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Settlement Analysis of a Sandy Clay Soil Reinforced with Stone Columns

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Abstract: Mat foundations are most typically used in locations featuring weak soils such as soft clays and silts, particularly when building in demanding geotechnical conditions. Because of their poor engineering characteristics and significant difficulties associated with workability, these soils are often removed or avoided by excavating down to a specific depth. However, if thick layers are present, their removal becomes unpractical, costly, and creates inconvenience during construction. To overcome this issue, various reinforcement strategies can be adopted. In this study, the use of stone columns under mat foundations was investigated via numerical modeling. Two scenarios were compared: one in which stone columns were installed without any soil removal and another in which a layer of soft ground was removed and the foundation was installed without any ground treatment. Numerical results showed the clear beneficial effect of stone columns, which can significantly reduce settlements even in the presence of a thick deformable soil layer.

Keywords: Stone column; Sandy clay soil; Excavation replacement method; Settlement; Hardening soil model.

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1 Introduction

Mat foundations are a common shallow foundation type in soft soils, mainly where more than 50% of the building plan area is supported by isolated footings [1,2]. Normally consolidated clays are known among soft soils for their poor engineering properties, including high compressibility, low permeability, and low shear strength. Therefore, the construction of shallow foundations on these soils requires attentive consideration of stability and deformation to avoid bearing capacity failure and differential and excessive settlements [3-6]. A typical workaround entails excavating the weakest, shallow soil layer and constructing the foundation on a more performing, deeper layer. Usually, this effectively reduces settlements and prevents damage to the superstructure. However, if the weak clay layer is particularly thick, its complete removal down to a significant depth becomes impractical and costly. In fact, this operation carries the risk of producing deformation and damage to adjacent structures and can pose logistic and environmental issues related to the displacement of the excavated soil [3, 7]. Therefore, alternative methods that do not involve massive excavation but can reinforce the soil in place have come to be preferred. Among them, the use of stone columns has gained attention in the geotechnical community [8–10].

Various researchers [11–13] demonstrated the effectiveness and efficiency of using stone columns for soil stabilization, as this method can improve the strength properties and reduce consolidation settlements in soft soils. It also provides a much more cost-effective and sustainable alternative than piling and deep foundation solutions. There is evidence in the literature [14–18] that stone columns are also influential in supporting large-area loads, such as in the case of mat foundations over soft clay beds. A study focusing on ground improvement using stone columns [14] demonstrated a significant reduction of settlements in soft soils. The behavior of stone columns supported by geosynthetic reinforcement in embankments was also investigated [19]. It was found that stiffness, spacing, and diameter of the stone columns and the thickness of the soft soil layer are the

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main parameters controlling soil deformation. Various researchers [20–22] analyzed the behavior of stone columns in the soft soil using the finite-element method and investigated the role of various parameters, such as the depth ratio, the column diameter and stiffness, and the soil's friction angle and Poisson's ratio. A study [8] concluded that the stiffness of the stone column material is a critical parameter controlling the settlement of the treated soil, observing that stiffer columns are associated with smaller vertical and lateral displacements. Finally, it was also pointed out [23] that stone columns can be used to reduce the liquefaction potential.

Despite the amount of theoretical and experimental studies in the past decade [24–27] concerning the use of stone columns for ground improvements, a numerical investigation comparing the settlement behavior of a soft soil reinforced with stone columns as opposed to that resulting from the installation of a mat foundation after conventional excavation is lacking. The work aims to fill this knowledge gap and provide insights into the main parameters (spacing, diameter, and length) affecting the performance of stone column reinforcement in sandy clay soil utilizing finite-element modeling.

2 Materials and methods

The numerical analysis was carried out using Sigma/W software, contained in the GeoStudio finite-element package. Via Sigma/W analysis, it is possible to simulate a wide range of stress and deformation issues. These can range from simple linear elastic problems to complex nonlinear consolidation conditions, slope stability problems, soil–structure interaction problems, and more. In addition, cyclic loading–unloading, stress redistribution, and stress correction for any material model with failure criteria are all possible with this software package. As an easy-to-use commercial software, Sigma/W was employed to demonstrate that engineering professionals can evaluate the reinforcement strategy proposed in this work using readily available modeling tools without the need for advanced software usually only available in research institutions.

