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<https://jurnalteknik.unisla.ac.id/index.php/CVL>
<https://doi.org/10.30736/cvl.v2i2>



Analysis of Technical Factors Causing Deviation of Spun Pile Coordinate Points in the Data Center Construction Project

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ARTICLE INFO

Article History :

Article entry : 30-12-2025

Article revised : 16-04-2026

Article received : 10-09-2026

Keywords :

Pile coordinate deviation,
Construction quality control,
Measurement accuracy, Field
coordination, Relative
Importance Index (RII)

IEEE Style in citing this article :

Sopar Butarbutar and
Mardiaman, "Analysis of
Technical Factors Causing
Deviation of Spun Pile
Coordinate Points in the Data
Center Construction Project",
CVL, vol. 11, no. 2, pp. 256–265,
Sep. 2026.

ABSTRACT

Foundation works, especially in high-precision buildings like data centers, must account for pile coordinate point deviation, which can cause structural eccentricity, pile cap redesign, cost overruns, and schedule delays. This study examines technical parameters affecting spun pile foundation coordinate deviation in a data center construction project (Data Centre X). A total of 153 respondents-surveyors, piling operators, site engineers, and supervisors-completed a standardized questionnaire administered through online platforms using a quantitative descriptive technique, and their responses were ranked using the Relative Importance Index (RII) to identify the technical aspects affecting pile position variation. Measurement-related factors dominate deviation, with total station instrument condition and calibration having the highest RII value (0.963), pile point marking clarity (0.957), and surveyor, operator, and foreman communication (0.945). Equipment condition, operator compliance, and experience also mattered. The data show that technical and operational factors, not geotechnical issues, determine spun pile coordinate variations. To assure foundation accuracy in high-precision building projects, this study emphasizes stringent measuring, staking out, and field coordination quality control.

1. Introduction

A foundation is a critical structural element in ensuring the stability and safety of buildings, particularly in large-scale construction projects that employ advanced technologies. In specialized facilities such as data centers, construction accuracy and precision are required to a much higher degree than in conventional buildings, as the structure must be capable of supporting heavy equipment loads, maintaining long-term stability, and minimizing the risk of deformation that could disrupt the operation of information technology systems. One of the most crucial aspects of deep foundation works is the accurate positioning of pile foundations in accordance with the designed coordinates, since even minor



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deviations can lead to load eccentricity, which adversely affects the performance and reliability of the superstructure [1].

Geometric tolerance of foundations is a critical factor in buildings with essential functions, such as data centers, because even minor deviations in pile positions can adversely affect the performance of the superstructure and the reliability of operational facilities, as demonstrated by recent studies on high-precision foundations for technology- and industry-sensitive buildings [2].

The issue of pile position deviation is not merely theoretical but has been empirically identified in various construction projects in Indonesia. A study of 19 projects using precast pile foundations found that only about 39–60% of large-diameter piles (500–600 mm) were installed within a deviation tolerance of ≤ 75 mm from the designed position. The other piles had deviations that were greater than the design limits. These findings confirm that pile position deviation is a systemic field phenomenon influenced by a combination of technical factors, installation methods, and site conditions [3]. Figure 1 shows the process of piling at the data centre building.



Source: Process of piling in the X centre project

Figure 1. Data center construction.

Modern construction widely adopts spun pile foundations due to their durability, construction speed, and consistent quality. Spun piles are hollow cylindrical precast concrete elements manufactured using centrifugal casting and prestressing techniques, resulting in high material density, strength, and structural capacity. Numerous studies have demonstrated that spun piles can provide reliable structural performance under various soil conditions, including soft and layered soils, when appropriate installation methods and quality control procedures are applied [4]. Despite their material advantages, spun pile foundations remain susceptible to coordinate deviations during on-site construction. Previous studies indicate that soil heterogeneity, measurement system accuracy, staking-out quality, and on-site technical coordination significantly influence pile positioning, often exerting a greater impact than purely geotechnical factors [5].

