

Parametric analysis of floating columns and basal reinforcement for embankments on soft soils

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ABSTRACT: The design of foundations on soft soils poses significant challenges for geotechnical engineers, requiring a performance-based design approach to balance settlement limits and bearing capacity while ensuring safety and cost-effectiveness. Among various solutions, the partial replacement of soft soils with floating or end-bearing stone columns has proven effective, resulting in a composite foundation with enhanced load-bearing capacity and reduced compressibility. The success of this technique depends on factors such as the improvement area ratio, which in turn is a function of the column diameter and spacing, and the contribution of geogrid basal reinforcement of the embankment. This study investigates the combined influence of floating columns and basal reinforcement with geogrid on the performance of embankments built on soft soils. A parametric study is conducted to evaluate the effects of column length, diameter and spacing, as well as the stiffness of the basal reinforcement, on the stability and settlement reduction of the foundation system. The analysis focuses on a 30 m deep soft soil deposit in Salamanga embankment, along the Maputo - Ponta do Ouro Road in Mozambique, where pre-fabricated vertical drains were installed, and settlements were monitored over 585 days during the construction phase. The study begins by analytically estimating the optimum improvement area ratio and corresponding column dimensions, ensuring both adequate bearing capacity and settlement reduction (according to the allowable residual settlement specified in the project). Finite element models are then used to simulate the behaviour of the reinforced foundation, considering triangular pattern with different spacing between columns, and a set of stiffness values of the basal reinforcement to assess their effect on the behaviour of the embankment. Results from the parametric study show the critical influence of column length, diameter and spacing and, also, of the geogrid stiffness on the performance of embankments on reinforced foundations.

KEYWORDS: Floating stone columns, improvement area ratio, geogrid basal reinforcement, soft soils.

1 INTRODUCTION

The use of stone columns as ground improvement measure for soft soils aims at increasing the bearing capacity of the foundation, accelerating the consolidation and reducing residual settlements. In the case of embankments, the reinforcement of the soft ground is often combined with geogrid reinforcement at the embankment base, leading to a better load-transfer between the columns and less differential settlements on the embankment crest.

According to Guetif, Bouassida and Debats (2007), columns installed by vibro-replacement improve the ground strength and stiffness by a factor ranging from 1.5 to 5 the pre-treatment values, depending on the soil type. Moreover, Vautrain (1980) reported significant improvement of the undrained cohesion of a treated ground obtained from field vane tests, which depicts the fact that bearing capacity failure can be of minor importance when designing foundations reinforced with stone columns.

Therefore, to achieve a cost-effective solution, it is thus important to estimate the improvement area ratio required to meet settlement requirements, provided that the bearing capacity is satisfied.

In this context, the present paper addresses the analysis of parameters governing the improvement area ratio η , namely: column spacing/diameter ratio (s/d_c) and column length (H_c). Additionally, it evaluates the influence of the geogrid basal reinforcement stiffness on the stress concentration factor and settlement reduction.

For this purpose, the study considers a section of the Maputo - Ponta do Ouro road embankment in Mozambique, on which wick drains were installed and the settlements were monitored from the beginning of construction in 2016, over 585 days. First, an optimum improvement area ratio is estimated analytically and then, numerical calculation is carried out to analyse the behaviour of the reinforced ground combined with

the geogrid basal reinforcement, as presented on the following sections.

The soil profile of the study comprises soft clays through 30 m deep, and the initial soil properties are as described by (Dete and Quadros, 2024).

2 METHODOLOGY

2.1 Analytical approach for optimizing the improvement area ratio

The improvement area ratio is generally defined as the ratio between the total cross-sectional area of the column reinforcement and the foundation loaded area. As discussed by Bouassida and Hazzar (2012), the optimal improvement area ratio is estimated by first predicting a lower bound value compliant with the allowable bearing capacity (Equation (1)).

$$\eta_{min} = \frac{F_{rs} \cdot q - \sigma_{ult,s}}{\sigma_{ult,c} - \sigma_{ult,s}} \quad (1)$$

where:

F_{rs} – Global factor of safety of the reinforced soil (between 1 and 3);

q – Assumed uniformly applied load;

$\sigma_{ult,s}$ – Ultimate bearing capacity of the soft soil;

$\sigma_{ult,c}$ – Ultimate bearing capacity of the columns.

