Numerical Analysis of Reinforced Embankments over Soft Foundations Using Stone Columns

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Received: 16 April 2025 | Revised: 27 May 2025 | Accepted: 1 June 2025

 DOI: https://doi.org/10.48084/etasr.11538

ABSTRACT

The improvement of soft soil foundations is essential in geotechnical engineering, particularly for infrastructure projects, such as highways, railways, and embankments. The soft soil formations pose significant challenges, including excessive settlement, low shear strength, and insufficient load-bearing capacity, which often render the traditional foundation methods inadequate. Stone columns are a widely adopted ground improvement technique due to their ability to enhance the soil stability, bearing capacity, and drainage efficiency. Advanced reinforcement techniques, such as stone columns, provide an effective solution, yet an understanding of the coupled soil-fluid interactions remains limited. This study employs a numerical approach to evaluate the stone column performance using a finite element model developed in FORTRAN 90. The model examines the embankment response under three conditions: without stone columns, with stone columns in a free-field scenario, and with stone columns under a surface foundation surcharge of 0.5 kN/m². The key parameters analyzed include Excess Pore Pressure (EPP) dissipation, deformation characteristics, and site stiffening effects. The numerical simulations indicate that the stone columns significantly reduce the settlement, accelerate the pore pressure dissipation, and improve the embankment stability by redistributing the stresses within the soil matrix. The findings confirm that the stone columns are a viable solution for soft soil reinforcement. The developed numerical model provides valuable insights into the effectiveness of the stone columns in embankment stabilization. Future research should focus on optimizing the stone column configurations, integrating real-time field monitoring, and exploring hybrid reinforcement techniques to further enhance the soil stabilization strategies.

Keywords-stone columns; numerical modeling; soil improvement; geotechnical engineering; embankment

I. INTRODUCTION

Soil improvement and land strengthening have become critical issues in geotechnical engineering. Enhancing the soil shear strength can lead to increased bearing capacity, reduced settlement, and improved resistance of the embankments and soil structures to liquefaction, sliding, shrinkage, and swelling. The overall improvement is particularly significant in soft cohesive soils with low undrained shear strength and loose sand with poor standard penetration test results.

Among the various improvement techniques, stone columns have proven highly effective in enhancing the weak soils, particularly beneath light infrastructure, such as railway and road embankments. Authors in [1] identified the key benefits of the stone columns, including the increased bearing capacity of shallow foundations on soft soils, reduced total and differential settlements, minimized liquefaction potential, and improved slope stability of embankments. Compared to other soil improvement methods, like geotextile reinforcement, grouting, and compaction, the stone columns are more cost-effective and easier to install. When placed in a regular grid pattern, they help homogenize variable soil properties, reducing the risk of differential settlement while enhancing the bearing capacity and reducing the compressibility.

The concept of stone columns for clay soil improvement dates back to the 1940s, with applications in Europe beginning in the 1960s. Their use expanded globally, with the first application in Japan in 1978 for liquefaction mitigation. Key studies, such as [2-4], proposed various methods for evaluating the bearing capacity and settlement of soil reinforced with stone columns. These studies typically utilized gravel or rubble-filled columns with diameters ranging from 0.6 to 1.2 m and depths between 4 and 15 m, functioning as a vertical support system for foundations or embankments. Research has demonstrated that stone columns not only withstand horizontal and inclined stresses, but also serve as an effective radial drainage system.

Reinforcing the soil with tensile elements in horizontal, vertical, and inclined directions has gained popularity. With advancements in polymer engineering, geosynthetics have become a crucial material for soil reinforcement. Authors in [5] pioneered the concept of geosynthetic-encased stone columns, followed by extensive experimental research. Other studies, such as [6-8], further explored techniques to enhance the bearing capacity of stone columns using geosynthetic reinforcement. In [9], a case study on a bridge approach embankment was conducted, where Finite Element Analysis (FEA) demonstrated the effectiveness of floating stone columns with a length-to-depth ratio of 0.5. Furthermore, an increase in the area replacement ratio was observed in an attempt to decrease the settlement reduction factor. In [10], it was found that encased stone columns significantly improved the bearing capacity and excess pore water pressure dissipation.

