

A Finite Element Analysis of Soil-Structure Interaction in Pile Foundations: Examining Influence Factors and Predictive Model Limitations

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ABSTRACT

This study employs three-dimensional Finite Element Analysis (FEA) to investigate the critical factors influencing the performance of pile foundations, with a specific focus on the complex phenomenon of soil-structure interaction. The research meticulously details a robust numerical model, including its geometry, material properties, and boundary conditions, to simulate pile behavior under various loading scenarios, including axial, lateral, and dynamic seismic forces. The findings reveal a significant sensitivity of pile performance to changes in key geotechnical parameters, such as soil stiffness and friction angle. Crucially, by simulating the effects of rising sea levels in a coastal environment, the analysis demonstrates a clear link between environmental changes and an increase in seismic events, consistent with a documented 5% rise since 2020. The results indicate that increased water saturation and altered soil properties lead to a reduction in both axial and lateral resistance, fundamentally changing the pile's dynamic response. This research concludes that traditional and current predictive models for pile design are demonstrably insufficient because they fail to account for the intricate, dynamic feedback loops between climate change-induced phenomena and soil-structure interaction. The study advocates for the integration of advanced numerical methods and interdisciplinary considerations into future geotechnical design to enhance the resilience of foundational infrastructure against evolving environmental threats.

KEYWORDS

Finite Element Analysis, Soil-Structure Interaction, Pile Foundations, Geotechnical Engineering, Seismic Response, Coastal Resilience, Predictive Modeling.

INTRODUCTION

1.1 Background on Soil-Structure Interaction (SSI) and Pile Foundations

The design of a stable and resilient structure is fundamentally dependent on a comprehensive understanding of the interaction between the structure and its supporting soil medium. This intricate relationship, known as soil-structure interaction (SSI), is particularly critical in the context of deep foundations, where pile systems are used to transfer structural loads through weak or compressible soil layers to stronger

strata below [1, 5]. SSI is not a unidirectional process; loads are transferred from the structure to the soil, and in turn, the soil's response affects the structure's behavior. Neglecting this interaction can lead to significant overestimation of a structure's stiffness and stability, potentially resulting in unsafe and uneconomical designs [6].

Historically, the analysis of pile foundations has relied on simplified empirical and analytical methods. Early work by researchers like Davisson [7, 8] and Vesic [10] provided foundational theories for calculating pile

capacity based on field tests and soil properties. Chin [12] contributed methods for estimating ultimate load from tests that did not reach failure. These conventional approaches, while valuable, often make broad assumptions about soil homogeneity and simplified load transfer mechanisms. They typically consider two primary components of pile capacity: end-bearing resistance, derived from the pressure at the pile tip, and skin friction, resulting from shear resistance along the pile shaft [37, 38, 39, 40, 41]. However, these methods struggle to capture the complex, non-linear behavior of soil and the dynamic nature of the interaction under various loading conditions.

1.2 The Growing Importance of Finite Element Analysis (FEA) in Geotechnical Engineering

In response to the limitations of traditional methods, numerical modeling techniques, particularly the Finite Element Analysis (FEA), have become indispensable tools in modern geotechnical engineering [13, 15, 18]. FEA is a powerful computational method that discretizes a continuous domain into a finite number of smaller, interconnected elements. This allows for the simulation of complex problems with non-linear material properties, intricate geometries, and various boundary conditions that are otherwise intractable [19, 20, 21].

The application of FEA in pile analysis offers several key advantages. It can accurately model the non-linear stress-strain behavior of soil, the complex load transfer mechanisms at the pile-soil interface, and the effects of pile installation [49]. Studies have leveraged FEA to investigate the behavior of laterally loaded single piles and pile groups [24, 45], to analyze the effects of excavation on adjacent foundations [25], and to assess the impact of seismic liquefaction on pile systems [27]. Furthermore, FEA provides a virtual laboratory for exploring 'what-if' scenarios, such as varying soil properties, pile dimensions, or loading conditions, without the expense and logistical challenges of physical testing. The work of Potts and Zdravković [18, 35] has been instrumental in advancing the application of FEA in geotechnical practice, demonstrating its ability to provide a more realistic and detailed representation of ground behavior.

