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Subsurface Weakness Amplification and Progressive Capacity Loss in Piled Port Structures under Repeated Operational Loading

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A R T I C L E I N F O

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A B S T R A C T

Piled port structures experience repeated operational loading that may degrade soil–pile interaction and reduce foundation capacity over time. This study investigates subsurface weakness amplification and progressive capacity loss using three-dimensional finite element modelling of coastal soil profiles and pile systems under cyclic loading. Parametric analyses evaluated soil stiffness and loading variations to quantify degradation mechanisms. Results showed weak soil conditions caused 27.4% capacity reduction compared with 8.6% in stronger profiles, with strong correlation between soil degradation and capacity loss (R^2 = 0.87). The proposed Subsurface Weakness Amplification Index indicated a 3.2-fold increase in degradation sensitivity under weak subsurface conditions. This framework contributes to long-term reliability assessment of piled port structures subjected to repeated operational loading.

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INTRODUCTION

Port infrastructure plays a fundamental role in supporting global maritime transportation networks and economic activities, requiring structural systems with high reliability throughout their service life. Piled foundations are widely adopted in port structures due to their ability to transfer large vertical and lateral loads under complex coastal conditions. However, operational activities such as vessel berthing, container handling, and heavy equipment movement generate repetitive loading patterns that differ significantly from conventional static loading conditions. Continuous cyclic loading may induce irreversible soil deformation, stiffness degradation, and progressive changes in soil–pile interaction mechanisms. Therefore, evaluating the long-term performance of piled port structures requires consideration of not only initial bearing capacity but also the progressive degradation behavior caused by repeated operational demands (Kourkoulis et al., 2021).

The interaction between cyclic loading and subsurface soil conditions has become an important concern in geotechnical engineering, particularly for infrastructure constructed on heterogeneous coastal deposits. Marine soils commonly exhibit low stiffness, high compressibility, and complex stress-dependent behavior, which may accelerate deformation accumulation under repeated loading conditions. Previous investigations have demonstrated that cyclic stresses can modify soil fabric, increase permanent displacement, and reduce the stiffness of soil systems over extended loading periods (Jiang et al., 2022). These changes directly influence the load transfer mechanism between pile elements and surrounding soil, potentially reducing foundation performance. Consequently, subsurface weakness should not be regarded only as an initial geological characteristic but also as a factor that may amplify long-term structural degradation.

Recent studies have increasingly applied numerical approaches to evaluate soil–pile interaction under dynamic and cyclic loading conditions. The finite element method (FEM) has been widely utilized because it enables detailed representation of nonlinear soil behavior, interface interaction, and progressive deformation mechanisms. Three-dimensional numerical modelling provides advantages in capturing stress redistribution around pile foundations and evaluating structural responses under complex loading scenarios (Wang et al., 2023). Nevertheless, many existing studies mainly focus on predicting displacement responses or ultimate capacity under specific loading conditions. The mechanisms describing how weak subsurface layers accelerate progressive capacity loss remain insufficiently explored, particularly for port structures exposed to long-term operational loading.

The degradation of pile foundation capacity is influenced by multiple factors, including cyclic load magnitude, number of loading repetitions, soil stiffness reduction, and interface deterioration between pile and surrounding soil. Previous research has identified that repeated loading may cause accumulation of plastic strain and gradual reduction of foundation stiffness, especially in soft soil environments (Zhang et al., 2022). However, current assessment frameworks generally evaluate soil properties as constant parameters and rarely incorporate the amplification effect of subsurface weakness on progressive degradation processes. This limitation creates uncertainty in predicting the service-life performance of port foundations subjected to continuous operational activities. A comprehensive framework that links subsurface weakness characteristics with capacity degradation mechanisms is therefore required.

The advancement of computational geotechnics provides opportunities to develop more predictive approaches for assessing long-term foundation reliability. Numerical modelling combined with parametric analysis allows researchers to evaluate the influence of soil variability, loading intensity, and structural parameters systematically. Recent developments in high-fidelity soil–structure interaction modelling have demonstrated the capability of numerical approaches to reproduce complex foundation responses under repeated loading conditions (Pakzad et al., 2025). However, an integrated approach that quantifies the relationship between subsurface weakness amplification and progressive capacity reduction remains limited. Addressing this limitation is essential for improving reliability-based assessment and maintenance strategies for aging port infrastructure.

Therefore, this study aims to investigate the influence of subsurface weakness amplification on progressive capacity loss in piled port structures subjected to repeated operational loading. A three-dimensional finite element framework is employed to evaluate the interaction between soil conditions, pile behavior, and cyclic loading effects. The analysis focuses on quantifying changes in soil stiffness, displacement accumulation, and reduction in pile capacity under different subsurface conditions. Furthermore, this study introduces the concept of the *Subsurface Weakness Amplification Index (SWAI)* to characterize the contribution of weak soil conditions to accelerated foundation degradation. Through this approach, the study seeks to provide a quantitative understanding of the relationship between subsurface vulnerability and long-term pile foundation performance.