Authors in [11] proposed an analytical design method to govern the stress levels in stone column reinforcement. It was concluded that factors, such as the modular ratio, spacing-to-diameter ratio, embankment height, soft soil depth, and geosynthetic stiffness significantly influence the behavior of reinforced stone columns. In [12], it was shown that increasing the geosynthetic stiffness enhances the soil stability. Authors in [13] investigated the performance of shallow foundations under earthquake loading in liquefiable soils using a 3D numerical model, revealing significant reductions in EPP and settlement. Authors in [14] studied the nonlinear soil behavior, including dilatancy and loading-unloading hardening, using the Pastor-Zienkiewicz Mark III model, demonstrating foundation settlement variations under different conditions. In [15], a numerical model was developed to evaluate the liquefaction countermeasures of shallow foundations underlain by stone columns, concluding that the granular column inclusion effectively mitigates displacement and EPP.

This study examines the performance of granular columns as a liquefaction risk mitigation measure. Biot's consolidation equations, incorporating cyclic loading effects, serve as the governing framework for assessing the ground subsidence and EPP changes. The coupled equations, comprising the continuity and mass moment balance equations, are transformed into a finite element form using a variational method. To conduct the coupled analysis, a FORTRAN 90 program is developed. A critical state model based on the generalized plasticity theory is employed to capture the loading-unloading hardening and dilatancy behavior of soil under dynamic loading. The analysis considers variations in column length and number to evaluate the effects on EPP generation, dissipation, and settlement behavior.

II. METHODOLOGY

A. Finite Element Mathematical Formulation

To analyze the fully saturated soil with an incompressible pore fluid, both equilibrium and continuity equations must be considered concurrently. The equilibrium equations in the x and z directions are given by:

$$\begin{aligned} \frac{\partial \sigma_{xx}}{\partial x}+\frac{\partial \sigma_{xz}}{\partial z}+\gamma_x=0 \\ \frac{\partial \sigma_{xz}}{\partial x}+\frac{\partial \sigma_{zz}}{\partial z}+\gamma_z=0 \end{aligned} \qquad (1)$$

where γ_x and γ_z represent the soil bulk unit weights in the x and z directions, respectively.

Applying a variational approach to (1), the finite element form becomes:

$$[K]u_e-[Q]P_e=[f_u] \qquad (2)$$

where $[K]$ is the stiffness matrix, $[Q]$ is the coupling matrix, $[f_u]$ is the force vector, u_e is the displacement vector, and P_e is the nodal pore pressure vector.

The equation of continuity is expressed by:

$$\frac{\partial v_x}{\partial x}+\frac{\partial v_y}{\partial y}+\frac{\partial v_z}{\partial z}-Q=\frac{\partial \in_v}{\partial t} \qquad (3)$$

where v_x, v_y, v_z are the components of the pore fluid velocity in the respective coordinate directions and $\in_v$ is the volumetric strain.

The generalized form of Darcy's law is given by:

$$v=ki \qquad (4)$$

where v is the velocity vector, k is the hydraulic conductivity tensor, and i is the hydraulic gradient.

Using (4) in (3) gives:

$$\int-\left([\nabla h]^T[k]\nabla p-\frac{\partial \in_v}{\partial t}p\right)dV=Qp \qquad (5)$$

where p is the pore pressure and h is the hydraulic head, which is defined by:

$$h=\frac{p}{\gamma}+\left(xi_{G_x}+yi_{G_y}+zi_{G_z}\right) \qquad (6)$$

where γ is the unit weight of the water and G_x, G_y, G_z are the directional gravity components.

Substituting h into (5) and applying the variational method yields the final finite element form of the continuity equation:

$$[Q]^T\{u_e\}-[H][p_e]=-\left[\{n_G\}+Q\right] \qquad (7)$$

where $\{n_G\}$ is the gravity contribution vector.

Equations (2) and (7) are solved simultaneously to determine the two primary unknowns: displacement and pore pressure. As (7) involves time-dependent terms, a time-stepping approach is essential for the solution.

B. Constitutive Behavior

The stress state within a soil mass varies considerably due to external influences, such as structural loads, surcharge pressures, and boundary conditions. These stress variations range from very low to extremely high magnitudes. Saturated sandy soils generally exhibit drained behavior under static conditions and undrained behavior during dynamic loading, such as earthquakes.

