

# Numerical Investigation of Shallow Foundations Reinforced with Soil-Cement Columns in Medium Stiff Clay, Soft Clay, and Peat

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## Abstract

Soil-cement columns (SCC) are widely used to improve the engineering properties of soft cohesive soils. Ensuring adequate bearing capacity and controlled settlement is critical in shallow foundation design. This study numerically investigates the effectiveness of SCC reinforcement using PLAXIS 2D, with analyses employing the Mohr-Coulomb and Soft Soil constitutive models. Three soil types—medium-stiff clay, soft clay, and peat—were evaluated to assess foundation performance with and without SCC in terms of load-settlement response, stress distribution, and deformation behavior. Results show that SCC substantially increases load-bearing capacity and stiffness while reducing settlement across all soils. The greatest improvements occur in medium-stiff clay (load: 97.7%, settlement: 70.5%), followed by peat (load: 92.3%, settlement: 69.1%) and soft clay (load: 82.3%, settlement: 63.6%). Stress transfer mechanisms are significantly modified, with stresses concentrated within the columns and their interfaces, resulting in reduced lateral displacement and overall settlement. SCC thus provides an effective approach for enhancing shallow foundation performance, although its efficiency strongly depends on soil type.

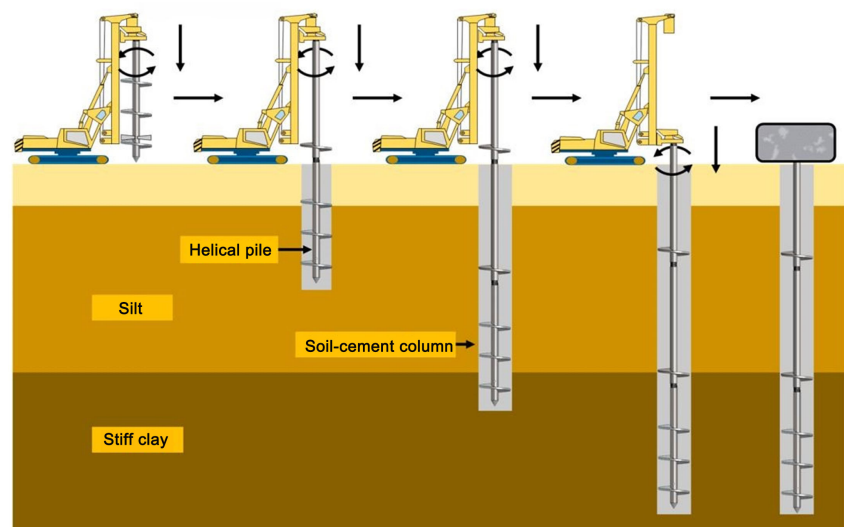
## Keywords

Soil-Cement Columns, Shallow Foundations, Soft Cohesive Soils, Ground Improvement, Bearing Capacity, Settlement Reduction

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## 1. Introduction

Shallow foundations are among the most widely used and cost-effective solutions for supporting civil engineering structures, particularly those with relatively light loads and constructed on competent soils. Characterized by a width greater than their depth, they are generally faster and more economical to construct than deep foundations [1]. However, their performance strongly depends on the underlying soil conditions, as both bearing capacity and settlement behavior are intrinsically linked to the soil's mechanical properties [2] [3]. When placed on weak or compressible deposits, shallow foundations often encounter significant challenges, including inadequate bearing capacity and excessive settlement [4]. Such deficiencies may lead to structural distress, functional limitations, or even catastrophic failure, highlighting the necessity for reliable ground improvement techniques [5] [6].



**Figure 1.** Soil cement column injection [7].

Among available ground reinforcement methods, soil-cement column injection has emerged as an effective and versatile approach to improve the engineering properties of treated soil masses, including increased stiffness and strength and reduced permeability [8] (see **Figure 1**). This technique involves injecting a cementitious grout into the ground to form discrete cylindrical columns, which substantially increase bearing capacity and reduce deformation under applied loads [9]. Its effectiveness across various soil types, from granular to cohesive, is well established in geotechnical practice [10]. Cement treatment improves key engineering properties such as unconfined compressive strength and elastic modulus, while also enhancing drying rate, workability, and compaction behavior [11].

Recent studies have explored the influence of various design parameters, such as column diameter, spacing, and cement content, on the mechanical performance of cement-treated ground [12] [13]. These investigations confirm that ce-

ment treatment markedly enhances soil stiffness and strength. However, the long-term durability of cemented soils, particularly under aggressive chemical or moisture fluctuations, still requires comprehensive numerical evaluation to ensure sustained performance [14] [15]. Moreover, numerical simulations are increasingly used to assess the dynamic response of cement-improved ground under cyclic or seismic loading, providing valuable insights into their seismic behavior [16]-[18].

The application of numerical methods is therefore essential for predicting the real-world behavior of shallow foundations on cement-improved ground with greater precision than empirical approaches allow [19]. Numerical modeling enables detailed examination of the interface behavior between cement columns and the surrounding soil, thereby clarifying load transfer mechanisms and the resulting composite response. Key advances in the numerical modeling of cement-column-supported foundations have been synthesized, emphasizing the method's value in improving bearing capacity and reducing settlement [20]-[23].

Comparative evaluations of finite element and discrete element techniques have further demonstrated their capacity to simulate time-dependent phenomena such as creep and shrinkage in cemented soils [24] [25]. Recent research has placed particular focus on the simulation of complex load transfer mechanisms within composite ground systems, integrating shear and bearing components that govern overall foundation stability [26].

Furthermore, numerical models have been widely applied to predict key engineering responses of ground improved with cement columns. Comprehensive overviews of cement-column applications for reducing settlement and enhancing bearing capacity are provided in [22] [23], while the importance of considering soil heterogeneity and anisotropy in optimizing column configuration and spacing is highlighted in [27].

A variety of soil conditions, including expansive clays, organic-rich soils, and loose granular deposits, can critically affect the performance and longevity of shallow foundations. Expansive soils undergo volume changes with moisture fluctuations, while organic soils compress over time as decomposition progresses; both phenomena result in differential settlement and potential structural distress [7]. Despite the widespread use of soil-cement columns, the effectiveness of these columns under different weak or highly compressible soils is not fully understood, highlighting the need for detailed investigation.

Given the paramount importance of achieving adequate bearing capacity and controlled settlement in shallow foundation design [4] [6], and the demonstrated effectiveness of soil-cement columns for ground improvement [28] [29], this study aims to:

- 1) investigate the effectiveness of soil-cement columns in enhancing the bearing capacity of shallow foundations; and
- 2) evaluate the reduction in settlement achieved through soil-cement column reinforcement under different soil conditions.

These objectives are intended to provide practical insights into the application of soil-cement columns for improving the performance of shallow foundations

constructed on weak or highly compressible soils.

## 2. Materials and Methods

This study employed PLAXIS 2D numerical modeling to evaluate the improvement in bearing capacity and reduction in settlement of shallow foundations with and without soil-cement column (SCC) reinforcement. The analysis compared untreated (without SCC) and treated (with SCC) soils under identical loading conditions. Three soil types—medium stiff clay, soft clay, and peat—were investigated.

### 2.1. Soil Properties

The soil parameters for all soil types are summarized in **Tables 1-5**. Each soil type was characterized by its unit weight ( $\gamma$ ), cohesion ( $c$ ), friction angle ( $\varphi$ ), compression index ( $\lambda^*$ ), swelling index ( $\kappa^*$ ), and permeability ( $k$ ). The soil-cement column was modeled as a high-strength material formed by the in situ mixing of cementitious grout with the native soil.

