Settlement Performance of an Embankment on Soft Clay Improved with Stone Columns, Encased Stone Columns and Granular Subbase: A Numerical Approach

[1]Gurthula Rakesh, [2]Darga Kumar N

[1]Post Graduate Student and [2]Associate Professor in Civil Engineering
JNTUH University College of Engineering, Science and Technology, Hyderabad, India
[1]rakeshgurthula@gmail.com , [2]ndkumar@jntuh.ac.in

Abstract

Embankments constructed on soft clay are prone to excessive settlement and deformation due to low shear strength and high compressibility. This study presents a finite element investigation using PLAXIS 3D to analyse the settlement of a 5 m high embankment with crest width of 16 m and side slopes of 1V:2H, constructed on soft clay (peat + clay) under untreated and improved conditions. Improvement methods considered include stone columns (SCs), geogrid encased stone columns (GESCs), and granular subbase (GSB) replacement, both independently and in combination. Combination includes peat replaced with GSB & clay treated with stone column and peat replaced with GSB & clay treated with encased stone column. Stone columns of 0.8 m diameter were installed at spacings of 3D (2.4 m), 2.5D (2.0 m), and 2D (1.6 m) to evaluate spacing effects, with geogrid encasement stiffness of 1000 kN/m providing lateral confinement. Numerical results revealed that untreated soft clay exhibited maximum settlement of 1.143 m. Ordinary stone columns reduced settlement by 20% (3D), 24% (2.5D), and 35% (2D), whereas GESCs further enhanced performance with 46% (3D), 47% (2.5D), and 62% (2D) reduction. GSB replacement alone achieved 82% reduction, while hybrid techniques such as GSB + SC (2.5D) and GSB + GESC (2.5D) delivered 86% and 88% reductions, respectively. The findings highlight that 2D spacing provides maximum settlement control, but 2.5D spacing offers the most economical balance between cost and performance. Overall, combined approaches, particularly GSB with geogrid encased stone columns, proved most effective in enhancing embankment stability and reducing long-term settlements.

Keywords: Soft clay, Embankment, Stone columns, Geogrid encased stone columns, Granular subbase replacement, PLAXIS 3D, Settlement reduction.

1 Introduction

Infrastructure development, particularly the expansion of highways, expressways, and railways, requires the construction of stable embankments. However, in regions with soft clay or peat deposits, embankments are prone to excessive settlement, low stability, and delayed consolidation due to the soil's high compressibility and low shear strength. Similar challenges have been reported in several field studies where untreated embankments exhibited settlements exceeding one metre, leading to cracking and serviceability issues (Shahu & Reddy, 2011; Ambily & Gandhi, 2007).

To address these problems, various ground improvement techniques have been introduced. Stone columns are widely used as they increase the composite stiffness of the soil and accelerate consolidation through radial drainage (Greenwood, 1970; Barksdale & Bachus, 1983; Priebe, 1995). However, in very soft soils, conventional stone columns may fail by bulging, limiting their effectiveness (Hughes et al., 1975). To overcome this limitation, geogrid encased stone columns (GESCs) have been developed, providing lateral confinement and enhancing load transfer efficiency. Numerical and experimental investigations have shown that encasement significantly improves settlement reduction and stability (Murugesan & Rajagopal, 2006; Murugesan & Rajagopal, 2010; Shahu et al., 2024).

Another effective approach is the replacement of weak upper layers with granular subbase (GSB), which provides immediate strength and reduces compressibility. GSB replacement alone has been demonstrated to control settlement effectively, while combined techniques such as GSB with stone columns or encased columns offer superior performance by addressing both shallow and deep soil weaknesses (Van Impe & De Beer, 1983; Castro & Karstunen, 2010).

In recent decades, finite element modelling has become an essential tool to evaluate the behaviour of embankments on soft ground. Software such as PLAXIS 3D enables realistic simulation of soil–structure interaction, accounting for staged construction and nonlinear soil behaviour (Raithel et al., 2005; Shahu & Reddy, 2011). Compared to conventional methods, numerical analysis provides more accurate predictions of settlement and deformation.

The present study focuses on the Settlement response of embankments on soft clay, improved with stone columns, geogrid encased stone columns, and granular subbase replacement. Using PLAXIS 3D, both individual and combined methods were analysed, with particular emphasis on the influence of stone column spacing (2D, 2.5D, and 3D). The objective is to quantify the settlement reduction achieved by different techniques and to identify the most effective and economical solution for embankments on weak soils.

2 Methodology

2.1 Numerical Modelling Approach

The numerical investigation was carried out using PLAXIS 3D, a finite element software developed specifically for geotechnical analysis. The study simulated the behaviour of a highway embankment constructed on soft clay under untreated conditions and with different ground improvement techniques. The model incorporated staged construction and consolidation to realistically represent field conditions.