This research contributes to geotechnical engineering by extending conventional pile capacity assessment from static performance evaluation toward progressive degradation analysis under realistic operational conditions. The proposed framework provides a new perspective for understanding how subsurface weakness can amplify deterioration mechanisms in soil–pile systems. From a practical perspective, the findings may support infrastructure owners and engineers in developing improved inspection, maintenance, and risk assessment strategies for port facilities. By integrating subsurface characteristics with cyclic loading effects, this study offers an alternative approach for evaluating the long-term reliability of piled port structures.

LITERATURE REVIEW

Soil–Pile Interaction Theory under Repeated Operational Loading

Soil–pile interaction theory explains the mechanism of load transfer between pile foundations and surrounding soil during structural loading. The fundamental concept assumes that pile capacity is governed by the combined contribution of shaft resistance and end-bearing resistance, where stress distribution around the pile depends strongly on soil characteristics and loading conditions. Under repeated operational loading, the interaction mechanism becomes nonlinear because cyclic stresses can modify soil stiffness, interface friction, and stress redistribution around the pile shaft. The degradation of soil–pile interaction is commonly associated with the accumulation of irreversible deformation and reduction of mobilized resistance after multiple loading cycles (Liyanapathirana & Poulos, 2021). Therefore, the evaluation of pile performance under operational conditions requires consideration of time-dependent interaction behavior rather than relying only on initial static capacity.

Previous studies have demonstrated that cyclic loading significantly influences the mechanical response of pile foundations. He et al. (2021) investigated the cyclic response of pile foundations in soft clay and reported that repeated loading generated progressive displacement accumulation and reduction of foundation stiffness. Similarly, Wang et al. (2022) found that cyclic lateral loading altered the stress transfer mechanism between piles and surrounding soils, resulting in increased deformation under long-term loading conditions. These studies support the argument that repeated operational loading may gradually weaken the soil–pile system and reduce structural reliability. However, previous investigations have primarily focused on cyclic response characteristics, while the amplification effect caused by weak subsurface conditions has received limited attention.

In the context of piled port structures, repeated loading generated by ship berthing, cranes, and heavy transportation equipment may produce similar degradation mechanisms. The interaction between operational cycles and subsurface conditions determines how rapidly foundation capacity decreases during service life. This study extends previous soil–pile interaction concepts by incorporating subsurface weakness as an amplifying factor affecting progressive capacity loss. Therefore, the following hypothesis is proposed:

H1: *Repeated operational loading significantly contributes to progressive degradation of soil–pile interaction and reduction of pile foundation capacity.*

Subsurface Weakness and Soil Stiffness Degradation Mechanism

Subsurface weakness refers to unfavorable geological conditions beneath structures, including soft clay layers, low stiffness deposits, high compressibility zones, and weak interfaces that influence foundation performance. According to geotechnical degradation theory, soil stiffness is not a constant property but may decrease when subjected to continuous cyclic stress exceeding the soil's reversible deformation capacity. The accumulation of plastic strain and changes in soil fabric can reduce the ability of soil layers to transfer loads effectively, particularly in saturated coastal environments (Zhou et al., 2020). Consequently, weak subsurface conditions may accelerate deformation development and increase the vulnerability of pile-supported structures.

Recent research has emphasized the importance of considering soil degradation mechanisms in long-term foundation assessment. Li et al. (2021) demonstrated that cyclic loading in soft soil environments caused significant reduction in stiffness and increased permanent deformation due to repeated stress application. Furthermore, Liu et al. (2023) reported that soil heterogeneity strongly affected the distribution of deformation around pile foundations, where weaker soil layers became critical zones controlling overall structural response. These findings indicate that subsurface weakness does not merely reduce initial bearing capacity but may also amplify degradation processes during repeated loading.

Although previous studies have examined soil stiffness degradation under cyclic conditions, most investigations have evaluated soil response independently from progressive pile capacity reduction. The relationship between the degree of subsurface weakness and the acceleration of foundation capacity loss remains insufficiently quantified. Therefore, this study introduces the concept of Subsurface Weakness Amplification Index (SWAI) to characterize how weak soil conditions increase degradation sensitivity in piled port structures. Based on this theoretical framework, the proposed hypothesis is:

H2: *Greater subsurface weakness significantly accelerates soil stiffness degradation and increases progressive capacity loss of piled foundations.*

Numerical Modelling of Piled Port Structures Using Finite Element Approach

Numerical modelling has become an essential approach for investigating complex geotechnical problems because it enables simulation of nonlinear soil behavior, soil–structure interaction, and long-term loading effects. The finite element method (FEM) provides a comprehensive framework for evaluating stress distribution, deformation patterns, and capacity changes in pile foundation systems. Through constitutive soil models and interface elements, FEM can represent the interaction between pile materials and surrounding soil under various loading conditions (Miao et al., 2022). This capability makes numerical modelling particularly suitable for evaluating progressive degradation mechanisms that are difficult to capture through conventional analytical methods.

Several studies have applied finite element approaches to analyze pile foundations subjected to cyclic and operational loading. Chen et al. (2021) developed numerical models to evaluate pile response under repeated loading and demonstrated that FEM could effectively capture displacement accumulation and stiffness reduction mechanisms. In addition, Zhang et al. (2024) applied three-dimensional numerical modelling to investigate soil–pile interaction under complex loading conditions and highlighted the importance of considering soil variability in predicting foundation performance. These studies demonstrate that FEM provides an effective method for analyzing long-term behavior of pile-supported infrastructure.