**Table 1.** Typical properties of medium-stiff clay soil [30].

Property	Symbol	Value	Unit
Unit weight	$\gamma$	18	(kN/m <sup>3</sup> )
Cohesion	$c$	5	(kN/m <sup>2</sup> )
Friction angle	$\varphi$	25	(°)
Compression index	$\lambda^*$	0.064	-
Swelling index	$\kappa^*$	0.026	-
Overconsolidation Ratio	OCR	1	-
Dilation Angle	$\psi$	0	(°)
Coefficient of Earth Pressure at Rest	$K_0$	0.577	-
Permeability	$k_x, k_y$	$8.6 \times 10^{-5}$	(m/s)
Drainage	-	Undrained	-

**Table 2.** Typical properties of soft clay soil [31] [32].

Property	Symbol	Value	Unit
Unit weight	$\gamma$	15	(kN/m <sup>3</sup> )
Cohesion	$c$	8	(kN/m <sup>2</sup> )
Friction angle	$\varphi$	18	(°)
Compression index	$\lambda^*$	0.18	-
Swelling index	$\kappa^*$	0.035	-
Dilation Angle	$\psi$	0	(°)
Coefficient of Earth Pressure at Rest	$K_0$	0.691	-
Permeability	$k_x, k_y$	$1.0 \times 10^{-8}$	(m/s)
Drainage	-	Undrained	-

**Table 3.** Typical properties of peat soil [33].

Property	Symbol	Value	Unit
Unit weight	$\gamma$	16	(kN/m <sup>3</sup> )
Cohesion	$c$	12	(kN/m <sup>2</sup> )
Friction angle	$\varphi$	18	(°)
Compression index	$\lambda^*$	0.129	-
Swelling index	$\kappa^*$	0.058	-
Dilation Angle	$\psi$	0	(°)
Coefficient of Earth Pressure at Rest	$K_0$	0.691	-
Permeability	$k_x, k_y$	$4.0 \times 10^{-4}$	(m/s)
Drainage	-	Undrained	-

**Table 4.** Properties of soil cement column material [34].

Property	Symbol	Value	Unit
Unit weight	$\gamma$	22	(kN/m <sup>3</sup> )
Cohesion	$c$	1000	(kN/m <sup>2</sup> )
Friction angle	$\varphi$	40	(°)
Young's modulus	$E$	$1.5 \times 10^7$	(kN/m <sup>2</sup> )
Poisson's ratio	$\nu$	0.25	-
Dilation Angle	$\psi$	0	(°)
Coefficient of Earth Pressure at Rest	$K_0$	0.357	-
Permeability	$k_x, k_y$	$1.0 \times 10^{-10}$	(m/s)
Drainage	-	Drained	-

**Table 5.** Properties of reinforced concrete for foundations [35].

Property	Symbol	Value	Unit
Unit weight	$\gamma$	22	(kN/m <sup>3</sup> )
Young's modulus	$E$	$1.5 \times 10^7$	(kN/m <sup>2</sup> )
Poisson's ratio	$\nu$	0.25	-

## 2.2. Constitutive Models

Two constitutive models were used in PLAXIS 2D to represent soil behavior:

1) Mohr-Coulomb (MC) model: A linear elastic-perfectly plastic model defined by five parameters ( $E$ ,  $\nu$ ,  $c$ ,  $\varphi$ ,  $\psi$ ). It was used for preliminary analyses due to its simplicity and ease of calibration.

2) Soft Soil Model (SSM): Based on Modified Cam Clay theory, the SSM provides a more realistic representation of the compressibility and plastic volumetric strain behavior of soft clays and peat. It employs  $\lambda^*$ ,  $\kappa^*$ , and  $\varphi$  to capture stress-dependent stiffness and consolidation characteristics.

The Soft Soil model available in PLAXIS 2D was adopted to simulate medium stiff clay, soft clay, and peat soil. These soils exhibit stress-dependent stiffness and high compressibility, particularly under normally consolidated conditions. The Soft Soil model is capable of representing logarithmic compression behavior through the modified compression index ( $\lambda^*$ ) and swelling index ( $\kappa^*$ ), making it suitable for capturing settlement and consolidation behavior in cohesive and organic soils.

The soil-cement columns (SCC) were modeled using the Mohr-Coulomb constitutive model. Since SCC materials behave as relatively stiff, cemented geomaterials with limited compressibility and failure governed primarily by shear strength, the Mohr-Coulomb model provides an adequate and computationally efficient representation.

The reinforced concrete foundation was modeled as a linear elastic material due to its high stiffness relative to the surrounding soil. Structural nonlinearity was not considered, as the study focuses on soil-foundation interaction and ground improvement performance rather than structural failure of the footing.

The soil-cement columns (SCC) were modeled as fully bonded material clusters, without interface elements along their shafts, implying perfect displacement compatibility with the surrounding soil. No interface strength reduction or slip criteria were applied along the columns, so the load transfer occurs entirely through the bonded connection between the SCC and soil.

To realistically simulate the foundation-ground interaction, a geogrid element was placed beneath the foundation, and interface elements were assigned to it. These elements allow for shear transfer with limited slip, capturing the frictional interaction between the foundation and the supporting soil. This modeling approach ensures that the SCC-soil system transfers loads through the bonded columns, while the foundation interface responds realistically to shear stresses.

### 2.3. Model Geometry and Boundary Conditions

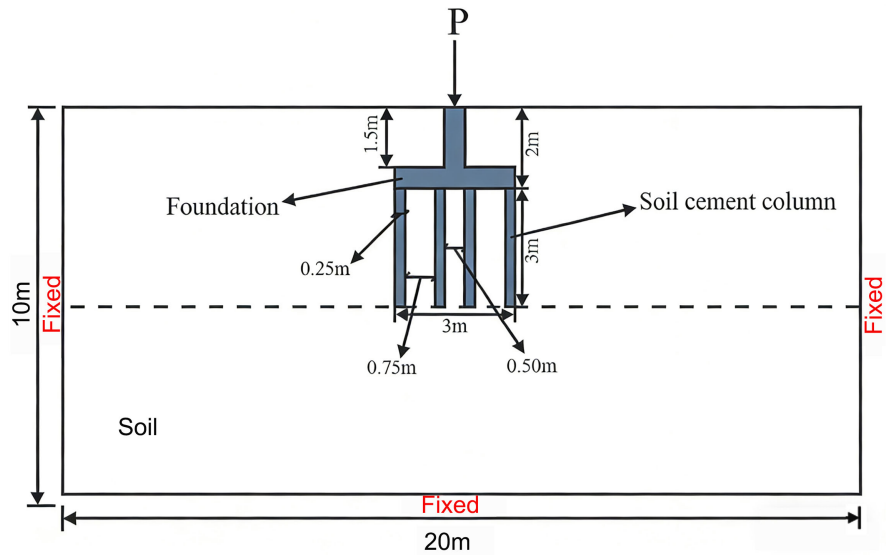
A plane-strain model was adopted. **Figure 2** shows the overall geometry of the soil domain and the arrangement of soil-cement columns (SCC) beneath the shallow foundation. Boundary conditions were defined such that the bottom boundary was fixed in both vertical and horizontal directions, while the vertical sides were restrained only in the horizontal direction, allowing free vertical movement.

The foundation was modeled as a square pad with a width of 3 m and an embedment depth of 2 m. A concrete column (width = 0.5 m) was located below the ground surface. Numerical analyses were performed using PLAXIS 2D.

Soil-cement columns (SCC) were installed directly beneath the foundation base, extending 3 m below the footing. Four columns were arranged across the foundation width in the modeled section. Each column had a diameter of 0.25 m, with center-to-center spacing of 0.75 m near the footing edges and 0.50 m in the central region.

