of the short-term trend was about 24 m, which was close enough to that of the N-value. The residual followed a normal distribution with a SD of 0.3 m (Figure 6), which was small enough to be practical.

4.2 Project o16007

The next project aimed to improve the earthquake resistance of a river wall. The pile diameter was 1.0 m, and there were 85 piles. The rotary cutting press-in piling was applied because the cutting bits at the pile tips could penetrate reinforced concrete and avoided removing the concrete blocks and tie rods in the existing wall in advance. The target middle layer was sand and gravel.

Figure 7 illustrates the distribution of the estimated N-values with the SPT N-value located at the center of the project. The estimated results captured the middle layer at around 10 m depth throughout the construction section.

Figure 8 shows the geometric mean of the estimated N-values for the lower 1.0 m of the middle layer. The averaged N-value was about 2.0, which differed from that of the prior SPT. This may be a bias due to the lack of the FFR data. Some averaged N-values also became lower than the threshold, which means the estimated N-value rose and fell in the middle layer. The boundary for ground where no clear boundary was apparent was difficult to estimate. On the other hand, the overall COV of the estimated N-value was 25%, and the SOF of the short-trend was 21 m, which, considering the previous studies, are within a reasonable range.

The boundary of the middle layer was located at around 5–10 m depth. Some of the estimation depths differed from the trend (Figure 9). The vertical distribution of N-values for the pile showed a different trend from that of the adjacent piles. This may be because the resistance measured was too small to estimate the N-value, as shown in Table 1. The SD of the depth measurement error was 0.8 m, which is larger than the previous project (Figure 10). This may be because of the large cumulative error, since this case considered the middle layer and the depth as being far from the final depth, unlike Project t15001.

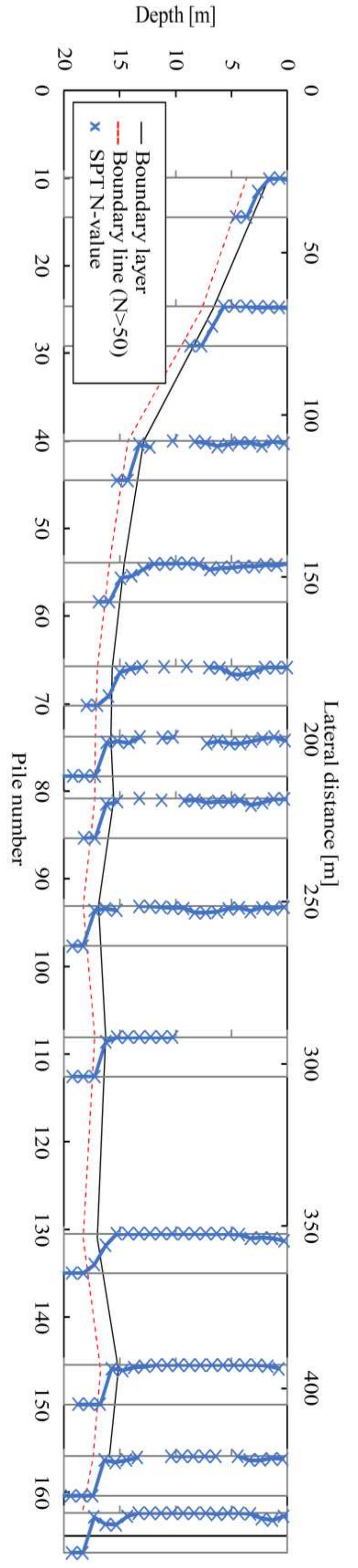

Figure 2: Longitudinal profiles: boundary layer based on borehole log and SPT N-value (Project ID=t15001)

