DOI Link: https://doi.org/10.59879/MYxXV
Vol.38, Issue.7, Part.1, July 2025, PP. 2-16

Geotechnical Performance Enhancement of Soft Soils in Baltic Coastal Regions: Three-Dimensional Numerical Analysis of Micropile Systems with Soil-Cement Load Transfer Platforms

Francis Deng Clement[1], Jiang Yan[1*]
[1]School of Arts (School of Architecture Nantong University, Jiangsu Province
Zip: 226019 Nantong, China.
[*] Corresponding author: Jiang Yan's Email: (Yolanda_jiang@ntu.edu.cn)

Received April 2025 Accepted June 2025 Published July 2025

Abstract

The Baltic region faces significant geotechnical challenges related to its widespread soft soil deposits, particularly along coastal areas. This investigation examines an innovative foundation solution combining micropiles with soil-cement Load Transfer Platforms (LTPs) designed to address these challenges. Through comprehensive three-dimensional Finite Element Modelling, we assess various configurations of micropile arrangements in soft soil conditions typical of Baltic coastal environments. Results demonstrate remarkable improvements in bearing capacity: individual micropiles show 2.1-fold increases, three-pile groups achieve 9-fold enhancements, and integration with LTPs produces up to 19-fold increases in load-bearing capacity. The most substantial improvements were observed in larger pile groups, with up to 80-fold capacity increases when combined with optimized LTPs. These findings offer promising solutions for construction on problematic soft soil deposits throughout the Baltic region, particularly for transportation infrastructure and medium-rise structures in developing coastal areas.

Keywords: Baltic soft soils; Micropile foundations; Soil-cement stabilization; Load transfer mechanisms; Coastal geotechnics; Numerical modelling

1. Introduction

The Baltic region presents distinctive geotechnical challenges characterized by extensive deposits of soft, unconsolidated soils that significantly impact infrastructure development. These problematic soil conditions, particularly prevalent in coastal areas and former glacial regions, exhibit low bearing capacities, excessive settlement potential, and considerable consolidation characteristics that severely constrain construction activities. Recent urban expansion and infrastructure development across Baltic nations have intensified the need for innovative foundation solutions capable of addressing these regional soil challenges. Small-diameter reinforcement elements, commonly termed micropiles, have emerged as a promising technique for improving structural support in these problematic soils. Initially developed for remedial applications, micropiles have gained prominence in new construction throughout Northern Europe due to their installation versatility, minimal environmental impact, and cost-effectiveness compared to traditional deep foundation methods. Their adaptability to various soil conditions makes them particularly valuable in the heterogeneous soil profiles characteristic of Baltic coastal regions.

The performance optimization of micropile systems has been extensively researched, with significant contributions from regional and international studies. Baruah and colleagues examined group efficiency in cohesive soils, identifying optimal arrangements for maximizing load distribution[1] .Liu et al. investigated axial load transfer mechanisms in soft soils similar to those found in Baltic harbours and coastal developments[2]. Installation methodology significantly influences performance, as demonstrated by Jeong et al., who documented superior load capacity in pressure-grouted systems compared to gravity-grouted alternatives. [3]. Recent advancements in understanding micropile behaviour have been particularly relevant to Baltic conditions. Peng et al. developed assessment methodologies for axial capacity under bundle effects in clayey deposits characteristic of the region.[4]. Abualigah and colleagues utilized both numerical and field-testing approaches to evaluate hollow-bar micropile groups in conditions resembling Baltic clay deposits.[5] The seismic resilience of these systems, an important consideration in certain Baltic areas with moderate seismic activity, has been documented by Abbott et al..[6]. and Salvatore et al.[7], who demonstrated significant improvements in liquefaction resistance with properly designed micropile configurations.
Despite these advances, limited research has addressed the specific integration of micropiles with soil-cement Load Transfer Platforms (LTPs) in the challenging soft soil conditions prevalent throughout the Baltic region. This research gap is particularly notable given the potential of combined systems to distribute loads more effectively while reducing settlement in problematic soils. Our investigation addresses this knowledge deficit through a comprehensive numerical assessment utilizing Plaxis 3D to model various micropile-LTP configurations in soft soil conditions representative of Baltic coastal deposits. We examine material properties derived from laboratory testing and conduct a parametric analysis to evaluate the influence of micropile geometry, quantity, and LTP characteristics on overall system performance.

2. Methods and Materials

2.1. Laboratory Characterization of Regional Materials

The soft soil materials examined in this study represent cohesive deposits commonly encountered throughout Baltic coastal regions. Laboratory testing was conducted on fine-grained cohesive clay and silty sand samples to establish their geotechnical properties. These materials were subjected to comprehensive moisture content, density, and shear strength assessments to characterize their behaviour under loading conditions.
Cohesive Clay Soil exhibited characteristics typical of Baltic marine deposits

with moisture content ranging between 15-20%, Young's modulus of 16 MPa, cohesion of 18 kPa, and a limited friction angle of 3°. This soil profile corresponds to the soft clay deposits frequently encountered in coastal construction projects throughout the region. The silty sand component demonstrated cohesion values of 12.5 kN/m² alongside a friction angle of 32°, representative of the transitional materials often found interbedded with marine clays in Baltic coastal sequences.

