Civil and Geoengineering Letters, 2025, 2(2): e100047
https://doi.org/10.22034/CGEL.2.2.e100047

Article Type: Research

Geotechnical Correlation based on SPT-CPT Values for Fine-Grained Alluvium of the Kahrizak Formation

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Received: 28 August 2025 / Accepted: 02 October 2025 / Published: 22 October 2025

Abstract: In geotechnical engineering, the correlation between Standard Penetration Test (SPT) and Cone Penetration Test (CPT) values plays a crucial role in soil characterization. This study focuses on developing new empirical relationships based on SPT and CPT values in the fine-grained riverside alluvium of the Karrizak Formation in Tehran, southern Alborz, Iran. SPT-CPT data were extracted from various previous studies, encompassing diverse geological and geotechnical investigations. By analyzing these datasets, we identified patterns and trends that allowed us to establish improved correlations between SPT and CPT values with soil properties of this formation. Our approach integrates both statistical and empirical methods to ensure that the proposed relationships accurately reflect the mechanical behavior of the fine-grained alluvium in the study area. The developed correlations provide a more reliable framework for geoengineers and researchers working on subsurface investigations and foundation design in similar geological settings. These findings contribute to enhancing the predictive capabilities of geotechnical assessments and improving the overall reliability of soil parameter estimations.

Keywords: SPT-CPT correlation, fine-grained alluvium, Kahrizak Formation, geotechnical engineering, Tehran.

I. INTRODUCTION

The Standard Penetration Test (SPT) and Cone Penetration Test (CPT) are two of the most widely used in-situ geotechnical tests for soil characterization and subsurface investigations (Fernando et al., 2021). These tests provide essential data on soil properties, which play a critical role in geotechnical engineering, particularly in foundation design, slope stability analysis, and earthquake engineering. The accuracy and reliability of these measurements are vital since they directly influence the safety, stability, and cost-effectiveness of engineering projects (Jarushi et al., 2015). Properly conducted SPT and CPT tests help engineers make informed decisions regarding soil behavior, bearing capacity, settlement potential, and liquefaction susceptibility (Yagiz et al., 2008). The SPT is a dynamic penetration test that involves driving a split-barrel sampler into the soil using a standard hammer and recording the number of blows required for penetration at specific depth intervals (Bol, 2023). The SPT blow count (N-value) serves as an indicator of soil density, strength, and stiffness (Khan et al., 2022). This test is relatively simple, cost-effective, and widely used, particularly in coarse-grained soils and mixed layers (Lingwanda et al., 2015). However, it has some limitations, such as energy losses due to hammer efficiency variations, operator dependency, and difficulty in obtaining continuous soil profiles (Lu et al., 2023).

The CPT, on the other hand, is a static penetration test that involves pushing an instrumented cone into the ground at a constant rate while continuously measuring resistance (Zhou et al., 2021). The cone resistance (q_c), sleeve friction (f_s) and friction ratio (R_f) obtained from the CPT provide detailed stratigraphic profiles, soil classification, and strength parameters (Baez et al., 2000). Unlike SPT, CPT produces high-resolution and repeatable data, making it highly valuable for assessing soft and fine-grained soils. However, CPT has its own limitations, such as difficulty in penetrating very dense or gravelly soils, higher operational costs, and the need for specialized equipment (Firuzi et al., 2019). Both tests play a crucial role in geotechnical site investigations, providing empirical data for engineering design (Poor et al., 2023). In foundation engineering, SPT and CPT results help determine allowable bearing capacity, settlement characteristics, and soil-structure interaction parameters (Cetin & Ozan, 2009). In seismic studies, these tests assist in evaluating liquefaction potential and dynamic soil properties. Their integration enhances the accuracy of geotechnical models and improves risk assessment in construction projects (Zhou et al., 2019).

The SPT is performed using a borehole, where a split-barrel sampler is driven into the soil by a 63.5 kg hammer falling from a height of 76 cm. The number of blows required to drive the sampler 30 cm into the soil (after an initial seating of 15 cm) is recorded as the N-value (Anbazhagan et al., 2012). This test is conducted at regular depth intervals, typically every 1.5m.

Corrections may be applied to account for overburden pressure, hammer energy efficiency, and borehole conditions to ensure reliable results (Barnes, 2016). The CPT is conducted by pushing an instrumented cone into the soil at a steady rate of 2 cm/s using a hydraulic system (Eslami & Fellenius, 2004). The q_c, f_s, and pore water pressure (u) are continuously recorded to provide a detailed soil profile (Baez et al., 2000). CPT data are then used to estimate soil parameters such as undrained shear strength, relative density, and friction angle. The ability to provide near-continuous reading makes CPT especially valuable for layered soils and fine-grained deposits (Barnes, 2016). Figure 1 illustrates the performance of the SPT and CPT tests in engineering geology. Both methods complement each other, with SPT being more practical in mixed and coarse-grained soils and CPT offering higher precision in fine-grained soils (dos Santos & Bicalho, 2017). Their combined use allows for a more comprehensive geotechnical evaluation, reducing uncertainties in soil behavior predictions and improving the overall reliability of engineering designs (Barnes, 2016).

SPT and CPT provide valuable in-situ measurements that allow engineers to assess soil properties directly at the project site (dos Santos & Bicalho, 2017). These tests help determine key geotechnical parameters such as soil strength, density, stiffness, and stratigraphy, which are fundamental in predicting how soil will behave under load. Without such data, engineers would have to rely on assumptions, leading to uncertainty in design and potentially unsafe construction practices (Firuzi et al., 2019). SPT and CPT data are essential for understanding the geotechnical behavior of the soil and informing crucial design decisions (Akca, 2003). For example, foundation design heavily depends on the soil's bearing capacity, which can only be reliably estimated through such in-situ testing (Anderson & Townsend, 2001). Moreover, these tests are indispensable for assessing the potential for soil liquefaction, settlement, and slope stability (Barnes, 2016; Farhangi et al., 2020). In seismic regions, the SPT and CPT also provide information on the soil's response to dynamic loading, which is key to designing structures that can withstand earthquakes (Boumpoulis et al., 2021). The accurate collection of these data helps ensure the safety and durability of infrastructure, making them indispensable tools in geotechnical site investigations (Anwar, 2018).

The importance of SPT and CPT tests also extends to cost-effectiveness in construction projects. By providing real-time data on soil behavior, these tests allow for more efficient foundation design, avoiding overdesign and excessive costs (dos Santos & Bicalho, 2017). Additionally, they reduce the need for extensive laboratory testing by providing a quick, reliable assessment of subsurface conditions (Wang et al., 2023). This efficiency not only saves time but also makes it possible to optimize resource allocation, ensuring that engineering projects are completed on budget and on time. Thus, these tests are fundamental to both the technical and economic success of geotechnical projects (Guan & Wang, 2022).

The primary objective of this study is to develop new empirical correlations between SPT and CPT values for the fine-grained riverside alluvium of the Kahrizak Formation in Tehran located in southern Alborz, Iran. Given the critical role of SPT and CPT in geotechnical site investigations, establishing accurate relationships between these two tests is essential for improving soil characterization and engineering design. By analyzing data extracted from various previous studies, this research aims to identify trends and patterns that allow for a more precise estimation of soil properties based on SPT and CPT results. The proposed correlations will help geotechnical engineers make more informed decisions in foundation design, site stability assessments, and seismic hazard evaluations, especially in regions with similar geological settings. Another key goal of this study is to enhance the efficiency and reliability of geotechnical investigations by providing a refined framework for converting between SPT and CPT values. Since each test has its own advantages and limitations, a robust correlation between them will allow engineers to utilize existing test data more effectively, reducing the need for extensive additional testing in future projects. This is particularly beneficial in cases where one test is more feasible than the other due to site constraints, cost considerations, or soil conditions. Ultimately, this study contributes to improving geotechnical modeling, risk assessment, and the overall accuracy of subsurface investigations in the Kahrizak Formation and other fine-grained alluvial deposits.

