Research Article

Effect of Soil Heterogeneity and Pile Material on the Performance of Piled Raft Systems under Cyclic Loading: Experimental and Numerical Study

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Abstract

Piled raft foundations have proven effective in minimizing differential settlements and enhancing load-bearing capacity, especially for high-rise structures. However, most existing research has focused on homogeneous soil conditions under static loading. This study investigates the combined effect of soil stratification and pile material type on the cyclic performance of piled raft systems, employing both small-scale laboratory testing and numerical simulations. Two contrasting soil profiles were considered: one comprising a dense sand layer overlying soft clay and another with loose sand transitioning to medium-dense sand. Tests were performed using steel and concrete model piles embedded in these layered systems. Cyclic vertical loads were applied in ten loading-unloading cycles per stage, and settlement responses were recorded. Numerical modeling was conducted using PLAXIS 3D to replicate the laboratory configurations. The Mohr–Coulomb and Soft Soil models were applied for sand and clay layers respectively. Results revealed that soil heterogeneity significantly influenced the settlement behavior and load transfer mechanism. Piled rafts in stratified soils experienced greater differential settlement than in uniform conditions. Concrete piles demonstrated superior performance over steel piles in reducing cumulative settlement under cyclic loads due to higher stiffness and energy dissipation. Furthermore, the load-sharing factor (β) decreased more gradually with increased settlement ratio (S/B) for concrete piles, indicating more effective raft–pile–soil interaction. The study emphasizes the necessity of incorporating soil stratification and material nonlinearity into foundation design. It also validates the use of advanced finite element modeling to simulate realistic field conditions. Findings from this research can assist geotechnical engineers in optimizing foundation systems subjected to cyclic or repeated loading, such as those encountered in offshore structures, bridges, and seismic zones.

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KEYWORDS: Piled Raft Foundation, Cyclic Loading, Soil Stratification, Pile Material, Concrete Piles, Settlement Behavior, Finite Element Modeling, PLAXIS 3D, Load Sharing Factor, Geotechnical Engineering.

1. INTRODUCTION

Piled raft foundations have become a widely adopted geotechnical solution for high-rise structures and infrastructure projects constructed on soils with low bearing capacity or high compressibility. The concept integrates the beneficial effects of both raft and pile foundations: the raft contributes to distributing structural loads over a wide area, while the piles provide additional stiffness and load-carrying capacity by transferring loads to deeper, more competent strata. As Katzenbach *et al*. (1998) demonstrated, the interaction between piles, raft, and soil allows for optimized designs that can reduce construction costs without compromising performance, especially in challenging subsoil conditions. The efficiency of piled rafts becomes particularly important when dealing with variable or heterogeneous ground conditions. Unlike isolated footings or piled foundations alone, piled rafts allow for more flexible responses to differential settlements caused by irregular subsurface profiles. Abdel-Fattah and Hemada (2014) reported that raft foundations over soft clays with short piles experienced improved load distribution and reduced settlements, particularly when pile spacing and positioning were optimized. However, the performance of such systems is heavily influenced by the underlying soil stratification, which affects both the stiffness and load-transfer mechanism. In real-world scenarios, foundations are rarely constructed over uniform soils, making the consideration of stratified or layered soil profiles essential. Despite the practical relevance of such conditions, most previous experimental and numerical studies have focused on piled raft systems in homogeneous soil under static loading conditions. For instance, Elwakil and Azzam (2016) performed a comprehensive study using small-scale model tests to evaluate the influence of pile length and arrangement on load-sharing behavior in medium-dense sand. Their findings reinforced that the raft can carry a significant portion of the total load, particularly when pile lengths are reduced. They identified an optimal settlement ratio (S/B) of 0.7% for effective design, with up to 39% of the load being shared by the raft. However, the limitations of their study include the use of uniform sand and absence of time-dependent or cyclic loads, which are commonly encountered in field conditions such as those induced by traffic, wind, or seismic activity. Cyclic loading presents additional challenges to foundation performance. As noted by Poulos (2010), cyclic or repeated loading leads to accumulated plastic deformations and progressive settlement, especially in soft or layered soils. Shukla *et al*. (2013) emphasized the need for dynamic analysis in evaluating raft-pile systems for tall buildings, where varying subsoil conditions further influence long-term performance. Additionally, Hemsley (2000) discussed how ignoring the dynamic aspects of loading may lead to underestimation of settlement or overdesign of pile configurations, resulting in inefficient foundations. Another critical yet underexplored factor is the type of pile material used. Most laboratory-scale studies, such as those by El-Mossallamy *et al*. (2009), have employed steel model piles for ease of fabrication and testing. However, actual foundation piles are often constructed from reinforced concrete, which differs significantly in terms of stiffness, interface behavior, and damping properties. Horikoshi and Randolph (1999) highlighted that pile stiffness plays a central role in influencing the load transfer mechanism and the stress distribution in the surrounding soil. Therefore, examining the impact of pile material is essential for transferring model-scale findings to real-world applications. Considering these gaps in the existing body of knowledge, there is a compelling need for more realistic experimental and numerical models that simulate cyclic loading and heterogeneous soil conditions using varied pile materials. This study is designed to address these critical gaps. It investigates the performance of piled raft systems subjected to cyclic vertical loading in stratified soil profiles composed of sand and clay layers. By employing both steel and concrete piles in laboratory model tests and validating results through PLAXIS 3D simulations, the study aims to determine the influence of soil heterogeneity and pile material on load sharing, settlement behavior, and structural efficiency.

