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Effect of Construction Parameters on the Behaviour of Embankment Resting Over Soft Soil Improved with ESC

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Abstract. The construction of embankments on soft soil poses severe challenges to their stability due to the characteristics of the soft soil. Therefore, to overcome the issues of excessive settlement and stability, the soft soil may be improved by including an encased stone column (ESC). Construction features including the stiffness of the encasement material, column length, and encasement length have a significant impact on how an embankment resting on soft soil behaves when modified with ESC. The impact of these construction characteristics on the behaviour of the embankment was therefore examined numerically in the current study using Plaxis 3D. The soft soil was represented by the soft soil (SS) model, and the stone column, embankment, and sand platform were represented by the Mohr-Coulomb (MC) model. The study results confirm that the settlement decreases with increased encasement stiffness and ESC length. In addition, load transfer mechanism, development of the plastic points, and stress concentration ratio are also significantly dependent on the mentioned parameters.

Keywords: Embankment; Consolidation; ESC; Settlement; Plaxis 3D.

1 Introduction

The world population is increasing rapidly, and approximately 60% of the world's total population (~4.7 billion) resides in Asia [1]. To accommodate this tremendous population growth in Asia, large numbers of infrastructure are required. Most Asiatic countries are developing rapidly and constantly working to bring their population out of poverty [2]. Therefore, the available land has to be judiciously utilized to meet the infrastructure requirement and food security. This poses serious concerns regarding the suitable land for the infrastructure projects, and most of the time, it has to be built on sites not suitable for the infrastructure [3]. Whenever we encounter problematic soils for the proposed infrastructure, the probable alternatives are to abandon the site, replace the unsuitable soils with suitable ones, modify the existing ground and design the structure accordingly [4]. Amongst mentioned alternatives, the most widely used alternative is employing suitable strategies for improving the ground to enhance their characteristic properties [3-4]. The use of geosynthetic materials [5-6], installation of vertical drains [7-8], stone columns [9], electrokinetic treatment [10-11] and chemical stabilization [12] are few of the widely used ground enhancement methods. The application of stone columns

(SCs) has been widely recognized in the recent decade to increase the soil's ability to carry more load, accelerating settlement and liquefaction mitigation (Barksdale and Bachus 1983). The SCs are constructed in soft soils with undrained shear strength lying between 15 to 35 kPa, and part of the soft soil is replaced with a material with an elastic modulus 10 to 20 times that of soft soil [9]. The enhancement in the load carrying capacity of the soft soil reinforced with SCs is achieved by the confinement of the column material by the surrounding soil [13-16]. If the soft soil's strength is less than 15 kPa, the restraint provided is insufficient, and the column will bulge. Therefore, the stone column is encased with suitable materials to provide additional confinement, and the column is collectively called encased stone column (ESC).

Various studies have assessed the performance after including ESC in soft soils [17-21]. Studies have also investigated alternate materials (brick rubble, tire chips, fly-ash, for column construction [20]. Pandey et al. [22] modelled single SC and adjacent soft soil as a unit cell to determine the impact of encasement and column length, and encasement stiffness and reported that these parameters significantly contribute to the performance. Further, studies have been conducted using a different material for encasement construction [20]. Pandey et al. [23] investigated the influence of uniquely prepared conductive jute geotextile and coupled it with electrokinetics. The study observed that coupling with electrokinetics quickens the consolidation process along with altering the physicochemical characteristics of soft soil. Through a centrifuge model test, Chen et al. [24] examined the impact of the encasement's strength and reported significant improvements in the stress concentration ratio, settlement reduction, and speedy pore pressure elimination. Gao et al. [25] revealed through an experimental model study that there was a substantial decrease in stresses in the soil for soil with the inclusion of ESC under cyclic loading. Yoo and Abbas [26] studied the impact of cyclic stress on the functionality of soft soil enhanced with ESC. They found that the functionality significantly improved over that under static loading conditions.

