Finite Element Analysis on Load-Settlement Behavior of Axially Loaded Pile on Sand

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Abstract

The analysis of geoengineering problems using various constitutive models necessitates substantial field and laboratory research, which entails a significant investment of time and money. As a result, the application of Finite Element Analysis in geoengineering projects is limited. This research focuses on numerically examining the behavior of a pile in a sandy soil layer. The study employs different relationships to estimate soil parameters from standard penetration tests and simple lab tests. These derived parameters, required for the Mohr-Coulomb & Hardening Soil constitutive model and the linear elastic model of the pile, are implemented in the PLAXIS 3D software. This software is used to simulate the settlement of the pile in sandy soil incorporating factors like mesh density and soil-pile interaction. The results of the study reveal that employing a finer mesh size leads to more precise results. Additionally, an interface strength of 67% proves to be more accurate for this study. Furthermore, the correlation introduced by Papadopoulos (1982) exhibits a close relation with field settlement values. In contrast, other correlations either overestimate or underestimate the results. Moreover, the study conclude that Mohr-Coulomb constitutive model satisfactorily predicts the behavior of the pile for the study area.

Keywords: *Constitutive model, Modulus of elasticity, Numerical analysis, Pile settlement*

Introduction

Given the soil's nature and the load imposed by superstructures, pile foundations have gained widespread adoption across diverse construction sites. In the design of vertically loaded piles, paramount importance is placed on the maximum settlement of the pile and its ultimate load-bearing capacity. This critical criterion is evaluated through a combination of theoretical and numerical approaches (Naveen et al., 2011). The accurate prediction of settlement behavior in axially loaded piles constitutes a significant concern within the realm of geotechnical engineering (Gowthaman & Nasvi, 2017). In the context of employing the Finite Element Method (FEM), the careful selection of soil constitutive models and their associated parameters is pivotal for achieving reliable predictions(Dahal et al., 2019). Even the simplest constitutive model, namely the linear-elastic-perfectly-plastic Mohr-Coulomb (MC) model, involves five input parameters: Modulus of Elasticity (E) and Poisson's ratio (ν) to describe soil elasticity, internal friction angle (φ) and cohesion (c) for soil strength, and dilation angle (ψ) for dilatancy (Brinkgreve et al., 2021). On the other hand, advanced models requires more soil parameters based on rigorous soil investigation, which might discourage their use in geotechnical project (Carter et al., 2009; Karstunen et al., 2008; Liu et al., 2011). As a result, there is an urgent need to conduct a systematic study and make recommendations for using correlated data in numerical modeling to simplify the calculation of model parameters.

Objective

The primary objective of the research is to assess the model parameters using various correlations with field pile load tests. Additionally, the study will conduct numerical simulations varying the mesh size and interaction between the soil and pile to observe their impact on the behavior of the model.

Literature Review

Over the past few decades, extensive research has been conducted to explore the characteristics of sands and clays(Dahal et al., 2018). Various scholars have delved into this subject and contributed to the field by presenting formulas, charts, and tables as valuable resources to aid in the design of geotechnical structures (Dahal et al., 2019; Paudyal et al., 2023). The parameters commonly studied in this context include mechanical attributes for sand, such as φ, E, ν, and ψ (Degago et al., 2010). On the other hand, parameters for clayey soil are contingent upon different constitutive models, encompassing the φ, c, E, ν, and compression characteristics (λ, κ, etc.) (Nguyen, 2016). Moreover, soil stiffness parameters, notably E and ν, inflict substantial influence over pile settlement, particularly within sandy soil. The existing body of literature presents a wide spectrum of values for E adapted from FHWA – IF – 02-034 [Webb (1969), Chaplin (1963), Papadopoulos (1982), Bowles (1996), Kulhawy and Mayne (1990)] for sand (Jones, 2020), leading to noteworthy disparities. While ν, like E, is non-linear and dependent on stress. However, the range of v is generally narrower than that of E, so less emphasis is typically placed on precise determination of v (Kulhawy & Mayne, 1990).