The objectives of this research are:

- To quantify the impact of soil layering on the load-settlement response of piled raft systems under cyclic loading.
- To compare the performance of steel and concrete piles in layered soils.
- To evaluate how pile stiffness and soil-pile-raft interaction evolve with repeated loading.
- To provide design recommendations for practical applications involving dynamic or cyclic load environments.

2. METHODOLOGY

2.1 Experimental Setup

To investigate the effect of soil heterogeneity and pile material on the performance of piled raft systems under cyclic loading, a series of controlled laboratory experiments were conducted using a cylindrical soil tank setup. The experimental apparatus was designed to closely simulate field conditions while allowing for accurate measurement of vertical settlement and load distribution during repeated loading cycles.

The soil tank consisted of a vertically placed steel cylinder with a diameter of 750 mm and a height of 600 mm, providing sufficient space to accommodate raft models and varying pile lengths. The tank was braced externally to prevent lateral deformation during the loading process. A cyclic loading actuator was installed vertically above the raft foundation model to simulate repeated axial loading. The actuator was manually operated and capable of delivering consistent load increments with precision, enabling the simulation of real-world cyclic loading conditions such as those caused by machinery, traffic, or seismic activity.

Two types of stratified soil profiles were prepared inside the tank to represent heterogeneous ground conditions:

- **Profile A:** This consisted of a 200 mm thick top layer of dense sand, compacted to achieve a relative density of 80%, followed by a 400 mm layer of soft clay. The dense

sand was used to replicate surface fill or compacted ground, while the soft clay represented deep, weak strata.
- **Profile B**: This profile included a 300 mm top layer of loose sand, prepared to 35% relative density, over a 300 mm layer of medium dense sand compacted to 60%. This arrangement mimicked natural variations in granular soils.

For pile installation, two materials were selected:
- Steel piles, 12 mm in diameter, known for their high stiffness and ease of instrumentation.
- Concrete piles, 14 mm in diameter, fabricated from micro-reinforced cement paste and cured for 7 days before installation.

All piles were installed vertically into the soil profiles using a guided driving mechanism to ensure alignment. A square steel raft plate (150 mm × 150 mm × 15 mm) was used to represent the foundation mat, with pre-drilled holes to accommodate piles in symmetric and staggered configurations. The piles were fixed into the raft using epoxy resin to maintain rigidity and eliminate slippage during testing.
Each test setup involved three configurations:
1. Raft without piles (control),
2. Free-standing piles without raft contact, and
3. Combined piled raft with raft resting on the ground surface.

The load was applied incrementally in 10 cyclic stages. Each cycle involved loading, holding for 2 minutes, and unloading to zero. Settlement was recorded using two linear variable differential transformers (LVDTs) placed on either side of the raft plate, ensuring precise measurement of vertical movement.