2.2 Embankment Geometry

A 5 m high embankment with side slopes of 1V:2H, crest width of 16 m, and base width of 36 m was adopted. A uniform surcharge load of 15 kN/m² was applied to simulate traffic and structural weight. The embankment was constructed in two lifts of 2.5 m each to allow pore pressure dissipation and to capture deformation during staged construction. **Fig. 1** Schematic of embankment geometry showing crest width, side slopes, height, and foundation soil layers

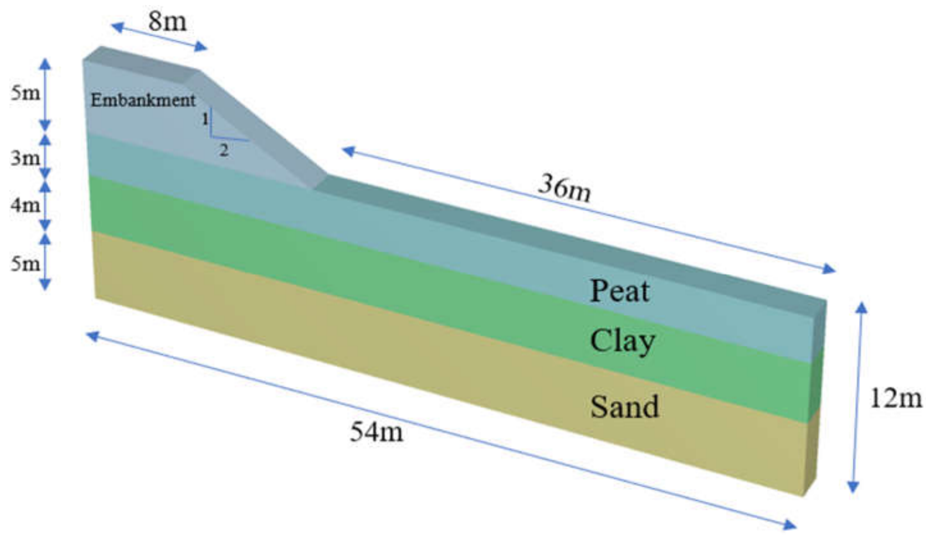


Fig. 1 Geometry of the modelled embankment

2.3 Soil Profile and Properties

The foundation soil consisted of two primary layers:

- **Soft clay (peat + clay):** Highly compressible, undrained shear strength < 25 kPa, modelled using the *Soft Soil* model.
- **Sand:** A dense underlying stratum providing support, modelled using the *Hardening Soil* model.

The groundwater table was assumed at 1 m below ground level to represent critical conditions. Soil parameters, including unit weight, modulus, cohesion, and permeability, were selected from published literature and standard references. **Tables 1 and 2** present soil input parameters and material properties of Embankment, stone column & GSB.

Table 1 Soil input parameters

S.No.	Parameter	Peat	Clay	sand
1	Thickness of each layer (m)	3	4	5
2	Material model	Soft Soil model	Soft Soil model	Hardening Soil
3	Drainage type	Undrained	Undrained (A)	Drained
4	Unit Weight (γ_{unsat}), kN/m^3	8	15	17
5	Saturated unit weight (γ_{sat}), kN/m^3	12	18	20
6	Initial void ratio, e_{int}	2.0	1.0	0.5
7	Modified compression index (λ*)	0.15	0.05	-
8	Modified swelling index (κ*)	0.03	0.01	-
9	Secant stiffness E_{50}^{ref} (kN/m^2)	-	-	35000
10	Young's modulus (E), kPa	-	-	-
11	Poisson's ratio ν	-	-	-
12	Tangential stiffness E_{oed}^{ref} ,(kN/m^2)	-	-	35000
13	Unloading and reloading stiffness E_{ur}^{ref} , (kN/m^2)	-	-	10.5*10^3
14	Power for stress-level dependency of stiffness (m)	-	-	0.5
15	Cohesion (c), kPa	2.0	1.0	0
16	Friction angle (ϕ) in Deg	23	25	33
17	Dilatancy angle (ψ) in Deg	0	-	3.0
18	Horizontal permeability (x direction) $\boldsymbol{K}_{HZ}$ (m/day)	0.1	47.52 x 10^{-3}	7.128
19	Vertical permeability $\boldsymbol{K}_{V}$ (m/day)	0.05	47.52 x 10^{-3}	7.128
20	Permeability change coefficient, Ck	1.0	0.2	1 x 10^{15}
21	Over-consolidation ratio	1.0	1.0	1.0
22	Pre-overburden pressure	5.0	0	0