The ultimate bearing capacity of the soft soil is estimated according to the classic Terzaghi equation. For the stone column, it depends first on its passive earth pressure coefficient, and therefore on its friction angle, and second on the cohesion of the surrounding soil.

Plugging the η_{min} into Equation (2) leads to an estimate of the upper bound limit of the short-term settlement of the reinforced foundation δ_{rs}^+ .

$$\delta_{rs}^+ = \frac{q_{all} \cdot H_c}{\eta E_c + (1 - \eta) \cdot E_s} \quad (2)$$

where H_c denotes the length of the stone columns.

If the short-term settlement target of the reinforced soil, for instance predicted based on the anticipated average degree of consolidation at the end of construction, is not greater than its upper bound limit, then the estimated η_{min} satisfies both bearing capacity and settlement requirements, and is then η_{opt} . Otherwise, η_{max} is estimated from Equation (3), increasing the columns length successively. This implies more short-term settlement due to almost immediate consolidation of the reinforced layers, and less long-term (residual) settlement resulting from the consolidation of the unreinforced layers.

$$\eta_{max} = \frac{(q_{all} \cdot \frac{H_c}{\delta_{rs}^+}) - E_s}{E_c - E_s} \quad (3)$$

2.2 Numerical calculations

After estimating the optimal improvement area ratio analytically, the behaviour of the foundation is simulated on Plaxis 2D considering a plane strain model with 15-node triangular mesh. In this case, the columns were modelled by equivalent trenches, as presented by (Mnaouar, Bouassida and Tabchouche, 2015).

The soil around the columns adopts the Mohr-Coulomb model with drained stiffness parameters and undrained shear strength. Meanwhile, the unreinforced ground adopts the Soft Soil model with undrained behaviour.

At this stage, the influence of the geogrid basal reinforcement stiffness is also evaluated for two different column spacing.

3 CASE STUDY

3.1 Background

The proposed parametric study considers the reinforcement of a thick soft soil deposit with stone columns to support a road embankment of 6.7 m design height and slopes 1V:1.5H. The soil profile comprises mostly fat clays with a total thickness of 40 m, overlying a layer of highly weathered mudstone. The initial undrained shear strength of the soft soil was 12 kPa.

For the existing construction, the maximum allowable residual settlement of the road pavement was defined as 0.5 m and is expected to be reached 6 years after end of construction, reason why the Managing Authorities refill the pavement periodically on the sections with considerable differential settlements. To account for large predictable long-term settlements, this study suggests a staged construction of an embankment of 8.0 m of height, applying a uniform load of 146 kPa.

The analytical approach assumes a construction period of two years, corresponding to an average degree of consolidation of approximately 27% for the unreinforced layers. Following (Vautrain, 1980), the improved undrained shear strength of the treated ground is taken as 40 kPa.

The Young's modulus of the soft soil varies between 3,000 kPa and 6,000 kPa, while for the stone columns a modulus of 40,000 kPa and a friction angle of 40° are adopted. A global safety factor of 1.5 is considered for the reinforced foundation system.

3.2 Estimate of the optimal improvement area ratio

Implementing the Equation 1 presented before, a minimum improvement area ratio of 6.7% was obtained. Then, the length of the column was successively increased on Equation (2) while checking the estimated residual settlement that results from the consolidation of the unreinforced layers.

As can be derived from Figure 1, column lengths greater than 16 m require an area ratio greater than 35% of the soft ground, which can imply higher costs.

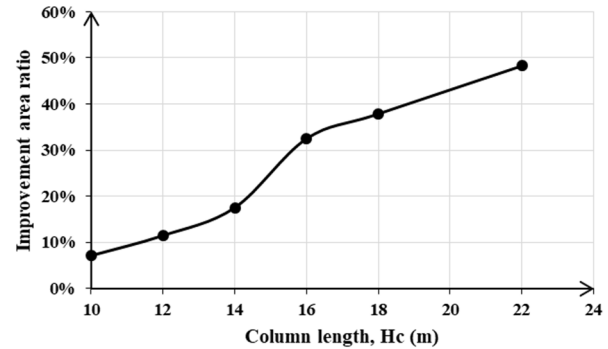


Figure 1. Improvement area ratio versus column length.