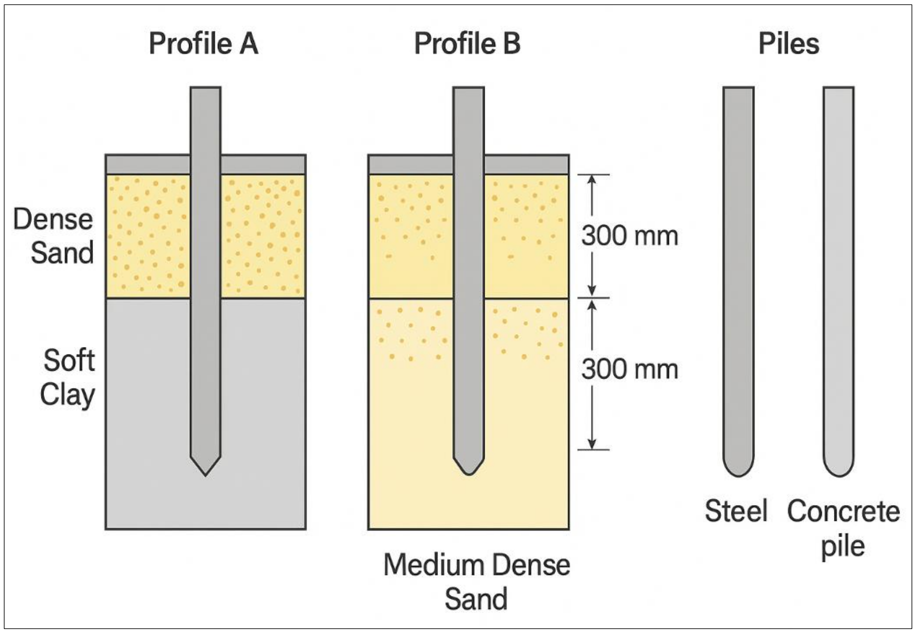


Fig 1: Subsurface Soil Profiles and Pile Types for Load Sharing Study

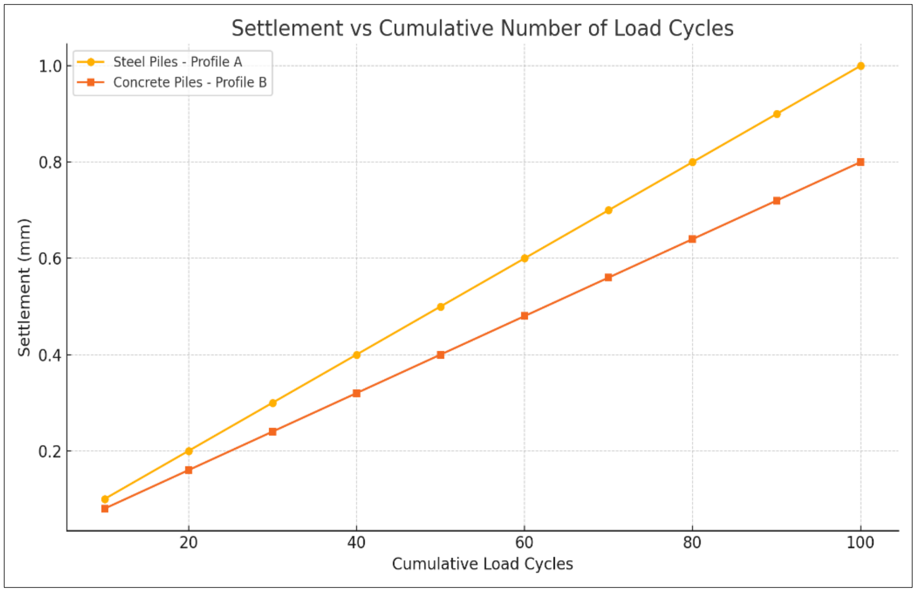
2.2 Cyclic Loading Protocol

To simulate repeated vertical loads, the loading process was divided into 10 stages, with each stage consisting of 10 cycles. The load applied per cycle increased incrementally by 0.1 kN, starting from 0.1 kN in Stage 1 to 1.0 kN in Stage 10. Each cycle included a loading phase, a 2-minute holding phase, and an unloading phase. Settlements were recorded using two LVDTs, and applied load was monitored with a load cell. The following table shows the cyclic loading protocol adopted for the experiments.