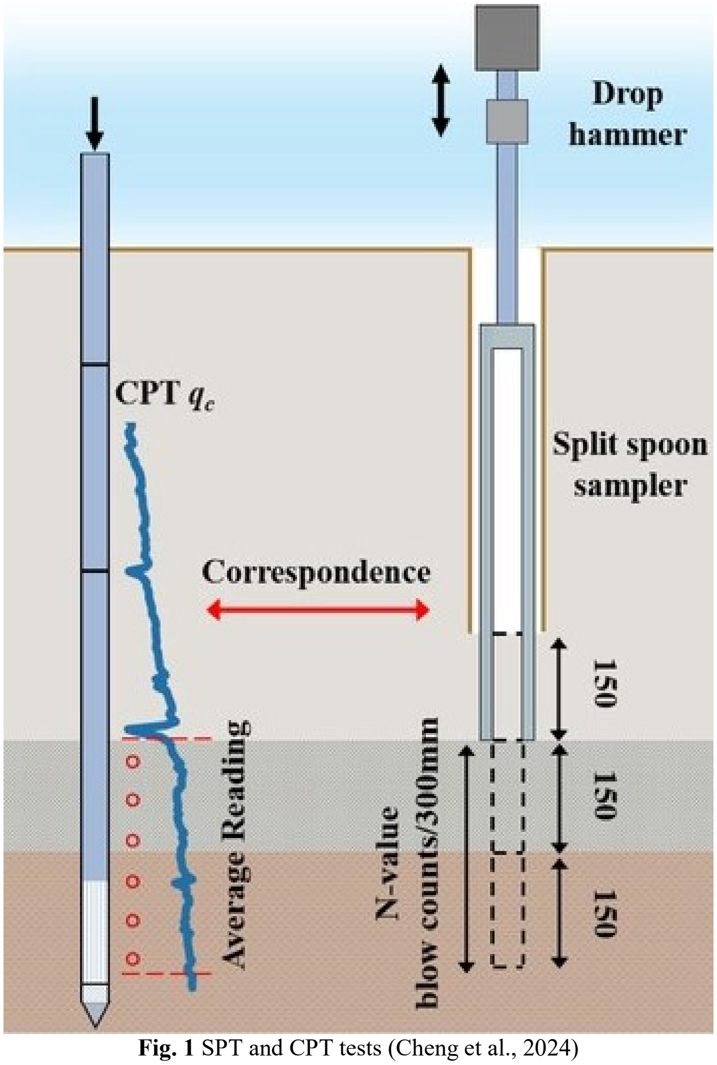

Fig. 1 SPT and CPT tests (Cheng et al., 2024)

II. SPT-CPT AND SOIL SPECIFICATIONS

The most critical soil properties estimated using SPT and CPT include the elastic modulus (E), undrained shear strength (C_u) of fine-grained soils, and the coefficient of compressibility (m_v). These parameters are fundamental in geotechnical engineering, as they influence foundation design, settlement prediction, and soil stability analysis. The E represents the stiffness of the soil and is crucial for evaluating how much a structure will settle under applied loads. Since direct laboratory measurement of E can be expensive and time-consuming, empirical correlations with SPT N-values and q_c provide a practical way to estimate this parameter efficiently. Another key property is the C_u of fine-grained soils, which determines the soil's ability to resist shear failure without drainage. This parameter is especially important in clayey soils and is widely used in slope stability analysis, bearing capacity calculations, and foundation design in cohesive soils. SPT N-values are often correlated with C_u using empirical formulas, while CPT data, particularly q_c and u readings, provide a more direct and continuous estimation of shear strength. These correlations allow engineers to assess soil stability and design safe and effective foundation systems. The m_v, which defines how much a soil layer will compress under applied stress, is another crucial factor estimated from SPT and CPT data. This property affects settlement analysis and plays a significant role in designing structures on soft and fine-grained soils. The m_v is often derived from SPT N-values and CPT pore pressure dissipation tests, providing insight into long-term settlement behavior. In this study, special attention has been given to these three properties (such as E, C_u, and m_v) to develop more precise correlations for the fine-grained alluvium of the Kahrizak Formation in Tehran. These improved relationships will help in better characterizing subsurface conditions and optimizing geotechnical design in similar geological settings.

The E is one of the most important parameters in geotechnical engineering, as it defines the soil's ability to deform under stress and recover upon unloading (Poor et al., 2023). This parameter is crucial for analyzing foundation settlement, soil-structure interaction, and overall stability assessments. However, direct measurement of the elastic modulus through laboratory tests can be time-consuming and expensive (Bozbey & Togrol, 2010). As a result, empirical correlations and regression analyses using SPT and CPT data have become widely used for estimating this essential parameter (Özvan et al., 2018). These methods allow engineers to derive reliable soil stiffness values efficiently, improving both cost-effectiveness and accuracy in geotechnical design (Firuzi et al., 2019). One of the most common approaches for estimating the E is using empirical correlations with SPT N-values. Several studies have established relationships between N-values and E based on statistical analyses of in-situ and laboratory test results. Table 1 provides several practical relationships that are developed by various researchers.

As seen in this table the general form of relations is $E=\alpha \cdot N$ where α is an empirical coefficient that depends on soil type, relative density, and stress conditions. General review of various empirical relationships shows that for coarse-grained soils, E is typically estimated as 150 to 300 times the SPT N-value, while for fine-grained soils, lower multipliers are used due to their higher compressibility. The variations in α indicate the need for site-specific calibration to improve prediction accuracy (Bowles, 1997). Similarly, CPT data provides a direct and continuous means of estimating the elastic modulus by using q_c. The general form of empirical correlations for CPT-based modulus estimation as general form as $E=\beta \cdot q_c$ where β is an empirical coefficient that varies based on soil type and stress conditions. Studies have shown that E is typically 5 to 10 times q_c in sandy soil, while in clays, additional factors such as pore water pressure and plasticity index influence the estimation (Bowles, 1997). Table 1 provides several practical relationships that are developed by various researchers for q_c and E correlations. Because CPT data provide more continuous and detailed stratigraphy than SPT, these correlations are often preferred in fine-grained soils where soil properties change significantly over short depths.

To enhance the accuracy of empirical correlations, regression analysis is widely applied to large datasets obtained from SPT and CPT tests (Jarushi et al., 2015). Linear regression is commonly used to determine the best-fit relationship between SPT N-values, CPT q_c, and E based on statistical significance (Boumpoulis et al., 2021). More advanced methods, such as nonlinear regression and multiple regression models, incorporate additional variables like depth, stress level, and soil type to improve predictions (Zhou et al., 2019). Although empirical and regression-based correlations provide useful estimates, several factors can influence their reliability (Bozbey & Togrol, 2010). Soil type, stress history, saturation level, and sample disturbance all affect the measured values of SPT N and CPT q_c, leading to variability in derived elastic modulus values. Additionally, energy efficiency corrections in SPT and pore pressure effects in CPT must be accounted for to ensure consistency across different test conditions (Anwar, 2018). Another limitation is that empirical correlations are region-specific, meaning they need calibration for different geological formations (Özvan et al., 2018). For instance, soils in the Kahrizak Formation may exhibit different stiffness characteristics than those in other regions, requiring site-specific adjustments to existing correlations. Therefore, geotechnical engineers must validate empirical equations with local field and laboratory data before applying them to design projects.

A more reliable approach to estimating the elastic modulus involves integrating both SPT and CPT data (Bowles, 1997). While SPT provides historical data and is more commonly available, CPT offers continuous and high-resolution profiling. By combining these datasets, engineers can cross-check estimated soil parameters and reduce uncertainty in their calculations (Arifuzzaman & Anisuzzaman, 2022). Advanced machine learning algorithms are also being developed to improve regression models by incorporating multiple in-situ and laboratory test results. The estimation of elastic modulus using SPT and CPT data is particularly valuable in designing deep foundations, embankments, and retaining structures (Patel & Parmar, 2021). It plays a crucial role in settlement analysis, ensuring that structures do not experience excessive deformation under load (Wadi et al., 2022). In seismic geotechnical engineering, E is also used to evaluate soil response under dynamic loading, helping engineers design earthquake-resistant structures (Akca, 2003).

