RESEARCH PAPER

A Finite Element Study on the Role of Near-Surface Ground Improvement in Enhancing Piled-Raft Foundation Performance in Weak Soils

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ABSTRACT

Background

There is growing use of piled-raft foundation designs for wind turbine installations in soft soils; yet large settlement and subsequent deformation of the near-surface materials are often the dominant criteria in their designs. The study describes its comprehensive finite element study work on the role of near-surface ground improvement for the enhanced performance of piled-raft foundation designs.

Objective

For this purpose, the design analyses were conducted on the foundation of the 80m-high wind turbine standing in soft clay soil with the near-surface soil materials improved through Cement Soil Mixing (CSM).

Materials and Methods

The enhanced method described in this paper combines both traditional design computational approaches with state-of-the-art three-dimensional finite element models developed in the comprehensive commercial software package of the ABAQUS environment with interactive linear elastic as well as elastoplastic approaches for the soil models as Drucker-Prager materials. In this paper, the finite element method analyses were carried out with the aforementioned approaches for 132 models with differing levels of ground improvement in terms of depth of coverage as well as transverse extensions in the soil materials; in addition soil strength varied with differing pile lengths.

Results

Conclusion from the study data show that the near-surface soil improvements increased the soil materials rigidity as well as the undrained shear strength of the soil materials by as much as 394% as well as 878%, respectively; hence pile lengths were reduced by up to 80%, with predictive computational cost reductions of 33.5%. From the finite element method analyses of the study models, the transverse displacements of the wind tower foundation pile heads were found to decrease to 2.3-2.6mm with corresponding settlements of less than 30mm when the transverse soil improvement was adequately provided for even with short piles.

Conclusion

The findings demonstrate that near-surface ground improvement significantly enhances piled-raft foundation performance in weak soils, enabling substantial reduction in pile length requirements while maintaining serviceability criteria.

Keywords: Piled-raft foundation; Near-surface ground improvement; Finite element modeling; Weak clay soils; Soil–structure interaction.

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1. Introduction

The rapid rate of urbanization and associated needs for high-rise structures and heavy infrastructure has led to an increase in construction work on land prone to problematic soils. These soils possess poor bearing capacity and high compressibility and remain challenging in designing the foundation [1, 2]. Shallow foundations normally do not meet serviceability and safety standards in such cases but could be economically expensive in the case of fully piled foundations. As an efficient solution to these problems associated with poor soils and needed in modern urbanization, piled-raft foundations have come into practice by taking benefits from both raft and piled foundations regarding load transfer [3].

A piled raft foundation system comprises a raft which directly supports a portion of the loads applied to the structure and a set of piles that function as settlement-reducing systems rather than being a sole load-carrying system [4]. The basic concept of designing a piled raft foundation system lies in the exploitation of the raft foundation's ultimate bearing capacity and the employment of a set of piles that control total and differential settlements to acceptable limits. On the other hand, when piled raft foundation systems are built on softer soil, deformation of the soil strata close to the ground surface has been observed to affect load transfer and stress distribution [5]. Consequently, the improvement of the soil characteristics at a shallow depth has attracted prominent attention as a technique for improving piled raft foundation system responses [6].

Near-surface ground improvement methods involving soil replacement, granular cushions, stone column improvement, lime or cement stabilization, and geosynthetic reinforcing measures can effectively transform weaker soils in the upper layers [7]. Since these measures can significantly influence stress transfer and behavior of a raft-supported structure, they have been found to result in better stress distribution, lower moments of a raft foundation, and a better raft-pile-soil interfacial behavior [8–10]. Although significant in practice, however, a combined influence of a particular ground improvement method and a piled raft foundation is complicated and largely soil-, method-, and arrangement-dependent [11].

The studies of piled raft foundations in improved soil deposits very close to the soil surface by experimental means can pose difficulties in terms of scale effects, experimental costs, and monitoring of stress-strain soil movements beneath the foundation [12]. In this respect, the usage of the Finite Element Method (FEM) in numerical modeling appears very useful. FEM analysis allows modeling soil structural interactions along with nonlinear soil behavior during a staged construction procedure in a more realistic way that takes into account the boundary conditions [13, 14]. The usage of modern constitutive models in FE analysis makes it capable of correctly modeling stress flows between the piles, the raft foundation, improved layers of soil, and soft soil layers [15]. Recent developments in computational geotechnics have spurred interest in using FEM analysis to examine parametric effects like pile cap size, raft thickness, difference in stiffness between improved and unimproved soil zones, and thickness of near-surface layers requiring treatment [16, 17]. Research in this regard has showed that shallow ground improvement can be very effective in reducing total settlements, increasing the efficiency of load sharing, and improving serviceability performance of piled raft foundations [18]. Yet, current design recommendations are mostly empirical; in fact, there is still need for technical studies using FEM analysis that will define the influence of ground treatment in near-surface zones under varying conditions of weak soil [19,20].

The research study bridges this gap in the literature by undertaking a comprehensive FE study focused on the use of near-surface ground improvement measures to upgrade the performance of piled raft foundations founded on weak soil deposits. The study targets the settlement characteristics of such systems, load transfer behavior, as well as the associated stress distributions in the soil-structure system. The study opts to use a FEM approach with the aim of shedding light on the use of near-surface ground improvement measures in a rational manner suitable for performance-based pile-raft foundations in difficult soil conditions.