Recently, FEM has increased in popularity for the design and analysis of geoengineering projects. In the realm of FEM, the mechanical behavior of soils is replicated through constitutive models(Devkota & Dahal, 2022; Puri & Dahal, 2022; Regmi et al., 2021). However, constitutive models range from the simple to the complex models. While simple models require a limited parameter selection, they might lack key soil behavior features. On the other hand, advanced models encompass more accurate behavior but necessitate more parameters based on soil investigation data, which might discourage their use in geoengineering project analysis and planning (Brinkgreve et al., 2021). The critical factor for successful numerical analysis lies in appropriately determining constitutive model parameters based on available, often limited, ground data and engineering judgment (Kulhawy & Mayne, 1990). Some authors have published predefined model parameter datasets for specific soil types. However, extending this concept to cover all global soil types is challenging and likely impractical(Brinkgreve et al., 2021). As an alternative, this study employs straightforward empirical relationships to estimate certain parameters of the constitutive soil model, such as the elastic parameters of soil materials, based on the SPT value. The most suitable correlation for calculating soil stiffness elastic modulus in FEM is then compared with field settlement values and settlements obtained from numerical simulations.

The numerical analysis relies on the modelling of soil structure interaction which includes the elastic modulus of soil (Esoil), the interface attributes (Eintr), and the friction angle at the interface (φintr). Similarly, satisfactory outcomes were observed in the numerical analysis when Eintr was taken as Esoil. Meanwhile, the friction angle at the interface significantly impacts the modeling process (Khelifi et al., 2011). A significant challenge in numerically simulating the settlement behavior of pile foundations lies in selecting suitable material models and modeling parameters, guided by the geological context and loading conditions. Conversely, different guidelines propose varying ranges for these parameters. Thus, accurately determining or estimating appropriate values for these parameters holds paramount importance for addressing geotechnical problems (Indraratna et al., 2018). The reliability of correlations used in this study is validated with available field data, which is subsequently applicable in solving geotechnical design challenges.

Methodology

The overall approach for conducting the research is outlined in Figure 1. It involves several steps, including reviewing existing literature, conducting field and laboratory investigations to establish geomechanical parameters, creating numerical models, and validating these models using pile load test data. The following section provides in-depth explanations of each step, including the techniques, tools, and materials employed.

Geometry

The computational time required for numerical analysis varies significantly based on the dimensions of the model and its composition in terms of element count (Nasasira Derrick, 2020). Correspondingly, the selection of suitable boundary conditions is a crucial aspect highlighted in various literature (Cho et al., 2012). Thus, for the model's boundary conditions, horizontal movement was constrained for side edges, while the bottom edge was fixed in all directions (Liyanapathirana et al., 2005). The mesh employed was axisymmetric, comprising 10-node triangular elements, enabling calculations for the actual model size completely. Moreover, to enhance model analysis, the mesh size varied from coarse, distant from the pile, to very fine, near the pile which is depicted in Figure 2.

