

EVALUATION OF SOIL STIFFNESS PARAMETERS FOR BORED PILE ANALYSIS USING FINITE ELEMENT METHOD AND LOAD–SETTLEMENT CURVES

EVALUATION OF SOIL STIFFNESS PARAMETERS FOR BORED PILE ANALYSIS USING FINITE ELEMENT METHOD AND LOAD–SETTLEMENT CURVES

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Abstrak

Penentuan parameter kekakuan tanah merupakan aspek penting dalam analisis fondasi *bored pile* menggunakan metode elemen hingga karena mempengaruhi akurasi prediksi deformasi. Penelitian ini bertujuan mengevaluasi parameter kekakuan pada model konstitutif *Hardening Soil* melalui validasi hasil analisis numerik terhadap kurva beban–penurunan *Static Load Test* (SLT). Parameter tanah diperoleh dari data lapangan, pengujian laboratorium, dan korelasi empiris, yaitu c' dari nilai *Standard Penetration Test* (SPT), ϕ' dari indeks plastisitas, E_{oed} dan E_{ur} dari uji konsolidasi, serta E_{50} dari korelasi terhadap E_{oed} . Validasi dilakukan menggunakan *Mean Absolute Percentage Error* (MAPE) berdasarkan gradien kurva beban–penurunan pada setiap fase pembebanan. Hasil menunjukkan bahwa nilai MAPE menurun secara konsisten seiring meningkatnya siklus pembebanan dan mencapai kategori *highly accurate* ($MAPE < 10\%$) pada siklus akhir. Evaluasi berbasis gradien menunjukkan bahwa E_{50} belum sepenuhnya merepresentasikan respons pembebanan awal, sedangkan E_{oed} dan E_{ur} mampu merepresentasikan perilaku kekakuan tanah pada pembebanan tinggi serta fase *unloading–reloading*. Pendekatan ini memberikan kerangka yang lebih komprehensif untuk mengevaluasi parameter kekakuan tanah pada model konstitutif *Hardening Soil* dibandingkan validasi yang hanya didasarkan pada deformasi total.

Kata kunci: tiang bor; metode elemen hingga; kurva beban–penurunan; kekakuan tanah.

Abstract

Determining soil stiffness parameters is essential in bored pile analysis using the finite element method because they strongly influence deformation predictions. This study evaluates the stiffness parameters of the *Hardening Soil* constitutive model by validating numerical results against *Static Load Test* (SLT) load–settlement curves. Soil parameters were derived from field investigation data, laboratory testing, and empirical correlations, including c' from *Standard Penetration Test* (SPT) values, ϕ' from the plasticity index, E_{oed} and E_{ur} from consolidation tests, and E_{50} from correlation with E_{oed} . Validation was performed using the *Mean Absolute Percentage Error* (MAPE) based on the gradients of the load–settlement curve during each loading phase. The results show that MAPE consistently decreased with increasing loading cycles and reached the highly accurate category ($MAPE < 10\%$) in the final loading cycle. The gradient-based evaluation indicates that E_{50} does not fully represent the initial loading response, whereas E_{oed} and E_{ur} adequately represent soil stiffness under higher stress levels and during the *unloading–reloading* phases. The proposed approach provides a more comprehensive framework for evaluating soil stiffness parameters in the *Hardening Soil* constitutive model than validation based only on total deformation.

Keywords: bored pile, finite element method, load-settlement curve, soil stiffness.

I. INTRODUCTION

Bored pile foundations are widely used in large-scale infrastructure projects due to their ability to support axial loads and control deformation under various soil conditions. The behavior of such foundations is commonly analyzed using finite element-based numerical methods, such as PLAXIS, which can represent soil–structure interaction more realistically than conventional empirical approaches. However, the accuracy of numerical predictions is highly dependent on the reliability of the input soil parameters, particularly stiffness parameters that exhibit nonlinear behavior and sensitivity to loading conditions[1]

In engineering practice, soil parameters are often determined using empirical correlations based on field data such as the Standard Penetration Test (SPT) and plasticity index. Although practical, this approach is associated with significant uncertainty due to soil variability and limitations of empirical relationships. Therefore, calibration and validation of soil parameters are essential to ensure that numerical models can accurately represent field behavior. A widely accepted approach is to compare numerical modeling results with Static Load Test (*SLT*) results, which are considered a reliable benchmark for foundation response[2].

The load-settlement curve of deep foundations represents the stress–strain relationship of soil developed during the loading process and can therefore be used to identify soil stiffness characteristics[3]. In numerical modeling using PLAXIS, particularly with the Hardening Soil constitutive model, the stress–strain response is governed by key stiffness parameters, namely the secant modulus (E_{50}), oedometer modulus (E_{oed}), and unloading–reloading modulus (E_{ur}). The parameter E_{50} is generally associated with soil stiffness during the initial loading stage, reflecting the nonlinear response of soil to increasing stress[2]. Meanwhile, E_{oed} is related to one-dimensional compression under higher stress levels, where the soil is more confined and undergoes dominant compressive behaviour. In contrast, E_{ur} represents the elastic response of soil during unloading and reloading phases, particularly for soils that have experienced pre-consolidation. Therefore, these parameters directly influence the shape and slope of the load–settlement curve, making it a fundamental basis for evaluating soil stiffness parameters in numerical models[4].

