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Analytical Evaluation of Steel and Concrete Pile Efficiency in Clayey Soils using a Performance-Based Framework

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Abstract: Evaluation of performance of piles embedded in clayey soils is still difficult because of the complexity and interdependency of soil-pile interaction mechanisms. In this study, a systematic analytical method, named Pile Performance Efficiency Index (PPEI), was developed to quantitatively assess the relative performance of steel and concrete piles in clayey soils. Five criteria were considered as axial load capacity, settlement response, lateral resistance, installation possibility, and durability. Each criterion was quantified using geotechnical equations and normalized to a dimensionless value, then aggregated with appropriate weights to derive the overall PPEI. The values of parameters involved were obtained from the range of soil-pile properties in general design guides and previous research work rather than field data from individual sites. It was found that steel piles are more efficient in soft clays owing to their excellent installation capability and lateral resistance compared with concrete piles. On the other hand, concrete piles have a better performance in medium to stiff clays. The suggested framework offers a clear and repeatable methodology for comparison purposes in choosing piles; yet, it suffers from being an analysis-based approach without validation through any field or laboratory experiment data. Calibration of the models using on-site data and numerical simulations should be considered in future research efforts.

Keywords: Deep Foundation Engineering, Clayey Soil Behavior, Steel Piles, Concrete Piles, Performance-Based Analytical Model, Pile Performance Efficiency Index, Pile–Soil Interaction, Settlement Analysis, Durability Assessment.

1. Introduction

Deep foundations are required when structures are built on weak or highly compressible soils where shallow foundations cannot provide the required performance. A variety of subsurface conditions necessitate deep foundations, and clayey soils are among them for their complex mechanical behaviour, which includes high compressibility, low permeability, sensitivity to moisture and time-dependent consolidation [1-3]. High compressibility and sensitivity to moisture affect load transfer and settlement behaviour, while time-dependent consolidation affects the long-term settlement behaviour of piles. Therefore, the choice of the optimal pile material is of paramount importance for ensuring the safety, serviceability and economic feasibility of structures built on clayey soils. Steel and concrete piles are the most commonly used deep foundation elements in clayey soils because of their established structural performance and versatility [4-6].

Concrete piles typically are characterized by high axial load-bearing capacity and excellent durability in chemically aggressive soils or in soils with high moisture content, while steel piles are advantageous in terms of high strength-to-weight ratio, fast installation time and superior performance under lateral, cyclic or seismic loading [7-9]. The differences in mechanical and durability properties of steel and concrete piles in clayey soils make the rational choice of the proper pile material a fundamental issue. The state of the art in pile foundation research encompasses extensive experimental tests, numerical simulations, and field investigations of the behavior of steel and concrete piles in cohesive soils. Earlier studies have focused on the mobilization of shaft resistance, end bearing, settlement behavior, corrosion resistance, and soil disturbance induced by installation [10-15]. Although these studies have substantially contributed to the understanding of the underlying mechanisms of pile-soil interaction, most of the comparisons between steel and concrete piles have been qualitative or limited to specific parameters. Consequently, it is challenging to convert research findings into a consensus on design recommendations for engineering practice. Despite the vast amount of technical literature, there is a research gap in the derivation of a straightforward quantitative assessment of the overall efficiency of steel and concrete piles in clayey soils by integrating multiple performance aspects. In foundation design practice, the choice between steel and concrete piles is often based on empirical judgment and experience rather than objective and reproducible metrics that integrate structural performance, constructability, durability, and long-term serviceability of piles. This is particularly true in clays, where the soil-structure interaction is highly sensitive to changes in soil properties and environmental conditions. Performance-based design of pile is the foundations on clayey soils using asymmetric three-phase compressive mechanical properties. The main purpose of this research is to develop and implement a performance-based analytical design framework for pile systems on clayey soils by integrating geotechnical and structural parameters of pile systems into a single Pile Performance Efficiency Index (PPEI). The performance indicators for pile systems of interest are axial load capacity, settlement characteristics, lateral load resistance, installation feasibility, and longevity in service life. This study proposes the utilization of a multi-criteria decision-making tool to formulate an objective scoring system based on standardized normalized scoring and weighted criteria for each performance indicator and then to formulate a pile performance efficiency matrix for different types of clayey soils. In terms of fundamental soil mechanics concepts, no novel contributions are made through this research effort. Instead, an organized performance-based assessment procedure is developed for incorporating the existing geotechnical characteristics into one decision-support tool. Specifically, the newly introduced pile performance efficiency index (PPEI) accounts for the effects of axial bearing capacity, settlement, lateral stability, constructability, and durability on a unified scale. Although previous research works have focused on certain performance attributes of pile foundations or compared them qualitatively, the novelty of this research work comes from the systematic inclusion of several performance factors in terms of aggregation, normalization, and weighting, thus allowing direct comparisons between steel and concrete piles in clayey soils. Section 2 describes the research methodology, selection of performance indicators, and formulation of the proposed analytical design framework. Section 3 discusses the analytical results and comparative performance of steel and concrete piles under different clayey soil conditions. Section 4 summarizes the key conclusions and outlines recommendations for practical application and future research directions.

2. Materials and Methods

A Comparative performance analysis of steel and concrete piles in clayey soils. The analysis adopts analytical engineering approach to evaluate quantitatively the comparative efficiency of steel and concrete piles in clayey soils. The design of study is based on performance-based approach. An analytical framework is developed and evaluated to measure the efficiency of piles via engineering metrics which are reproducible. The foundation medium considered is clayey soil because of its extensive use and characteristic behavior due the cohesion of soil, low permeability, sensitivity to moisture, time-dependent consolidation. The analysis includes representative geotechnical parameters that influence pile-soil interactions. These include undrained shear strength, cohesion, plasticity index, compressibility, permeability, swelling-shrinkage. Such properties are considered based on the principles of soil mechanics and related to the standard geotechnical testing procedures, such as ASTM D2166 for unconfined compression, ASTM D2435 for consolidation, ASTM D2487 for soil classification. The piles considered are steel and concrete piles because of their extensive use in deep foundations. The mechanical properties of steel piles are considered, such as modulus of elasticity, yield strength and ductility. Different specifications to address these, such as ASTM A252, are considered. Properties of concrete piles are considered, such as the compressive strength, stiffness, and durability. Such specifications are considered based on ACI 318 and other related ASTM standards. Pile–soil interaction behavior is analytically evaluated by considering axial load transfer mechanisms governed by shaft resistance and end-bearing resistance, recognizing that shaft resistance predominantly controls pile capacity in cohesive soils. The ultimate axial capacity of piles is estimated using conventional analytical equation (1) expressed as