Table 1 Several empirical relationships estimated by scholars for E based on SPT and CPT

Researcher(s)	Empirical relationship	Soil type	R^2 value
E vs SPT			
Yagiz et al. (2008)	E_m = 388.67 SPT(N) + 4554	Sandy silty soils with clay	0.83
Bozbey & Togrol (2010)	E_m = 1.33 $SPT(N)^{0.77}$	Sandy soils	0.82
	E_m = 1.61 $SPT(N)^{0.71}$	Clayey soils	0.72
Kayabasi (2012)	E_m = 0.29 $SPT(N)^{1.4}$	Clayey soils	0.74
	E_m = 1.2 $SPT(N)^{-3.9}$	Fine-grained soils	0.64
Balachandran et al. (2015)	E_m = 1.58 SPT(N)	Cohesive soils	0.86
	E_m = 1.09 SPT(N)	Cohesionless soils	0.28
Cheshomi & Ghodrati (2015)	E_m = SPT(N) - 2.6748	Silty clay soils	0.85
Naseem & Jamil (2016)	E_m = 165.88 SPT(N) + 1364.1	Sandy soils	0.85
Ghali et al. (2018)	E_m = 2.0 SPT(N)	Clean sands	-
Özvan et al. (2018)	E_m = 2.611 SPT(N) - 26.03	Sandy-silty clay	0.91
Firuzi et al. (2019)	E_m = 6.4 $e^{0.04SPT(N)}$	Fine-grained soils	0.83
Kamei et al. (2020)	E_m = 5.5 SPT(N)	Sandy soils	0.85
Li et al. (2022)	E_m = 6.8 SPT(N)	Silty soils	0.88
Poor et al. (2023)	E_m = -1.286 SPT(N) + 371.1	Coastal alluvium (mix)	0.076
E vs $_c$			
Briaud et al. (1985); Briaud & Garland (1985)	E_m = 2.0 q_c	Clayey soils	0.06
	E_m = 2.5 q_c	Clayey soils	0.06
	E_m = 1.15 q_c	Sandy soils	0.06
Hamidi et al. (2000)	E_m = 1.35 q_c	Carbonate Sandy soils	-
Mezouar et al. (2017)	E_m = 0.37 q_c + 6.5	Sandy soils	-
Tarawneh et al. (2018)	E_m = 0.46 q_c + 11.44	Desert sand	0.91
Zhang & Wang (2021)	E_m = 4.2 q_c	Clayey soils	0.90
Poor et al. (2023)	E_m = 0.442 q_c + 2.221	Coastal alluvium (mix)	0.99

The C_u is a key parameter in geotechnical engineering that defines the soil's resistance to shear stress under undrained conditions, meaning there is no time for pore water to dissipate (Talamkhani & Naeini, 2021). This property is particularly important for fine-grained soils, such as clays and silts, which exhibit different behaviors under short-term (undrained) and long-term (drained) loading conditions (Cao & Wang, 2014). In fine-grained soils, C_u primarily depends on factors such as soil composition, water content, stress history, and plasticity. Unlike coarse-grained soils, where strength is largely governed by frictional forces, the shear strength of fine-grained soils is heavily influenced by cohesion and interparticle bonds (Briaud, 2023).

The SPT is one of the most common in-situ tests used to estimate C_u, particularly for cohesive soils (Briaud, 2023). Empirical relationships have been established between SPT N-value and C_u, allowing engineers to quickly estimate shear strength without requiring expensive laboratory tests. A typical correlation takes the form as C_u=k·N where k is an empirical coefficient that depends on soil type and overburden stress (Rémai, 2013). For soft clays, C_u is generally found to be 4 to 6 times the SPT N-value, while in stiff clays, the multiplier is higher (Lunne & Andersen, 2007). However, SPT-based Cu estimates have limitations, as the test is primarily designed for coarse-grained soils and may not always provide accurate readings in highly plastic clay or very soft sediments (Nassaji & Kalantari, 2021). On the other hand, the CPT is a more effective method for estimating C_u in fine-grained soils, as it provides continuous data and minimizes disturbance (Poor et al., 2023). CPT's q_c is directly related to C_u, and empirical formulas are widely used for estimation as $C_u = q_c/N_k$; where N_k is the cone factor, typically ranging from 14 to 18 for normally consolidated clays and varying based on soil structure and stress conditions (Rémai, 2013). Additionally, CPT pore pressure measurements (u^2) can be used to refine Cu estimates, especially in saturated clays, making CPT a more reliable tool for assessing fine-grained soil strength compared to SPT (Alshibli et al., 2011). The accurate estimation of C_u is key for designing foundations, embankments, and slopes in fine-grained soils (Kim et al., 2010). Table 2 provides a summary of recently provided empirical relationships for driven C_u form the SPT and CPT data.

Shallow and deep foundations rely on C_u to determine bearing capacity, ensuring that structures do not experience excessive settlement or failure under applied loads (Briaud, 2023). In embankment design, C_u is crucial for evaluating stability and deformation behavior, particularly in soft clay deposits, where failure risks are high. Additionally, in tunnel and excavation projects, C_u plays a vital role in assessing soil stability and support requirements to prevent collapse or excessive deformation (Çinicioğlu & Toğrol, 1991). One of the other applications of C_u is in slope stability analysis, where it helps engineers assess the potential for landslides and determine appropriate reinforcement methods. The lower the C_u, the higher the risk of slope failure, making accurate measurements essential for designing retaining structures, stabilizing embankments, and predicting soil movement (Hicks & Samy, 2002). Despite the availability of empirical correlations, estimating C_u from SPT and CPT data comes with challenges. The accuracy of C_u predictions depends on several factors, including soil type, stress history, drainage conditions, and equipment calibration (Motaghedi & Eslami, 2014). SPT-based C_u estimates can be affected by hammer energy efficiency, borehole disturbance, and overburden stress corrections, leading to variability in results. CPT-based C_u values, while generally more reliable, require careful selection of N_k factors, which can vary significantly depending on soil consistency and consolidation state.

Table 2 Several empirical relationships estimated by scholars for C_u based on SPT and CPT

Researcher(s)	Empirical relationship	Soil type	R^2 value
C_u vs SPT			
Sowers (1962)	C_u = 24 SPT(N)	Highly plastic clay	-
	C_u = 14.4 SPT(N)	Medium to low plastic clay	-
	C_u = 6.7 SPT(N)	Plastic silts and clays with failure	-
Terzaghi & Peck (1967)	C_u = 12.5 SPT(N)	Fine-grained soil	-
Sivrikaya & Toğrol (2002)	C_u = 4.85 SPT(N)	Highly plastic clay	-
	C_u = 3.35 SPT(N)	Low plastic clay	-
	C_u = 4.32 SPT(N)	Fine-grained soil	0.68
Hettiarachchi & Brown (2009)	C_u = 4.1 SPT(N)	Fine-grained soil	0.74
Nassaji & Kalantari (2011)	C_u = 1.6 SPT(N) + 15.4	Fine-grained soil	0.72
Urmi & Ansary (2017)	C_u = 9.19 SPT(N) + 12.63	Fine-grained soil	0.504
Balachandran et al. (2017)	C_u = 8.32 SPT(N)	Cohesive glacial tills	0.79
White et al. (2019)	C_u = 5.5 SPT(N)	London Clay	-
Nixon (2021)	C_u = 12 SPT(N)	Clay	0.80
C_u vs $_c$			
Lunne et al. (2005)	$C_u = (q_c-\sigma_{vo})/12$	Offshore clays	-
	$C_u = (q_c-\sigma_{vo})/3$	Onshore clays	-
Low et al. (2010)	$C_u = (q_c-\sigma_{vo})/11.9$	Fine-grained soil	-
	$C_u = (q_c-\sigma_{vo})/13.6$	Fine-grained soil	-
Mayne et al. (2015)	$C_u = (q_c-\sigma_{vo})/11.8$	Soft to firm intact clays	-
Mayne (2016)	$C_u = [(q_c-\sigma_{vo})/3.9] \times 0.35$	Bothkennar clay	-
Urmi & Ansary (2017)	$C_u = 2(q_c/\sigma_{vo}) + 11.31$	Fine-grained soil	0.4

Therefore, site-specific calibration using laboratory tests (e.g., unconfined compression or triaxial tests) is often necessary to refine C_u estimates (Hossain, 2018). To improve the reliability of C_u estimations, geotechnical engineers often combine SPT and CPT data with laboratory test results (Mbarak et al., 2020). By using multiple sources of data, uncertainties can be minimized, and more accurate soil strength profiles can be developed.

One other high impact factor in geotechnical design is m_v or compressibility coefficient. The m_v is a key soil parameter that defines the volume change of fine-grained soils under an applied load (Hossain, 2018). It is typically expressed as the change in void ratio per unit change in effective stress and is crucial for understanding the settlement behavior of clayey and silty soils (Ahmed et al., 2014). The compressibility of fine-grained soils is strongly influenced by their mineral composition, water content, and structure, making m_v an essential factor in geotechnical engineering (Mohamedzein & Aboud, 2006). Since excessive settlement can lead to structural instability, accurately estimating m_v is critical for foundation design and other geotechnical applications (Urmi & Ansary, 2019). The SPT provides an indirect estimation of m_v by correlating the N-value with soil stiffness and compressibility (Mbarak et al., 2020). In general, lower SPT-N values indicate softer, more compressible soils with higher m_v, while higher N-values suggest denser soils with lower compressibility (Urmi & Ansary, 2019). Empirical correlations have been developed to estimate m_v from SPT data, especially for cohesive soils, where the penetration resistance reflects soil structure and consolidation behavior (Mohamedzein & Aboud, 2006). However, since SPT is an impact-based test, its accuracy in soft clays and silts may be affected by factors such as soil sensitivity and hammer energy variations (Mahmoud, 2013).

