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Subsurface Characterization Using Cone Penetration Test Data for Pile Group Performance Evaluation

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Abstract— Subsurface characterization plays a critical role in foundation planning, particularly in areas with weak soil conditions where accurate assessment of soil behavior is required to ensure structural stability. This study aims to evaluate the influence of pile group configuration on pile efficiency and bearing capacity using Cone Penetration Test (CPT) data as the primary source of subsurface information. The research employed a quantitative analytical approach based on CPT-derived soil parameters, where single-pile capacity was calculated using the Direct Method and group-pile capacity was determined through pile efficiency factors. Several pile group configurations consisting of three and four piles were modeled and compared to identify the most effective arrangement. The results indicate that pile group configuration significantly affects pile efficiency and overall bearing capacity. Configurations with higher efficiency factors produced greater allowable group capacities, demonstrating a direct relationship between pile arrangement and foundation performance. The highest efficiency values reached 0.861 for three-pile configurations and 0.844 for four-pile configurations, resulting in improved bearing capacities compared with conventional arrangements. These findings highlight the importance of integrating CPT-based subsurface characterization into foundation design and engineering surveying practices. It is recommended that pile group layouts be optimized during the planning stage to maximize load-bearing performance and minimize potential settlement. The study contributes to geotechnical surveying applications by demonstrating the value of CPT data in supporting evidence-based foundation design decisions.

Keywords: Cone Penetration Test, subsurface characterization, engineering surveying, pile group efficiency, bearing capacity, foundation design.

1. Introduction

Subsurface characterization is a critical component of engineering surveying and geotechnical investigation because the safety and performance of civil infrastructure are highly dependent on the properties of the supporting soil. Accurate identification of soil stratification, strength parameters, and bearing characteristics is essential for minimizing uncertainties during foundation design and construction. Recent advances in data-driven geotechnical investigation have demonstrated the increasing capability of Cone Penetration Test (CPT) data for soil characterization, classification, and engineering decision-making [1], [2].

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The Cone Penetration Test has become one of the most widely adopted in-situ investigation techniques due to its ability to provide continuous subsurface information with high repeatability and relatively low operational cost. CPT-derived measurements have been successfully utilized for evaluating pile capacity, estimating soil properties, and improving the understanding of soil–structure interaction mechanisms [3], [4]. Recent studies have also shown that CPT data can be integrated with machine learning techniques to improve the prediction of soil behavior and foundation performance [5], [6].

Beyond foundation capacity assessment, CPT data play an important role in subsurface characterization and soil classification. Previous investigations have demonstrated the effectiveness of CPT and CPTu measurements for classifying marine soils, identifying soil stratigraphy, and delineating geotechnical zones across complex subsurface environments [7], [8]. The increasing availability of high-resolution CPT records has further enabled the development of advanced predictive models for estimating pile performance and soil mechanical properties [9], [10].

The application of CPT data in foundation engineering has expanded significantly over the last decade. Studies have examined pile shaft resistance, end-bearing mechanisms, and the influence of cone resistance on the ultimate capacity of pile foundations [11], [12]. CPT-based approaches have also been employed to evaluate liquefaction susceptibility and characterize soil behavior under dynamic loading conditions, demonstrating the versatility of this investigation method in engineering practice [13], [14].

Recent developments in computational intelligence have accelerated the use of CPT datasets for geotechnical prediction. Artificial intelligence and machine learning algorithms have been applied to estimate pile bearing capacity, load–settlement response, resilient modulus, and liquefaction potential with promising levels of accuracy [15]–[18]. These developments highlight the growing importance of CPT data as a reliable source of information for both geotechnical analysis and engineering surveying applications

Site characterization remains a fundamental requirement for foundation planning because variations in subsurface conditions directly influence load transfer mechanisms and settlement behavior. Comprehensive geotechnical surveys have been shown to improve foundation integrity assessment and support more reliable infrastructure development [19], [20]. In addition, recent studies have demonstrated that CPT-based investigations can be used to evaluate contaminated soils, classify fine-grained materials, and characterize geotechnical variability in complex geological environments [21]–[23].