Numerous elastoplastic models have been developed to capture the soil behavior more accurately. Many of these models build upon the Cam-Clay theory, a widely accepted constitutive framework for cohesive soils. Among them, the Modified Cam-Clay (MCC) model [16] has shown strong predictive capabilities, especially under monotonic and quasi-static loading. It introduces refinements in the curvature of the yield surface and provides better agreement with experimental data on soft clay behavior [17-19].

This study incorporates the original Cam-Clay model to describe the deformation and pore water response of an embankment subjected to plastic yielding and potential liquefaction. The model is used to simulate the mechanical behavior of saturated clays under varying loading conditions, capturing both the plastic flow and consolidation effects. The Cam-Clay framework describes the consolidation behavior in the void ratio (e) versus the logarithm of the mean effective stress (ln$p$) space (Figure 1). During the loading and unloading cycles, the total change in the void ratio can be expressed through the combination of elastic and plastic components [20-22].

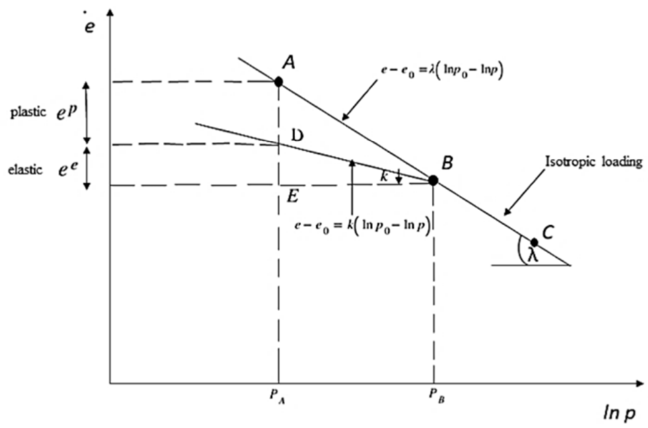

Fig. 1. Consolidation behavior in *e-lnp* space.

The total change in the void ratio Δe during a loading–unloading cycle consists of both plastic and elastic components and can be expressed by:

$$\Delta e^{plastic} = \Delta e^{p} = e_A - e_B = \lambda \ln\left(\frac{P_B}{P_A}\right) = \lambda\left(\ln P_B - \ln P_A\right) \quad (8)$$

$$\Delta e^{elastic} = \Delta e^{e} = e_D - e_E = k \ln\left(\frac{P_A}{P_B}\right) = k\left(\ln P_B - \ln P_A\right) \quad (9)$$

where λ is the slope of the normal consolidation line and k is the slope of the swelling line.

Differentiating the constitutive relations provides expressions for incremental strains, which are then integrated into the finite element model to evaluate the time-dependent deformations and settlement. By combining this constitutive behavior with the finite element framework and Biot's consolidation theory, the model captures complex interactions, such as:

- Time-dependent settlement due to consolidation.
- Changes in pore pressure.
- Yielding and hardening behavior of the soft soil layer.
- Shear-induced dilatancy or contraction during the loading cycles.

This integration allows for a more realistic simulation of the embankment behavior on soft, saturated soils, especially under dynamic or cyclic loading conditions.

C. Validation

To assess the accuracy of the developed finite element formulation, it is validated against the well-established Terzaghi's theory of one-dimensional consolidation. The benchmark problem considers a clay layer of 5 m thickness, subjected to a constant vertical pressure of 100 kPa, with double drainage, which means that the drainage is permitted at both the top and bottom surfaces (Table I). A time step of 0.01 s was adopted for the analysis.

TABLE I. SOIL PROPERTIES USED FOR VALIDATION

Property	Value
Modulus of elasticity, E	4131 kPa
Coefficient of permeability, kv	1.38×10^{-7} m/s
Coefficient of consolidation, Cv	5×10^{-5} m²/s
Depth of soil layer, z	5 m

The results obtained from the numerical analysis, at different degrees of consolidation 30%, 50%, and 90% are compared against those of the analytical solution, demonstrating a strong correlation:

- At 30% consolidation:

  Numerical EPP ≈ 97.90 kPa, while analytical EPP ≈ 98.40 kPa, which shows excellent agreement at mid-depth and indicates a precise simulation during the early consolidation stages.

- At 50% consolidation:

  Numerical EPP ≈ 73.2 kPa and analytical EPP ≈ 77.95 kPa, a slight deviation is observed but within acceptable bounds.