Table 2 Material properties of Embankment, stone column & GSB

S.No.	Parameter	Embankment	Stone column	GSB
1	Thickness of each layer (m)	5	-	3
2	Material model	Hardening Soil	Mohr-Coulomb	Mohr-Coulomb
3	Drainage type	Drained	Drained	Drained
4	Unit Weight (γ_{unsat}), kN/m^3	16	19	19
5	Saturated unit weight (γ_{sat}), kN/m^3	19	20	20
6	Initial void ratio, e_{int}	0.5	0.5	0.5
7	Secant stiffness E_{50}^{ref} (kN/m^2)	25000	-	-
8	Young's modulus (E) kPa	-	35000	35000
9	Poisson's ratio ν	-	0.3	0.3
10	Tangential stiffness E_{oed}^{ref} (kN/m^2)	25000	-	-
11	Unloading and reloading stiffness E_{ur}^{ref} (kN/m^2)	75000	-	-
12	Power for stress-level dependency of stiffness (m)	0.5	-	-
13	Cohesion (c), kPa	1.0	1.0	1.0
14	Friction angle (ϕ) in Deg	30	35	35
15	Dilatancy angle (ψ) in Deg	0	5	5
16	Horizontal permeability (x direction) $\boldsymbol{K}_{HZ}$ (m/day)	3.499	10.37	10.37
17	Vertical permeability $\boldsymbol{K}_{V}$ (m/day)	3.499	10.37	10.37
18	Permeability change coefficient, Ck	1 x10^{15}	1 x10^{15}	1 x 10^{15}
19	Over-consolidation ratio	1.0	-	-
20	Pre-overburden pressure	0	-	-

2.4 Ground Improvement Techniques

The ground improvement techniques were modelled:

1. **Stone Columns (SCs):**
   - Diameter = 0.8 m
   - Length = 7 m (penetrating the soft clay into sand)
   - Spacing = 3D (2.4 m), 2.5D (2.0 m), and 2D (1.6 m)
   - Modelled using the *Mohr–Coulomb* model.
2. **Geogrid Encased Stone Columns (GESCs):**
   - Same dimensions as SCs
   - Encased with geogrid stiffness EA = 1000 kN/m
   - Same spacing variations (3D, 2.5D, 2D).
3. **Granular Subbase (GSB) Replacement:**
   - Top 3 m peat replaced with compacted granular fill
   - Modelled using *Mohr–Coulomb* parameters.
4. **Combined Improvements:**
   - GSB replacement + SCs (2D, 2.5D, 3D)
   - GSB replacement + GESCs (2D, 2.5D, 3D).

2.5 Simulation Cases

The following cases were analysed:

- Case 1: Untreated soft clay (reference).
- Case 2: Stone columns (SCs) with three spacings.
- Case 3: Geogrid encased stone columns (GESCs) with three spacings.

- Case 4: GSB replacement.
- Case 5: GSB + SCs (three spacings).
- Case 6: GSB + GESCs (three spacings).

3 Results and Discussion

3.1.1 Settlement behavior of an embankment constructed directly on untreated soft clay

The untreated soft clay foundation exhibited very high settlement under the embankment load. PLAXIS 3D analysis showed a **maximum settlement of 1.143 m** at the bottom of the embankment centre, with values gradually decreasing towards the side slopes. The vertical displacement contour confirmed that the weak peat + clay layer, with its high compressibility and low shear strength, could not withstand the applied loading. Such excessive deformation exceeds allowable settlement limits and would inevitably cause instability, cracking, and long-term serviceability issues in practice. **Fig. 2 and 3** present the total displacement of an untreated embankment from PLAXIS 3D out put and displacement verses time of an untreated embankment.

