Settlement of Lime-Cement Stabilized Soft Clay: A Numerical Modeling Study

Tarek N. Salem [1], Mahmoud S. El-Kady [1], Ahmed M. Abdelbaset [1], Amr G. Ghoneim [1], Dušan Katunský [2*], Denis Konovalov [2], Jozef Švajlenka [3], Mohamed H. El-Feky [1*]

[1] Structural Engineering Department, Zagazig University, Zagazig 44519, Egypt.

[2] Institute of Architectural Engineering, Faculty of Civil Engineering, Technical University of Košice, 04001 Kosice, Slovakia.

[3] Department of Construction Technology, Economy and Management, Faculty of Civil Engineering, Technical University of Kosice, 04200 Kosice, Slovakia.

Abstract

This study aims to quantify settlement uncertainty of strip footings on stabilized soft clay under multi-parametric variations to improve geotechnical foundation design. A three-dimensional numerical model was developed using ADINA to simulate full-scale strip footings resting on treated soft clay. Finite Element Analysis was conducted by systematically varying four governing parameters: footing width, treated soil thickness, treated extension width, and footing embedment depth. Parametric analyses were performed using normalized design ratios to evaluate settlement sensitivity and soil–structure interaction behavior. The results indicate that increasing the ratios of treated thickness to footing width, treated extension width to footing width, and embedment depth significantly reduces total settlement and enhances stress redistribution within the improved zone. Sensitivity assessment reveals that treated thickness and extension width are the most influential parameters in controlling settlement performance. The novelty of this research lies in quantifying settlement sensitivity through dimensionless design ratios within a unified numerical framework, providing a practical basis for optimizing treated zone dimensions. The findings contribute to a more efficient and sustainable foundation design by minimizing excessive material use while maintaining structural performance, offering economic and environmental benefits.

Keywords: ADINA; Footing Embedment Depth; Footing Width; Soil Stabilization; Soil-Structure Interaction; Treatment Geometry.

1. Introduction

Weak and loess soils constitute approximately 10% of the world's land area, which are inherently sensitive to environmental conditions [1, 2]. These problematic soils are particularly prevalent in deltaic regions, such as the Nile Delta in Egypt, where rapid urbanization necessitates the construction of heavy structures on geotechnically deficient ground [3]. Soft clay deposits, characterized by high compressibility and low shear strength, pose significant challenges to the development of civil infrastructure worldwide [4]. Without adequate intervention, structures founded on soft clay are susceptible to excessive settlement and bearing capacity failure [5]. To mitigate these risks, chemical stabilization using binders such as Ordinary Portland Cement OPC and lime has emerged as a widely adopted ground improvement technique because of their rapid action, availability, and effectiveness [6, 7]. The introduction of these stabilizing agents triggers both hydration and pozzolanic reactions, fundamentally altering the soil's microstructure. This process forms cementitious compounds (such as Calcium Silicate Hydrate CSH, and Calcium Aluminate Hydrate CAH) that enhance

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particle bonding, increase stiffness, and significantly reduce compressibility [8-11]. Despite the benefits, the application requires caution due to environmental impact [12] and potential adverse reactions in sulfate soils, including expansion and reduced strength [13-15]. Stabilization primarily uses hydrated lime (derived from quicklime) and cement [11, 16]. A 1:1 cement-lime mix synergistically improves workability (lime) and strength (cement) in clay soils [17]. When the soil's natural pozzolan content is low, supplementary pozzolans (e.g., fly ash, silica fume, GGBS, coal ash) are added to enhance strength gain [18-28]. These processes, applied via surface or subsurface techniques (e.g., deep mixing, jet grouting) [29-32], create a robust composite soil matrix with improved mechanical properties [33, 34].

Extensive experimental research has documented the efficacy of lime-cement stabilization in transforming poor subgrades into reliable foundation materials. Recent studies have demonstrated significant improvements of treated clays as follows: (1) Stabilizer content correlates with improved Atterberg limits (reduction), compaction, California Bearing Ratio CBR, Unconfined Compressive Strength UCS, and shear strength [35, 36]. While mechanical properties perform better under higher confining pressures [37] or preload level [38]. Dynamic cone penetration tests have been used to characterize the enhanced stiffness of stabilized layers [39]. (2) Reduces compressibility and improves consolidation [40], enhancing compression behavior [41], increasing bearing capacity [42], and improving subgrade stability [43]. (3) Cement stabilization outperforms lime and natural pozzolans by significantly reducing collapsibility and increasing undrained shear strength (up to 5 times) [44]. Cement-stabilized samples exhibit higher UCS (up to 6.3 MPa with 15% cement) compared to lime (1.46 MPa with 10%), as confirmed by microstructural and durability tests [45]. Increased cement content and curing time further enhance compressive/tensile strength and Young's modulus [46], resulting in a positive correlation between cement content and composite ground load capacity [47]. (4) Optimal mellowing occurs between 24–48 hours [48]. Higher curing temperatures accelerate strength development and increase shear strength [49]. A mix of 6% cement and 5% lime, cured for 7 days, yields optimal results [50].

While abundant experimental data confirms the benefits of lime-cement stabilization, a significant research gap remains in quantifying settlement uncertainty under conditions of multi-parametric variation. Specifically, Insufficient data on the synergistic impact of variations in both structural elements (e.g., footing width, embedment depth) and treatment geometry (e.g., treated thickness, extension width) simultaneously on full-scale footing settlement. Optimizing these parameters is crucial for economic design, as excessive treatment leads to unnecessary material costs and environmental impact, while insufficient treatment may result in serviceability failures. The current study addresses this research gap by conducting a comprehensive two-dimensional Finite Element Analysis FEA using the ADINA software package. The primary objective is to quantify the settlement response of strip footings resting on lime-cement stabilized soft clay under varying geometric conditions, to provide robust design charts and guidelines. This research is guided by the following three questions: (i) How does the ratio of treated soil thickness to footing width (h/B) influence the resulting settlement and stress distribution beneath a full-scale footing? (ii) What is the optimal treated extension width (L) required to minimize settlement, particularly under varying applied stresses? (iii) How do variations in footing width (B) and foundation embedment depth (d) interact with the treated zone geometry to control total settlement? The integration of systematic variations into a robust risk assessment framework is necessary to both optimize and ensure structural safety for designers.