2.1.1. Cohesive Clay Properties

The soft cohesive clay underwent detailed characterization to establish its mechanical properties. Table 1 presents the comprehensive geotechnical properties of this material, which exhibits behaviour consistent with normally consolidated marine clays found throughout Baltic coastal plains.

Table 1 Geotechnical Properties of Soft Cohesive Clay

Properties	Value
Density ratio	2.70
Soil liquidity threshold (%)	43.50
Liquidity index (%)	21.50
Soil consistency index (%)	22.00
34% moisture bulk weight (KN)	16.00
elasticity coefficient, V	0.40
Young's modulus[8], E (MPa)	16.00
Soil angle of friction ϕ (°)	0.03
Cohesion strength C_u (kPa)	18
Soil classification	CL

2.1.2. Silty and Clayey Sand Composition Characterization.

The silty sand component, frequently encountered as intermediate layers within Baltic soft soil profiles, was characterized through standard geotechnical procedures. Enhanced compaction assessment utilizing the standardized Modified Proctor methodology indicated peak soil hydration levels at 15.1%, yielding optimal densification measurements of 18.05 kN/m³ when fully dehydrated. Laboratory shear strength evaluation through three-dimensional stress application protocols determined an inherent material binding coefficient (c-value) of 12.5 kN/m² accompanied by internal resistance mechanics quantified at a 32° angular

ISSN: 0067-3064

measurement. Comprehensive geotechnical characteristics for this granular material have been consolidated within the accompanying reference document (Table 2). [9, 10].

Table 2: Fundamental Features of Cohesive-Frictional Soil

Characteristics	Values
Threshold moisture content (%)	22.50
Upper moisture limit (%)	30.10
Relative density	2.68
Peak dry density (kN/m³)	18.50
Lowest dry density (kN/m³)	11.20
Optimal water content (%)	17.00
Internal friction angle, ϕ (°)	32.50
shear strength (kPa)	12.00
Soil classification	SC

2.1.3. Soil-Cement Composite Development

To enhance foundation performance in these problematic soils, a soil-cement Load Transfer Platform was developed using locally sourced materials that would be readily available throughout the Baltic region. Modified Proctor compaction testing was conducted with cement proportions ranging from 3% to 7% to determine optimal mix characteristics. While higher cement contents generally improved strength characteristics, proportions exceeding 5.5% introduced practical challenges including increased porosity and reduced workability during placement. Consequently, a 5% cement content was identified as optimal for field implementation, yielding an optimum moisture content of 19.5%.

The resulting soil-cement mixture demonstrated significantly enhanced mechanical properties compared to the untreated soil. Table 3 summarizes the mechanical characteristics of the hardened soil-cement composite after the standard 28-day curing period.[11].

Table 3: Mechanical Characteristics of Soil-Cement Mixture

Characteristics	Values
Internal friction angle, ϕ(°)	39
Cohesion strength, cc (kN/m²)	47.2
Tensile resistance (kPa)	140
Unconfined compressive resistance (MPa)	1.40
Elastic modulus (MPa)	95

The relationship between cement content and maximum dry density followed established patterns for soil stabilization, with optimal proportions identified at 5% cement content (Figure 1). The moisture retention characteristics during curing

ISSN: 0067-3064

demonstrated progressive reduction over time, stabilizing after approximately 14 days (Figure 2).

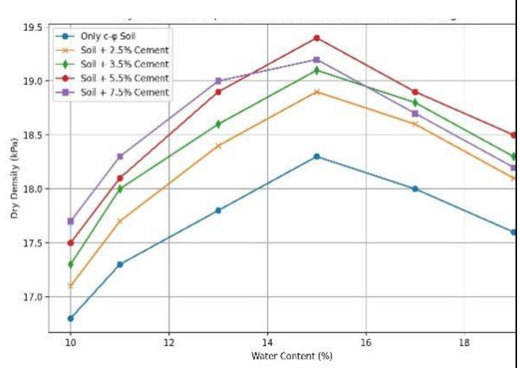

Fig.1. Mini-Compaction Test with Increased Cement Percentages.

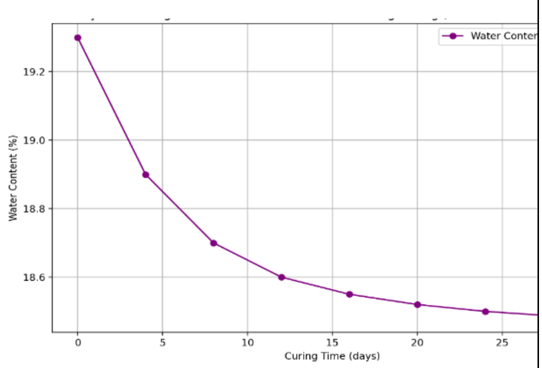

Fig.2. Change in Water Content Over Time During Curing.