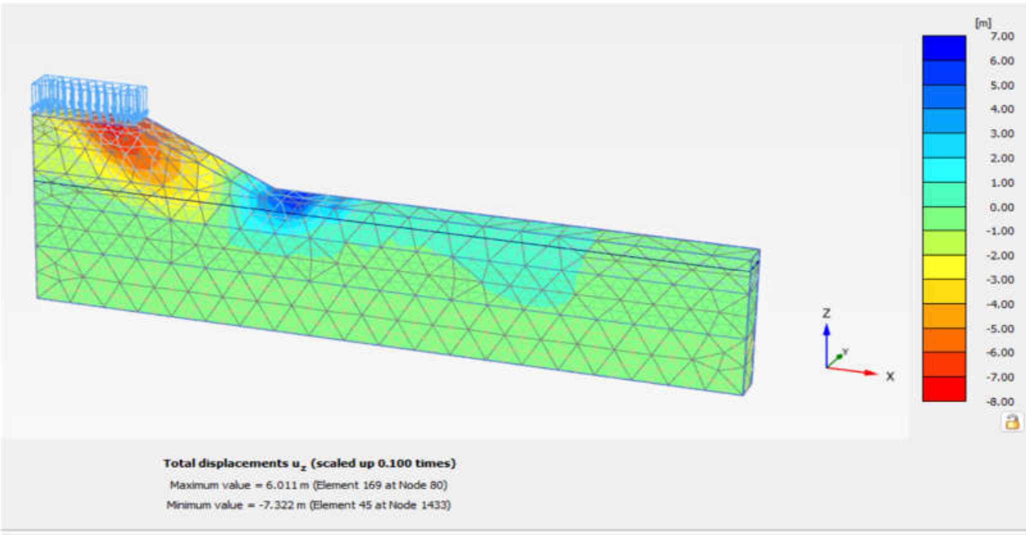


Fig. 2 Total displacement of an untreated embankment

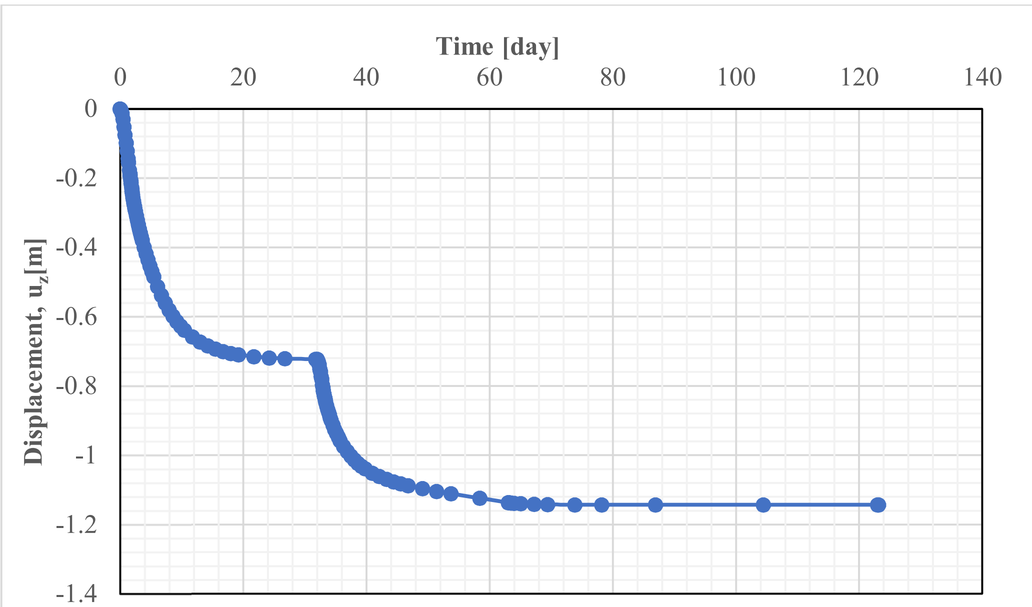


Fig. 3 Displacement verses time of an untreated embankment

3.1.2 Settlement behavior of an Embankment Foundation Soil Treated with Stone Columns, Geogrid Encased Stone Column, GSB, GSB + Stone Column & GSB + Encased Stone Column

Fig. 4 to 6 show the reduced settlements compared to untreated soft clay for different methods stone columns (SCs), geogrid encased stone columns (GESCs), granular subbase (GSB) replacement, and their combinations—were analysed to evaluate their effectiveness.

For stone columns (SCs) of 0.8 m diameter and 7 m length:

- Settlement reduced to 0.913 m at 3D spacing (20% reduction),
- 0.868 m at 2.5D spacing (24% reduction), and
- 0.739 m at 2D spacing (35% reduction).

For geogrid encased stone columns (GESCs) with the same configuration and geogrid stiffness of 1000 kN/m:

- Settlement reduced to 0.609 m at 3D spacing (46% reduction),
- 0.600 m at 2.5D spacing (47% reduction), and
- 0.433 m at 2D spacing (62% reduction).

For GSB replacement alone, the settlement reduced drastically to 0.205 m, corresponding to an 82% reduction from the untreated case.

For combined improvement measures:

- GSB + SCs (2.5D spacing): Settlement reduced to 0.162 m (86% reduction).
- GSB + GESCs (2.5D spacing): Settlement reduced to 0.132 m (88% reduction).

The results clearly demonstrate that GSB replacement provided the most significant settlement reduction among the single methods, while combined techniques achieved the highest overall performance. Although 2D spacing yielded the lowest settlement for SCs and GESCs, 2.5D spacing emerged as the most practical option due to its balance between effectiveness and construction economy.