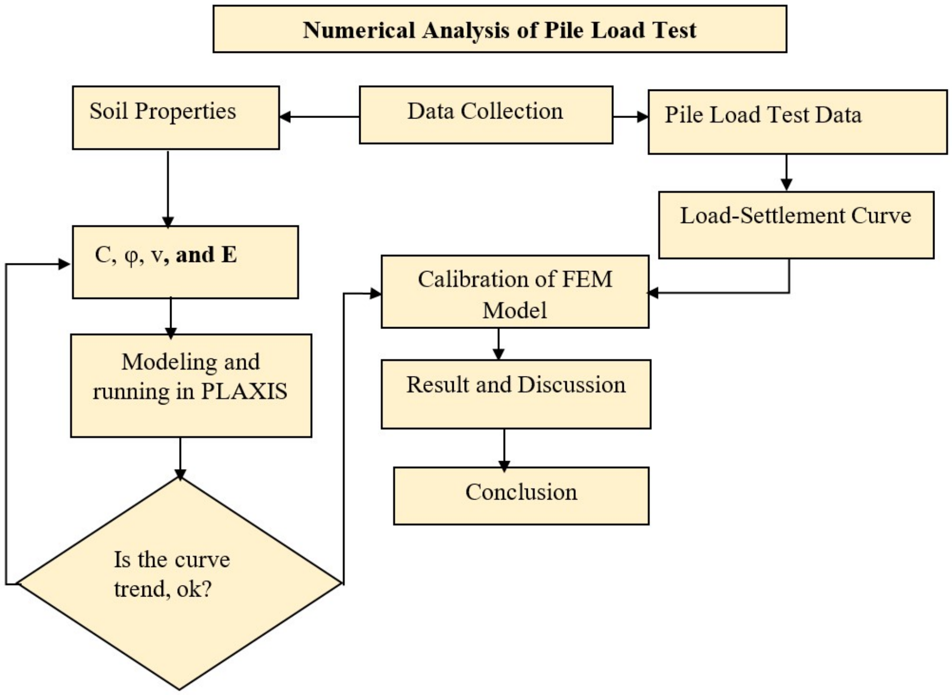

Figure 1: Conceptual framework of the study

The dimension of the model was taken as 20m x 20m x 30m which is actually the 20xB along x and y axis and (D+9B) along z axis.

Geomechanical parameters

The soil investigation program was carried out at Mahuli Khola Bridge in Saptari, Nepal. Laboratory and field investigations were used to determine most parameters, while some relied on correlations (Kulhawy & Mayne, 1990). Standard penetration test (SPT) was performed at different depths and recorded as presented in Table 1.

When conducting numerical simulations for accurate settlement predictions, it's crucial to appropriately select the material model. The choice of material model is influenced by both soil properties and structural loading conditions (Gowthaman & Nasvi, 2017). Piles were simulated using a linear elastic (LE) model, while the soil was represented by the MC model, which is elastoplastic and captures non-linear stress-strain behavior (Yapage & Liyanapathirana, 2017). Soil properties for various layers were assigned based on presumed failure criteria, as indicated in Table1: Unit weight (γ), c, φ, E, and ν. Parameters like c, φ, and γ are determined via lab tests, while E and ν are calculated through different correlations. The MC model approximates primary soil or rock behavior and is recommended for initial problem analysis. Additionally, initial stress conditions are significant in soil deformation issues, and suitable K0 values should be chosen to generate initial horizontal soil stresses (Brinkgreve et al., 2021).

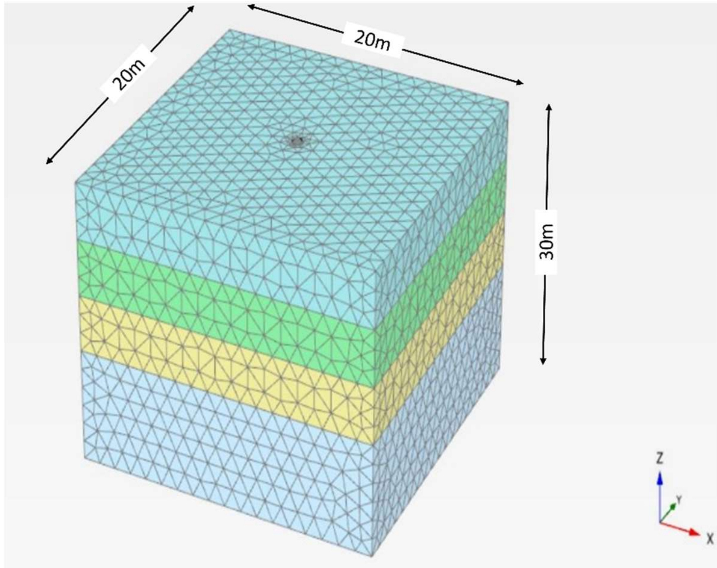

Figure 2: Plaxis 3D model with mesh

Table 1: Soil Properties

Soil Layer	SPT Value (N)	φ^0	Modulus of Elasticity (Mpa)						v
			Bowels (1997)	Tromienkov (1974)	Webb (1969)	Chaplin (1963)	Papadopoulos (1982)	Kulhawy and Mayne (1990)	
L-1	16	30	24220	42114	16620	14650	20300	11000	0.28
L-2	24	30	33541	48121	20824	19740	26565	21166	0.27
L-3	32	31	40927	53627	26383	25890	34860	31400	0.29
L-4	30	32	34756	48647	21270	20260	27230	22666	0.28
L-5	47	32	47940	58523	33247	32885	45100	43000	0.30