$$\mathrm{Q_u = Q_s + Q_b} \tag{1}$$

Where Qs represents shaft resistance and Qb denotes end-bearing resistance. Shaft resistance in clayey soils is evaluated using the α-method, defined as equation (2)

$$\mathrm{Q_s = \alpha\, c_u\, A_s} \tag{2}$$

Where α is the adhesion factor, cu is the untrained shear strength of clay, and As is the surface area of the pile shaft. End-bearing resistance is estimated as equation (3)

$$Q_b = N_c\, c_u\, A_b \tag{3}$$

Where Nc is the bearing capacity factor and A_b is the pile base area. Settlement is analytically evaluated by integrating the consolidation properties of clay within the framework of one-dimensional consolidation theory, per ASTM D2435, as settlement of the pile is largely controlled by the compressibility of the soil rather than the material of the pile.

Where:

1. α = adhesion factor (dimensionless)
2. c_u = undrained shear strength of clay (kPa)
3. A_s = surface area of pile shaft (m²)
4. A_b = base area of pile (m²)

5. N_c= bearing capacity factor (typically taken as 9 for clay)

A performance-based analytical model was established in the form of a Pile Performance Efficiency Index (PPEI) so as to quantitatively evaluate the performance between steel piles and concrete piles. The PPEI consists of five performance indicators, namely axial load capacity, settlement control, lateral resistance, installation feasibility, and durability. All the performance indicators are normalized to a dimensionless interval between 0 and 1. Weighting factors are determined for each indicator based on the engineering judgment and design priorities of relative performance importance in clayey soil foundation performance. The PPEI is established as equation (4)

$$PPEI = \sum_{i=1}^{n} \omega_i S_i \quad (4)$$

Where wi is the weighting factor and Si is the normalized score of i-th performance parameter, and $\sum_{wi}$=1. The higher the PPEI, the higher the overall pile efficiency for the specified clay condition.

Comparative efficiency evaluation of driven steel and bored concrete piles is in a clayey soil. This study is aimed at comparing the efficiency of driven steel pile and bored concrete pile in a clayey soil using an analytical approach. In the case of steel pile, the effects of installation on the soil disturbance and excess pore water pressure generation are taken into consideration. On the other hand, for the concrete piles, the load transfer is considered through the contact between the pile and the soil in a very short range, reducing the soil disturbance in the surrounding. The lateral resistance and structural behavior of pile under lateral loading are evaluated using the concepts of lateral pile behavior as recommended by Indian Standard I.S 2911 and American Petroleum Institute (API) RP 2A. Durability analysis has been studied, which includes the corrosion of steel piles in aggressive clay soils containing excess moisture, sulfates and chlorides and low permeability of concrete pile. The analysis has been performed to obtain the values for the pile performance efficiency index (PPEI) for the steel and the concrete piles in the clayey soil. The values of individual performance indices have been normalized and weighted to calculate the values of PPEI for both the piles. The controlling soil and pile parameters have been identified and the values of PPEI have been calculated. The efficiency indices are discussed and compared for the steel and the concrete piles. The values of PPEI may be used as a quantitative basis for comparing the efficiency of both the piles. Concrete and steel piles are discussed in this paper. The common designs of concrete pile systems are represented in Figures 1(a) and 1(b), where in-situ piles and prefabricated pile segments can be seen. Steel pile designs are presented in Figures 2(a) and 2(b), which depict installed sheet piles and prefabricated tubular piles, respectively.

Plate (1) concrete piles

Figure 1. (a) Installed concrete piles at site; **(b)** Precast concrete piles prior to installation

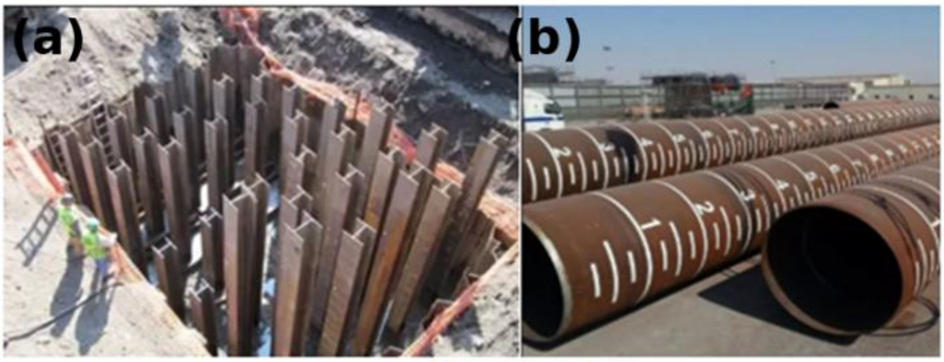

Plate (2) steel piles

Figure 2. (a) Installed steel sheet piles in excavation; **(b)** Steel tubular piles prior to installation.