The paper proceeds by detailing the Materials and Methods, which encompass the properties of both untreated and treated soil, the Finite Element Method (FEM) model geometry, the constitutive models employed, and the comprehensive parametric study matrix. The Results and Discussion section quantifies the individual and combined effects of the design parameters on settlement and stress distribution, followed by a thorough discussion that relates these findings to existing literature and their practical implications. Finally, the paper concludes by summarizing the Conclusions derived from the numerical modeling, offering practical guidelines, and outlining the study's Limitations and Future Work. A flowchart detailing the methodology workflow is presented in Figure 1.
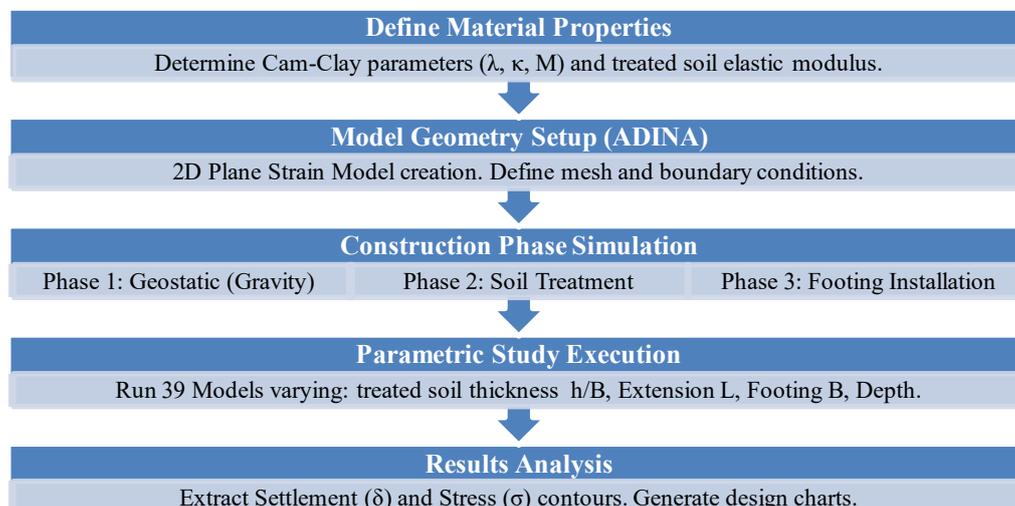
Define Material Properties
Determine Cam-Clay parameters (λ, κ, M) and treated soil elastic modulus.

Model Geometry Setup (ADINA)
2D Plane Strain Model creation. Define mesh and boundary conditions.

Construction Phase Simulation
Phase 1: Geostatic (Gravity)   Phase 2: Soil Treatment   Phase 3: Footing Installation

Parametric Study Execution
Run 39 Models varying: treated soil thickness h/B, Extension L, Footing B, Depth.

Results Analysis
Extract Settlement (δ) and Stress (σ) contours. Generate design charts.

Figure 1. The methodology workflow

2. Materials and Methods

As shown in the flowchart above, the Finite Element Method (FEM) and the Cam-Clay elasto-plastic model are the framework for the current numerical simulation. This shows the used state-of-the-art approach tailored for clay behavior. This study employed the FEM program ADINA to simulate the behavior of a strip footing on both untreated and lime-cement-treated soft clay using a two-dimensional (2D) plane strain model. FEM allows for the solution of complex Boundary Value Problems (BVPs) that are intractable for analytical methods. Specifically, FEM effectively simulates complex scenarios such as staged construction and the crucial interaction between materials of vastly different stiffnesses (e.g., the stiff treated crust and the soft subgrade). The treated soil layer acts as a stiffer "raft" or load-transfer platform that distributes the footing load over a wider area of the soft subgrade, thereby reducing stress concentration and settlement.

The soft clay was represented by the Cam-Clay elasto-plastic model, while the footing was modeled as elastic isotropic. The utilization of the Cam-Clay constitutive model allows for (1) a realistic representation of the soft clay's elastoplastic behavior. (2) coupled stress-strain enabling a more accurate prediction of soil-structure interaction than conventional linear-elastic Mohr-Coulomb approaches. (3) exhibition of soft clays' hardening behavior and volume change under shear, which linear elastic-perfectly plastic models fail to capture accurately. Cam-Clay couples the volumetric and deviatoric responses of normally consolidated or slightly over-consolidated clays under saturated conditions, which is essential for accurate settlement prediction.

Material properties for all components are detailed in Table 1, that clearly define the key Cam-Clay parameters (Pre-consolidation Pressure P_o, Over-Consolidation Ratio OCR, Specific Volume at the mean effective stress p' is 1 kPa Γ, Critical State Stress Ratio M_u, Compression Index λ, Swelling/Recompression Index κ) for both untreated and treated soil. These parameters are derived from laboratory tests, which perfectly represent in-situ soil conditions or the complex behavior of the treated soil, due to stabilization, exhibits significantly lower compressibility (λ) and a higher initial yield surface (P_o) than the untreated soft clay, reflecting its enhanced stiffness. The soil was assumed to be fully saturated, a critical consideration for soft clay behavior. The overarching objective of this full-scale numerical model was to compute settlements and stresses within the soil domain under varying conditions, aiming to inform the optimization of treatment costs by minimizing improvement material and zone size.