It is clear from the discussion above that different feature like the stiffness and length of the ESC dictates how an embankment resting over soft soil with ESC behaves. Furthermore, very few studies in the literature explain how an embankment resting on soft clay responds over time and how ESC enhances this. Therefore, the current work aims to comprehend how the encasement features and stiffness affect the behaviour of an embankment lying on soft soil and enhanced with ESC. The performance of embankment during and after construction was studied by considering various construction parameters.

2 Numerical Simulation and Validation

In this study, a hypothetical road embankment six-meter high and 44 m wide makes a slope of 26.57° with the ground using Plaxis 3D [27]. The embankment was built over soft soil and had a 9.5 m thickness. On top of the soft soil was a layer of sand that was 0.5 meters deep. The column has a radius of 32.5 cm constructed at a spacing of 227 cm in a square pattern. The groundwater is assumed to be underneath the sand layer. The arrangements mentioned here are close to the arrangements adopted by Yoo [28]. Using the embankment's symmetry and reducing calculation time, half of the embankment is modelled as shown in Fig. 1.

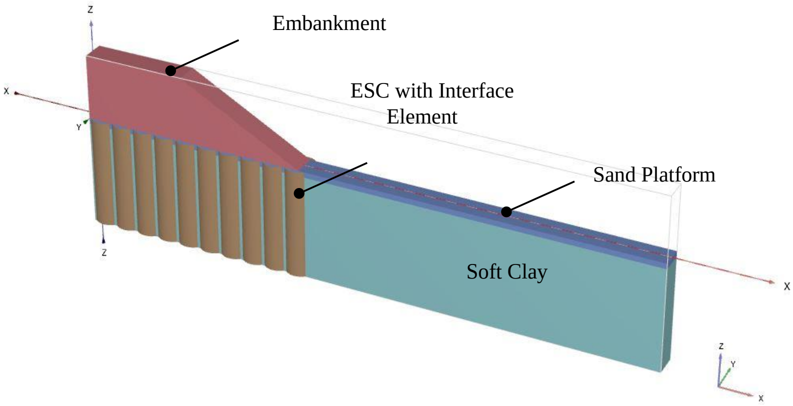


Fig. 1. Numerical model of the embankment with full-length ESC.

The embankment was constructed in three lifts, with each lift (2 m thick) comprising two periods, i.e., construction (*Cp1*, *Cp2*, and *Cp3*) trailed by a rest period (*Rp1, Rp2).*

Table 1 A list of the material properties used in the investigation

Properties	SC	Soft Soil	Sand layer	Em-bankment
$\gamma(kN/m^3)$	13.24	17.26	13.24	20
$E(kPa)$	38845	2000	10000	20000
v	0.35	0.35	0.33	0.30
$c'(kPa)$	0	6.46	0	5
$\varphi'(0^o)$	49.37	27.58	34.09	30
$\Psi(0^o)$	19.37	-	-	-
C_c	-	0.14	-	-
C_s	-	0.01	-	-
$k_h(m/day)$	3.214	4.401×10^{-4}	1.693	1
$k_v(m/day)$	3.214	4.401×10^{-4}	1.693	1

Each lift would need to be built in twenty days, trailed by 30 days of consolidation (rest period), during which any excess pore pressure would be partially expelled. After the embankment's construction was complete, the soft clay reinforced with ESC was left to solidify as a result of the loading caused by the embankment till the surplus pore pressure was diminished to 0.01 kPa. According to symmetry, the hydraulic and displacement boundary conditions are selected. At the bottom, a complete fixity was offered, and the model is said to have no flow and no deformation in the direction perpendicular to the symmetry plane [14-15]. Table 1 depicts a summary of material properties adopted in the present work from the study of Pandey et al. [15]. In addition, modelling of geotextile and soil-geotextile interaction was carried out in accordance with Pandey et al. [15]. The strength reduction factor (R_{inter}) is the primary interface parameter used for Soft-Soil and Mohr-Coulomb material model. For the soft clay, drainage layer, SC and embankment, the R_{inter} value adopted follows Aljanabi et al. [29]; however, for the encasement-soil interface, it is 0.7, following Chen et al. [30]. Table 2 depicts the construction parameters varied in the present study.