In the validation of numerical models, a quantitative indicator is required to assess the

agreement between predicted and observed responses. One commonly used statistical tool is the Mean Absolute Percentage Error (*MAPE*), which measures the relative deviation between predicted and observed values in percentage form. *MAPE* is advantageous due to its simplicity and ease of interpretation, providing a direct measure of prediction accuracy[5]. In geotechnical applications, this approach allows for a more objective evaluation of model performance, particularly in comparing load–settlement curve characteristics.

Previous studies have shown that advanced computational approaches and intelligent algorithms can improve the prediction accuracy of pile bearing capacity by minimizing the discrepancy between predicted and measured responses[6]. In addition, recent studies have successfully applied finite element analysis in conjunction with Static Load Tests to validate the behaviour of bored piles, demonstrating good agreement between numerical predictions and field observations in terms of ultimate bearing capacity and the overall load–settlement response[7], [8]. These studies have contributed significantly to improving the reliability of numerical analysis for pile foundations.

However, the validation process in most previous studies has primarily focused on matching the ultimate load capacity or the overall settlement response. Although these indicators are essential for evaluating the global performance of pile foundations, they do not necessarily ensure that the adopted soil stiffness parameters accurately represent the nonlinear deformation behavior throughout the loading process. Different combinations of stiffness parameters may produce similar ultimate settlements while exhibiting different load–settlement curve characteristics, particularly during loading, unloading, and reloading stages. Consequently, the evaluation of Hardening Soil stiffness parameters (E_{50} , E_{oed} , and E_{ur}) based on the slope characteristics of the load–settlement curve remains limited in previous studies.

Therefore, this study aims to evaluate soil stiffness parameters in bored pile analysis using the finite element method through a slope-based load–settlement curve approach, with validation performed using *MAPE* during unloading and reloading phases. Unlike previous studies that mainly emphasized the agreement of ultimate bearing capacity and overall settlement, this study focuses on evaluating the representation of soil stiffness through the slope of the load–settlement curve. The proposed approach is expected to provide a more systematic basis for

calibrating Hardening Soil parameters and improve the reliability of finite element analyses in bored pile design, thereby contributing to the development of numerical modeling practices in geotechnical engineering.

II. LITERATURE REVIEW

A. Finite Element Methode

The Finite Element Method (FEM) has become a widely adopted approach for analyzing pile–soil interaction because it can simulate nonlinear soil behavior, complex boundary conditions, and stress-dependent material properties. Numerical software such as PLAXIS implements the Hardening Soil constitutive model, which provides a more realistic representation of soil behavior than linear elastic models by distinguishing loading, primary compression, and unloading–reloading stiffness [1], [9]. The accuracy of numerical predictions, however, strongly depends on the appropriate selection of soil stiffness parameters.

B. Load-Settlement Curve

The load–settlement curve is a fundamental indicator used to evaluate the performance of pile foundations under axial loading. Obtained from Static Load Tests (SLT), this curve represents the relationship between the applied load and the corresponding settlement, providing direct information on the mechanical response of the soil–pile system. In engineering practice, the load–settlement curve is widely used to assess the serviceability and bearing performance of constructed pile foundations, verify design assumptions, and validate numerical models because it reflects the actual in-situ behavior of the foundation under loading [3]. Besides indicating the ultimate bearing capacity, the curve also provides valuable information on the stiffness characteristics of the supporting soil. In particular, variations in the slope of the load–settlement curve represent changes in the deformation response of the soil–pile system at different loading stages. Therefore, the interpretation of slope characteristics offers a rational basis for evaluating soil stiffness and serves as an important reference for calibrating stiffness parameters in finite element analyses [10].

C. Soil Stiffness

Soil stiffness is one of the governing factors controlling the deformation behavior of pile

foundations subjected to axial loading. In the Hardening Soil constitutive model, the stiffness response is represented by three principal parameters: the secant stiffness (E_{50}), the oedometer stiffness (E_{oed}), and the unloading–reloading stiffness (E_{ur}) [2]. These parameters describe different stress paths and collectively control the nonlinear stress–strain response of the soil. Consequently, they directly influence the shape and slope of the load–settlement curve obtained from both field testing and numerical simulation.

The load–settlement curve represents the global deformation response of the soil–pile system, changes in its slope can be associated with variations in soil stiffness during different loading stages. Therefore, comparing the slope characteristics between the Static Load Test and finite element simulation provides a rational basis for evaluating whether the selected stiffness parameters adequately represent field behavior [3], [11].

D. Mean Absolute Percentage Error

Model validation requires a quantitative measure to evaluate the agreement between numerical predictions and field observations. In this study, the Mean Absolute Percentage Error (MAPE) is employed to quantify the percentage difference between the slopes of the load–settlement curves obtained from the Static Load Test (SLT) and the finite element model. A lower MAPE value indicates better agreement and, consequently, a more representative selection of soil stiffness parameters. Owing to its simplicity and straightforward interpretation, MAPE has been widely adopted as an indicator of prediction accuracy in engineering applications [5].