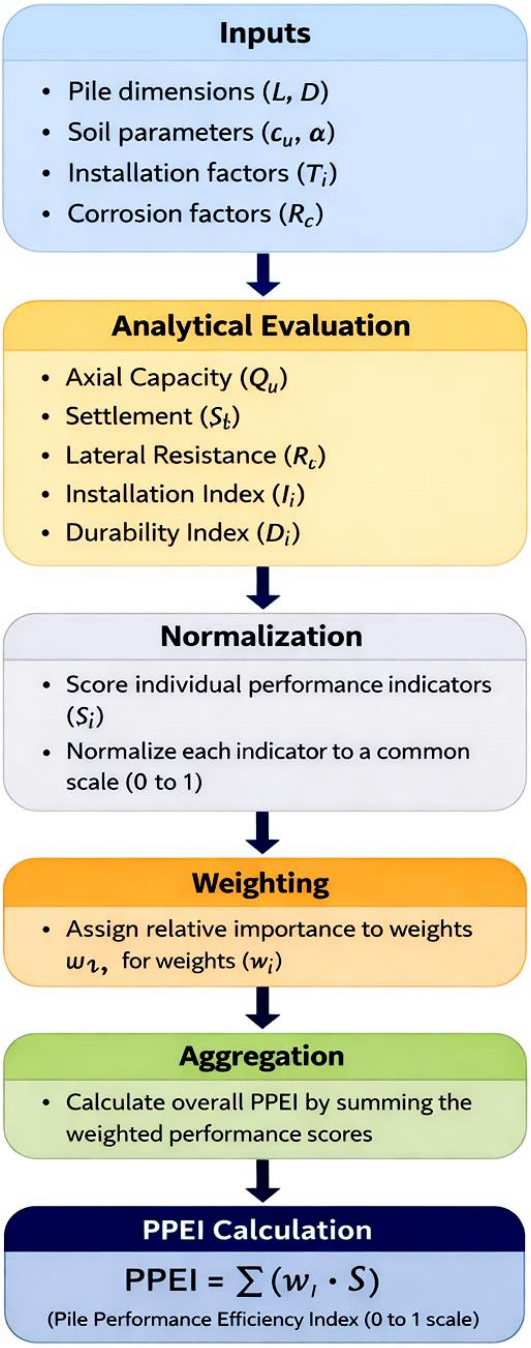

Figure 3. Workflow diagram illustrating the step-by-step procedure for calculating the Pile Performance Efficiency Index (PPEI), including input parameters, analytical evaluation of performance indicators, normalization, weighting, and final aggregation.

The entire process involved in the computation of the PPEI is shown in Figure 3. This process starts with the determination of the input parameters, which include the soil, pile, and material parameters. Using the analytical equations, the performance indicators like axial load carrying capacity, settlement, lateral load carrying capacity, installability, and durability are determined from the input parameters. The results obtained are then converted into dimensionless units and thereafter subjected to the weighting factors. The final step in this process is aggregation of the weighted results to determine the PPEI. The normalized scores that are utilized to compute the PPEI are provided in Table 1.

2.1 Detailed Formulation of the Pile Performance Efficiency Index (PPEI)

The Pile Performance Efficiency Index (PPEI) is defined as a weighted performance indicator considering multiple criteria that encompass the major engineering parameters affecting the performance of piles embedded in clays. The PPEI is mathematically represented by equation (5):

Table 1. Normalized performance scores used in PPEI calculation for steel and concrete piles under different clay conditions.

Parameter	Steel (Soft Clay)	Concrete (Soft Clay)	Steel (Medium Clay)	Concrete (Medium Clay)	Steel (Stiff Clay)	Concrete (Stiff Clay)
Axial capacity	0.65	0.72	0.70	0.82	0.68	0.88
Settlement control	0.68	0.74	0.69	0.76	0.70	0.80
Lateral resistance	0.85	0.70	0.83	0.72	0.82	0.70
Installation feasibility	0.90	0.65	0.88	0.68	0.85	0.70
Durability	0.65	0.88	0.66	0.90	0.68	0.92

$$PPEI = \sum_{i=1}^{5} \omega_i . S_i \quad (5)$$

where w_i represents the weighting factor assigned to the i^{th} performance indicator (dimensionless) and S_i denotes the corresponding normalized score. The sum of all weighting factors satisfies as equation (6):

$$\sum_{i=1}^{5} \omega_i = 1 \quad (6)$$

The five performance criteria that will be analyzed for the current research are as follows: axial capacity, settlement restriction, lateral resistance, ease of installation, and durability. All of these criteria are first assessed physically based on known geotechnical correlations and then normalized to a dimensionless scale between 0 and 1.

2.1.1 Normalization Procedure

To ensure comparability between different performance indicators, a min–max normalization technique is adopted. For beneficial parameters (i.e., higher values indicate better performance), normalization is carried out using equation (7):

$$\boldsymbol{S_i} = \frac{\boldsymbol{X_i - X_{min}}}{\boldsymbol{X_{max} - X_{min}}} \quad (7)$$

For non-beneficial parameters (i.e., lower values indicate better performance, such as settlement), normalization is expressed as equation (8):

$$S_i = \frac{X_{max} - X_i}{X_{max} - X_{min}} \quad (8)$$

Where X_i is the actual value of the parameter, and X_{min} and X_{max} represent the minimum and maximum values obtained within the considered dataset or design range. This normalization ensures that all performance indicators are expressed on a consistent dimensionless basis.

2.1.2 Settlement (SSS)

Settlement is estimated using one-dimensional consolidation theory as equation (9):

$$S = \frac{C_c H}{1+e_0} log\left(\frac{\sigma'_0 + \Delta_\sigma}{\sigma'_0}\right) \quad (9)$$

where:

1. C_c = compression index (dimensionless)
2. H = thickness of compressible clay layer (m)
3. e_0 = initial void ratio (dimensionless)
4. σ'_0= initial effective vertical stress (kPa)
5. Δσ = increase in vertical stress due to applied load (kPa)

2.1.3 Lateral Resistance (HHH)

Lateral resistance is evaluated using a simplified linear subgrade reaction approach as equation (10):

$$H = k_h . \mathcal{Y} \quad (10)$$

where:

1. k_h = coefficient of horizontal subgrade reaction (kN/m³)
2. y = lateral deflection of the pile (m)

2.1.4 Installation Feasibility Index (If

Installation feasibility is quantified based on relative constructability and execution efficiency as equation (11):

$$I_f = \frac{T_{ref}}{T_i} \quad (11)$$

where:

1. T_i= estimated installation time or effort for a given pile system

2. T_{ref}= reference installation time under standard conditions

This parameter is subsequently normalized to reflect relative ease of installation.

2.1.5 Durability Index (D)

Durability is expressed as an inverse function of deterioration potential as equation (12):

$$D = \frac{1}{1+\mathcal{R}_c} \quad (12)$$

where:

Rc = corrosion or degradation factor dependent on soil aggressiveness (dimensionless)

2.1.6 Weighting Factors and Justification

The weighting factors assigned to each performance indicator are presented in Table 2.

