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Behavior of Horizontally Reinforced Stone Column in a Layered Soil: Enhancing Ground Improvement

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Abstract

Among all methods for ground improvement, stone columns have become more popular recently, owing to their simple construction and plentiful availability of raw materials. However, in relatively softer soils, ordinary stone columns (OSCs) experience significant bulging owing to the minimal confinement offered by the surrounding soil. This necessitates the introduction of reinforcements in the stone column, to enhance their strength in such circumstances. The subject of this investigation was the assessment of the behavior of horizontally reinforced stone columns (HRSCs), introduced in layered soil, under the raft foundation. The soil material included was idealised using an isotropic linearly elastic fully plastic model with a Mohr-Coulomb failure criterion. There are a total of six separate factors required by the Mohr-Coulomb criterion. These include cohesion (c), the soil's dry unit weight (γd), the Poisson ratio (μ), the angle of internal friction (φ), the angle of dilatancy (ψ), and the Young's modulus of elasticity (E). At the very beginning, the load-settlement response of unreinforced soil was evaluated followed by a comparative study between square and triangular arrangements of stone columns, at different spacings, under the raft, to arrive at the configuration that encounters minimal settlements and lateral deformations. Furthermore, circular discs of suitable geogrid material were introduced along the length of the stone column. The elastic behaviour of geogrids is governed by two properties: tensile modulus and yield strength. The load-settlement behavior and lateral deformations of the resulting reinforced stone columns, with OSCs were compared. Furthermore, the spacing between the circular discs of geogrids was kept at D/2, D, 2D, and 3D, where D is the diameter of the stone column. According to the findings of an investigation conducted using FEM software, the performance of a granular pile group that is laid out in the shape of a triangle encounters much less lateral deformation and settlement than the square arrangement. The results also show that the performance of HRSCs was way better than those of OSCs, under the same in-situ soil conditions.

1. Introduction

In countries like India, owing to the exponential increase in infrastructure development and population, the engineers are forced to construct structures on fragile soils like soft clays, which cover most parts of the country. To enhance the properties of these soils that are extremely fragile in shear and have high compressibility, various approaches to the manipulation and development of the ground are used in numerous regions of the globe. Methods similar to, vibrio compaction, vertical drains, grouting, and soil reinforcement are widely used. Amongst these methods of enhancement of localised ground circumstances, fortifying the ground with granular piles also called granular columns is one of that is the most prevalent and economical approaches. The range of the investigation is to simulate and assess the changes in settlement and load-bearing capacity in layered soils, before and after the incorporation of granular columns with and without reinforcement.

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In this case, a numerical analysis is conducted, wherein the FEM software, PLAXIS-3D, is put into use to simulate the behavior of a weak-layered soil system before and after the incorporation of reinforced and non-reinforced stone columns, under the raft foundation.

The utilization of stone columns as a ground improvement technique has garnered significant attention and investigation within geotechnical engineering. Ordinary stone columns (OSCs) or simply stone columns are a powerful and efficient ground development technology used to enhance poor soil or boost bearing capacity. The technique entails employing specialised machinery to create vertical columns of compacted stone or gravel in the soil. By creating a strengthened vertical passage for the load to travel from the structure to the deeper, more capable soil layers, the stone columns raise the strength and the stability of the soil. The columns raise the soil's effective stress, which reduces settlement and boosts the effectiveness of the foundation system. Horizontally reinforced stone columns (HRSc) are a variation of traditional stone column ground improvement technique. The insertion of vertical granular columns into the soil and the horizontal reinforcement of those columns with geogrids are two ground improvement techniques. By acting as a tension element, the geogrids improve bearing capacity, lessen settlement, and raise ground stability. The procedure entails boring a hole into the ground, placing a cylindrical stone column inside of it, then compacting the dirt around it. The geogrids are then positioned between the stone columns horizontally, with their ends secured into the ground. The geogrids serve as a tension element, distributing the load and minimising soil lateral displacement.

The failure criteria of stone columns are the conditions under which the columns may no longer perform their intended functions and show undesirable behaviour. For columns having length greater than its critical length (that is about 4 times the column diameter) and irrespective whether it is end bearing or floating, it fails by bulging. Bulging failure in stone columns refers to the lateral deformation or expansion of the column, where the stone material undergoes outward displacement due to the applied loads. This type of failure is particularly relevant when stone columns are used to reinforce weak soils or improve the bearing capacity of the ground. When vertical loads are applied to the stone column, the column experiences compression. The vertical stress is transmitted to the surrounding soil, resulting in soil densification around the column. As the stone column undergoes compression, it exerts lateral forces on the surrounding soil. Depending on the relative stiffness between the stone column and the soil, this lateral force can cause the soil to undergo radial expansion. The lateral expansion leads to a bulging deformation of the stone column, where it displaces outward. This deformation can be more pronounced at the top of the column, creating a bulge or an expanded region.

This section provides a glimpse into previous studies that have explored the benefit and application of stone columns as a ground improvement method [1] demonstrated the Vibro replacement granular columns versatility in improving the integrity of the embankment via full-scale field testing. The test program included setting up granular columns, constructing a fortified earth embankment over the earth that had been stabilized by the granular/stone columns and on untreated unaltered soil, and assessing how treated and untreated foundation soils behaved. According to the results of this field research, stone columns increased the integrity of embankments constructed on weak cohesive soil and slopes carved into this earth. It successfully minimized horizontal movement, over all settlements, and also sped up consolidation. To sustain a wastewater treatment facility, [2] explored the effectiveness of stone columns buried 15 meters deep in soft estuarine deposits. Additionally, several laboratory investigations were conducted to gather the information on soil properties necessary for finite element analysis to predict the settlements of finished structures and the behavior of load tests. A settlement dip to between 30 and 40 percent of what might have been anticipated on unaltered topography was observed due to stone column installation. [3] conducted a full-scale field load testing on tender Bangkok clay stabilized with stone piles of varying densities and a mixture of fine gravel and sand. The results of load tests were used to estimate each granular pile's maximum carrying load capability. According to the research, Gravel was the most efficient granular column material. It had the highest friction angle at the lowest compaction energy, and most of the bulging developed between 10 cm and 30 cm below the ground. [4] examined floating stone columns in kaolin clay and some transparent materials with clay-like attributes and concluded that the existence of columns significantly boosted the soft clay's capacity to withstand weights. The columns, however, failed to show a further increase in capacity when they were lengthier than 6 times their diameter. [5] carried out both experimental and finite element analyses to study the behavior of stone columns by varying spacing, shear strength of soil, and loading conditions. The numerical results and the experimental results showed a similar trend. Columns spaced more than three times the diameter of the column do not provide a substantial benefit. Many researchers performed numerical simulation for near surface excavation on adjacent structure and also the effect of confining pressure on vertical settlement [6-10]. [11] performed large-scale laboratory tests on stone columns reinforced with steel bars and discs. Results show that the load-bearing capacity was found to be more when steel bars and discs were used to reinforce stone columns compared to the geotextile reinforcement under the same conditions. [12] conducted small-scale laboratory tests on reinforced floating stone columns. The research aimed to investigate the effect of different positions of geotextiles. The impact of diameter, spacing, and length of reinforcement was also studied. Results show that increasing the diameter of vertical encasement stone columns was observed to diminish the benefits of the encasement. In the case of horizontal and vertical horizontal encasement stone columns, reinforcement performance showed improvement. [13] put up a technique of analysis to measure the impact of dilatancy on the settlement response of stone column stabilized ground. The findings highlight the significance of considering the impact of dilatancy on the likelihood of settlement, on the stress placed on the stone column, and on the soft soil. A straightforward method for estimating the mobilization of shear stress was presented by [14], along the juncture of the surrounding soft soil and the granular column. It was discovered that the column's depth did not affect the vertical stress distribution inside the unit cell. Additionally, it was discovered that the shear stress mobilization along the interface of the column and soil causes variations in the stress distribution. For the 2D consolidation study of two test embankments on soft Bangkok clay modified by granular piles and prefabricated vertical drains using the finite element method, [15] suggested a revised Cam clay model. The observed and expected time settlements showed excellent agreement. [16] introduced a method based on the cavity expansion approach and the idea of an equivalent coefficient of volume compressibility for estimating the ultimate bearing capacity and settlement of ground treated with granular piles. Grounds treated with granular piles exhibited elastic stress deformation behavior in the early portion of the curve and plastic behavior in the latter half. Additionally, it was determined that the two crucial parameters are the effective modular ratio and the area replacement ratio. [17] produced a lower-limit solution for the strength of composite soil exposed to a triaxial load and provided a novel design approach for a foundation on soil reinforced with columns. The analysis was first conducted on a representative volume made up of a single column before being expanded to include a group of columns. To investigate the behavior of a stiff foundation lying on soft soil and supported by several stone columns, [18] developed an inventive analytical approach. The findings of the analysis using the finite element technique and the elastoplastic finite element method were compared. There was found to be good agreement between the total ground settlements determined by the suggested closed-form solution and the finite element calculations. [19] with reference to the authors' experience with five field cases, presented the applications and performance of rammed stone columns for strengthening a wide variety of alluvial soils, including loose to medium dense sand, silty sands, and clayey silt/silty clay soils with and without fill over them.[20] performed both numerical as well as experimental analysis on group of 3 to 4 stone columns and compared the adequacy of both encased stone columns and horizontally reinforced stone columns. Results show that horizontally reinforced stone columns produced better performance in ground improvement. [21] studied the mechanical behavior of ordinary and reinforced stone columns using the FEM software Abaqus. Parametric studies were completed, and results show that reinforcing columns with geosynthetics effectively reduces the soil settlements.