For a residual settlement of 0.5 m, Figure 2 shows that the required reinforcement length is 14.8 m, which yields to an improvement area ratio of 22.9%, deemed optimal.

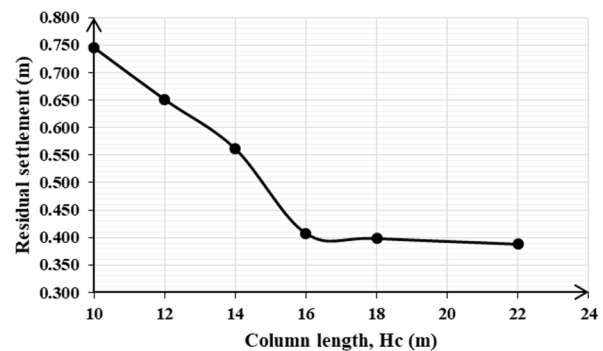


Figure 2. Residual settlement versus reinforcement length.

On the other hand, Figure 2 also shows that further increasing the reinforcement length beyond 16 m would not result in significant settlement reduction in this case.

3.3 Influence of the column spacing and diameter

Considering triangular reinforcement pattern, it is noted that desirable residual settlements can be achieved for s/d_c ranging from 1.7 to 2.5. As shown on Figure 3, tighter layout of the columns does not imply significant settlement reduction.

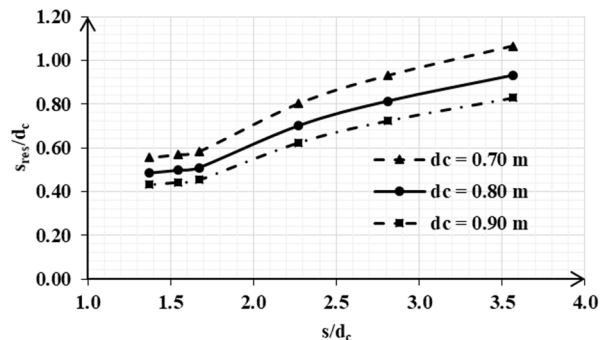


Figure 3. Influence of the spacing to column diameter ratio.

3.4 Influence of the geogrid basal reinforcement stiffness

In order to evaluate the influence of the geogrid basal reinforcement stiffness, following parameters were considered for the numerical calculations:

- Column length: 14.8 m;
- Column spacing: 1.69 m ($\eta = 22.9\%$) and 1.87 m ($\eta = 18.7\%$);
- Geogrid stiffness: 500 kN/m, 1000 kN/m, 2000 kN/m and 4000 kN/m;
- Permeability coefficient of the soft soil: 8.64E-05 m/day;
- Permeability coefficient of the stone material: 8.64 m/day;
- Permeability coefficient of the fill: 0.864 m/day.

Further parameters are as presented in Table 1, Table 2, and Table 3.

Table 1. Mohr-Coulomb drained soil model.

Layer	E (kPa)	ν	c' (kPa)	ϕ' ($^\circ$)	γ (kN/m ³)
Stone columns	40000	0.25	1	40	19.0
Drainage layer	20000	0.25	2	38	19.0
Embankment	20000	0.25	2	35	18.5

Table 2. Mohr-Coulomb undrained B soil model.

Layer (depth, m)	Soil (USCS)	E (kPa)	ν	c_u (kPa)	γ_{sat} (kN/m ³)
1 (0.0 – 3.8)	CH	3000	0.40	40	14.6
2 (3.8 – 9.3)	SC	3000	0.40	40	14.5
3 (9.3 – 18.6)	CH	4000	0.40	40	14.2

Table 3. Soft Soil undrained A soil model.

Layer (depth, m)	Soil (USCS)	e_0	λ^*	c_u (kPa)	γ_{sat} (kN/m ³)
4 (18.6 – 33.6)	CH	1.6	0.063	30	16.1
5 (33.6 – 39.0)	CH	0.95	0.057	30	18.3

If the embankment was built in stages over the natural ground without any reinforcement, the maximum total expected settlement would be 2.578 m on the crest and 1.905 m on the base center (Figure 4). Adopting reinforced ground with the geogrid basal reinforcement with stiffness J ranging from 500 to 4000 kN/m, the settlement reduction factor (SRF) increases linearly from 1.67 to 1.76 (Table 4). Figure 6 shows the vertical displacements obtained for $\eta = 22.9\%$ and $J = 2000$ kN/m.