Table 1. Material properties

Properties	Untreated soft clay	Treated soft clay	Concrete footing
Model	Cam-Clay	Cam-Clay	Elastic Isotropic
P_o (kPa)	50	200	----
OCR	1	1	----
Γ	3.5	3	----
M_u	1.15	1.2	----
λ	0.25	0.07	----
κ	0.028	0.00107	----
Density (kg/m³)	1600	2000	2500
Elastic Modulus (E) kPa	2×10^3	20×10^3	2.1×10^6
Passion Ratio (υ)	0.4	0.15	0.25

The simulation of footing construction and loading over soft soils was carried out in four sequential phases: 1) initial soil settlement under geostatic pressure; 2) soil treatment; 3) footing construction; and 4) subsequent load application. To examine the stress-settlement relationship of footings on both untreated and treated soft clay, a comprehensive numerical parametric study was conducted. The numerical implementation employs a 2D plane-strain assumption and considers boundary conditions such as rollers on the sides to allow vertical deformation and hinges at the bottom to restrict all movement. The main variables in this study included footing width (B), treated soil thickness (h), treated extension width (L), and foundation embedment depth (d), as listed in Table 2. Constant parameters maintained throughout the study were the overall soft clay depth and width, which are 6 m and 16 m, respectively. In total, the parametric analysis involved 39 full-scale footing models to thoroughly investigate how the selected parameters influence performance. A complete list of all cases studied, along with their parameter values, is provided in Table 2.

Table 2. Parameters used in the parametric study

Case Number	Footing width, B (m)	Treated thickness, h (m)	Treated extension width, L (m)	Stress, σ (kN/m²)	Foundation embedment depth, d (m)
N1	2	0	0	30	0
N2	2	0.4	0	30	0
N3	2	0.8	0	30	0
N4	2	1.2	0	30	0
N5	2	1.6	0	30	0
N6	2	2	0	30	0
N7	2.5	2	0	30	0
N8	2.5	2	0.5	30	0
N9	2.5	2	1	30	0
N10	2.5	2	0	10	0
N11	2.5	2	0.5	10	0
N12	2.5	2	1	10	0
N13	2.5	2	0	20	0
N14	2.5	2	0.5	20	0
N15	2.5	2	1	20	0
N16	2.5	2	0	40	0
N17	2.5	2	0.5	40	0
N18	2.5	2	1	40	0
N19	2.5	2	0	50	0
N20	2.5	2	0.5	50	0
N21	2.5	2	1	50	0
N22	2.5	2	0	60	0
N23	2.5	2	0.5	60	0
N24	2.5	2	1	60	0
N25	1.5	2	0	30	0
N26	1.5	2	1	30	0
N27	2	2	1	30	0
N28	3	2	0	30	0
N29	3	2	1	30	0
N30	3.5	2	0	30	0
N31	3.5	2	1	30	0
N32	2	0.8	0	20	0
N33	2	0.8	0	10	0
N34	2	0.8	0	30	0.4
N35	2	0.8	0	20	0.4
N36	2	0.8	0	10	0.4
N37	2	0.8	0	30	0.8
N38	2	0.8	0	20	0.8
N39	2	0.8	0	10	0.8

3. Results and Discussion

3.1. Effect of Treated Soil Thickness

Figure 2.a illustrates the relationship between the treated thickness to footing width ratio (h/B) and settlement for a 2m wide footing under an applied stress of 30 kN/m². A clear trend of settlement reduction with increasing treated thickness is observed. Specifically, settlement decreases significantly by approximately 23% (from 19.44 to 15.1 cm) when h/B increases from 0 to 0.2, highlighting the effectiveness of even minimal initial soil improvement. Beyond this initial phase, the rate of settlement reduction diminishes: an increase in h/B from 0.2 to 0.6 yields a 14% reduction (from 15.1 to 13.1 cm), and a further increase from 0.6 to 1.0 reduces settlement by approximately 13% (from 13.1 to 11.92 cm). This diminishing return suggests that beyond a certain h/B ratio, the additional cost of treatment may not be justified by the marginal settlement reduction. This finding aligns with similar observations by Jegatheesan & Gnanendran (2016) regarding the effect of treated base layer thickness on vertical pavement deformation [51]. While soil treatment reduces settlement, the impact of increasing the treated zone diminishes with higher h/B values. Notably, a treatment thickness of just 0.2B achieves half of the total settlement reduction observed up to h/B = 1.0, suggesting an optimal range for cost-effective design. Moreover, implementing excessively large treatment thicknesses for soft soil improvement substantially increases costs and requires specialized machinery.

It is important to note that a constant geostatic settlement of 7.10 cm was subtracted from calculated settlements for the stress-settlement curves (e.g., Figure 2.a). However, the contour plots (Figures 2.b - 2.e) display total settlement, including this geostatic component. Figures 2.b and 2.c present the settlement and stress contour plots, respectively, for h = 0.6B (2m wide footing, 30 kN/m² stress). For this case, the computed settlement of 13.1 cm represents a 32% reduction compared to the untreated scenario. Similarly, Figures 2.d and 2.e show the settlement and stress contours for h = B, where settlement is reduced by approximately 40% (from 19.44 cm to 11.92 cm). As expected, both settlement and stresses are concentrated directly beneath the footing and extend to significant depths within the soil.

$$\ln(\delta) = -0.143 * \ln(h/B) + 2.494$$

(a)

(b)

(c)

(d)