The MAPE is calculated using Equation (1).

$$MAPE = \left| \frac{k_{slt} - k_{fem}}{k_{slt}} \right| 100\% \quad (1)$$

Table 1. MAPE Result Interpretation

MAPE	Interpretation
<10%	Highly accurate forecasting
10% – 20%	Good forecasting
20%–50%	Reasonable forecasting
>50%	Inaccurate forecasting

Source:[5]

where k_{slt} is the slope of the load–settlement curve obtained from the field Static Load Test and k_{fem} denotes the slope of the load–settlement curve

predicted by the finite element model. The interpretation of the calculated MAPE values follows the classification presented in Table 1.

III. PLANNING METHODE

Back analysis is an inverse modeling approach widely used in geotechnical engineering to estimate representative soil parameters by matching numerical predictions with observed field responses. In foundation engineering, this method is commonly applied by comparing calculated and measured load–settlement behavior to reduce uncertainty associated with empirical correlations and limited subsurface data. Through an iterative calibration process, selected soil parameters are adjusted until the numerical model can adequately reproduce the measured response within an acceptable level of error. In this study, back analysis was employed to evaluate soil stiffness parameters of a bored pile foundation by matching the finite element results with Static Load Test (SLT) data, with particular emphasis on the slope characteristics of the load–settlement curve during loading, unloading, and reloading stages. After the calibrated parameters were obtained, they were considered to represent the actual in-situ soil behavior and used as the basis for subsequent interpretation.

A. Soil Data and Parameter Determination

Soil parameters used in this study were obtained from a combination of field investigation data and laboratory testing. The primary field data consisted of Standard Penetration Test (SPT) results, which were used to estimate the effective cohesion (c') through empirical correlations. The undrained shear strength C_u is determined as $4,5N$ for soils with a plasticity index (PI) $> 30\%$, and increases to $8N$ for low-plasticity clays with $PI < 15\%$. To maintain a conservative analysis, C_u value of $4,5N$ is adopted[11]. Furthermore, according to [12], the effective cohesion c' is correlated to the undrained shear strength as $0,1C_u$.

The effective internal friction angle ϕ' was determined based on correlations with the plasticity index (PI) derived from laboratory testing. Following established empirical relationships, two correlation levels were considered: a moderate correlation, as defined by Equations (2) and (3)..

$$\text{moderate} \quad \phi' = 43 - 10 \log(PI) \quad (2)$$

$$\text{conservative} \quad \phi' = 39 - 11 \log(PI) \quad (3)$$

These parameters represent the shear strength characteristics of the soil and serve as fundamental inputs in the numerical model [12]. In addition to strength parameters, soil stiffness parameters were determined from laboratory consolidation tests. The oedometer modulus (E_{oed}) and unloading–reloading modulus (E_{ur}) were obtained directly from the consolidation curves, reflecting the compressibility and elastic response of the soil. The secant stiffness modulus (E_{50}), which represents soil stiffness under primary loading conditions, was estimated through correlation with E_{oed} based on established empirical relationships. These stiffness parameters are essential for capturing the nonlinear stress–strain behavior of soil[13].

The initial soil parameters adopted in the finite element model were obtained from a combination of field investigations, laboratory testing, and empirical correlations. Specifically, the effective cohesion (c') was estimated from SPT data, the effective friction angle (ϕ') was determined from the Plasticity Index (PI), the stiffness parameters (E_{oed} and E_{ur}) were obtained from consolidation tests, and E_{50} was estimated through its empirical correlation with E_{oed} . Table 2 summarizes the initial soil parameters used in the numerical model.

Table 2. Initial Soil Parameters Used in the FEM

Soil Stratigraphy	c'	ϕ'	E_{50}^{ref} (kN/m ²)	E_{oed}^{ref} (kN/m ²)	E_{ur}^{ref} (kN/m ²)
Embankments	non-cohesive	25	15000	15000	75000
Soft Stiff					
Silty Clay	16,3	20	1996	1996	7245
Loose Silty Sand	14,4	24	3324	3324	10080
Medium					
Dense Silty Sand	non-cohesive	23	4173	4173	10004
Dense, Silty Sand	non-cohesive	20	5270	5270	13001
Medium Stiff					
Silty Clay	15,6	25	3865	3865	9762
Alluvium	15,6	25	4679	4679	10707

Therefore, these initial values were treated as preliminary inputs and were subsequently refined through the back analysis procedure to obtain representative in-situ soil stiffness parameters.

B. Finite Element Method (FEM) Modeling

The analysis was carried out using the finite element method implemented in PLAXIS. The soil behavior was modeled using the Hardening Soil constitutive model, which is capable of simulating

nonlinear and stress-dependent stiffness. This constitutive model distinguishes between loading, unloading, and reloading conditions, making it suitable for representing the nonlinear behavior of soil surrounding bored pile foundations under axial loading [2].