Plane strain conditions were assumed, thus the software defined a two-dimensional domain. A hardening soil constitutive model was considered to reproduce the soft soil behavior for the current task. Among the possible constitutive models, hardening soil models entail over 10 parameters to simulate the stress–strain behavior of real soils under various loading conditions [28, 29]. Model calibration requires the knowledge of several experimental results [29], most of which can be obtained via triaxial and oedometer tests. Since the stiffness parameters (E_{50}, E_{ur}, and E_{oed}) depend on the stress path, they were derived at a set reference stress p_{ref} from triaxial and oedometer tests.

Similarly, values of c′ and ø′ can be obtained from the relationship between the deviatoric stress and effective mean stress from triaxial tests. The values of the other parameters were assumed based on realistic values. In particular, a value of Poisson's ratio $\nu = 0.4$ was considered. The lateral earth pressure coefficient at rest (K_o) was obtained via Jaky's formula,

$$K_o = 1 - \sin\varnothing.$$

Column installation increases the horizontal stresses of the surrounding soil, which is beneficial for soil stability. For instance, to consider a realistic situation, Priebe (1995) assumed K_o=1 in his study, which is greater than the initial value at rest for most soils. Recently published findings [30–32] also confirmed the beneficial effects of stone columns, but specific observations on the increase of K_o are lacking.

The failure ratio (R_f) should be smaller than 1; hence, a default value of 0.9 was taken. The overconsolidation ratio (OCR) was set equal to 1.

Despite the more significant number of parameters, the chosen constitutive model was deemed more realistic than simpler elastic or elasto-plastic formulations owing to the stress–strain dependency of stiffness and strength resulting from installation effects and excavation on the soil surrounding the columns (unloading, compression, shearing, bulging). However, published studies [5,27,28] confirmed that using a single Young's modulus for different loading orientations and other fixed parameters does not produce satisfactory simulation results owing to the imperfect characterization of the actual variable (stress-path–dependent) soil parameters. In fact, studies in the literature [29–31] indicate a preference for the use of the hardening soil model as the constitutive model in foundation design.

The dimensions of the model domain, the stone columns' characteristics, and the foundation's size were chosen based on current building practices, as reported in the literature [17, 24–26]. More specifically, a 30-m-thick homogeneous sandy clay soil overlying an undeformable bedrock was considered, with stone column treatment down to a depth of 10 m. The presence of such a thick soil layer was confirmed by field investigation in a study area available at the Jimma Institute of Technology (Ethiopia) and represents a realistic condition in the area that can be encountered in the local engineering practice.

Table 1: Material properties used in the model.

Material properties	Symbol	Unit	Soft clay	Stone columns	Gravel filling
Initial void ratio	e_o	-	0.7	0.8	0.6
Unit weight	γ	kN/m^3	16	22.5	18
Overconsolidation ratio	OCR	-	1	1	1
Lateral earth pressure coefficient at rest	K_o	-	1	0.2175	0.1473
Poisson's ratio	v	-	0.4	0.18	0.25
Stiffness modulus for unloading/reloading	E_{ur}	MPa	13.02	210	180
Stiffness modulus for primary loading	E_{50}	MPa	1.86	90	35
Oedometric modulus	E_{oed}	MPa	5.56	60	45
Power for stress-level dependency	m	-	0.5	0.6	0.6
Cohesion	c	kPa	40	4	7
Friction angle	∅	°	5	48	40
Dilation angle	ψ	°	0	18	10
Failure ratio	R_f	-	0.9	0.9	0.9
Layer thickness	z	m	30	10	1

The stone columns were assumed to be made of a well-graded crushed aggregate in agreement with studies from the literature [25, 39] and installed with a spacing of 2 m to support the load of a superstructure resting on a rigid mat foundation made of reinforced concrete. The bottom end of the stone columns was assumed to rest directly on the clay soil to reproduce the condition in which drilling down to the depth of the bedrock (here, at 30-m depth) would have been unfeasible. A 1-m-thick gravel layer was placed on top of the stone columns just below the mat foundation to make the surface properly leveled and allow an even stress distribution.