The CPT is a more precise tool for evaluating m_v, as it provides continuous resistance measurements that better capture soil behavior (Mohamedzein & Aboud, 2006). The q_c and f_s obtained from CPT are strongly related to compressibility. Low q_c values typically correspond to high m_v values, indicating softer, more compressible soils (Ahmed et al., 2014). Additionally, the ratio of f_s/q_c is used to assess soil type and structure, helping to refine m_v estimates. Since CPT provides a more detailed stratigraphic profile compared to SPT, it is often preferred for assessing fine-grained soil compressibility (Özkahriman, 2004). Understanding m_v is essential in geotechnical design because it directly influences settlement predictions (Urmi & Ansary, 2019). In foundation engineering, accurate m_v values help determine the rate and magnitude of primary consolidation settlement, which is crucial for structures built on clayey deposits (Mbarak et al., 2020). Overestimating m_v can lead to excessive conservatism in design, increasing construction costs, while underestimating it may result in unexpected settlements and structural damage (Hossain, 2018). For embankments, retaining walls, and deep excavations, precise m_v values are required to ensure long-term stability (Mahmoud, 2013). Table 3 provides a summary of recently provided empirical relationships for driven m_v form the SPT and CPT data. The primary objective of this study is to establish new empirical correlations between SPT and CPT values for fine-grained river-side alluvium of the Kahrizak Formation in Tehran. Given the critical role of these in-situ tests in geotechnical engineering, accurately estimating soil properties such as elastic modulus, C_u, and compressibility is essential for safe and efficient foundation design. By analyzing data from various studies and integrating multiple sources of field and laboratory information, this research aims to provide more reliable relationships that enhance the predictive accuracy of geotechnical investigations.

Table 3 Several empirical relationships estimated by scholars for m_v based on SPT and CPT

Researcher(s)	Empirical relationship	Soil type	R^2 value
Lunne et al. (1997)	$q_c/p_a = 8.5(1-m_v)$	Calcareous soils	0.068
		Siliceous soils	0.193
Robertson (2012)	$[q_c/p_a]/SPT(N) = 10^{(1.126-0.2817mv)}$	Calcareous soils	0.096
		Siliceous soils	0.221

Furthermore, this study seeks to address the limitations of existing empirical correlations by focusing specifically on the fine-grained alluvial soils of the Kahrizak Formation. The unique geological characteristics of this region require tailored correlations to improve the interpretation of SPT and CPT data. By refining these relationships, the study contributes to better geotechnical modeling and site characterization, ultimately supporting safer infrastructure development. The outcomes of this research will be valuable for engineers and researchers involved in foundation design, slope stability analysis, and other soil-structure interaction problems in similar geological settings.

III. STUDIED LOCATION

The Kahrizak Formation is a geological formation located in the southern foothills of the Central Alborz mountain range, within the Tehran region of Iran. Named after Mount Kahrizak, situated south of Tehran, this formation dates back to the Middle to Late Pleistocene epoch (Aghanabati, 2012). It unconformably overlies the Hezardarre Formation and is overlain by the Tehran alluvial deposits (De Martini et al., 1998). The Kahrizak Formation is characterized by its reddish hue, indicative of semi-arid depositional environments. Its lithology predominantly comprises conglomerates and alluvial deposits, with a thickness ranging between 10m to 50m (Rezaei et al., 2017). Petrographic analyses reveal that the constituent materials of this formation are primarily derived from the erosion of older strata, notably the Karaj Formation, which includes tuff, limestone, shale, and basalt (Khaksar & Khaksar, 2012). These sediments were deposited in fluvial braided river systems, reflecting dynamic sedimentary processes during the Quaternary period (Aghanabati, 2012). The Kahrizak alluvium represents the oldest Quaternary floodplain deposits in the Tehran area, often referred to as "Series B" following the classification by Rieben in 1955 (Nazari et al., 2010). This alluvium is predominantly composed of coarse-grained materials, including gravel and sand, with a notable presence of calcareous nodules and clay, imparting a characteristic reddish coloration (Azadi et al., 2010). The sedimentary structures and grain size distribution suggest deposition in a high-energy fluvial environment, likely associated with braided river systems (Azad, 2023). The alluvium's composition indicates it originated from the erosion of older geological formations, such as the Karaj Formation, and was subsequently transported and deposited by riverine processes (Rezaei et al., 2017). The stratigraphic position of the Kahrizak alluvium, lying unconformably above the Hezardarre Formation and beneath the Tehran alluvial deposits, underscores its significance in reconstructing the paleoenvironmental and geological history of the Tehran region during the Pleistocene epoch (Aghanabati, 2012). The geological map and stratigraphic chart of the Kahrizak Formation and studied region has been provided in Figures 2 and 3.

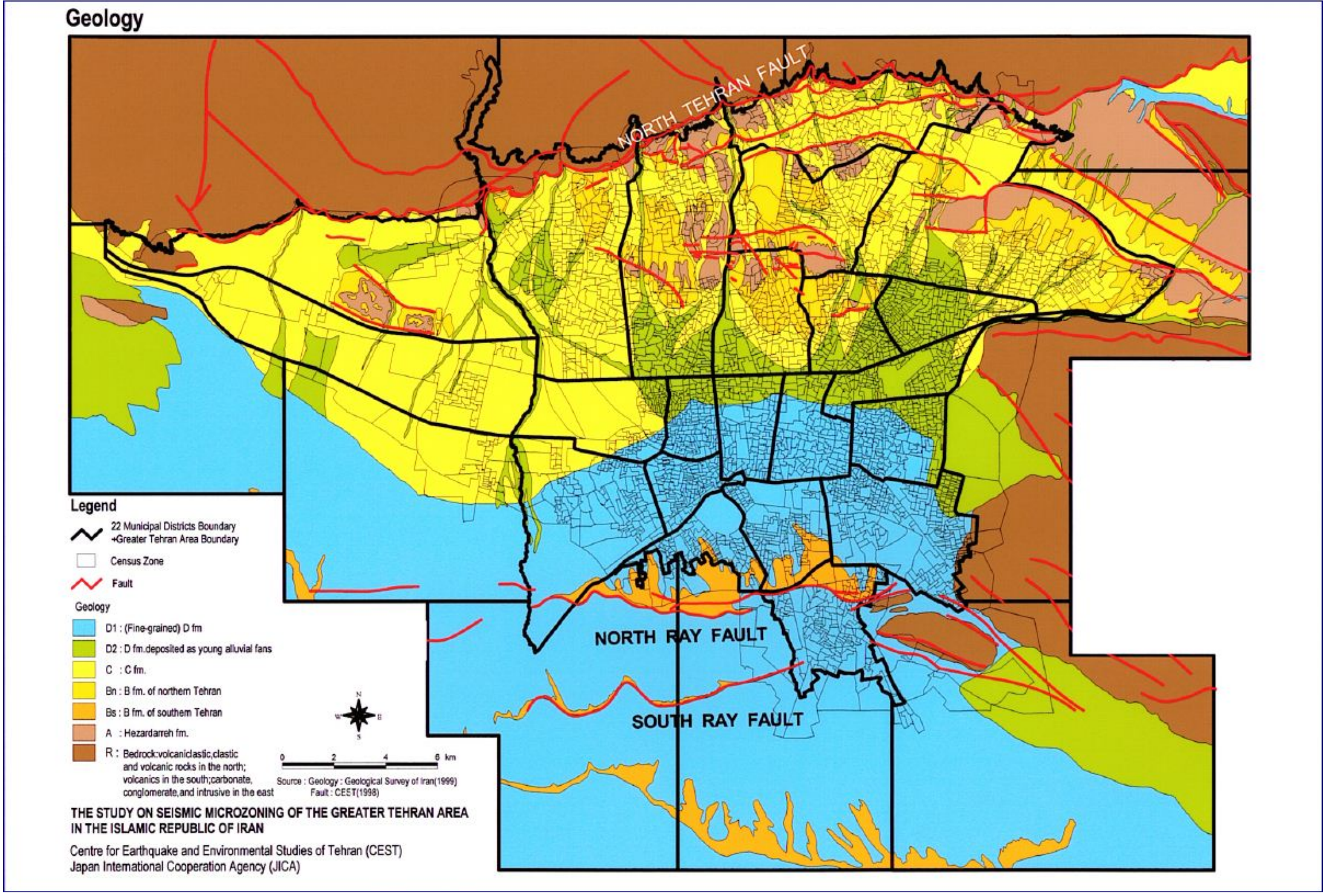

Fig. 2 Geological map of Kahrizak Formation in Tehran (adapted from Matsumoto, 2006)