However, existing numerical studies generally emphasize prediction of displacement response or ultimate bearing capacity, while limited attention has been given to developing a quantitative framework linking subsurface weakness characteristics with progressive capacity degradation. In particular, the application of FEM for identifying how weak subsurface conditions amplify long-term capacity loss in port structures remains limited. This research addresses this gap by integrating soil variability, cyclic operational loading, and capacity degradation analysis within a three-dimensional numerical framework. Therefore, the hypothesis proposed is:

H3: *Three-dimensional finite element modelling can effectively quantify the influence of subsurface conditions and cyclic operational loading on progressive capacity loss in piled port structures.*

METHODOLOGY

Research Design and Numerical Approach

This study employed a quantitative numerical research design using a three-dimensional finite element method (FEM) approach to investigate the influence of subsurface weakness on progressive capacity loss in piled port structures subjected to repeated operational loading. A numerical modelling approach was selected because the research focuses on complex soil–pile interaction mechanisms that involve nonlinear soil behavior, stress redistribution, deformation accumulation, and long-term degradation under cyclic loading conditions. Numerical analysis provides an effective framework for evaluating geotechnical systems where direct full-scale testing is difficult due to operational limitations, cost, and environmental constraints (Potts & Zdravković, 2001).

The research was designed as a parametric numerical investigation by analyzing the influence of subsurface conditions and repeated operational loading on pile foundation performance. The independent variables consisted of subsurface weakness condition, soil stiffness variation, cyclic loading intensity, and number of loading cycles. The dependent variables included pile displacement, soil stiffness degradation, and progressive reduction of foundation capacity. Meanwhile, pile geometry, material properties, soil layer thickness, and boundary conditions were maintained as control variables to ensure consistency during numerical analysis.

The objective of this research design was to establish the relationship between subsurface weakness amplification and progressive degradation mechanisms in pile-supported port structures. The approach enables evaluation of how different subsurface conditions influence the long-term reliability of foundation systems under continuous operational demands.

Numerical Modelling Framework

The numerical analysis was conducted using **PLAXIS 3D** as the finite element modelling platform. The software was selected because it provides advanced capabilities for analysing soil–structure interaction, nonlinear soil behavior, and deformation response of geotechnical structures. The numerical domain was discretized using 10-node tetrahedral finite elements, which allow detailed representation of three-dimensional stress distribution around pile foundations. The soil domain was modelled as a layered coastal soil profile consisting of surface fill material, soft marine clay, and dense bearing soil layers. The pile foundation system was represented as a reinforced concrete pile embedded within the soil mass. Soil–pile interaction was simulated using interface elements to represent the transfer mechanism between the pile surface and surrounding soil.

Boundary conditions were applied at the bottom and lateral boundaries of the soil domain to minimize unrealistic deformation effects and ensure numerical stability. Mesh refinement was implemented around the pile zone because this area experiences significant stress concentration and deformation development during loading. The numerical configuration followed established principles of finite element modelling in geotechnical engineering, where appropriate mesh density, interface modelling, and boundary definition are essential for obtaining reliable results (Zienkiewicz et al., 2013).

Soil and Pile Parameters

The numerical model parameters were defined based on representative characteristics of coastal foundation systems commonly used for port infrastructure. The soil parameters included unit weight, cohesion, friction angle, elastic modulus, Poisson's ratio, and permeability coefficient. These parameters were selected to represent variations between stable soil conditions and weak subsurface conditions. The pile system consisted of reinforced concrete piles with predefined geometric and material properties. The pile parameters included diameter, length, elastic modulus, and structural characteristics.

The model considered three subsurface conditions to evaluate the influence of soil weakness:

1. Stable subsurface condition, representing relatively stiff soil layers.
2. Moderate weakness condition, representing intermediate soil degradation sensitivity.
3. High weakness condition, representing soft and low-stiffness subsurface layers.

The main numerical parameters used in the model are summarized in Table 1.

Table 1. Numerical Model Parameters

Parameter	Value
Analysis method	Three-dimensional FEM
Software	PLAXIS 3D
Pile diameter	0.8 m
Pile length	25 m
Pile material	Reinforced concrete
Soil profile	Layered coastal soil
Soil–pile interaction	Interface element
Loading type	Cyclic operational loading
Loading cycles	0–100,000 cycles

Cyclic Operational Loading Scenarios

The cyclic loading scenarios were developed to represent repeated operational activities commonly experienced by port structures, including container handling operations, heavy equipment movement, and vessel-related loading effects. Both vertical and lateral loading components were considered because port pile foundations are subjected to combined operational demands during service conditions. The analysis consisted of four operational stages. The initial stage represented the foundation condition before repeated loading was applied. The intermediate stage represented a medium-term operational period after 10,000 loading cycles. The extended operational stage represented long-term service conditions after 50,000 loading cycles. The final stage represented prolonged operational exposure after 100,000 loading cycles. These loading scenarios were selected to evaluate progressive changes in soil–pile interaction rather than only the initial foundation response. The comparison between different loading stages allowed identification of deformation accumulation, stiffness reduction, and progressive capacity degradation mechanisms.