Pile and pile load test

A bored pile constitutes a deep foundation, created by pouring concrete into a drilled hole, aiming to transfer the load to deeper layers of the ground(Timilsina & Yadav, 2022). To ensure its design's integrity, static pile load tests are commonly carried out to measure the pile head displacement caused by the load. Gaining insight into the distribution of force along the pile's core, its sharing into friction on the shaft and resistance at the base, and their combined effects can be highly advantageous. This information can be obtained through strain gauge pile instrumentation (Naveen et al., 2011; Zhang et al., 2013). The analysis of an individual pile subjected to axial compression lays the groundwork for the relevant theoretical examination of static pile load tests. Moreover, this analysis aids in predicting settlement and load distribution within a single pile using numerical simulations (Potts & Zdravković, 2001). The characteristics and dimensions of the test pile are summarized in Table 2.

Table 2: Test Pile Properties

Materials	Concrete
Length (m)	22.77
Outer Diameter (m)	1
Young's Modulus (GPa)	30
Poisson's ratio	0.15

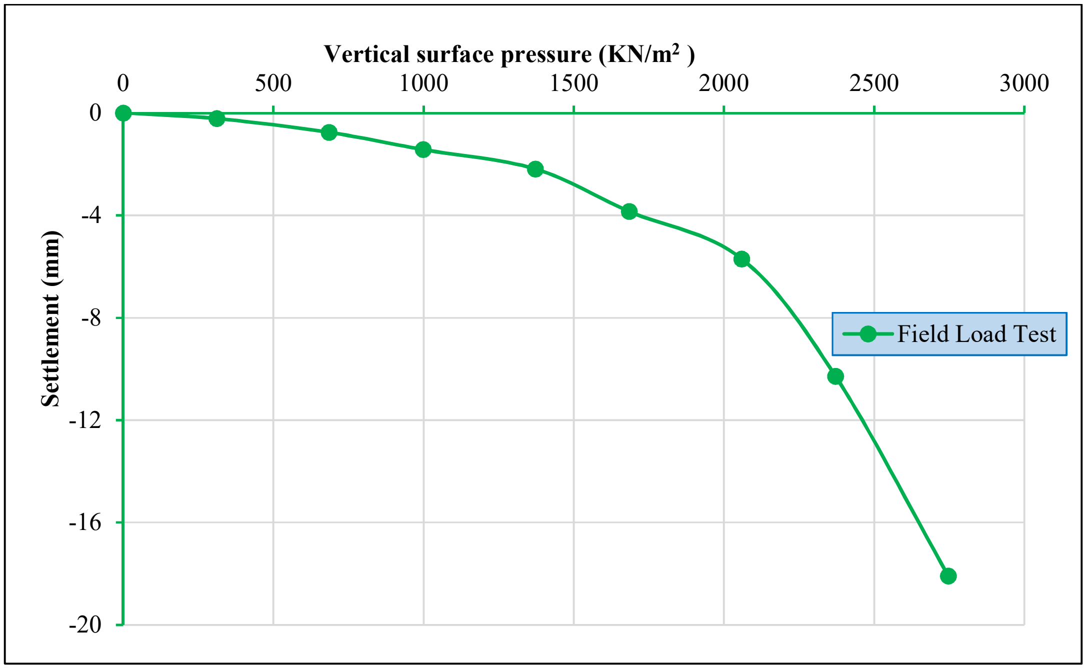

Figure 3: Load vs settlement (Pile load test)

Numerical Analysis

Numerical analysis involves the examination of algorithms that employ numerical approximations to address problems within mathematical analysis. In the context of this study, the aforementioned soil constitutive parameters for MC model are utilized for the analysis, with the drainage condition being taken as drained due to the soil's notable high permeability. While, the pile is model with linear elastic material.

This study employs PLAXIS 3D for both modeling and analysis, as detailed in the PLAXIS CONNECT Edition V21.01 Material Models Manual (Brinkgreve et al., 2021). This numerical analysis encompasses the study of various parameters to assess the effect on the results i.e., effect of meshing on the model, interactions between the soil and piles, as well as the relationship between load and settlement. Finally, the results obtained from the numerical analysis are subsequently compared with results from field pile load tests to validate the model.