Based on the modeled configuration, the equivalent area replacement ratio

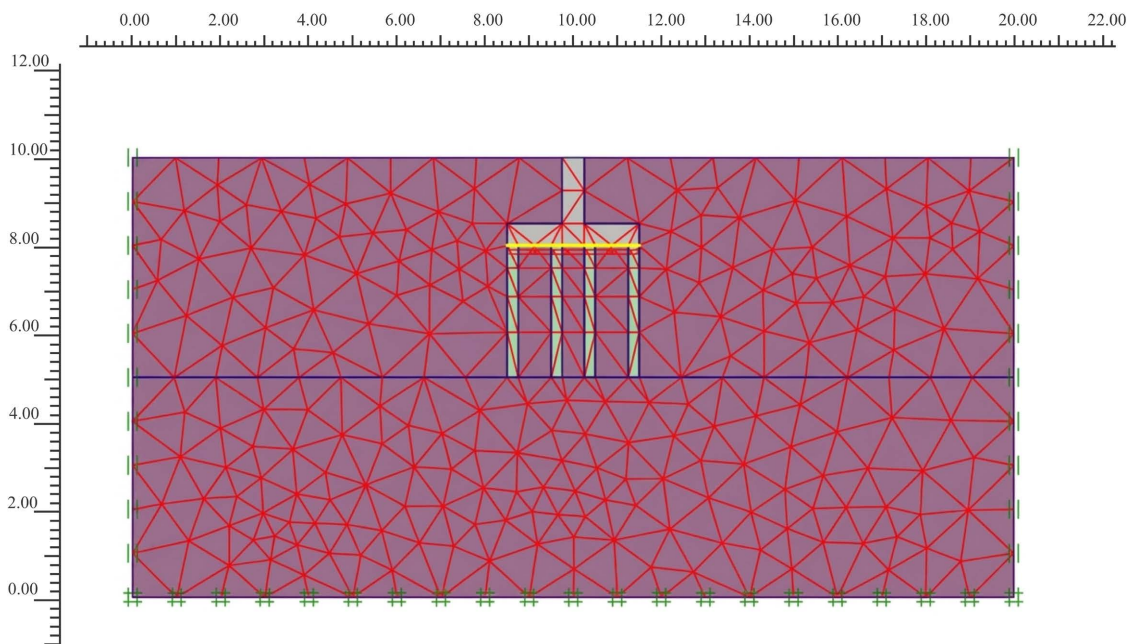
within the plane-strain section was approximately 6.6%. The soil domain dimensions were 20 m in width and 10 m in depth, corresponding to approximately 6.7 B horizontally and 3.3 B vertically.



**Figure 2.** An overall diagram illustrating the foundation and soil cement column.

#### 2.4. Mesh Generation

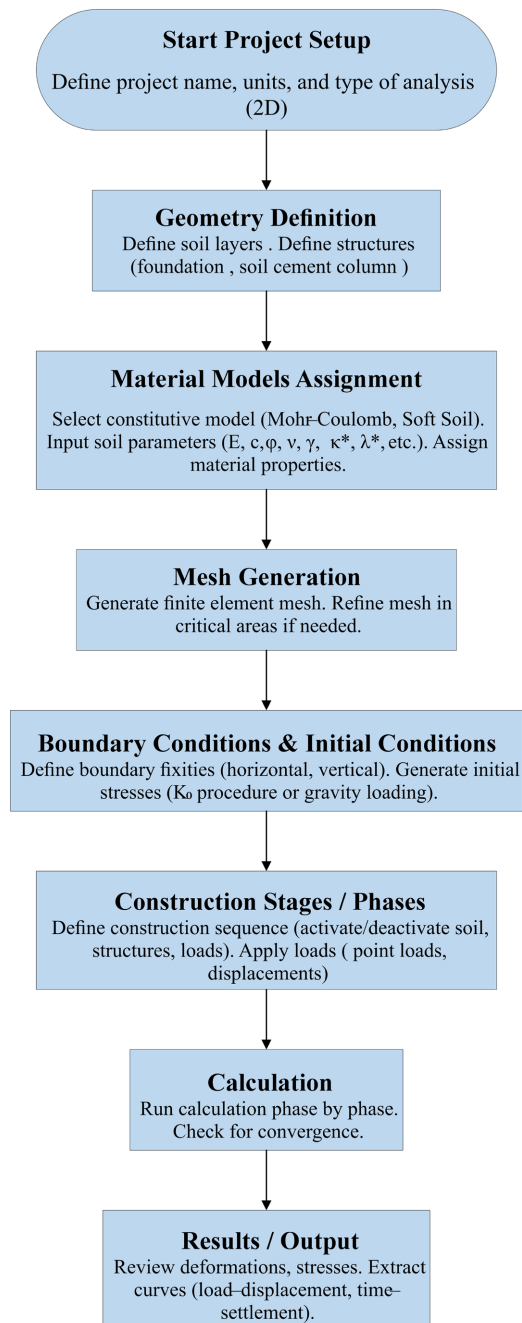
The automatic mesh generation option in PLAXIS was used to discretize the model domain, with appropriate refinement around the soil-cement column and foundation area, as shown in **Figure 3**. This ensures accurate capture of stress and deformation gradients in critical regions.



**Figure 3.** Finite element mesh of the foundation and soil cement column.

## 2.5. Loading and Analysis Procedure

A static vertical load was applied to the foundation to simulate bearing capacity. Two cases were analyzed for each soil type: untreated soil (without SCC) and reinforced soil (with SCC foundation). The load-settlement curves, stress distributions, and deformation contours were extracted for comparison. Performance was evaluated based on ultimate bearing capacity (kN), total settlement (m), and improvement ratio (%) between treated and untreated soils. **Figure 4** illustrates the flowchart of the numerical analysis procedure in PLAXIS 2D.



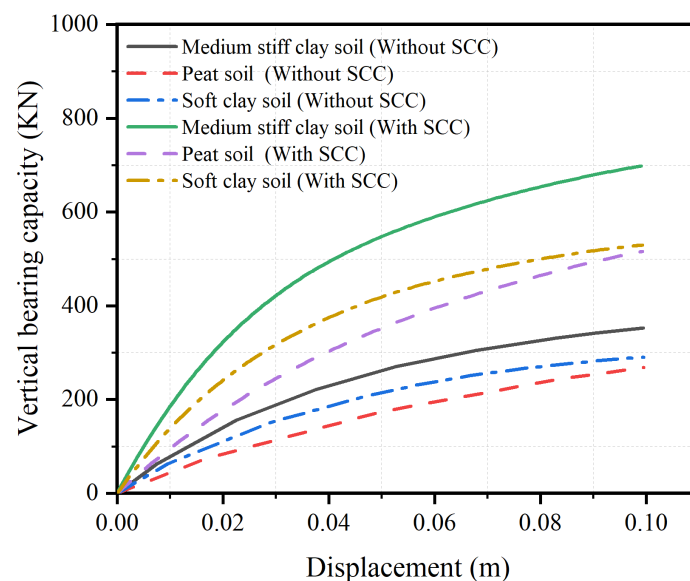
**Figure 4.** Flowchart of the numerical analysis procedure in PLAXIS 2D.

### 3. Results and Discussion

#### 3.1. Vertical Load Bearing Capacity

In this study, the ultimate bearing capacity was defined using a displacement-controlled criterion corresponding to a foundation settlement of 0.10 m. Given the footing width of  $B = 3$  m, this settlement represents approximately 3.3% of the footing width. This consistent criterion was applied to all untreated and SCC-reinforced cases to ensure uniform and reproducible comparison of bearing capacity among different soil types.

**Figure 5** presents the relationship between vertical load-bearing capacity and displacement for various soil types, both with and without soil-cement columns (SCC). The soils examined include medium-stiff clay, soft clay, and peat. Among the untreated soils, medium stiff clay exhibits the highest load-bearing capacity, soft clay is intermediate, and peat exhibits the lowest resistance. This trend is expected because medium-stiff clay has higher stiffness and shear strength than soft clay and peat, which are more compressible. The curves show a gradual increase in bearing capacity with displacement, reflecting the typical settlement behavior of untreated soils.



**Figure 5.** Vertical bearing capacity-displacement response of shallow foundations on medium-stiff clay, soft clay, and peat, with and without soil-cement columns (SCC).