The deviation in pile positioning is defined as the difference between the actual position of a pile after installation and the planned position indicated in the construction drawings, both in the horizontal and vertical directions. This deviation cannot be entirely avoided because the pile driving process involves complex interactions among the pile, soil, equipment, and installation methods. Field observations indicate that while some piles remain within an allowable deviation of ≤ 75 mm from the designed position, others exceed the prescribed design tolerance limits. This recurring pattern indicates that pile position deviation is not an isolated occurrence but a field-level phenomenon shaped jointly by technical conditions, installation procedures, and site-specific circumstances [6]. Various international technical standards, such as ASTM and Eurocode, have established allowable deviation tolerances to

ensure that any deviations do not compromise the structural performance of buildings. However, under certain field conditions—particularly in large-scale projects or at sites with complex soil characteristics—actual deviations frequently exceed the recommended tolerance limits [7].

Several international studies indicate that deviations in pile positioning can lead to significant technical consequences. Horizontal deviations may cause load eccentricity on pile caps and columns, thereby inducing additional moments that were not considered in the initial design and may exceed the recommended tolerance limits [8]. In addition, coordinate deviations among piles within a pile group may reduce the efficiency of the pile group due to uneven load distribution, which can ultimately lead to differential settlement and damage to the superstructure [9]. Buildings requiring high precision, such as data centers, this condition becomes increasingly critical because structural stability is closely related to the operational reliability of the facility.

Various studies have identified that the primary causes of pile coordinate deviation originate from interacting technical factors. Soil conditions are the most frequently reported dominant factor. Soft soils, layered soils, and reclaimed or fill soils exhibit non-uniform mechanical characteristics, resulting in varying lateral resistance during the pile driving process [10]. Variations in elastic modulus among soil layers may cause bending of the pile shaft and changes in penetration direction, ultimately resulting in deviation of the pile position from the designed axis [11]. Recent numerical studies also indicate that soil heterogeneity plays a significant role in increasing the risk of pile deviation, particularly for long piles penetrating multiple soil layers [12].

In addition to soil conditions, the pile driving equipment used also influences the accuracy of pile installation. Wear of equipment components, imperfections in the clamping or guiding systems, and mismatches between equipment capacity and soil conditions may cause piles to be installed out of vertical alignment and to deviate from their planned positions [13]. Experimental and field studies indicate that the use of piling equipment equipped with well-controlled guidance systems can significantly reduce the risk of pile position deviation compared to conventional equipment with limited directional control. Therefore, the selection and condition of piling equipment constitute critical technical factors that cannot be overlooked.

The pile driving method also plays an important role in determining the accuracy of pile coordinates. Dynamic pile driving methods that involve repeated impact energy tend to generate greater vibrations and lateral forces compared to static methods, thereby increasing the potential for positional deviation, particularly in soft soil conditions [14]. On the other hand, static installation methods such as jack-in piles offer higher installation precision but are limited in capacity and involve higher costs. In addition, the driving sequence within a pile group (group pile effect) may induce lateral displacement of previously installed piles due to soil stress redistribution, making cumulative deviations difficult to avoid if not properly controlled.

In the context of data center construction projects, pile coordinate point deviation has become a relevant issue. Data centers are buildings with stringent structural tolerance requirements due to their direct relationship with the safety and operational continuity of high-technology equipment. Deviations in pile positioning not only affect structural performance but also have the potential to trigger pile cap redesign, additional reinforcement, increased construction costs, and delays in project execution. Consequently, a thorough comprehension of the technical factors leading to pile coordinate deviations is crucial for quality control in foundation works, especially when these deviations are inadequately managed.