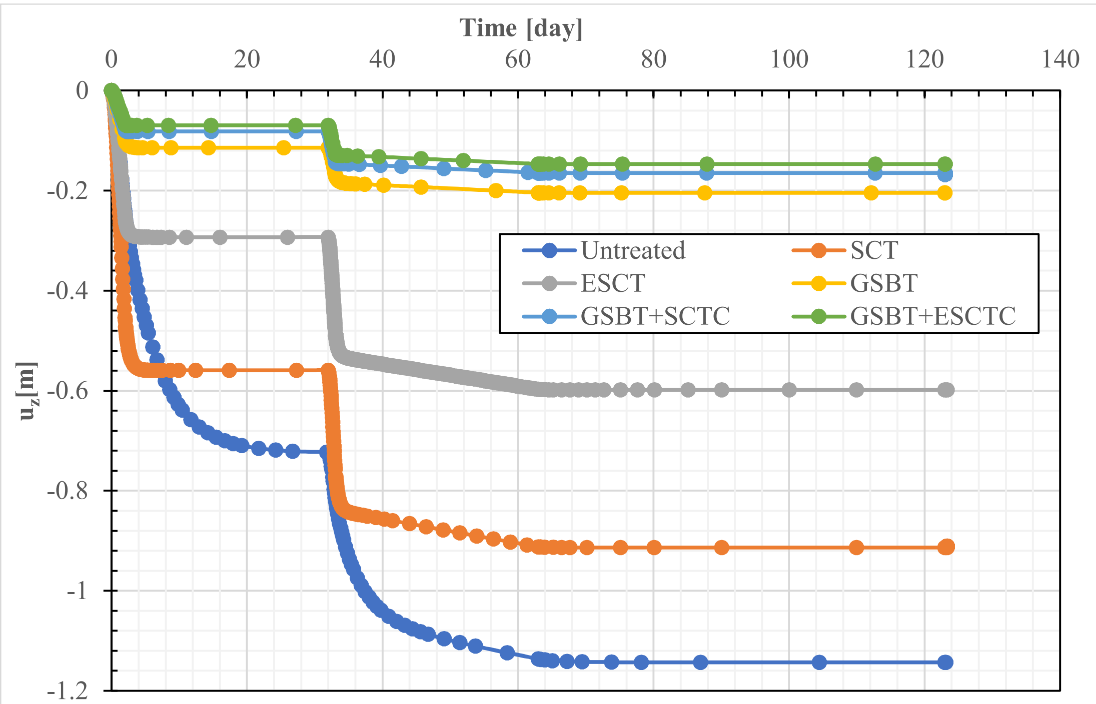


Fig. 4 Settlements at a midpoint of the embankment versus time for spacing of column at 3D

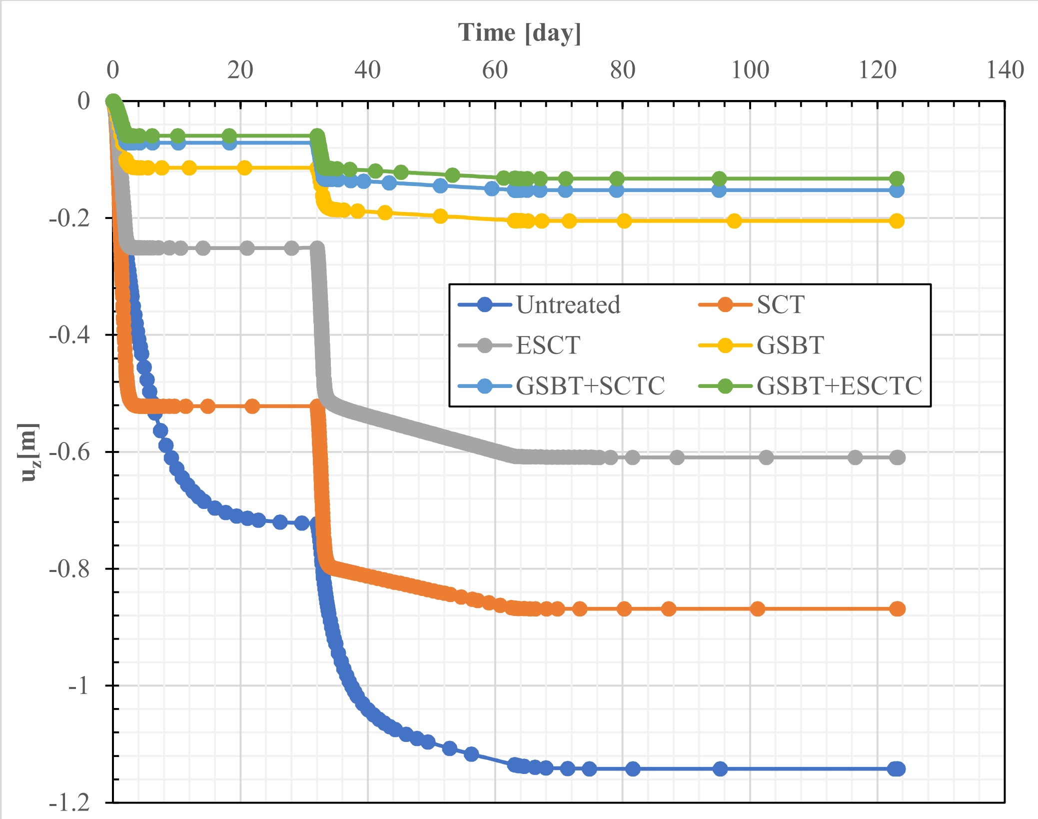


Fig. 5 Settlements at a midpoint of the embankment versus time for spacing of column at 2.5D