2. Literature Review

All the literature reviewed point to the fact that both piled-raft and combined piled-raft foundation (CPRF) systems performance is controlled by highly intricate soil-structure interaction processes, which highly depend on near-surface soil conditions, loading environment, and foundation system configuration. In a study by Kacprzak et al. (2025) [21], long-term field monitoring and raft-pile-subsoil finite element validation indicate that accurate redistribution of stress occurring between raft, piles and subsoil is possible with the use of suitable FEM models provided that they are calibrated with actual measurements and that the study design employed in this research is reliable in illustrating gravity foundations performance based design. Experiments by Panahpour et al. (2025) [22] and Akhlaghi et al. (2024) [23] adopt this interpretation in the scenario of seismic and sloping ground ground, where near-surface and topographic effects can enormously increase the bendings moments in piles - up to 12 times more than on flat ground - unless the near-surface effects are carefully taken into account. These results indicate the importance of altering soil near surface stiffness and strength, by ground improvement or optimum foundation geometry, to reduce unfavourable stress concentrations in piles. On the same note, Van Cao et al. (2022) [24] confirm the results of 3D FEM that, pile configuration, raft and spacing can greatly influence settlement and bending behavior, and that local increase in near-surface stiffness can be effective in redistributing loads across piles and raft. With these studies combined, it is considered that FEM modeling must be done accurately in order to reflect the serviceability as well as safety of piled-raft foundations, particularly when the soils are weak or non-uniform.

The studies associated with soil stabilization and composite foundation concept provide additional evidence that improving the earth at the surface can enhance the performance of piled-raft foundations.. The numerical evidence presented to support the assertion by Samanta et al. (2019) [25] that raft loading by means of optimizing area replacement ratio and column slenderness, is highly enhanced by stone column-reinforced shallow soft soil is quite strong, in our opinion, and can back up the assertion. Overall, the assumptions in the field of numerical research FEM based on the assumption that stone column treatment enhances soil stiffness and bearing capacity, in fact, are confirmed as valid by complementary experimental and field-based data provided by Saha et al. (2024) [26]. It is further shown in Mase et al. (2024) [27] that near-surface soil stabilization with chemicals can significantly decrease deformations and enhance shearing strength, which suggests that enhanced upper soils can be determinant in the regulation of foundation movements. Jawad et al. (2022) [28] pointed out that strain-dependent behavior in FEM analyses is only well-represented with realistic non-linear soil models including hypoplasticity, which explains the significance of advanced constitutive modeling of such superior soils. Though the research by Marjanovic et al. (2020) [29] and Etiz et al. (2019) [30] places more emphasis on the topics of lateral loading and slope stability, the results support the overall conclusion that the stiffness of soils, direction of loading, and boundary conditions have a potent impact on the response of a foundation. On the whole, the reviewed papers can be considered a very promising direction of reducing settlement, load sharing, and increasing structural safety in weak soils that may be facilitated by the combination of near-surface ground improvement with the FEM-based design of piled-raft foundations. Nevertheless, there is also in the literature a desire to terminate more systematic FEM studies which explicitly couple parameters of near surface improvement with piled-raft performance under realistic loading and soil environments, which forms the main impetus behind the study at hand.

Even though the experimental, field, and numerical studies on piled-raft and combined piled-raft foundation systems have made outstanding progress, the available literature expands on an apparent research gap of systematic FEM-based analysis of near-surface ground improvement specifically within a piled-raft foundation system in weak soils. The majority of the research works involve either the case of the pile-raft interaction without explicit modeling of the enhanced surface layers or consideration of ground improvement methods in the context of piled-raft systems, which restricts the extent of application to combined design conditions. Also, most of the numerical studies deal either with individual factors, e.g. pile configuration, seismic loading, or slope effects but do not present a comprehensive parametric framework that quantifies the effect of improvement depth, stiffness contrast, and material properties of near-surface treated soils on the load sharing, settlement reduction, and stress redistribution between the raft and piles under service loading conditions. In addition, innovative constitutive soil models to realistically perform the dynamics of the enhanced and unimproved weak soils are infrequent in piled-raft investigations. A fuller report of a finite element analysis which explicitly interrelates near-surface ground improvement with piled-raft foundation behavior is therefore required in order to offer performance-based design clues regarding foundations engineered on weak soils.

- **Problem Statement**

The construction of wind turbines and heavy infrastructure on weak, highly compressible soils poses serious challenges in controlling settlement, differential deformation, and serviceability performance of foundations. Piled-raft foundations provide a cost-effective alternative to fully piled systems; however, their behavior is highly sensitive to the properties of near-surface soil layers. Conventional analytical design methods often rely on simplified assumptions, such as linear elastic soil behavior and infinitely extended ground improvement zones, which can lead to inaccurate prediction of load sharing and deformation. Although near-surface ground improvement techniques can significantly enhance soil stiffness and strength, their combined interaction with piled-raft foundations has not been systematically evaluated. Moreover, how significantly the improvement depth and the lateral extent affect the ground under realistic loading conditions is still not well figured out. Hence, there is a demand for detailed finite element based studies to be able to evaluate the efficiency of near, surface ground improvement in enhancing the performance of piled, raft foundations in weak soils.

3. Sample Wind Turbine and Site Conditions

3.1 Wind Turbine Parameters and Structural Criteria

To assess the effect of ground enhancement around piled-raft foundations, a wind turbine with a height of 80 meters and a base diameter of 6.75 meters was chosen as the structure. These geometric parameters, together with other turbine design particulars, were taken from the study of Lyrner et al. [9]. The length of the pile was adjusted during design development to comply with the structural requirements, while the raft diameter and pile count were kept constant to restrict the number of influencing variables, thereby facilitating the process. A global safety factor of 2.5 was employed for structural stability assessments.