Although numerous studies have examined pile foundation deviations, most previous research has primarily focused on specific project contexts, such as marine bridges or offshore infrastructure, and has tended to emphasize isolated technical aspects, such as soil conditions or pile driving methods. Studies that specifically investigate the technical factors causing coordinate point deviations of spun pile foundations in high-precision vertical building projects, such as data centers, remain relatively limited. Previous studies on bridge and pier foundations have generally relied on deterministic tolerance checks or structural reliability methods, such as first-order reliability analysis of pile cap punching shear capacity, to evaluate the consequence of a pile deviation that has already occurred [8], or on risk-matrix assessments limited to the precast pile fabrication stage [15]. These approaches examine deviation as a downstream structural or fabrication issue for linear infrastructure elements, where load paths and tolerance margins differ substantially from those of a vertical building. In contrast, the present study applies a perception-based Relative Importance Index across measurement, equipment, and field-

coordination factors simultaneously, specifically within the context of a high-precision vertical building project, to identify the upstream technical causes of deviation before it occurs. This distinction in analytical scope and project type constitutes the specific research gap addressed by the present study. In addition, quantitative approaches based on field data to systematically identify the relative contribution of each technical factor have not been widely applied. Pile coordinate deviations not only affect structural technical aspects but may also trigger pile cap redesign, additional reinforcement requirements, increased construction costs, and project schedule delays if not properly controlled. Therefore, a comprehensive understanding of the technical factors causing pile coordinate deviations is essential as a basis for effective quality control in foundation works.

However, most previous studies have still treated pile deviation as a secondary variable in capacity analysis or soil–structure response evaluations. Consequently, research that explicitly prioritizes field technical factors causing the coordinate deviation of spun pile foundations in high-precision buildings remains very limited.

In addition to measurement errors and human factors, dynamic disturbances during construction activities may also affect the accuracy of pile positioning. Recent experimental and numerical studies indicate that three-dimensional vibrations generated by underground construction activities and heavy construction operations can induce lateral responses in pile foundations, with different displacement characteristics along each coordinate direction. This condition becomes increasingly critical in high-precision buildings such as data centers, where allowable pile position tolerances are extremely limited and even minor deviations may significantly affect the alignment and performance of the superstructure [16].

Based on these conditions, this study aims to analyze the technical factors influencing the occurrence of coordinate point deviations of spun pile foundations in the construction project of Data Centre X. The technical factors examined include soil conditions, piling equipment, pile driving methods, and interaction among piles within a pile group. Using a questionnaire-based quantitative approach and statistical analysis, this study seeks to give empirical information about the dominant factors causing pile coordinate deviations. The findings are expected to serve as a reference for practitioners and academics in improving quality control of foundation works, particularly in construction projects with high precision requirements.

2. Research Method

This study employs a descriptive quantitative approach using a survey method to identify the technical factors influencing the occurrence of coordinate point deviations of spun pile foundations in the construction project of Data Centre X. The quantitative approach was selected because it enables objective and measurable assessment of the influence level of each technical factor based on the perceptions of respondents directly involved in pile driving activities.

3. Description and Technical

Primary data were obtained through a structured questionnaire developed based on an extensive literature review and findings from previous studies related to pile coordinate deviation. The questionnaire was distributed to respondents online using WhatsApp and internet-based platforms (Google Forms) to facilitate efficient distribution and broaden respondent coverage. The online data collection method was selected due to its efficiency, ability to reach a large number of respondents, and suitability for the dynamic conditions of construction site operations.

A total of 153 respondents participated in this study, which is considered sufficient for descriptive statistical analysis and factor ranking using the Relative Importance Index (RII) method. A five-point Likert scale was employed for assessment, ranging from 1 (very low influence) to 5 (very high influence).

3.1 Population and Sampling Technique

The research population comprises all personnel directly involved in spun pile driving works in the Data Centre X construction project. The sampling technique employed was purposive sampling, in which respondents were selected based on specific criteria relevant to the research objectives. The respondent criteria include:

3.2 Research Instrument

The research instrument consisted of a closed-ended questionnaire containing statements related to technical factors causing pile coordinate deviation, including soil conditions, piling equipment, pile driving methods, and inter-pile interaction (group pile effect). Each statement was assessed using a five-point Likert scale ranging from 1 to 5. Prior to the main analysis, the questionnaire data were examined for completeness and screened to ensure that no duplicate or invalid responses were included.