Despite these advances, the practical application of CPT-based subsurface characterization for evaluating alternative pile group configurations remains relatively limited. Existing studies primarily focus on predicting the capacity of individual piles or developing data-driven models for foundation performance. Comparatively fewer studies have investigated how variations in pile group geometry influence pile efficiency and group bearing capacity under identical subsurface conditions derived from CPT investigations. Furthermore, the integration of engineering surveying information with pile group optimization has received limited attention in the current literature [24].

The novelty of this study lies in the integration of CPT-based subsurface characterization with comparative evaluation of multiple pile group configurations. Unlike previous studies that primarily emphasize single-pile capacity prediction, this research investigates the relationship between pile arrangement, pile efficiency, and group bearing capacity using identical subsurface conditions derived from CPT data. The study highlights the role of engineering surveying and geotechnical site investigation in supporting evidence-based foundation design.

Therefore, this study aims to evaluate the influence of different pile group configurations on pile efficiency and bearing capacity using CPT-derived subsurface information. The findings are expected to contribute to engineering surveying practices by demonstrating how subsurface characterization can support foundation planning, optimize pile group design, and improve decision-making in geotechnical engineering projects.

2. Method

This study employed a quantitative analytical approach to evaluate pile group performance based on subsurface characterization derived from Cone Penetration Test (CPT) data. The research focused on examining the influence of different pile group configurations on pile efficiency and bearing capacity under identical subsurface conditions. CPT data were utilized as the primary source of geotechnical information because they provide continuous measurements of soil resistance and enable reliable characterization of subsurface stratigraphy for foundation design applications.

The research procedure began with the collection and verification of CPT data obtained from geotechnical site investigations. The acquired data were reviewed to identify representative soil profiles and engineering parameters relevant to pile foundation analysis. The interpretation of CPT measurements was subsequently used to characterize subsurface conditions and estimate the geotechnical properties required for evaluating foundation performance.

Following subsurface characterization, a series of pile group configurations were developed for comparative analysis. The investigated configurations consisted of pile groups containing three and four piles arranged in different geometric layouts. Each configuration was assessed under the same soil conditions to ensure that observed differences in performance were primarily associated with pile arrangement rather than variations in subsurface characteristics. The overall research workflow adopted in this study is illustrated in Figure 1.

The bearing capacity of a single pile was first estimated using CPT-derived parameters. The resulting values were then incorporated into pile group analyses to determine group bearing capacity and allowable capacity. In addition, pile efficiency was evaluated for each configuration to quantify the interaction effects among piles within a group. Comparative analysis was subsequently conducted to identify the configuration that produced the most favorable combination of efficiency and load-bearing performance

The analysis results were organized and compared using descriptive and quantitative evaluation techniques. The relationships between pile arrangement, pile efficiency, and group bearing capacity were examined to determine how subsurface information obtained from CPT investigations can support foundation design decisions. The methodological framework adopted in this study emphasizes the integration of geotechnical survey data with foundation performance assessment, thereby demonstrating the role of engineering surveying in evidence-based subsurface characterization and infrastructure planning.

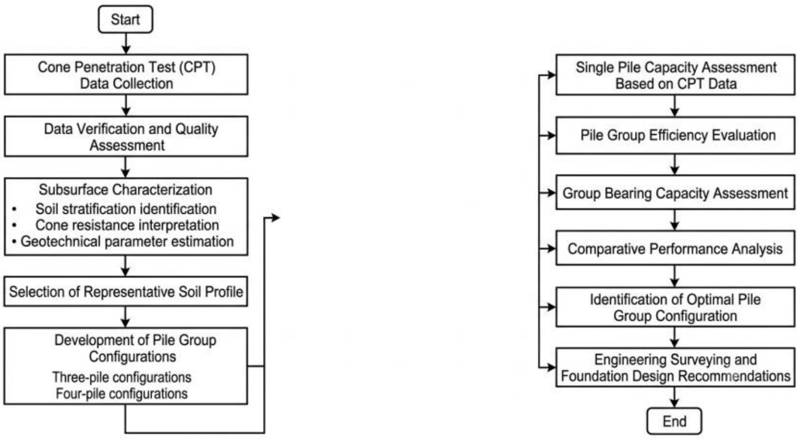

Figure 1. Research Workflow for CPT-Based Subsurface Characterization and Pile Group Performance Evaluation.