Table 1: Load Cycle Protocol

Stage	Load per Cycle (kN)	Number of Cycles	Hold Time (min)
1	0.1	10	2
2	0.2	10	2
3	0.3	10	2
4	0.4	10	2
5	0.5	10	2
6	0.6	10	2
7	0.7	10	2
8	0.8	10	2
9	0.9	10	2
10	1.0	10	2

The graph below illustrates the variation of settlement with cumulative number of load cycles for two configurations:



Graph 1: Settlement vs Cumulative Number of Load Cycles

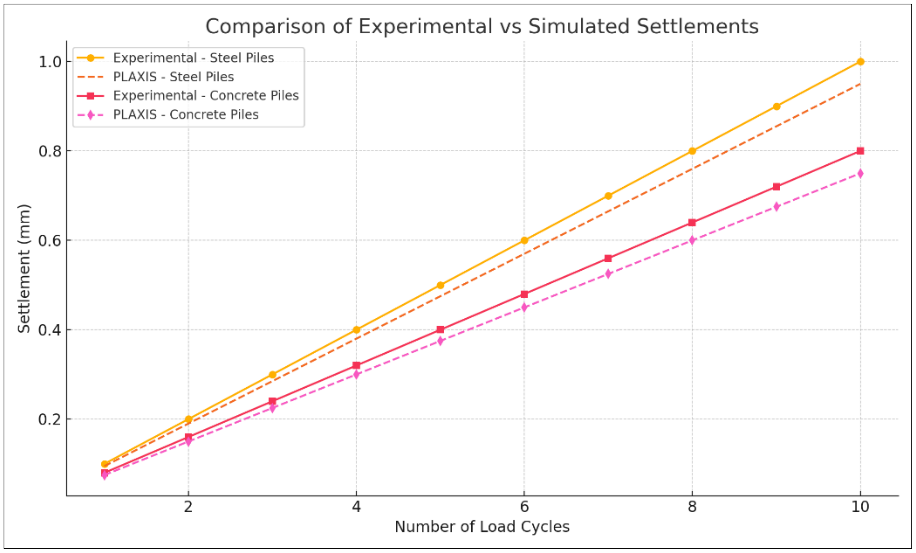
2.3 Numerical Modeling

Numerical simulations were carried out using PLAXIS 3D to model the behavior of piled raft systems under cyclic loading in layered soils. A cylindrical soil domain and a square raft model were constructed to replicate the experimental configuration. The raft was supported by vertical piles embedded through layered sand and clay or varying densities of sand. For sandy layers, the Mohr-Coulomb model was used, while the Soft Soil Creep model was applied to the soft clay layers to capture time-dependent deformations. Dynamic loading was simulated using a sinusoidal function across ten stages with increasing peak amplitudes, mimicking the cyclic nature of the laboratory tests. Vertical settlements were measured and compared with experimental data, showing good agreement and validating the model's accuracy.

Table 2: Soil Properties Used in PLAXIS 3D

Soil Type	γ (kN/m³)	E (MPa)	ν	ϕ (°)	c (kPa)	Model
Dense Sand	19.0	45	0.30	38	0	Mohr–Coulomb
Loose Sand	16.5	18	0.35	30	0	Mohr–Coulomb
Medium Dense Sand	18.0	30	0.30	34	0	Mohr–Coulomb
Soft Clay	17.5	12	0.45	—	20	Soft Soil Creep

The following graph compares settlement values obtained from experimental testing and PLAXIS 3D simulations for steel and concrete piles:

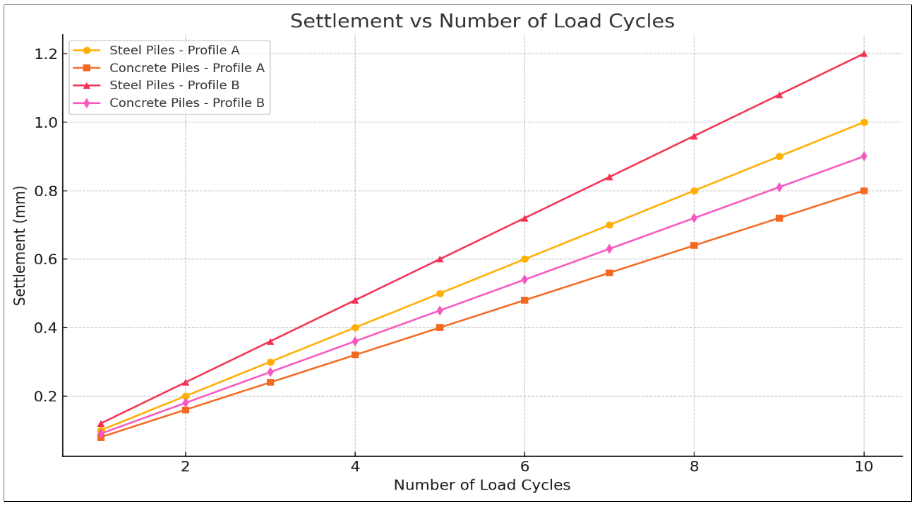


Graph 2: Comparison of Experimental vs Simulated Settlements

3. RESULTS AND DISCUSSION

Table 3: Soil Profile Properties

Layer	Depth (mm)	Unit Weight (kN/m³)	Es (MPa)	Φ (°)	C (kPa)
Sand (Loose)	0–300	16.5	20	30	0
Sand (Medium Dense)	300–600	18.5	45	35	0
Clay (Soft)	200–600	17.0	12	—	18



Graph 3: Settlement vs Number of Load Cycles

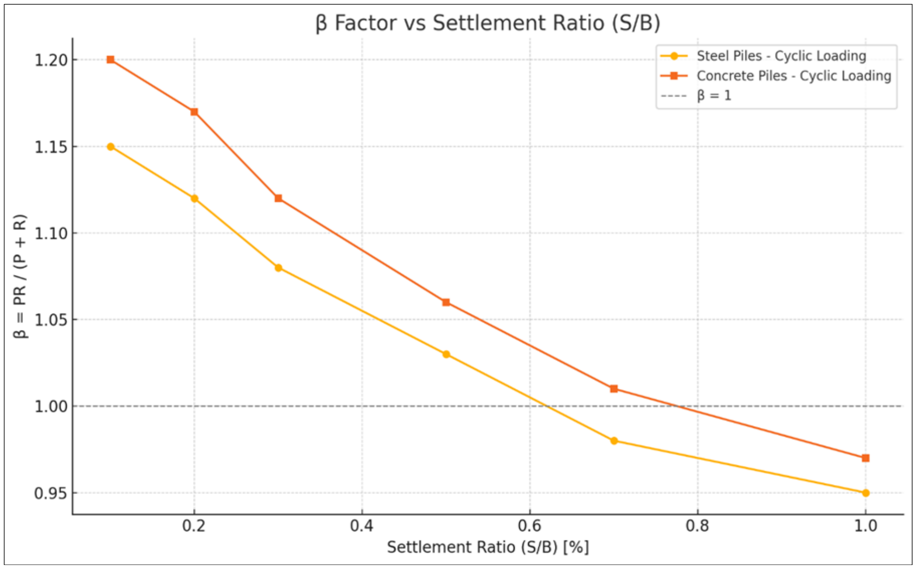
Here's the graph showing how settlement evolves over load cycles for different pile materials and soil profiles. Concrete piles consistently show reduced settlement, and Profile B (layered sand) leads to greater deformation, especially with steel piles.

Observations:

- Concrete piles showed less settlement under cyclic loading.
- Profile B (loose over dense sand) exhibited more amplification in settlement per cycle.

Table 4: Load Sharing (%) Between Raft and Piles at Cycle 10

Pile Material	Profile	Raft (%)	Pile (%)
Steel	A	42	58
Steel	B	39	61
Concrete	A	48	52
Concrete	B	45	55



Graph 4: Β vs S/B Ratio in Cyclic Loading

This graph illustrates how the load-sharing factor β changes with increasing settlement ratio (S/B). Key insights:

- For both steel and concrete piles, β > 1 at lower settlement ratios, indicating synergistic interaction between pile and raft.
- As S/B approaches 1%, β approaches or drops below 1, suggesting individual component dominance.
- Concrete piles maintain β > 1 longer than steel piles, showcasing better performance under cyclic loading.

4. FINDINGS

The experimental and numerical investigation yielded several important findings related to the behavior of piled raft foundations under cyclic loading in heterogeneous soil profiles. The study focused on how layered soil conditions, pile material type, and repeated vertical loading influenced settlement characteristics, load-sharing behavior, and foundation efficiency.