The paper conducts a comparative study between square and triangular arrangement of stone columns at different spacing and addresses the challenge of bulging experienced by ordinary stone columns. Circulars disc of geogrid materials is introduced along the length of stone columns. So far most of the research had been done on stone columns that were vertically encased with geogrids. Since geotextiles are expensive, vertically encasing the whole stone body involves a bag load of money. Hence, in this analysis, instead of vertically encasing the columns, they have been incorporated with discs of geogrids placed horizontally at fixed spacings along the length of column. This way, there’s a reduction in geogrid material being used. Hence, contributes to economy in construction. Furthermore, most of the studies in the past focused on a Single layered soil impregnated with stone columns. However, the occurrence of a single layered soil below a is a rare occurrence. Therefore, this study focuses on stone column incorporation in a Layered soil system. This provides valuable insight into the effectiveness of the proposed reinforcement method.

2. Problem Statement

Soils like marine soil, compressible soil, and weak layered soil are not ideal for any form of building work due to their inadequate load-bearing capacity. Hence, it is essential to improve these types of soils before any type of construction. Stone column repair is a common approach for improving these types of soils. The Problem concerned with investigating the effect on the bearing capacity of a layered soil, after the introduction of a group of unreinforced and reinforced stone columns in the soil using a finite element software PLAXIS-3D. A circular oil storage tank of radius 3.5 m is placed over the ground and set above the raft foundation. Stone columns are introduced in the soil below the raft foundation in various configurations. Utilizing PLAXIS-3D, the estimated elevation in bearing capacity for each arrangement is analyzed. Furthermore, geogrids are added throughout the body of a stone column at various spacings, and the resulting variation in the load-carrying capacity is examined.

2.1. Methodology

In PLAXIS 3D [22], settlement calculations are typically based on the principles of soil mechanics and finite element analysis. PLAXIS-3D commonly used for geotechnical engineering applications. It is designed to analyse and simulate the behaviour of soil-structure interaction in three-dimensional space. The finite element method is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. PLAXIS-3D employs the finite element method to discretize the problem domain into a mesh of small, simple geometric shapes called elements. These elements are interconnected at points called nodes. The behaviour of the structure or soil within each element is approximated, and the overall system behaviour is derived from the behaviour of these individual elements.

To analyse this interaction problem, the Finite Element Method (FEM) has been adopted in this study. Procedure of FEM is as follow:

1. Initial Stress: The initial stress state prior to foundation construction is controlled by the self-weight of the soil, groundwater conditions, and many other factors like plate tectonics, weathering and erosion, previous overburden, etc. Because of the high number of influencing factors, the initial stress distribution is often very difficult to evaluate. In numerical calculations, however, reasonable assumptions regarding the initial stress state are required [23].

Gravity loading and K_0-procedure are widely used to generate the initial stresses. In this study, K_0-procedure are used for the determination of initial stress condition. The K_0-procedure is used to compute initial stresses for situations with a horizontal ground surface and homogeneous or horizontally layered ground. Effective vertical stresses σ_v' depend on the effective weight of the soil γ' and depth h. Effective horizontal stresses σ_h' are calculated by multiplying the vertical stresses with the coefficient of lateral earth pressure at rest K_0. Pore water pressure, u is taken into account beneath the ground water table. Effective vertical stresses and effective horizontal stresses are calculated by Equations (1) and (2), respectively.

$$\sigma_v' = \sigma_v u = \gamma * h - u = (\gamma - \gamma_w) * h \quad (1)$$

$$\sigma_h' = k_0 \sigma_v' \quad (2)$$

The K_0-procedure imposes an initial stress state as a starting point for the numerical analysis. Hence, no deformations are calculated.

2. Displacement function: The displacement can be determined by the Equation (3) that corresponds to the static deformation.

$$Ku = F \quad (3)$$

where K = stiffness matrix
F = Applied force
U = Generated deformation

With the help of displacement, the generated strain can be calculated as follows:

$$\varepsilon = \partial u / \partial x \quad (4)$$

Generated stress can be calculated with the help of strain:

$$\sigma = \varepsilon E \quad (5)$$

where E = elastic Modulus

With the help of displacement vector, velocity and acceleration can be find out by integration method. Global equations can be expressed as in Equation (6).

$$K_g\, u_g = Fg \quad (6)$$

Equation (6) is formed by assembling all element equations of the problem domain. The global stiffness matrix K_g is singular. Prescribed nodal forces are included into the Fg vector while u_g incorporates the prescribed nodal displacements.

Following are the parameters that influenced the numerical prediction.

2.1.1. Soil Model

PLAXIS-3D supports different soil models such as Mohr-Coulomb, Hardening Soil, and soft soil. The choice of the soil model influences how the soil behaves under loading and affects settlement predictions.

2.1.2. Material Parameters

Parameters like cohesion, friction angle, dilation angle, Young's modulus, and Poisson's ratio are crucial for defining the material properties of the soil and influence the numerical predictions of model. These parameters dictate the stress-strain behaviour and affect settlement predictions.

2.1.3. Loading Conditions

Loading conditions also influence the numerical prediction. The type and magnitude of loads applied to the foundation are significant. Point loads, distributed loads, and external pressure are considered. Time-dependent loading such as construction sequences can also be simulated.

2.1.4. Boundary Conditions

The way the model is constrained or supported at its boundaries is important. This includes fixed boundaries, roller boundaries, or other constraints that mimic the actual site conditions. Boundary conditions influence significantly numerical predictions; therefore, boundary conditions should be chosen such that it would not affect the response of problem.

2.2. Numerical modelling

For all the numerical analysis FEM, software PLAXIS-3D was utilized. A 25 m x 25 m soil contour was measured to account for all the pressure bulb effects that had developed around the stone column group. Utilizing a plate with the same diameter as the RCC Footing, the burden is transmitted to the structure-supporting stone columns. To discretize the soil media, ten tetrahedral components with nodes have been employed. A typical soil model depicts stone columns laid out in a square configuration, as shown in Figure 1a.

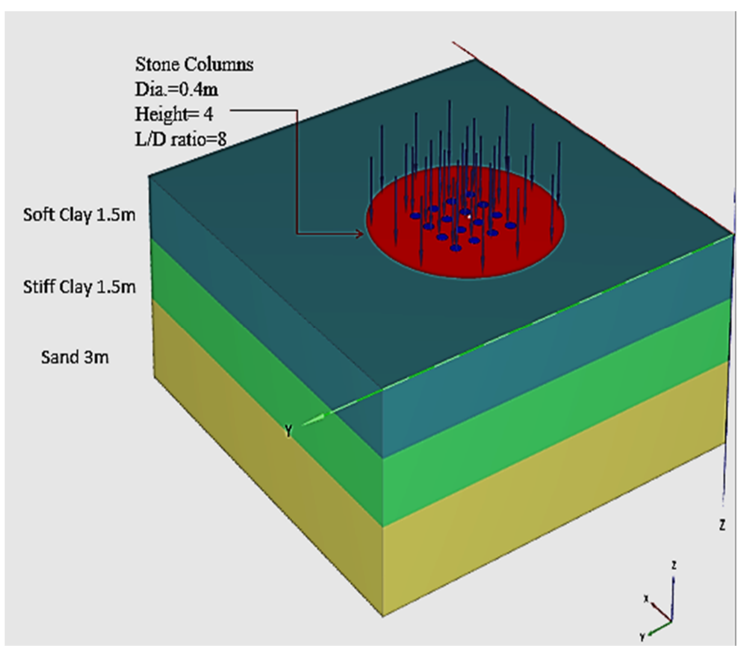

Figure 1a. Symmetrical square arrangement of stone columns.

