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CASE REPORT

Effect of Installation Method on the Uplift Capacity of Single Driven Steel Piles: Full-Scale Field Study

Iman Golpazir[1,2] · **Ali Dehghanbanadaki**[1,2] · **Reza Akherati**[3] · **Anahita Akherati**[4]

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Abstract This study examines the pullout behavior of steel piles used as foundations for solar panels in Shahrebabak city, Iran. The site's geotechnical characteristics were assessed through 15 boreholes using the wash boring method. A total of 40 tests were conducted, evenly divided between UNP 120 and UNP 100 piles, to record penetration rates under constant energy during pile driving. The load-settlement behavior of all piles was systematically compared. Initial results showed no consistent correlation between uplift load and penetration rate. The calculated tensile loads were compared with predictions from the Tomlinson equation, based on standard penetration tests (SPT), yielding consistent results. To enhance the accuracy of predicting pile uplift, two computational estimation models were developed using the *LinearRegression* class from the Python library scikit-learn, with penetration rate and average SPT values as inputs. The models demonstrated strong predictive performance, with a mean squared error (MSE) of 0.123 Ton and an R-squared (R^2) of 0.94 for UNP 120 and an MSE of 0.118 Ton and an R^2 of 0.928 for UNP 100. Given these strong performance indices, geotechnical engineers can reliably use these models for accurate estimation of pile uplift.

Keywords Driven piles · Pull out tests · SPT · Penetration rate · Uplift load

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✉ Ali Dehghanbanadaki
A.Dehghanbanadaki@damavandiau.ac.ir

Iman Golpazir
I.golpazir@damavandiau.ac.ir

Reza Akherati
Rezaakherati1354@gmail.com
https://zamin-run.com/en/

Anahita Akherati
anahitaakherati09@gmail.com

1 Department of Civil Engineering, Damavand Branch, Islamic Azad University, Damavand, Iran

2 Research Center of Concrete and Soil, Damavand Branch, Islamic Azad University, Damavand, Iran

3 ZaminRun Ravesh Geotechnical Company, Tehran, Iran

4 Department of Civil Engineering, University of Tehran, Tehran, Iran

Introduction

Numerous studies have primarily focused on determining the ultimate bearing capacity (UBC) of piles under compressive loading conditions. Researchers have employed a variety of methods, including full-scale field tests [1–6], laboratory-scale tests (e.g. [7–13]), numerical modeling, [14–19] and the application of machine learning techniques (e.g., [20–24]) to assess the UBC. However, it's important to note that in some instances, piles are subjected to tensile loads, making it essential to accurately determine their uplift load capacities.

Piles can be subjected to uplift loads in a range of applications, including structural foundations, retaining walls, bridge abutments and similar structures. Uplift forces may arise from factors such as differential settlement, soil pressure, wave action, tidal fluctuations, seismic events, gravitational forces on slopes, and architectural design requirements [25]. Therefore, engineers must consider uplift loads in the design and analysis of piles to ensure structural stability and safety. This involves using various testing, analytical, and design methods to determine the appropriate pile configurations capable of resisting these upward forces.

Numerous researchers have investigated the determination of uplift forces on piles; however, the diverse results obtained from field and experimental tests can be attributed to the various influencing factors, including the geotechnical properties of the site, pile types, installation methods, and loading conditions. For instance, Gaaver [26] investigated the uplift capacity of single piles and pile groups in cohesionless soil. This study involved a series of experimental model tests on vertical steel piles with a 26 mm outer diameter, conducted in a steel soil bin. The sand bed was prepared at three different relative densities—75%, 85%, and 95%. The findings indicated that the uplift behavior of single piles is primarily influenced by the pile's embedment depth-to-diameter ratio and the soil properties. An empirical equation was proposed to model the load–displacement relationships for single piles in sandy soil under uplift conditions. The study demonstrated that the relative density of the sand, which reflects its strength properties, significantly affects the uplift capacity.

In the other study, [27] investigated the behavior of single piles in sandy soil under combined uplift and lateral loads using small-scale laboratory experiments. The study employed a model pile made of aluminum with outer and inner diameters of 25.4 mm and 19.0 mm, respectively. By varying the pile length, length-to-diameter ratios (*L/D*) of 18, 28, and 38 were achieved, allowing for the simulation of both stiff and flexible piles. The experiments included single piles subjected to independent uplift and lateral loading, as well as combined lateral and uplift loading. The results revealed nonlinear load–deflection behavior in both independent and combined loading scenarios. Interestingly, the behavior of piles under independent loading was found to differ significantly from that under combined loading conditions. While the ultimate lateral/uplift load capacity increased considerably under combined loading, the pile head deflection/displacement at safe lateral/uplift loads also rose. These findings suggest that the behavior of piles under combined uplift and lateral loads is complex and cannot be accurately predicted based on independent loading tests alone.

The behavior of a granular anchor pile (GAP) system in loose sandy soil was investigated by Kranthikumar et al. [28] through small-scale laboratory tests. The effect of the embedded length of the pile on the uplift capacity of the GAP system was examined. Results were compared with numerical analysis using three-dimensional finite-element analysis software. The study explored key parameters such as pile length (*L*), diameter (*D*), and the elastic modulus of surrounding soil, analyzing their effects on the uplift capacity of the GAP. The load–displacement response of the GAP was reported. It was observed that, for a constant GAP diameter, the ultimate uplift capacity increases with an increasing *L/D* ratio, but beyond a ratio of 10, further increases do not significantly contribute to load sharing. Bulging failure predominantly occurs in GAP with a higher modulus ratio, while shaft failure occurs with lower modulus ratios.

In the other research, Sakr et al. [29] conducted a series of physical modeling tests focusing on investigating the uplift capacities of single regular piles (without wings) and anchor winged vertical piles installed in dry sand with different densities. A total of sixty experimental model tests were executed on both single regular and anchor winged piles, with the model test series conducted at a fixed embedment depth and pile diameter. The findings indicated that the uplift capacity of anchor winged piles increased with the escalation in sand relative densities. Specifically, at the ratio of wing length to pile length equal to 0.50 and at the ratio of the maximum diameter between the outer edges of the wing to pile diameter equal to 3.0, the efficiency of improvement in the uplift capacity reached 2.0, 2.38, and 2.77 times that of regular piles without wings at sand relative densities of 30%, 50%, and 80%, respectively.