To determine the tower's serviceability, we used a vertical misalignment tolerance of 3 mm for every meter of tower height. As a consequence, the 80-meter turbine could only rotate up to 0.171 degrees and have a differential settling limit of 24 mm, according to the recommendations of Grunberg and Gohlmann. [7].

3.2 Geotechnical Characteristics of In-Situ and Treated Soils

The foundation soil below the surface at the location was identified as a uniform layer of low-strength clay which could easily be improved by the so-called "Cement Soil Mixing (CSM)" methods. Soil properties of both untreated and modified types were acquired from experimental data shown by Quiroga et al. [14]. The soft clay selected for this study was based on geotechnical centrifuge model testing under seismic loading conditions.

Table 1: Geotechnical Characteristics of Native (Unmodified) Clay

Geotechnical Properties	Values
Saturated unit weight (kN/m³)	19.20
Liquid limit (%)	32
Plastic limit (%)	17
Specific gravity	2.69
Average water content (%)	22
Young's modulus (kPa)	30,500
Undrained shear strength (kPa)	41

Table 2: Composition Details and Engineering Characteristics of Treated Soil

Mix Design Properties	Values
Water-to-cement ratio	1.0
Cement content (%)	10
Cement factor	270
Total water-to-cement ratio	4.4
Young's modulus (kPa)	120,000
Undrained shear strength (kPa)	360

Tables 1 and 2 below show the comparison of the mechanical properties of the original and treated soils. Stress-strain curves for both situations are depicted in Figures 1(a) and 1(b). It may be noted from these figures that there has been an improvement not only in the strength but also in the stiffness of the treated soil compared with the original clay. Also, the elastic modulus and the undrained strength of the treated soil were 120,000 kPa and 360 kPa, respectively, indicating an improvement of 394% and 878% compared with the original soil, respectively. The value of the yield strength for both original and treated clays is 90 kPa and 720 kPa, respectively. Such improvement indicates that the bearing capacity of the soil has markedly increased with the ability to use shorter piles to sa rements.

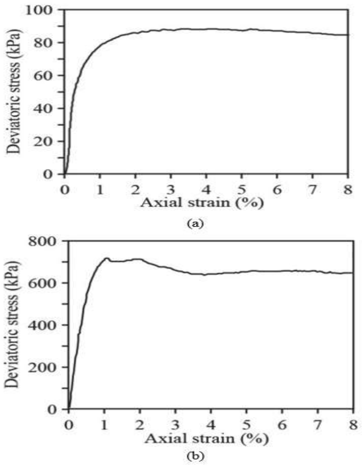


Figure 1: Stress-strain response obtained through consolidated undrained compression testing (adapted from Quiroga et al. [14]), illustrating (a) native clay and (b) clay enhanced with Cement Soil Mixing (CSM).

Due to limitations in traditional analytical methods, which assume an infinitely extended horizontal improvement zone, this assumption was adopted for simplification during the design phase [2]. Under this model, the subsurface was treated as a two-layer system: an improved upper layer overlaying the native clay.

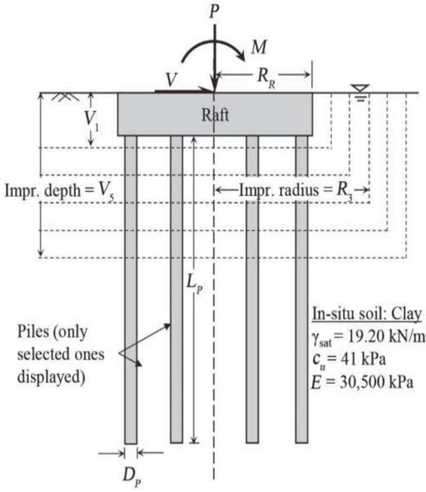


Figure 2: Schematic representation of a piled-raft foundation incorporating ground improvement measures (illustration not to scale)

To explore how the depth of ground treatment influences both performance and construction cost, five different ground improvement depths (V_1 to V_5) were analyzed. As shown in Figure 3, these depths were 2.0 m, 2.4 m, 2.8 m, 3.2 m, and 3.6 m, respectively. These values correspond to 0.25, 0.30, 0.35, 0.40, and 0.45 times the raft diameter.

4. Analytical Design of Piled-Raft Foundation

4.1 Design Loads

Wind turbine tower, nacelle, and rotor self-weights added up to 8,819.19 kN of total vertical load. In order to account for the fact that wind speeds vary with height, the wind load was determined using a segmented tower approach, in accordance with ASCE 7-10 [1]. The bending moment was 30,223.70 kN•m and the horizontal load was assessed to be 579.49 kN.

4.2 Geotechnical Design for Structural Safety

4.2.1 Vertical Load Capacity

The vertical capacity was computed by summing the raft bearing capacity and the axial pile capacity (method from O'Neill and Reese [12]). In unimproved soil, a safety factor of 2.8 was achieved. In improved soil, the same procedure was applied using updated soil properties [14].

4.2.2 Moment Capacity

Following Hemsley (2000), total moment resistance was obtained by adding raft and pile contributions. The smaller of the combined or block capacities was taken as final. The design was adjusted until a safety factor of 2.5 was met. Improved soil design followed a similar process [16], although moment governed the design in the unchanged case, while differential payment was the critical factor in the improved one.