Table 4: Engineering parameters of Materials

Material	Constitutive Model	Unit Weight, γ (kN/m ³)	Elastic Modulus, EE (MPa)	Poisson's Ratio, νν	Friction Angle, ϕϕ (°)	Cohesion, cc (kPa)
Fine-Grained Soil	Mohr–Coulomb	16.00	16.50	0.38	0.03	12.00
Micropile	Mohr–Coulomb	26.00	60.00	0.20	45.00	0.00
Load Transfer Layer	Mohr–Coulomb	16.50	95.00	0.22		

The relationship between cement content and maximum dry density followed established patterns for soil stabilization, with optimal proportions identified at 5% cement content (Figure 1). The moisture retention characteristics during curing demonstrated progressive reduction over time, stabilizing after approximately 14 days (Figure 2).

2.1.4. Model Characteristics and Specifications

The numerical simulation employed Plaxis 3D to model the complex interaction between soil, micropiles, and the LTP under various loading conditions. The model incorporated 50 mm diameter micropiles within a 4-meter deep soft soil layer representing Baltic coastal deposits. Multiple configurations were examined, including single micropiles, three-pile groups, seven-pile groups, and nine-pile arrangements, with varying LTP thicknesses to establish optimal design parameters. A total of 73 distinct numerical models were developed to comprehensively evaluate performance across different conditions. Tie constraints were implemented at material interfaces to ensure realistic simulation of pile-soil interaction mechanisms. The micropile structural response was modelled using elastic

 ISSN: 0067-3064

parameters while material failure was assessed through the Mohr-Coulomb yield criterion for both clay and the LTP component. Material properties including Poisson's ratio values derived from previous studies of Baltic soils were incorporated alongside laboratory-determined parameters to ensure regional relevance.

An axisymmetric modelling approach was utilized to evaluate the LTP's effect on micropile bearing capacity, with mesh refinement concentrated around critical regions such as the micropile-soil interface and progressively coarsened toward boundary regions to optimize computational efficiency. The model employed 10-noded tetrahedral elements to ensure numerical stability and solution accuracy.

Settlement data following load application was carefully recorded, with particular attention to displacement values under standardized loading conditions of 30 kN. The model geometry and boundary conditions were established to minimize boundary effects while accurately representing field conditions typical of Baltic coastal environments.

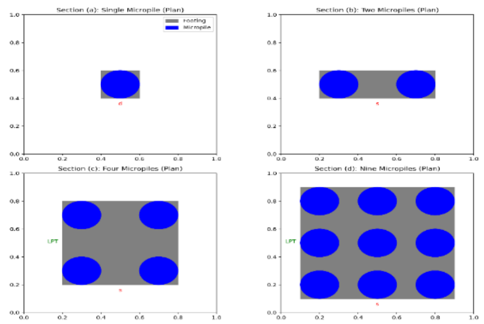

Fig.3. Diagram showing four sections of micropile arrangements in a footing plan.

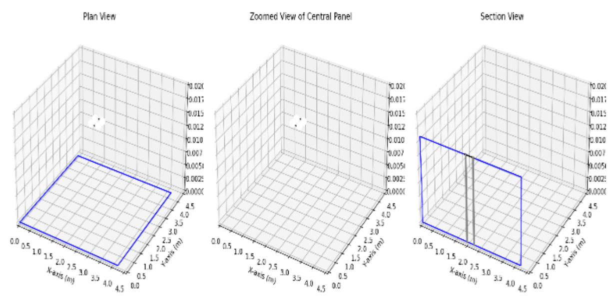

Fig.4. The figure consists of three 3D plots.

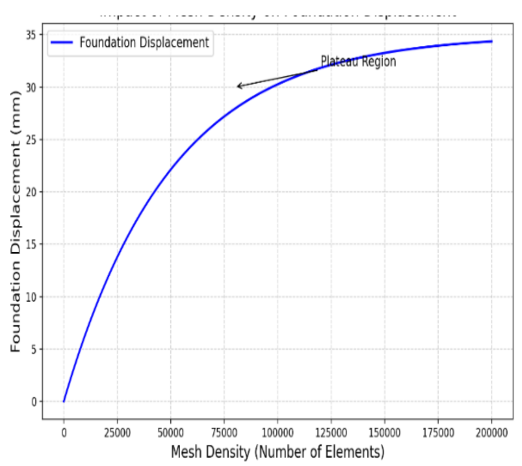

Fig.5. Three 3D plots: Plan View, Grid, and Square.