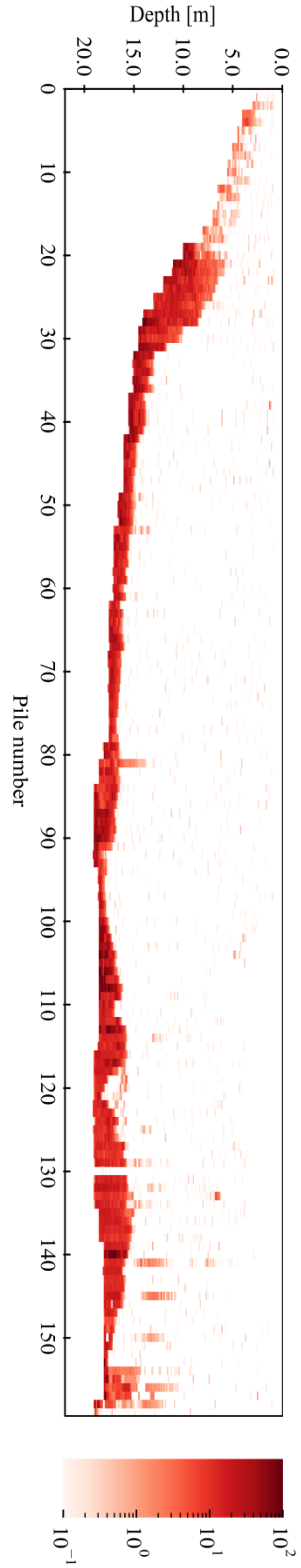

Figure 3: Estimated N-value based on press-in piling data (Project ID=t15001)