3.3 Data Analysis Technique

Data analysis was conducted using the Relative Importance Index (RII) method to determine the relative level of importance of each technical factor causing deviation of pile coordinate points. The RII method is widely applied in construction research because it is effective in prioritizing factors based on respondents' perceptions in a quantitative manner.

The Relative Importance Index (RII) approach is strongly recommended in construction management and engineering studies for identifying dominant factors derived from practitioners' experience, particularly when the variables are technical–operational in nature and difficult to measure experimentally.

Data analysis was performed using the Relative Importance Index (RII) method to rank the relative significance of technical factors contributing to pile coordinate deviation.

The formula for the Relative Importance Index (RII) is expressed as follows:

$$RII = \frac{\sum W}{A \times N} \quad (1)$$

where:

W = weight assigned by respondents (1–5),

A = highest weight on the Likert scale (5),

N = number of respondents (153).

The RII value ranges from 0 to 1, where values closer to 1 indicate a higher level of influence of the factor. All technical factors were then ranked based on their RII values from the highest to the lowest in order to identify the dominant factors causing deviation of spun pile coordinate points. The results of the RII analysis are presented in tabular form and discussed descriptively to explain the technical implications of each factor on the execution of pile driving works in the data center project.

4. Results and Discussions

The analysis was conducted on 153 responses obtained from technical project personnel, including surveyors, piling equipment operators, foremen, site executors, engineers, and supervisors. Each statement was assessed using a 1–5 Likert scale and subsequently analyzed using the Relative Importance Index (RII) method to determine the level of influence of each technical factor on the deviation of spun pile coordinate points.

The RII values range from 0 to 1, where values closer to 1 indicate a higher level of influence.

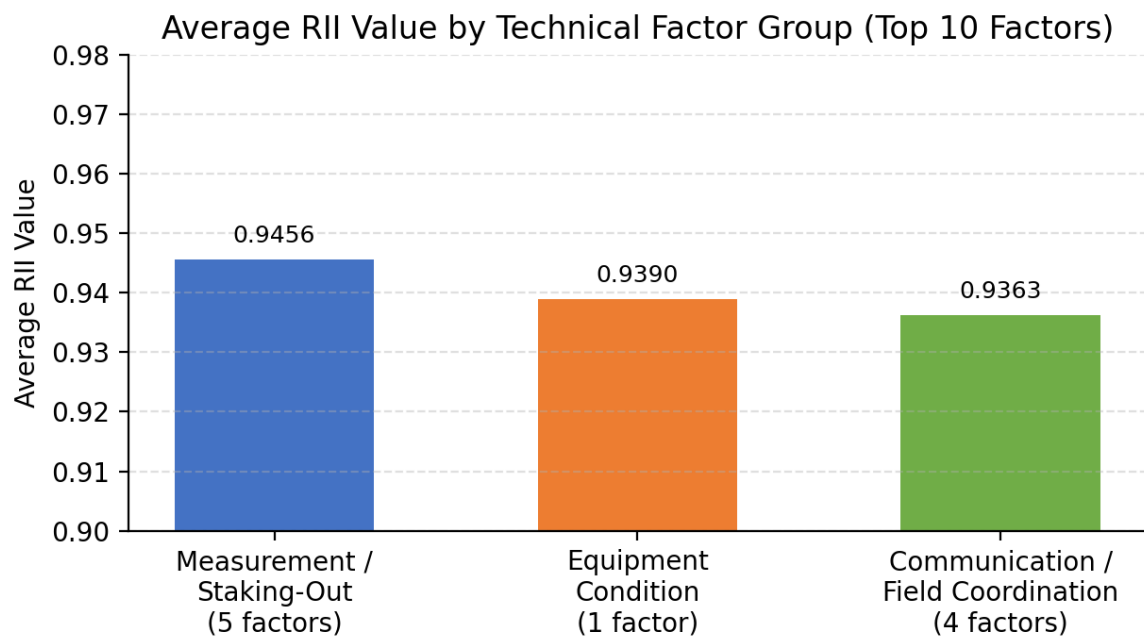
Table 1. Results of RII Calculation for Technical Factors (Top 10)