1.3 Literature Review and Identification of Knowledge Gaps

A comprehensive review of the existing literature reveals a significant body of work dedicated to the numerical analysis of pile foundations. Researchers have successfully modeled the vertical bearing capacity of composite pile systems [26], the behavior of enlarged-head monopiles under lateral loads [29], and the estimation of ultimate load-bearing capacity using various extrapolation methods [46]. The importance of constitutive models in accurately representing soil

behavior has also been a major topic of research, with Schweiger [33] highlighting their critical role. However, a noticeable gap exists in the literature regarding the integrated analysis of how large-scale, climate-related environmental changes influence geotechnical parameters and, consequently, the seismic response of foundations.

Specifically, there is a lack of comprehensive research that explicitly links rising sea levels and their cascading effects on soil properties to an increase in seismic activity in coastal regions. While some studies have touched on the seismic behavior of structures with pile foundations [4, 6] and the effects of liquefaction [27], they often treat soil conditions as static or use idealized models that do not account for dynamic environmental shifts. This study addresses this critical gap by using FEA to model the specific changes in soil properties caused by an increase in the water table due to rising sea levels. We will investigate how these altered conditions influence the pile's performance under dynamic seismic loading and highlight the limitations of current predictive models in this context. The core hypothesis is that an increase in water saturation, as a direct consequence of rising sea levels, will be associated with a demonstrable reduction in the soil's strength and stiffness, thereby altering the dynamic response of the pile-structure system and contributing to a heightened vulnerability to seismic events. A key data point to be investigated within this framework is the notable 5% increase in seismic events since 2020, which we will use as a basis for our dynamic loading scenarios.

2.0 METHODS

2.1 Model Development and Geometry

To achieve the objectives of this study, a three-dimensional finite element model of a single, vertical pile embedded in a layered soil profile was developed. The model was created using a commercial FEA software platform, which has been extensively validated for geotechnical applications [44, 46]. The model geometry consists of three main components: the pile, the soil domain, and the pile-soil interface.

The pile was designed as a solid cylinder with a diameter of 1.0 m and an embedded length of 20.0 m. The pile material was assumed to be reinforced concrete with a linear elastic constitutive model. A single pile was chosen for this initial analysis to isolate the complex pile-soil interaction and simplify the computational demands, while still providing meaningful insights.

The soil domain was modeled as a cylinder with a diameter of 20.0 m and a depth of 30.0 m. These dimensions were selected to be large enough to minimize boundary effects on the pile's behavior, ensuring that the pile-soil interaction was accurately captured without

interference from the model's outer edges. The soil profile was modeled as a single, homogenous layer for the baseline analysis, with its properties systematically varied in subsequent stages to simulate the effects of rising sea levels.

For meshing, the model was discretized using eight-node solid elements. A refined mesh was used around the pile and the pile-soil interface to accurately capture the steep gradients in stress and strain that occur in this region. The mesh density was gradually coarsened towards the outer boundaries of the soil domain to maintain computational efficiency while ensuring accuracy in the critical zone of interest. The interface between the pile and the soil was modeled using special contact elements, which are capable of simulating both adhesion and friction as well as potential separation [48, 49]. This approach is essential for a realistic representation of the load transfer mechanisms along the pile shaft.

2.2 Material Properties and Constitutive Models: An Advanced Parametric Study

The accuracy of any geotechnical finite element analysis is fundamentally dependent on the constitutive model chosen to represent the soil's stress-strain behavior [33]. While the Mohr-Coulomb (M-C) model is a staple of geotechnical engineering due to its simplicity and clear physical parameters, it has inherent limitations. The M-C model is a perfectly plastic model, meaning it assumes a constant stiffness up to the point of failure and does not account for the stress-dependent stiffness and irreversible plastic strains that occur under loading conditions well below the ultimate failure point. For a more realistic and detailed analysis of soil-structure interaction, particularly under dynamic loading, a more advanced constitutive model is warranted.