- At 90% consolidation:

  Numerical EPP ≈ 14.6 kPa, while analytical EPP ≈ 15.71 kPa, which means that the pore pressure dissipation trends align well across the depth.

The settlement comparisons (Table II) show that the numerical model closely replicates the analytical predictions for both EPP and settlement. The small variation percentages across different consolidation stages and permeability values confirm the model's accuracy. The results demonstrate the expected dissipation behavior of EPP and the corresponding increase in effective stress over time, which are consistent with the Terzaghi's theory.

TABLE II. SETTLEMENT COMPARISON

Sl. No.	Degree of consolidation (%)	Cv (m^2/s)	z/H	Settlement (cm) analytical	Settlement (cm) FEM	Variation (%)
1	90	5×10^{-5}	0.75	2.72	2.89	6.25
2	90	7×10^{-5}	0.75	1.94	2.07	6.70
3	50	5×10^{-5}	0.70	2.41	2.46	2.07
4	50	7×10^{-5}	0.70	1.72	1.76	2.32
5	30	5×10^{-5}	0.55	1.90	1.93	1.58
6	30	7×10^{-5}	0.55	1.36	1.38	1.47

D. Numerical Analysis

A detailed parametric analysis was conducted using a finite element numerical model developed in FORTRAN90 to evaluate the performance of stone column-reinforced embankments constructed over soft soil. The primary objective was to predict the settlement and EPP under varying design conditions and stone column configurations.

1) Model Setup

- Domain dimensions: 24 m (length) × 10 m (height).
- Loading condition: Surface load 0.5 t/m², simulation of the combined load from foundation and embankment.
- Assumptions: Plane strain condition to reduce the computational complexity.
- Soil and stone column behavior: Simulated using four-node quadrilateral elements with two degrees of freedom (horizontal and vertical displacements).

2) Material Properties

a) Soft Soil (Brermerhaven Clay)

- Saturated unit weight: 15 kN/m³
- Cohesion (c'): 5 kPa
- Friction angle (Φ'): 35°
- Permeability: $k_h = 2.3\times10^{-10}$ m/s, $k_v = 1.1\times10^{-10}$ m/s
- Cam-Clay parameters: $\lambda^* = 0.203$, $\kappa^* = 0.007$, $\psi = 0°$

b) Stone Column

- Saturated unit weight: 20.4 kN/m³
- Modulus of Elasticity (E'): 54 MPa
- Friction angle (Φ'): 31°
- Permeability: $k_x = k_y = k_z = 2.3\times10^{-5}$ m/s
- Poisson's Ratio (v): 0.3
- Initial void ratio: 0.546

c) Boundary Conditions

- X_{min}, X_{max}, Y_{min}, Y_{max}: Viscous boundaries
- Z_{min}, Z_{max}: Free (none specified)

3) Stone Column Configurations

Stone columns of various lengths (2 m, 4 m, 6 m, and 8 m) were evaluated under identical loading and soil conditions. The embankment was modeled with half symmetry, reducing the computation without loss of generality.

III. RESULTS AND DISCUSSIONS

The current study primarily focused on how varying stone column lengths, modulus of elasticity, and area replacement ratios influence the settlement and EPP behavior of the soil-structure system.

A. Effect of Stone Column Length

The embankment response was analyzed for different column lengths: 2 m, 4 m, 6 m, and 8 m. The key observations were:

- For the case with no columns, the maximum settlement was 0.0820 m at day 98, with EPP peaking at 14.49 kPa.
- With 2 m columns, the settlement decreased to 0.069 m, and EPP increased to 76.14 kPa initially, but decreased over time.
- With 4 m columns, the settlement was further decreased to 0.056 m and displayed both positive and negative pore pressures (−6.13 kPa at day 98), indicating stress redistribution.
- With 6 m and 8 m columns, the settlement was minimized at 0.055 m and 0.046 m, respectively, while significant negative pore pressures were observed, as low as −239.74 kPa, likely due to the Mandel–Cryer effect.

In conclusion, increasing the column length effectively reduces the settlement and promotes a faster dissipation of EPP, that is up to 6 m.