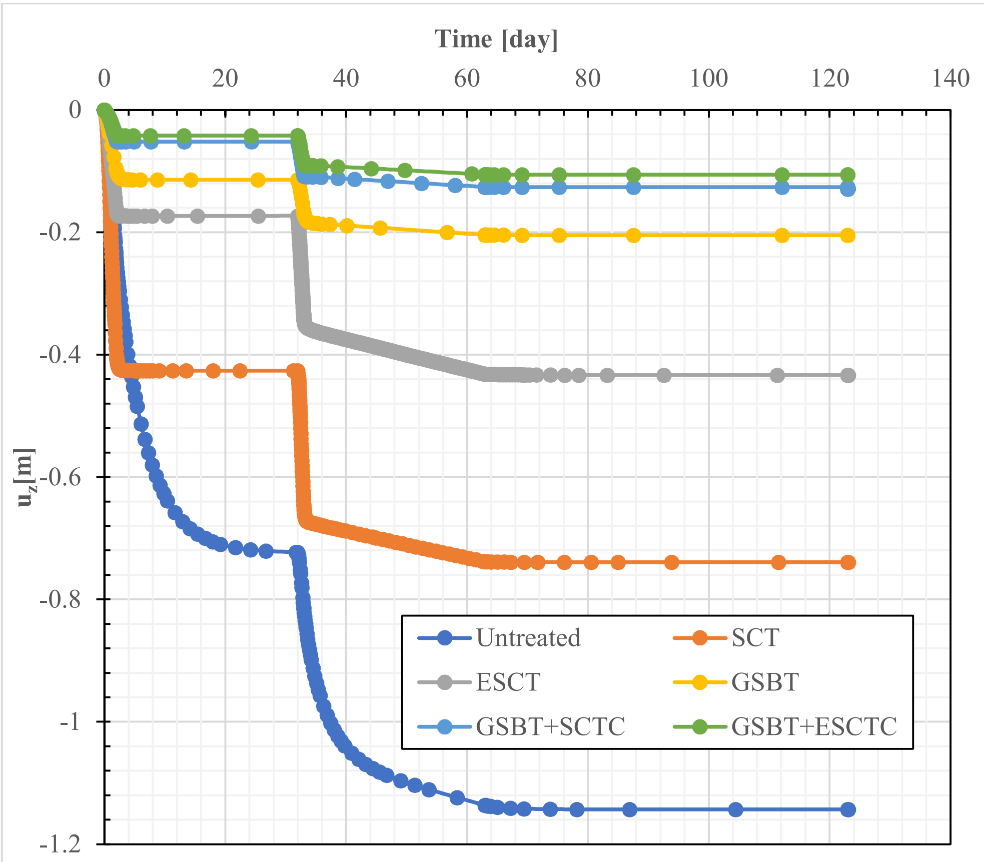


Fig. 6 Settlements at a midpoint of the embankment versus time for spacing of column at 2D

Table 3 presents the vertical displacement (settlement) values corresponding to different soil improvement techniques adopted for embankment foundation soil, considering three different spacings of stone columns (3D = 2.4 m, 2.5D = 2.0 m, and 2D = 1.6 m).

It can be observed that the untreated soil (peat + clay + sand) shows the maximum vertical displacement of 1.143 m, which remains constant for all column spacings, indicating the absence of improvement. When treated with ordinary stone columns, the settlement reduces significantly to values ranging between 0.739 m – 0.913 m, depending on spacing. The inclusion of geogrid encased stone columns further improves performance, reducing settlements to 0.433 m – 0.609 m, highlighting the beneficial effect of confinement.

Replacement of peat with granular subbase (GSB + clay + sand) shows a much lower settlement of 0.205 m, independent of spacing. A further improvement is observed when GSB replacement is combined with stone columns and treated clay + sand (GSB + SCTC), where settlements drop to as low as 0.147 m. The best performance is achieved when peat is replaced with GSB and encased stone columns along with treated clay + sand (GSB + ESCTC), with vertical displacements reduced to 0.106 m – 0.147 m, demonstrating the most effective technique in minimizing settlement.

Overall, the results clearly indicate that settlement decreases with reduction in column spacing and with the application of combined soil improvement measures. Among all methods, GSB replacement with encased stone columns (GSB + ESCTC) proved to be the most efficient in controlling settlement.