Results and Discussion

Effect of meshing on model

Mesh refinement serves as a method employed to enhance the precision of finite element analysis. This technique involves dividing larger elements into smaller ones to increase the element count within the model. Its application proves beneficial in scenarios involving intricate geometry or significant stress gradients. The impact of incorporating mesh refinement into load settlement analysis results in increasing result accuracy by reducing the errors linked to element dimensions (Nasasira Derrick, 2020). As a result, the analysis employs elements containing 10 nodes. It is observed from Figure 4 that finer meshing leads to improved accuracy in settlement trends and predictive capabilities.

Soil pile Interaction

The interaction between soil and pile plays a crucial role in the design of pile foundations. To analyze the load-settlement behavior of these foundations, the PLAXIS software offers a valuable finite element analysis tool. This software facilitates the modeling of soil-pile interaction and the prediction of load-settlement patterns in pile foundations (Naveen et al., 2011).

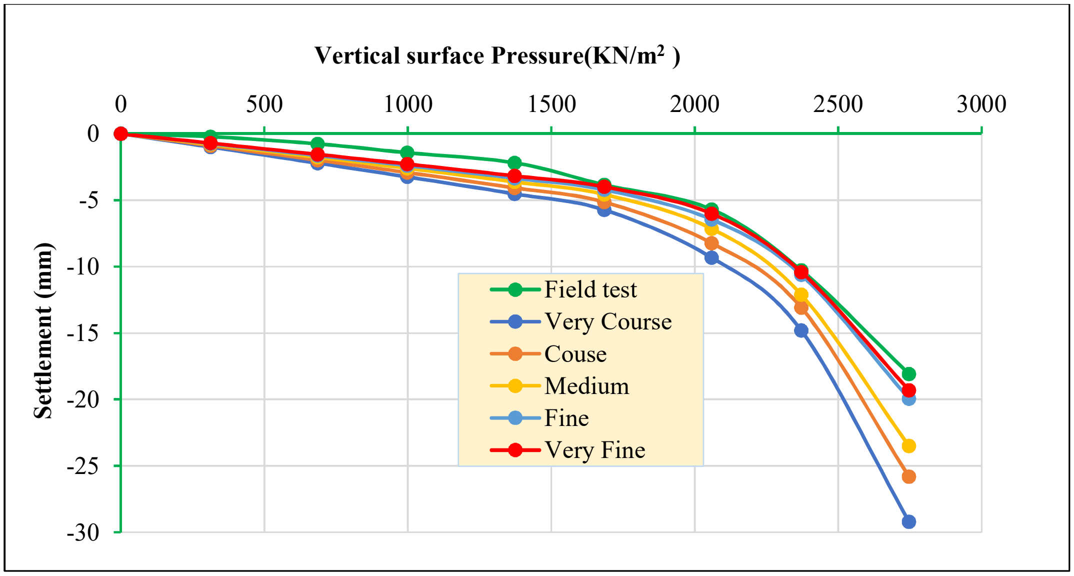

Figure 4: Effect of mesh size on model prediction

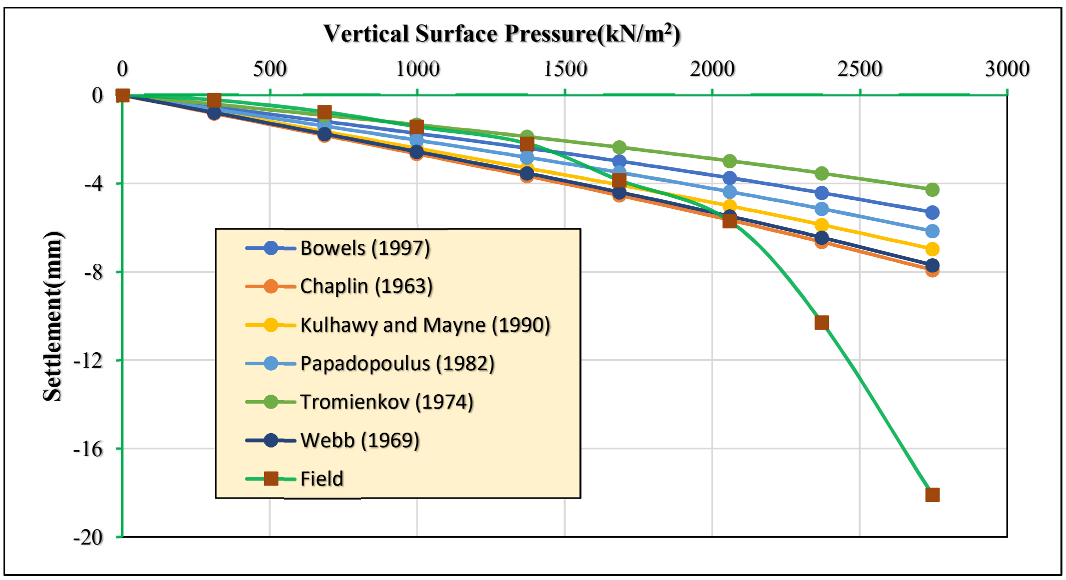

Figure 5: Load vs settlement (Rint=1)

Within PLAXIS 3D, an interface element serves as a bridge between nodes representing different materials. This element effectively models the interaction between the structure and the soil, accounting for factors such as friction resistance and relative movement like slipping and gapping. Importantly, it prevents any overlap between soil and structural elements. To investigate the effects of this interface, we constructed a model of an axially loaded pile. By introducing interfaces with differing strength values (ranging from 0.5 to 1) between the pile and the soil, we aimed to understand their impact on the behavior of the pile-soil system (Khelifi et al., 2011). In the context of soil-pile interactions, the software's interface mechanism yields varying behaviors. For instance, a rigid interface between the soil and pile elements results in a linear correlation between load and settlement, as depicted in Figure 5. Conversely, when dealing with a more flexible interface (Rinter = 0.5), settlement estimation tends to be overly conservative, as illustrated in Figure 7.