B. Effect of Modulus of Elasticity

The settlement and pore pressure behavior were studied for various modulus of elasticity E values, from 20,000 to 60,000 kPa, across all column lengths. The results were:

- For E = 60,000 kPa, the lowest settlements were observed across all lengths.
- EPP decreased significantly with an increasing stiffness, particularly for longer columns.
- For 2 m columns, increasing E from 20,000 to 60,000 kPa decreased the settlement from 0.072 m to 0.055 m.
- At 8 m column length, EPP varied from −150.43 kPa with E = 20,000 kPa to −80.98 kPa with E = 60,000 kPa.

It is, therefore, understood that a higher modulus of elasticity enhances the load transfer and minimizes the settlement. However, deeper installations display diminishing returns, likely due to the changes in the effective stress with depth.

C. Effect of Area Replacement Ratio

A parametric study was conducted for varying percent area replacement ratios A_r, such as 10%, 20%, 30%, and 40%, corresponding to column lengths of 2 m, 4 m, 6 m, and 8 m, respectively, (Table III).

TABLE III. AREA RATIO FOR STONE COLUMN AT DIFFERENT DEPTHS

Depth (m)	Condition	Area ratio (A_r)
2 m	1	0.10
4 m	2	0.20
6 m	3	0.30
8 m	4	0.40

Increasing the area ratio significantly reduced the vertical settlement and excess pore pressure. In addition, the maximum improvement was observed for Condition 1 with A_r = 10%, showing 93.8% decrease in settlement and 425.8% decrease in EPP compared to the untreated soil.

D. Settlement Behavior and Pore Pressure Dissipation

The settlement and lateral spreading are critical concerns in embankment stability. The stone columns not only improve the shear resistance, but also facilitate the drainage, leading to faster pore pressure dissipation, increased effective stress, and reduced long-term settlements.

The results (Table IV) show that the progressive reduction in deformation is observed with stiffer columns and greater depths. Additionally, the pore pressure dissipation was more pronounced at shallow depths, which is consistent with the Mandel–Cryer phenomenon.

TABLE IV. PEAK PERFORMANCE

Case	Settlement (m)	% Decrease	EPP (kPa)	% Decrease
Bench model	1.13	0	14.48	0
Condition 1	0.069	93.8	76.14	425.8
Condition 2	0.069	0	196.74	158.3
Condition 3	0.068	1.1	−158.49	180.5
Condition 4	0.062	8.0	−93.38	41.1

IV. CONCLUSIONS

The current study presents a comprehensive numerical investigation into the behavior of stone column-reinforced embankments over soft soil using a coupled finite element formulation. The analysis explores the effects of the stone column length, modulus of elasticity, and area replacement ratio on the settlement reduction and Excess Pore Pressure (EPP) dissipation.

The main conclusions drawn from the study are:

- Stone column length: The settlement significantly decreases with an increasing stone column length. A notable improvement in both the settlement and EPP behavior was observed up to a column length of 6 m beyond which the gains were marginal. This suggests an optimal length of 6 m for performance-efficiency balance.
- Modulus of Elasticity: An increase in the stiffness (modulus of elasticity) of the stone column material further enhances performance. The dissipation of EPP was more pronounced with stiffer materials, particularly at shallow depths, where the Mandel–Cryer effect was evident.
- Area Replacement Ratio: A higher area replacement ratio improves the overall stability of the embankment. The most significant performance was observed at an area ratio of 10%, where the vertical settlement decreased by 93.8% and EPP was reduced by over 425%.
- Pore Pressure and Depth: The dissipation rate of EPP decreases with depth. At shallower depths, the drainage paths provided by the stone columns are more effective, making the Mandel–Cryer effect more pronounced.
- Composite Ground Improvement: The stone columns increase the lateral confinement and shear strength, and act as vertical drains, thereby enhancing the overall stability of the embankments on weak soils. The numerical model validated with the Terzaghi's consolidation theory confirms the accuracy and reliability of the developed simulation framework.

This study contributes to the existing body of knowledge by validating a coupled soil-fluid finite element model through a comparison with Terzaghi's analytical solution and by further investigating the Mandel–Cryer effect in detail. Unlike prior works that focused on laboratory or simplified models, this study integrates the Cam-Clay constitutive behavior and highlights an optimal stone column length of 6 m for performance-cost balance. It stresses the effectiveness of the stone columns as a cost-efficient and performance-enhancing ground improvement technique. The finite element model incorporating coupled soil-fluid interaction enables engineers optimizing the design parameters to ensure the stability, serviceability, and durability of infrastructure on the soft soil foundations.

DATA AVAILABILITY

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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