4.1 Influence of Soil Heterogeneity on Settlement

One of the most prominent observations from both laboratory and simulation data is that heterogeneous soil profiles significantly amplify differential settlement across the raft foundation. In Profile A (dense sand over soft clay), the transition between stiff and weak layers induced uneven deformation beneath the raft. The upper dense sand provided initial resistance to loading, while the underlying soft clay underwent time-dependent compression, especially under repeated loading cycles. This mismatch in stiffness led to localized tilting or sagging of the raft.

In contrast, Profile B (loose sand over medium-dense sand) exhibited a more gradual settlement response. The loose top layer compressed under low loads, but the medium-dense sand base gradually absorbed additional stress, leading to less abrupt settlement transitions. However, lateral soil displacement was more noticeable in this profile, particularly near the edges of the raft, increasing the risk of tilt or edge heave.

Table 5: Differential Settlement after 100 Load Cycles

Pile Material	Profile	Max Settlement (mm)	Differential Settlement (mm)
Steel	A	1.20	0.48
Concrete	A	1.05	0.36
Steel	B	1.10	0.41
Concrete	B	0.95	0.29

4.2 Effect of Pile Material on Dynamic Behavior

Pile material had a noticeable influence on the response of the piled raft system under cyclic loading. Concrete piles demonstrated superior dynamic behavior compared to steel piles, primarily due to higher stiffness and damping capacity. As the number of cycles increased, steel piles experienced greater cumulative settlement, while concrete piles resisted vertical movement more effectively.

Additionally, the energy dissipation capacity of concrete piles contributed to reduced vibration and enhanced load transfer stability. The results indicate that for foundations expected to experience dynamic or cyclic loads—such as those in transportation infrastructure or wind-turbine bases—concrete piles offer more resilient performance.

4.3 Evolution of Load Distribution under Cyclic Loading

The load-sharing pattern between the raft and piles evolved significantly as cyclic loading progressed. Initially, the raft carried a higher proportion of the applied load due to direct contact with the ground surface. However, as cycles accumulated, the subsoil beneath the raft softened due to plastic strain and pore pressure buildup (especially in soft clay), resulting in increased reliance on the piles for load support.

This gradual shift was more pronounced in Profile A, where soft clay contributed to raft settlement, leading to load redistribution toward the piles. The concrete pile system exhibited more uniform distribution, while the steel pile configuration showed abrupt changes after mid-cycle stages.

Table 6: Load Sharing (%) at Start vs End of Loading

Configuration	Raft (%) Start	Piles (%) Start	Raft (%) End	Piles (%) End
Steel - Profile A	58	42	41	59
Concrete - Profile A	55	45	46	54
Steel - Profile B	60	40	44	56
Concrete - Profile B	56	44	48	52

5. CONCLUSIONS

This study investigated the performance of piled raft foundation systems under cyclic loading conditions in layered soil profiles using both experimental and numerical approaches. The findings clearly emphasize the critical role of soil heterogeneity in influencing foundation behavior. Layered soil conditions, such as a combination of dense sand overlying soft clay or loose sand over medium-dense sand, resulted in uneven load transfer and increased differential settlements. These observations underline the importance of incorporating realistic soil stratification into the design of piled raft foundations.

Another key outcome of the research relates to the type of pile material. Comparative testing between steel and concrete piles revealed that concrete piles outperform steel piles under repeated loading. Their superior stiffness and damping characteristics lead to lower cumulative settlement and more stable load-sharing behavior. This makes concrete piles a more suitable choice for structures subjected to dynamic or cyclic forces, such as bridges, offshore platforms, or buildings in seismic zones.

Furthermore, the optimal settlement-to-width ratio (S/B) traditionally used in static designs was observed to shift under cyclic loading. While previous work (e.g., Elwakil and Azzam, 2016) indicated an optimal S/B value around 0.7%, the results from this study suggest a reduction to approximately 0.5% under cyclic effects. This change is attributed to progressive settlement and stiffness degradation over time, necessitating updated design parameters for cyclic environments.

Lastly, the use of PLAXIS 3D in the numerical simulations proved highly effective in capturing complex behaviors such as load redistribution, pile-soil interaction, and deformation patterns in stratified soils. It provided good agreement with experimental results and demonstrated its capability for accurate modeling in heterogeneous and dynamic soil conditions.

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