2.2.1. Material used

The soil parameters for the present investigation are shown in Table 1. The simplest and most frequently used Mohr-Coulomb constitutive model was considered for observing the behavior of soil as well as stone columns. Material properties have been obtained from [24].

Table 1. Description of the materials used.

Material	E (MPa)	γ_{dry} (kN/m^3)	γ_{bulk} (kN/m^3)	C (kN/m^2)	Φ (degree)	Ψ (degree)	µ
Soft clay	3000	14.6	18.6	15	16	0	0.37
Stiff clay	15000	17.0	20.4	20	30	0	0.35
Sand	20000	15.5	-	-	30	0	0.3
Stone columns	55000	16.0	-	-	41	0	0.3

The geogrid was modeled as a continuous elastic element. The elastic behavior of geogrids is governed by two properties: tensile modulus and yield strength. The range of axial stiffness EA_1(= EA_2) is 2000 kN/m to 11000 kN/m.

2.2.2. Modelling of footing

The force on the oil storage tank was modelled as a surface load with uniform distribution, and the flexible foundations of the tank with a radius of 3.5 metres were modelled as a plate. Table 2 represents the characteristics of the plate used according to IS code [25]. In compliance with the design requirements stated in [26], stone columns with a diameter of 0.4 meters were positioned at various distances from one another underneath the footing. Linear elastic behavior of footing is considered.

Table 2. Characteristics of the malleable foundation plate used in the simulation.

Parameters	Values
Modulus of elasticity (GPa)	200
Poisson's ratio	0.3
Thickness (mm)	5

2.2.3. Boundary conditions

Boundary conditions of the model are depicted in Figure 1b:

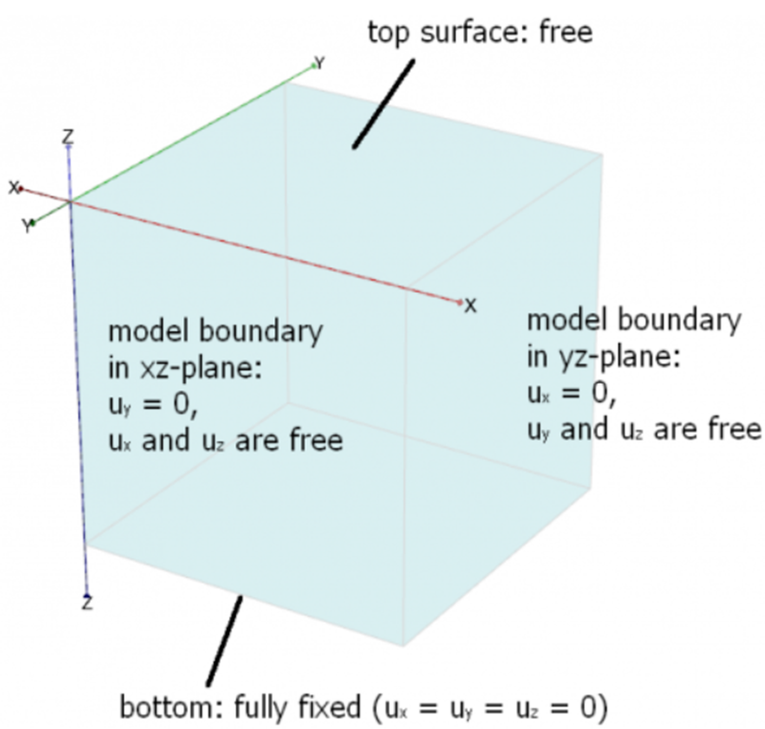

Figure 1b. Boundary conditions of the model.

- Vertical model boundaries with their normal in x-direction (i.e. parallel to the yz-plane) are fixed in x-direction ($U_x = 0$) and free in y- and z-direction.
- Vertical model boundaries with their normal in y-direction (i.e. parallel to the xz-plane) are fixed in y-direction ($U_y = 0$) and free in x- and z-direction.
- Vertical model boundaries with their normal neither in x- nor in y-direction are fixed in x- and y-direction ($U_x = U_y = 0$) and free in z-direction.
- The model bottom boundary is fixed in all directions ($U_x = U_y = U_z = 0$).
- The 'top surface' is free in all directions.

3. Results and Discussion

The results and observations of finite element analysis for four different circumstances are presented and discussed:

- Case 1: Raft footing on layered soil, without the erection of stone columns.
- Case 2: RCC footing on layered soil with a triangular arrangement of OSCs with different spacing.
- Case 3: RCC footing on layered soil with square arrangement of OSCs with different spacing.
- Case 4: RCC footing on layered soil with stone columns reinforced with geogrids.

3.1. Raft footing on layered soil, without erection of stone columns

In this case, raft foundation was considered in layered soil without stone columns. PLAXIS 3D used a finite element analysis (FEA) to calculate the settling and load-carrying capacity of the RCC raft footing. Figure 2, which was produced using layered soil, shows the distorted mesh of the RCC raft footing. Maximum deformation for this case was 30 cm.

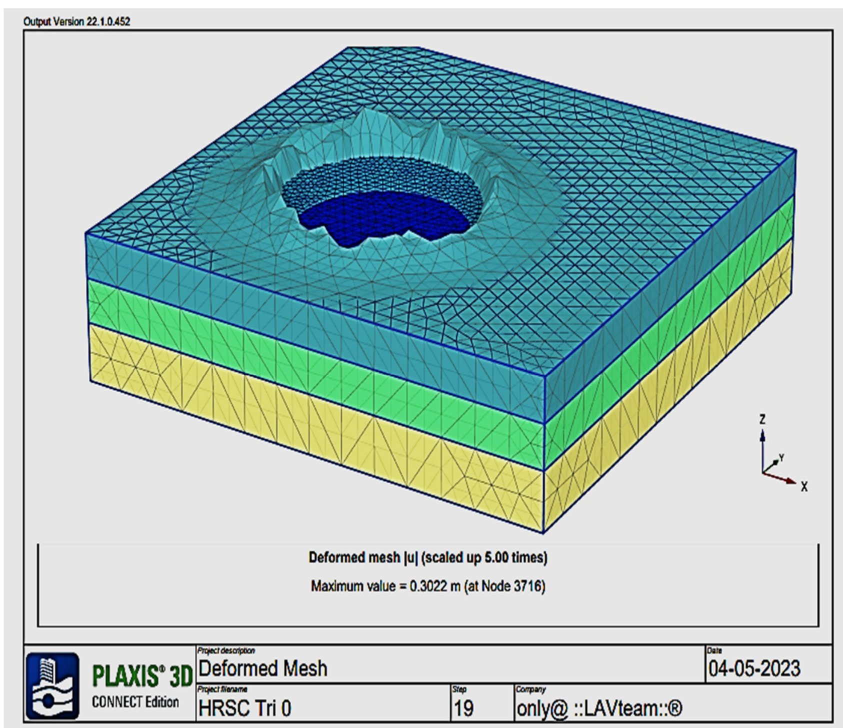

Figure 2. Deformed mesh of raft footing on layered soil.

Figure 3 depicts the global displacement contour of the RCC raft footing on the stratified soil. It shows that the ultimate value of total deformation was 261.8 mm. Maximum displacement occurs just beneath the foundation and it decreases with an increase in depth.