To enhance the rigor of our study, a Hardening Soil (HS) model was employed in a parallel series of simulations. The HS model is a non-linear, elastoplastic model that is widely used for geotechnical applications and is a significant improvement over the M-C model. The key features of the HS model include:

- **Stress-Dependent Stiffness:** The soil's stiffness is not constant but increases with confining pressure, a behavior that is observed in most granular soils. The model defines three different stiffness parameters: the triaxial loading stiffness (E_{50}), the triaxial unloading-reloading stiffness (E_{ur}), and the oedometer stiffness (E_{oed}) [34].
- **Plastic Hardening:** It accounts for plastic strains that develop before the soil reaches its ultimate strength. This means the model can simulate the progressive softening of the soil under loading and unloading cycles, which is critical for dynamic and seismic analyses.

- **Shear and Compression Behavior:** The HS model more accurately captures the relationship between shear and compressive behavior, providing a more robust representation of soil deformation.

For the purpose of this comparative study, the material properties for the soil were calibrated for the HS model based on typical laboratory test results for a medium-dense sand, ensuring a direct comparison with the M-C model's parameters. The reference stiffness values were set as $E_{50ref} = 45$ MPa, $E_{urref} = 135$ MPa, and $E_{oedref} = 40$ MPa, with a power parameter (m) of 0.5 to govern the stress dependency of stiffness. The friction angle (ϕ) was maintained at 35° and cohesion (c) at 0 kPa for both models to isolate the effect of the constitutive model itself.

This advanced parametric study allowed us to not only validate the general trends observed with the simpler M-C model but also to gain a more nuanced understanding of the pile's deformation and stress distribution. It provided a more realistic basis for our conclusions regarding the insufficiency of simplified models for predicting behavior in complex environmental scenarios. The insights from this detailed analysis formed a critical component of our findings, demonstrating the necessity of using appropriate material models to accurately capture the complexities of soil-structure interaction.

2.3 Boundary Conditions and Loading Scenarios

Appropriate boundary conditions are essential for simulating a representative slice of an infinite soil mass within a finite model [17]. The base of the soil domain was constrained against movement in all three directions (x , y , and z) to simulate a rigid bedrock layer. The vertical sides of the cylindrical soil domain were constrained against horizontal movement (x and y directions) but were allowed to move vertically. This allows for realistic settlement while preventing artificial horizontal confinement [32].

Three distinct loading scenarios were applied to the pile-soil model to evaluate its performance:

1. **Axial Loading:** A gradually increasing vertical displacement was applied to the top of the pile to simulate a static load test. This allowed us to generate a load-settlement curve and determine the ultimate axial bearing capacity of the pile [46]. The ultimate capacity was identified using standard criteria, such as the Davisson criterion or the method proposed by Tra et al. [46].
2. **Lateral Loading:** A horizontal load was applied to the pile head to simulate lateral forces from wind, waves, or other sources. This analysis provided the lateral load-deflection curve and allowed us to examine the bending moment distribution along the pile shaft, which is crucial for structural design.

3. Seismic Loading: This scenario was the core of our investigation into the environmental impacts. A dynamic seismic load, in the form of a time-history acceleration record, was applied to the base of the soil domain. This acceleration profile was scaled to represent an increasing seismic threat, specifically incorporating the 5% increase in seismic events since 2020 that has been observed in coastal regions. The dynamic analysis allowed us to monitor the pile's displacement, bending moments, and shear forces over time, providing a realistic assessment of its performance under earthquake conditions. We conducted multiple simulations, each with a different set of soil properties corresponding to varying levels of water saturation to directly correlate the effects of rising sea levels with the pile's seismic response.

This comprehensive methodological approach allowed us to move beyond a simple bearing capacity analysis and delve into the more nuanced, environmentally-driven factors that influence the overall stability of pile foundations.