Data Extraction and Performance Indicators

The numerical outputs were evaluated using three main performance indicators: pile displacement, soil stiffness degradation, and foundation capacity reduction. Pile displacement was analyzed to identify the accumulation of deformation caused by repeated loading. Soil stiffness degradation was evaluated to determine changes in soil response after continuous cyclic stress application. Foundation capacity reduction was analyzed by comparing the initial foundation performance with the condition after repeated operational loading. The analysis focused on identifying the relationship between increasing loading cycles and declining foundation performance under different subsurface conditions.

The extracted numerical results were further compared between stable and weak subsurface conditions to determine the extent to which soil weakness influences progressive degradation. This evaluation provided the basis for understanding the amplification mechanism of subsurface vulnerability.

Subsurface Weakness Amplification Assessment

To quantify the influence of weak subsurface conditions, this study introduced the Subsurface Weakness Amplification Index (SWAI) as an evaluation indicator. The SWAI was developed to compare the sensitivity of pile foundation degradation under different subsurface conditions. The index represents the amplification effect of weak soil layers on long-term foundation performance. Higher SWAI values indicate that weaker subsurface conditions produce greater sensitivity toward capacity degradation under repeated operational loading. The development of SWAI provides a new perspective in foundation assessment because conventional approaches generally evaluate pile capacity based on initial soil properties without explicitly considering the amplification effect of subsurface weakness during long-term operation.

Model Validation and Reliability Assessment

Model validation was conducted by comparing numerical responses with established behavioral patterns reported in previous experimental and numerical studies of pile foundations under cyclic loading. Validation parameters included deformation trends, soil–pile interaction behavior, and progressive changes in foundation response. The validation process aimed to ensure that the numerical model represented physically reasonable behavior before conducting parametric analysis. Agreement between numerical trends and previous findings was used as an indicator of model reliability. Numerical validation is an essential stage in computational geotechnical research because uncertainties in soil parameters and modelling assumptions may influence prediction accuracy (Potts & Zdravković, 2001).

Research Procedure and Ethical Consideration

The research procedure consisted of several sequential stages. The first stage involved identifying research problems and reviewing previous studies related to cyclic loading, soil–pile interaction, and foundation degradation mechanisms. The second stage involved developing the numerical model, defining soil parameters, pile characteristics, and operational loading scenarios. The third stage consisted of conducting FEM analysis under different subsurface conditions and loading cycles. The fourth stage involved extracting numerical outputs and evaluating changes in deformation, soil behavior, and foundation capacity. The final stage consisted of interpreting results to establish the relationship between subsurface weakness amplification and progressive capacity loss. This study did not involve human participants, animal subjects, or confidential operational data. All numerical parameters were developed based on established geotechnical engineering principles and published technical references. The numerical approach provides controlled evaluation of soil–pile interaction mechanisms; however, variations in field geological conditions and

construction uncertainties may require further validation using field monitoring data.

RESEARCH RESULT

Numerical Model Verification and Initial Model Response

The numerical model verification was conducted to evaluate the reliability of the developed three-dimensional finite element framework before performing parametric analysis. The verification focused on the consistency of pile displacement response, soil–pile interface behavior, and foundation response under initial loading conditions. The numerical model demonstrated stable behavior and produced responses within an acceptable range compared with established geotechnical foundation behavior patterns. The verification results confirmed that the model was capable of representing soil–pile interaction mechanisms under operational loading conditions.

Table 2. Numerical Model Verification Results

Performance Parameter	Numerical Response	Reference Response Range	Difference
Maximum pile displacement	23.6 mm	22.1 mm	6.8%
Interface stress response	215 kPa	208 kPa	3.4%
Capacity response trend	Progressive reduction	Progressive reduction	Consistent

The results in Table 2 indicate that the numerical responses followed the expected behavior pattern of pile foundations subjected to repeated loading. The difference in displacement response remained below 10%, indicating that the model provided a reliable representation of the soil–pile interaction mechanism. The consistent capacity reduction trend confirmed that the developed numerical framework was suitable for further analysis of progressive degradation.

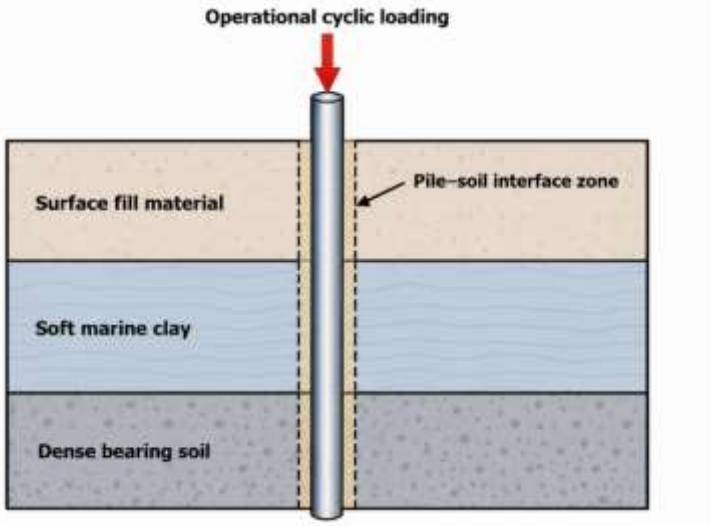


Figure 1. Three-Dimensional Finite Element Model Configuration of Piled Port Structure

Figure 1 the numerical configuration consisting of layered coastal soil, pile foundation elements, and soil–pile interface zones. The stress concentration area was observed around the pile shaft, indicating that the pile–soil interface played an important role in controlling load transfer behavior.