Malhotra and Singh [30] investigated the pull-out behavior of granular anchor pile foundations (GAPFs) in sandy soil. They conducted pull-out load tests on GAPFs with varying pile lengths, *L/D* ratios, and group configurations. The results showed that the pull-out capacity of GAPFs decreased with increasing L/D ratio and that group effect increased the uplift load compared to a single GAP. Finite element analysis using PLAXIS 3D software validated the physical model test results.

A recent study by Hu et al. [31] investigated the pull-out behavior of belled piles in soil-rock composite ground subjected to both axial and oblique loads. The researchers performed failure model tests to explore various aspects of the pile's performance, including load–displacement characteristics, ground displacement curves, failure modes, and load transfer mechanisms. Their results showed that oblique loading, with a deviation angle of 14° from the vertical, decreased the ultimate uplift capacity of the belled pile by 16.3% compared to axial loading. Additionally, the study found that the pile's bending moment initially increased with depth but later decreased. The peak bending moment was observed just below the ground surface, at a depth ranging from 2.3 d to 2.8 d.

Objectives

In light of existing literature, numerous experimental and field tests have been conducted on diverse piles to ascertain uplift loads. Some studies have even introduced computational estimation models. However, the complex interplay of various influencing parameters, such as distinct geotechnical properties of the site and pile geometrical characteristics, necessitates the development of more user-friendly estimation models for accurate uplift predictions. Therefore, the principal objectives of this paper are twofold: firstly, to investigate and analyze the pullout behavior of steel piles designed as foundations for solar panels in Shahrebabak city, Iran; and secondly, to conduct a comparative assessment of the load-settlement behavior among all piles. Furthermore, the study will juxtapose the calculated tensile loads with the Tomlinson equation, based on standard penetration test (SPT) values. To refine precision in predicting pile uplift, the paper will develop computational estimation models utilizing penetration rate and SPT data as input parameters. The broader implications of this research include enhancing the design and analysis of pile foundations in renewable energy projects and similar applications, leading to more reliable and efficient construction practices. This can ultimately contribute to improved structural stability and sustainability in geotechnical engineering.

Field Tests

Case Study and Basic Tests

Shahrebabak city, Iran, is experiencing a growing demand for renewable energy, highlighting the importance of solar panel installations. This study, which marks the beginning of primary research efforts to optimize steel pile foundations for solar panels in this region, was conducted in collaboration with Zaminrun Geotechnical Company. The project includes comprehensive elements such as solar panel design, geotechnical basic tests, and full-scale pull-out tests, aimed at addressing the unique geotechnical and environmental conditions in Shahrebabak city. (https://zamin-run.com/en/). To assess the geotechnical properties of the site, a series of boreholes were executed, as depicted in Fig. 1 and summarized in Table 1. The Wash Boring method was employed for machine boreholes, resulting in a total of 15 boreholes. Additionally, 14 manual wells were installed, with each reaching a depth of 5 m. To obtain crucial data regarding the site's strength properties, SPT tests were conducted in all the boreholes.

Piles Installations

Two different UNP sizes, namely UNP100 and UNP120, were selected as pile options. In order to ensure the durability of the UNP sections against impact, ST52 material was chosen. The length of all the UNPs was standardized at 3 m to ensure that at least one meter of each UNP remained above ground level when driven to a depth of 2 m. The selected 2-m pile length was chosen to accommodate the lightweight solar panels planned for construction at the site. The pile driving operation was conducted using the ORTECO model (BTP800HD) hydraulic machine. It should be noted that the blow rate during this operation was maintained at 9–10 blows per second. In all the tests, efforts were made to minimize deviations from the center and keep the point close to the surface's center. To prevent any alterations in the pile locations due to the reaction force resulting from the pulling operation, the crane's

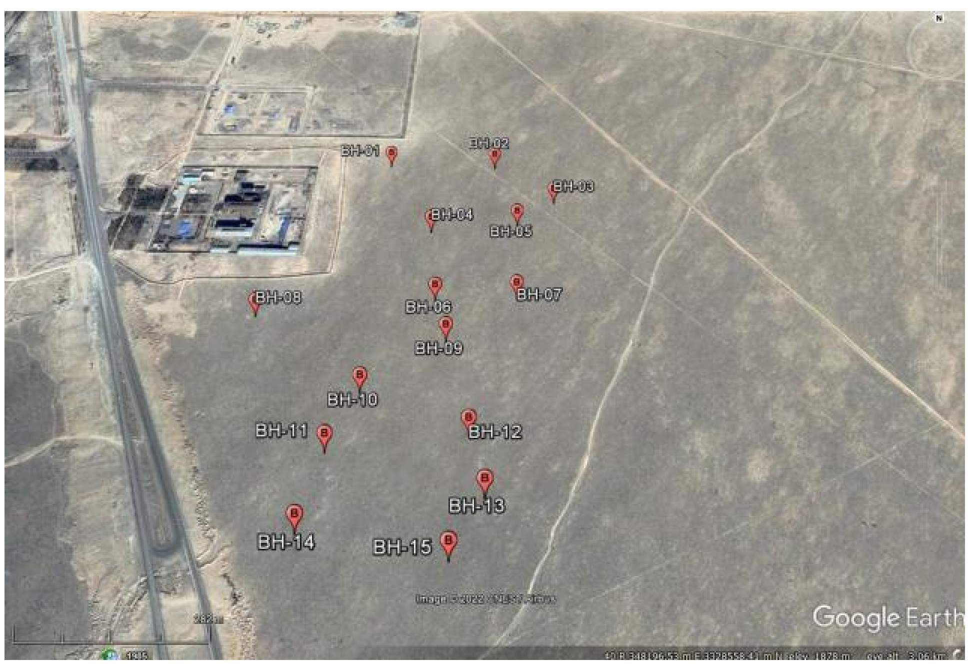

Fig. 1 Borehole locations on the map

Table 1 Details of the bore holes

Borehole No	Coordinates		Depth (m)	Water table level (m)	Organic soil thickness (m)	Soil type USCS
	X	*Y*				
BH-01	347018.0139	3328263.2342	10	–	1.5	SP
BH-02	347254.8316	3328254.6451	10	–	1.0	SP
BH-03	347381.9237	3328130.8120	10	–	1.5	SP
BH-04	347116.7776	3328037.1760	10	–	1.2	SP
BH-05	347298.1623	3328057.2894	10	–	1.0	SP
BH-06	347129.1463	3327838.0575	30	–	1.5	SP
BH-07	347289.3173	3327842.8214	10	–	1.0	SP-SM
BH-08	346782.1113	3327802.5146	10	–	0.8	SP
BH-09	347152.0244	3327732.8809	10	–	0.7	SP
BH-10	347000.2645	3327614.8214	10	–	0.7	SP
BH-11	346951.3065	3327489.3890	10	–	1.5	SP-SM
BH-12	347195.2639	3327519.7326	10	–	1.2	SP
BH-13	347221.5513	3327397.3541	10	–	0.8	SP
BH-14	346921.9933	3327337.8370	10	–	1.5	SP-SM
BH-15	347164.4169	3327287.1363	10	–	1.2	SP

distance (point of effect) from the piles was maintained at a minimum of 1.5 m. In the current study, a total of 40 tests were conducted, comprising 20 tests on UNP 120 (designated as P1-P3…P39) and 20 tests on UNP 100 (designated as P2-P4…P40).