Table 2 Variables used in the numerical analysis

Description	Column length (m)	Encasement	
		Length (m)	Stiffness (kN/m)
Soft Soil	-	-	-
SC	10	-	-
ESC	10	10	0.5, 1, 3 and 5 thousand
ESC	10	4, 7, 9, 10	3 thousand
ESC	4, 6, 8, 10	-	3 thousand

The in-field findings of Almeida et al. [19] validate the modelling approach given in this paper. The cited study by Almeida et al. [19] contains the specifics of the embankment building time and the material characteristics for the chosen material model.

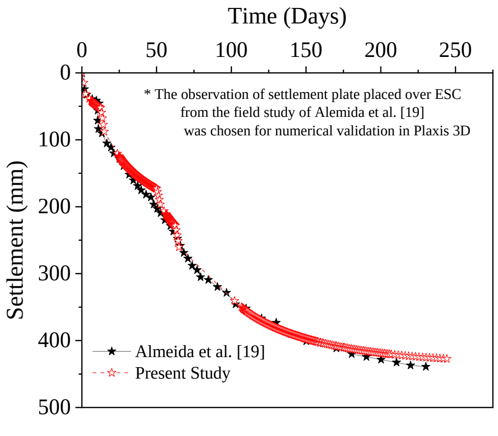


Fig. 2. Validation of modelling process

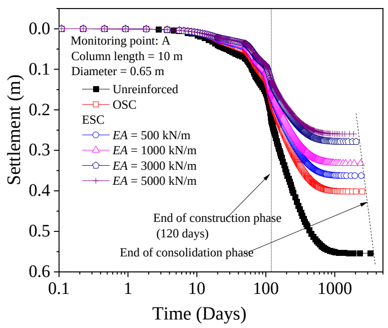
Fig. 2 shows the response of the present study compared with the referred results of Almeida et al. [19]. The settlement was found to vary by less than 1% most of the time. At the end of the third lift of the embankment, a difference of up to 12 percent is also seen. This shows that the selected modelling approach is appropriate for simulating soft soil with ESC and that the current model is in good accord with the aforementioned field findings.

3 Result and Discussions

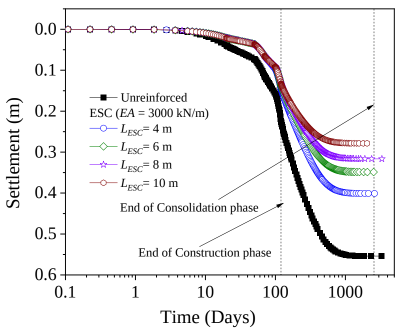
3.1 Settlement Behaviour

Fig. 3 demonstrates the settlement variation incorporating the influence length of encasement and ESC and encasement stiffness. As observed in Fig. 3(a), after the completion of embankment construction, the settlement for the soft soil is 0.224 m. With the insertion of SCs, the settlement declines to 0.179 m. A further drop was observed in after encasing the SCs. The settlement depends on the encasement stiffness, and it declined to 0.126 m from 0.162 m with a corresponding increase in encasement stiffness of 500 to 5000 kN/m. In contrast, for stiffness over 3000 kN/m has a much less impact on settlement reduction. Similar trends can be seen in the settlement after the consolidation phase. Therefore, it can be concluded that for the selected configuration and soil types, 3000 kN/m is the ideal encasement stiffness to produce a higher reduction in a settlement.