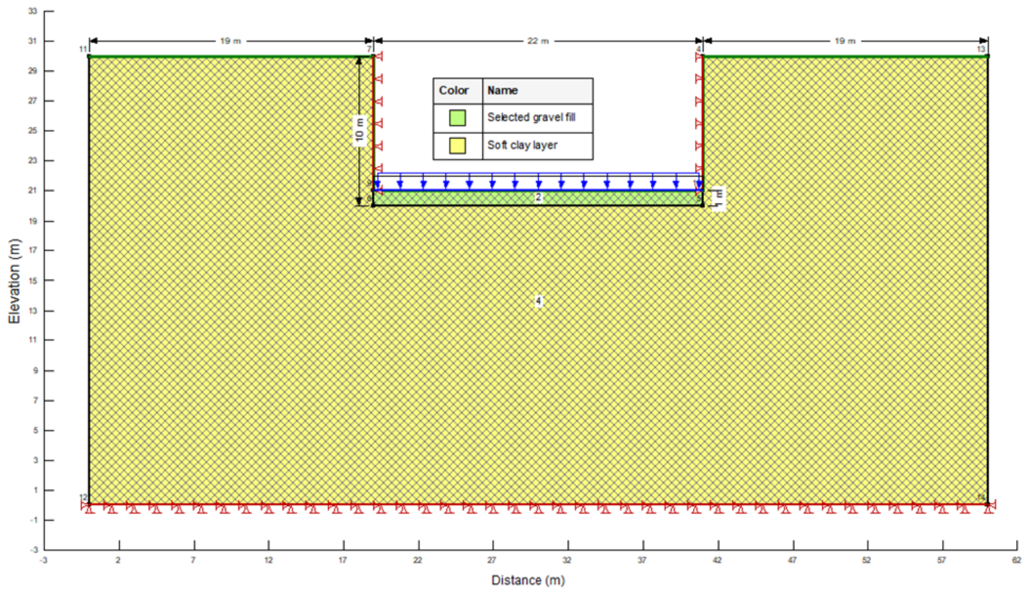
Settlement prediction and computation are critical for determining the safety of foundations built on soft ground. Therefore, the load deformation analysis problem was underlined by considering a 2D model raft foundation in both scenarios, adopting a uniform loading of 35 kPa (as shown in Figure 1a and b) according to the construction practices in the study area. In Ethiopia, the vertical drain and stone column approach has recently gained attention from international contractors, based on their use of locally available materials. However, the implications of ground improvement for buildings in use or under construction have not been investigated. Despite that, the authors of this work tried to approach the problem by conducting a comprehensive set of experimental subsoils data in the northeastern part of Ethiopia. The oedometer and triaxial tests were considered to determine the stiffness and strength parameters of the hardening soil model. In Table 1, the characteristics of the materials are summarized.

The boundary conditions in the model were set as follows: vertical boundaries were assumed to be free vertically and restrained horizontally, while the bottom horizontal boundary was assumed to be completely fixed to the bedrock. The presence of groundwater was not considered, and thus, the analysis was conducted in total stress.