Pull Out Tests

In the vertical tensile loading test, a crane was employed to apply precise and controlled force, maintaining a significant distance from the foundations to minimize the impact of reaction forces on the test results. Ensuring accuracy in testing, a force gauge was securely attached to the crane, and force transmission was facilitated through a chain connected to the foundation. This connection was achieved by creating a 30 mm diameter hole in the piles, positioned approximately 10 cm from their upper edge. The pullout tests were conducted in accordance with ASTM D3689. In the initial phase of the pull-out tests, a force of 500 kgf was applied, and the final displacement was recorded after approximately one minute when the vertical displacement stabilized. Subsequently, the forces were incrementally increased in 500 kgf steps. To meet the requirements of the designed solar panel foundations, the ultimate tensile bearing capacity was determined based on the corresponding upward movement of 20 mm. Detailed information on these tests is depicted in Fig. 2a–e.

Results and Discussions

Load–Displacement Behaviour

The load–displacement behavior of the piles is illustrated in Fig. 3a for UNP120 piles and Fig. 3b for UNP100 piles. It's important to note that, given that the lengths of the piles were considered to be the same, the primary influencing factors were the section of the piles and the geotechnical properties of the site. The load settlement curves for the piles in the study exhibited variations between Fig. 3a and Fig. 3b due to the use of different section sizes—UNP120 and UNP100 served as the test bases. The differing section sizes resulted in variations in stiffness and load-bearing capacity, leading to distinctive load settlement behaviors. Moreover, the geotechnical properties of the site, including soil composition and strength (SPT), exhibited spatial variations. These differences in soil characteristics had a direct impact on the interaction between the piles and the surrounding soil, further contributing to the observed variations in load settlement behavior.

Initially, during the uplift tests, the load-settlement behavior of single piles indicated minimal settlement under increasing applied loads. This consistent behavior across all piles can be attributed to the resistance provided by the surrounding soil and the pile's embedment depth. However, as

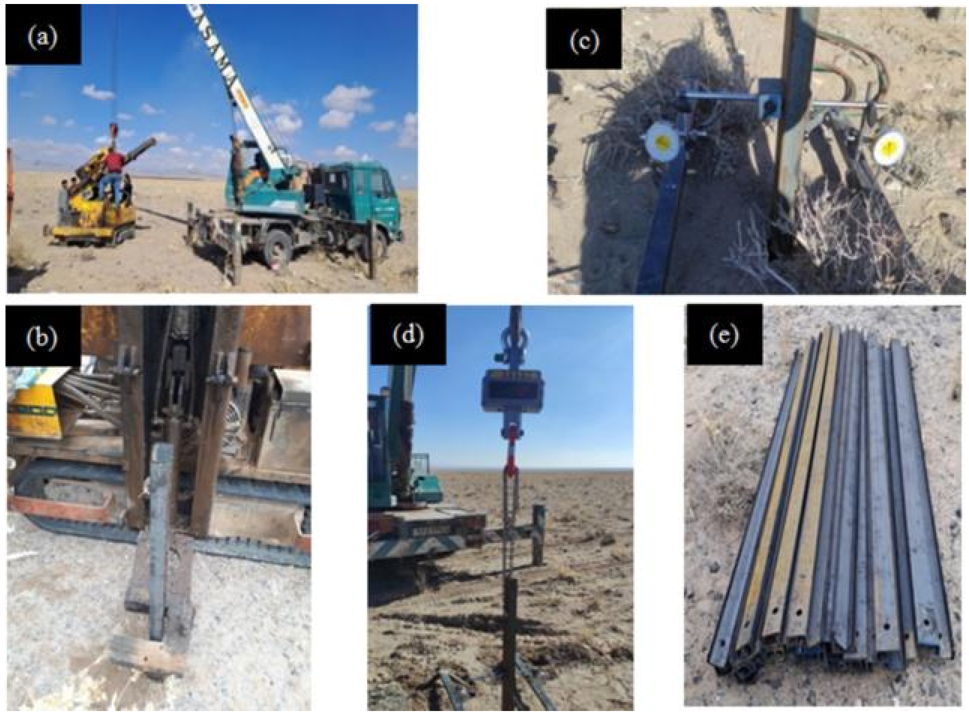

Fig. 2 **a** Pile installations, **b** Pile diving **c** Settlement monitoring, **d** Pull out tests and **e** Pile sections

the load continued to increase, the settlement of the piles also gradually increased. This change in behavior was influenced by factors such as the stiffness of the pile, the properties of the surrounding soil, and the load distribution along the pile.At a certain threshold, known as the ultimate uplift capacity or maximum uplift load, the pile exhibits a rapid increase in settlement, signaling that it is nearing uplift failure. This stage is typically marked by a notable rise in the applied load. Once the ultimate uplift capacity is reached, the pile may undergo sudden and substantial settlement, or even complete failure, depending on the specific conditions of the soil and the pile.

Based on the specific requirements of the project, it was recommended to consider the corresponding force at a upward movement of 2 cm as the final uplift failure load. This criterion takes into account the desired performance and stability of the solar panel structure foundations, ensuring that the uplift forces do not exceed a predetermined acceptable limit. Figure 4a–d depicts the corresponded final load of each curve at upward movement of 2 cm as the failure uplift load. It should be mentioned that the test P09, which had a failure load of 0.29 tons, experienced a failure due to improper installation of the pile. During the test, it was observed that this particular pile underwent inclined penetration, indicating a lack of proper interaction between the pile and the surrounding soil. Consequently, the expected load-bearing capacity and behavior of the pile were not achieved due to this installation failure. Referring to both Figs. 3 and 4, it is evident that this study yielded a diverse range of uplift loads. This variability can be primarily attributed to the distinct geotechnical properties of the soil within the investigated area.