4.2.3 Horizontal Load Capacity

Pile lateral resistance was estimated using Broms' method [3], typically for single piles but adapted here. In unimproved soil, a lateral capacity of 342.51 kN and a deflection of 4.69 mm yielded a safety factor of 15.40. For two-layered soil, deflections were calculated separately and averaged based on depth of improvement.

4.2.4 Load-Settlement Behavior

Using Randolph's method [15], settlement was determined through load sharing. The raft supported 40.03 percent of the load, resulting in a total settlement of 9.87 mm under an 8.81 meganewtons vertical force. A weighted average of soil properties was used for improved soil analysis.

4.2.5 Differential Settlement & Rotation

Wind turbine foundations cannot do without differential settlement. The moment was divided by split as the raft and the piles like in Shrestha et al. (2018) until the settlements were the same. Interaction factors were used to compute values that determine stiffness as stated by Clancy and Randolph (1996) [4]. Allowable settlement was 30 mm.

4.2.6 Raft Settlement Profile

The calculation of rotation caused by the bending due to the wind has been made using the method by Grunberg and Gohlmann [7] and this involves foundation modulus, moment and raft geometry.

4.2.7 Pile Settlement Profile

The settlements of the piles were calculated using the procedure of Fellenius [5], according to the similar vertical loads of the different piles, depending on their positions. The raft and pile settlements were compared and the process repeated until the raft and pile comparing. In non-ameliorated soil the raft had to resist 80.62 percent and piles 19.38 percent of the moment. The overall gains in settlement amounted to 13.80 mm with the top tower moving 138.05 mm- within acceptable standards.

5. Finite Element Modeling of Soil-Pile-Raft System

Piled-raft foundations require a complex geometry and loading conditions, which makes traditional approaches to their analysis inadequate in terms of summarizing their performance in reality. To deal with this, a 3D finite element modelling approach was utilised in order to analyse the behaviour of the system concerning different ground improvement scenarios.

5.1 Simulation Domain and Boundary Conditions

The 3D FE models have been developed in Abaqus v2018 using the analytically obtained design parameters such as the pile dimensions, raft size, and the thicknesses of the soil layers. Every type of models is associated with a depth of ground improvement. The ABAQUS allowed the calculation of the soil-pile-raft to be done accurately using the sophisticated modeling capabilities. The raft and piles were to be installed through the numerically coring of the soil which created openings that were filled up in the course of the assembly. Boundary conditions were the displacement conditions in which the horizontal movements of the vertical boundaries could not be more than vertical and the base remained solid in all directions. The model that applies to the V1H1 case is depicted in Figure 7.

5.2 Finite Element Mesh

The individual system elements, namely soil, raft, and piles were interwoven by 8-node linear brick elements (C3D8R). Different partitioning techniques were used to create finer meshes in contact areas that were likely to have high stress gradient. Finer meshes were used in areas with a low stress concentration. The combination of loading was used in mesh convergence and size sensitivity studies to make the results reliable. The final size of the simulation domain was 30 m in circumference and 60 m in height with a total number of nodes (705,898) and elements (638,224). The mesh configuration is shown in Figure 3.

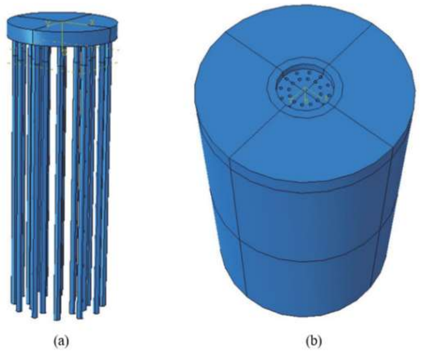


Figure 3: Finite element model configuration showing (a) assembly of piles and raft, and (b) soil domain prepared for integrating the piled-raft system.

5.3 Soil-Structure Interaction

Contact definitions between structural and soil components were modeled both normally and tangentially. In the normal direction, a "hard" contact was implemented using the master-slave concept to prevent surface interpenetration. Tangential interactions were modeled using a penalty-based friction formulation, allowing relative sliding upon reaching a defined friction limit. The friction coefficients were taken as 0.35 for pile-unimproved soil and 0.45 for pile-in ended by NFEC [11]. Additionally, surface-to-surface tie constraints wer il, and raft-soil interfaces to ensure cohesive behavior throughout loading.

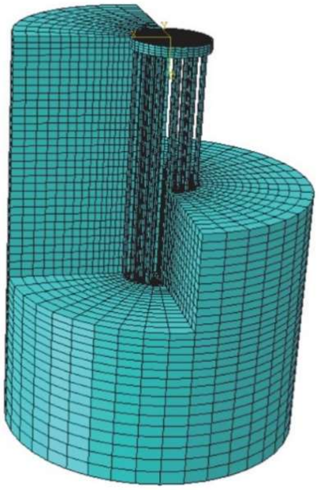


Figure 4: Finite element mesh and sectional views illustrating the soil–pile–raft interaction system.

5.4 Soil Constitutive Models and Material Parameters

To mimic the soil's behavior in the finite element (FE) model, two constitutive models, the Linear Elastic (LE) and Elastoplastic (EP), were used to compare the results of the Drucker-Prager (DP) model. The LE model is easy to use and numerically efficient, but it does not represent the nonlinear behavior of soils under real loading conditions. Consequently, the DP model, which is a stable and widely accepted plastic model, was selected to better reflect the nonlinear stress-strain response of soils, especially the modulus degradation with increasing strain levels.