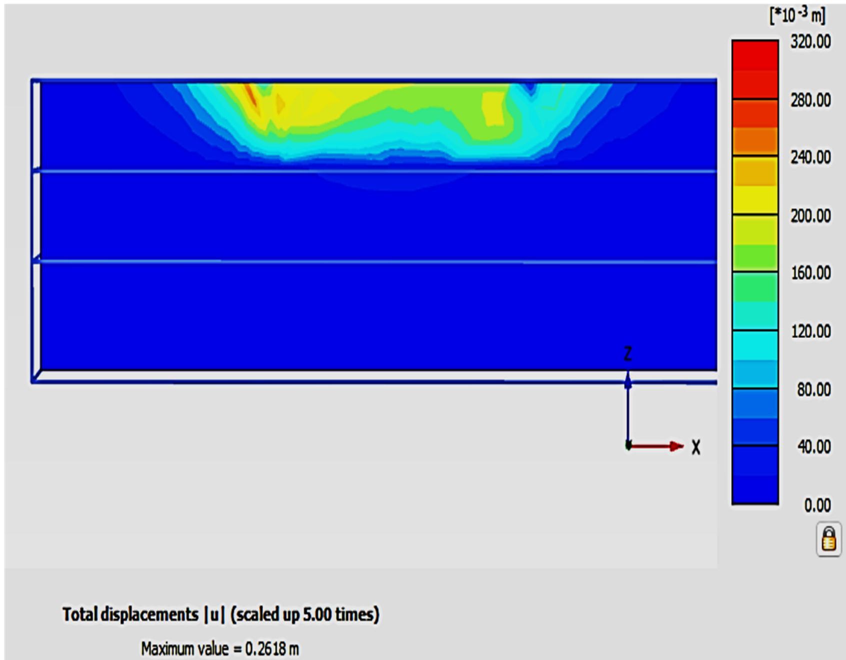

Figure 3. Overall footing displacement contour of the raft on the stratified soil.

Figure 4 depicts the load-displacement curve of an RCC raft substructure installed on layered soil. It clearly illustrates that for the permitted settlement of 200 mm at the top, the load-bearing capacity of the soil underlying the raft was 108.3 kN/m^2 when no stone columns were installed.

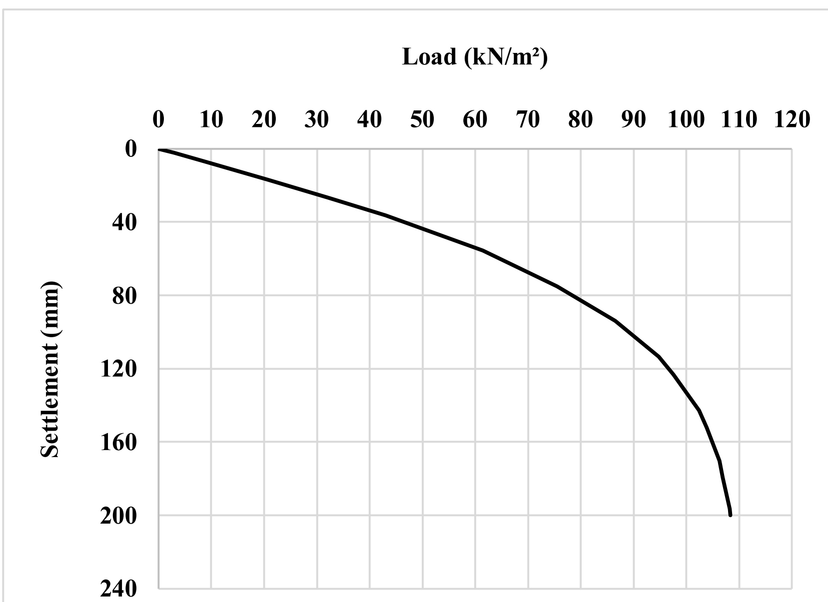

Figure 4. Load-displacement curve of unreinforced soil under the raft foundation.

3.2. RCC footing on layered soil with triangular arrangement of Ordinary Stone Columns (OSCs) with different spacings

In this case, focus was on analysing the effect that triangularly arranged OSCs had on the load settlement behavior of the soil. The stone columns were installed below the raft.

It is crucial to determine how the soil's bearing capacity has been impacted by the installation of stone columns placed in a triangle pattern below the raft. Thus, OSCs with a diameter of 400 millimetres and a height of 4 metres were placed in a triangle-like formation below the footing. Figure 5 shows the triangular arrangement of stone columns in the soil model. The distance between the stone columns was varied in accordance with IS-15284 (2003) between 2D to 5D, where D represents the diameter of the stone column.

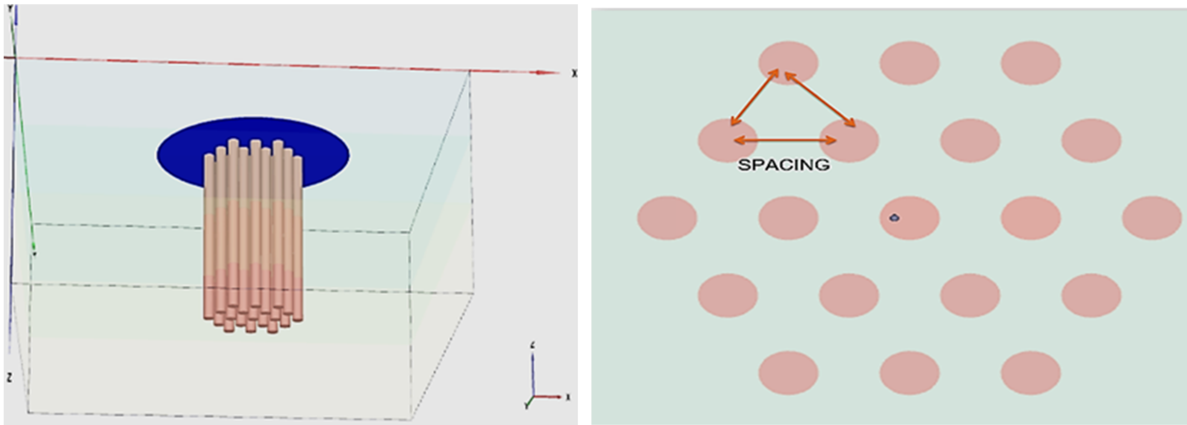

Figure 5. Stone columns arranged triangularly.

Figure 6 depicts the load settlement curve of reinforced soil with stone columns positioned triangularly at 2D, 3D, 4D, and 5D centre-to-centre spacing demonstrating that the load-bearing capacity of the raft foundation decreased as the center-to-center spacing of the stone columns increased.

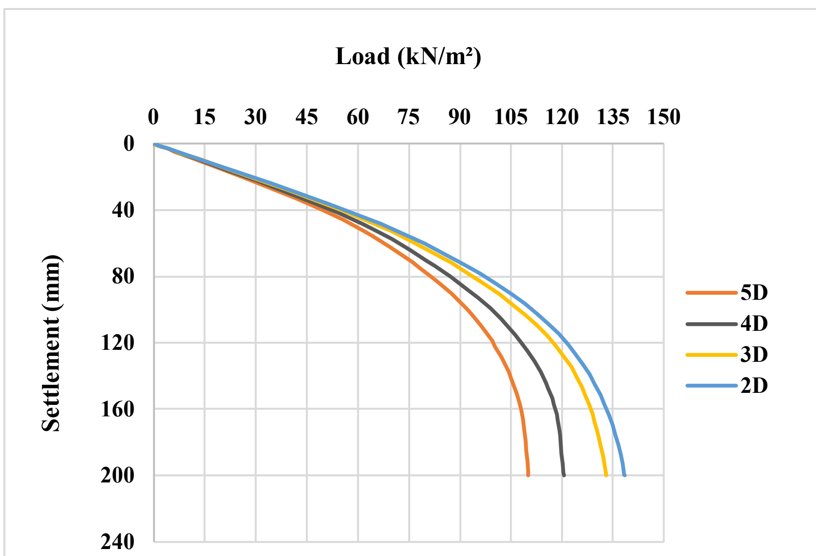

Figure 6. Comparative load settlement graph.

From the graph, it is clear that when the columns were separated from 5D center to centre, the load-bearing capability of the raft foundation decreased from 137.42kN/m^2 (where D is the diameter of the stone columns) to 110.10kN/m^2. As a result, there had been an almost 20% reduction in load bearing capacity.

Figure 7 shows the displacement contours of stone columns when arranged in a triangular patter with spacing ranging from 2D to 5D. it is clear from the figure as we go away from the footing's centre, the amount of lateral confinement to the stone column decreases.