3. Results and Discussion

The Cone Penetration Test (CPT) data were first interpreted to characterize the subsurface conditions relevant to pile foundation design. The investigation indicated the presence of relatively weak near-surface soil layers characterized by low cone resistance values, followed by denser strata at greater depths. This variation in soil resistance confirms the importance of subsurface characterization in determining appropriate foundation systems and evaluating pile performance. The interpreted CPT profile used in this study is presented in Figure 2.

Based on the interpreted CPT data, the bearing capacity of a single pile was evaluated using the selected design parameters. The analysis produced a single-pile ultimate bearing capacity of 83.75 tons and an allowable bearing capacity of 27.91 tons. These values served as the basis for subsequent pile group analyses. Since all pile group configurations employed identical pile dimensions and were assessed under the same subsurface conditions, variations in group performance were primarily attributed to differences in pile arrangement and pile interaction effects.

To investigate the influence of pile arrangement on foundation performance, several pile group configurations consisting of three and four piles were analyzed. The evaluated configurations are illustrated in Figure 3.

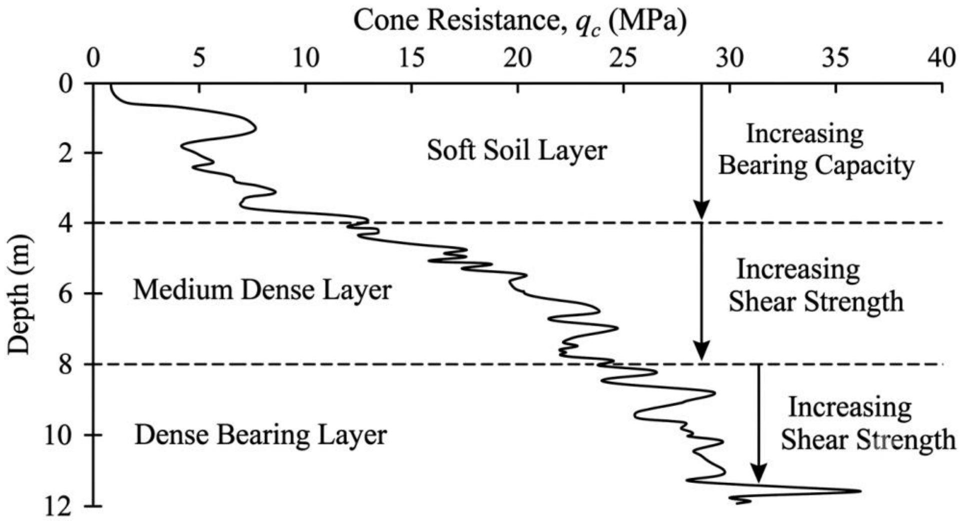

Figure 2. Representative CPT-Based Subsurface Characterization Profile

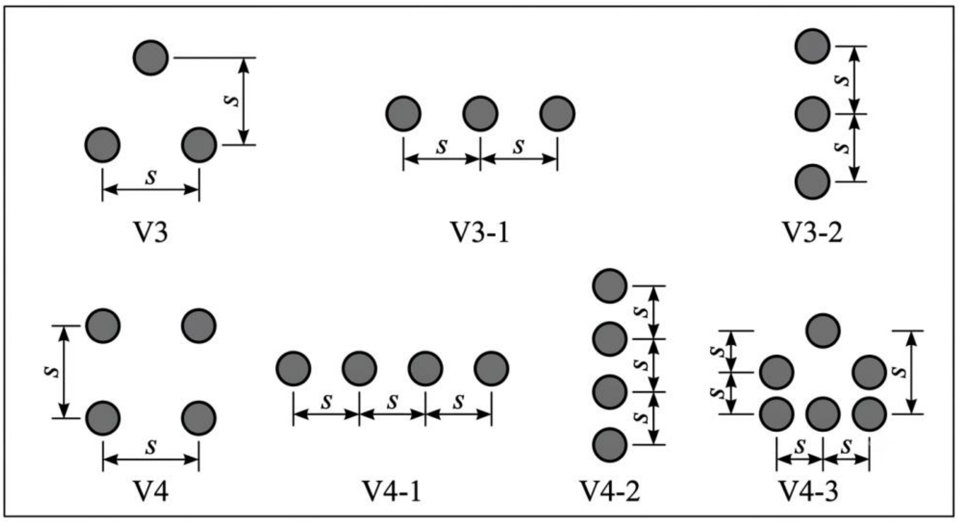

Figure 3. Evaluated Three-Pile and Four-Pile Group Configurations

The calculated pile efficiency and group bearing capacity values for the three-pile configurations are summarized in Table 1. The results demonstrate that pile arrangement significantly affects pile efficiency and, consequently, the overall load-bearing capacity of the pile group.

Table 1. Performance of Three-Pile Configurations