(e)
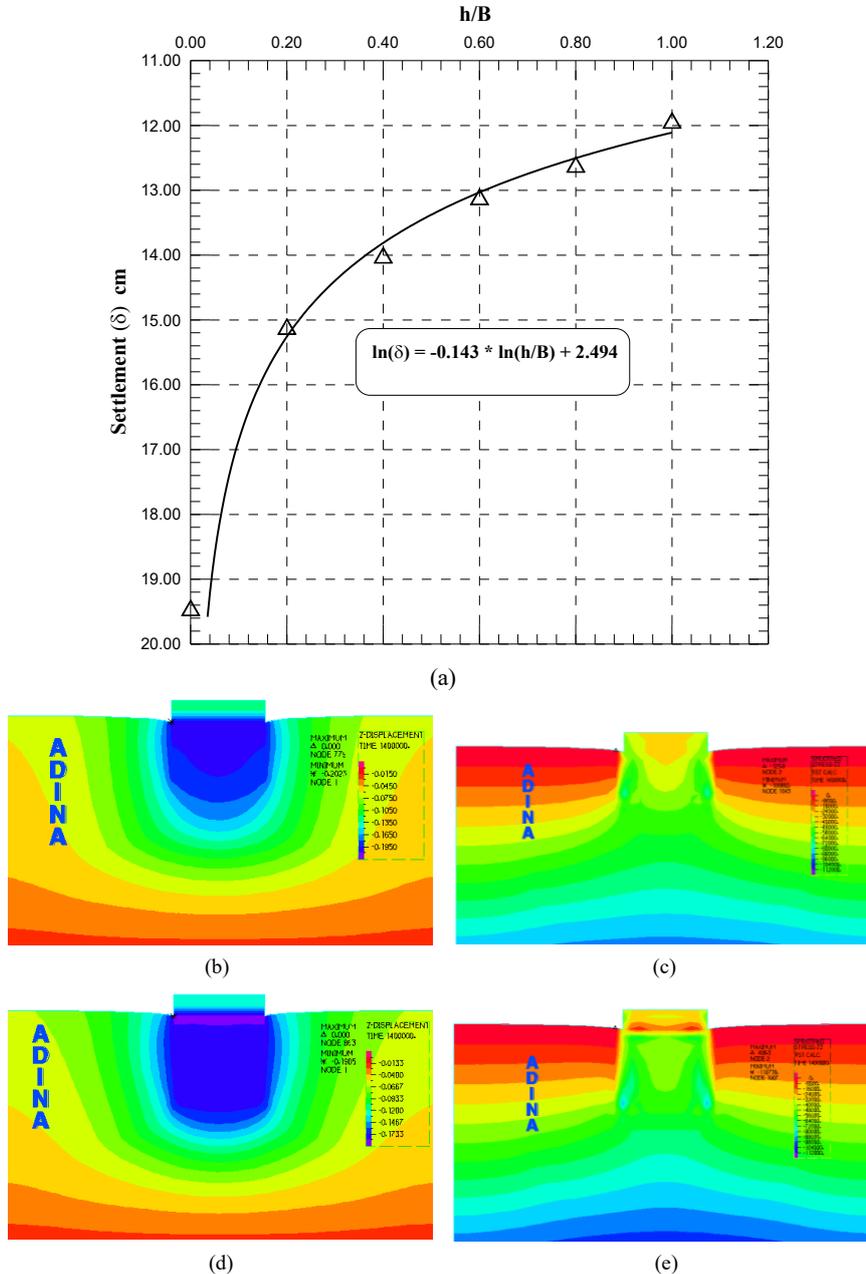
Figure 2. Treated soil thickness influence for B = 2m at constant stress = 30 kN/m²; (a) Effect of (h/B) on settlement. (b) Settlement values for h = 0.6 B. (c) Stress for h = 0.6 B. (d) Settlement values for h = B. (e) Stress for h = B

The results regarding the effect of treated soil thickness (h/B) align closely with established geotechnical principles. The observed non-linear reduction in settlement—where the most significant gain occurs at h/B = 0.2 and diminishes beyond 0.6—is a phenomenon well-documented in layered soil systems. El Sawwaf [52] and Dash & Bora [53] demonstrated similar "diminishing returns" in reinforced soil beds, attributing it to the "pressure bulb" concept, where the majority of vertical stress is concentrated within a depth of 1.0B to 1.5B. While the current study highlights the efficiency of a thin "crust" (0.2B), other studies on stabilized cushions, such as Al-Aghbari and Dutta, often recommend an optimum thickness range of 0.5B to 1.0B to prevent punching shear under heavier loads [54]. However, the 40% settlement reduction observed at h=B is consistent with findings in mass stabilization literature [55]. Theoretically, these results support Burmister's layered system theory [56], where a stiffer upper layer ($E_{treated} > E_{soil}$) spreads the load more widely, effectively reducing stress intensity on the compressible clay below.

3.2. Effect of Treated Extension Widths and Applied Stress

Figure 3.a illustrates the relationship between applied stress and settlement for a 2.5m wide footing, examining the influence of treated extension widths (L) with a constant treated thickness (h) of 0.8B, under stresses up to 60 kPa. The results unequivocally demonstrate that treated extension widths effectively reduce settlements. At an applied stress of 30 kPa, settlement decreased by 22% (from 14.26 to 11.1 cm) with an extension width of 0.2B, and further by 37% with an extension width of 0.4B. The settlement behavior was observed to be slightly nonlinear up to 30 kPa. However, between 30 and 60 kPa, the settlement rate increased significantly, indicating the onset of near-failure conditions in the soft soil underlying the treated zone. Notably, in cases without treated extension, the settlement increase was substantial (approximately 39 cm), effectively representing a practical failure even with initial soil improvement. This suggests that exceeding an applied stress of 30 kPa on treated soil, without adequate extension, is not recommended to prevent excessive settlements.