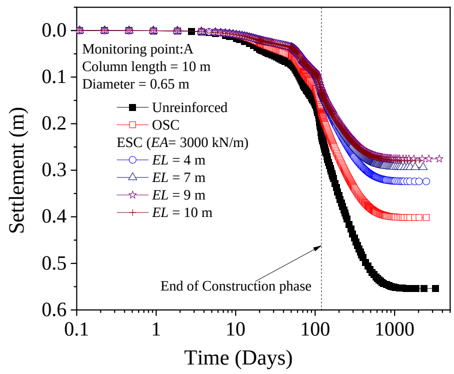
Further, from Fig. 3(b), a substantial decline in the settlement is detected with an increment in the ESC length (L_{ESC}) than soft soil. After the completion of embankment construction, the decline in the settlement is roughly 35% to a level of 0.145 m for a 4 m length of ESC. The settlement further declines with an increase in length, and the decline is not significant for the LESC beyond 6 m. For the 10 m length of ESC, the settlement at the conclusion of the consolidation phase following the building of the final lift is 52% higher than the settlement at the conclusion of the final lift. Therefore, the entire length column outperforms the other lengths.



(a)



(b)



(c)

Fig. 3. Settlement variation of incorporating the impact of (a) stiffness of encasement, (b) ESC length, and (c) length of encasement

As observed from Fig. 3(c), using geotextile to encase the SCs has dramatically reduced the settlement of soft soil with ESC. For instance, the final lift of the embankment building has reduced settlement to 0.133 m from 0.179 m while enclosing SCs up to 4 m from the top of the column. The final settlement, however, is significantly influenced by the length of the encasement. Due to an increase in encasement length from 4 to 10 meters, the final settlement decreased from 0.324 meters to 0.279 meters. Beyond 7 m, the encasement length has a significantly reduced (4%) impact on settlement reduction.

3.2 Vertical Stress Distribution

The effects of ESC length and encasement stiffness on the vertical stress distribution on the surrounding soil and SC/ESC are shown in Fig. 4. Due to the increased geostatic force brought on by the construction of the embankment, the effective vertical stress of soft soil increases; however, the amount of this increase varies depending on the embankment's design. It is greatest beneath the crest of the embankment and progressively gets smaller as it approaches the toe of the embankment. In comparison to soft soil alone, the vertical stress experienced by soft clay following ESC incorporation was significantly lower. The ESC length and the stiffness of the encasement regulate how much additional effective stress is experienced by the ESC/SCs and subsequently lessen the stress on the soft soil.

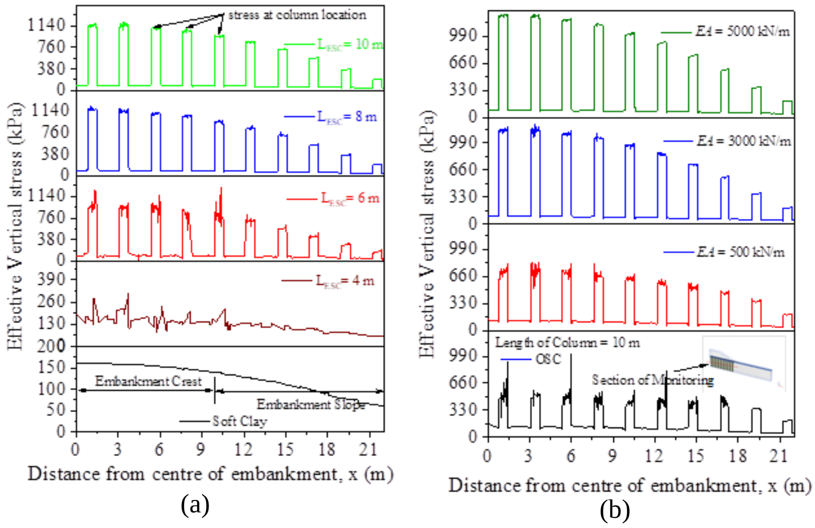
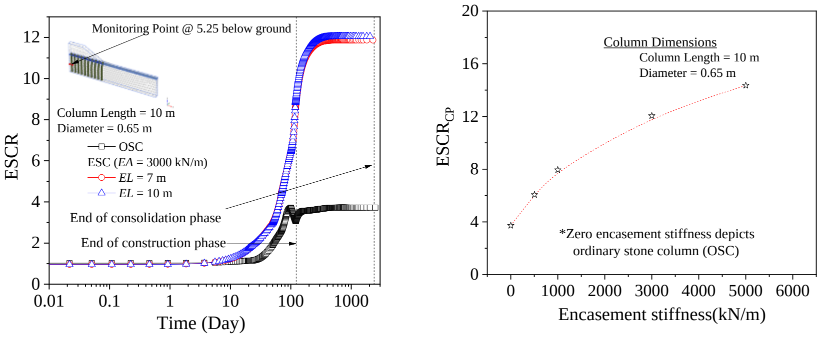