Load versus Settlement

In PLAXIS 3D, the load versus settlement analysis serves as a means to assess the response of both soil and structures when subjected to varying loading conditions. This analytical process entails the application of a load onto a structure, followed by the measurement of resultant soil settlement. The outcome of this analysis is then utilized to construct a load versus settlement curve, effectively illustrating the interplay between the applied load and the ensuing settlement magnitude.

In the context of PLAXIS 3D, the software's output from simulating model piles can be harnessed to establish load versus settlement curves. These curves are generated for diverse estimated values of E. Notably, two representative curves have been depicted in Figure 5 to Figure 7, showcasing the load versus settlement relationships based on different correlation. Additionally, to enhance the accuracy, an attempt has been made for more precise correlation by employing a finer mesh, as presented in Figure 4. This analysis shows the impact of mesh refinement on the accuracy of numerical analysis.

The data depicted in Figure 6 elucidates discernible correlation approaches: The Bowels and Tromienkov methods lead to an underestimation of settlement. While the Webb and Chaplin methods overestimate the value significantly. Furthermore, the Papadopoulos correlation closely aligns with actual field settlement values, particularly improving in accuracy with a finer mesh.

Model Validation

Model validation encompasses the systematic procedure of ascertaining whether a model truly represents the dynamics of a given system. This validation process entails a comparison between the model's outputs and data captured from experiments or field tests (Feng et al., 2017). The accuracy with which a model captures reality is what validation is all about (Brinkgreve et al., 2021).

In this study, validation is carried out through the load settlement data acquired from field pile load tests. A series of model analyses have been conducted to assess the settlement variations with the different correlations considered. Notably, both the field data and the Hardening soil (HS) model serve as benchmarks for validating the MC model. The outcomes are presented graphically in Figure 8, illustrating the satisfactory alignment between the simulated field pile settlement and the predictions of the MC model.