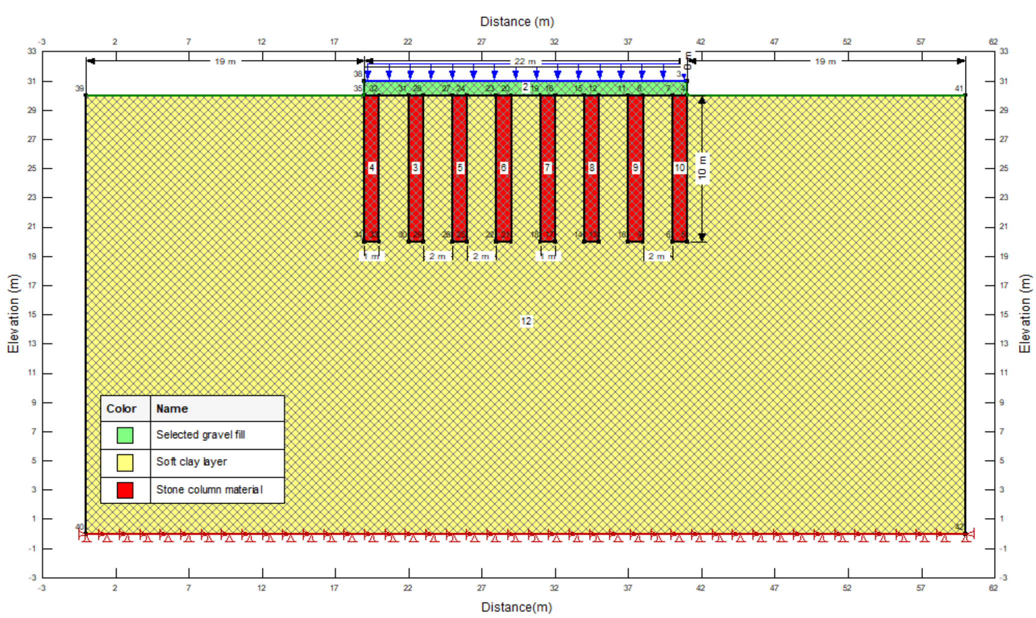
Second-order elements of quadrilateral and triangular shapes with an average dimension of 0.5 m were used for meshing. In addition, the mesh's local refinements were implemented to capture better the spatial variations of settlements, strains, and stresses.

Two scenarios were considered as follows:

– **Scenario 1.** A case was considered in which stone columns were not deployed and conventional excavation down to a depth of 10 m was used. After excavation, well-graded gravel was installed for 1-m thickness following the common practice to increase the bearing capacity and reduce the potential deformation in the underlying load-bearing stratum. Then, the stiff mat foundation supporting the superstructure was erected. A horizontal boundary constraint was used to support the two vertical edges of the soil exposed because of the excavation, as depicted in Figure 1a. The lateral fixities to the exposed walls due to excavation were assumed to be laterally supported by a cantilever retaining wall.



(a)



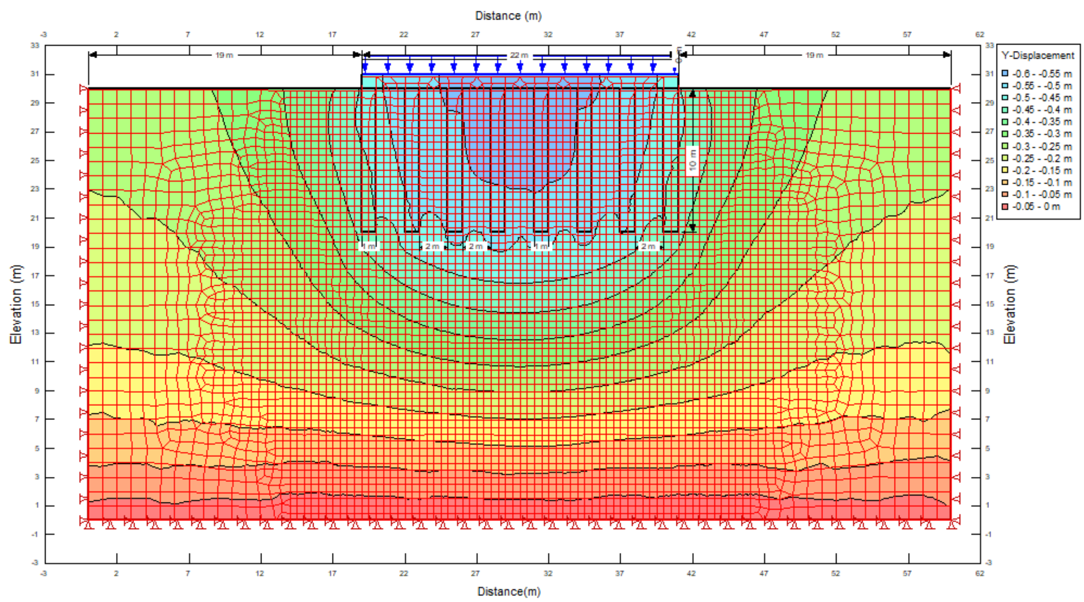
(b)

Figure 1: Geometry and boundary conditions for scenario 1 (a) and scenario 2 (b).