Configuration	Pile Efficiency (Eg)	Group Bearing Capacity (Qg), ton	Allowable Group Capacity (Qga), ton
V3	0.817	205.27	68.42
V3-1	0.861	216.32	72.1
V3-2	0.861	216.32	72.1

As shown in Table 1, the V3-1 and V3-2 configurations achieved the highest efficiency value of 0.861. This increase in efficiency resulted in a group bearing capacity of 216.32 tons and an allowable capacity of 72.10 tons. Compared with the conventional V3 arrangement, the improved configurations provided an increase of approximately 5.4% in allowable group capacity. These findings indicate that pile spacing and geometric arrangement play a critical role in minimizing negative pile interaction and enhancing load transfer efficiency. The results obtained for the four-pile configurations are presented in Table 2. Similar trends were observed, where differences in pile arrangement produced measurable variations in efficiency and bearing capacity despite identical subsurface conditions.

Table 2. Performance of Four-Pile Configurations

Configuration	Pile Efficiency (Eg)	Group Bearing Capacity (Qg), ton	Allowable Group Capacity (Qga), ton
V4	0.817	273.69	91.23
V4-1	0.844	282.74	94.24
V4-2	0.844	282.74	94.24
V4-3	0.756	253.26	84.42

Table 2 shows that the V4-1 and V4-2 configurations produced the highest pile efficiency value of 0.844 and the highest allowable group capacity of 94.24 tons. In contrast, the V4-3 configuration yielded the lowest efficiency value of 0.756, resulting in a substantial reduction in group bearing capacity. The difference of nearly 10 tons in allowable capacity between the best and least efficient configurations demonstrates the significant influence of pile arrangement on foundation performance. To facilitate comparison between all evaluated configurations, the relationship between pile efficiency and allowable group bearing capacity is illustrated in Figure 4.