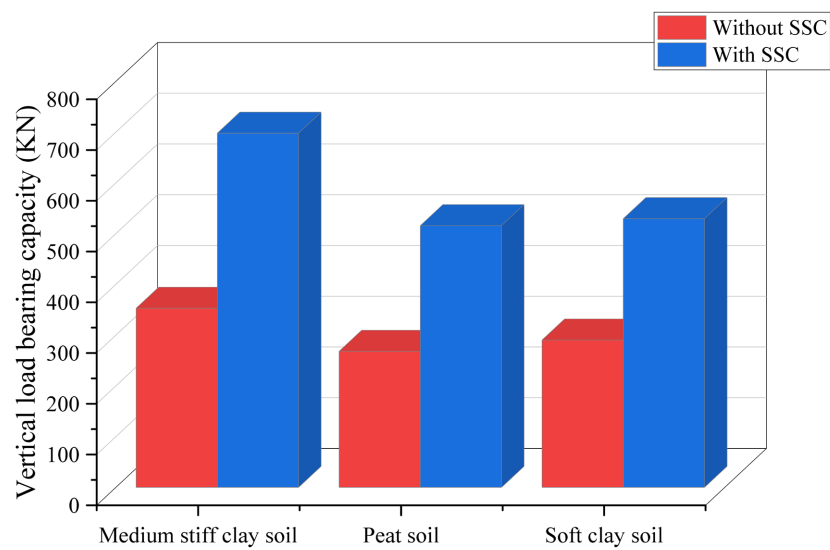
For all soil types, the inclusion of soil-cement columns significantly enhances load-bearing capacity. Medium-stiff clay with SCC shows the largest improvement, reaching values close to 700 kN, indicating that the reinforcement mechanism is most effective when the natural soil already has moderate strength. Peat and soft clay also show marked improvements, though their overall capacities remain lower than that of medium-stiff clay. With SCC, the bearing capacity of soft clay approaches that of medium stiff clay without SCC, highlighting the efficiency of the reinforcement technique. Peat soil, while improved, still lags behind soft

clay with SCC, reflecting its high compressibility and organic content, which limit the reinforcement effectiveness.

All SCC-treated soils exhibit steeper initial slopes, indicating increased initial stiffness and reduced settlement at lower loads, which is beneficial for foundation stability. At higher displacements, the gap between untreated and treated soils widens, confirming the long-term benefit of SCC in enhancing ultimate load-bearing capacity.

**Figure 6** and **Table 6** present a comparison of the vertical load-bearing capacity of three soil types—medium stiff clay, peat soil, and soft clay—under conditions without and with soil-cement columns (SCC). The inclusion of SCC nearly doubles the vertical load-bearing capacity in all soil types, highlighting its effectiveness as a ground-improvement technique. Medium stiff clay shows the greatest improvement, increasing from 353.039 kN to 698.035 kN, corresponding to an improvement rate of 97.7%. Peat soil capacity increases from 268.144 kN to 515.747 kN, an improvement of 92.3%, while soft clay improves from 290.448 kN to 529.537 kN, representing an improvement of 82.3%.

Without SCC, medium-stiff clay exhibits a higher load-bearing capacity than peat and soft clay due to its greater stiffness and strength. With the inclusion of SCC, medium-stiff clay continues to show the highest capacity, confirming that the reinforcing effect is more efficient in soils with moderate inherent strength. Although peat soil initially exhibits the weakest capacity, SCC reinforcement provides substantial gains, bringing its performance closer to that of soft clay. The greatest relative improvement occurs in medium stiff clay (97.7%), followed closely by peat soil (92.3%), while soft clay records the lowest improvement (82.3%). These results suggest that the effectiveness of SCC is influenced by the soil's natural strength and compressibility.



**Figure 6.** Comparison of ultimate vertical load-bearing capacity of the three soil types before and after SCC reinforcement.

**Table 6.** Ultimate vertical load-bearing capacity and improvement rate for medium-stiff clay, peat, and soft clay with and without SCC.

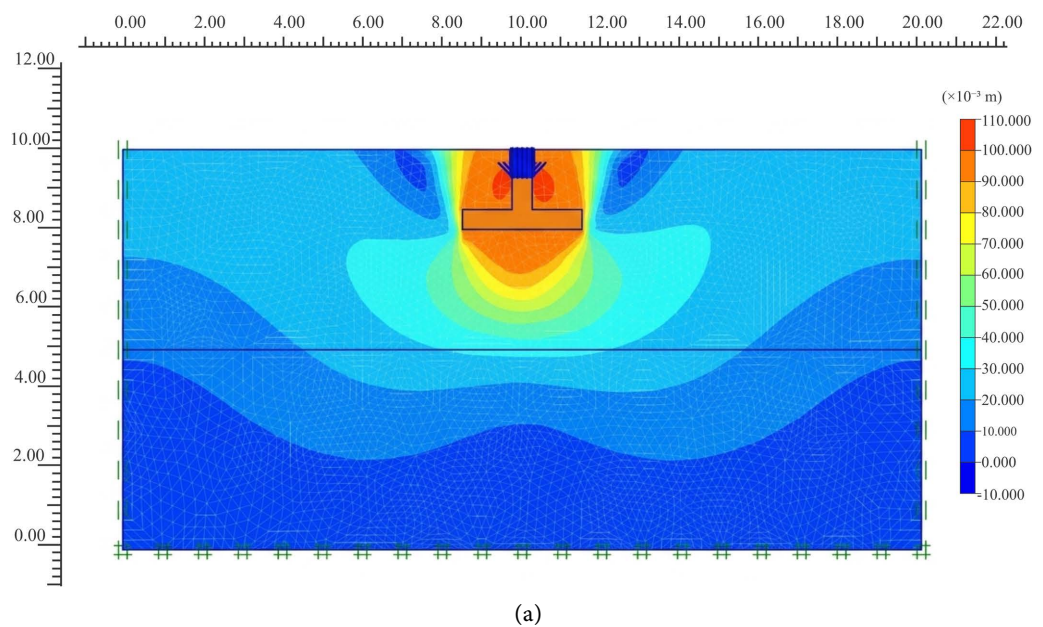
Soils	Without SSC (kN)	With SSC (kN)	Improvement rate (%)
Medium-stiff clay soil	353.039	698.035	97.7
Peat soil	268.144	515.747	92.3
Soft clay soil	290.448	529.537	82.3