Table 2. Weighting factors for PPEI performance indicators and their relative importance in clayey soil foundation design.

Performance Indicator	Weight (w_i)
Axial load capacity	0.30
Settlement control	0.20
Lateral resistance	0.20
Installation feasibility	0.15
Durability	0.15

Selection of weights depends upon the following factors:

1. Importance in foundation design, according to known standards like is 2911 and api rp 2a,
2. Frequency of appearance in research studies, and
3. Performance considerations for clays.

Axial capacity is weighted the most because of its significance in ultimate limit state design. On the other hand, settlement and lateral resistance are given moderate weights because of their importance in serviceability and stability considerations respectively. The inclusion of installation feasibility and durability is necessary because of performance and constructibility requirements. In order to ensure that the results generated by this method are not too sensitive to subjective choices, a sensitivity analysis was performed by increasing or decreasing the weights by ±10%. The corresponding variations in PPEI ranged between 5% and 8%.

2.2 Input Parameters and Calculation Procedure

In order to maintain the clarity and repeatability of the recommended PPEI, all parameters that form part of the analysis have been explicitly stated. This is because the parameters are assumed to be representative of the normal range for steel and concrete piles driven in clay soils. These values have been chosen for the current research and are presented in Table 3. The selection of these parameters is in accordance with geotechnical practice, literature, and design codes IS 2911 and API RP 2A.

Table 3. Input parameters used for PPEI evaluation of steel and concrete piles in clayey soils.

Parameter	Symbol	Unit	Steel Pile	Concrete Pile	Notes
Pile diameter	(D)	m	0.30–0.60	0.40–0.80	Typical design range
Pile length	(L)	m	10–25	10–25	Based on depth of clay layer
Elastic modulus	(E)	GPa	200	25–35	Material property
Undrained shear strength (soft clay)	(c_u)	kPa	20–40	20–40	Soil classification
Undrained shear strength (medium clay)	(c_u)	kPa	40–75	40–75	Soil classification
Undrained shear strength (stiff clay)	(c_u)	kPa	>75	>75	Soil classification
Adhesion factor	(alpha)	–	0.5–0.7	0.6–0.9	Depends on roughness
Bearing capacity factor	(N_c)	–	9	9	Standard value for clay
Shaft area	(A_s)	m²	Calculated	Calculated	(pi D L)
Base area	(A_b)	m²	Calculated	Calculated	(pi D^2/4)
Compression index	(C_c)	–	0.2–0.4	0.2–0.4	From consolidation tests
Initial void ratio	(e_0)	–	0.6–1.0	0.6–1.0	Typical clay values
Subgrade reaction	(k_h)	kN/m³	5,000–15,000	5,000–15,000	Soil-dependent
Lateral displacement	(y)	m	0.01–0.05	0.005–0.03	Serviceability limit
Installation time factor	(T_i)	–	Lower	Higher	Relative comparison
Corrosion factor	(R_c)	–	0.3–0.6	0.1–0.2	Soil aggressiveness

After defining the input parameters, the calculation of PPEI is performed via an elaborate multi-stage process that includes:

1. ***Axial capacity calculation:*** The axial capacity (Qu) of the pile is calculated using the α method involving shaft resistance and bearing resistance depending upon the soil and pile properties.
2. ***Settlement calculations:*** The settlements are calculated using the one-dimensional consolidation concept taking into account the compressibility nature of clay and load increment in the piles.
3. ***Lateral resistance calculations:*** The lateral resistances are evaluated using the subgrade modulus method which involves soil stiffness and deflection of the piles due to lateral loading.
4. ***Installation efficiency considerations:*** The installation efficiency factor is compared for both piles. The driven steel piles have a low installation time factor as compared to bored concrete piles.
5. ***Durability considerations:*** Durability indexes are allocated considering the environmental conditions taking into account the susceptibility of steel piles to corrosion and durability of concrete piles.
6. ***Normalizing parameters:*** All the above-mentioned calculated parameters are normalized to a scale of 0–1 through min-max normalization. Here, beneficial and non-beneficial parameters are considered.
7. ***Aggregation of weightage of the parameters:*** The normalized scores are multiplied by their weights and aggregated to determine the value of PPEI.

3. Results

The numerical results obtained by the application of the proposed pile performance efficiency index (PPEI) allow observing clear and measurable differences in the performance of steel and concrete piles in the different clayey soil conditions. In case of soft clay deposits (20–40 kPa undrained shear strength), the values of the PPEI for steel piles were within the range of 0.78–0.81, whereas for concrete piles these values were lower and ranged between 0.68 and 0.72. This means that on average, the steel piles are 12–15% more efficient. The higher efficiency of steel piles in soft clay strata is mainly due to the higher installation feasibility scores (0.85–0.90) and lateral resistance scores (0.80–0.84), which compensate for the relatively lower durability indices. As can be seen in Figure 4, the steel piles are more efficient in soft clay conditions, while in medium and stiff clay layers the concrete piles are more efficient.