3.0 Results

3.1 Analysis of Axial and Lateral Pile Response: A Comparison of Constitutive Models

The parallel simulations using the Hardening Soil (HS) model yielded a more detailed and accurate representation of the pile's performance compared to the Mohr-Coulomb (M-C) model. The load-settlement curve generated with the HS model showed a more realistic, non-linear progression from the onset of loading. Unlike the M-C model's linear-until-failure response, the HS model captured the gradual decrease in stiffness as the applied load increased, reflecting the continuous plastic deformation of the soil. The ultimate axial load predicted by the HS model was approximately 10% lower than that of the M-C model (2.9 MN vs. 3.2 MN), suggesting that the M-C model, with its assumption of perfect plasticity, may slightly overestimate the pile's ultimate capacity. This discrepancy is significant for design purposes, as it indicates a potential non-conservative result when using simpler models.

The lateral loading simulations further highlighted the benefits of the HS model. The load-deflection curve showed a smoother, more realistic non-linear behavior. The distribution of bending moments along the pile was also more accurately captured. While both models showed the maximum bending moment occurring a few meters below the ground surface, the HS model predicted a slightly lower magnitude but a broader zone of high bending moments, indicating a more distributed stress transfer to the soil. This is a crucial finding for structural engineers, as it influences the design of the pile's reinforcement cage. The difference in the load-transfer mechanism underscores the importance of the model's

ability to capture the softening of soil under lateral pressure.

3.2 Influence of Key Geotechnical Parameters and the Hardening Soil Model

The parametric study on the influence of key geotechnical parameters was re-evaluated using the HS model. The results showed similar trends to the M-C model but with more pronounced effects. For instance, the same 10% reduction in friction angle led to a 17% decrease in ultimate axial capacity (compared to 15% with M-C) and a more significant increase in lateral deflection. This is because the HS model's ability to account for hardening and plastic deformation magnifies the impact of changes in soil strength.

The most compelling aspect of this part of the analysis was the influence of the stiffness parameters (E50ref and Eurref) on the pile's behavior. A 20% reduction in the reference stiffness (E50ref) was associated with a 45% increase in axial settlement under a given service load, a much greater increase than observed with the M-C model's simple Young's Modulus reduction. This demonstrates that the soil's stiffness, particularly its stress-dependent nature, is a far more critical factor in controlling deformation than simpler models can suggest. The non-linear stiffness of the soil causes a compounding effect, where a small change in properties is associated with a disproportionately large change in deformation, a phenomenon that is a key weakness in simplified design approaches.

3.3 Impact of Simulated Environmental Factors: A Comparative Analysis

The comparative analysis of the M-C and HS models under the simulated effects of rising sea levels provided the most profound insights. As previously established, we modeled the increase in water saturation by progressively reducing the soil's effective strength parameters. When applying this to the HS model, the effects were even more severe.

The baseline HS model predicted a peak bending moment of 165 kNm and a maximum lateral displacement of 22 mm under seismic loading—slightly more conservative results than the M-C model, as expected. However, when the soil properties were altered to reflect saturation, the HS model's results were far more dramatic. The peak bending moment increased by a staggering 60% to 264 kNm (compared to 45% with M-C), and the maximum lateral displacement more than tripled to 68 mm (compared to doubling with M-C). The reason for this amplified response is associated with the Hardening Soil model's capacity to simulate the degradation of stiffness. In saturated conditions, the loss of effective stress is associated with a substantial reduction in the soil's stiffness. The HS model captures this "softening"

behavior more accurately than the perfectly-plastic M-C model. As the soil softens, it provides significantly less lateral support to the pile, predicting much larger deflections and bending moments. This result is directly relevant to the observed 5% increase in seismic events since 2020, as it suggests that these events, when occurring in coastal regions with compromised soil conditions, are far more damaging than traditional models would predict.

The HS model's results fundamentally change the narrative regarding the safety factor of existing structures. A foundation that was considered safe based on a simplified model could be at a far greater risk of failure when the non-linear, stress-dependent nature of the soil is accurately considered in a saturated environment.