The bored pile was modelled as a linear elastic structural element embedded within the soil domain. Appropriate boundary conditions were applied to minimize boundary effects, including fixed boundaries at the bottom and restrained horizontal movement along the lateral boundaries. A refined finite element mesh was generated around the pile to improve the accuracy of stress and deformation calculations within the critical soil–pile interaction zone. The initial soil parameters obtained from field investigations, laboratory testing, and empirical correlations were assigned to the corresponding soil layers. The axial loading was then applied incrementally to reproduce the loading sequence of the Static Load Test (SLT), including loading, unloading, and reloading phases. This procedure enabled the numerical model to capture the complete nonlinear response of the soil–pile system.

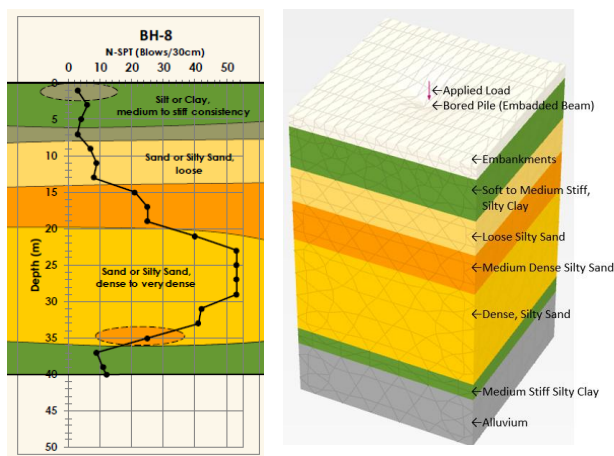


Figure 1. (a) Actual soil stratigraphy interpreted from borehole investigation and (b) finite element model developed based on the representative soil layers.

Figure 1(b) illustrates the finite element model established from the interpreted borehole stratigraphy presented in Figure 1(a). The original subsurface profile was simplified into several representative soil layers according to changes in soil type and consistency, while preserving the actual stratigraphic sequence. Each representative layer was assigned homogeneous engineering properties using the initial soil parameters presented in Table 2. The soil domain was discretized into finite elements, and the bored pile was modelled as an embedded structural element

within the layered soil profile. The model boundaries were defined sufficiently far from the pile to minimize boundary effects, with the bottom boundary fully restrained and the lateral boundaries restricted against horizontal displacement. This modeling strategy provides a representative numerical simulation of the in-situ soil condition and enables the nonlinear soil–pile interaction and depth-dependent variation in soil stiffness to be evaluated under axial loading.

C. Simulation of Static Load Test (SLT) Response Using FEM

The primary output of the finite element analysis was the load–settlement curve, which represents the relationship between the applied axial load and the resulting pile settlement. This curve was generated by recording the displacement response of the pile head at each loading increment. The resulting curve provides a comprehensive representation of the deformation behavior of the pile–soil system.

In addition to the overall load–settlement response, the curve was analyzed in terms of its slope at different loading stages. The initial loading phase reflects the stiffness associated with E_{50} , while the unloading and reloading phases are primarily influenced by E_{ur} . At higher load levels, the curvature of the curve is associated with increasing confinement and is influenced by E_{oed} . Therefore, the load–settlement curve serves as an indirect representation of the underlying soil stiffness parameters.

The generated numerical curve was then compared with the load–settlement curve obtained from the Static Load Test (SLT). Both curves were analyzed not only in terms of total displacement but also in terms of their shape and slope characteristics. This comparison forms the basis for evaluating the accuracy of the numerical model.

D. Model Validation

The validation of the numerical model was conducted using the Mean Absolute Percentage Error (MAPE) as a quantitative measure of agreement between numerical predictions and field observations. Unlike conventional approaches that compare only total settlement, this study evaluates the error based on the slope of the load–settlement curve, particularly during unloading and reloading phases. This slope-based approach provides a more sensitive assessment of soil stiffness behavior.

An iterative back analysis procedure was performed by adjusting the stiffness parameters,

particularly E_{50} and E_{ur} , to minimize the $MAPE$ value. The process was repeated until an acceptable level of agreement was achieved. The final calibrated parameters were considered representative of in-situ conditions and used as the basis for further interpretation of soil behavior.

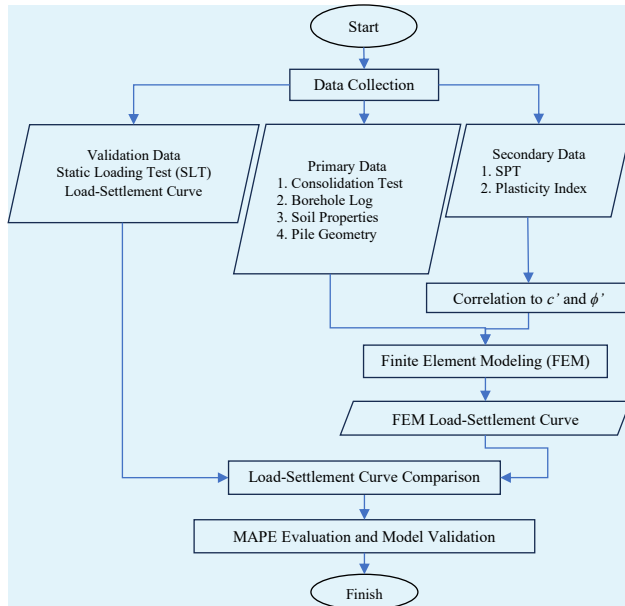


Figure 2. Flowchart of the research methodology

IV. RESULTS AND DISCUSSION

The results of the numerical analysis are presented in terms of load–settlement response obtained from the finite element modeling using PLAXIS. The primary objective of this study is to evaluate the soil stiffness parameters by comparing the numerical predictions with field measurements from the Static Load Test (SLT). Therefore, the discussion focuses not only on the magnitude of settlement but also on the shape and slope characteristics of the load–settlement curve, which reflect the underlying soil stiffness behaviour.