As the excavation depth is significant, a retaining structure is used in practice to keep the exposed vertical face in place.

– **Scenario 2.** In the second case, an analysis was carried out considering the presence of stone columns without excavating any soft soil, as shown in Figure 1b. However, unlike scenario 1, no part of the soil mass was removed through excavation, and the soft clay was directly reinforced with installation, assuming it adversely affects the drainage capacity and reduces the consolidation rate [32].

In particular, 10-m-long columns with a diameter of 1 m were installed with a spacing of 2 m. Also, in this case, before placing the mat foundation, a 1-m-thick gravel layer was laid on top of the soft soil (this time reinforced), right above the top surface of the stone columns.



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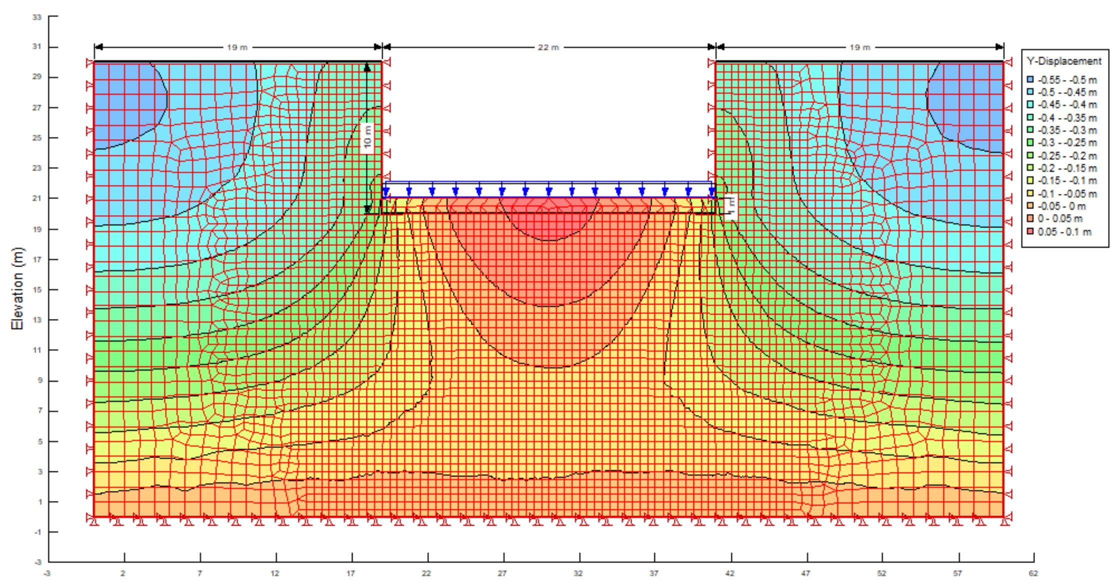

(b)

Figure 2: Vertical settlements evaluated for scenarios 1 (a) and 2 (b).

Gravel fill material is used in practice to improve the load-bearing capacity and deformation characteristics of clay soils [9]. It can be installed after removing part of the compressible mass (scenario 1) or without removing any part of it (scenario 2). It is typically placed over the loading area and gently compacted to make the loading surface leveled, avoid looseness of aggregate, and for interlocking with the surrounding subsoil interface. Owing to its good performance in permeability, it also serves as a horizontal drain [42].