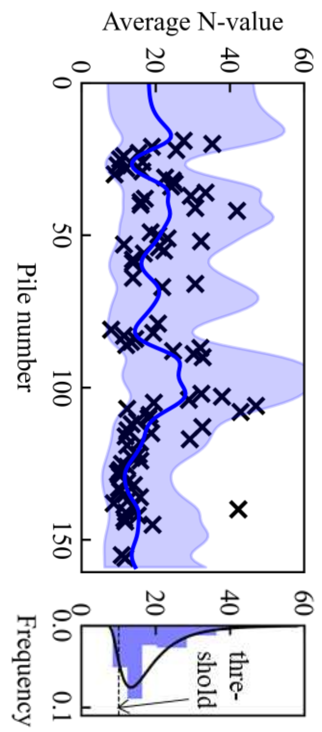

Figure 4: Geometric mean of the estimated N-value

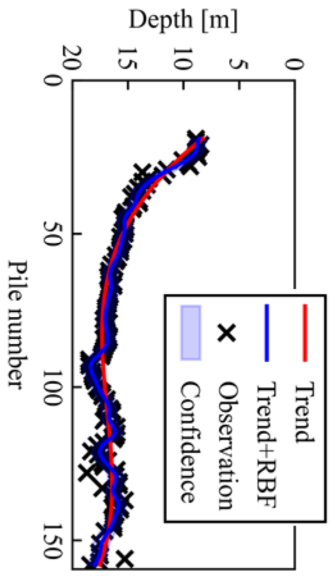

Figure 5: Boundary depth

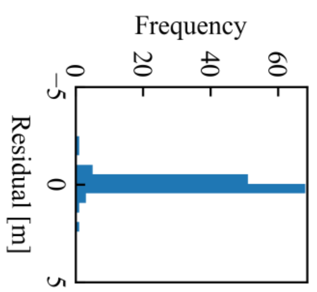

Figure 6: Estimated error

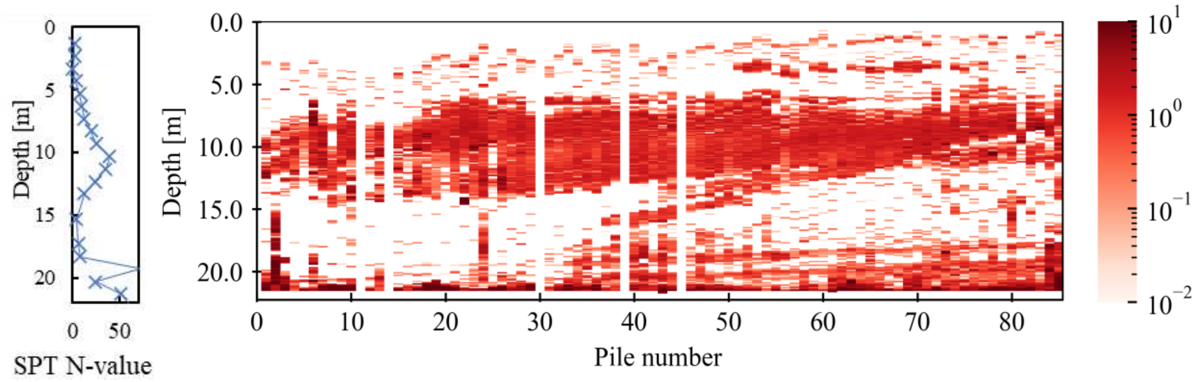

Figure 7: SPT N-value and the distribution of the estimated N-value (Project ID=o16007)

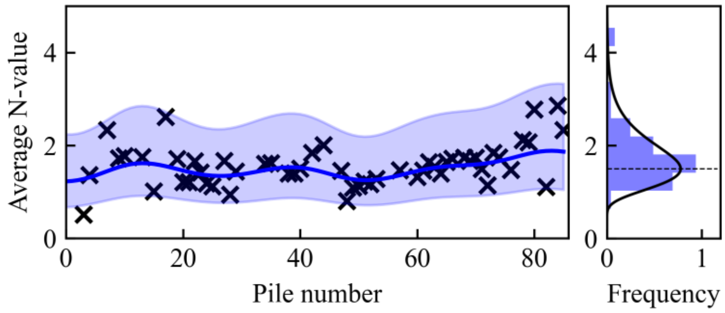

Figure 8: Horizontal spatial distribution of geometric mean of N-values in the middle layer

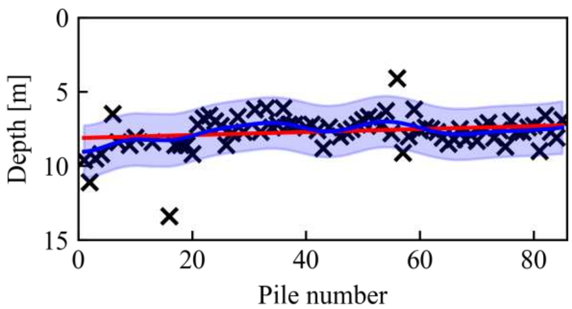

Figure 9: Horizontal spatial distribution of the upper boundary of the middle layer

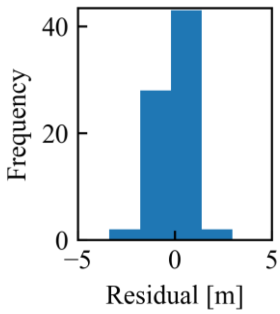

Figure 10: Residuals from trend (Estimation error)

5. Discussions and conclusions

This paper mapped the geotechnical distributions of two sites using the piling data of the rotary cutting press-in method by estimating the N-value and the boundary depth. Due to the site conditions, the boundary layer of the second site seemed to be more difficult to estimate. The spatial analysis indicated that the estimation seemed reasonable in view of the preliminary geotechnical investigations and the previous studies on the uncertainty of the ground. In the spatial analysis, it was assumed that the estimation had no bias and that the variations were only inherent variability and measurement errors, which were independently distributed. The analysis showed that the SDs of the measurement errors of the boundary depth were 0.3 m and 0.8 m, though they should depend on the condition of the projects, such as the difference in the N-values of the stiff ground and the upper layers, as well as the depth of the piles.

Also, the estimation could be improved by the methods to accommodate errors mentioned in Table 1, but the estimation errors in this study were not greater than those of the existing technology (geophysical surveys). The intervals used for estimation and techniques to reduce uncertainty, such as using a minimum in the interval, should be further studied. The other research topic is using data from multiple piles to increase reliability.

Considering the normal spacing of the geotechnical investigations, the estimation in this study could supplement the gap in the prior geotechnical investigations, even though the estimation has some variations. It is believed that this geotechnical mapping can help to improve the reliability of pile structures. Some proposals are presented in Suzuki et al. (2021a). The results of this paper would be helpful for the quality control of press-in piling.

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