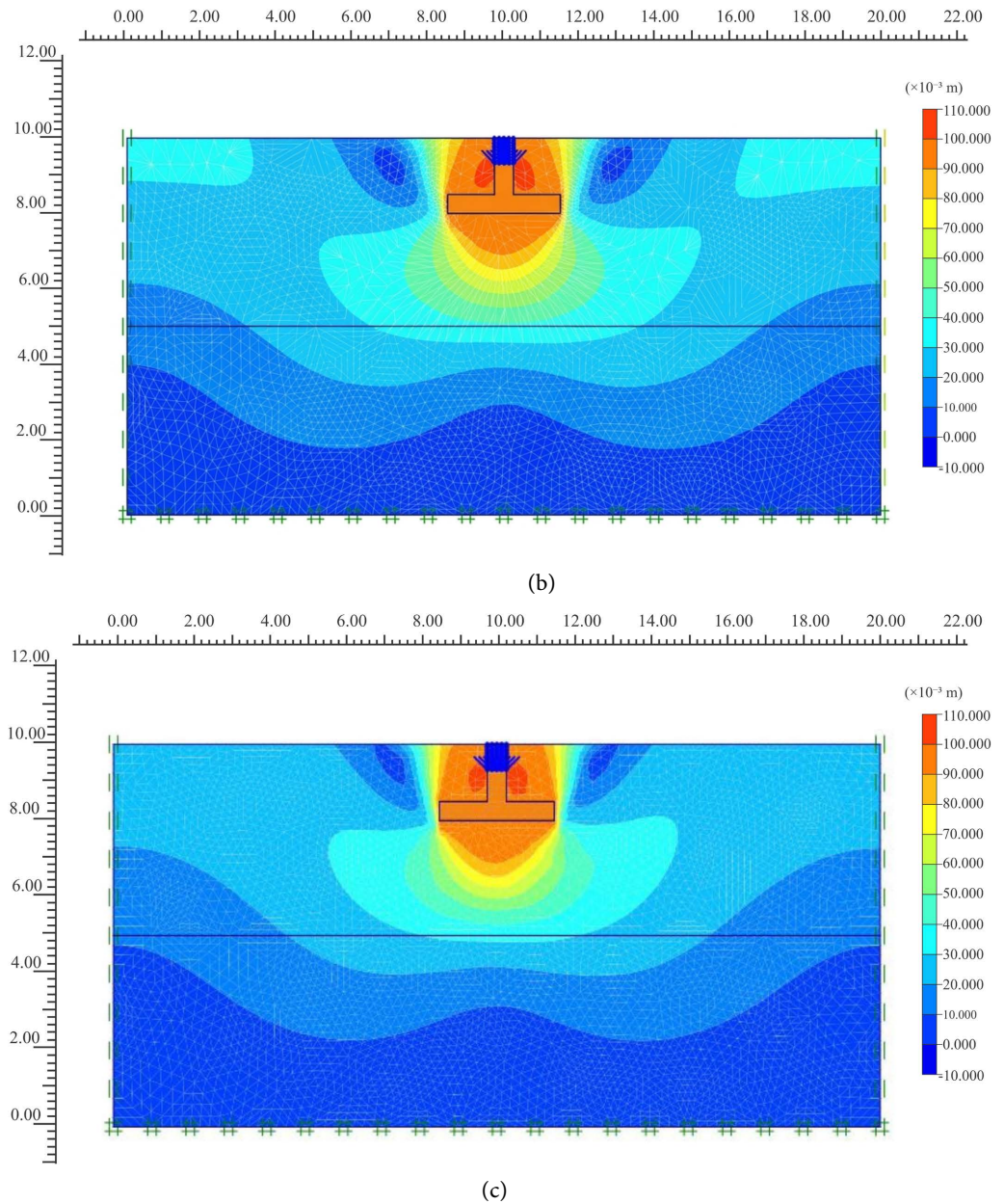
### 3.2. Total Displacement

In **Figure 7**, medium-stiff clay exhibits rapid attenuation of displacements with both depth and lateral distance, showing only modest curvature extending to the mid-depth of the model domain. This behavior reflects adequate native stiffness and limited volumetric strain. In soft clay, the displacement zone is wider and extends deeper than in medium-stiff clay. The contours are more widely spaced near the surface, indicating larger movements and noticeable lateral spreading above the interface, consistent with a lower shear modulus and higher compressibility.

Peat soil displays the largest and deepest displacement region among the three soils. High vertical settlements are concentrated beneath the footing and propagate laterally, forming pronounced lobes of displacement beside the load, characteristic of soils with very low stiffness, high void ratio, and significant susceptibility to creep.

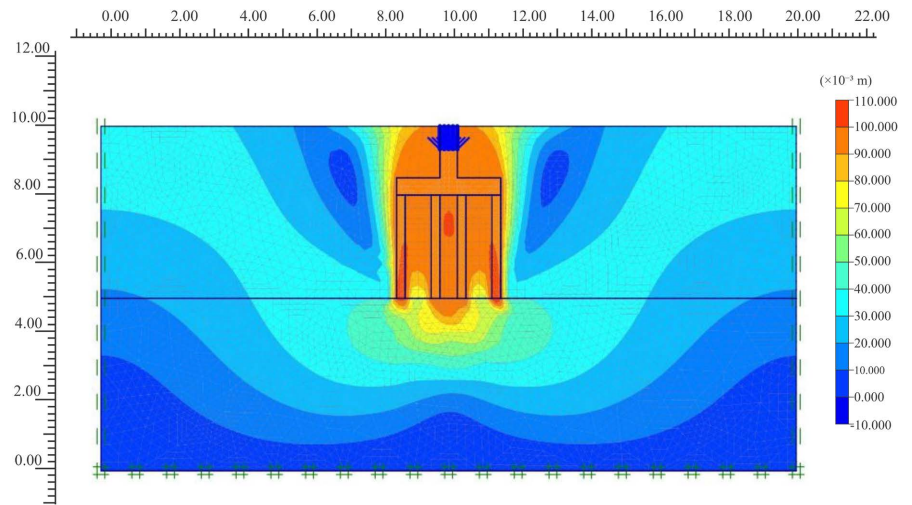
SCC acts as stiff columns that carry and redistribute load, generating the soil-structure arching effect. This modifies the displacement contour topology; high-displacement zones beneath the footing narrow, and iso-displacement lines become more vertical near the column group, indicating reduced lateral spread. The depth of significant movement decreases, and the transition to far-field ground becomes smoother.



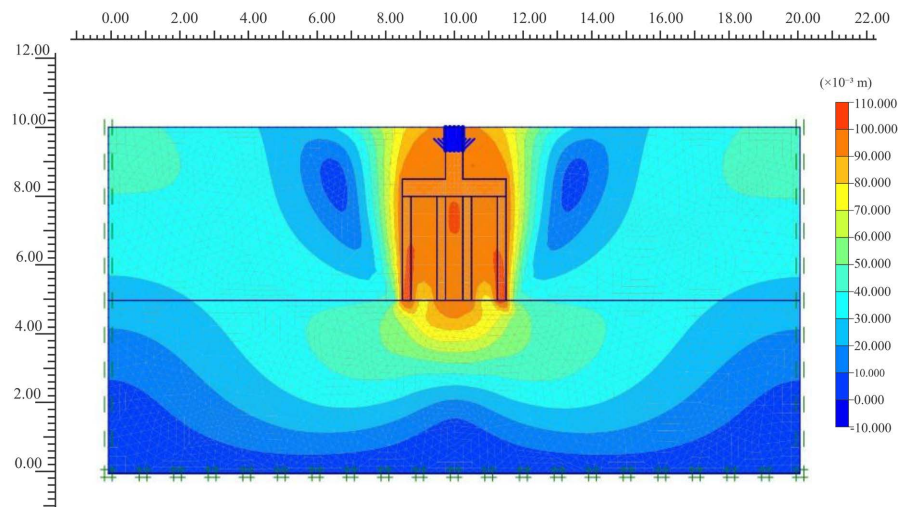


**Figure 7.** Total displacement for the foundation without SCC: (a) Medium stiff clay soil, (b) Peat soil, and (c) soft clay soil.

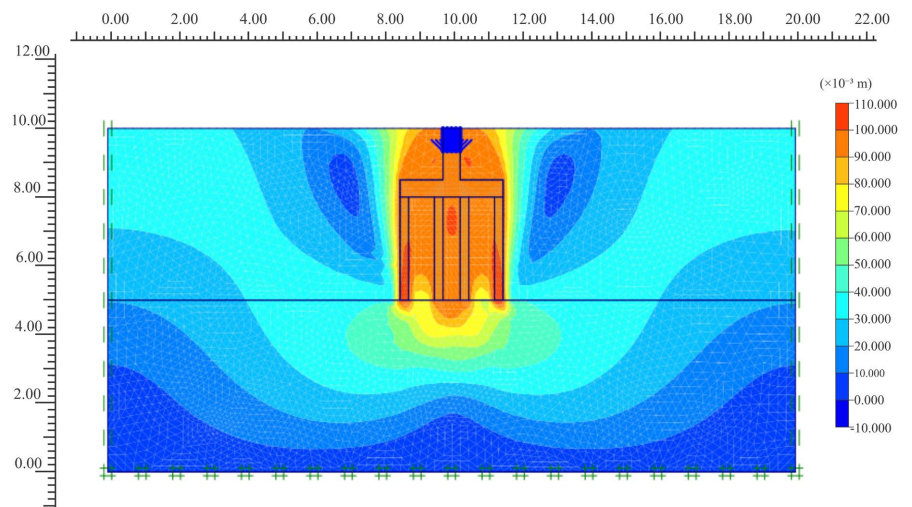
In **Figure 8**, for medium-stiff clay with SCC, settlement reduction is evident but moderate. The displacement region becomes narrower and shallower, with residual settlement concentrated immediately beneath and around the column heads. In soft clay with SCC, the displacement region tightens beneath the footing, while lateral wing-shaped displacements above the interface are greatly diminished. The zone of noticeable movement is markedly reduced in both width and depth. In peat soil with SCC, lateral displacement lobes on either side of the footing largely disappear, indicating effective load transfer into the stiff columns and a pronounced reduction in overall deformability.