Penetration Rate Versus Uplift Load

It is estimated that the uplift load of the piles is directly dependent on the penetration rate during pile driving. Since the energy applied in the pile driving process was kept constant for all piles during the installation phase, the penetration rate of the pile can be considered indicative of the stiffness of the ground. In this context, Fig. 5a illustrates the relationship between penetration rate (cm/s) and failure uplift load (ton) for each pile. As shown in Fig. 5a, a decrease in penetration rate is associated with an increase in uplift load, likely due to the greater stiffness and strength properties of the ground. Figure 5b presents the developed regression model for penetration rate (cm/s) versus failure uplift load (ton). However, the model exhibits very weak performance indices, particularly a low R^2 value, indicating poor reliability. Therefore, this study does not recommend using this regression model for predicting uplift.

Comparison to Tomlinson Equation and Previous Studies

The Tomlinson equation offers a more straightforward and practical solution, especially in the context of preliminary design considerations, for estimating uplift loads of the piles. The foundation of the Tomlinson equation lies in the principle that the uplift capacity of a pile is primarily influenced

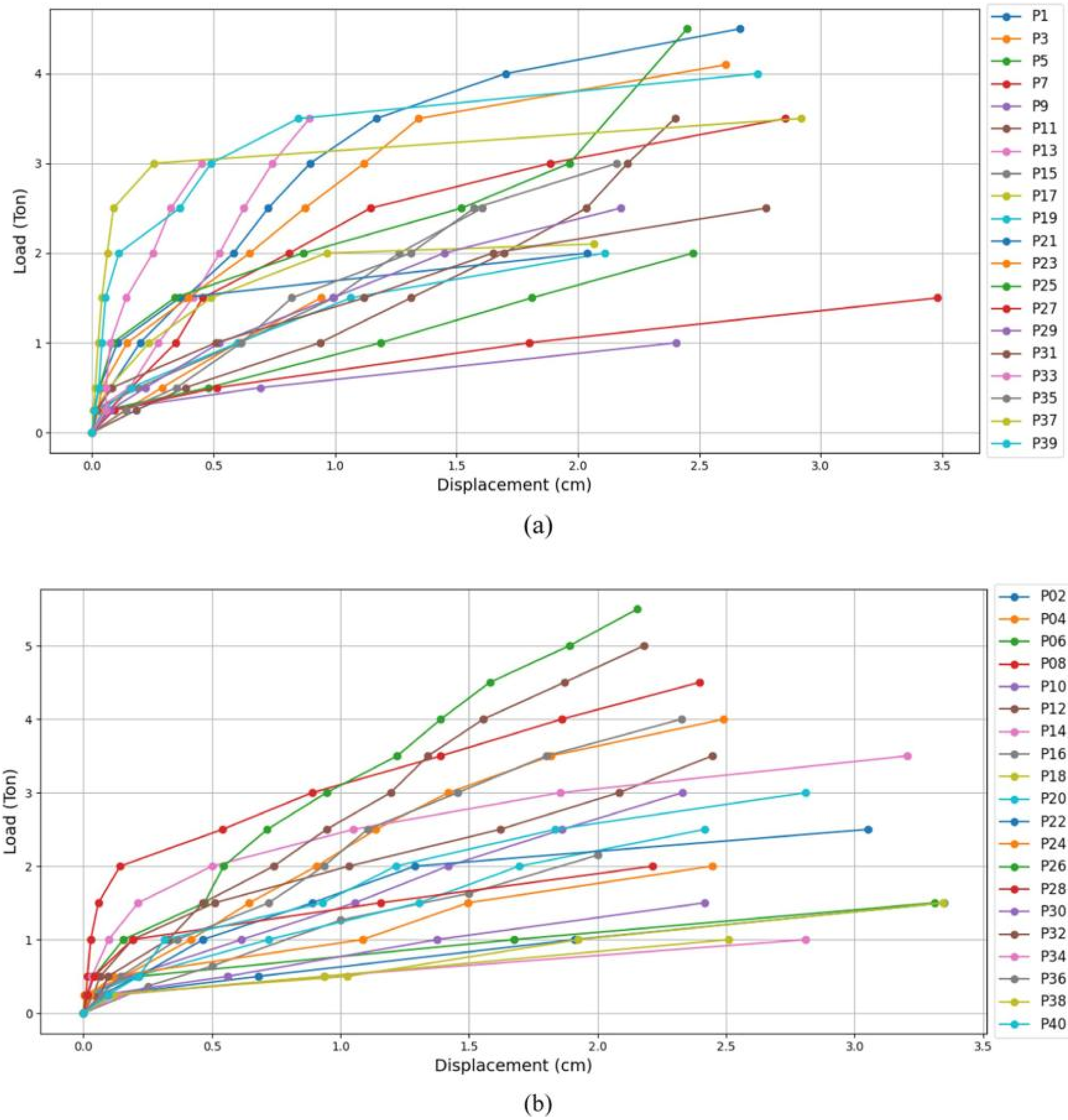

Fig. 3 Load–displacement of the piles **a** UNP 120 and **b** UNP 100

by the side friction developed between the pile surface and the surrounding soil. This side friction is directly proportional to the embedded length of the pile (L) and the SPT value. The SPT value, serving as an indicator of soil density and resistance, reflects the potential for side friction. Hence, given the presence SPT data at the pile locations, the Tomlinson equation emerges as the most suitable method for the purpose of comparison.