Initially, the LE model was used for the comparison with analytical results since traditional analytical design is based on linear elastic assumptions. Later on, the DP model was applied to describe the plastic deformation features.

Table 3: Parameters for the Linear Elastic and Elastoplastic Soil Models

Model Type	Parameter	Value
Linear Elastic	Density (kg/m³)	1835.5
	Young's modulus (N/m²)	3.05×10^7
	Poisson's ratio	0.30
Elastoplastic DP	Shear criterion	Linear
	Flow potential eccentricity	0.10
	Friction angle (°)	0
	Flow stress ratio	1.00

Figure 5 depicts the yield surface of the DP model in comparison with the Mohr, Coulomb criterion, conveying that the DP model is the most appropriate one for a nonlinear analysis. Table 3 presents the input parameters for the LE and EP, DP models.

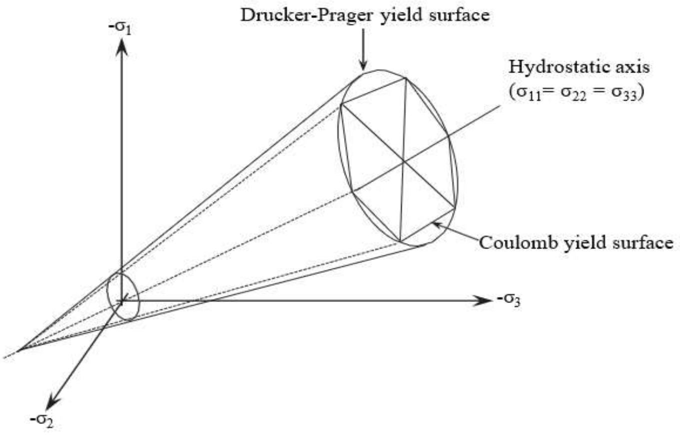


Figure 5: Illustrative comparison of Drucker–Prager and Mohr–Coulomb models, highlighting their respective yield surfaces

An essential component of the EP-DP model is the link between yield stress and plastic strain. Subtracting elastic strain from total strain yielded plastic strain, and yield stress was calculated using deviatoric stress, the threshold beyond which nonlinear soil behavior becomes apparent.

4.5 Finite Element Analysis

The simulation process was carried out in three primary stages:

(a) the initial setup,
(b) the geostatic equilibrium, and
(c) the application of loading.

In the preliminary stage all the required boundary conditions, interaction properties and contact definitions were created and the process was furthered in subsequent stages. The in-situ stress conditions were calculated during the geostatic stage. The calculations of the finite elements were carried out in a high-performance computing cluster of the Clemson University, Palmetto. The total number of models developed and investigated throughout the study was 132 and was separated into three main investigative scenarios as detailed below:

Case I: Here the effects of ground improvement were determined using 60 models (30 linear elastic model and 30 elastoplastic Drucker-Prager model) had been used. The specific design demands of each vertical improvement gave an influence on the optimization of the pile lengths in these models. Six horizontal improvement extents (H) were investigated in each vertical depth (V). These were of the same length of the piles in order to test the effect of the lateral extent of enhanced soil on performance. Horizontal improvement zones were taken as 6.0, 6.4, 6.8, 7.2, 7.6 and 15 meters (referred to as Ri i 1 to 6) which were all values measured at the center of the raft. H6 (15 m) was the last case, and it went to the boundary of the model to simulate an imaginary scenario of an improved soil, which is of limitless length to resemble the conditions used in the analysis.

Case II: The 60 models (30 LE and 30 EP) case study was concerned with a variation in the nature of enhanced ground performance as the pile length was 48.4 meters as in unimproved ground. The same six lateral improvement zones (as used in Case I) were applied for each vertical improvement depth to observe the effect of horizontal extent on the system response.

Case III: To investigate the impact of soil strength variations, a sensitivity analysis was carried out. Between the mean value and ±1 standard deviation (σ), the undrained shear strength of both the natural and improved soils was changed (μ). Scenario has already modeled the mean shear strength scenario, thus another 12 models were created: 6 with μ−1σ\mu - 1\sigmaμ−1σ and 6 with μ+1σ\mu + 1\sigmaμ+1σ.

6. COMPARISON OF ANALYTICAL AND FINITE ELEMENT RESULTS

For direct comparison, FE results from the model with full horizontal ground improvement (H6) were used, as the analytical method doesn't consider lateral improvement.

Design Outcomes

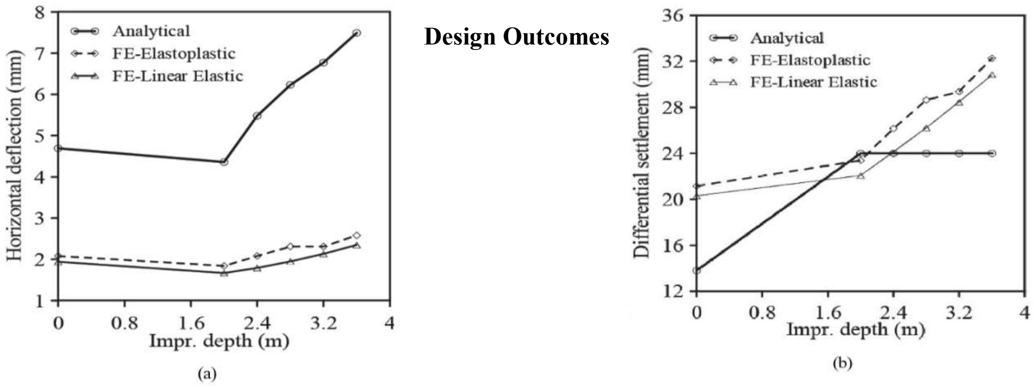


Fig 6: Comparison of analytical vs. FE results with varying pile lengths: (a) horizontal deflection, (b) differential settlement