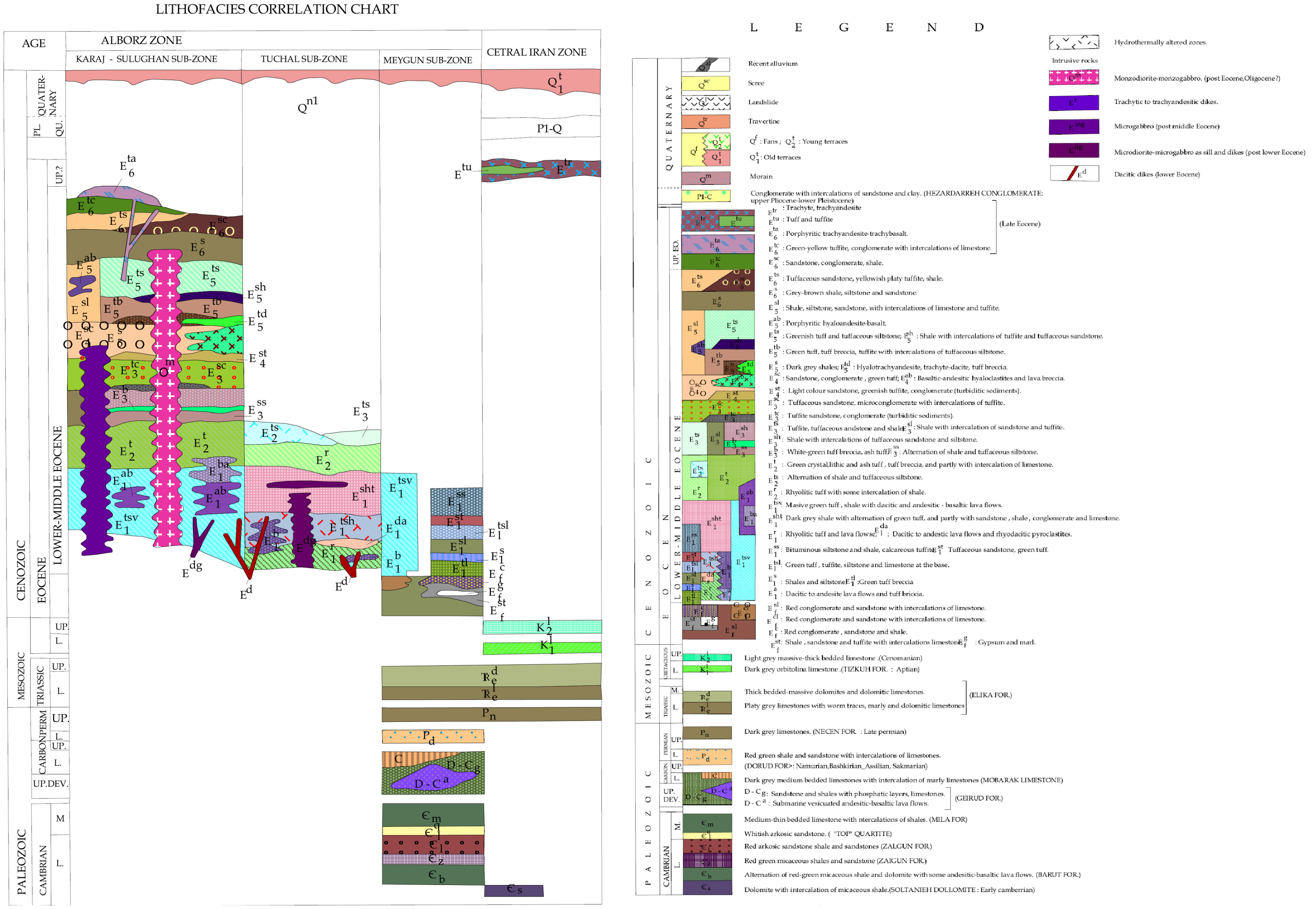

Fig. 3 The stratigraphic chart of Tehran geology (adapted from Geological Survey of Iran, 2010)

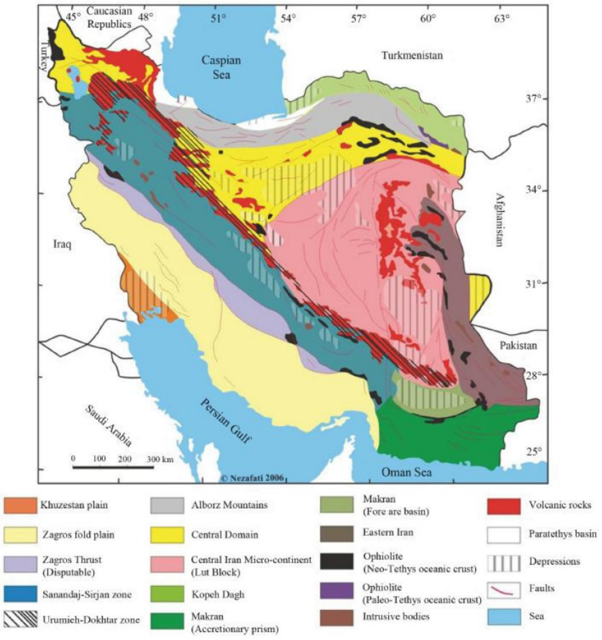

Fig.4 Location of studied area (Khaksar & Khaksar, 2012)

Iran is geologically diverse, consisting of several structural zones formed due to complex tectonic interactions between the Arabian, Eurasian, and Indian plates. These structural zones include the Zagros Fold and Thrust Belt, the Sanandaj-Sirjan Zone, the Urumieh-Dokhtar Magmatic Arc, the Central Iranian Zone, the Lut Block, the Eastern Iran Zone, the Kopet Dagh Zone, and the Alborz Zone (Zanchi et al., 2006). Each of these regions has distinct geological characteristics shaped by different tectonic forces over millions of years (Alavi, 1996). The Alborz Zone, located in the northern part of Iran, represents an orogenic belt that extends from Azerbaijan in the northwest to the east of Iran, forming part of the Alpine-Himalayan mountain chain (see Figure 4). The Central Alborz Zone, specifically, is a highly deformed region consisting of a mix of sedimentary, metamorphic, and igneous rock formations (Malekzade & Bellier, 2023). This zone has experienced significant compressional forces due to the collision of the Arabian and Eurasian plates, resulting in complex faulting and folding structures (Naeimi et al., 2022). The geology of this region includes formations from various geological periods, ranging from the Paleozoic to the Cenozoic (Tchalenko et al., 1974). The presence of volcanic and intrusive igneous rocks also suggests past magmatic activities, which played a crucial role in shaping the geological history of the area (Zanchi et al., 2006). Additionally, this region is highly seismically active due to its tectonic setting, making it an essential area of study for earthquake hazard assessments (Tchalenko et al., 1974).

The Kahrizak Formation, the subject of this study, is situated within the Central Alborz structural zone. This formation, dating back to the Middle to Late Pleistocene, consists of conglomerates and alluvial deposits, which were primarily sourced from the erosion of older formations such as the Karaj Formation. The Central Alborz Zone, where the Kahrizak Formation is located, provides essential insights into the sedimentary processes and paleoenvironmental conditions that prevailed in northern Iran during the Quaternary period. Understanding this formation within the broader structural framework of Iran helps geologists reconstruct the region's tectonic and sedimentary history.

IV. MATERIALS AND METHODS

In this study, we conducted a comprehensive survey of previous research and existing literature on the correlation between SPT and CPT values in geotechnical engineering. By analyzing various geological and geotechnical investigations related to the Kahrizak Formation in southern Alborz, Tehran, we extracted key geotechnical parameters, including SPT and CPT results, from multiple sources. Table 4 is provided the basic information that has been used in this study as sources of analysis. The collected data encompassed different soil types, geological conditions, and testing methodologies, ensuring a robust foundation for developing empirical relationships. This approach allowed us to identify trends and establish meaningful correlations that improve the characterization of fine-grained riverside alluvium in the study area. To derive these correlations, we employed a linear regression approach alongside empirical methods. Linear regression is a statistical technique used to model the relationship between dependent and independent variables. In this study, SPT values served as the independent variable, while CPT results and other geotechnical parameters acted as dependent variables. The linear regression model was applied to assess the degree of correlation, quantify variations, and minimize prediction errors. This approach provided a mathematical framework for defining a reliable predictive model that captures the mechanical behavior of the Kahrizak Formation's alluvial deposits. The regression analysis was further validated by comparing our results with previously established correlations to ensure consistency and accuracy. The combination of statistical regression and empirical evaluation allowed us to refine and enhance existing SPT-CPT relationships for the study area. The developed correlations provide geotechnical engineers with a more precise estimation of subsurface properties, improving the reliability of foundation design and soil behavior predictions in similar geological settings. This methodology contributes to advancing geotechnical assessments and offers a practical framework for future studies on subsurface characterization in complex alluvial environments.