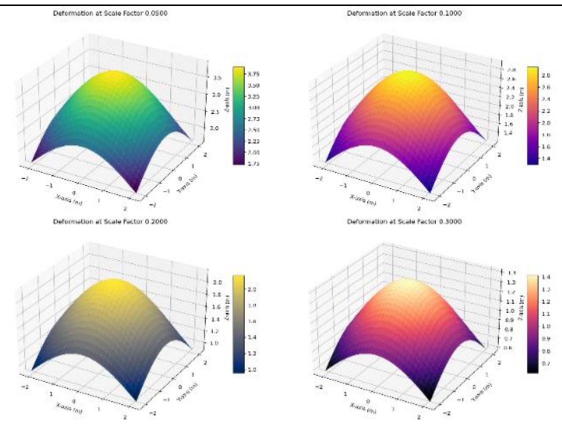

Fig.6. Four 3D surface plots showing deformation.

ISSN: 0067-3064

Tie constraints were applied at the interfaces to prevent separation or sliding between the soft clay and micropiles. The micropile the structural response was represented through a Hookean elastic framework, whereas the material rupture was evaluated using the shear-normal stress relationship developed by Mohr and Coulomb. was used for both clay and the LTP. Material properties, including Poisson's ratio values from previous studies, and additional parameters from laboratory tests, are recorded in Table 5.[12].
An axisymmetric analysis using Plaxis-3D software evaluated the LTP's effect on micropile bearing capacity. The mesh was refined around the micropile and clay bed and coarsened at the perimeter to optimize computational efficiency. The model utilized 10-noded tetrahedral elements.
A total of 73 numerical models were developed, encompassing micropiles with and without LTPs. Settlement data after load application was recorded, with displacement values under 30 kN shown in Figure 6 (a–d). This figure displays four 3D surface plots illustrating deformation at different scale factors (0.0500, 0.1000, 0.2000, and 0.3000). Each plot shows a curved surface with varying colors representing Z-axis values, from purple to yellow. The X and Y axes are labeled in meters, and decreasing Z-axis values with increasing scale factors indicate changes in deformation intensity.

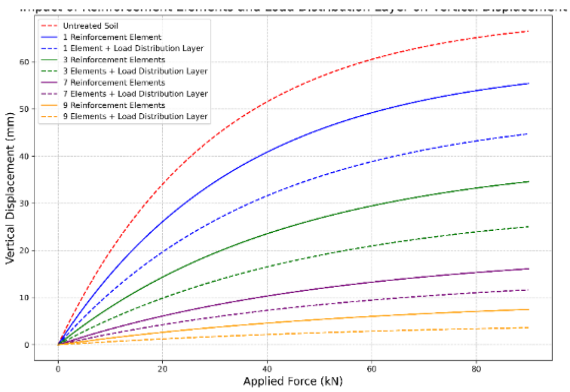

Fig.7. Graph showing force vs. vertical displacement for soil treatments

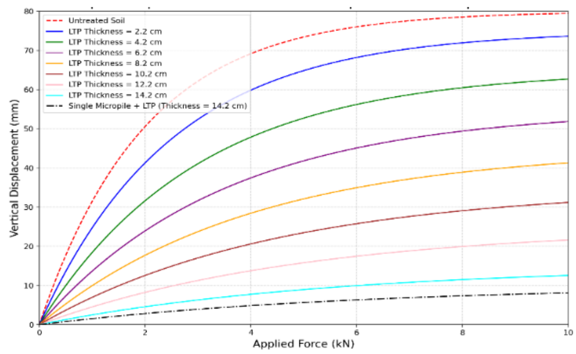

Fig.8. Graph showing LTP thickness, micropile impact on displacement.

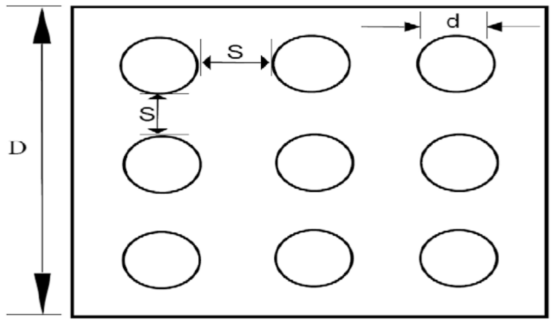

Fig.9. A 3x3 circle grid within a rectangle.

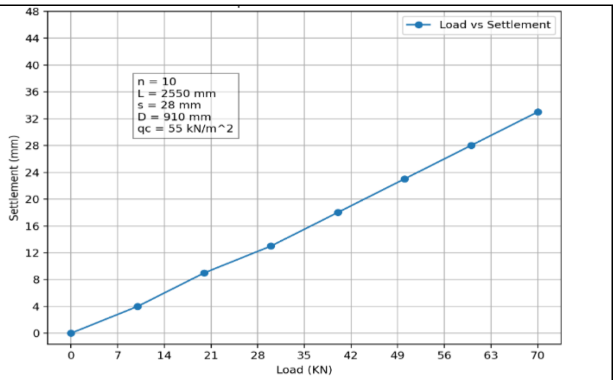

Fig.10. Graph showing Load-displacement relationship.