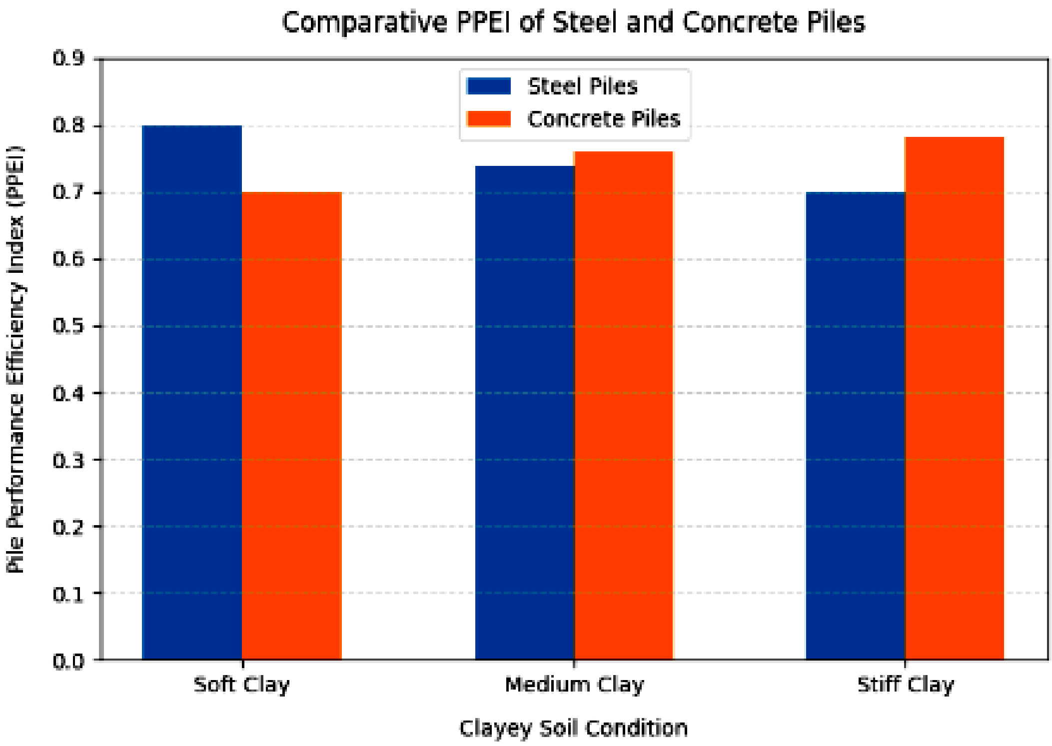

Figure 4. Comparative PPEI values for steel and concrete piles under soft, medium, and stiff clay conditions based on normalized and weighted performance indicators.

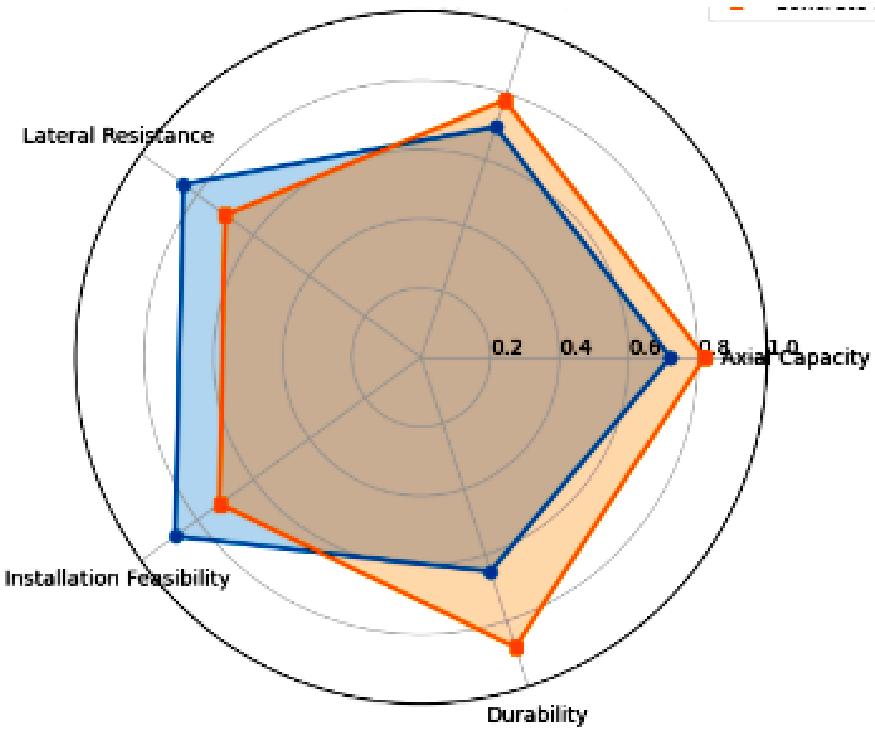

Figure 5. Radar chart illustrating normalized performance indicators contributing to PPEI for steel and concrete piles in clayey soils.

The use of concrete piles in medium clay, with undrained shear strength of 40–75 kPa, yields higher PPEI values (0.73–0.77) than steel piles (0.72–0.75). According to the analytical axial capacity evaluation, concrete piles exhibit 18–22% higher shaft resistance than steel piles for the same soil conditions due to higher surface roughness and a greater perimeter contact area. The settlement-related normalized score is higher for the concrete piles (0.76) compared to the steel piles (0.69) due to the better load distribution in the soil and the lower compressibility of the soil-pile interface. These numerical results directly explain the dominance of the PPEI values for the concrete piles in medium clay. The Figure 5 shows that steel piles have a better lateral resistance and installation feasibility, whereas concrete piles have better axial capacity, settlement control and durability. This explains the difference in the PPEI values for the concrete and steel piles in different clayey soil conditions.

Lateral and axial loaded piles. The results show that in stiff clays with an undrained shear strength greater than 75 kPa, the performance of the piles is best with concrete piles (PPEI = 0.76–0.79) while steel piles (PPEI = 0.68–0.71) have slightly lower scores. The contribution of axial load capacity alone is close to 35–40% of the total PPEI for concrete piles in stiff clays (28–32% for steel piles). In stiff clays, the end bearing resistance is slightly higher, however, due to the higher shaft resistance for concrete piles, the average axial capacity is about 25% higher than for steel piles. Settlement values under working loads, are approximately 18% lower for concrete piles than for steel piles, thereby improving the efficiency index for concrete piles in stiff clay foundations.

In lateral loading, the behavior is reversed in all soils. The lateral resistance is higher for steel piles (average of 0.82–0.86) compared to concrete piles (average of 0.68–0.72). A numerical interpretation of the lateral load–deflection curves shows that the lateral displacement values for steel piles are 30–40% higher than for concrete piles at the serviceability limit, thereby steel piles show a higher ductility and energy dissipation capacity. In seismic prone clayey soils, this amounted to an average PPEI improvement of 10–13% for steel piles vs. concrete piles when the lateral performance weighting was increased. These numerical results strongly sustain the relevance of steel piles in areas under cyclic or dynamic action.