One of the primary advantages of using linear regression in this study is its simplicity and effectiveness in identifying relationships between SPT and CPT values. Linear regression provides a straightforward mathematical model that quantifies the correlation between these geotechnical parameters, making it easier to interpret and apply in engineering practice. This method allows for the prediction of unknown soil properties based on available data, enhancing the efficiency of subsurface investigations. Additionally, linear regression offers a statistical basis for analyzing large datasets, helping to identify patterns and trends within the collected geotechnical information. By leveraging this approach, we developed improved empirical relationships that provide reliable estimates of soil behavior in the Kahrizak Formation. Despite its advantages, linear regression has certain limitations when applied to complex geotechnical datasets. One major limitation is its assumption of a linear relationship between variables, which may not always hold true in highly heterogeneous alluvial deposits. Soil behavior is often influenced by multiple nonlinear factors such as varying grain size distributions, moisture content, and lithological variations. If the actual correlation between SPT and CPT values exhibits nonlinear characteristics, a simple linear model may lead to inaccuracies or oversimplifications. Furthermore, regression models are sensitive to data quality, meaning that outliers, measurement errors, or inconsistencies in the dataset can significantly affect the accuracy of predictions. To address these limitations, additional statistical and empirical techniques may be required to refine the predictive capabilities of the regression model. In some cases, nonlinear regression or machine learning algorithms could offer better accuracy in capturing complex geotechnical behaviors. Additionally, validating the regression model with independent field data and cross-comparing results with existing studies helps improve reliability. While linear regression remains a valuable tool for establishing empirical correlations in geotechnical engineering, its application should be carefully evaluated within the geological and geotechnical context of the study area.

Table 4 The sources of the information that has been used in this study

Researcher(s)	Location	Number of tests		Soil type
		On-site	Laboratory	
Ghayoumian et al. (2006)	Tehran	950	-	Alluvium and Quaternary sediments
Matsumoto (2006)	Tehran	-	-	Technical report on Quaternary sediments
Rezaie et al. (2013)	South of Tehran	18	55	Cleyey silty alluvium
Ebadati & Hagi (2014)	South of Tehran	233	238	Alluvium and Quaternary sediments
Golpasand et al. (2016)	Tehran	24	60	Cleyey silty soil with low plasticity
Cheshmi et al. (2018)	North of Tehran	97	66	Alluvium and Quaternary sediments
Mirhaji et al. (2018)	West of Tehran	45	24	Kahrizak alluvium in landfill site
Keramati et al. (2019)	West of Tehran	-	24	Kahrizak alluvium in landfill site

Table 5 Geotechnical properties summary for Kahrizak Formation in Tehran

Parameters	Unit	Maximum	Minimum	Mean	Standard Deviation	Skewness
Bulk unit weight	kN/m^3	19.50	16.50	17.9	1.04	0.216
Saturate unit weight	kN/m^3	22.50	17.50	19.3	1.47	0.885
Soil class	-	CL, ML, SC, SM	CH, MH	CL-ML	-	-
Moisture Content	%	25	7	16.6	6.03	-0.196
Grain size	mm	1500	500	994	341.1	0.123
Cohesion	kPa	60	8	36.5	17.35	-0.232
Friction angle	degree	42	20	32	6.81	-0.269
Elastic modulus	MPa	200	15	72.5	49.69	1.153
SPT(N)	-	50	4	26	16.69	0.075
CPT (q_c)	MPa	5	0.5	1.81	1.23	1.477
Shear velocity (V_s)	m/sec	900	450	631	185.5	0.416
Tensile strength	kN/m	29	10.5	20.4	5.61	-0.133
Poisson's ratio	-	0.35	0.30	0.31	0.021	0.538
Undrained shear strength	kPa	150	30	77.8	36.34	0.306

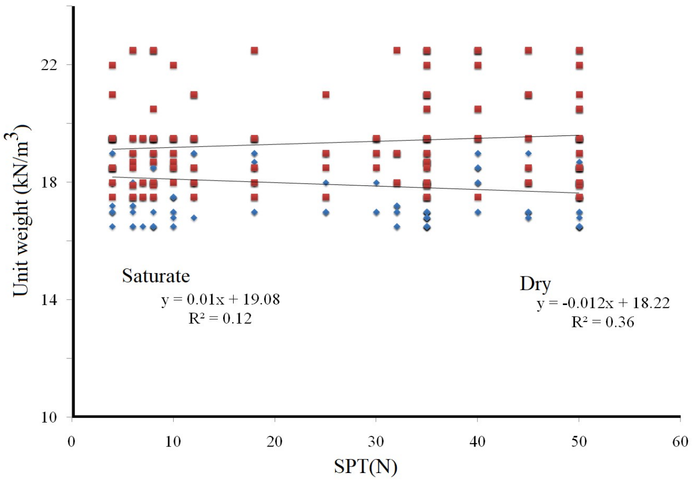

Fig. 5 Correlation between dry/saturated unit weight with SPT

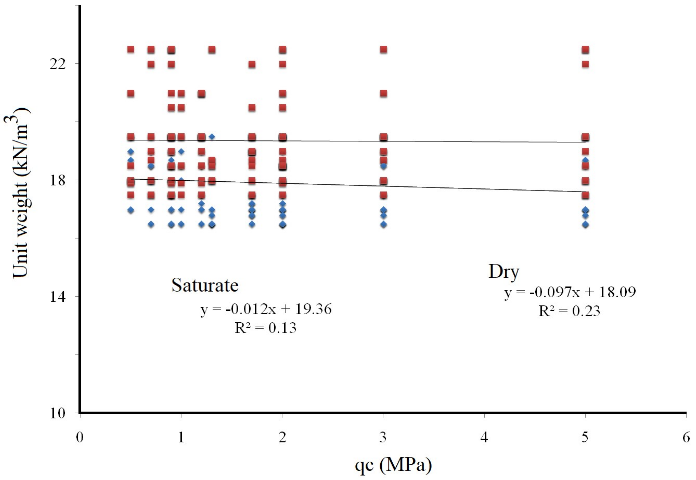

Fig. 6 Correlation between dry/saturated unit weight with CPT

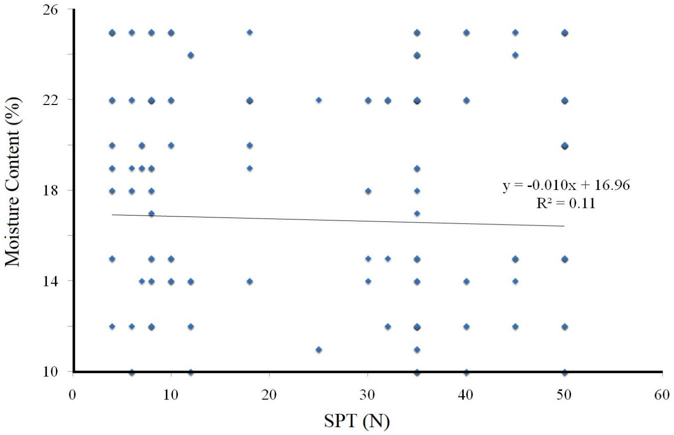

Fig. 7 Correlation between moisture content with SPT

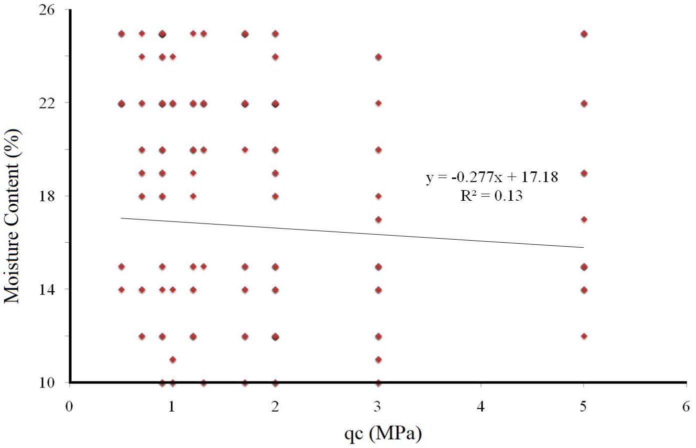

Fig. 8 Correlation between moisture content with CPT

V. RESULTS AND DISCUSSION

In this study, empirical correlations were developed to estimate the unit weight of soils based on SPT (N-values) and CPT (q_c values). The relationship for saturated unit weight using SPT is given by $\gamma_{sat} = 0.01SPT(N) + 19.08$ with a determination coefficient of $R^2 = 0.12$, while for dry unit weight, the equation is $\gamma_d = -0.012SPT(N) + 18.22$ with $R^2 = 0.36$. Similarly, correlations derived from CPT data indicate that the saturated unit weight follows $\gamma_{sat} = -0.012q_c + 19.36$ with $R^2 = 0.13$, and the dry unit weight is estimated as $\gamma_d = -0.097q_c + 18.08$ with $R^2 = 0.23$. These equations suggest that unit weight decreases slightly with increasing penetration resistance in both SPT and CPT methods, though the relatively low R^2 values indicate moderate to weak correlation, emphasizing the need for additional factors such as soil type, moisture content, and compaction conditions in more precise estimations (Figures 5 and 6).