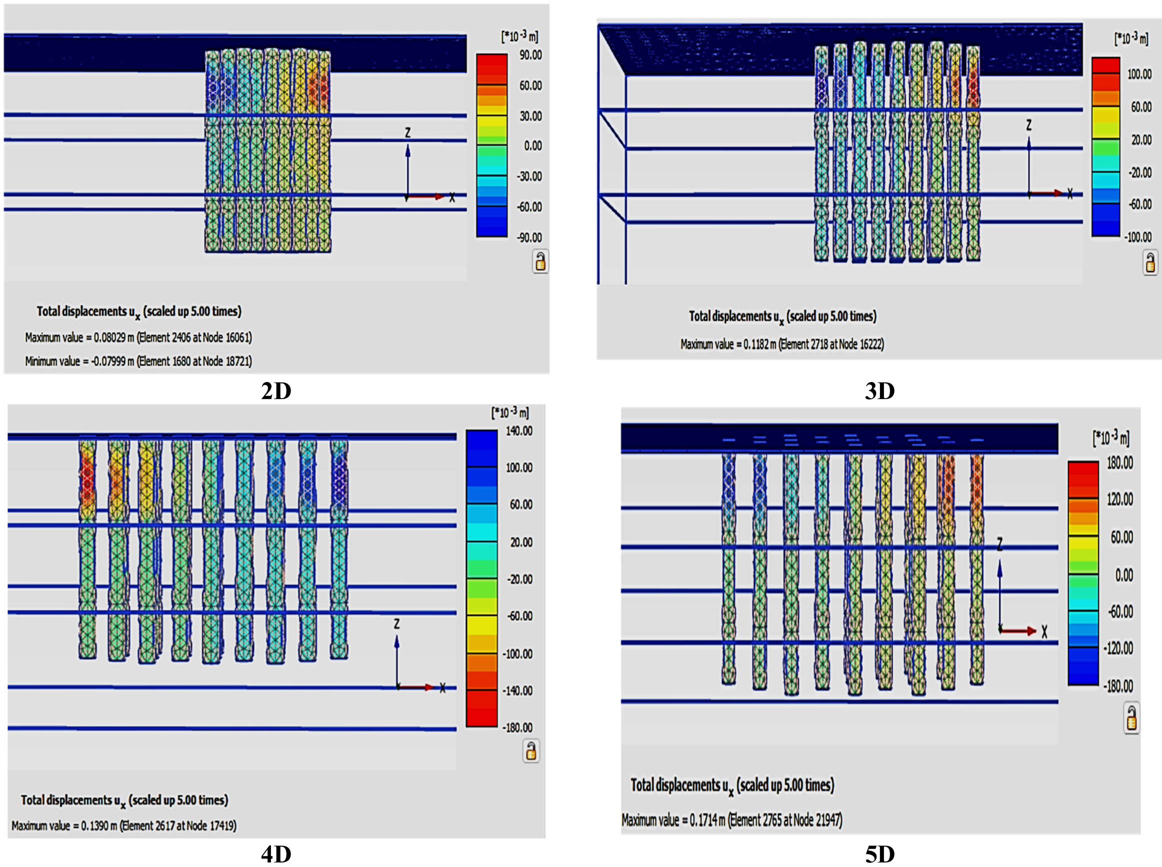

Figure 7. Displacement contours of stone columns in triangular arrangement with spacing ranging from 2D to 5D.

Table 4. Variation of lateral deformation of columns with spacing.

Spacing (mm)	2D	3D	4D	5D
Lateral deformation (mm)	80.29	118.2	139	171.4

It is clear from Table 4, that the stone columns lateral distortion increased as the distance between them increased from centre to centre. The columns nearest to the center showed the least degree of lateral displacement, whilst the columns further out showed the most column distortion.

3.3. RCC footing on layered soil with square arrangement of Ordinary Stone Columns (OSCs) with different spacing

This case focused on analysing the effect on load settlement behaviour when OSCs are arranged in a square pattern. The soil model was then outfitted with OSCs that had a diameter of 400 millimetres and a height of 4 metres. These columns were arranged in a square shape as shown in figure 8. During the process of installing the stone columns, the spacing between each pair of columns ranged anywhere from 2D to 5D (where D refers diameter of the stone column).

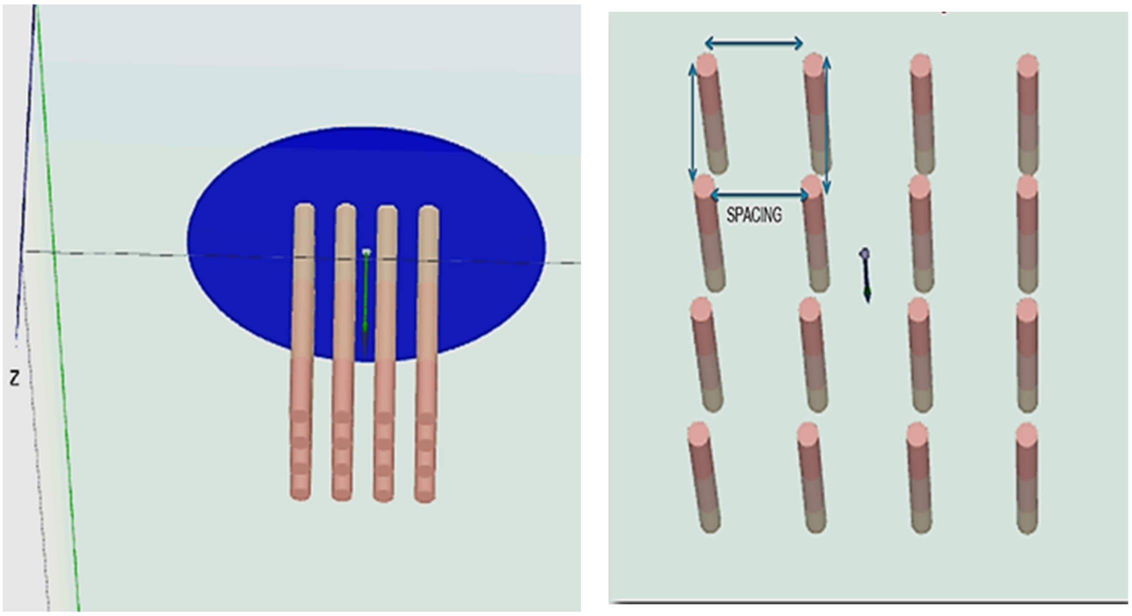

Figure 8. Stone columns arranged in a square pattern.

Figure 9 depicts the comparative load settlement curve of reinforced soil with ordinary stone columns spaced in a square shape at 2D, 3D, 4D, and 5D centre-to-centre spacing demonstrates. The load-bearing capacity of the raft foundation decreased as the center-to-center distance between the stone columns increased. It is clear from Figure 9 that the load-bearing capacity of the raft foundation decreased from 131.40 kN/m^2 (where D is the diameter of the stone columns) to 110 kN/m^2 when the stone columns were spaced 5D apart. As a direct result, the utmost load-bearing capacity of the granular columns had decreased by roughly 17%.

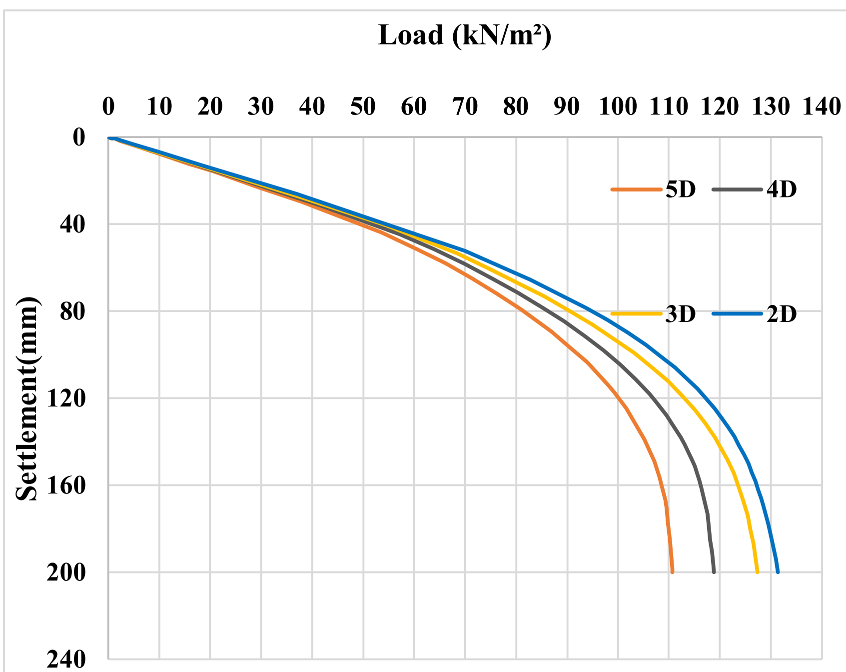

Figure 9. Comparative load settlement graph.