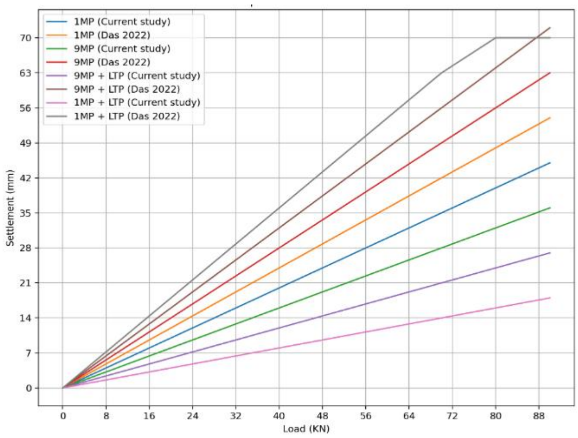

Fig. 11. Comparison of load-settlement curves from the current study and previous research.

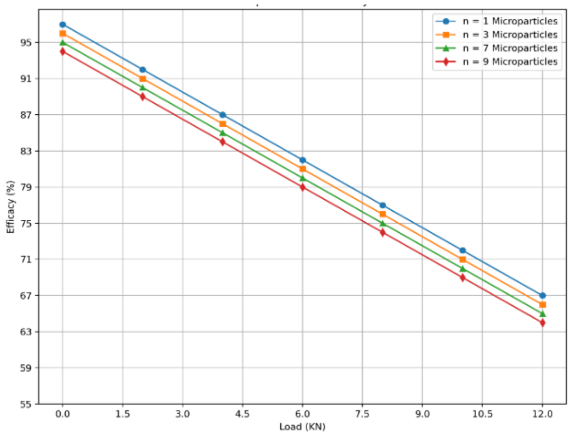

Fig. 12. Graph showing Load vs. Efficacy percentage.

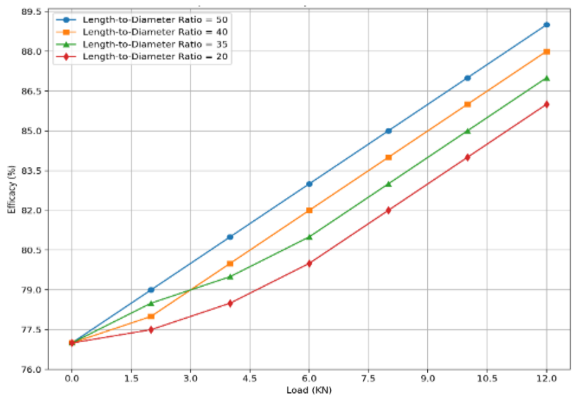

Fig. 13. Relationship between applied load and LTP efficacy for various micropile length-to-diameter (L/d) ratios.

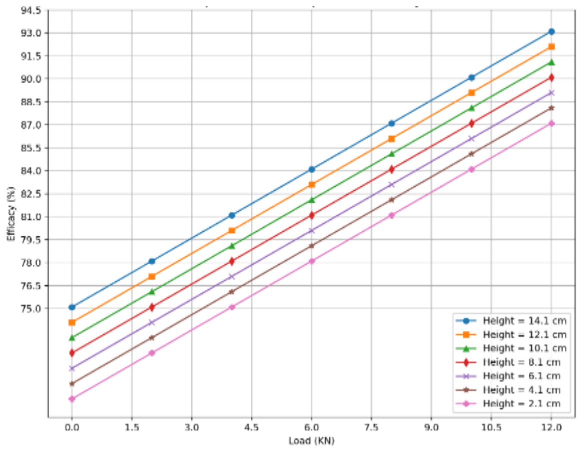

Fig. 14. Relationship between applied load and efficacy for various LTP thicknesses.

Table 5: Overview of Numerical Simulation Parameters

Trial No.	Reinforcement Category	Parameter Particulars	No. /Experiments
1	Basic Clay Stratum	–	1
2	Soil + Individual Micro pile	Single: Length(l) = 35d, diameter (d) = 45 mm, Diam. = 140 mm, Suc = 12 kPa, 22 kPa	10
		Micro pile Groups	
		3 MP: L = 35d, d = 45 mm, s = 5d, D = 450 mm, Su = 12, 22, 32 kPa	
		7 MP: L = 35d, d = 45 mm, s = 5d, D = 850 mm, Su = 12, 22, 32 kPa	
		9 MP: L = 35d, d = 45 mm, s = 5d, D = 850 mm, Su = 12, 22, 32 kPa	
3	Micropile + LTP in Clay	Single: L = 35d, d = 45 mm, D = 140 mm, Su = 12 kPa, 22 kPa	55
		Micro pile Groups	
		3 MP: L = 35d, d = 45 mm, s = 5d, D = 450 mm, Su = 12, 22, 32 kPa	
		7 MP: L = 35d, d = 45 mm, s = 5d, D = 850 mm, Su = 12, 22, 32 kPa	
		9 MP: L = 25d, 35d, 55d; Su = 12-32 kPa	

Legend:
L = micropile length (expressed as multiples of diameter d)
d = micropile diameter (45 mm)
D = footing or plate diameter (varies with group size)
s = spacing between micropiles (expressed as multiples of diameter d)
Suc = unconfined compressive strength of soil (kPa).