The coefficient (k) in the Tomlinson equation accommodates the variability in side friction due to soil type and other factors. Empirical values of 'k' have been established for various soil types, ranging from approximately 0.01–0.03 for cohesive soils. This equation is expressed as:

$$Q_u = k \times L \times N(SPT) \quad (1)$$

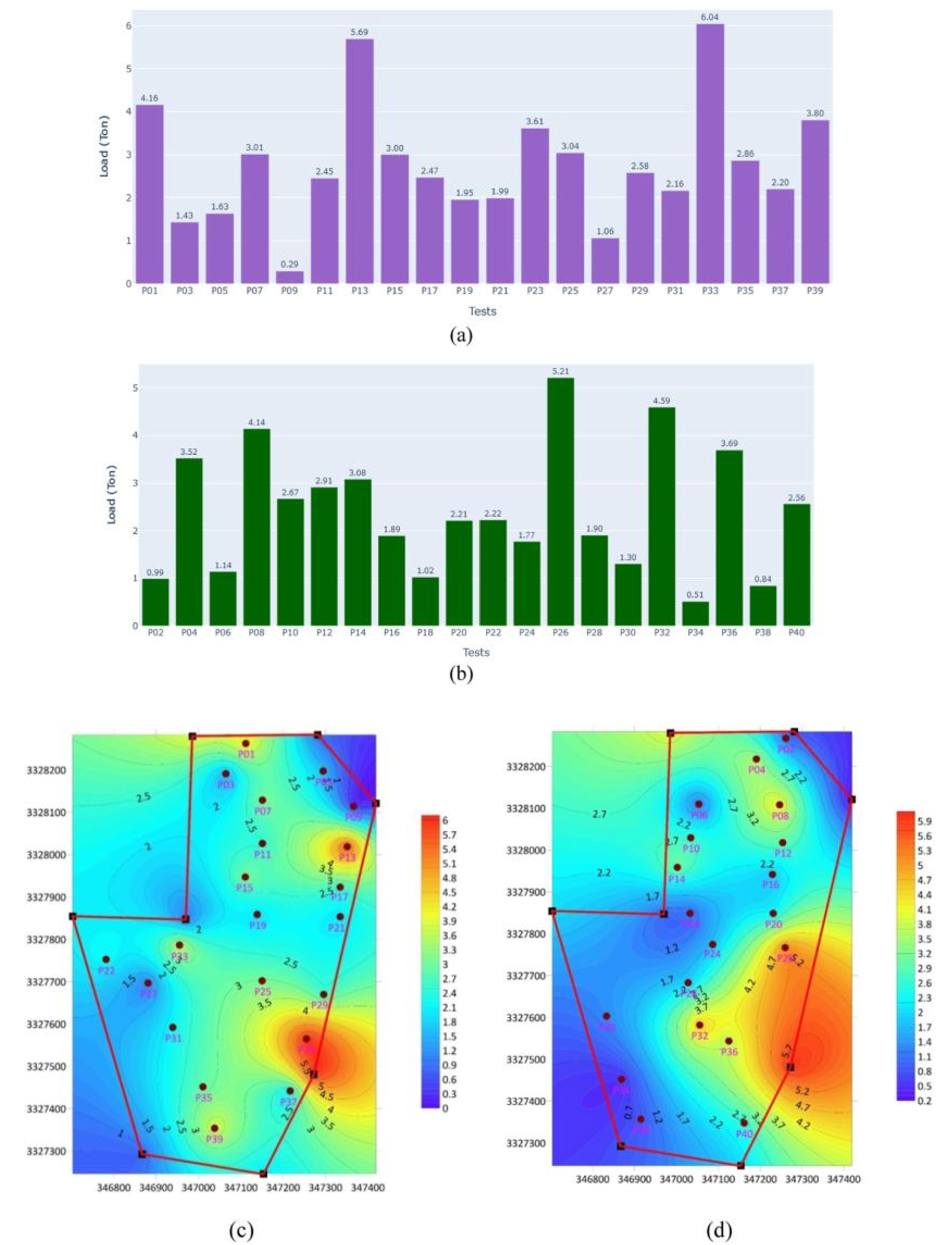

Fig. 4 Failure uplift load of each piles **a** UNP 120, **b** UNP 100 Piles uplift at the site, **c** UNP 120 and **d** UNP 100

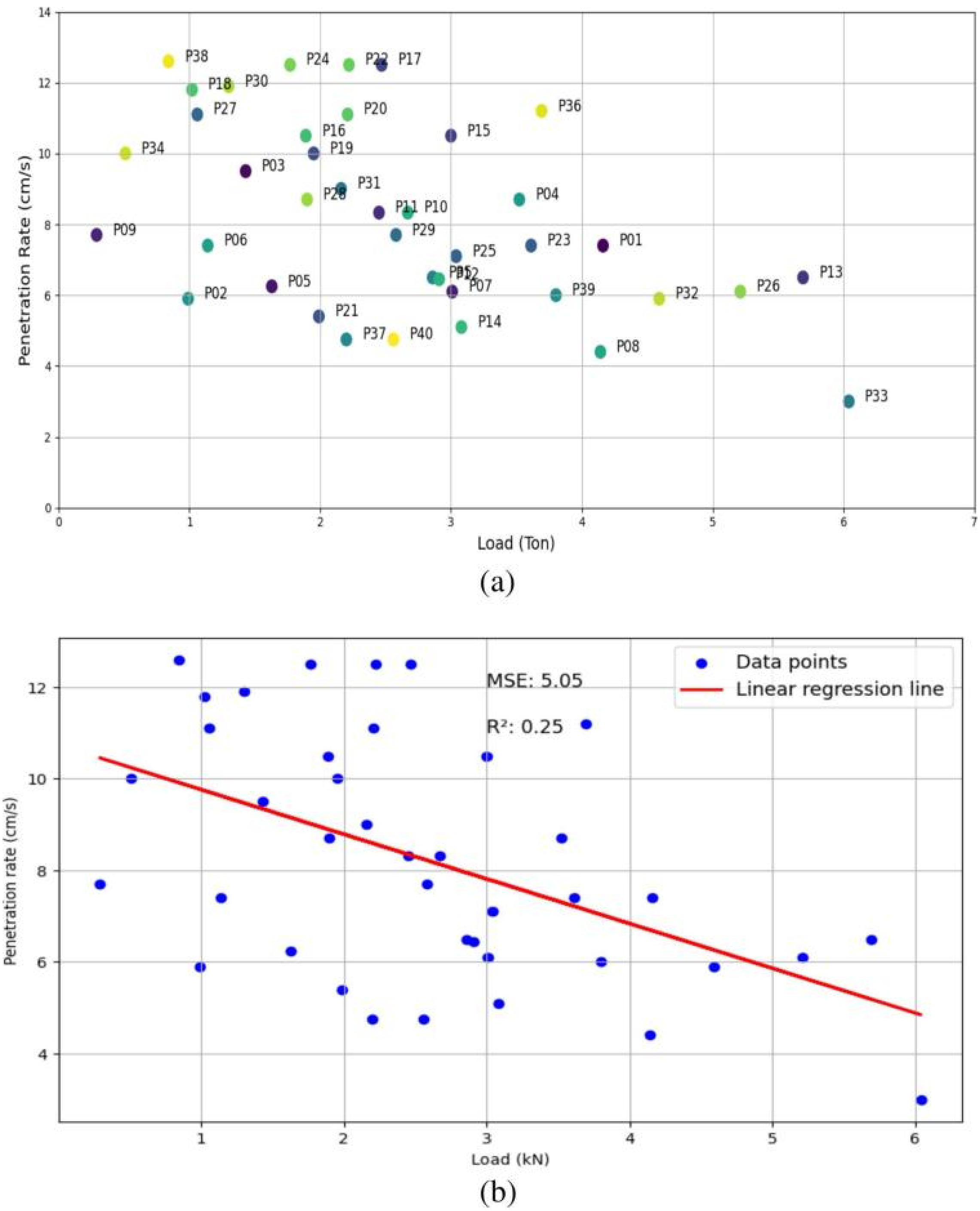

Fig. 5 Penetration rate vs. failure uplift load **a** Piles and **b** Linear regression

where:

- Q_u is the ultimate uplift capacity of the pile (in units of force)
- k is a coefficient that depends on the soil type (typically between 0.01 and 0.03)
- L is the embedded length of the pile (in units of length)
- N(SPT) is the SPT value at the pile location

It is essential to note that the Tomlinson equation comes with several limitations that demand careful consideration in its application. Originally devised for cohesive soils like clays and silts, its efficacy in granular soils, such as sands and gravels, is less established and may require adjustments.

The empirical coefficients of the equation, particularly the '*k*' value, are determined based on observations, introducing uncertainty and potentially overlooking complex factors influencing pile uplift capacity. The equation primarily emphasizes side friction and embedded length, while neglecting secondary effects like soil consolidation, pile group effects, and dynamic loading conditions. In this context, the determined '*k*' values for each pile are illustrated in Fig. 6. As per Eq. 1, the recommended range for '*k*' values is between 0.01 and 0.03. The blue dots in Fig. 6 depict that the calculated piles in the present study align with Eq. 1, whereas the red dots, representing the majority of the data, indicate higher 'k' values were determined.

The observed higher '*k*' values for uplift, compared to the suggested range in the Tomlinson equation, can be attributed to several factors. For instance, the Tomlinson equation presumes a specific range of '*k*' values tailored for cohesive soils. However, the inherent variability in actual soil conditions can significantly deviate from these assumed norms. The equation adopts a generalized approach, and site-specific conditions may introduce variations. Factors such as soil composition, structure, and moisture content, which can differ widely, may contribute to the observed elevation in '*k*' values.

As anticipated, our tests show that increasing the average SPT value of the soil around the piles leads to a corresponding increase in the uplift capacity of single piles. This trend is detailed further in Sect. "Computational Estimation Models". Similar findings are reported in existing studies, which demonstrate that higher soil strength parameters result in increased uplift capacities of piles. For instance, Emirler et al. [32] conducted a series of physical modeling tests to investigate the uplift capacity of both a single rough steel pile and a pile group embedded in sand. Their study evaluated the effects of various parameters, including pile embedment ratio (*L/D*), spacing ratio between piles (*S/D*), and relative density of sand (*Dr*). The experiments used a rough steel pile with a circular cross-section and a diameter of 25 mm. Their results revealed that the uplift capacity of piles increased significantly with the optimization of these parameters, and the interaction between piles diminished in dense soil conditions with larger S/D values. This aligns with our observations, where increased soil strength correlates with enhanced uplift performance of steel piles. The increase in sand strength, which enhances the uplift capacity of single piles, was similarly observed in the study by Abdelgwad et al. [33]. Their research, consistent with our findings, demonstrated that variations in the relative density of the sand (30%, 50%, and 80%) led to a significant improvement in pile uplift capacity, with increases of up to 11 times.

Computational Estimation Models

In this study, we aimed to formulate two computational estimation models for predicting uplift loads in UNP-100 and UNP-120 piles based on available results. The models incorporate the penetration rate of the piles and the average SPT values along the pile length as inputs, while the determined failure uplift load in tons serves as the target variable. The developed estimation models, utilizing the SPT data from the tests, are illustrated in Figs. 7 and 8. For enhanced clarity and comprehension, the SPT values for the pile locations are presented alongside the 3D estimator surfaces to facilitate a more comprehensive presentation and understanding.