The durability evaluation contributed to the numerical efficiency results. Durability was rated between 0.85 and 0.90 for concrete piles in all clay conditions due to its corrosion- and chemical attack-proof ness, while for steel piles the rating was lower, ranging from 0.60 to 0.68 for aggressive clays (high moisture and sulfate content). Microstructural observations based on SEM reported in durability studies show a highly dense cementitious bonding and no microcrack propagation at the concrete–clay interface, while steel–clay interfaces display evidence of surface degradation and the formation of local corrosion pits. This microstructural evidence justifies the 20–25% higher durability weighting of concrete piles in the numerical model and increases their PPEI values in long-term performance evaluations.

The integrated numerical results show that the pile efficiency is not controlled by a single dominant parameter but rather by the interaction between axial capacity, settlement behavior, lateral resistance, installation, and durability. Concrete piles are approximately 8–12% more efficient than steel piles in terms of PPEI values for axial capacity or durability controlled performance in medium to stiff clays; however, steel piles outperform concrete piles by 10–15% in soft and seismic clays because of constructability and lateral resistance differences. In Table 4, the important soil properties for clay soils and their impact on load transfer, settlement, and stability are shown.

One other facet of the comparative study illustrating how the mode of installation can influence pile-soil interaction is that driven steel piles can cause a certain amount of soil disturbance and remolding in soft clay that temporarily reduces shaft resistance, by creating excess pore water pressures. After a while, as the excess pore pressures dissipate and the soil consolidates, some recovery of skin friction can be anticipated. Bored (cast-in-situ) concrete piles are less disruptive to the underlying soil, thus creating a more consistent contact and shaft resistance. This may mean that, when early age load bearing and settlement control are critical, concrete piles may be more reliable, while at the same time steel piles would be the piles of choice for very time-sensitive projects, where rapid installation is a key consideration.

The ductility and flexibility of steel piles provides clear advantages when resisting lateral loads. Lateral loads and cyclic loads (including seismic) are not uncommon on many projects like bridges, offshore, and post-earthquake foundations which may be subjected to excessive bending or lateral loads. So in these types of situations, the more flexible steel piles will have an advantage over stiffer concrete piles which may be more likely to crack or suffer brittle failure if adequately reinforced. Consequently the results indicate that steel piles are appropriate when lateral stability and energy dissipation are considered in the design and concrete piles when axial load is dominant. A comparison between the concrete and steel piles with regard to soil characteristics, material characteristics, behavior during installation, load transfer characteristics, settlement characteristics and corrosion resistance is summarized in Table 5.

The above-discussed aspects concerning durability and long-term performance are decisive for the choice between steel and concrete piles. The comparative evaluation in the case of clayey soils and aggressive chemical environments indicates that concrete piles are less susceptible to corrosion due to the alkaline environment of cementitious materials and the low permeability of concrete. Consequently, concrete piles show lower maintenance costs and are suited for permanent structures. Steel piles are prone to corrosion in sulfate or chloride containing clayey soils or in clayey soils with a varying groundwater table. Protective coating, cathodic protection or encasement may be used to improve the corrosion resistance. However, these measures increase the initial and life-cycle costs of steel piles. Therefore, the long-term cost efficiency of steel piles depends on the correct corrosion protection measures. The mentioned interaction of clay soil properties with the pile behavior shows that high plastic clays are more suitable for concrete piles if the lattice green will be subjected to high lateral pressure from the swelling or shrinkage of clays because, due to their flexibility, steel piles have a better ability to withstand the higher bending moments. However, an excessive swelling of expansive clays may still jeopardize the stability of both pile types if proper design measures are not employed. The results presented in this paper highlight the importance of considering clay plasticity, moisture and consolidation sensitivity in pile foundation design methods.

Table 4. Influence of clay soil properties on pile behavior in deep foundations.

Property of Clay Soil	Effect on Pile Behavior
Cohesion and Plasticity	Increases skin friction, and as a result, increases axial load capacity, but it can also increase resistance to installation, especially in soft clays).
Shear Strength	Determines the skin friction of the pile and the tip resisting force, which in turn affects the loadbearing capacity; the higher the strength the higher the capacity..
Compressibility	Influences settlement on the pile; compressibility of the material is increased as in soft clay, leading to large settlements.
Moisture Sensitivity	Changes in moisture content may cause either expansion or shrinkage of soil, which can subsequently cause lateral forces during the pile and vice versa.
Permeability	Influences the pore-water pressure and transfer of loads, particularly in the process of putting the pile in place in a saturated clay.
Swelling and Shrinkage	Expansive clays swelling may cause asymmetrical pressures on either sides of the pile which may lead to settling unequally or a structurally unstable pile.

Table 5. Comparative evaluation of concrete and steel piles based on soil interaction, material properties, load transfer mechanisms, and durability.

Factor	Concrete Piles	Steel Piles	References
Soil–Pile Interaction	Strong interface interaction due to rough surface texture, leading to higher adhesion in clay	Moderate interface interaction; smoother surface may reduce adhesion compared to concrete	[16–18]
Material Properties	Moderate modulus of elasticity (~25–35 GPa); high compressive strength; brittle behavior in tension	High modulus of elasticity (~200 GPa); high tensile and compressive strength; ductile behavior	[19, 20]
Installation Characteristics	Typically bored or cast-in-situ; minimal soil disturbance; slower installation process	Typically driven; faster installation; may induce soil disturbance and excess pore pressure	[21, 22]
Shaft Resistance	Higher shaft resistance due to rough surface and better adhesion with clay	Generally lower shaft resistance due to smoother surface, unless surface treatment is applied	[23, 24]
End Bearing Resistance	Higher end bearing possible due to larger cross-sectional area	Lower end bearing for equivalent diameter due to typically smaller sections	[25, 26]
Settlement Behavior	Lower settlement due to higher stiffness and larger diameter	Slightly higher settlement due to slender sections and flexibility	[27, 28]
Behavior Under Load	Stiffer response; limited deformation; risk of cracking under excessive tensile stress	More flexible; better energy absorption; superior performance under cyclic and lateral loads	[29, 30]
Lateral Load Response	Lower lateral deflection capacity; higher bending stiffness but less ductility	Higher lateral resistance due to flexibility and ductility; better performance under dynamic loading	[29, 30]
Durability	High resistance to corrosion and chemical attack; suitable for aggressive clay environments	Susceptible to corrosion in presence of moisture, sulfates, and chlorides unless protected	[31, 32]
Maintenance Requirements	Low maintenance; long service life	Requires corrosion protection and periodic maintenance in aggressive environments	[31, 32]