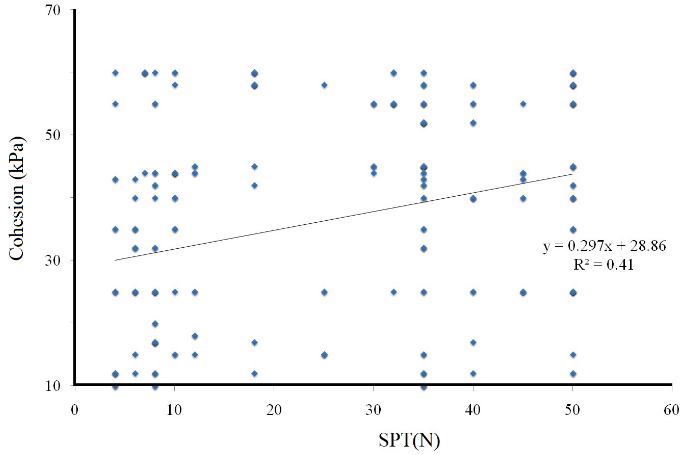

Fig. 9 Correlation between cohesion with SPT

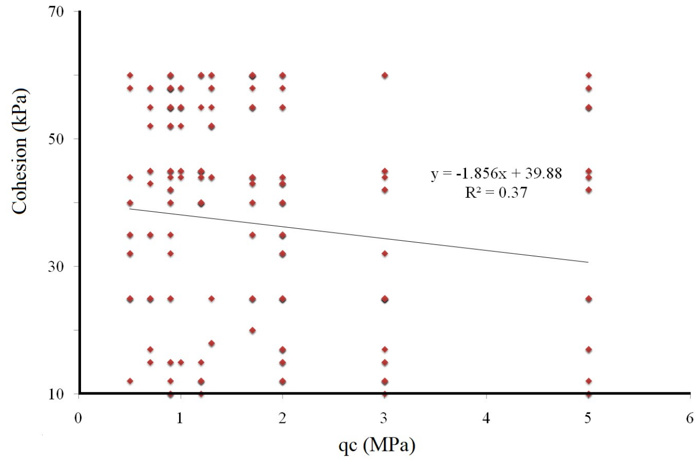

Fig. 10 Correlation between cohesion with CPT

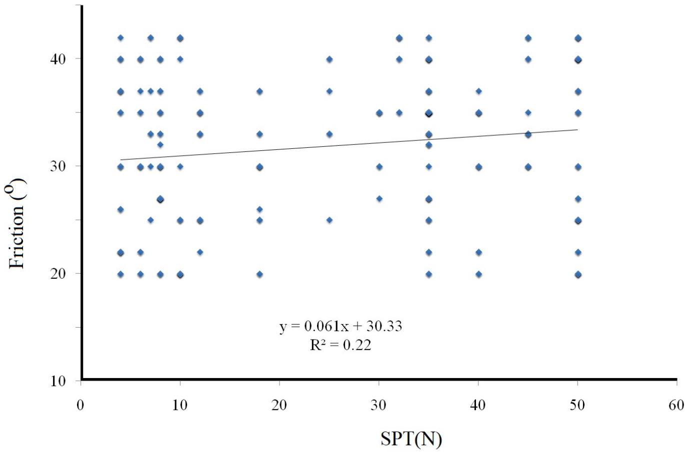

Fig. 11 Correlation between friction with SPT

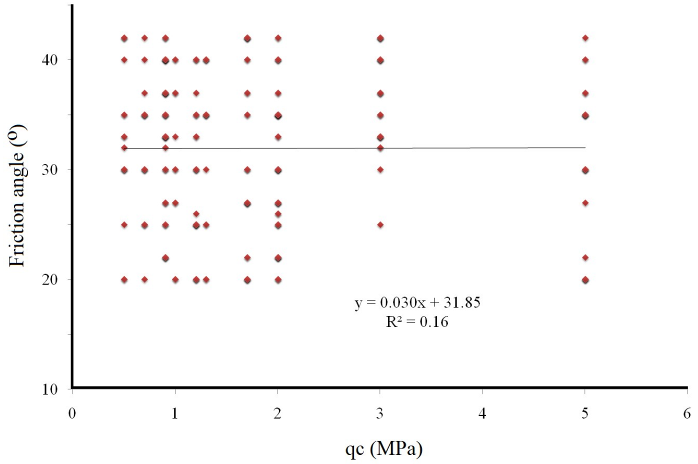

Fig. 12 Correlation between friction with CPT

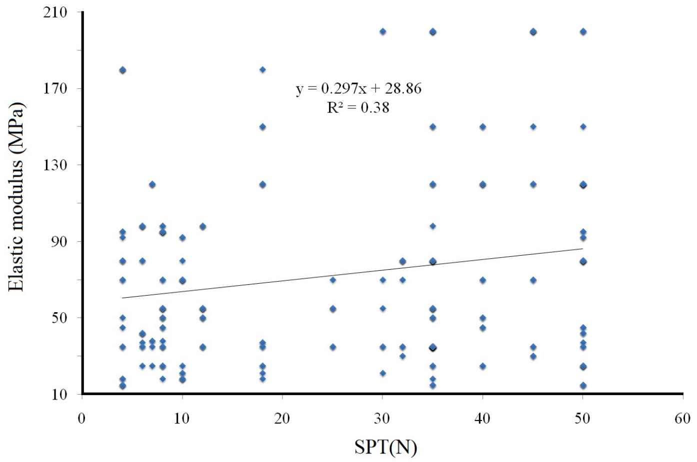

Fig. 13 Correlation between elastic modulus with SPT

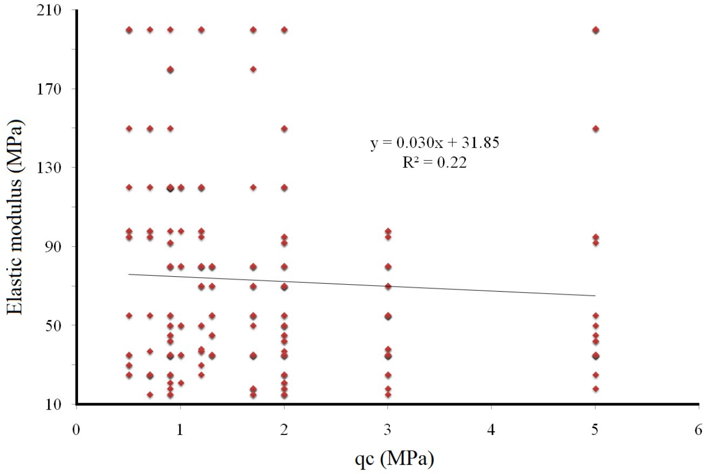

Fig. 14 Correlation between elastic modulus with CPT

Additionally, based on Figures 7 and 8, an empirical relationship was established between moisture content (MC) and SPT and CPT values. The correlation between moisture content and SPT (N-values) is given by MC = -0.01SPT(N) + 16.96 with a determination coefficient of $R^2 = 0.11$, while for q_c, the relationship follows MC = $-0.227q_c + 17.18$ with $R^2 = 0.13$. These equations indicate a slight decrease in moisture content as penetration resistance increases, which are expected in denser or more compacted soils where water-holding capacity is lower. However, the low R^2 values suggest weak correlations, implying that moisture content is influenced by additional factors such as soil composition, porosity, and drainage conditions, which should be considered for more accurate predictions. Based on Figures 9 and 10, the variation of cohesion (C) against SPT and CPT values was analyzed. The relationship between cohesion and SPT is expressed as C = 0.0297SPT(N) + 28.86 with a determination coefficient of $R^2 = 0.41$, while for q_c, the equation is C = $-1.856q_c + 39.88$ with $R^2 = 0.37$. These correlations suggest a moderate relationship between penetration resistance and cohesion, with cohesion generally increasing with higher SPT values, whereas a slight negative trend is observed for CPT-based correlation, which may be influenced by soil type and stress conditions. Additionally, Figure 11 illustrates the variation of SPT values with friction angle (ϕ), following the equation $\phi = 0.061SPT(N) + 30.33$ with $R^2 = 0.22$, indicating a weak correlation. Similarly, Figure 12 presents the relationship between CPT values and friction angle, given by $\phi = 0.030q_c + 31.85$ with $R^2 = 0.16$, which also shows a low correlation, implying that factors beyond penetration resistance, such as mineral composition and particle shape, influence the friction angle significantly. Furthermore, Figures 13 and 14 illustrate the variation of elastic modulus (E) with SPT and CPT values. The equation $E = 0.297SPT(N) + 28.86$ with $R^2 = 0.38$ represents the SPT-based correlation, while for CPT, the relationship is given by $E = 0.030q_c + 31.85$ with $R^2 = 0.22$. These findings suggest that elastic modulus tends to increase with penetration resistance, but the relatively low R^2 values indicate that additional geotechnical parameters, such as overburden pressure and soil type, must be considered for a more accurate estimation of soil stiffness.