A. Load-Settlement Curve Comparison

The load–settlement curves obtained from the field Static Load Test (SLT) are presented in Figure 2. Following the ASTM D1143 testing procedure, the pile was subjected to four consecutive loading cycles with maximum applied loads of 1000, 2000, 3000, and 4000 kN, respectively. In each loading cycle, the applied load was increased incrementally to the designated maximum load and subsequently reduced to zero during the unloading stage. After complete unloading, the next loading cycle was initiated from zero load and continued beyond the maximum load of

the preceding cycle until reaching the next target load[14]. This loading sequence enabled the evaluation of pile behavior under progressively increasing stress levels and was consistently reproduced in the finite element simulation.

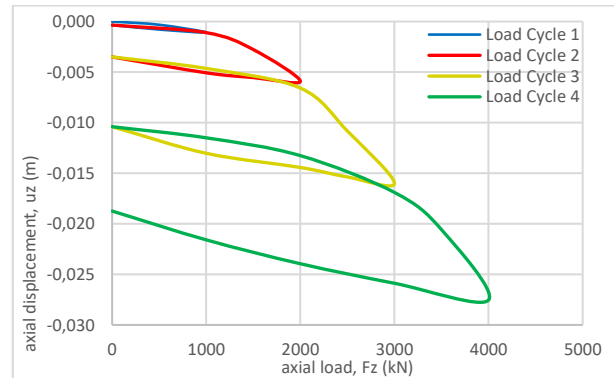


Figure 3. Load-displacement curve SLT

The field load–settlement curves shown in Figure 3 represent the actual pile response under successive loading, unloading, and reloading cycles. As the maximum applied load increases from one cycle to the next, the curves exhibit progressively larger settlements and a more pronounced nonlinear response, reflecting the stress-dependent stiffness characteristics of the surrounding soil. These measured responses serve as the benchmark for evaluating the capability of the finite element model to reproduce the in-situ pile–soil behavior.

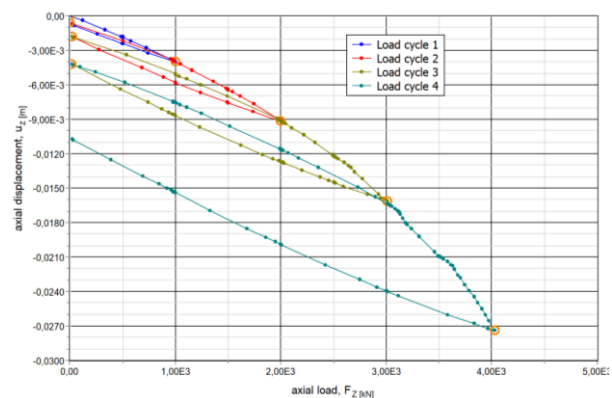


Figure 4. Load-displacement predicted with FEM

Figure 4 presents the load–settlement curves predicted by the finite element model using the same loading sequence adopted in the Static Load Test. Comparison of Figure 3 and Figure 4 demonstrates that the numerical model successfully reproduces the overall nonlinear behavior of the pile–soil system throughout the four loading cycles. Larger discrepancies are observed during Load Cycle 1 and Load Cycle 2, indicating that the initial loading

stiffness is not yet fully represented by the adopted soil parameters. In contrast, closer agreement is achieved during Load Cycle 3 and Load Cycle 4, where the FEM curves exhibit similar nonlinear trends and unloading–reloading behavior to the measured responses. Overall, the agreement between the numerical and experimental curves indicates that the adopted soil parameters provide a reasonable initial representation of the in-situ soil behavior.

Although the overall agreement between the FEM and SLT curves can be assessed visually, evaluation of soil stiffness requires a more objective interpretation based on the gradient of the load–settlement curves. Therefore, the subsequent discussion focuses on the slope characteristics of Load Cycle 3 and Load Cycle 4, where the influence of the Hardening Soil stiffness parameters (E_{50} , E_{oed} , and E_{ur}) becomes more pronounced.

B. Slope-Based Analysis of Soil Stiffness Parameters

The slope of the load–settlement curve is used in this study as a key indicator to evaluate soil stiffness behavior under different loading conditions. As previously discussed, the load–settlement response can be interpreted as a field-scale representation of the stress–strain relationship, where load corresponds to stress and settlement corresponds to strain. Therefore, variations in the slope of the curve reflect changes in soil stiffness, allowing different stiffness parameters in the Hardening Soil constitutive model to be interpreted according to the corresponding loading stage [2].