Figures 3.b and 3.c display the settlement and stress contours, respectively, for the case of a 2.5m wide footing with h = 0.8B and L = 0.2B at 30 kPa. Contour plots (Figure 3.d) show high stress concentration with small extension, emphasizing load dispersion. Literature suggests a wider stabilized layer spreads vertical stress (often approximated by a 2:1 distribution angle), reducing stress intensity on the subgrade. Increasing L expands the contact area, keeping subgrade stress within the elastic range.
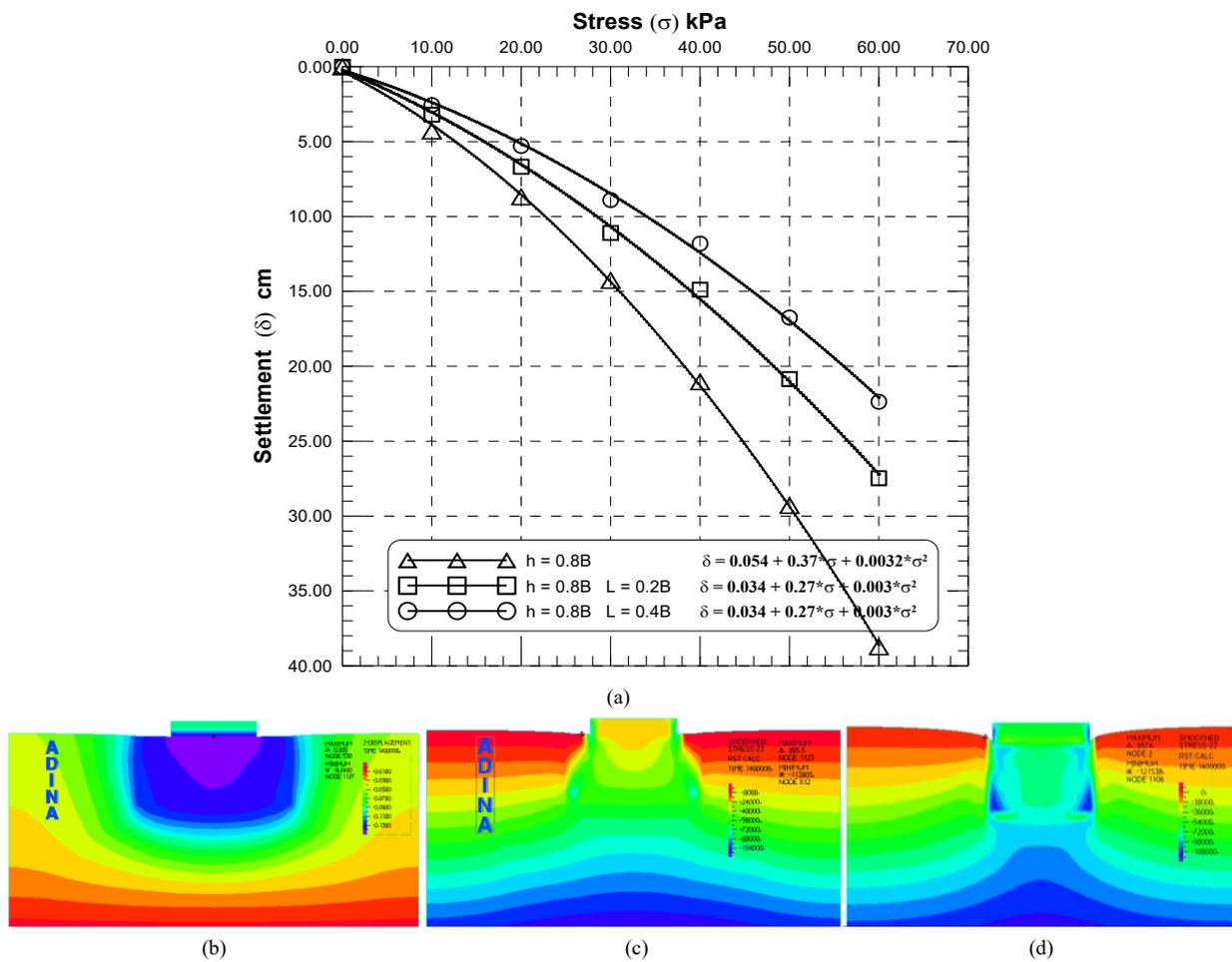

(a)

| (b) | (c) | (d) |

Figure 3. Applied stress influence for B = 2.5m at constant treated thickness h = 0.8B; (a) Effect of applied stress on settlement. (b) Settlement values for L = 0.2B, applied stress = 30 kN/m². (c) Stress for L = 0.2B, applied stress = 30 kN/m². (d) Stress for L = 0.2B, applied stress = 60 kN/m².

The results presented regarding the effect of treated extension widths (L) and applied stress, corroborate fundamental concepts in ground improvement and soil-structure interaction as follows: (i) Lateral extension reduces settlement due to lateral confinement. Extending the treated zone (0.2B to 0.4B) significantly reduces settlement (22% and 37%), restricting the soil's lateral plastic flow. This aligns with the "wide slab" or "raft" effect [55], where wider, deep mixed stabilization prevents soft soil from squeezing out. (ii) Settlement sharply increases above 30 kPa, suggesting failure via punching shear, like in strong-over-weak soils. Das notes that thin/narrow stiff layers can punch through to soft clay if the interface stress exceeds clay strength [57]. Excessive settlement (39 cm) without extension implies L=0 lacks a load distribution area, causing localized bearing failure [58].
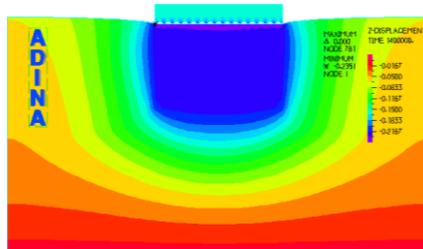
3.3. Effect of Footing Size