3 Results

3.1 Effect of stone columns on settlements

A comparison between the two scenarios in terms of the magnitude of vertical deformation according to the depth was conducted. The load deformation analysis revealed that, below the center of the footing at any depth, the magnitude of settlement below the embedment depth of the stone columns (scenario 2) remained smaller than

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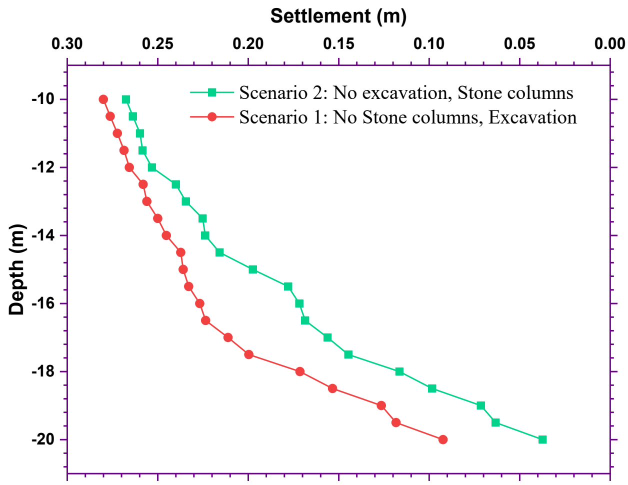

Figure 3: Vertical settlement below the center of the foundation footing and at the tip of the stone column.

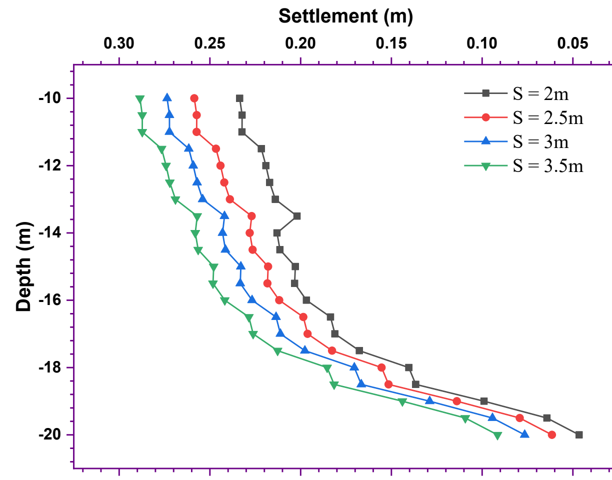

Figure 4: Effect of stone column spacing (S, taken as interaxial distance) on vertical settlements as a function of depth.

that evaluated below the gravel filling placed on top of the excavation horizon (scenario 1), as shown in Figures 2 and 3. In other words, the chosen geometric configuration in scenario 2 is such that the stiffening is brought by the columns according to their length and spacing. Therefore, it counterbalances the beneficial effect of the excavation that not only reduces the overburden pressure in the soil below the foundation, but also causes stiffening in response to the unloading–reloading cycle (this stiffening is captured well by using the hardening soil model).

3.2 Parametric analyses

A parametric study was conducted to evaluate the sensitivity of the model result to the column spacing, diameter, and length.

The influence of the inter-column spacing was investigated by varying the spacing between 1.5 and 3.5 m and leaving all the other parameters unchanged. As expected, as the spacing increases, the settlement becomes larger at any depth (Figure 4). Taking the case with an inter-column spacing of 0.5 m as the baseline, quite significant increases in the settlement are observed, by 14.7%, 26.6%, 36.0%, and 45.5% upon increasing the spacing by 0.5, 1, 1.5, and 2 m, respectively.

The sensitivity of the settlements to the diameter of the stone columns was examined by performing analyses with diameters of 0.75, 1, 1.25, and 1.5 m, while keeping the other parameters unaltered (i.e., length of stone column: 10 m and interaxial distance: 2 m). The results are shown in Figure 5 and highlight quite a substantial influence of the diameter, particularly when its value becomes large