3. Analysis & Results

3.1 Load-Settlement Behavior

The numerical analysis revealed significant performance improvements when integrating LTP with micropiles in soft soil conditions. The load-settlement relationship demonstrated markedly reduced settlement for reinforced configurations compared to untreated soil. Figure 7 illustrates the comparative performance across different reinforcement scenarios, with untreated soil exhibiting the largest displacement while the nine-micropile group with integrated LTP showed minimal settlement under identical loading conditions.

The bearing capacity enhancement achieved through various reinforcement strategies was quantified relative to the baseline capacity of untreated soil (approximately 1 kN at 60 mm settlement). A single micropile increased bearing capacity 2.1-fold, while a three-micropile group achieved a 9-fold improvement. The most substantial enhancements were observed when combining micropiles with LTP, where a three-micropile group with integrated LTP demonstrated a 19-fold increase in bearing capacity. For larger micropile arrays with complementary LTP, the improvement reached up to 80-fold for nine-micropile configurations.

The influence of LTP thickness on system performance was particularly noteworthy, with direct correlation observed between LTP thickness and both bearing capacity and settlement reduction (Figure 8). An LTP thickness of 14 cm independently increased the bearing capacity of unreinforced soil by approximately five-fold, highlighting the significant contribution of this component to overall system performance.

3.2 Parametric Sensitivity Analysis

A comprehensive parametric study was conducted to evaluate the influence of key design variables on system performance. The investigation focused particularly on micropile quantity, length-to-diameter ratio, and LTP thickness as primary design parameters.

The influence of micropile quantity demonstrated diminishing returns as group size increased, with the nine-micropile configuration showing optimal performance under most loading conditions. Efficacy analysis revealed generally high performance (above 75%) across all group sizes, with the nine-micropile arrangement achieving peak efficacy at 8 kN loading before experiencing gradual decline with increased loading (Figure 12)..

Micropile length, expressed as length-to-diameter ratio, showed consistent influence on system performance. Longer micropiles (higher L/d ratios) demonstrated superior efficacy under identical loading conditions (Figure 13), reflecting enhanced skin friction development along the pile shaft in these deeper installations.

LTP thickness emerged as a critical parameter influencing overall system performance. Increasing LTP thickness from 3 cm to 15 cm substantially improved load distribution characteristics and settlement resistance. At a representative 10 kN loading condition, system efficacy increased from 80% with a 3 cm LTP to 90.5% with a 15 cm LTP (Figure 14). This performance enhancement reflects the improved load distribution mechanism enabled by thicker LTP configurations.

3.3 Case Study: A 9-Micropile Group in Soft Clay

A detailed case study examining a nine-micropile configuration in soft clay conditions representative of Baltic coastal deposits confirmed the substantial performance enhancement achieved through integrated micropile-LTP systems. The numerical results were compared with simplified theoretical calculations to assess the adequacy of traditional design approaches for these complex foundation systems.

The simplified analytical approach, based on conventional geotechnical formulas, incorporated the following parameters:

Nine micropiles of 5 cm diameter, 2.5 m length, at 300 mm spacing Soil with unconfined compressive strength of 60 kN/m² and undrained shear strength of 30 kN/m²Adhesion factor of 0.77 and Factor of Safety of 2.7

Two primary failure mechanisms were evaluated: block failure (treating the pile group as a unified element) and individual pile failure. The analytical approach yielded an allowable capacity of 30.27 kN based on the more conservative individual pile failure mode. The finite element analysis of the identical configuration produced substantially different results, with an allowable load of approximately 50 kN at a settlement of 31.25 mm (Figure 10). This significant discrepancy highlights the limitations of simplified analytical methods in capturing complex group effects, non-linear soil behaviour, and precise stress distribution patterns beneath the foundation system. The more comprehensive FEM results were consequently adopted for subsequent analysis and design recommendations.

3.1.1. Simplified Analytical Approach

A simplified analysis was first performed to estimate the load capacity based on conventional geotechnical formulas. The parameters are as follows:

- Micropiles: 9 piles, 5 cm diameter (d), 2.5 m length (L), 300 mm spacing (s).
- Soil: Unconfined compressive strength (q_c) = 60 kN/m², Undrained Shear Strength (c_u) = 30 kN/m².
- Assumptions: Adhesion factor (α) = 0.77, Factor of Safety (FoS) = 2.7.

Two primary failure modes were considered:

1. Block Failure: Treating the pile group as a single block, the allowable capacity was calculated to be 55.61 kN.
2. Individual Pile Failure: Summing the capacity of individual piles, the allowable capacity was calculated to be 30.27 kN.

The governing allowable load from this simplified analysis is the lower of the two values, which is 30.27 kN.