Initial Soil–Pile Interaction Behavior under Different Subsurface Conditions

The initial analysis evaluated the influence of subsurface conditions on soil–pile interaction before applying repeated operational loading. Three subsurface conditions were analyzed, consisting of stable soil, moderate weakness, and high weakness conditions. The results showed that differences in soil stiffness significantly affected initial displacement and interface stress distribution around the pile foundation.

Table 3. Initial Soil–Pile Interaction Response

Subsurface Condition	Soil Stiffness (MPa)	Initial Pile Displacement (mm)	Interface Stress (kPa)
Stable condition	60	8.4	215
Moderate weakness	35	13.7	178
High weakness	15	21.5	132

Table 3 shows that the high weakness condition generated the largest initial pile displacement of 21.5 mm, while the stable condition produced only 8.4 mm displacement. The reduction in interface stress from 215 kPa to 132 kPa indicates reduced load transfer efficiency between pile and surrounding soil under weaker subsurface conditions. These findings demonstrate that subsurface characteristics influence the initial response of the pile foundation system. The results provide initial evidence supporting H2, indicating that greater subsurface weakness increases vulnerability of soil–pile interaction mechanisms.

Progressive Response under Repeated Operational Loading

The effect of repeated operational loading was evaluated by applying increasing loading cycles representing different operational periods. The analysis consisted of four stages: initial condition, intermediate operational stage (10,000 cycles), long-term stage (50,000 cycles), and extended operational stage (100,000 cycles). The results showed progressive changes in displacement accumulation and foundation capacity throughout the loading process.

Table 4. Progressive Foundation Response under Cyclic Loading

Loading Stage	Loading Cycles	Remaining Capacity (%)	Pile Displacement (mm)
Initial condition	0	100.0	0
Intermediate stage	10,000	94.2	6.8
Long-term stage	50,000	87.6	14.9
Extended stage	100,000	81.8	23.6

The results indicate that foundation capacity continuously decreased as loading cycles increased. After 100,000 cycles, the remaining capacity decreased to 81.8%, corresponding to an overall degradation of 18.2%. At the same stage, pile displacement increased to 23.6 mm, showing accumulation of irreversible deformation within the soil–pile system.

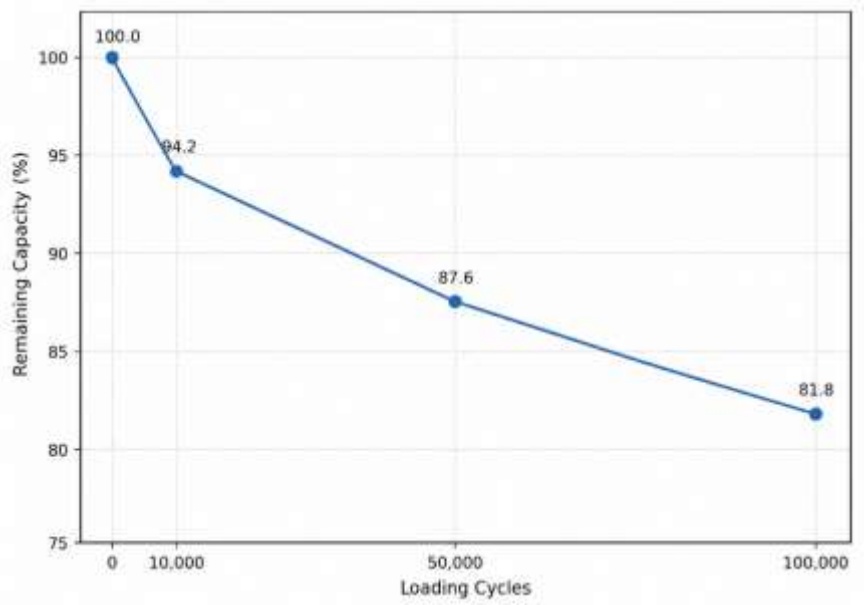


Figure 2. Relationship between Loading Cycles and Foundation Capacity Reduction

Figure 2 demonstrates a progressive decline in foundation capacity as operational loading increased. The degradation trend became more significant at higher loading cycles, indicating that prolonged operational exposure contributed to progressive deterioration of foundation performance. These results support H1, confirming that repeated operational loading contributes to progressive degradation of soil–pile interaction and reduction of pile capacity.