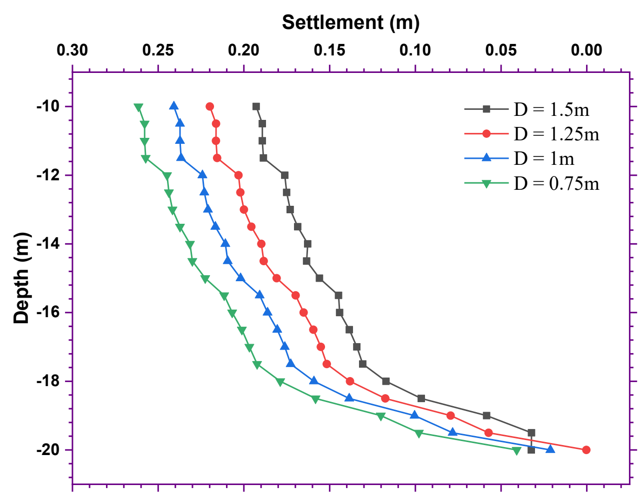

Figure 5: Effect of stone column diameter (D) on vertical settlements as a function of depth.

(D = 1.5 m). The latter case, in fact, displays settlements up to 50% smaller than those evaluated with columns of half of the diameter (D = 0.75 m). These results are in good agreement with the findings reported in the literature [20,37,38].

Finally, the effect of the column length (treatment depth) was investigated by considering depth values of 8, 10, 12, 15, and 18 m at the diameter of stone column, 1 m. The results are displayed in Figure 6. Evidently, columns reaching larger depths are beneficial in terms of reducing the settlements at any depth. In fact, starting from a depth of 10 m, an increment in column length by 2, 5, and 8 m leads to a reduction in settlements by 12%, 20.9%, 32.2%, and 43.2% on average, respectively. The effect is

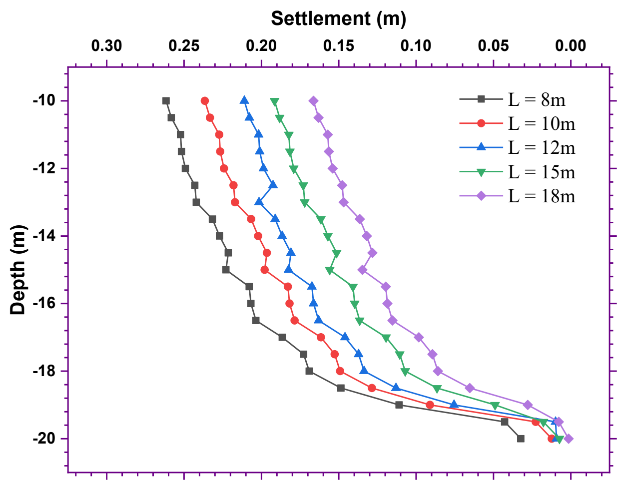

Figure 6: Effect of stone column length (L) on vertical settlement.

of similar magnitude as that achievable by increasing the diameter or reducing the spacing. This contrasts with some results shown in the literature [3,4] that suggest that column lengthening does not significantly contribute to settlement reduction.

4 Discussion and conclusion

The analyses conducted in this study pointed out a clear beneficial effect, in terms of reduced soil settlements, of the use of stone columns to reinforce a sandy clay soil below a mat foundation, as opposed to the case (common in engineering practice) of laying the foundation after excavating and removing a rather thick soil layer.

However, many factors can affect the deformation-reducing effect of stone columns. These include the roughness and angularity of the material and the stiffness, length, spacing, diameter, length-to-diameter ratio, and the spacing-to-diameter ratio of the columns [18, 20, 39, 42, 43]. Stone columns cannot be installed in fine-grained soils as in some soils, and their effect can be counterproductive regardless of their diameter, spacing, and height. Loose sandy soils (including silty or clayey sands) are a potential type of soil in which stone columns can be installed without extra lateral support, but stone column installation in sensitive clays and silts is limited [12, 18, 44]. The characteristics of the soil investigated in this study (having a sensitivity value <4) are such that a beneficial effect from the installation of stone columns could be evaluated.

In the literature, experiences with various stone column geometries can be found. In India, for example, the average depth of stone columns seems to be around 15 m, although, with equipment modification, higher depths beyond 20 m are now becoming widespread. According to a numerical study [33], in order to fully and evenly spread the axial stress over the entire area reinforced with stone columns, a length-to-diameter ratio of 4.5 or higher should be used. Another study [48] suggests that this ratio be increased to 8–10 for optimal performance. The use of stone columns with a length of 10 m and a diameter of 1 m in the present study fully meets these requirements.