3.1.2. Finite Element Model (FEM) Results and Comparison

The same 9-micropile configuration was analyzed using the Plaxis 3D model. The force-displacement graph produced through the FEM analysis is shown in Figure 10. From this graph, a settlement of 31.25 mm corresponds to an applied load of approximately 50 kN.

This result (50 kN allowable load) shows a significant discrepancy with the simplified analytical result (30.27 kN). This highlights the limitations of basic analytical methods, which do not fully capture:

- Complex Group Effects: Including end bearing and sophisticated pile-soil interaction factors.
- Non-linear Soil Behavior: True load-transfer mechanisms between the footing, piles, and soil.
- Accurate Stress Distribution: Precise stress and strain fields beneath the foundation.

Therefore, the FEM results are considered a more comprehensive and accurate prediction of the system's performance and are used for the subsequent analysis.

3.2. Load–Deflection Behavior and Bearing Capacity Improvements

Numerical simulations were performed to evaluate the system's performance across different configurations. The load-deflection curves for groups of 1, 3, 7, and 9 micropiles, with and without an LTP, are shown in Figure 7. The untreated soil exhibits the highest displacement, while the 9-micropile group with an LTP shows the least, confirming that reinforcement substantially reduces settlement.

The integration of an LTP and micropiles led to remarkable improvements in bearing capacity compared to untreated soft soil (which had a capacity of 1 kN at 60 mm settlement).

- A single micropile increased bearing capacity 2.1-fold.
- A group of three micropiles achieved a 9-fold increase.
- Adding an LTP to three micropiles resulted in a 19-fold increase.
- For larger groups with an LTP, the enhancement was even greater, reaching 80-fold for nine micropiles.

Increasing the LTP thickness also directly correlated with higher bearing capacity and reduced settlement (Figure 8). An LTP with a thickness of 14 cm increased the bearing capacity of the unreinforced soil by five times on its own. These results unequivocally demonstrate that combining micropiles with an LTP is a highly effective method for reinforcing soft soils.

3.3. Parametric Analysis

- The efficacy of the LTP, defined as its efficiency in distributing load to the micropiles, was evaluated in a parametric study.
- Effect of Micropile Quantity: Efficacy was generally high (above 75%) for all group sizes but showed diminishing returns, with the 9-micropile group peaking in efficacy at an 8 kN load before declining (Figure 12).
- Effect of Micropile Length: As shown in Figure 13, longer micropiles (higher L/d ratios) consistently resulted in higher efficacy under the same applied load.
- Effect of LTP Thickness: Increasing the LTP thickness from 3 cm to 15 cm significantly improved performance. For example, at a 10 kN load, efficacy increased from 80% with a 3 cm LTP to 90.5% with a 15 cm LTP (Figure 14).

The only notable exception was with the 9-micropile configuration, which showed an increase in maximum bearing capacity during the fourth sample**[13].**

For instance, the bearing capacity with LTP ranged from 3.2 kN to 81 kN, aligning with findings from other studies[14].

4. Discussion

4.1. Load Transfer Mechanism Interpretation

The load-settlement curves revealed a distinctive three-phase load transfer process within the integrated micropile-LTP system. During initial loading, the relatively rigid LTP component bears the majority of applied load with minimal observed settlement. As loading intensifies, progressive transfer to the micropile elements occurs, characterized by non-linear settlement behaviour. At ultimate loading

conditions, system capacity becomes fully mobilized, transferring residual load to the underlying soft soil and resulting in accelerated settlement rates characteristic of approaching failure.
The LTP component significantly enhances load distribution efficiency, enabling more uniform engagement of all micropiles within a group arrangement. This load-spreading mechanism substantially improves the system's overall capacity compared to conventional pile groups without LTP integration. These observations align with previous research findings while confirming the particular effectiveness of micropile-LTP systems in the soft soil conditions typical of Baltic coastal environments.

4.2. Validation Against Previous Research

To ensure reliability of the current three-dimensional FEM approach, results were compared with previous two-dimensional Plaxis studies conducted by Smith [15]. under comparable soil and pile conditions. As illustrated in Figure 11, the load-displacement relationships observed in the present study demonstrated strong correlation with earlier research for both single micropile and group configurations. This agreement validates the accuracy of the three-dimensional analysis methodology employed in this investigation and provides confidence in the findings of the subsequent parametric study.

4.3. Regional Implications and Limitations

The findings of this investigation hold particular relevance for geotechnical engineering practice throughout the Baltic region, where problematic soft soils frequently constrain infrastructure development. The demonstrated improvements in bearing capacity offer an effective and economical foundation solution especially suited to the low- and medium-rise structures commonly constructed in developing coastal areas across Baltic nations.
Several limitations must be acknowledged when interpreting these results. The numerical models were based on specific soil properties representative of typical Baltic coastal deposits but may require adjustment for site-specific conditions. The analysis focused primarily on static loading scenarios; performance under dynamic or seismic loading conditions would require additional investigation, particularly for structures in seismically active zones within the region. Long-term performance aspects including creep and consolidation effects were beyond the scope of the current study but warrant consideration in actual project implementation.
While the findings provide valuable guidance for implementation in Baltic regional conditions, site-specific testing and calibration are recommended prior to deployment in actual construction projects. Further research including physical model testing would be beneficial for refining understanding of these systems and expanding their applicability across the diverse ground conditions encountered throughout the region.