Figure 15 illustrates the variation of undrained shear strength (C_u) with SPT and CPT values. The results indicate that the relationship between Cu and SPT (N-values) follows a linear equation: $C_u = 0.128SPT(N) + 74.5$ with a determination coefficient of $R^2 = 0.13$. Similarly, the correlation between Cu and CPT (q_c values) is expressed as $Cu = -0.15q_c + 78.14$, with $R^2 = 0.10$. These relatively low R^2 values suggest a weak correlation, indicating that undrained shear strength is influenced by additional factors such as soil type, overconsolidation ratio (OCR), and drainage conditions. The slight negative trend observed in the CPT-based equation may be attributed to variations in soil structure and stress history, which can affect cone resistance measurements. Overall, while these equations provide an initial estimation, incorporating more geotechnical parameters would enhance the reliability of undrained shear strength predictions.

The empirical correlations developed in this study provide valuable insights into the relationships between penetration resistance (SPT and CPT values) and key geotechnical parameters in the fine-grained alluvium of the Kahrizak Formation, Tehran. The results demonstrate that while some correlations exhibit moderate predictive capability, others show weak relationships, highlighting the complexity of soil behavior and the influence of multiple interacting factors. The unit weight equations derived from SPT and CPT data suggest a slight decrease in unit weight with increasing penetration resistance, but the low R^2 values indicate that other variables, such as compaction, moisture content, and soil fabric, play significant roles. This suggests that while these equations can serve as a general guideline, site-specific calibration may be necessary for more accurate estimations. The relationship between moisture content and penetration resistance revealed a weak correlation, with moisture content slightly decreasing as SPT and CPT values increased. This trend is expected in denser soils, where higher penetration resistance corresponds to lower void ratios and reduced water retention capacity. However, the low R^2 values (0.11 for SPT and 0.13 for CPT) indicate that moisture content is also strongly influenced by soil type, permeability, and seasonal groundwater fluctuations. This finding reinforces the need for direct moisture content measurements in geotechnical investigations, as indirect estimations based on penetration resistance alone may lead to unreliable conclusions.

Similarly, the C correlations with SPT and CPT values demonstrated moderate relationships, with an R^2 of 0.41 for SPT and 0.37 for CPT. While SPT-based correlation showed a positive trend, the CPT-based equation exhibited a slight negative relationship, which may be due to variations in soil structure, stress history, and effective stress conditions. Cohesion is highly dependent on factors such as clay content, cementation, and mineralogy, which are not directly captured by penetration resistance tests. Therefore, while these equations provide a useful approximation, additional laboratory tests such as direct shear or unconfined compression tests are recommended for more precise cohesion estimation. The analysis of ϕ with SPT and CPT yielded weak correlations, with R^2 values of 0.22 and 0.16, respectively. The results indicate a slight increase in friction angle with increasing penetration resistance; however, the weak correlation suggests that friction angle is controlled by grain size distribution, particle shape, and mineral composition rather than penetration resistance alone. This underscores the importance of conducting triaxial shear tests or direct shear tests for a more accurate determination of soil shear strength parameters, rather than relying solely on empirical relationships. The E correlations with penetration resistance also exhibited moderate predictive capability, with R^2 values of 0.38 for SPT and 0.22 for CPT.

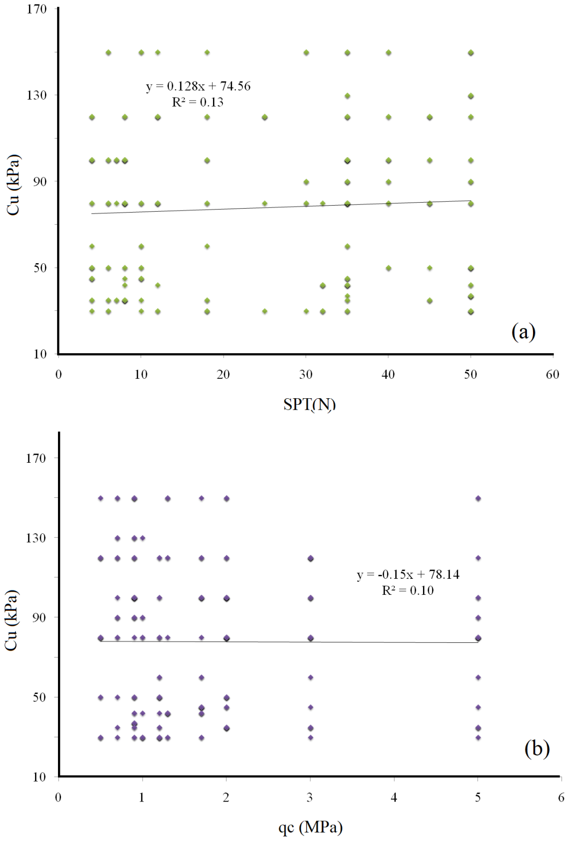

Fig. 15 Correlation between C_u with: (a) SPT, (b) q_c

The increasing trend suggests that soils with higher penetration resistance tend to have greater stiffness, which aligns with previous research findings. However, since soil stiffness is significantly influenced by stress conditions, loading history, and strain levels, the moderate R^2 values highlight the need for additional testing, such as plate load tests or pressuremeter tests, to refine elastic modulus estimations in real-world applications. Finally, the C_u correlations demonstrated the weakest relationships, with R^2 values of 0.13 for SPT and 0.10 for CPT, suggesting that penetration resistance alone is not a reliable predictor of Cu. This is likely due to the strong dependency of undrained shear strength on soil structure, overconsolidation ratio, and drainage conditions. The negative trend observed in the CPT-based equation may be a result of local variations in soil composition or stress states, further emphasizing the limitations of empirical approaches in estimating C_u. To improve the accuracy of undrained shear strength predictions, a combination of laboratory testing (such as vane shear or unconfined compression tests) and field tests should be considered. Overall, while the correlations presented in this study offer valuable insights into soil behavior, their limitations highlight the necessity of integrating multiple testing methods for more robust geotechnical assessments.

VI. CONCLUSION

This study developed empirical correlations between SPT and CPT values with key geotechnical parameters in the fine-grained alluvium of the Kahrizak Formation, Tehran. The results provided useful insights into unit weight, moisture content, cohesion, friction angle, elastic modulus, and undrained shear strength, highlighting both the strengths and limitations of using penetration resistance as a predictive tool. The unit weight correlations indicated a weak dependency on penetration resistance, suggesting that compaction, moisture content, and soil composition play crucial roles in determining bulk density. Similarly, the moisture content relationships exhibited a low R^2, reinforcing the idea that moisture variations are influenced by groundwater fluctuations and soil permeability rather than solely by penetration resistance. These findings emphasize the importance of direct measurements for accurate geotechnical evaluations. The cohesion correlations showed moderate reliability, particularly with SPT values, while friction angle relationships exhibited weaker trends. This indicates that soil cohesion and internal friction are significantly affected by particle size distribution, cementation, and stress history, necessitating supplementary laboratory testing. The elastic modulus correlations suggested a moderate predictive capability, indicating that penetration resistance is a useful but not entirely sufficient parameter for stiffness estimation. Among all parameters, the C_u correlations exhibited the weakest relationships, with low R^2 values for both SPT and CPT. This highlights the strong dependency of C_u on soil structure, drainage conditions, and overconsolidation ratio, making it essential to integrate laboratory and field tests for more reliable assessments. Overall, while the developed correlations provide a preliminary framework for geotechnical investigations in similar geological settings, they should not replace detailed laboratory and in-situ testing.

ACKNOWLEDGMENT

We extend our thanks to the reviewers for their meticulous attention to detail and constructive suggestions that greatly improved the quality of this manuscript. Your contributions have been instrumental in shaping this work.

AUTHORS' CONTRIBUTIONS

Naser Nourani conducted the main data analysis, contributed to the data collection, preprocessing, and interpretation, and was responsible for drafting the initial manuscript. Akbar Ghazifard performed supervision, conceptual guidance and conducted critical revision of the manuscript and final approval of the version to be published. All authors read and approved the final manuscript.

CONFLICT OF INTEREST

The authors have not disclosed any competing interests.

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