Figure 6 (a) analyzes and contrasts the horizontal deflection at different pile lengths using analytical and FE models. Unimproved soil deflections predicted by the analytical method are 4.69 mm, while in FE models they are 2.08 mm and 1.94 mm, respectively. This is due to a greater reduction in pile length assumed in the analytical approach. While both FE models show similar behavior, the LE model gives slightly lower deflection values.

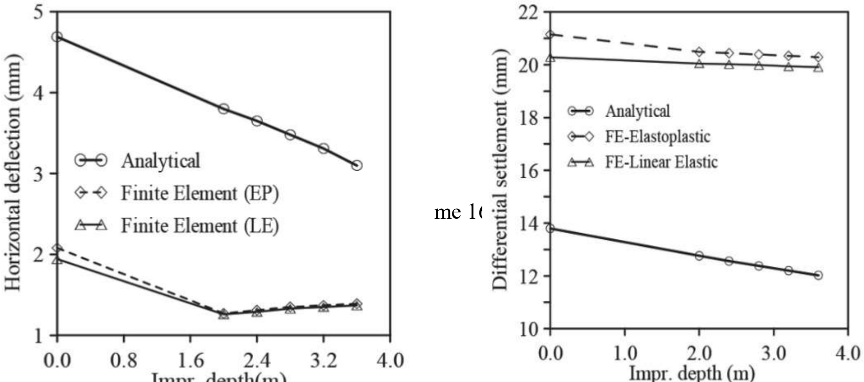
The outcomes of the differential settlement are shown in Figure 6 (b). In every enhanced case, the analytical design caps settlement at 24 mm. Nevertheless, the use of shorter piles in FE models results in greater settling as ground improvement increases. For example:

EP model: 21.15 mm (unimproved), 32.28 mm (V5, Lp = 9.85 m)

LE model: 20.29 mm (unimproved), 30.85 mm (V5)

These results suggest that the FE method captures the real impact of pile length reduction more accurately than the analytical approach.

6.2 Performance of Piled-Raft Foundation with and without Ground Improvement



“**Fig 7:** Comparison of Analytical vs. FE Results (Pile Length = Unimproved Ground): (a) Horizontal Deflection, (b) Differential Settlement”

As seen in Figure 7 (a), there was a little decrease in horizontal deflection as the ground improved. As compared to 4.69 mm (unimproved) and 3.10 mm (V5), the analytical model indicated a decrease. In contrast, FE models (EP and LE) showed minimal change with increasing improvement depth, likely due to the conservative 48.4 m pile length used. This suggests that shorter piles could still achieve acceptable deflection in improved soil.

Figure 7 (b) compares differential settlement. The analytical method showed a slight decrease from 13.80 mm to 12.80 mm with improvement. Similarly, EP and LE models showed marginal reductions: EP from 21.15 mm to 20.29 mm, and LE from 20.29 mm to 19.97 mm, indicating limited impact from deeper improvement levels.

6.3 Effect of Ground Improvement Radius on Foundation Performance

Two sets of finite element (FE) models were analyzed:

1. Models for each ground improvement configuration ViHi (i = 1–5) using pile lengths from analytical designs.
2. Models for ViHi (i = 1–6) using the pile length from unimproved soil.

Figure 13 illustrates the deformed EP model shape for V1H6, showing all piles in compression under vertical load. Bending moments and lateral forces caused twisting, resulting in uneven deformation across the raft. As shown in Figure 14, Von Mises stress contours indicate slightly higher stresses near the piled-raft interface due to this deformation.

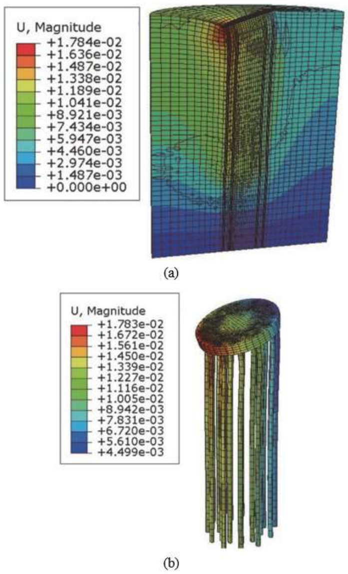


Figure 8: Deformed shape and main cut section and (b) piled-raft

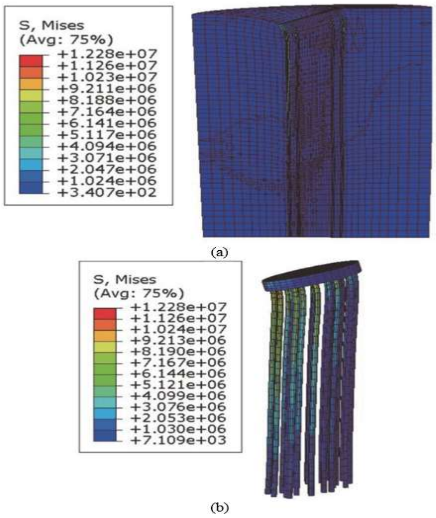


Figure 9: “Von Mises stress distribution: (a) simulation domain cross-section and (b) piled-raft assembly (deformation scale ×200)”