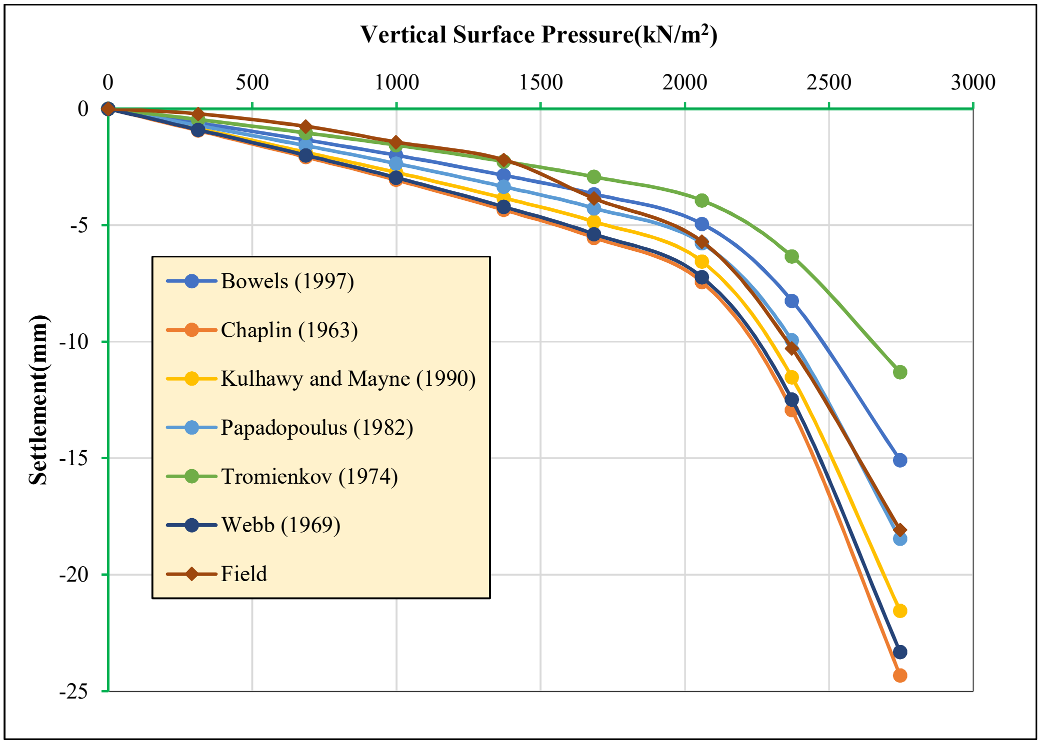

Figure 6: Load vs settlement (Rinter=0.67)