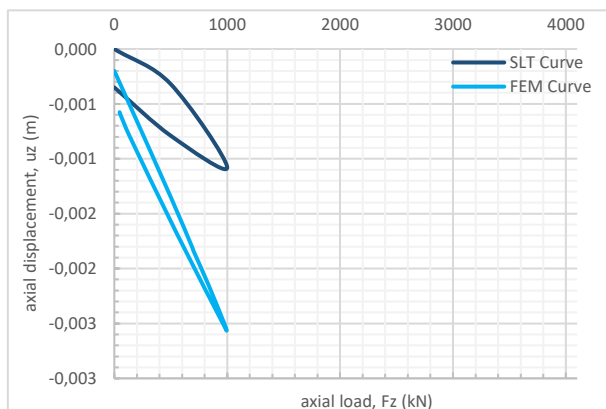


Figure 5. Curve gradient comparison by load cycle 1

Figure 5 compares the gradients of the load–settlement curves obtained from the FEM simulation and the SLT measurements during Load Cycle 1. At this initial loading stage, a significant difference is

observed between the numerical and field responses. The FEM model exhibits a higher load–settlement stiffness gradient ($\Delta F_z / \Delta u_z$), indicating that the adopted stiffness parameters produce a response closer to linear elasticity during the initial loading stage. This behavior is further evidenced by the nearly overlapping loading and unloading curves predicted by the FEM model, suggesting that only limited permanent deformation develops within the simulated soil. Conversely, the SLT response shows a clearer separation between the loading and unloading curves together with a more pronounced change in curve shape, indicating that the stiffness of the in-situ soil decreases progressively as the applied load increases. These observations suggest that the adopted E_{50} parameter does not yet fully reproduce the initial nonlinear stress–strain behavior of the in-situ soil. Since E_{50} represents the secant stiffness under primary loading in the Hardening Soil constitutive model, this discrepancy indicates that the initial loading stiffness is not yet adequately represented in the numerical model [2].

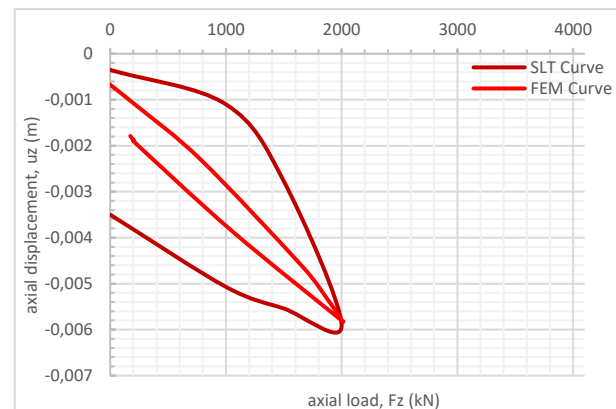


Figure 6. Curve gradient comparison by load cycle 2

Figure 6 compares the gradients of the load–settlement curves obtained from the FEM simulation and the SLT measurements during Load Cycle 2. Compared with Load Cycle 1, the overall shape of the numerical and field responses remains different, particularly during the loading stage. However, the discrepancy between the two responses becomes smaller as the applied load increases. The SLT curve exhibits a gradual reduction in stiffness with increasing load, resulting in a load–settlement response that approaches the FEM prediction. Consequently, both curves reach nearly the same settlement at the maximum applied load of 2000 kN, indicating that the numerical model provides a reasonable representation of the soil behavior under higher stress levels. In the SLT response, the

reloading, loading, and unloading paths are clearly distinguishable, reflecting the progressive change in soil stiffness during the loading cycle. In contrast, the FEM response still shows very similar gradients between the reloading and loading paths, whereas the unloading path begins to separate more distinctly from the loading curve. This indicates that the numerical model starts to capture the unloading behavior more realistically than in Load Cycle 1, although the stiffness evolution during reloading and subsequent loading is not yet fully represented.

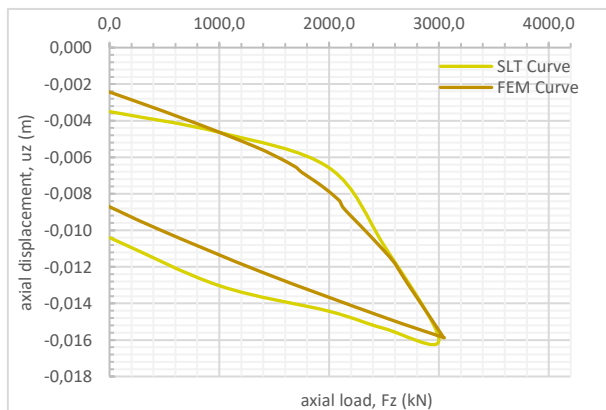


Figure 7. Curve gradient comparison by load cycle 3

Figure 7 compares the gradients of the load–settlement curves obtained from the FEM simulation and the SLT measurements during Load Cycle 3. Compared with the previous loading cycles, the agreement between the numerical and field responses becomes more consistent throughout the loading history. The loading, unloading, and reloading paths predicted by the FEM model are more clearly distinguished and closely follow the corresponding SLT response. Although slight differences are still observed in the intermediate loading range, where the FEM curve exhibits a smoother transition than the SLT curve, both responses converge to nearly identical settlements at the maximum applied load of 3000 kN. This result indicates that the numerical model is able to represent the stress-dependent stiffness behavior more realistically under higher stress levels. In the Hardening Soil constitutive model, soil stiffness progressively shifts from the primary loading stiffness (E_{50}) toward the constrained compression stiffness (E_{oed}) as compression develops under increasing stress levels [11]. The close agreement observed between the FEM and SLT responses therefore suggests that the initial E_{oed} value adopted in this study provides a reasonable representation of the in-situ soil behavior under relatively high loading conditions.