5. Conclusions and Future Recommendations

This investigation has demonstrated that integrating micropiles with soil-cement Load Transfer Platforms offers a particularly effective solution for foundation challenges in Baltic soft soil environments. The key findings include:

1. Substantial Capacity Enhancement: Micropile groups with integrated LTP demonstrated up to 80-fold increases in bearing capacity compared to untreated soil, providing a robust foundation solution for problematic Baltic soil conditions.
2. Optimized Design Parameters: Longer micropiles and thicker LTP configurations consistently delivered superior performance, with 14-15 cm LTP thickness offering optimal balance between performance and material efficiency.
3. Regional Applicability: The micropile-LTP system presents a particularly promising solution for Baltic coastal areas where traditional deep foundations may be cost-prohibitive or logistically challenging to implement.

The findings suggest several recommendations for geotechnical practice in Baltic regions:

1. Consider micropile-LTP systems as a primary option for low- to medium-rise structures in areas with problematic soft soils, particularly in coastal development zones.
2. Optimize design by incorporating LTP thicknesses of at least 10-15 cm to maximize load distribution efficiency and minimize settlement.
3. For large foundations, configure micropiles in groups of 7-9 elements to achieve optimal load-sharing characteristics while maintaining cost efficiency.

Future research directions should include validation through field-scale testing in typical Baltic soil conditions, exploration of system performance under dynamic loading scenarios relevant to regional seismic considerations, and investigation of long-term durability in the corrosive environments often encountered in coastal Baltic settings.

Data availability

Data can be provided upon request

Declaration of Competing Interests

The research team attests that no conflicts of interest exist related to the present study.

Contributions of Authors

All authors made equal Participations to the development of the article.

Financial Support

The authors gratefully acknowledge the financial support they provided themselves.

ISSN: 0067-3064

References

1. Baruah, S., et al., *Seismic monitoring of 2020 Baghjan oil-well blowout incident in Assam, India.* Sci Rep, 2024. **14**(1): p. 24108.
2. Liu, J., et al., *Longitudinal characteristics of lymphocyte responses and cytokine profiles in the peripheral blood of SARS-CoV-2 infected patients.* EBioMedicine, 2020. **55**: p. 102763.
3. Jeong, M., et al., *Stable perovskite solar cells with efficiency exceeding 24.8% and 0.3-V voltage loss.* Science, 2020. **369**(6511): p. 1615-1620.
4. Peng, X., et al., *Analysis of Magnetic-Flux Leakage (MFL) Data for Pipeline Corrosion Assessment.* IEEE Transactions on Magnetics, 2020. **56**(6): p. 1-15.
5. Abualigah, L., et al., *The Arithmetic Optimization Algorithm.* Computer Methods in Applied Mechanics and Engineering, 2021. **376**: p. 113609.
6. Salvatore, E., et al., *Experimental Evidence of the Effectiveness and Applicability of Colloidal Nanosilica Grouting for Liquefaction Mitigation.* Journal of Geotechnical and Geoenvironmental Engineering, 2020. **146**(10): p. 04020108.
7. Das, S., et al., *Transistors based on two-dimensional materials for future integrated circuits.* Nature Electronics, 2021. **4**(11): p. 786-799.
8. Zhang, W. and A.P. Watkinson, *Carbonaceous Material Deposition from Heavy Hydrocarbon Vapors. 1. Experimental Investigation.* Industrial & Engineering Chemistry Research, 2005. **44**(11): p. 4084-4091.
9. Viso, M., *ISRO, India*, in *Encyclopedia of Astrobiology*. 2023, Springer. p. 1558-1559.
10. Shukla, S.K., *Geotechnical characteristics of soils and rocks of India*. 2021: CRC Press.
11. Alijani Mamaghani, O. and E. Noorzai, *A framework to implement augmented reality based on BIM to improve operation and maintenance of mechanical facilities of commercial complexes.* Facilities, 2023. **41**(3/4): p. 229-247.
12. Greaves, G.N., et al., *Poisson's ratio and modern materials.* Nat Mater, 2011. **10**(11): p. 823-37.
13. Li, H. and G. Ren, *Horizontal and Uplift Bearing Characteristics of a Cast-In-Place Micropile Group Foundation in a Plateau Mountainous Area.* Sustainability, 2023. **15**(18): p. 13554.
14. Rakib, M.R.J., et al., *Spatiotemporal trends and characteristics of microplastic contamination in a large river-dominated estuary.* Environ Sci Process Impacts, 2023. **25**(5): p. 929-940.
15. Smith, A., *Labour migration, mass unemployment and the state: Class, gender and work in the Land Settlement Association in inter-war rural England.* Journal of Rural Studies, 2025. **114**: p. 103498.