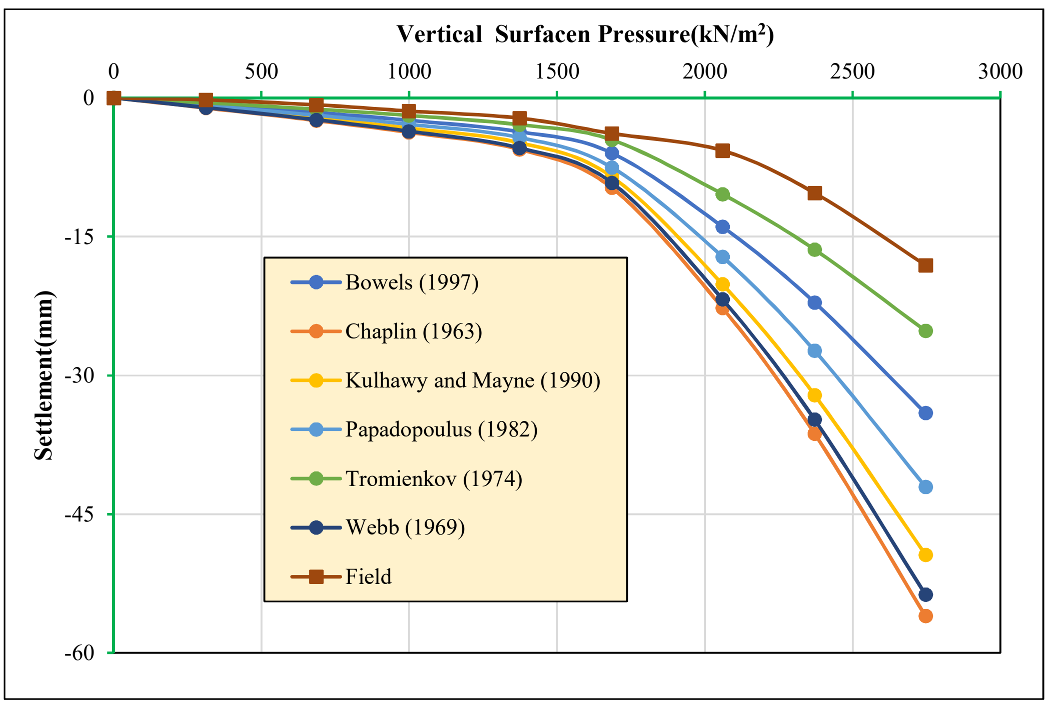

Figure 7: Load vs settlement (Rinter=0.5)

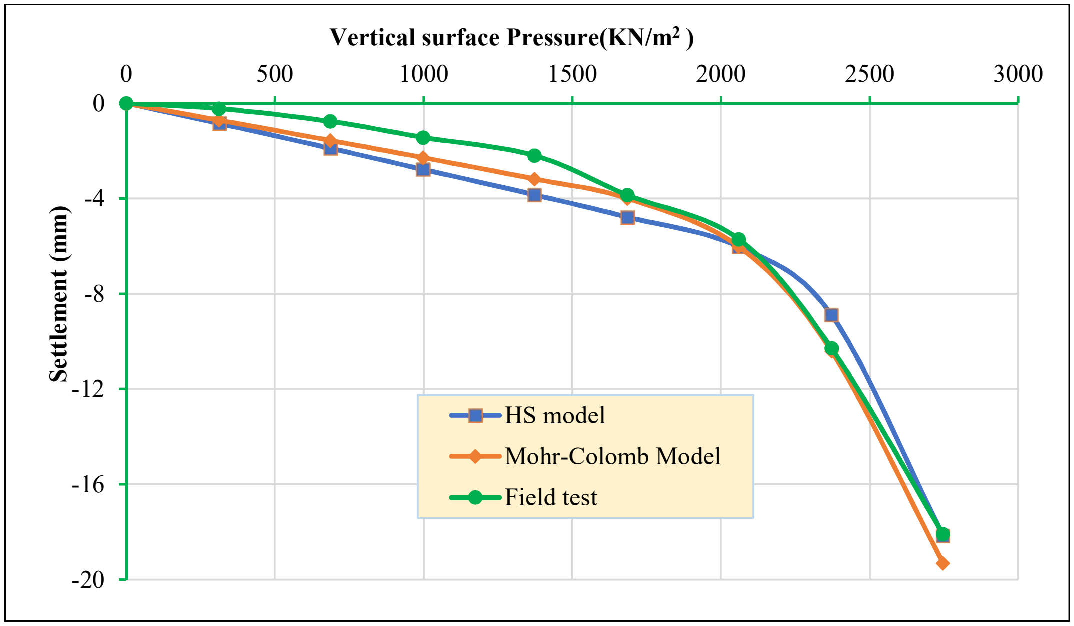

Figure 8: Load vs settlement (Rinter=0.67)

Conclusion

The study analyzed the pile load settlements using different correlations for the modulus of elasticity in the Finite Element Analysis Framework. The investigation takes into account the influence of mesh size and soil-structure interaction on the outcomes. The key findings of the study can be summarized as follows:

- It is observed that employing a finer mesh size yields more accurate results.
- Two correlations, namely Bowles (1996) and Tromienkov(1974), emerge as noteworthy in their tendency to significantly underestimate settlement values. Conversely, the correlations proposed by Webb (1969) and Chaplin (1963) tend to overestimate settlement values.
- The correlation introduced by Papadopoulos (1982) demonstrates close prediction with field settlement values. Moreover, the accuracy of this correlation becomes more pronounced as the mesh size is refined.
- Furthermore, the characteristics and values of settlements are markedly influenced by the interface conditions. When rigid soil-pile interfaces are considered, the load settlement behavior exhibits an approximately linear relationship, and the predictions are underestimated. While the reduced interface strength (as Rinter = 0.67) is considered, both settlement trends and final settlement are close to the filed values.
- Finally, the numerical analysis using the Mohr-Coulomb constitutive model provides satisfactory predictions for pile settlement within the sandy layer.

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