Figure 10 shows displacement contours of ordinary stone columns when arranged in square pattern with spacing ranging from 2D to 5D. It is clear from Figure 10 that the least amount of column displacement was seen in the columns that were the closest to the centre.

Table 5 denotes the variation in lateral deformation of stone columns with respect to variation in spacing. The lateral deformation of the stone columns rose as the space between them from centre to centre was widened, as seen in Table 5. The data in Table 5 indicates that when the column spacing changed from 2D to 5D, the lateral deformation increased from 90.94 mm to 172 mm. The most lateral displacement and the most column distortion were seen in the columns that were farthest from the centre.

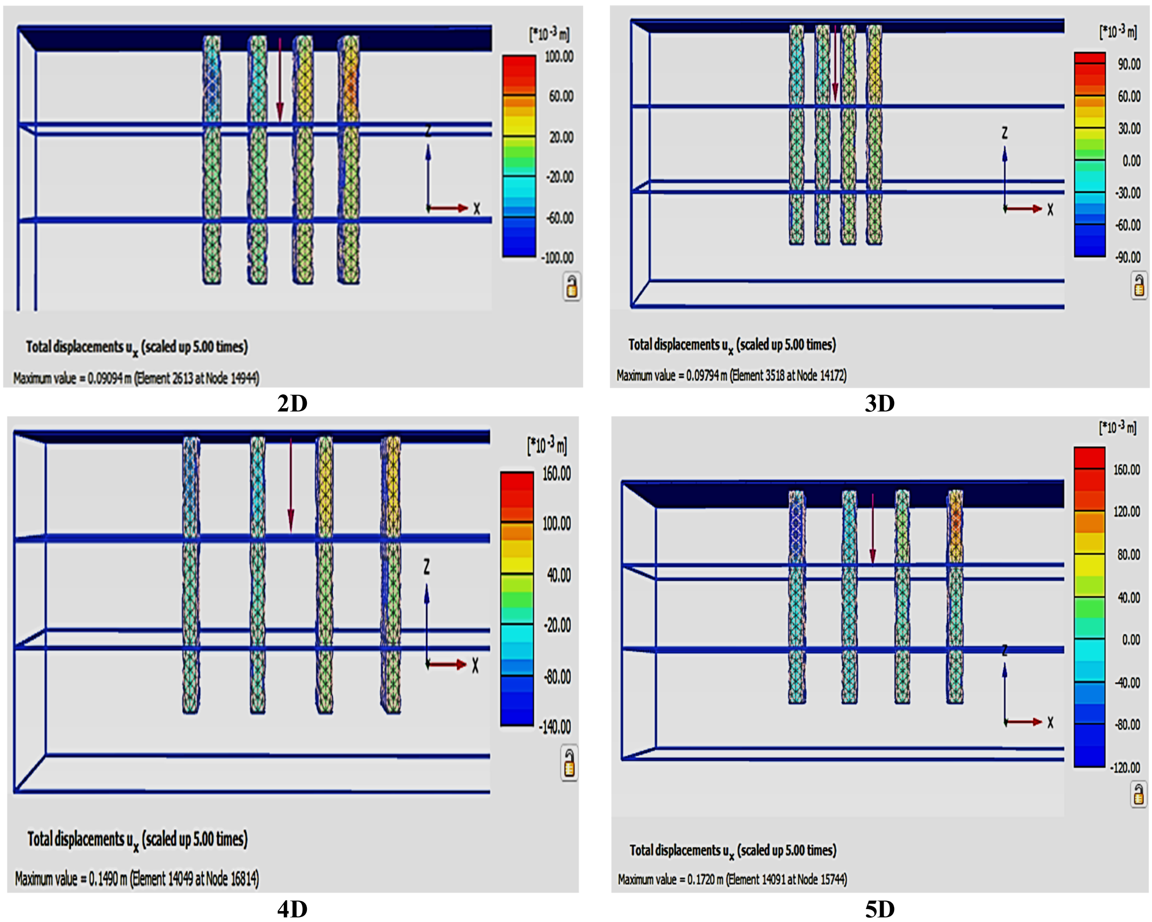

Figure 10. Displacement contours of stone columns in square arrangement with spacing ranging 2D to 5D.

Table 5. Variation of lateral deformation of columns with spacing.

Spacing (mm)	2D	3D	4D	5D
Lateral deformation (mm)	90.94	97.94	149	172

3.4. Comparison in load settlement behaviour of unreinforced soil and soil fortified with OSCs

Figure 11 illustrates the load settlement behaviour of unreinforced soil and soil that has been reinforced with ordinary stone columns. Stone columns that were placed in either a triangular or square arrangement and spaced 2D apart from the middle of each column were used for the comparison. The graph shows that the unreinforced soil's allowed bearing capacity is 108.38 kN/m^2, which equates to a settlement of 200 mm. When the OSCs were arranged in square pattern the bearing capacity increased to 131.40 kN/m^2 and further increased to 138.42 kN/m^2 when arranged in triangular pattern. Hence, bearing capacity of soil increases when the stone columns were installed in either square or triangular pattern. It can conclude that the bearing capacity was found to be more for reinforced soil (triangular arrangement) than the unreinforced soil, reinforced soil (square arrangement).

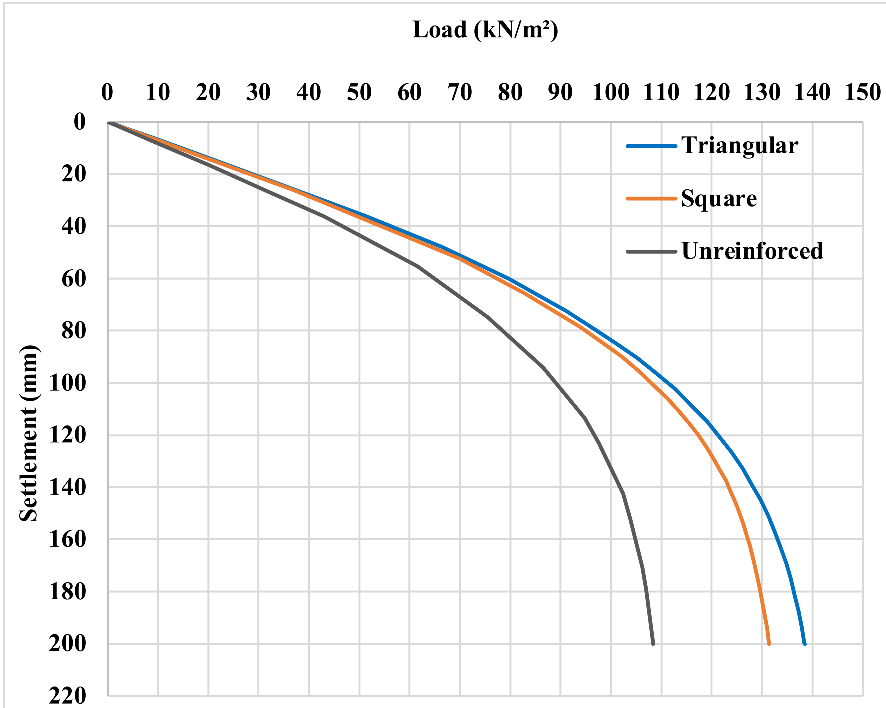

Figure 11. Comparative load settlement graph.

From the graph, it is clear that once the soil was reinforced with OSCs, its bearing capacity increased by a factor of between 22% to 28%. Ordinary stone columns (Oscs) act as a vertical reinforcement in the soil, providing additional strength and stiffness to the ground. Stone columns create a confining effect on the surrounding soil. This confinement creates a radial stress zone in the surrounding soil, and this can mobilize the shear strength of the soil resulting in increased load resistance. Hence, the load carrying capacity of soil increased after the inclusion of stone columns. Triangular arrangement shows less deformations and more load carrying capacity then square arrangement. This outcome was consistent with IS-15284 (2003), which claims that the triangular arrangement of stone columns is the best configuration. Table 6 compares the lateral displacement of stone columns resulting from triangular arrangement and square configuration.

Table 6. Comparative values of lateral deformation.