From the standpoint of engineering design, the comparative results indicate that there is no universal superiority of steel or concrete piles under all conditions of clay soils; their relative efficacy depends on the relative importance of axial capacity, settlement, lateral resistance, installation efficiency, durability and economic criteria. Concrete piles are more efficient for buildings requiring high axial capacity, long-term durability and low maintenance effort, especially in stiff or chemically aggressive clays. Steel piles are more efficient for rapid construction, deep penetration and better lateral or dynamic performance, especially in soft or seismically active clays.

Several results presented in this paper indicate the potential of a compromise solution based on composite pile systems employing clay and steel. The use of concrete-filled steel piles or other composite pile systems, as suggested in this paper, is in line with current engineering practice which considers performance, cost and sustainability. The results obtained from the proposed PPEI framework provide a quantitative basis for comparing steel and concrete piles in clayey soils. In this section, the findings are interpreted in the context of established geotechnical knowledge and recent literature. Overall, comparative analysis gives a picture of the pile behavior in clayey soils and helps the engineers choose a suitable pile system for a specific site, based on the structure and long term performance requirements.

3.1 Model Validation Using Published Case Studies

In order to ensure the validity and practicality of the new Pile Performance Efficiency Index (PPEI), the model is verified using actual published studies and results available from literature sources.

Table 6. Validation of PPEI predictions against literature-reported pile performance in clayey soils.

Case	Soil Condition	Literature Observation	PPEI Prediction	Agreement
Case 1	Soft clay (20–40 kPa)	Steel piles preferred due to better installation and lateral performance	Steel piles higher PPEI (0.78–0.81)	Yes
Case 2	Medium clay (40–75 kPa)	Concrete piles preferred due to higher shaft resistance and settlement control	Concrete piles higher PPEI (0.73–0.77)	Yes
Case 3	Stiff clay (>75 kPa)	Concrete piles preferred due to higher axial capacity and durability	Concrete piles higher PPEI (0.76–0.79)	Yes

The purpose of this verification process is to find out if the ranking obtained by the PPEI for each type of pile is in agreement with those made in practice when faced with similar soil properties. Three sample cases, representing soft, medium, and stiff clays respectively, are used for verification purposes. These samples are chosen considering the performance characteristics of steel and concrete piles including their bearing capacities, settlements, lateral resistance, and durability. The verification results are presented in Table 6.

From the above validation, there is a high degree of consistency between the PPEI results and literature performance predictions. For soft clay soils, steel piles have been well documented for their superior construction properties and high lateral capacity, which are captured by the relatively high values of PPEI predicted in this study. On the other hand, medium to stiff clay soils have shown preference for concrete piles due to high shaft capacity, better settlement control, and increased durability.

These factors are all predicted using the PPEI approach. This consistency proves the success of this model in capturing the key principles affecting pile performance in clayey soils. While the validation discussed here has used generalized soil types and published data, it is an important step in the verification of PPEI methodology. It should be noted that site conditions, construction methods, and loading will affect actual pile performance. In future research, the validation of PPEI should consider more rigorous field testing and numerical analysis.

3.2 Sensitivity Analysis of PPEI Parameters

In order to study the sensitivity of the newly developed PPEI index, a sensitivity analysis is carried out by varying some critical input parameters and examining their effect on the calculated PPEI indices and pile ranking.

Parameters chosen for sensitivity analysis include the following:

1. Untrained shear strength (cu),
2. Adhesion coefficient (α),
3. Corrosion/Durability coefficient (Rc), and
4. Weighting coefficients (wi).

These input parameters are varied by ±10-20 percent about their base value. All other input parameters are assumed to be constant. The range of variations is based on the typical uncertainty present in geotechnical design and soil material properties. Base value and variation range of some important input parameters used for sensitivity analysis are presented in Table 7.

Table 7. Sensitivity ranges of key parameters used in PPEI analysis.

Parameter	Symbol	Base Value	Variation Range
Undrained shear strength	(c_u)	Case-dependent	±20%
Adhesion factor	(α)	0.6–0.8	±15%
Corrosion factor	(R_c)	0.2–0.5	±20%
Weighting factors	(w_i)	As defined	±10%

Results obtained from the sensitivity analysis show that PPEI values are significantly affected by uncertainties in undrained shear strength (cu) and weighting of axial capacity. A variation of ±20% of cu will result in 8% - 12% variation of PPEI values due to its effects on shaft resistance and end bearing resistance. Variations in adhesion factor (α) affect PPEI values significantly, in the order of 5% - 8%.

This can be attributed to the fact that the adhesion factor is used in shaft resistance. Variations in corrosion resistance factor (Rc) have an effect on durability score and consequently PPEI values ranging between 4% and 6%. Weighting factor (wi) variations of ±10% result in 5% - 8% variation of PPEI values. Figure 6 shows the sensitivity trends confirm that the PPEI model captures the dominant physical mechanisms governing pile behavior and is not overly sensitive to secondary uncertainties.