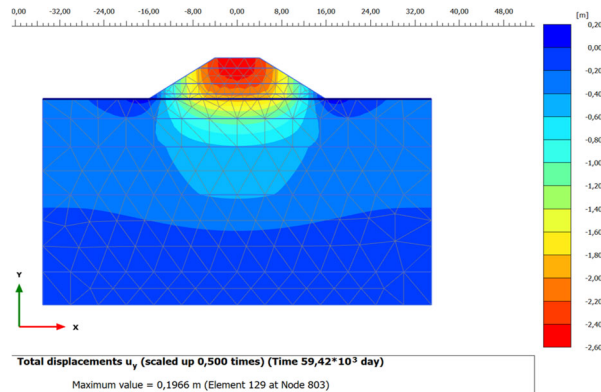


Figure 4. Total settlement of the natural (unreinforced) ground.

Figure 5 and Figure 7 indicate a marginal enhancement in stress transfer between columns and surrounding soil beneath the embankment. For all geogrid stiffness values, the stress concentration ratio ranged from 1.3 to 2, with central peaks remaining well below the practical limit of 5 (Almeida and Marques, 2010). Similar values were obtained for $\eta = 18.7\%$.

Table 4. Settlement reduction factor (SRF) for $\eta = 22.9\%$.

J (kN/m)	S_{tot} (m)	Sur. layers (m)	δ_{rs} (m)	S_{res} (m)	SRF
0	1.154	0.536	0.618	0.499	1.65
500	1.139	0.540	0.599	0.493	1.67
1000	1.120	0.537	0.583	0.484	1.70
2000	1.105	0.531	0.574	0.478	1.72
4000	1.080	0.534	0.546	0.467	1.76

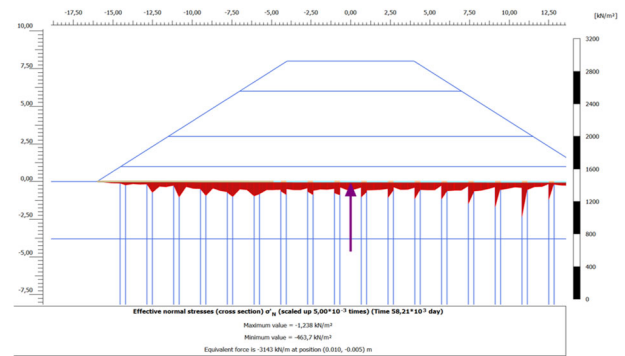


Figure 5. Effective normal stress at the base for $\eta = 22.9\%$ and $J = 0$.

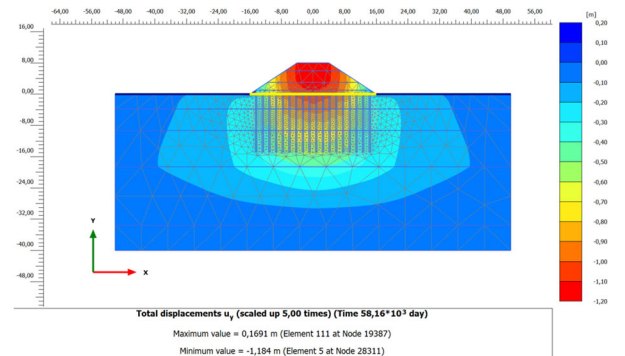


Figure 6. Total settlements for $\eta = 22.9\%$ and $J = 2000$ kN/m.

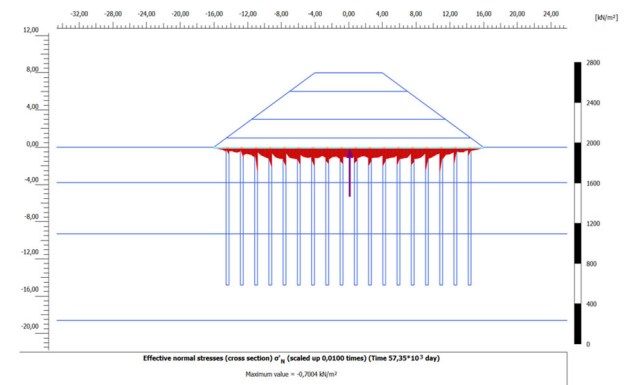


Figure 7. Effective normal stresses at the base for $\eta = 22.9\%$ and $J = 2000$ kN/m.