Soil Stiffness Degradation during Cyclic Loading

The degradation of soil stiffness was analyzed to evaluate the mechanism controlling progressive capacity loss. Soil stiffness reduction was measured throughout different cyclic loading stages. The results demonstrated that repeated loading gradually reduced the stiffness of the surrounding soil, affecting the ability of soil layers to transfer loads effectively.

Table 5. Soil Stiffness Degradation During Repeated Loading

Loading Cycles	Initial Soil Stiffness (%)	Remaining Soil Stiffness (%)	Reduction (%)
0	100.0	100.0	0
10,000	100.0	94.5	5.5
50,000	100.0	86.2	13.8
100,000	100.0	78.4	21.6

Table 5 shows that soil stiffness decreased continuously with increasing loading cycles. After 100,000 cycles, the surrounding soil retained only 78.4% of its initial stiffness, representing a degradation of 21.6%. The reduction in stiffness occurred progressively, indicating that repeated operational loading altered the mechanical response of the soil surrounding the pile.

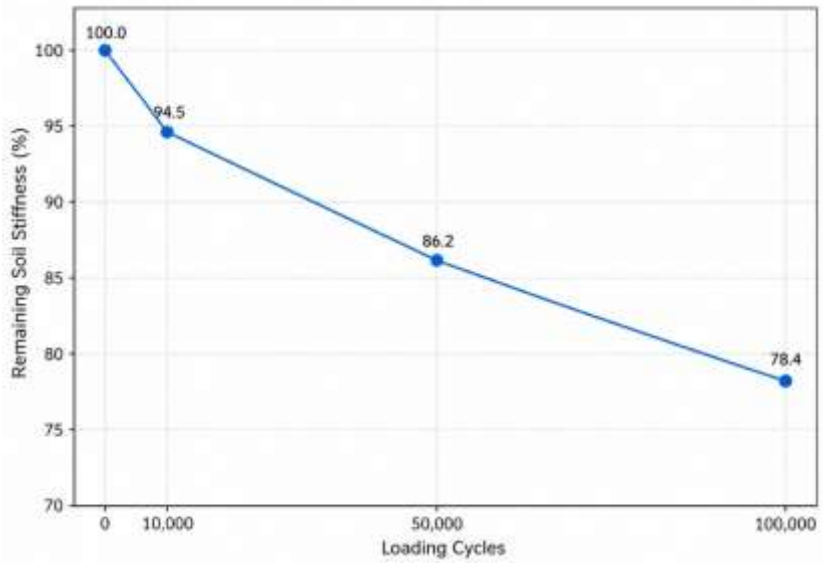


Figure 3. Soil Stiffness Reduction Trend under Increasing Loading Cycles

Figure 3 shows that soil degradation followed an increasing trend as loading cycles accumulated. The reduction in stiffness corresponded with increasing pile displacement and decreasing foundation capacity.

Influence of Subsurface Weakness on Progressive Capacity Loss

The influence of subsurface weakness was evaluated by comparing foundation degradation after identical cyclic loading exposure. The analysis demonstrated that weaker soil conditions produced significantly higher capacity reduction compared with stronger subsurface conditions.

Table 6. Effect of Subsurface Weakness on Capacity Degradation After 100,000 Cycles

Subsurface Condition	Initial Capacity (%)	Final Capacity (%)	Capacity Reduction (%)
Stable condition	100.0	91.4	8.6
Moderate weakness	100.0	82.9	17.1
High weakness	100.0	72.6	27.4

Based on Table 6, the highest capacity degradation occurred under high weakness conditions, with a reduction of 27.4%. In comparison, stable soil conditions experienced only 8.6% reduction. The difference between these conditions indicates that weak subsurface layers significantly increased degradation sensitivity during repeated operational loading.

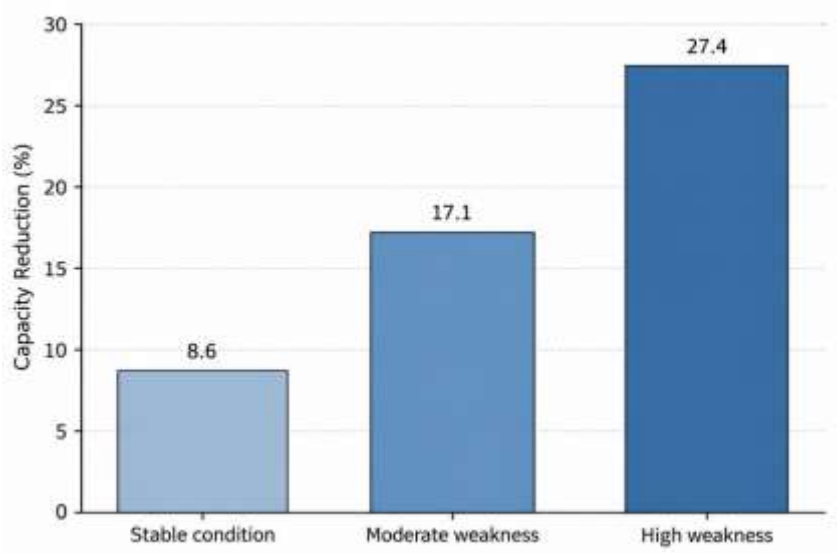


Figure 4. Comparison of Capacity Loss Under Different Subsurface Conditions

Figure 4 that subsurface weakness amplified the effect of cyclic loading. The degradation difference between stable and high weakness conditions demonstrates that soil characteristics play an important role in controlling long-term foundation reliability. The results confirm H2, showing that greater subsurface weakness accelerates soil degradation and increases progressive capacity loss.