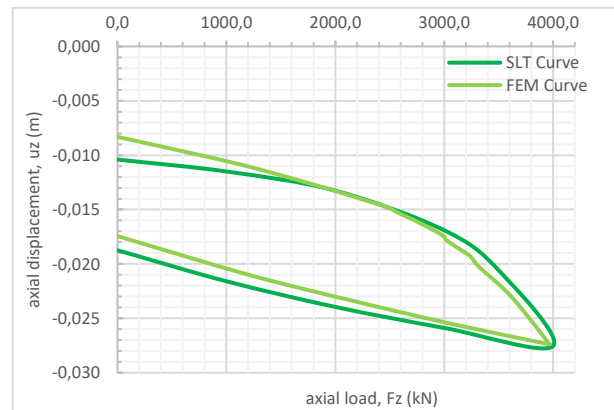


Figure 8. Curve gradient comparison by load cycle 4

Figure 8 presents the comparison between the FEM and SLT curve gradients during Load Cycle 4. Among all loading cycles, this stage exhibits the closest agreement between the numerical simulation and the field measurements. The loading, unloading, and reloading paths show similar shapes, gradients, and maximum settlements throughout almost the entire loading range. Only minor differences remain near the transition between loading and unloading, while the overall nonlinear response is consistently reproduced by the FEM model. This close agreement indicates that the calibrated numerical model successfully reproduces the unloading–reloading response observed during the Static Load Test. In the Hardening Soil constitutive model, the unloading–reloading behavior is primarily represented by the unloading–reloading stiffness modulus (E_{ur}), which governs the recoverable stiffness during stress reversal [1]. Therefore, the close agreement between the FEM and SLT responses suggests that the adopted E_{ur} value provides a realistic representation of the in-situ soil behavior.

Overall, the comparison of the four loading cycles reveals a progressive improvement in the agreement between the FEM simulation and the SLT measurements as the applied load increases. In Load Cycle 1, the numerical model exhibits a predominantly elastic response with a higher load–settlement stiffness gradient than the field measurements, indicating that the adopted E_{50} parameter does not fully reproduce the initial nonlinear stress–strain behavior of the in-situ soil. During Load Cycle 2, the field response gradually approaches the numerical prediction as soil stiffness decreases with increasing load, although differences between the loading and reloading paths remain evident. In Load Cycle 3, the numerical model reproduces the nonlinear response more consistently, suggesting that the influence of E_{oed} becomes more

representative under higher confinement conditions. Finally, Load Cycle 4 demonstrates the closest agreement between the FEM and SLT responses, indicating that the unloading–reloading stiffness represented by E_{ur} has been successfully captured. These observations confirm that evaluating the gradient of the load–settlement curve provides a more comprehensive assessment of soil stiffness parameters than validation based solely on the final settlement or ultimate load.

C. Model Validation

Error! Reference source not found. Table 3 summarizes the MAPE values calculated from the gradients of the load–settlement curves for each loading phase throughout the four loading cycles. In general, the MAPE values consistently decrease from Load Cycle 1 to Load Cycle 4, indicating a progressive improvement in the agreement between the finite element simulation and the Static Load Test (SLT) results. The highest discrepancies are observed during the initial loading cycle, whereas the lowest MAPE values are obtained in the fourth loading cycle, with errors below 3% for all loading phases. This trend demonstrates that the calibrated numerical model becomes increasingly capable of representing the in-situ soil response as the applied load and confinement level increase.

Table 3. Gradient-based MAPE values for the FEM and SLT load–settlement curves

Load Cycle 1			
phase	k_{slt}	k_{fem}	MAPE
reloading	-	-	-
loading	-156,25	-42,93	72,5%
unloading	-136,99	-48,58	64,5%
Load Cycle 2			
phase	k_{slt}	k_{fem}	MAPE
reloading	-133,33	-48,07	63,9%
loading	-20,79	-28,88	38,9%
unloading	-106,38	-49,67	53,3%
Load Cycle 3			
phase	k_{slt}	k_{fem}	MAPE
reloading	-87,72	-45,51	48,1%
loading	-9,67	-11,84	22,5%
unloading	-53,57	-49,98	6,7%
Load Cycle 4			
phase	k_{slt}	k_{fem}	MAPE
reloading	-27,47	-28,05	2,1%
loading	-9,15	-9,36	2,3%
unloading	-50,42	-50,06	0,7%