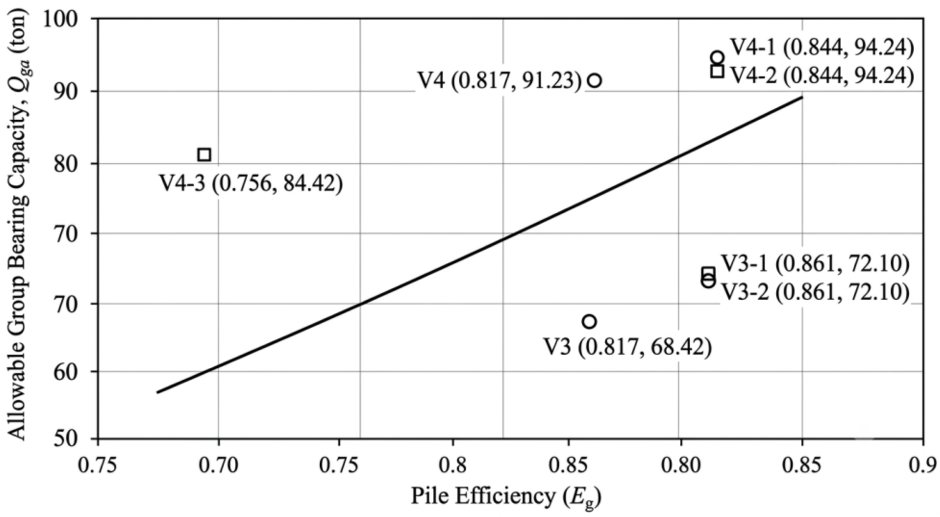

Figure 4. Relationship Between Pile Efficiency and Allowable Group Bearing Capacity

The comparison presented in Figure 4 reveals a clear positive correlation between pile efficiency and allowable group bearing capacity. Configurations exhibiting higher efficiency factors consistently generated greater load-bearing capacities. This behavior reflects the reduction of adverse interaction effects among piles when more favorable geometric arrangements are adopted. The findings further demonstrate that efficient pile layouts can improve foundation performance without increasing the number of piles or modifying pile dimensions.

From the perspective of engineering surveying, the results emphasize the importance of integrating CPT-based subsurface characterization into foundation planning. The ability of CPT investigations to provide continuous soil resistance data enables more reliable estimation of pile capacity and facilitates objective comparison of alternative pile group arrangements. Rather than relying solely on conventional design assumptions, the use of subsurface survey information supports evidence-based decision-making during the foundation design process.

The findings of this study indicate that pile group configuration is a key parameter affecting foundation performance under identical subsurface conditions. Configurations with higher pile efficiency factors consistently produced greater allowable capacities, highlighting the value of combining geotechnical survey data with pile group optimization. This integrated approach contributes to more effective foundation design and demonstrates the practical role of subsurface characterization in engineering surveying applications.

4. Conclusion

This study evaluated the influence of pile group configuration on pile efficiency and bearing capacity using subsurface information derived from Cone Penetration Test (CPT) data. The results demonstrate that CPT-based subsurface characterization provides reliable geotechnical information for assessing foundation performance and comparing alternative pile group arrangements under similar soil conditions.

The analysis revealed that pile group configuration significantly affects both pile efficiency and group bearing capacity. For the three-pile configurations, the highest efficiency value was obtained by the V3-1 and V3-2 arrangements, with an efficiency factor of 0.861 and an allowable group bearing capacity of 72.10 tons. For the four-pile configurations, the V4-1 and V4-2 arrangements achieved the best performance, producing an efficiency factor of 0.844 and an allowable group bearing capacity of 94.24 tons. In contrast, configurations with lower efficiency factors exhibited reduced load-bearing capacity, confirming the importance of pile arrangement in foundation design.

The findings indicate a positive relationship between pile efficiency and allowable group bearing capacity, where higher efficiency values consistently result in improved foundation performance. These results highlight that optimizing pile group geometry can enhance load-bearing capacity without increasing the number of piles or modifying pile dimensions.

From an engineering surveying perspective, the study demonstrates the value of integrating CPT-based subsurface characterization into foundation planning and design. The use of geotechnical survey data enables more informed and evidence-based decisions regarding pile group selection and foundation performance evaluation.

Future research is recommended to incorporate additional geotechnical investigation methods, settlement analysis, and numerical modeling approaches to further improve the accuracy of pile group performance assessment under varying subsurface conditions.

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[24] Literature synthesis of recent CPT-based subsurface characterization, soil classification, and pile foundation performance studies used to establish the research gap and motivation of the present study.