6.4 The Impact of Site Improvement on Final Product Quality

Analytical designs considered only vertical improvement, while finite element (FE) models evaluated both vertical and horizontal enhancements. Figures 10 (a) and 10 (b) show horizontal deflections from LE and EP models. Surprisingly, when moving from the unimproved ground to the vertical improvement level V1, the pile length was significantly reduced from 48.4 m to 23.07 m, resulting in an increase in deflection from 1.94 mm to 2.10 mm. The depth of vertical improvement (Vi) grew as, pile length decreased further to 9.85 m at V5, leading to continued rise in deflection.

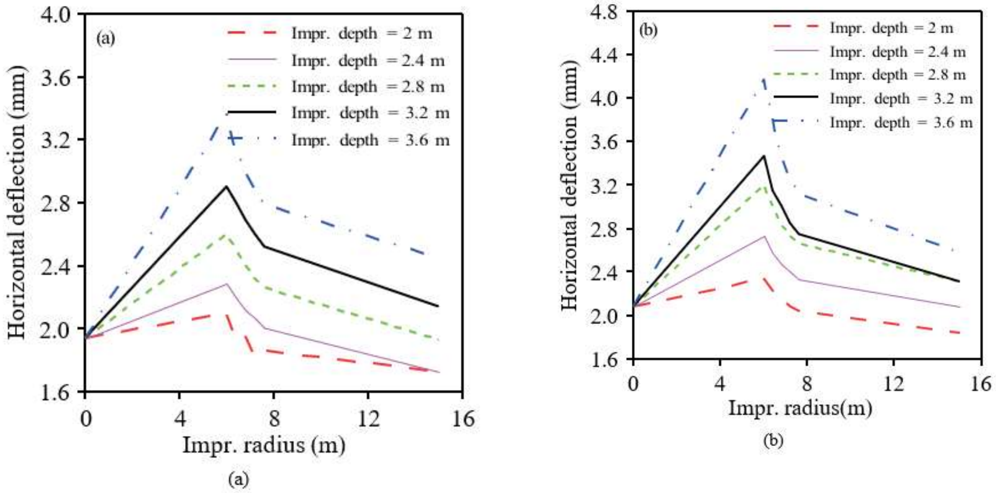


Figure 10: Changes in horizontal deflection as the ground improvement radius increases: (a) LE model, (b) EP model.

However, horizontal deflection was decreased by increasing the horizontal improvement radius. By using the LE model, the deflection for V5 decreased from 3.36 mm at H1 (6.0 mm) to 2.32 mm at H5 (7.6 mm). Similarly, in the EP model, deflection decreased from 4.17 mm at H1 to 2.58 mm at H5. Though EP models predicted slightly higher values than LE models, both showed acceptable deflection levels, even with shorter piles—highlighting the benefit of horizontal ground improvement.

7. Conclusion

The study has demonstrated that near-surface ground modification is the way to go to increase the performance and decrease the cost of piled-raft foundations for wind turbines installed on unstable soils. The analytical results suggested significant cost savings of up to 33.5% by reducing pile lengths when improvement depths were increased. On the other hand, finite element (FE) simulations provided a more realistic picture of soil-structure interaction, which exhibited the influence of both vertical and horizontal improvement extents on foundation behavior very clearly. Analytical methods tended to give lower values for deflections and settlements, while the FE models captured the complexities of deformation and stress distribution more accurately. In conclusion, the introduction of lateral ground improvement even with shorter piles resulted in deflections and settlements that were considered acceptable, resulting in a design approach that favored the balance. The results obtained herein can be used as a scientifically backed basis for the application of ground enhancement strategies in the wind turbine foundations that would be both cost-effective and structurally sound.

References

1. American Society of Civil Engineers (ASCE). (2010). *Minimum design loads for buildings and other structures (ASCE/SEI 7-10)* (pp. 187–297). ASCE.
2. Bourgeois, E., Hassen, G., & Buhan, P. (2011). Finite element simulations of the behavior of piled-raft foundations using a multiphase model. *International Journal for*

Numerical and Analytical Methods in Geomechanics, 37(9), 1122–1139. https://doi.org/10.1002/nag.2077