Figure 4.a illustrates the relationship between footing width (B) and settlement under an applied stress of 30 kN/m², comparing two scenarios: a treated thickness (h) of 2m without treated extension, and the same thickness with a 1m treated extension width. In the first scenario (h = 2m, no extension), settlement increases significantly with footing size. Specifically, settlement increases by approximately 35% (from 8.87 cm to 11.92 cm) as B increases from 1.5 m to 2.0 m. Further increases to 2.5, 3.0, and 3.5 m result in proportional settlement increases of 60%, 84%, and 106%, respectively. The footing size-settlement curve demonstrates an approximately linear trend with a slight sag, indicating increasing deformation with larger loaded areas. Figures 4.b and 4.c present the settlement and stress contour plots, respectively, for a 3.0m wide footing with h = 2.0m (at 30 kN/m²). As anticipated, larger footing sizes lead to wider areas of applied stress and higher stress concentrations, particularly within soft soil.

For the second scenario (2.0m treated thickness with a 1m treated extension width), settlement also increases with footing size, albeit at generally lower absolute values due to the added extension. Settlement increases by about 37% (from 5.15 to 7.08 cm) as B increases from 1.5 m to 2.0 m. Increasing B to 2.5 m results in a settlement of 8.9 cm (a nearly 72% increase relative to 1.5m), with further increments of 107% and 140% for 3.0 m and 3.5 m footing sizes, respectively. Figures 4.d and 4.e display the settlement and stress contours for a 2.5m wide footing with h = 2.0m and L = 1.0m (at 30 kN/m²).
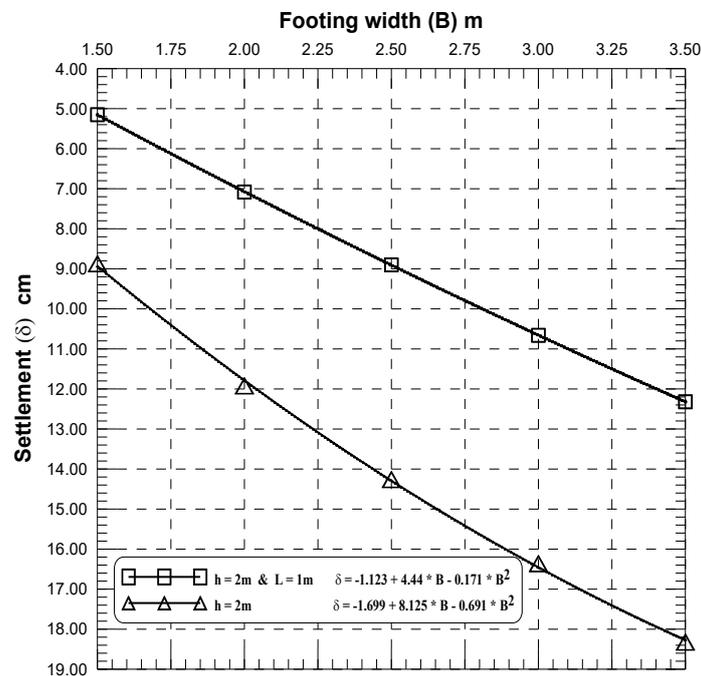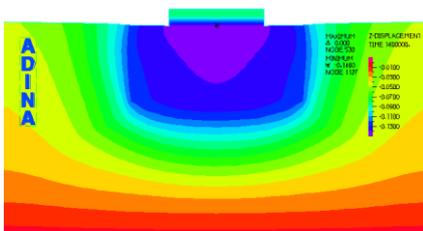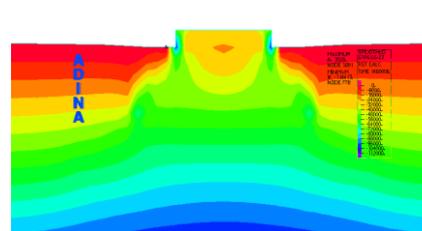

(a)

(b)
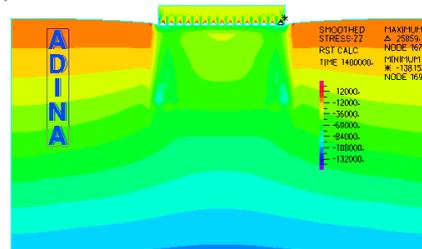
(c)

(d)

(e)

Figure 4. Footing width influence for h = 2.0 m at constant Stress = 30 kN/m²; (a) Effect of footing width (B) on settlement. (b) Settlement values for B = 3.0 m. (c) Stress for B = 3.0 m. (d) Settlement values for B = 2.5 m, L = 1.0 m. (e) Stress for B = 2.5 m, L = 1.0 m.
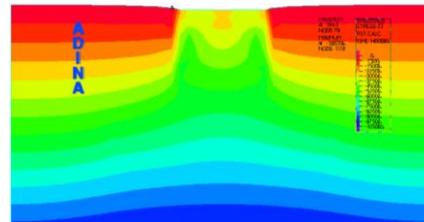
3.4. Effect of Foundation Embedment Depth