Ranking	Technical Factors	RII Value
1	Good condition of measuring instruments (total station)	0.963
2	Clarity of pile location point marking in the field	0.957
3	Effective communication between surveyor, operator, and foreman	0.945
4	Staking out errors causing pile position deviation	0.941
5	Condition of piling machine/rig	0.939
6	Operator compliance with surveyor's markings	0.939
7	Trained workforce following designated coordinates	0.937

Ranking	Technical Factors	RII Value
8	Rechecking pile position before driving	0.935
9	Errors in initial pile position setting	0.932
10	Lack of experience of piling machine operators	0.924

Source: Data Analysis Results

Overall, all technical factors analyzed have RII values exceeding 0.90, indicating that respondents perceived these factors as having a very strong influence on the occurrence of coordinate point deviations in spun pile foundations.”



Source: Data Analysis Results

Figure 2. Average RII value by technical factor group, computed from the Top-10 factors reported in Table 1.

To provide an aggregate comparison, the ten factors in Table 1 were grouped into three categories—measurement/staking-out, equipment condition, and communication/field coordination—and the RII values within each category were averaged. As shown in Figure 2, the measurement/staking-out group recorded the highest average RII (0.9456), followed closely by the equipment-condition group (0.9390) and the communication/field-coordination group (0.9363). The narrow spread between group averages (0.0093) reinforces the observation, discussed further below, that respondents perceived all three categories of technical factors as jointly critical rather than as clearly separated in importance.

The uniformly high RII values obtained in this study, all exceeding 0.92 and reaching 0.963 for the condition of the total station, indicate a narrow spread of responses rather than a clear ordinal separation between factors. This pattern is consistent with a known methodological characteristic of the RII technique: because RII is derived from ordinal Likert-scale perceptions rather than from objective, independently measured outcomes, it ranks the relative importance that respondents assign to each factor but does not by itself establish a causal relationship between a factor and the magnitude of deviation actually observed in the field [17]. Three explanations are considered plausible for the observed homogeneity. First, the respondents—surveyors, operators, and supervisors directly engaged in pile driving—share a common professional frame of reference regarding acceptable tolerances, which tends to compress their perceptions toward the upper end of the scale. Second, social desirability in a technical self-assessment context may lead respondents to rate nearly all listed factors as highly influential, since acknowledging any factor as unimportant could be interpreted as a lapse in professional vigilance. Third, human-error studies in construction similarly report that once a set of factors is explicitly named in a

survey instrument, practitioners tend to endorse most of them strongly, since the underlying causes of error are frequently interdependent rather than mutually exclusive [18]. Consequently, the RII ranking in this study should be interpreted as an indication of the relative priority attributed by practitioners to each technical factor, rather than as direct proof of the statistical magnitude of each factor's contribution to deviation. This distinction is made explicit to avoid overstating the causal strength of the findings.

Dominance of Measurement and Staking-Out Factors

The results of the analysis indicate that measurement and staking-out factors are the most dominant technical causes of pile coordinate point deviation. The condition of measuring instruments (total station) achieved the highest Relative Importance Index (RII) value (0.963), followed by the clarity of pile location marking in the field (0.957). These findings suggest that initial accuracy in the measurement process and pile point determination plays a critical role in ensuring the final position accuracy of piles after installation.

The dominance of measurement and staking-out factors identified in this study is consistent with the findings reported by Huang, which emphasize that inaccuracies at the initial positioning stage significantly contribute to pile coordinate deviation during pile driving operations [7], which states that initial positioning errors and measurement accuracy are the primary causes of coordinate deviation, even in projects with strict quality control. This indicates that errors occurring at the early stages are systemic in nature and are difficult to correct once the pile has been driven into the ground.

Errors at the staking-out stage tend to be systemic, as these initial inaccuracies are carried through the entire pile driving process and are difficult to rectify after the pile has been embedded in the soil. This is consistent with field practice, where minor deviations at the initial stage can develop into significant deviations at the final stage, particularly in soft and layered soil conditions.