Table 3 Vertical Displacement values in meters

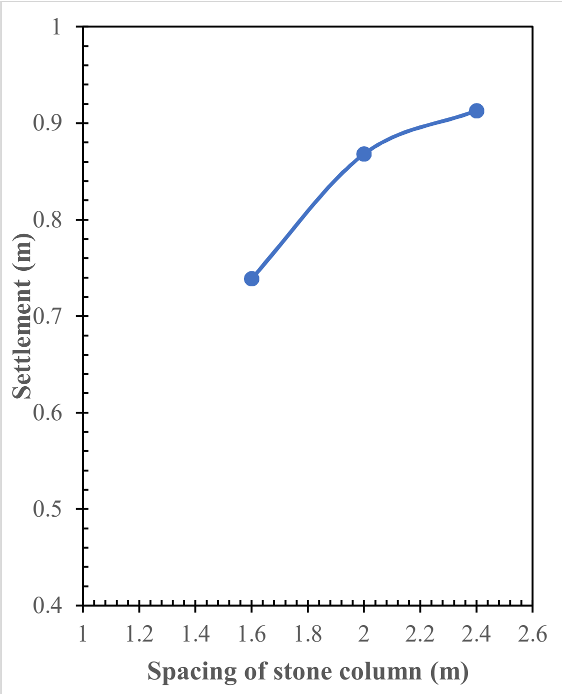
S.No.	Improvement Technique	Spacing of stone columns		
		3D (2.4m)	2.5D (2.0m)	2D (1.6m)
1	Untreated (Peat + clay +sand)	1.143	1.143	1.143
2	Treated with stone column	0.913	0.868	0.739
3	Treated with encased stone column	0.609	0.600	0.433
4	Peat replaced with granular subbase (GSB +clay +sand)	0.205	0.205	0.205
5	Peat replaced with GSB+ Stone Column treated clay + Sand (GSB + SCTC)	0.165	0.152	0.147
6	Peat replaced with GSB+ Encased Stone Column treated clay + Sand (GSB + ESCTC)	0.147	0.132	0.106

3.1.3 Effect of spacing of stone on settlement

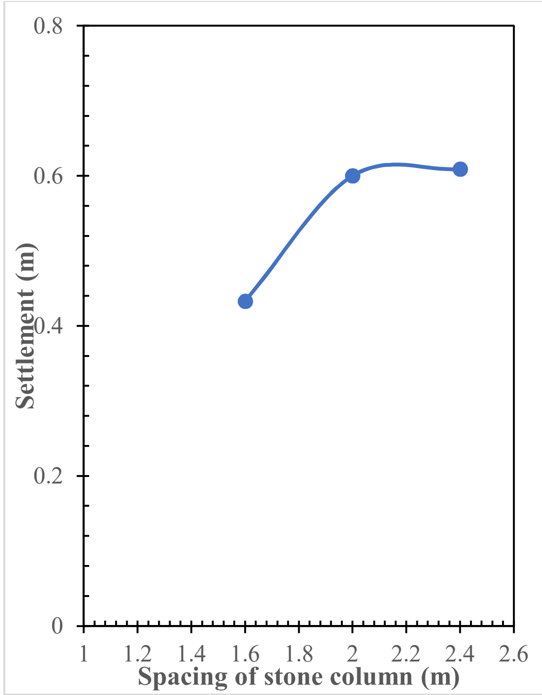
Fig.7 shows the influence of stone column spacing on embankment settlement evaluated by considering three configurations: **3D (2.4 m), 2.5D (2.0 m), and 2D (1.6 m)**. The results clearly demonstrate that decreasing the spacing between stone columns significantly reduces settlement due to enhanced composite stiffness and improved stress distribution.

The trend indicates that closer spacing (2D) consistently provided the highest settlement reduction for both SCs and GESCs. However, the 2.5D spacing condition delivered an optimal compromise, offering substantial settlement reduction at a lower construction cost compared to 2D spacing.

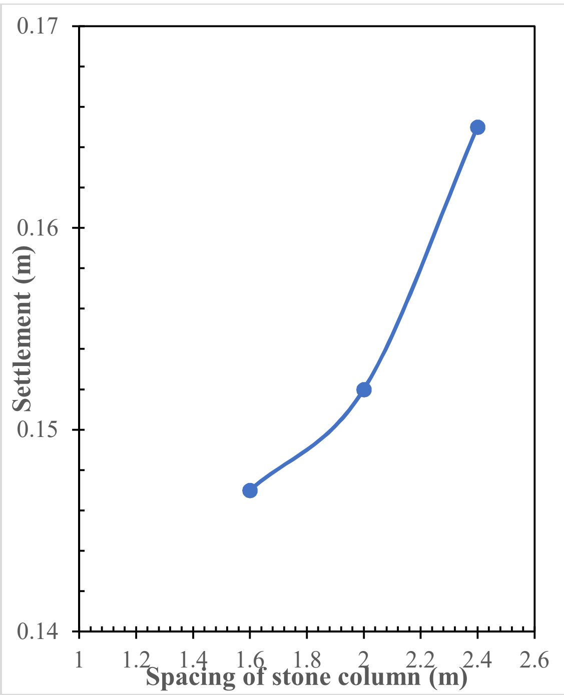
This analysis confirms that stone column spacing plays a critical role in settlement control, and that geogrid encasement further enhances the efficiency of the system.