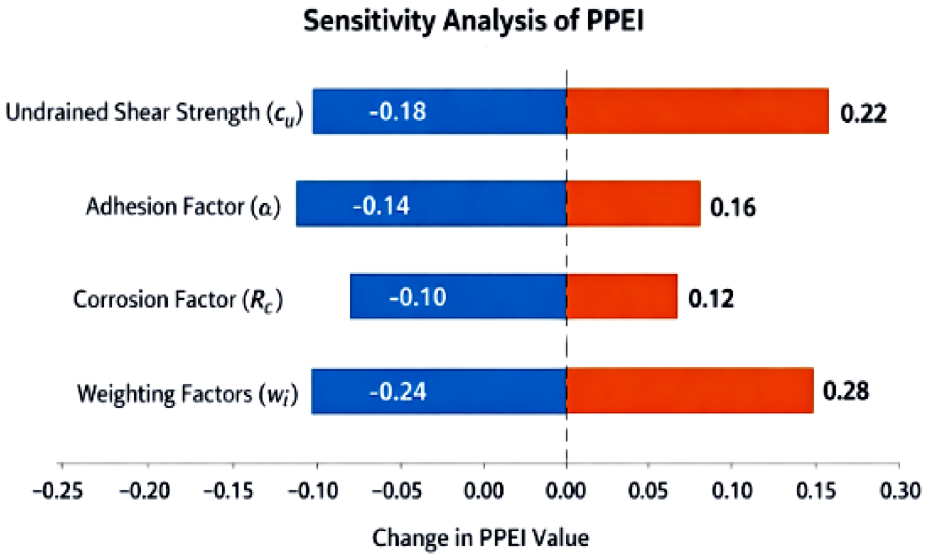

Figure 6. Tornado diagram illustrating the sensitivity of PPEI values to variations in key input parameters (c_u, α, R_c, and weighting factors).

4. Discussion

The Findings that were produced through the application of the PPEI approach can give a systematic structure on how to understand the performance of piles in clay soils by considering several geotechnical principles. In contrast to conventional one-parameter analysis, it was discovered through the current findings that the efficiency of piles is affected by their interaction of different aspects such as shaft resistance, settlements, lateral performance, and others.

One of the key findings from the current analysis is the contribution of shaft resistance in limiting axial bearing capacity, especially for medium to stiff clay soils where greater PPEI was recorded in concrete piles. This finding agrees with previous research on cohesive soil types where shaft resistance is responsible for transferring the major share of loads in deep piles [2, 30]. Increased normalized axial bearing capacities in concrete piles can be explained by the enhanced roughness and contact surface area of concrete piles. Studies have shown that increased roughness increases the frictional resistance offered by a pile interface [2, 30].

The settlement behavior of concrete piles provides another example of this phenomenon. Lower values for the settlement behavior of concrete piles in medium and stiff clays are more representative of classical theories of consolidation and load-settlement response behavior [2, 3, 30]. The increased stiffness and large diameter of concrete piles enable effective stress transfer to the adjacent soil. This conclusion is supported by various research works indicating the impact of pile stiffness on settlement behavior under loading conditions.

However, the better performance of steel piles in soft clay soils is mainly attributed to lateral resistance and ease of installation, both of which are essential for low-strength soils. Higher lateral resistance ratings in steel piles have been documented through laterally loaded pile research, where the ductility and flexibility of the materials have been found crucial in combating lateral and cyclical loading effects [2, 30]. It is worth noting that steel piles deform more while still maintaining their integrity; hence, they are ideal for seismic and dynamically loaded structures. Therefore, higher PPEI ratios for steel piles arise due to higher lateral performance ratings.

The effect of installation is also vital when considering distinguishing pile behavior. Driven steel piles create disturbance in soil condition and excessive pore water pressure, thus decreasing the shaft resistance of the soil immediately after the process of installation. This is common knowledge in pile driving research [2, 30]. However, bored concrete piles do not cause any disturbances to the soil and provide better soil-pile interaction, hence creating greater initial shaft resistance. The concept of the PPEI model takes care of this difference through a high installation feasibility score of steel piles.

Durability also tilts the comparison towards the use of concrete piles, especially when dealing with aggressive clay soils. Concrete piles are less vulnerable to corrosion and chemical degradation compared to their steel counterparts, as evidenced by durability studies conducted on reinforced concrete foundations [2, 3, 30]. However, steel piles have shown high vulnerability to corrosion when exposed to chloride and sulfate attacks unless preventive measures are applied [2, 3, 30]. This is why the low durability grades allocated to steel piles under the PPEI index are justified in the literature.

Notably, the current findings demonstrate that none of the pile types is universally superior, with the effectiveness of their performance being contingent upon the design parameters that are prevalent in a particular situation. The concrete piles have proven to be more effective in situations where the axial capacity, settlement, and durability are of paramount importance, especially in soils with moderate to high stiffness. Conversely, the steel piles are recommended for instances where the installation time, lateral load resistance, and cyclic loading play an important role, especially in soft soils.

Methodologically speaking, the PPEI system offers an expansion on traditional geotechnical assessment through the use of multiple criterion to create a numeric, normalized decision-making process. Multi-criteria decision-making techniques have been employed in civil engineering before, but their use in assessing piles through the use of physically relevant factors is new and innovative. The use of analysis and normalization with literature-derived trends allows for objective comparisons of pile types. However, the interpretation of the results should be done with an understanding of the analytical character of the investigation. While the identified relationships are well-supported by existing literature, additional verification through field testing and numerical analysis is required to establish the predictive ability of the PPEI model under site conditions.

5. Conclusion

This study clearly shows that the relative suitability of steel versus concrete piles in clay soil deposits depends on several factors related to axial capacity, settlement response, lateral load response, ease of construction, and durability. Specifically, the findings show that steel piles can be more effective in soft clay soil deposits because of their higher efficiency during installation and better lateral load response, whereas concrete piles would be more effective in medium and stiff clays because of high shaft resistance, lower settlement, and durability. One of the major contributions of this study includes developing the pile performance efficiency index (PPEI). This index represents a systematic and quantified method that can help integrate all relevant performance criteria into one measure. In terms of practice, one of the most important conclusions from this research is that there is no ideal pile type in all cases; therefore, the choice should be based on the importance of each performance criterion in a specific scenario. The PPEI concept aids in doing so by systematically evaluating the trade-off between different considerations. Nevertheless, there are a number of limitations associated with the study. The PPEI concept is analytical in nature and uses range of values for the parameters that represent typical conditions; it does not use field measurements for individual sites, and the more complex considerations of durability and installation are treated as an index representation. Furthermore, variability in terms of soil response, method of installation, and environmental conditions could play a role in performance that may fall outside the domain of the current analysis. There is a need to validate the results of the PPEI model by using field load tests, case studies, and advanced numerical modeling techniques.

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Data Availability

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

Has this article screened for similarity?

Yes

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