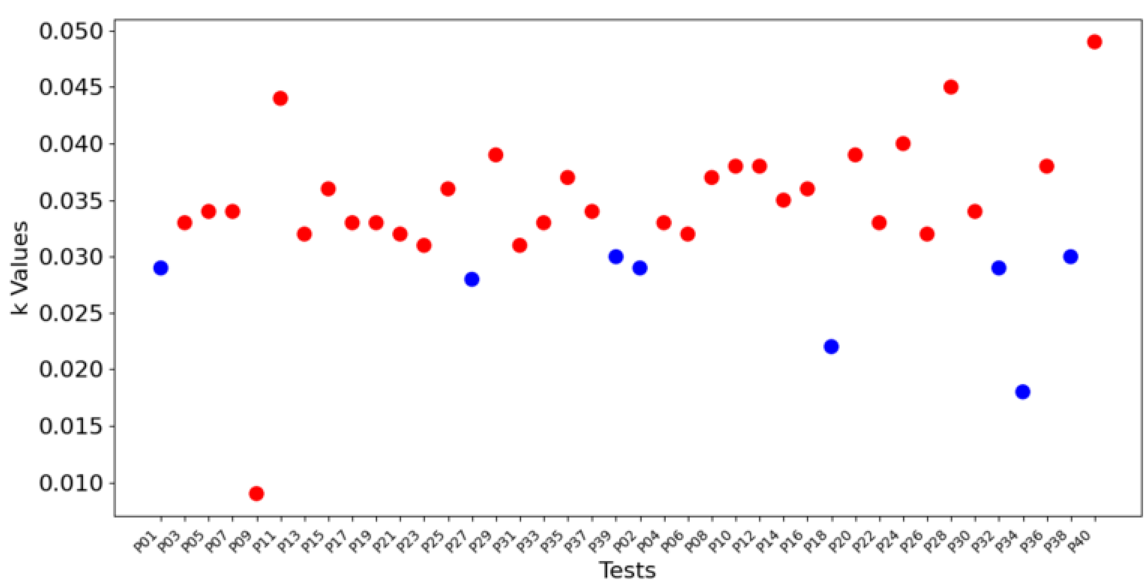

Fig. 6 *k* values of the tests

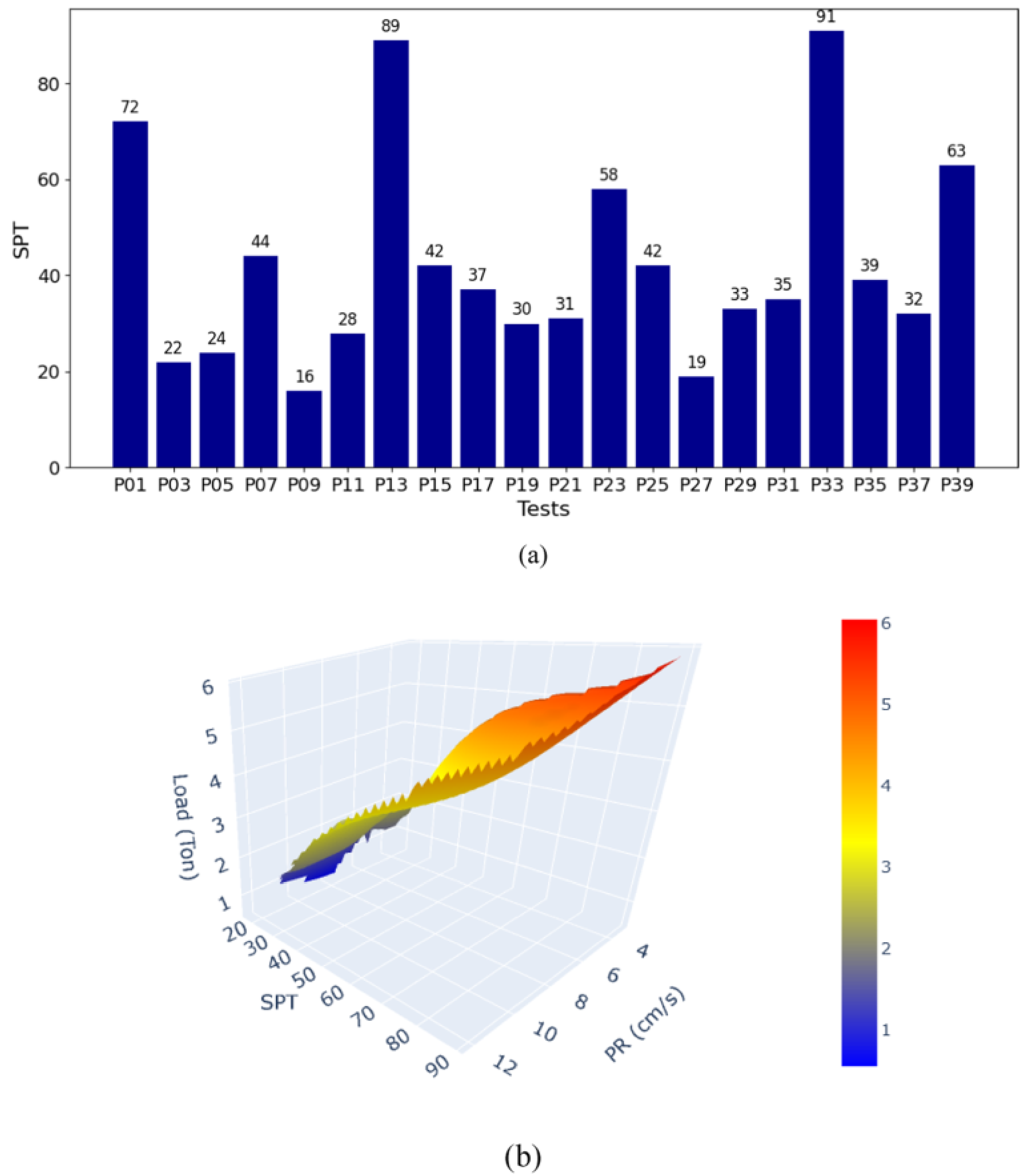

Fig. 7 **a** SPT and **b** Computational estimation surface for UNP 120 (P1-P3…P39)

Upon estimation and analysis of the generated 3D surfaces, a discernible trend emerges: an increase in the SPT values coupled with a decrease in pile penetrations signifies an augmentation in the soil's stiffness and shear strength. Consequently, this leads to a corresponding increase in the determined uplift load. Notably, this trend was consistently observed across all piles.

The computational estimation models were developed using the *LinearRegression()* class in the Python machine learning library scikit-learn (https://scikit-learn.org/) [34]. To be noted, several machine learning models were tested and evaluated using scikit-learn to find the most reliable function for estimating uplift. Among these models, *LinearRegression()* demonstrated the best performance indices. It should be mentioned that, the model for UNP-120 (Eq. 2) exhibited promising performance with performance indices of MSE (mean squared error) = 0.123 tons and R-squared = 0.94. Similarly, the UNP-100 model (Eq. 3) demonstrated favorable results with MSE = 0.118 tons and R-squared = 0.928. These outcomes underscore