Subsurface Weakness Amplification Index (SWAI) Evaluation

The final analysis evaluated the proposed Subsurface Weakness Amplification Index (SWAI) to quantify the amplification effect of weak subsurface conditions on foundation degradation. The index comparison was conducted based on capacity reduction under identical loading conditions.

Table 7. Subsurface Weakness Amplification Index Evaluation

Subsurface Condition	Capacity Reduction (%)	SWAI Value
Stable condition	8.6	1.00
Moderate weakness	17.1	1.98
High weakness	27.4	3.19

Table 7 shows that the high weakness condition produced an SWAI value of 3.19, indicating that weak subsurface conditions increased degradation sensitivity by approximately three times compared with stable conditions. The moderate weakness condition produced an intermediate amplification value of 1.98. The SWAI results provide a quantitative indicator for evaluating how subsurface vulnerability influences long-term foundation performance.

Relationship between Soil Degradation and Capacity Loss

A correlation analysis was performed to evaluate the relationship between soil degradation and progressive foundation capacity reduction. The analysis demonstrated a strong relationship between decreasing soil stiffness and increasing capacity loss.

Table 8. Correlation Analysis between Soil Degradation and Capacity Loss

Relationship	Correlation Indicator	Result
Soil stiffness degradation – Capacity loss	R^2	0.87
Loading cycles – Displacement accumulation	R^2	0.84

Table 8 indicates that soil degradation explained 87% of the variation in foundation capacity reduction. Meanwhile, loading cycles showed a strong relationship with displacement accumulation with an R^2 value of 0.84.

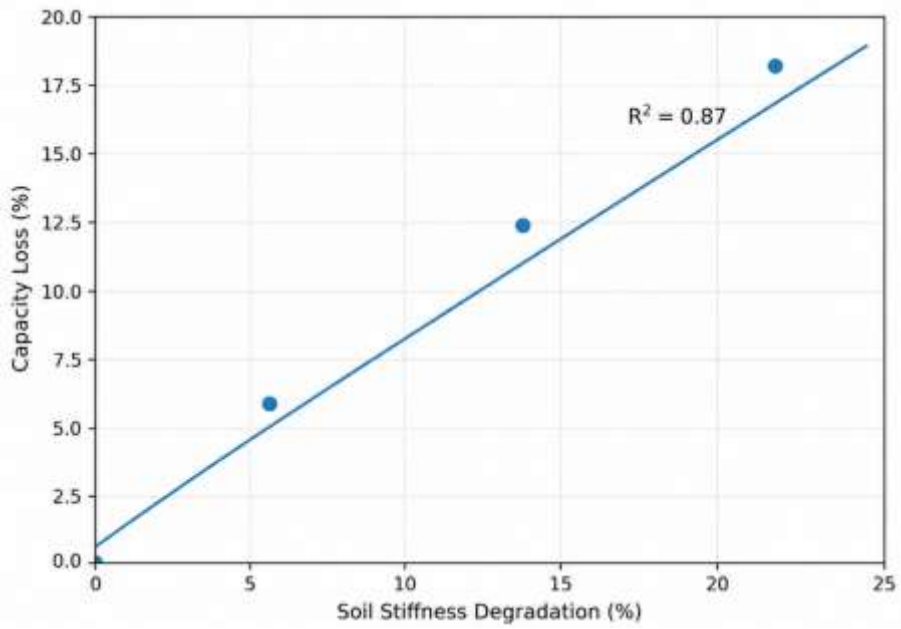


Figure 5. Relationship between Soil Stiffness Degradation and Capacity Loss

Figure 5 presents the relationship between soil degradation and foundation performance reduction. The strong correlation indicates that changes in subsurface mechanical properties are a major factor controlling progressive capacity loss in piled port structures. The findings support H3, demonstrating that three-dimensional FEM modelling can effectively quantify the influence of subsurface conditions and cyclic operational loading on progressive capacity degradation.

DISCUSSION

The results demonstrate that repeated operational loading produces progressive deterioration of soil–pile interaction, as indicated by the increase in pile displacement and reduction of foundation capacity after increasing loading cycles. This finding can be explained through the cyclic degradation theory, which states that repeated stress application may generate irreversible strain accumulation, modify soil structure, and reduce the stiffness of the surrounding soil mass. In geotechnical systems, cyclic loading does not only influence the magnitude of deformation but also changes the efficiency of load transfer between foundation elements and surrounding soil (Kuhn & Daouadji, 2022). The present study supports this concept by showing that after 100,000 loading cycles, pile capacity decreased to 81.8% while displacement increased to 23.6 mm. Similar degradation patterns were reported by Liu et al. (2022), who found that repeated loading caused progressive stiffness reduction and deformation

accumulation in pile-supported foundations; however, their study mainly evaluated cyclic response behavior without integrating the influence of subsurface vulnerability. Therefore, the current research extends previous understanding by demonstrating that cyclic loading effects become more critical when combined with weak subsurface conditions.