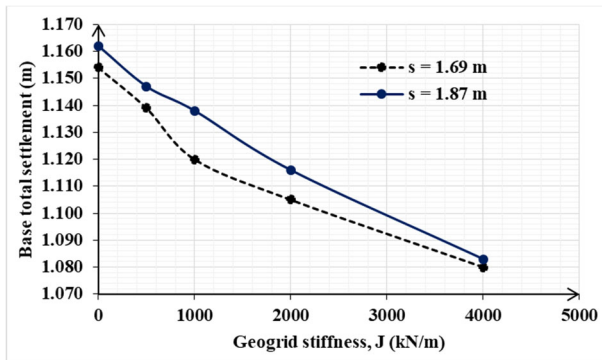


Figure 8. Base settlement versus geogrid stiffness.

Figure 8 summarizes the effect of the geogrid stiffness on the settlement reduction at the embankment base. The evaluation refers to $\eta = 22.9\%$ ($s = 1.69$ m) and $\eta = 18.7\%$ ($s = 1.87$ m) and shows that the base total settlement decreases almost linearly with increasing geogrid stiffness. However, the reduction amounts to less than 10% comparing to the situation where there is no basal reinforcement ($J = 0$ kN/m).

3.5 Settlement evolution with time

In addition to providing enhanced bearing capacity and stiffness, the stone column reinforcement contributes to increase the consolidation rate due to high permeability of the column material and small distance between them, reducing the drainage path, and thus the consolidation time.

As highlighted on Figure 9, if the proposed reinforcement solution was adopted, the construction could be finished in almost 1.5 years, and the allowable residual settlement would not be reached before the project life cycle of 15 years.

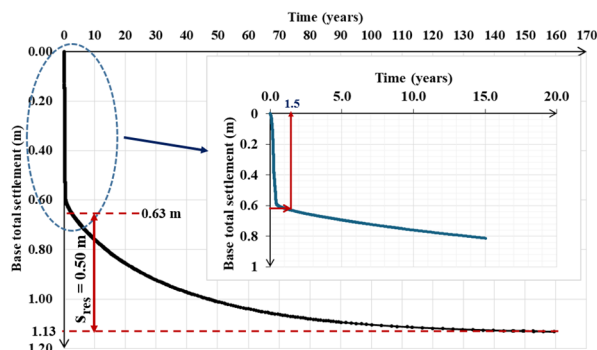


Figure 9. Settlement evolution with reinforced foundation.

4 CONCLUSIONS

This paper addresses the performance-based design concept of stone column reinforced foundations, focusing in the analysis of critical parameters to overall performance of the structure. The parameters comprise not only the column length, spacing and diameter, but also the stiffness of geogrid basal reinforcement.

The analytical calculations first confirmed that stone columns introduce significant settlement reduction if the ratio spacing/diameter is between 1.7 and 2.5. Effectively, installing the columns in a highly dense pattern poses practical installation problems. Second, widely spaced columns cannot redistribute the loads efficiently, reason why the soft soil still experience relatively high loads and, consequently, higher settlement.

In addition, the numerical calculations show that the stiffness of the geogrid basal reinforcement did not play an

important role neither on the stress distribution beneath the embankment base, nor on the settlement reduction. This contrasts with what would be expected, but can be explained by the fact that the adopted drainage cushion of 1 m thickness and Young modulus of 20 MPa acts as a load transfer platform, meaning that similar results could be achieved with a less thick layer combined with geogrid.

Moreover, the numerical results highlighted the efficiency of the stone columns in accelerating the consolidation settlements with a rate higher than the obtained with pre-fabricated vertical drains (wick drains).

In conclusion, the study demonstrates that the length of the stone columns is the governing parameter for optimizing the estimation of the improvement area ratio, which is essential to prevent the overestimation of material requirements. This analytical approach confirms that stone columns represent a cost-effective and efficient solution for improving soft soil foundations within a performance-based design framework. However, further experimental and numerical studies are recommended to more accurately quantify the stiffness and strength enhancement induced by column installation.

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