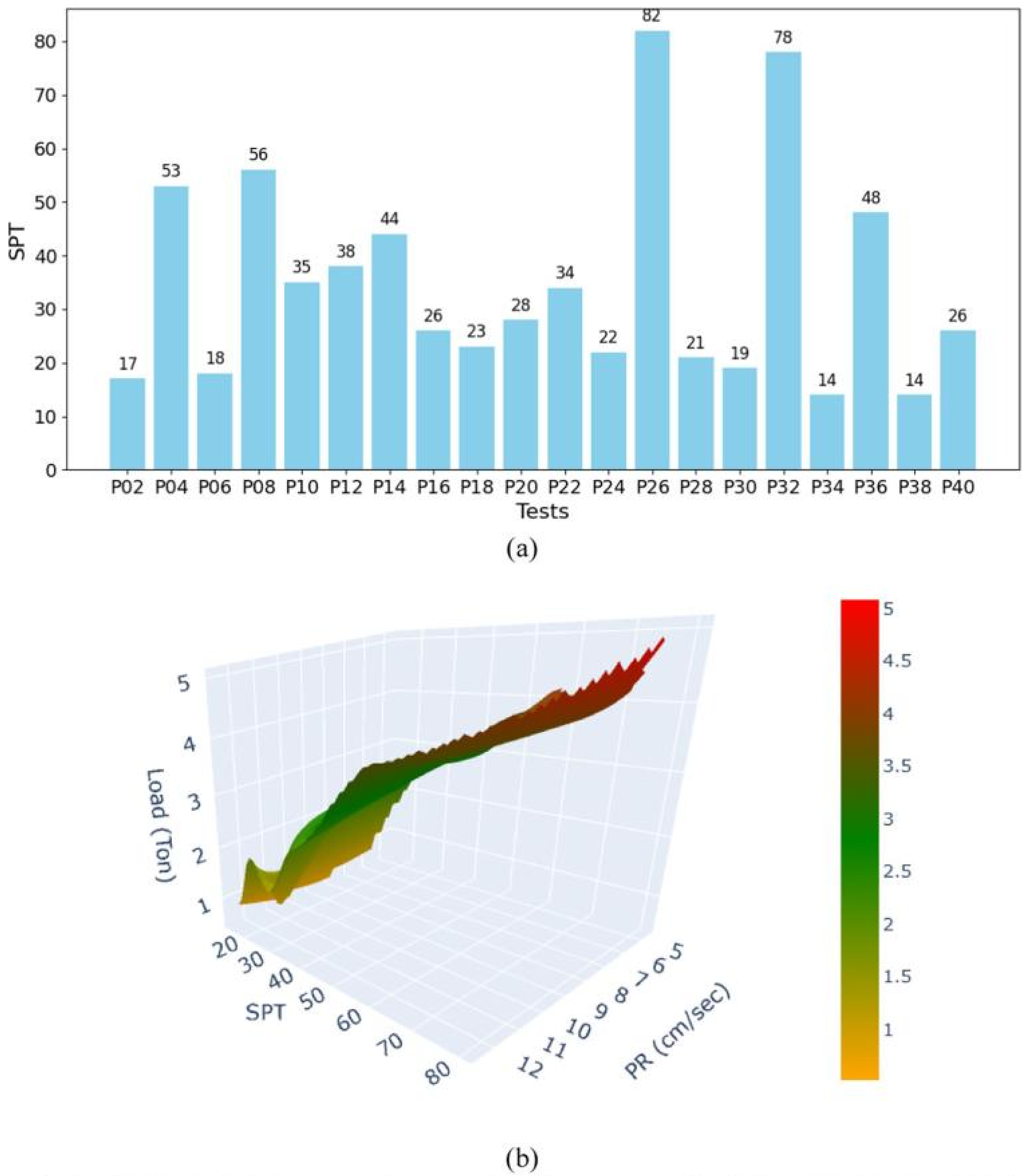

Fig. 8 **a** SPT and **b** Computational estimation surface for UNP 100 (P2-P4…P40)

the satisfactory accuracy of the models in estimating pile uplift. Consequently, these computational tools can be regarded as reliable instruments for geotechnical engineers seeking precise predictions of pile uplift, especially when dealing with similar geotechnical properties. The models provide a valuable resource for enhancing the efficiency and accuracy of uplift load predictions in geotechnical engineering applications.

$$
\begin{aligned}
&\text{Load (Ton)} = \beta_0 + \beta_1 \cdot \text{PR (cm/s)} + \beta_2 \cdot \text{SPT} \\
&\text{Intercept } (\beta_0) : 0.444 \\
&\text{Coefficient for rate } \left(\beta_1\right) : -0.02 \\
&\text{Coefficient for SPT } \left(\beta_2\right) : 0.095 \\
&\text{Mean squared error (MSE)} : 0.123 \text{ Ton} \\
&R - \text{squared } \left(R^2\right) : 0.94
\end{aligned}
\tag{2}
$$

$$\begin{aligned}&\text{Load (Ton)} = \beta_0 + \beta_1 \cdot \text{PR (cm/s)} + \beta_2 \cdot \text{SPT}\\&\text{Intercept } \left(\beta_0\right) : 0.602\\&\text{Coefficient for rate}\left(\beta_1\right) : -0.036\\&\text{Coefficient for SPT}\left(\beta_2\right) : 0.061\\&\text{Mean squared error(MSE)} : 0.118\\&R-\text{squared } \left(R^2\right) : 0.928\end{aligned} \tag{3}$$

Limitations and Future Studies

Despite the promising results, this study has some limitations that should be acknowledged. The research was conducted under specific geotechnical conditions present in Shahrebabak city, which may limit the generalizability of the findings to other regions with different soil properties. Additionally, the study focused on a particular type of steel pile and did not consider other pile materials or geometries, which might exhibit different uplift behaviors. In our study, the use of a high blow rate during pile driving, while effective in achieving rapid penetration, may have introduced certain complexities such as potential grain crushing and altered compaction states of the surrounding soil. These factors could influence the uplift capacity of the piles, and their effects warrant further investigation. To address this limitation, future studies will include a comparative analysis of piles installed with a drop hammer, which operates at a lower blow rate. This comparison will provide deeper insights into the impact of installation methods on pile performance, particularly in terms of uplift capacity and soil-pile interaction under different compaction conditions.

Future studies could explore the application of these models to different geographic locations and soil types, thereby testing their versatility and adaptability. Furthermore, integrating additional machine learning techniques and exploring non-linear models might offer improved predictive capabilities and deeper insights into the complex relationships between geotechnical parameters and pile performance. These steps would not only validate the current findings but also contribute to the development of more universal and reliable predictive models in geotechnical engineering.

Conclusions

In conclusion, this study thoroughly investigates the pullout behaviour of steel piles used as foundations for solar panels in Shahrebabak city, Iran. It includes a comprehensive series of 40 tests, divided evenly between UNP 120 and UNP 100 piles, capturing penetration rates during pile driving under constant energy. Although the preliminary results did not reveal a consistent correlation between uplift load and penetration rate, a detailed analysis of load-settlement behaviour was conducted. The study also compared calculated tensile loads with predictions from the Tomlinson equation, based on standard penetration test (SPT) values, and found consistent results. To enhance the accuracy of predicting pile uplift, two computational models were introduced using the *LinearRegression()* class from the Python machine learning library scikit-learn. By incorporating penetration rate and average SPT values, these models demonstrated strong performance. For UNP-120 piles, the mean squared error (MSE) was 0.123 Ton with an R-squared (R^2) value of 0.94. For UNP-100 piles, the MSE was 0.118 Ton with an R^2 value of 0.928. These results highlight the reliability and effectiveness of the models for accurately estimating pile uplift. Overall, this research provides valuable insights into the pullout behaviour of steel piles in solar panel foundations and presents practical tools for geotechnical engineers to improve uplift load predictions. The robust methodology and findings contribute significantly to the field, offering valuable resources for both future research and engineering applications.

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Data Availability The data for this research is available.

Declarations

Conflict of interest The authors declare no conflicts of interest in presenting this manuscript.

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