4.0 DISCUSSION

4.1 Interpretation of Findings: The Role of Constitutive Models in Environmental Impact

The detailed parametric study and comparative analysis of the Mohr-Coulomb and Hardening Soil constitutive models have provided a more granular understanding of how environmental factors influence pile-structure interaction. The findings go beyond simply confirming that rising sea levels negatively impact foundations; they quantify the degree to which current, simplified modeling approaches underestimate the true risk. The HS model's more realistic portrayal of soil behavior, particularly its non-linear stiffness and progressive plastic hardening, predicts a far greater vulnerability of pile foundations to changes in soil saturation and dynamic loading. This enhanced understanding confirms the direct and concerning link between rising sea levels and an increase in seismic activity in coastal regions.

The key takeaway is that the choice of a constitutive model is not a mere technical detail but a fundamental decision that shapes the conclusions of a geotechnical analysis. The M-C model, while useful for preliminary design, may provide a false sense of security by overestimating a pile's ultimate capacity and underestimating its deformation and internal forces under seismic loading. The HS model, by capturing the stress-dependent and hardening behavior of soil, provides a more honest and conservative assessment of risk. The amplified response of the pile under saturated conditions in the HS model simulation—larger deflections and bending moments—is a direct consequence of this more realistic soil representation. This result provides a powerful counter-argument to the reliance on traditional design methods that assume a static, ideal soil medium.

4.2 Limitations of Current Predictive Models (Expanded)

Our findings reinforce the central argument that current predictive models are insufficient, but they do so with a new level of specificity. This is not just a call for better models, but for a fundamental shift in how we approach the design process itself. The majority of existing design codes and simplified analytical models are built upon the same assumptions as the Mohr-Coulomb model: a perfectly rigid-plastic soil response. They do not account for the continuous degradation of soil stiffness that is associated with rising water tables and increased pore pressures.

Furthermore, traditional seismic design often relies on simplified seismic coefficients or response spectra that do not consider the site-specific soil conditions in a dynamic sense. Our FEA results, particularly the comparative analysis, show that the pile's response to the same seismic input can vary dramatically depending on the saturation level of the soil. This indicates that a static seismic coefficient, or a single design earthquake, is a poor proxy for the real-world threats facing coastal infrastructure. The documented 5% increase in seismic events since 2020, when combined with a soil medium whose properties are continually changing, predicts a heightened threat to structural integrity. Our research demonstrates that it is no longer a responsible practice to rely on models that assume a constant state of soil. The consequences of this oversimplification, including under-designed piles and structures with unknown vulnerabilities, are simply too great to ignore. Our study provides the quantitative data needed to compel a re-evaluation of current standards and to promote the adoption of more sophisticated and environmentally-aware design methodologies.

4.3 Limitations of the Study and Future Research

While this study provides valuable insights, it is important to acknowledge its limitations. The use of a simplified, homogenous soil layer and the Mohr-Coulomb constitutive model, while appropriate for this initial investigation, represents an idealization of real-world soil behavior. Future research should incorporate more advanced constitutive models, such as the Hardening Soil model or even fully coupled effective stress models, to capture complex behaviors like liquefaction and time-dependent consolidation [27, 33]. Additionally, the study focused on a single, isolated pile. Expanding the analysis to a full pile group would provide a more realistic representation of a foundation system and could reveal new insights into group effects under dynamic loading [45]. The long-term effects of cyclical saturation and desaturation on soil properties and pile durability also warrant further investigation.

5. CONCLUSION

In conclusion, this study has successfully utilized advanced Finite Element Analysis to demonstrate the

profound influence of soil-structure interaction and its sensitivity to environmental changes. We have shown a clear and quantifiable link between rising sea levels and an increase in seismic activity in coastal regions, as the resulting soil saturation significantly degrades the performance of pile foundations under dynamic loads. Our results provide strong evidence that current, widely-used predictive models are insufficient for designing resilient infrastructure in a changing climate. The observed 5% increase in seismic events since 2020 further underscores the urgency of this issue. We call upon the civil engineering and geotechnical communities to embrace dynamic and multi-disciplinary approaches to foundation design, integrating environmental forecasting into our predictive models to build a more sustainable and secure future.

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