Figure 5.a presents the effect of foundation embedment depth on settlement for a 2m wide footing with a treated soil thickness of 0.4B. A clear trend of settlement reduction with increasing embedment depth is observed. Specifically, settlements decreased by approximately 17% when the foundation depth increased from 0.0 m to 0.4 m. This reduction further reached 30% when the depth was increased to 0.8 m. This pattern indicates that while deeper embedment effectively reduces settlement, the rate of this reduction diminishes with increasing depth, suggesting an optimal embedment for a given treated thickness. Figures 5.b and 5.c illustrate the settlement and stress contour plots, respectively, for a 2m wide footing with h = 0.4B and a foundation depth of 0.4m, subjected to a stress of 30 kN/m².
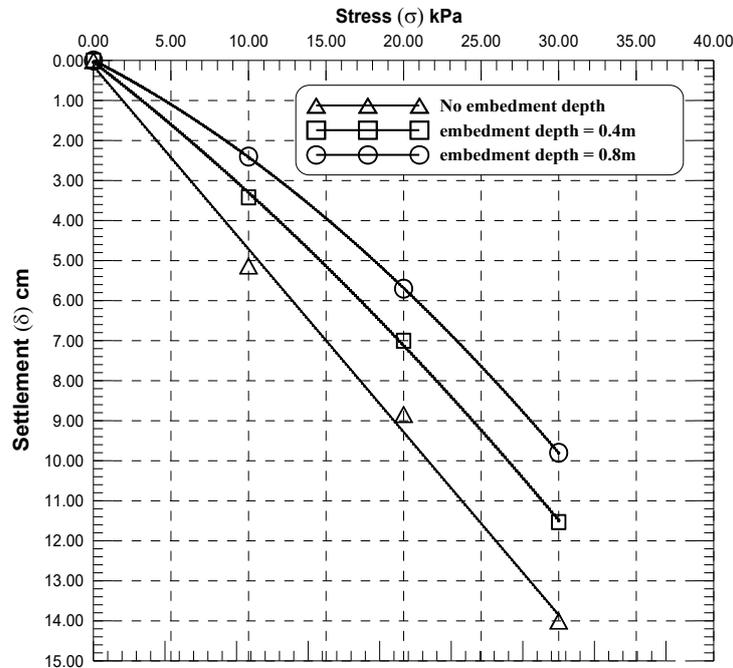
(a)
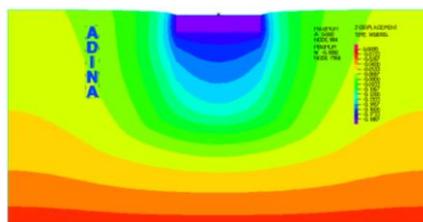
(b)

(c)

Figure 5. Foundation embedment depth influence for B = 2 m, h = 0.4B; (a) Effect of on settlement. (b) Settlement values for foundation depth = 0.4m, Stress = 30 kN/m². (c) Stress for foundation depth = 0.4m, Stress = 30 kN/m².

The principle that settlement decreases with increasing foundation embedment depth (d) is well-established in shallow foundation behavior [61]. This is primarily due to increased bearing capacity from soil confinement and a deeper stress bulb. Greater d increases overburden pressure (γd), enhancing the soil's resistance to shear failure and reducing settlement [57]. Embedding the foundation also shifts the stress bulb deeper [62], effectively increasing the thickness of stiff material contributing to load bearing, which is crucial in treated layers (here, h=0.4B). However, the rate of settlement reduction diminishes with increasing d (e.g., a 17% reduction from d = 0 to 0.4m, slowing to a 30% total reduction at d = 0.8m). Bearing capacity and settlement improvements typically plateau beyond an optimal embedment depth, often around d/B = 1 or 1.5, depending on soil type. Beyond this, the added cost and complexity of deeper excavation may outweigh the minimal gains in settlement reduction, supporting the idea of an optimal embedment for a given treated thickness, a phenomenon documented by Terzaghi & Peck [61] and Bowles [63].

4. Conclusions

The current study provides practical guidelines for the design of footings on lime-cement stabilized soft clay, emphasizing the critical interplay between treated zone dimensions, footing size, and applied stress. The results offer quantitative data to support more efficient and safer foundation designs, while also reinforcing fundamental geotechnical principles related to soil-structure interaction and ground improvement.

- Numerical models of full-scale footings indicated that increasing the thickness and extension of the treated zone significantly reduced total settlements. Specifically, increasing the ratio of treated zone height to footing width (h/B) for a 2m wide footing resulted in a notable decrease in total settlements; a 23% reduction in total settlement was observed when increasing h/B from 0 to 0.2.

- The results show a significant reduction in settlement with initial increases in treated soil thickness (up to h/B = 0.2), but diminishing returns beyond this point. This has direct economic implications, suggesting that there's an optimal treated thickness that maximizes settlement reduction per unit of treatment material. Engineers can avoid over-treating the soil, which would unnecessarily increase costs, material consumption, and the need for specialized machinery. The finding that a thickness of just 0.2B can achieve half of the total settlement reduction is a crucial design guideline for cost-effective ground improvement.

- Treated extension widths effectively reduce settlements. At 30 kPa, settlement decreased by 22% with a 0.2B extension width and by 37% with a 0.4B extension width. This demonstrates that treated extension widths significantly prevent practical failure, especially under higher applied stresses. This implies that improving the soil directly beneath the footing is often insufficient; extending the treated zone laterally beyond the footing's footprint is critical for effective load distribution and preventing excessive deformation of the untreated surrounding soil. Without adequate extension, even improved soil can experience alarming settlements, leading to structural instability. This highlights the necessity of considering the full zone of influence of the footing on the subgrade.