Spacing (mm)	**Lateral deformation** (mm)	
	Triangular	**Square**
2D	82.29	90.94
3D	118.2	97.94
4D	139	149
5D	171.4	172

According to the data presented in the Table 6, it is exceedingly clear that lateral deformation of stone columns was found to be more prevalent in square configurations than in triangular configurations. Triangular arrangement of stone columns allows more efficient distribution of vertical stresses into the soil compared to square arrangement. Triangular arrangement enhances shear resistance and promotes better soil arching effect that redistributes load more efficiently. The triangular shape can provide better lateral stability, reducing the likelihood of buckling or deformation under load. This enhanced stability contributes to the overall load-carrying capacity of the column. Therefore, it was found that these findings are consistent with IS-15284 [26], which asserts that the triangular arrangement of stone columns is the optimal design.

3.5. Horizontally Reinforced Stone Columns (HRSCs)

It has also been extensively studied how the inclusion of reinforcement affects the lateral deformation of stone columns. To track growth, the column is horizontally stacked with the suitable geogrids at spacings D/2 to 3D, where D is the diameter of stone columns. Figure 12 below displays a schematic representation of HRSCs in PLAXIS 3D.

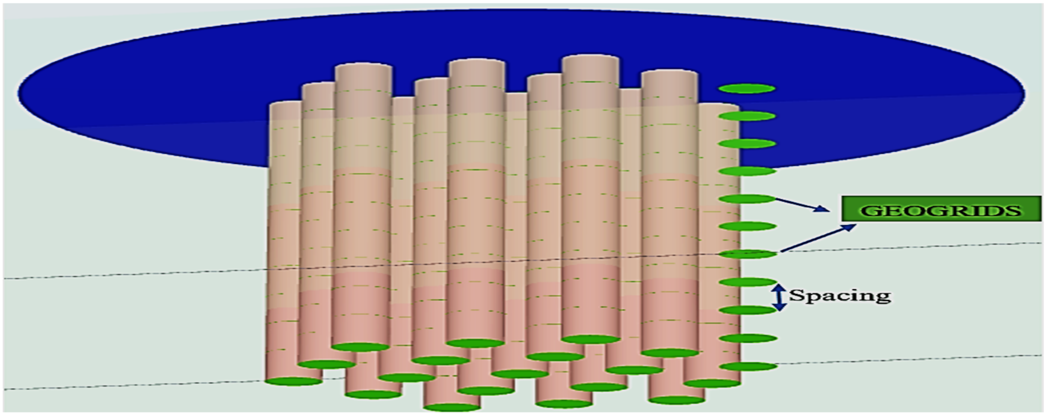

Figure 12. Circular geogrids along the length of stone columns.

The load settling behaviour of HRSC is depicted below in Figure 13. This behaviour is exhibited when the vertical spacing of horizontal geogrids is adjusted between D/2 and 3D.

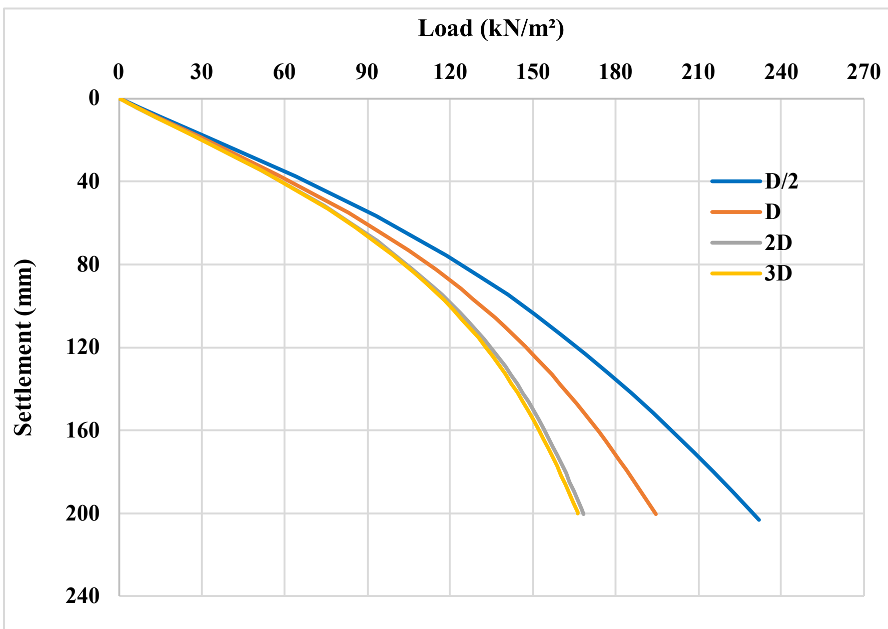

Figure 13. Comparative load settlement plot.

Figure 13 depicts that the load bearing capability of the raft rose from 166.35 kN/m^2 to 232.03 kN/m^2 when the spacing of geogrids inside the HRSC was lowered from 3D to D/2. The comparative load settlement graph abundantly made it clear that there is 40% rise in the load carrying capacity of HRSCs when the vertical separation of horizontal geogrids is decreased from 3D to D/2.

Figure 14 shows the displacement contours of HRSCs with geogrid spacing ranging from D/2 to 3D. It cans be seen from Figure 14 that as the value of lateral deformation of HRSCs increased as the vertical space that separated the circular geogrids grew wider.

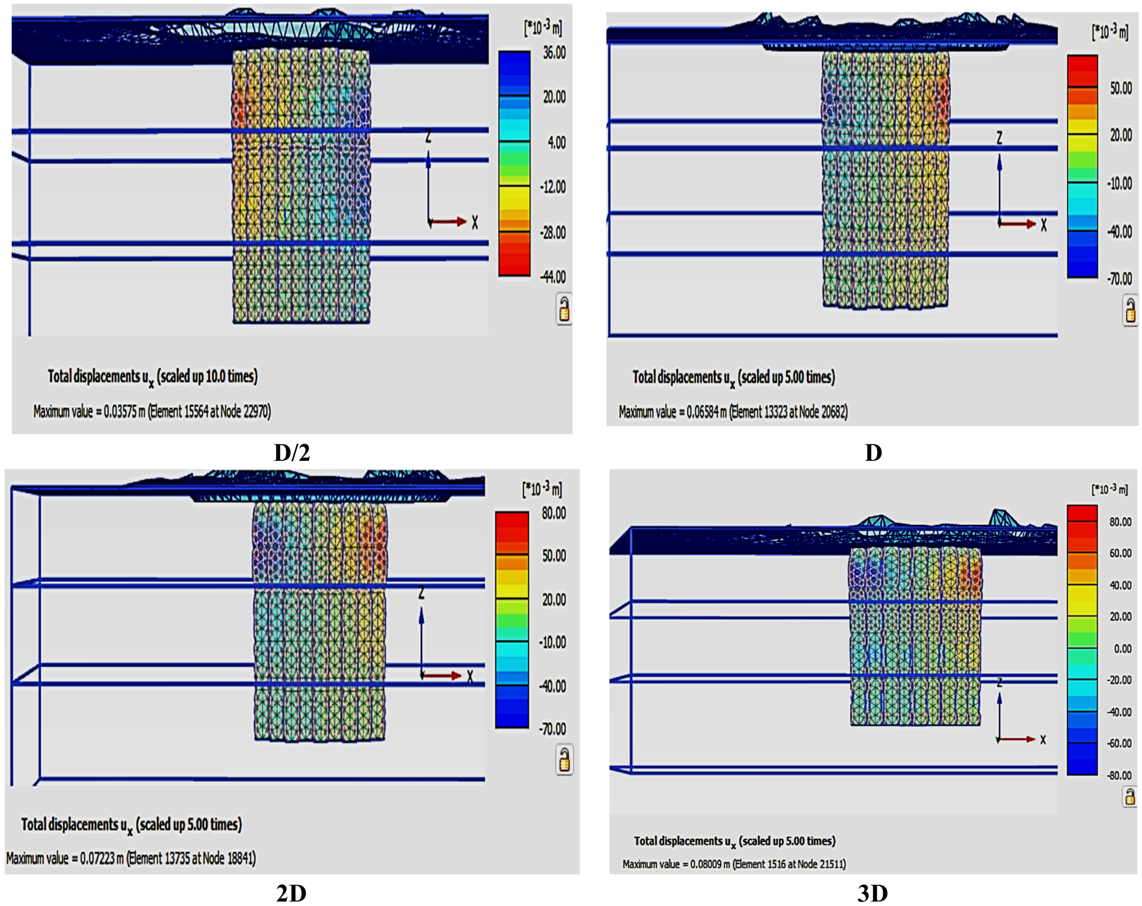

Figure 14. Displacement contours of HRSCs with geogrid spacing ranging from D/2 to 3D.