(a)



(b)

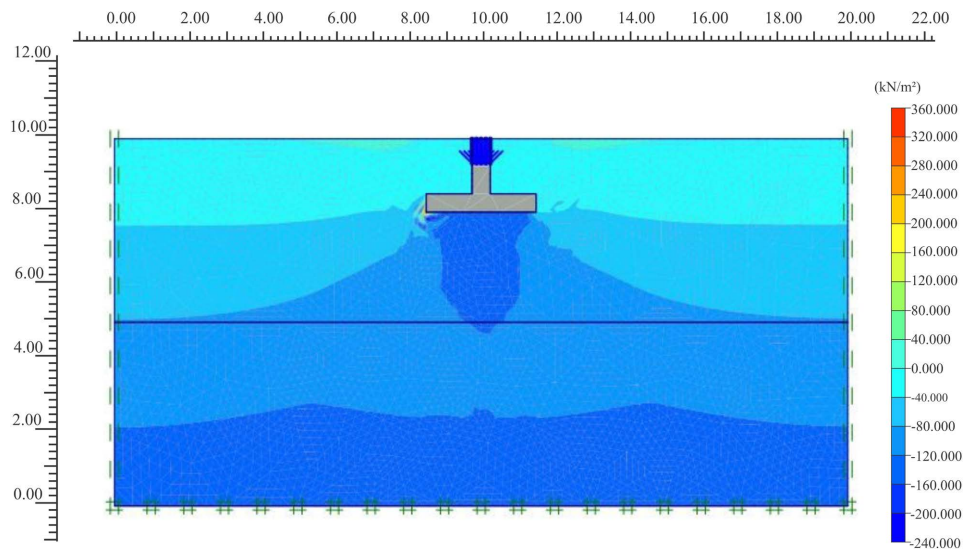


(c)

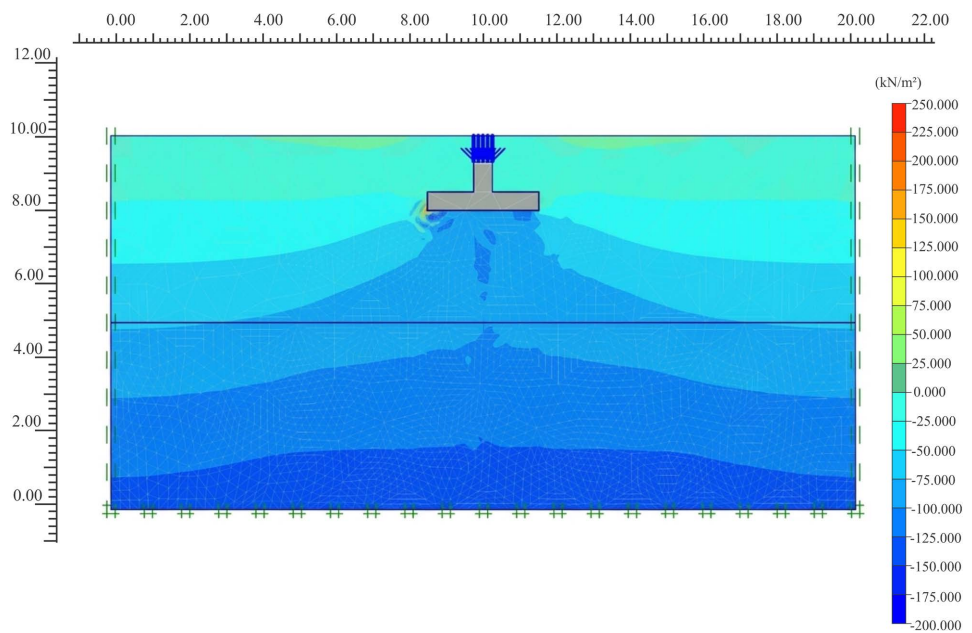
**Figure 8.** Total displacement for the foundation with SCC: (a) Medium stiff clay soil, (b) Peat soil, and (c) soft clay soil.

### 3.3. Total Stress

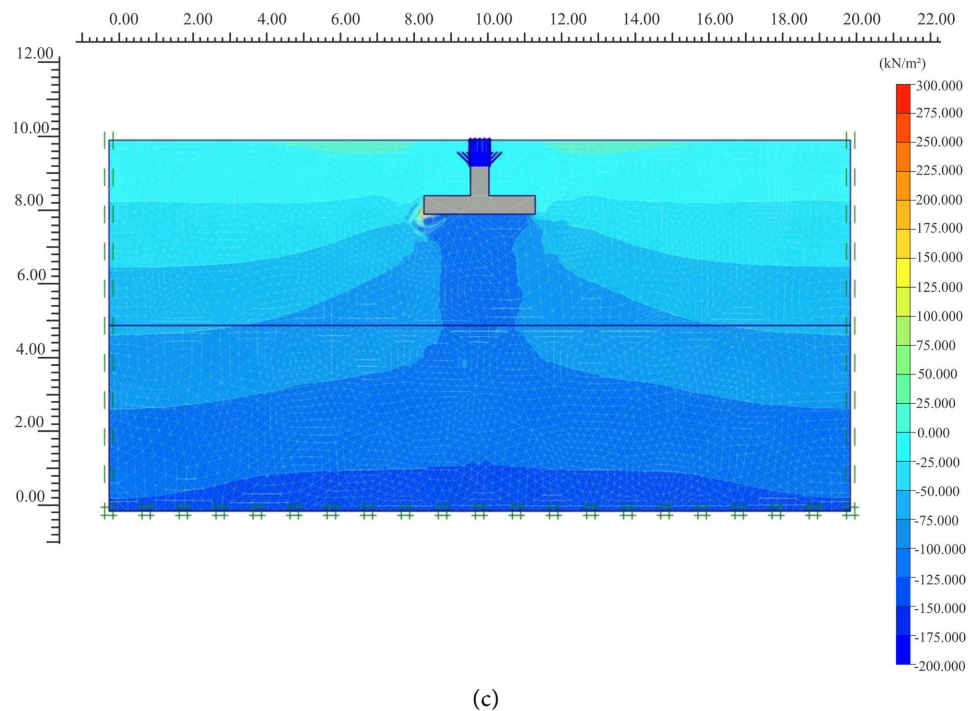
In **Figure 9**, for medium-stiff clay without SCC, a classic stress region develops beneath the footing, narrow and relatively deep due to the higher soil stiffness. Peak total stresses concentrate directly beneath the footing and extend downward, while lateral stress ridges appear near the ground surface beside the footing, consistent with shallow heave and localized shear zones. In **Figure 9**, with SCC in medium stiff clay, very high total stresses are instead confined within the columns and immediately along the column soil interface, reflecting strong load transfer and soil structure arching. The surrounding clay and the underlying stratum carry much lower stresses than in the untreated case, as the stress region is effectively pinched and terminates around the column.



(a)



(b)



**Figure 9.** Total stress for the foundation without SCC: (a) Medium stiff clay soil, (b) Peat soil, and (c) soft clay soil.