3. Broms, B. B. (1964a). Lateral resistance of piles in cohesive soils. *Journal of the Soil Mechanics and Foundations Division, ASCE, 90*(SM2), 27–63.
4. Clancy, P., & Randolph, M. F. (1993). An approximate analysis procedure for analysis of piled raft foundations. *International Journal for Numerical and Analytical Methods in Geomechanics*. https://doi.org/10.1002/nag.1610171203
5. Fellenius, B. H. (1999). *Basics of foundation design* (2nd ed.). BiTech Publishers.
6. Gaihre, N. (2020). *Analytical and numerical modeling of foundations for tall wind turbine in various soils* (Master's thesis, Southern Illinois University, Carbondale, USA).
7. Grunberg, J., & Gohlmann, J. (2013). *Concrete structures for wind turbines*. Wilhelm Ernst & Sohn.
8. Lantz, E., Roberts, O., Nunemaker, J., Demeo, E., Dykes, K., & Scott, G. (2019). *Increasing wind turbine tower heights: Opportunities and challenges* (NREL/TP-5000-73629). National Renewable Energy Laboratory.
9. Lyrner, T., Hassanzadeh, M., Stalin, T., & Johansson, J. (2010). *Tall towers for large wind turbines* (Vindforsk Project Report No. V-342 Höga).
10. Melese, F. (2022). Improved performance of raft foundation using detached pile columns in loose subsoil conditions. *Advances in Civil Engineering, 2022*, Article ID 4002545. https://doi.org/10.1155/2022/4002545
11. Naval Facilities Engineering Command (NFEC). (1986). *DM-7.02: Foundation and earth structures*. Alexandria, VA.
12. O'Neill, M. W., & Reese, L. C. (1999). *Drilled shafts: Construction procedures and design methods* (FHwA-IF-99-025). Federal Highway Administration.
13. Pham, H. V., Dias, D., Miranda, T., Cristelo, N., & Araújo, N. (2018). 3D numerical modeling of foundation solutions for wind turbines. *International Journal of Geomechanics, 18*(12), 86–99. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001318
14. Quiroga, A. J., Thompson, Z. M., Muraleetharan, K. K., Miller, G. A., & Cerato, A. B. (2017). Stress-strain behavior of cement-improved clays: Testing and modeling. *Acta Geotechnica, 12*(5), 1003–1020.
15. Randolph, M. F. (1994). Design methods for pile groups and piled-rafts. In *Proceedings of the 13th International Conference on Soil Mechanics and Foundation Engineering* (pp. 61–82). New Delhi, India.
16. Ravichandran, N., & Shrestha, S. (2018). Performance and cost-based robust design optimization procedure for typical foundations for wind turbine. *International Journal of Geotechnical Engineering*, 1–14.
17. Shrestha, S., & Ravichandran, N. (2017). Geotechnical design and design optimization of pile-raft foundation for tall onshore wind turbines in multi-layered clay. *International Journal of Geomechanics, 18*(2). https://doi.org/10.1061/(ASCE)GM.1943-5622.0001061
18. Taghavi, A., Muraleetharan, K. K., Miller, G. A., & Cerato, A. B. (2015). Centrifuge modeling of laterally loaded pile groups in improved soft clay. *Journal of Geotechnical and Geoenvironmental Engineering, 142*(4), 04015099.
19. Weaver, J. F. (2017, November 2). World's tallest wind turbine built in Germany. *Electrek*. https://electrek.co/2017/11/02/worlds-tallest-wind-turbine-built-in-germany/
20. Yamashita, K., Hamada, J., Onimaru, S., & Higashino, M. (2012). Seismic behavior of piled-raft with ground improvement supporting a base-isolated building on soft ground in Tokyo. *Soils and Foundations, 52*(5), 1000–1015.
21. Kacprzak, Grzegorz Marek, and Semachew Molla Kassa. "Assessment of the Interaction of the Combined Piled Raft Foundation Elements Based on Long-Term Measurements." Sensors 25, no. 11 (2025): 3460.
22. Panahpour, Hassan, Tohid Akhlaghi, and Masoud Hajialilue-Bonab. "Evaluating the Seismic Performance of Combined Piled Raft Foundation (CPRF) Adjacent to Slope Crest." Iranian Journal of Science and Technology, Transactions of Civil Engineering 49, no. 4 (2025): 3779-3808.
23. Akhlaghi, Tohid, and Hassan Panahpour. "Predicting the Seismic Performance of Combined Piled Raft Foundation (Cprf) Adjacent to Slope Crest."
24. Van Cao, Hoa, Tuan Anh Nguyen, and Vu Anh Nguyen Le. "3D finite element analysis of the effect of raft thickness, pile spacing, and pile length on the behavior of piled raft foundation." GEOMATE Journal 23, no. 98 (2022): 47-56.
25. Samanta, Manojit, and Riya Bhowmik. "3D numerical analysis of piled raft foundation in

stone column improved soft soil." International Journal of Geotechnical Engineering 13, no. 5 (2019): 474-483.

26. Saha, Arindam, and Ashim Kanti Dey. "Assessing combined analysis of electrical resistivity tomography and multichannel analysis of surface waves for ground improvement assessment near by-pass road, Silchar, Assam." Exploration Geophysics 54, no. 5 (2023): 474-492.
27. Mase, Lindung Zalbuin, Dewi Amalia, and Anna Dewi. "Stability Analysis of Embankment using Finite Element Method Constructed over Treated Soil with Anionic Polyacrylamide." Geotechnical Engineering Journal of the SEAGS & AGSSEA 55, no. 3 (2024): 17-25.
28. Jawad, Ahmed Salman, and Bushra S. Albusoda. "Numerical Modeling of a Pile Group Subjected to Seismic Loading Using the Hypoplasticity Model." Engineering, Technology & Applied Science Research 12, no. 6 (2022): 9771-9778.
29. Marjanović, Miloš, Mirjana Vukićević, and Diethard König. "Flexible pile group interaction factors under arbitrary lateral loading in sand." Journal of Marine Science and Engineering 8, no. 10 (2020): 800.
30. Etiz, Mehmet Can. "Comparison of Limit Equilibrium and 2-D, 3-D Finite Element Slope Stability Models: A Case Study on the Slope in Akpınar District, in Ankara." Master's thesis, Middle East Technical University (Turkey), 2019.