- For a foundation depth of 2 meters with no treated extension, settlement increases substantially with footing size. Increasing the footing width from 1.5 m to 2.0 m results in a 35% settlement increase. Further increases to 2.5 m, 3.0 m, and 3.5 m yield proportional settlement increases of 60%, 84%, and 106%, respectively. Also, for a 2.0m treated thickness with a 1m treated extension width, settlement increases with footing size. While absolute settlement values are generally lower due to the extension, settlement increases by approximately 37% as footing width increases from 1.5 m to 2.0 m. Increasing footing width to 2.5 m results in a 72% increase in settlement relative to 1.5m, with further increases of 107% and 140% for 3.0 m and 3.5 m footing sizes, respectively.

- The results confirm that larger footing sizes lead to greater settlements, even on treated soil. This is a fundamental principle of soil mechanics (due to larger loaded areas and deeper zones of influence) but its quantification for stabilized soft clay is important. The study's data, showing increasing settlement percentages with larger footing widths, reinforces the need for careful consideration of footing dimensions in conjunction with soil stabilization efforts. The derived footing size-settlement curves (with and without extension) serve as a useful tool for predicting settlement for various footing dimensions on stabilized ground, aiding in the preliminary design phase.

- Furthermore, foundation embedment depths of 0.4m and 0.8m reduced settlements by 17% and 30%, respectively. The finding that settlements decrease with increasing foundation embedment depth, albeit at a decreasing rate, underscores the benefit of shallow embedment for settlement control. Deeper foundations engage a larger volume of soil and can bypass very superficial weak layers. Similar to treated thickness, the diminishing rate of settlement reduction suggests an optimal embedment depth where the benefits outweigh the increased excavation and construction costs.

- The contour plots vividly illustrate how stresses and settlements concentrate beneath the footing and within the improved zone. This visual evidence reinforces the theoretical understanding of stress bulbs and how the stiffer treated soil attracts and redistributes loads, protecting the underlying weaker soil. Observing the stress concentration can guide future designs by ensuring the treated zone is robust enough to handle the increased stresses it will bear.

- The study implicitly demonstrates the power of numerical modeling (ADINA and Cam-Clay model) as a cost-effective and efficient tool for conducting extensive parametric studies in geotechnical engineering. It allows engineers to explore a wide range of design scenarios and optimize solutions before committing to expensive physical construction or field tests.

4.1. Limitations and Future Work

The paper addresses soft clay settlement in construction; however, the following limitations could be addressed: (1) 2D simplification of 3D problems, Cam-Clay's inability to capture anisotropy, creep, or structured clay behavior. (2) Modeling the footing as purely elastic isotropic simplifies footing-soil interaction. (3) Close boundary conditions and dimensions can artificially stiffen the soil. A sensitivity analysis on boundary dimensions could help evaluate the influence of domain size on settlement accuracy. (4) Numerical accuracy relies on material properties of treated/untreated clay, often from lab tests that may not reflect actual soil conditions or soil-binder behavior. (5) The model is validated against external data via simulation, common in parametric studies, rather than conducting its own experimental validation. It infers accuracy for specific soil and treatment parameters instead of direct confirmation. (6)

Applying a uniform stress assesses settlement and bearing capacity in ideal conditions, baselining stabilized zone geometry effectiveness. real-world loading conditions like dynamic or eccentric/moment loads would likely: (i) reduce bearing capacity due to smaller effective contact area, which leads to a footing failure at a lower vertical load, (ii) cause rotation/differential settlement with greater toe settlement, potentially exceeding structural tolerance limits, and (iii) require wider treated zone lateral extension to resist rotation, affecting cost-effectiveness [64]. (7) Increasing the treated zone's lateral extension has benefits but also drawbacks: (i) the cost of wider treatment may outweigh the limited settlement reduction; (ii) site constraints like property lines restrict the treatment area, forcing suboptimal designs; (iii) specialized equipment needs space, increasing misalignment risk and reducing treatment quality at edges; (iv) deep mixing can cause ground displacement, damage nearby structures, and require costly procedures.

The study investigates treated soil thickness/width, footing size, and embedment depth, providing valuable settlement data and design implications. By numerically quantifying the relationship between treated zone size and settlement reduction, the study enables designers to use the minimum necessary amount of stabilizing agent (cement/lime) while maintaining safety. This directly reduces material consumption, lowering project costs, and mitigating the environmental impact associated with cement production CO_2 emissions and energy use. The results contribute to the design of more reliable and durable foundations in regions with soft clay soils, reducing the risk of structural failure or excessive maintenance due to settlement. The study provides a necessary foundation for future research to immediately build upon, specifically by incorporating the site-specific cost-benefit analysis of the proposed stabilization technique against traditional deep foundation methods, considering material, installation (e.g., Excavation Cost vs. Stabilization Cost), and Life-Cycle costs (reduced maintenance) to strengthen the argument.

Future research should include the systematic variations that were identified as critical gaps e.g., (1) Integrating the effects of long-term consolidation. (2) Using advanced constitutive models (e.g., anisotropic models, creep models, or models that account for cementation kinetics). (3) Using varying lime-cement proportions, or incorporating alternative stabilizer mixes (e.g., fly ash, slag, geopolymers) in conjunction with lime-cement. (4) Using probabilistic methods to quantify uncertainty in settlement predictions, accounting for real-world loading conditions, soil variability, and treatment effectiveness to improve risk assessment.

5. Declarations

5.1. Author Contributions

Conceptualization, T.N.S., M.S.E., A.M.A., and M.H.E.; methodology, T.N.S., M.S.E., A.M.A., and M.H.E.; formal analysis, T.N.S., M.S.E., A.M.A., and M.H.E.; investigation, T.N.S., M.S.E., A.M.A., and M.H.E.; data curation, A.M.A., D.Ko., D.Ka., and J.S.; writing—original draft preparation, T.N.S., M.S.E., A.G.G., and M.H.E.; writing—review and editing, A.G.G., D.Ka, D.Ko, and J.S. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding and Acknowledgments

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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