During the loading phase, the largest MAPE is obtained in Load Cycle 1 (72,5%), indicating that the numerical model does not fully reproduce the initial stiffness observed during the field test. At this stage, the load–settlement response is primarily governed by the secant stiffness parameter (E_{50}), suggesting that the initial E_{50} estimated from empirical correlations is insufficient to represent the actual stress–strain behavior of the soil at relatively low stress levels. As the loading cycles progress and higher load levels are reached, the MAPE decreases significantly to 38.9% in Load Cycle 2, then 22,5% in Load Cycle 3, and finally 2,3% in Load Cycle 4. Under these higher stress conditions, soil compression becomes more dominant, and the stiffness behavior gradually transitions from being primarily represented by the secant stiffness (E_{50}) during the initial loading stage to being better represented by the oedometer stiffness (E_{oed}), which characterizes the compressive response of the soil under increased confinement. The substantial reduction in MAPE therefore indicates that the adopted E_{oed} parameter provides a realistic representation of the soil behavior at higher loading levels, whereas refinement is mainly required for the initial loading stiffness represented by E_{50} .

A similar improvement is observed during the unloading and reloading phases, where the agreement between the FEM and SLT responses increases progressively with successive loading cycles. The MAPE values for the reloading phase decrease from 63,9% in Load Cycle 2 to 48,1% in Load Cycle 3 and finally to 2,1% in Load Cycle 4. Likewise, the unloading phase exhibits a substantial reduction in error, decreasing from 64,5% in Load Cycle 1 to 53,3%, then 6,7%, and ultimately 0.7% in Load Cycle 4. These results demonstrate that the numerical model becomes progressively more capable of reproducing the unloading and reloading behavior observed during the field static load test.

Furthermore, the load–settlement gradients during the unloading and reloading phases become increasingly similar in both the FEM model and the SLT measurements, particularly in Load Cycle 4. The similarity is evident not only from the low MAPE values but also from the comparable slopes of the unloading and reloading branches presented in Figure 7 and Figure 8. Following the primary loading stage, the dominant stiffness behavior transitions to the unloading–reloading response, which is represented by the E_{ur} parameter in the Hardening Soil model. Therefore, the close agreement between the numerical and field gradients indicates that the calibrated E_{ur} parameter successfully represents the elastic stiffness

of the soil during stress release and subsequent reloading.

Overall, the progressive reduction in MAPE across the loading, unloading, and reloading phases confirms that the proposed slope-based validation approach provides a reliable framework for evaluating the stiffness parameters of the Hardening Soil model. The large discrepancy observed during the initial loading stage indicates that refinement is primarily required for the secant stiffness (E_{50}), whereas the close agreement obtained under higher loading levels demonstrates that the adopted oedometer stiffness (E_{oed}) appropriately represents the compressive response of the soil. Similarly, the excellent agreement observed during unloading and reloading confirms that the unloading–reloading stiffness (E_{ur}) successfully captures the elastic recovery behavior of the soil. Therefore, the proposed slope-based validation method enables a comprehensive evaluation of the three principal stiffness parameters (E_{50} , E_{oed} , and E_{ur}) governing the Hardening Soil model.

V. CONCLUSION

A. Conclusion

The comparison between the FEM simulation and the Static Load Test (SLT) demonstrates that the proposed slope-based approach is capable of evaluating the stiffness parameters of the Hardening Soil model through the load–settlement response of bored piles. The numerical model successfully reproduces the overall nonlinear behavior observed in the field, while the agreement between the FEM and SLT responses progressively improves with increasing loading cycles.

The results indicate that the large discrepancy observed during the initial loading stage is primarily associated with the secant stiffness (E_{50}), suggesting that the initial E_{50} estimated from empirical correlations does not fully represent the in-situ stress–strain behavior of the soil under relatively low stress levels. As the applied load increases and soil compression becomes more pronounced, the stiffness behavior gradually transitions from the initial secant stiffness (E_{50}) to the constrained compressive stiffness represented by E_{oed} , resulting in a substantial reduction in the MAPE values at higher loading cycles. Furthermore, the close agreement achieved during the unloading and reloading phases confirms that the unloading–reloading stiffness (E_{ur}) adequately represents the soil stiffness response

during stress release and subsequent reloading, as reflected by the comparable load–settlement gradients obtained from both the FEM simulation and the Static Load Test.

Therefore, the proposed slope-based validation method provides a more comprehensive framework for evaluating soil stiffness parameters than conventional validation approaches that rely solely on ultimate load or total settlement. By incorporating the gradient characteristics of the load–settlement curve throughout the loading history, the method enables a more reliable evaluation of the three principal stiffness parameters (E_{50} , E_{oed} , and E_{ur}) in finite element analysis of bored pile foundations.

B. Recommendation

Future studies are recommended to extend the validated numerical model developed in this study to investigate the ultimate axial and lateral capacities of bored pile foundations under failure conditions. Such analyses would enable direct comparison between finite element predictions and conventional empirical methods, thereby providing further insight into the applicability of classical design approaches after the numerical model has been validated against field load–settlement behavior. In addition, since the largest discrepancy was observed during the initial loading stage, future research may consider implementing the Hardening Soil Small-Strain (HSsmall) model to improve the representation of the initial stiffness governed by E_{50} .

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