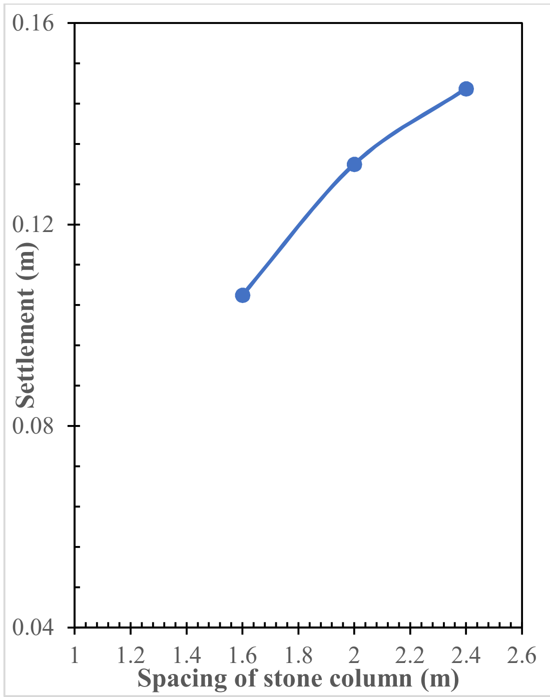
(a)



(b)



(c)



(d)

Fig.7 Settlement versus spacing of stone column (2D, 2.5D & 3D) for different improvement techniques (a) Treated with stone column, (b) Treated with Encased stone column, (c) GSB + SCTC and (d) GSB + ESCTC

4 Conclusions

This study investigated the settlement behaviour of embankments founded on untreated soft clay and improved using stone columns, geogrid encased stone columns (GESCs), granular subbase (GSB) replacement, and their combinations through PLAXIS 3D finite element analysis. Based on the results, the following conclusions are drawn:

1. The untreated soft clay foundation exhibited **excessive settlement of 1.143 m**, far beyond permissible limits, confirming the need for ground improvement measures.
2. Ordinary stone columns reduced settlement by **20% (3D spacing), 24% (2.5D spacing), and 35% (2D spacing)**. Closer spacing improved performance, but 2.5D spacing offered a better cost–performance balance.
3. Geogrid encased stone columns (GESCs) provided enhanced settlement control, with reductions of **46% (3D), 47% (2.5D), and 62% (2D)**. The geogrid confinement significantly increased load transfer efficiency and prevented column bulging.
4. GSB replacement alone proved highly effective, reducing settlement by **82%**, owing to the elimination of weak peat material and replacement with compacted granular fill.
5. Combined techniques achieved the greatest overall performance, with **GSB + SCs (2.5D) reducing settlement by 86%** and **GSB + GESCs (2.5D) reducing settlement by 88%**.
6. Comparative analysis confirmed that while **2D spacing minimizes settlement**, **2.5D spacing remains the most practical choice**, offering substantial reduction at lower construction costs.
7. Among all methods, the **GSB + GESC combination** emerged as the most effective and economical ground improvement solution for embankments on weak clayey soils.

REFERENCES

1. Ambily, A. P., and Gandhi, S. R. (2007). Behaviour of stone columns based on experimental and FEM analysis. Journal of Geotechnical and Geoenvironmental Engineering, 133(4), 405–415.
2. Barksdale, R. D., and Bachus, R. C. (1983). Design and construction of stone columns. Report No. FHWA/RD-83/026. Federal Highway Administration, Washington, DC.
3. Castro, J., and Karstunen, M. (2010). Numerical modelling of stone column reinforced foundations. International Journal of Geomechanics, 10(3), 110–123.
4. Greenwood, D. A. (1970). Mechanical improvement of soils below ground surface. Ground Engineering, 3(6), 42–50.
5. Hughes, J. M. O., Withers, N. J., and Greenwood, D. A. (1975). A field trial of the reinforcing effect of a stone column in soil. Geotechnique, 25(1), 31–44.
6. Murugesan, S., and Rajagopal, K. (2006). Geosynthetic-encased stone columns: Numerical evaluation. Geotextiles and Geomembranes, 24(6), 349–358.
7. Murugesan, S., and Rajagopal, K. (2010). Studies on the behaviour of single and group of geosynthetic encased stone columns. Journal of Geotechnical and Geoenvironmental Engineering, 136(1), 129–139.
8. Priebe, H. J. (1995). The design of vibro replacement. Ground Engineering, 28(10), 31–37.
9. Raithel, M., Kirsch, F., and Kirsch, K. (2005). Deep vibro techniques: Ground improvement by vibratory methods. Ground Improvement, 9(3), 151–162.
10. Shahu, J. T., and Reddy, Y. R. (2011). Settlement and bearing capacity of stone column improved ground. Geotechnical and Geological Engineering, 29(2), 329–342.
11. Van Impe, W. F., and De Beer, E. (1983). Improvement of soft soils by stone columns. Proc. 8th European Conference on Soil Mechanics and Foundation Engineering, Helsinki, 309–312.