The overall effect is a higher bearing resistance and a marked reduction in settlement. In peat soil without SCC (**Figure 9**), the stress region is shallow and very wide due to the soil's low stiffness and strength, with stresses dissipating laterally more than vertically. Peak stresses beneath the footing are lower than in clays, but they influence a much larger area, leading to large settlements and broad surface heave zones. With SCC, the columns in peat soil (**Figure 10**) attract the load almost exclusively, while the intervening peat exhibits very low total stresses, indicating effective stress-shielding. The depth of the stress region now corresponds to the column length rather than the peat stiffness, and lateral stress spread is greatly reduced compared to the untreated case, thereby limiting lateral strains and outward ground movement.

In soft clay without SCC (**Figure 9**), the stress region is deeper than in peat but wider than in medium-stiff clay, as typically observed for soft clays. A pronounced vertical core of higher stress extends to the lower layer, indicating significant consolidation demand beneath the footing. With SCC (**Figure 10**), high total stresses are concentrated within and along the columns, while the soft clay experiences substantially reduced stresses both beneath and around the footing. The lower layer is subjected to far less transmitted stress than in the untreated case, shortening consolidation paths and reducing long-term settlements.

### 3.4. Vertical Load

The load-displacement curves shown in **Figure 11** exhibit nonlinear behavior typical of soil-structure interaction under vertical loading. In all soil types (medium-

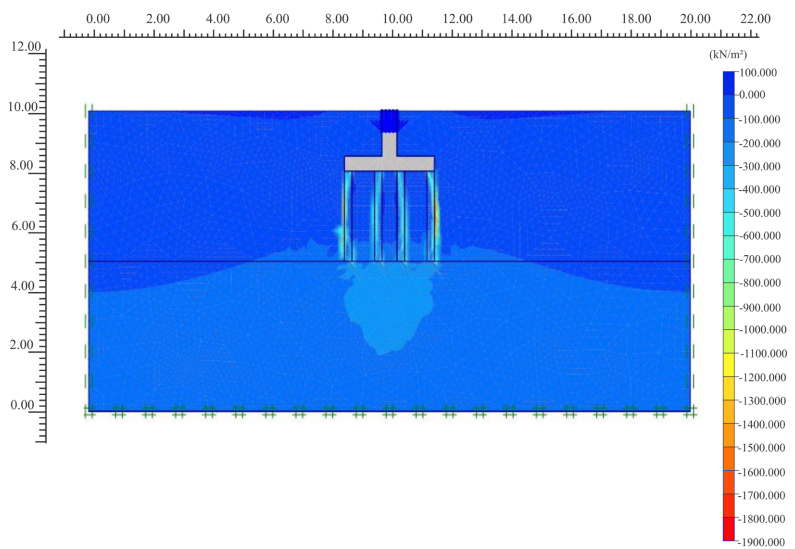
stiff clay, peat, soft clay), the inclusion of soil-cement columns (SCC) enhances the load-bearing capacity of the foundation. The curves rise steeply at the initial stage, indicating higher stiffness, and then gradually flatten as displacement increases, reflecting plastic deformation and settlement development.

**Figure 11(a)**, at 300 kN, the initial stiffness dominates the response, with curves showing relatively small displacement ranges (up to ~0.04 m). At 500 kN, the curves extend further, with displacements exceeding 0.08 - 0.1 m. Differences between soil types become more pronounced, particularly highlighting the weak compressibility of peat compared to stiffer clay. Among the three soil types, medium-stiff clay exhibits the highest stiffness and load-bearing capacity, particularly when reinforced with SCC. In contrast, peat soil, being highly compressible and organic, shows the lowest stiffness, with earlier settlement under lower loads; nevertheless, SCC significantly improves its performance compared to untreated peat. Soft clay behaves between these two extremes, where SCC provides appreciable improvement in stiffness and ultimate load capacity.

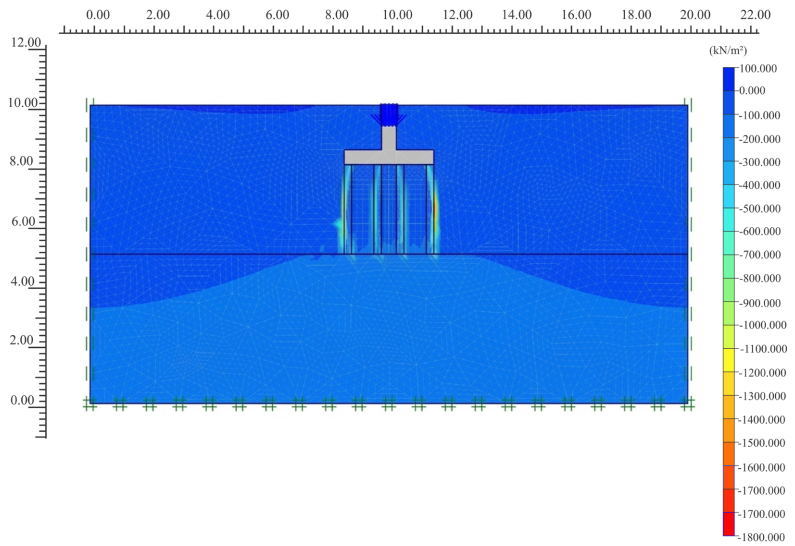
To quantitatively evaluate settlement reduction, settlement values were extracted from **Figure 11(b)** at a representative service load level of 300 kN for all soil conditions. The results are summarized in **Table 7**. For medium stiff clay, settlement decreased from 0.06528 m (untreated) to 0.01928 m with SCC, corresponding to a reduction of 70.5%. For soft clay, settlement reduced from 0.09953 m to 0.03078 m, representing a 69.1% improvement. For peat soil, settlement decreased from 0.11687 m to 0.04255 m, corresponding to a 63.6% reduction.

**Table 7.** Settlement comparison at 300 kN for the soils without SCC and with SCC.

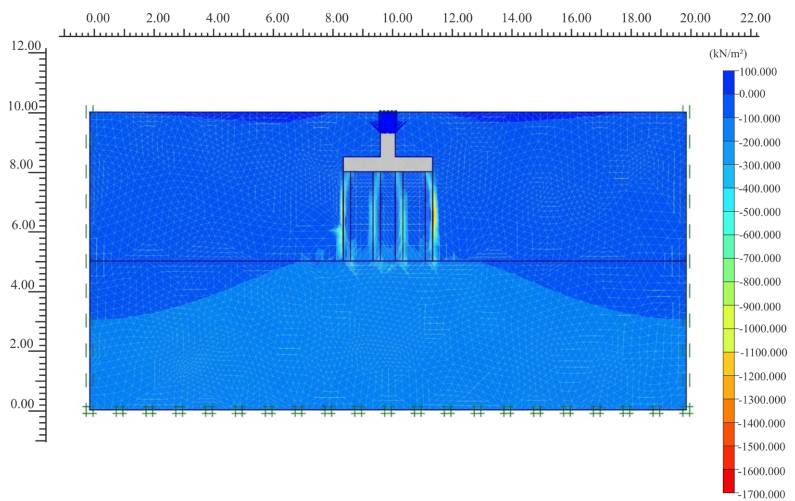
Soil Type	Settlement without SCC (m)	Settlement with SCC (m)	Settlement Reduction (%)
Medium-stiff clay soil	0.06528	0.01928	70.5%
Peat soil	0.09953	0.03078	69.1%
Soft clay soil	0.11687	0.04255	63.6%



(a)

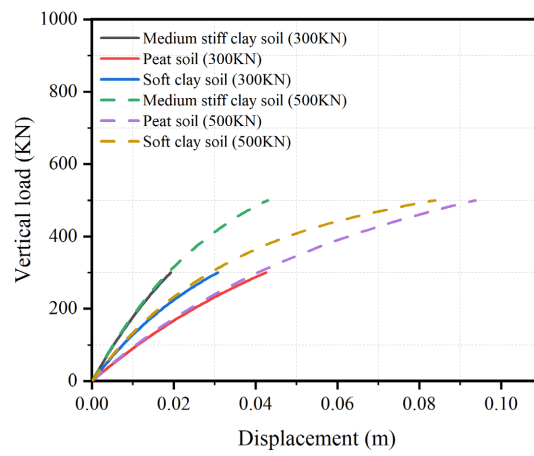


(b)