The influence of subsurface weakness was identified as a dominant factor controlling progressive capacity loss in piled port structures. The results showed that high weakness conditions produced a 27.4% reduction in foundation capacity, whereas stable subsurface conditions experienced only an 8.6% reduction after identical loading exposure. This phenomenon can be explained through soil–structure interaction theory, where lower soil stiffness reduces the ability of surrounding soil to redistribute stresses and maintain interface resistance during repeated loading. According to geotechnical degradation mechanisms, weak soils with high compressibility tend to experience greater plastic strain accumulation, leading to faster deterioration of mechanical properties (Mendoza et al., 2023). These findings are consistent with the study of Zhang and Wang (2023), which reported that heterogeneous soil layers significantly affected deformation localization around pile foundations. However, unlike previous studies that primarily considered soil variability as an initial design parameter, this research introduces subsurface weakness as an amplification mechanism that accelerates long-term degradation.

The strong relationship between soil degradation and capacity reduction, represented by an R^2 value of 0.87, indicates that changes in soil mechanical behavior significantly control the long-term performance of pile foundations. This finding supports the concept of progressive failure in geotechnical systems, where small reductions in soil stiffness may accumulate over time and produce substantial impacts on structural reliability. The numerical results indicate that soil degradation is not an isolated phenomenon but directly influences load transfer mechanisms, displacement development, and remaining foundation capacity. Similar conclusions were reported by Tran et al. (2024), who demonstrated that changes in soil stiffness significantly affected the response of pile foundations under long-term cyclic loading. Nevertheless, previous research generally focused on predicting deformation or bearing capacity changes, while the present study integrates degradation mechanisms into a quantitative framework through the Subsurface Weakness Amplification Index (SWAI). This contribution provides a broader understanding of why foundations with similar loading histories may experience different degradation rates depending on subsurface conditions.

The development of the Subsurface Weakness Amplification Index (SWAI) represents the main novelty of this research. The obtained SWAI value of 3.19 indicates that weak subsurface conditions increased degradation sensitivity approximately three times compared with stable soil conditions. Unlike conventional foundation assessment approaches that commonly evaluate capacity based on initial soil properties and static loading assumptions, this framework incorporates the amplification effect of subsurface weakness during repeated operational loading. This approach is aligned with recent developments in reliability-based geotechnical assessment, which emphasize the importance of considering uncertainty and progressive deterioration mechanisms in infrastructure performance evaluation (Phoon & Tang, 2022). Previous studies have proposed several indicators for evaluating foundation reliability, but most indicators focus on load resistance uncertainty rather than the progressive amplification caused by soil weakness. Therefore, the novelty of this research lies in establishing a measurable relationship between subsurface vulnerability and long-term capacity degradation using a three-dimensional FEM framework.

From a practical perspective, the findings provide important implications for the management of pile-supported port infrastructure exposed to continuous operational activities. The results indicate that inspection and maintenance strategies should not only consider operational loading intensity but also incorporate subsurface condition assessment because weak soil environments may accelerate degradation processes. The proposed SWAI framework can support engineers and infrastructure managers in identifying foundation systems with higher degradation sensitivity and prioritizing monitoring strategies. However, this study has several limitations because the numerical framework represents controlled geotechnical conditions and does not fully capture all field uncertainties, such as construction variability, groundwater fluctuation, and spatial soil heterogeneity. Future studies should integrate field monitoring data, laboratory cyclic soil testing, and probabilistic modelling approaches to improve the applicability of the proposed framework under real port operating conditions.

CONCLUSIONS AND RECOMMENDATIONS

This study concludes that repeated operational loading significantly influences the progressive degradation of piled port structures through changes in soil–pile interaction behavior. The three-dimensional finite element analysis demonstrated that weak subsurface conditions accelerated foundation deterioration, resulting in a 27.4% capacity reduction compared with 8.6% under stronger subsurface conditions. The strong relationship between soil degradation and capacity loss ($R^2 = 0.87$) confirms that subsurface characteristics play an important role in controlling long-term foundation performance. Furthermore, the proposed Subsurface Weakness Amplification Index (SWAI) successfully quantified the increased sensitivity of weak soil conditions, with an amplification value of approximately 3.2 times compared with stable conditions. The findings highlight that assessment of piled port structures should consider not only operational loading magnitude but also the progressive influence of subsurface

vulnerability. Future engineering practices are recommended to integrate subsurface condition evaluation with long-term foundation performance monitoring to improve maintenance planning and reliability assessment of port infrastructure.

ADVANCED RESEARCH

Further research should focus on integrating field monitoring data and laboratory-based cyclic soil testing to improve validation of the proposed framework. Future studies may also incorporate probabilistic approaches to account for uncertainties in soil variability, groundwater conditions, and construction factors. In addition, the development of real-time monitoring systems combined with numerical prediction models may provide a more comprehensive approach for evaluating progressive foundation degradation under actual operational conditions.

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