Critical Role of Communication and Technical Coordination

Communication among surveyors, piling operators, and foremen ranked third with an RII value of 0.945. This finding confirms that coordinate deviation is not solely caused by equipment limitations or soil conditions, but is also strongly influenced by technical coordination mechanisms in the field. Lack of synchronization in information related to alignment, positioning, and corrective actions during pile driving may result in operators failing to accurately follow the designated pile locations.

These results reinforce the view that effective control of pile coordinate deviation requires an integrated operational system involving measurement, execution, and supervision, rather than relying solely on the reliability of construction equipment.

Influence of Equipment Condition and Operator Performance

The condition of the piling rig/machine (RII = 0.939) and operator compliance with surveyor markings (RII = 0.939) were also identified as highly significant factors. An unstable or poorly calibrated piling rig may cause lateral displacement of the pile during the driving process. Furthermore, even when pile locations are accurately determined, operator errors in following surveyor references or in setting the initial pile position can still lead to coordinate deviations.

The lack of experience among piling equipment operators (RII = 0.924) further reinforces the finding that field-level technical skills directly contribute to the accuracy of pile installation. Experienced operators tend to be more responsive to early indications of deviation and are better able to apply corrective measures during the pile driving process.

The finding that measurement equipment condition and pile installation methods emerge as dominant factors is consistent with recent studies reporting that displacement pile installation effects can induce structural position shifts due to soil deformation during driving. Consequently, the RII results of this study not only reflect respondents' perceptions but are also supported by geotechnical mechanisms that have been numerically and experimentally validated [19].

Implications for Data Center Projects

In data center projects that require a high level of precision, the dominance of technical factors becomes critically important. Deviations in pile coordinate points not only affect structural performance but also have the potential to trigger pile cap redesign, additional reinforcement, increased construction costs, and project delays. Therefore, the findings of this study emphasize that quality control during the measurement, staking out, and technical coordination stages must be prioritized in spun pile driving works for data center projects.

In high-precision projects such as data centers, the implications of coordinate deviations are more critical than in conventional building projects, as the potential for pile cap redesign and cost escalation is significantly greater than in projects that primarily focus on foundation capacity and cost efficiency, as commonly reported in industrial building projects [20].

5. Conclusion and Suggestion

5.1 Conclusion

Based on the analysis of questionnaire data from 153 respondents using the Relative Importance Index (RII) method, this study successfully identified the technical factors influencing the deviation of spun pile coordinate points in the construction of Data Centre X. The most dominant technical factors include the condition and accuracy of measuring instruments, clarity of pile point marking, staking-out errors, and the effectiveness of technical communication among surveyors, operators, and foremen. In addition, the condition of the piling equipment as well as the experience and skill level of operators were found to contribute significantly to the occurrence of deviations. These findings emphasize that rigorous technical quality control, from the measurement stage through pile installation, is crucial to ensuring accurate pile positioning in high-precision construction projects.

5.2 Suggestion

It is recommended that similar projects enhance quality control during the measurement and staking-out stages through proper calibration of surveying instruments, rechecking of pile coordinates, and strengthening technical coordination in the field. In addition, improving operator competency and prioritizing regular maintenance of piling equipment are essential to minimize the risk of pile coordinate deviation. Given that the condition and calibration of the total station obtained the highest RII value in this study, a specific and verifiable calibration schedule is warranted rather than a general recommendation. Common surveying practice suggests that field calibration checks (collimation and vertical-axis error checks) be performed at least once at the start of each measurement day and repeated whenever the instrument is relocated, subjected to a temperature change, or after any physical impact, in addition to a full manufacturer-specified calibration on a periodic basis (e.g., annually or per the manufacturer's service interval). For a high-precision project such as Data Centre X, it is further advisable to schedule an interim field accuracy check after every major staking-out campaign (for example, after each block or zone of pile points has been set out) rather than relying solely on daily checks, so that any drift in instrument accuracy is detected before it propagates to a large number of piles. Automating part of this verification process, for instance through calibration-assisted setting-out algorithms that have been shown to reduce setting-out error in recent studies [20], may further reduce the dependency on manual calibration discipline.

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