The design and implementation of stone columns are influenced by the local stratigraphy and how the properties of the soft soil, particularly its stiffness and density, are altered (improved) by the treatment. However, no standards or guidelines exist on the optimal column spacing, and the choice is left to the designer according to the site-specific conditions. In practice, spacings of 2–3 m are commonly used based on the loading arrangement, installation mechanism, deformation tolerances, and site conditions [49]. In the present study, a 2-m spacing between columns was used.

Stone column spacing, length, and diameter significantly impact settlements in the treated soil, as revealed by parametric studies and shown in Figure 7. However, as shown in Figure 7, the geometric parameter that has the greatest impact on the outcome of potential settlement reduction is the extension of length to the deep ground, the same as the length of the stone column (18 m influences load settlement reduction, as shown in Figure 6), despite the effects being all similar in magnitude. As a result, the authors conclude that addressing the role of the stone column with a finding of [27, 39] various geometric patterns, spacing, length, and diameter has a significant impact on accelerating consolidation, reducing flow path, reducing settlement, and decreasing compressibility. This allows for some flexibility in the design; for example, the column length might be shortened while compensating with an appropriate increase in diameter or a reduction in spacing.

This flexibility also leaves room for cost/time optimization, as changes in column diameter, length, and spacing not only produce changes in the total volume of the material to be replaced, but also demand the use of different drilling/installation machinery characterized by different operational costs. This cost/time optimization analysis, which is site/region/country dependent, could represent a direction for further research, along with further parametric analyses to explore different site conditions (e.g., more complex stratigraphy). Finally, in site-specific implementations, experimental evaluation of the soil characteristics is certainly recommended, as it can

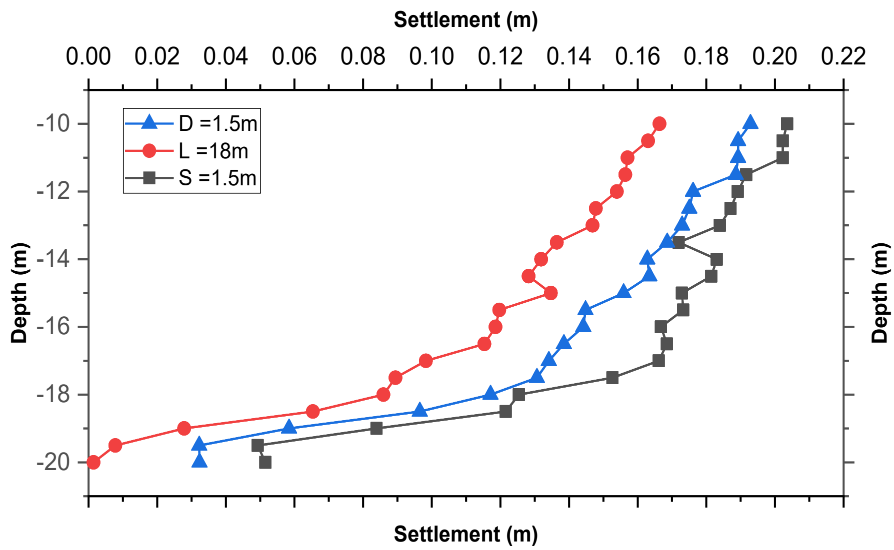

Figure 7: Effect of stone column optimal design parameters on settlement.

provide a better calibration of the model parameters and thus lead to more accurate results without the inherent uncertainty coming from the use of "typical" values for soil types that are derived from the literature or common practice. The use of three-dimensional modeling is also recommended in cases where the foundation geometry is such that the condition in the underground cannot be assimilated to quasi-planar stress and strain states.

Author Contributions: Conceptualization, methodology, software, validation, formal analysis, investigation: ABN and YTB; resources: GS and WP; data curation: ABN and YTB; writing—original draft preparation: ABN and YTB; writing—review and editing: GS and WP. All authors have read and agreed to the published version of the manuscript.

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