Fig. 4. Impact of (a) ESC length and (b) stiffness of encasement on vertical stresses

Further, the variation of stresses experienced by the column and adjacent soft soil is expressed in the effective stress concentration ratio (ESCR). Fig. 5(a) illustrates the ESCR variation of ESC and SCs. The ESCR remains constant (almost one) for the first ten days of embankment construction, but as time goes on, the ESCR rises because columns share increasing stresses compared to adjacent soft clay.

Interestingly, after the construction of the embankment, a sharp decline in ESCR for the SCs case can be noticed, indicating that much more considerable stresses were transferred to the neighbouring soil. However, for the ESC case, the ESCR upsurges considerably compared to SCs. Furthermore, there was no decline in ESCR, indicating that the ESC is more effective than the SCs in the reinforcement mechanism. The performance could be enhanced even by only partially encasing the SCs. The impact of stiffness of



(a)

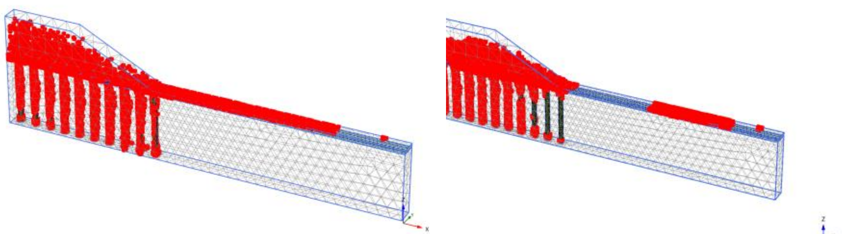
(b)

Fig. 5. Impact of (a) ESC length and (b) stiffness of encasement on the ESCR

encasing material on the ESCR after the completion of the consolidation period is expressed as ESCR$_{CP}$ and is revealed in Fig. 5(b). With an increase in the stiffness of the encasing material, the ESCR$_{CP}$ can be shown to increase considerably. For example, ESCR$_{CP}$ has improved by 63% through the encasing of SCs with an encasement material of 500 kN/m stiffness. The findings show that when an SCs was enclosed in a stiff enough geosynthetic material, the embankment load was predominantly distributed to the column (ESCs), causing less stress on the neighbouring soil.

3.3 Formation of Plastic/Failure Points

Fig. 6 depicts the failure points for the ESC case after accomplishment of the construction and consolidation period. The plastic points can be seen in three separate places: at the soil-column interface, embankment and the sand layer. On the other hand, pore pressure ejection causes the plastic point's surface area to decrease. Compared to columns near the toe, the failure points are more intense around the column in the embankment.



(a)

(b)

Fig. 6. Formation of plastic points for L_{ESC} = 10 m after (a) construction and (b) consolidation period is over

4 Conclusions

The present study studied the consequence of construction characteristics on the behaviour of embankment with inclusions of SCs/ESC. From the study following inferences can be drawn:

- For the selected arrangement and material properties, the settlement of soft soil after completion of embankment construction was 0.224 m and declined by approximately 20% to 0.179 m after the inclusion of SCs. Further decline of 9 to 30% is observed by encasing the SCs with a geotextile having stiffness lying between 500 to 5000 kN/m respectively. No substantial decrease in the settlement was noted for ESC cases beyond 3000 kN/m of stiffness and length of encasement beyond 7 m.
- The ESCR varies with variation ESC and encasement length and encasement stiffness.
- The plastic points are confined in the three regions, and the area decreases after the consolidation time than after the construction of the embankment is over.

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