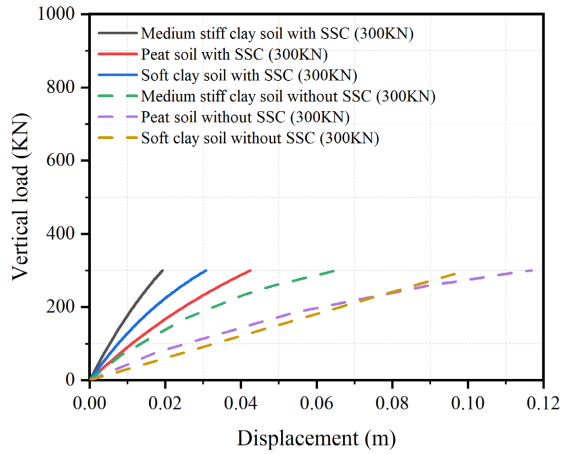


(c)

**Figure 10.** Total stress for the foundation with SCC: (a) Medium stiff clay soil, (b) Peat soil, and (c) soft clay soil.

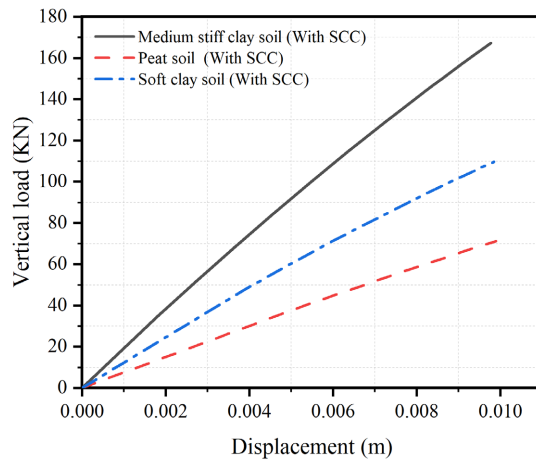


(a)

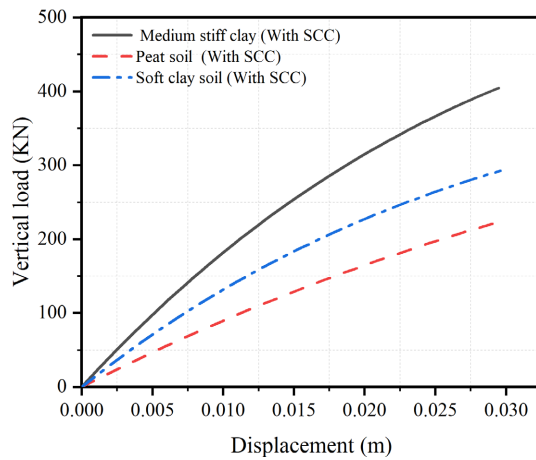


(b)

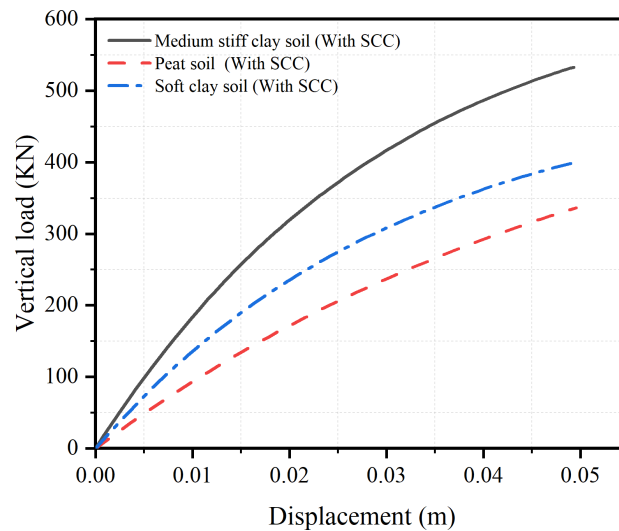
**Figure 11.** Vertical load-displacement response of the foundation: (a) soils with SCC under varying vertical loads; (b) comparison of soils with and without SCC.



**Figure 12.** Vertical load-displacement curves of the foundation with displacement 0.01 m (with SCC).



**Figure 13.** Vertical load-displacement curves of the foundation with displacement 0.03 m (with SCC).



**Figure 14.** Vertical load-displacement curves of the foundation with displacement 0.05 m (with SCC).

**Figures 12-14** illustrate the vertical load-displacement response of foundations resting on different soil types—medium stiff clay, soft clay, and peat soil—all reinforced with soil-cement columns (SCC). Across all cases, the curves exhibit non-linear hardening behavior, with vertical load capacity increasing with displacement. The soil type strongly influences stiffness and load-bearing capacity.

At a displacement of 0.01 m (**Figure 12**), the foundation supported 167 kN on medium-stiff clay, 110 kN on soft clay, and 71 kN on peat soil. The slopes of the load-displacement curves are distinctly different, reflecting the relative initial stiffness of the soils. Medium-stiff clay shows the steepest gradient (highest stiffness), while peat soil has the lowest.

At 0.03 m displacement (**Figure 13**), the load capacities increased to 404 kN (medium-stiff clay), 292 kN (soft clay), and 224 kN (peat soil). The curves begin to flatten, indicating stiffness degradation with increasing displacement, especially for peat soil.

At 0.05 m displacement (**Figure 14**), medium-stiff clay sustained 533 kN, soft clay 399 kN, and peat soil 336 kN. Nonlinearity becomes more pronounced for peat and soft clay, indicating progressive yielding of the soil matrix despite SCC reinforcement. Medium-stiff clay continues to outperform the others, but both peat and soft clay show improved capacities compared to earlier displacements, highlighting the stabilizing role of SCC at large deformations.

#### 4. Conclusions

This study presented a numerical investigation of shallow foundations reinforced with soil-cement columns (SCC) to enhance bearing capacity and reduce settlement. The main findings are summarized as follows:

- 1) SCC significantly increases vertical load-bearing capacity and stiffness of shallow foundations, leading to reduced settlement across all soil types.

2) The largest improvements are observed in medium-stiff clay (load: 97.7%, settlement: 70.5%), followed by peat (load: 92.3%, settlement: 69.1%) and soft clay (load: 82.3%, settlement: 63.6%), with peat showing noticeable gains despite its high compressibility.

3) The load-displacement response indicates that SCC mobilizes greater soil resistance. Medium-stiff clay maintains higher resistance over larger displacements, whereas peat exhibits earlier softening.

4) SCC fundamentally modifies stress transfer mechanisms: stresses are concentrated within the columns and their interfaces, reducing lateral displacement, and settlement. These effects are more pronounced in weaker soils.

5) Despite substantial improvements, highly compressible soils such as peat may still experience excessive settlement, highlighting a critical design limitation.

6) Overall, SCC provides a practical and effective method for enhancing shallow foundation performance, with soil type strongly influencing the degree of improvement.

### Author Contributions

Conceptualization, T.I., M.I.A., M.A.F., J.Y., and H.X.; methodology, T.I., M.I.A., M.A.F., R.L., and W.W.; Software, T.I., M.A.F., J.Y., R.L., and H.X.; formal analysis, T.I.; writing-original draft preparation, T.I.; writing-review and editing, M.I.A., M.A.F., H.X., and W.W.; supervision, M.I.A.; project administration, J.Y., R.L., H.X., and W.W.; funding acquisition, J.Y., R.L., H.X., and W.W. All authors have read and agreed to the published version of the manuscript.

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### Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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