Table 7. Lateral displacement values of HRSC for different spacings.

Spacing (mm)	D/2	D	2D	3D
Lateral deformation (mm)	35.75	65.84	72.23	80.09

Table 7 shows that when the vertical spacing between geogrids was extended from D/2 to 3D, lateral deformation rise from 35.75 mm to 80.09 mm. In other words, the tendency of stone columns to bulge laterally was reduced by about 55% when the spacing of geogrids was dropped from 3D to D/2.

3.6. Comparison in load settlement of unreinforced soil, soil fortified with OSC and soil reinforced with HRSC

Figure 15, which can be seen below, illustrates a comparison of the load settlement behaviour of unreinforced soil (soil that does not include any stone columns), soil that has been reinforced with ordinary stone columns (OSC), and soil that has been reinforced with horizontally reinforced stone columns (HRSC).

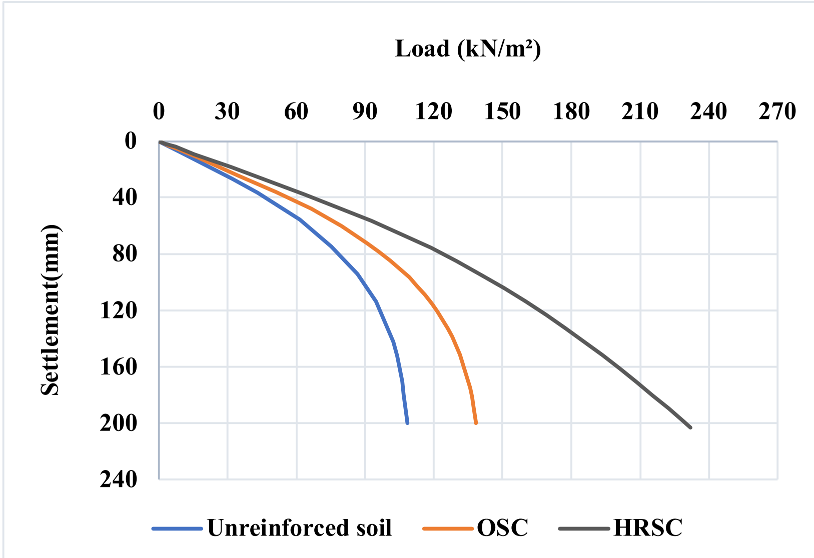

Figure 15. Comparative load settlement curve.

The load bearing capacity of the raft increased from 108.38 kN/m^2 to 232.02 kN/m^2 when an unreinforced soil was reinforced with horizontally reinforced stone columns (HRSC), as shown in Figure 15. Hence, the load-bearing capacity of the raft's foundation increased by almost 115% to that of the unreinforced soil. Also, the comparative curve indicates that by horizontally strengthening the stone columns below the raft with appropriate geogrids, their load bearing capacity improved by about 68% as compared to ordinary stone columns. Using geogrids significantly reduced the lateral deformation. It was seen that as compared to ordinary stone columns, the tendency of horizontally reinforced stone columns (HRSC) to bulge laterally into the earth around them was reduced by about 56% when geogrid was used in the soil.

4. Conclusions

The following are some of the outcomes that may be gathered from this study:

- The introduction of ordinary stone columns resulted in a substantial increase in the soil's load-bearing capacity, demonstrating a notable increase of approximately 28%. This enhancement can be attributed to the reinforcing effect of the stone columns within the soil matrix, which mitigates settlement and improves overall stability. Furthermore, a comparative analysis revealed that the load carrying capacity of columns arranged in a triangular configuration surpassed that of columns arranged in a square pattern. The triangular arrangement exhibited superior load distribution and resistance to applied forces, leading to an increased capacity to bear loads. The triangular arrangement's superior performance can be linked to its geometric advantages, such as enhanced load transfer paths and a more efficient distribution of stresses, compared to the square arrangement.
- A 20% reduction in load carrying capacity of ordinary stone columns was seen, as the spacing between them was widened from 2D to 5D. This reduction can be attributed to the larger spacing leading to diminished interaction and load-sharing among adjacent stone columns. As the spacing widens, the columns become less effective in distributing and transferring loads, resulting in a decrease in overall load carrying capacity. Additionally, the observed approximate 113% rise in lateral bulging of stone columns under the same variation in spacing (from 2D to 5D) highlights the impact of increased spacing on the lateral deformation behavior of the columns. The larger spacing facilitates greater lateral displacement, indicating reduced lateral confinement and soil restraint.
- The load carrying capacity of the soil increased by almost 115% after the inclusion of horizontally reinforced stone columns into the unreinforced soil. The horizontal reinforcement in stone columns acts as a stabilizing element, preventing excessive vertical settlement and enhancing the load distribution mechanism within the soil. The reinforcement mitigates the potential for shear failure and increases the soil's overall bearing capacity by introducing tensile forces that counteract the applied loads. Furthermore, the observed 68% increase in load carrying capacity in HRSC compared to ordinary

stone columns (OSCs) underscores the superior performance of horizontally reinforced columns. The improved performance of HRSC over OSC can be attributed to the increased tensile strength and confinement provided by the horizontal reinforcement.

- A 40% increase in the load carrying capacity was seen in HRSC, as the vertical spacing of horizontal reinforcement was decreased from 3D to D/2. The same variation in spacing also resulted in an approximate 55% decrease in the lateral bulging of HRSC.
- The study also concluded that, as compared to ordinary stone columns (OSCs), the tendency of horizontally reinforced stone columns (HRSC) to bulge laterally into the earth around them was reduced by about 56%. The reinforcement acts as a restraining force, effectively countering the lateral pressures and displacements induced by applied loads or soil movements. The horizontal reinforcement creates a more rigid framework within the stone columns, enhancing their ability to withstand lateral forces and limiting deformations.

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چکیده:

در میان تمام روش‌های بهسازی زمین، ستون‌های سنگی به دلیل ساخت ساده و در دسترس بودن فراوان مواد خام اخیراً محبوب‌تر شده‌اند. با این حال، در خاک‌های نسبتاً نرم‌تر، ستون‌های سنگی معمولی (OSC) به دلیل حداقل محصور شدن توسط خاک اطراف، برآمدگی قابل توجهی را تجربه می‌کنند. این امر مستلزم وارد کردن آرماتورها در ستون سنگی برای افزایش استحکام آنها در چنین شرایطی است. موضوع این تحقیق، ارزیابی رفتار ستون‌های سنگی تقویت‌شده افقی (HRSCs)، وارد شده در خاک لایه‌ای، زیر پی رافت بود. مواد خاک شامل با استفاده از یک مدل کاملاً پلاستیکی الاستیک خطی همسانگرد با معیار شکست مور-کولن ایده‌آل شد. در مجموع شش عامل جداگانه مورد نیاز معیار موهر-کولن وجود دارد. اینها شامل چسبندگی (c)، وزن واحد خشک خاک (γd)، نسبت پواسون (μ)، زاویه اصطکاک داخلی (φ)، زاویه اتساع (ψ)، و مدول کشش یانگ (E) می‌باشند. در همان ابتدا، پاسخ بار- نشست خاک تقویت نشده مورد ارزیابی قرار گرفت و پس از آن یک مطالعه مقایسه‌ای بین آرایش مربع و مثلث ستون‌های سنگی، در فواصل مختلف، زیر کلک، برای رسیدن به پیکربندی که با کمترین نشست و تغییر شکل جانبی مواجه می‌شود، مورد ارزیابی قرار گرفت. علاوه بر این، دیسک‌های مدور از مواد ژئوگرید مناسب در طول ستون سنگی معرفی شد. رفتار ارتجاعی ژئوگریدها توسط دو ویژگی کنترل می‌شود: مدول کششی و استحکام تسلیم. رفتار نشست بار و تغییر شکل‌های جانبی ستون‌های سنگی تقویت‌شده حاصل، با OSCs مقایسه شد. علاوه بر این، فاصله بین دیسک‌های دایره‌ای ژئوگریدها در D/2، D، 2D و 3D نگه داشته شد که در آن D قطر ستون سنگی است. بر اساس یافته‌های تحقیقی که با استفاده از نرم‌افزار FEM انجام شده است، عملکرد یک گروه شمع دانه‌ای که به شکل مثلث قرار گرفته‌اند، با تغییر شکل و نشست جانبی بسیار کمتری نسبت به آرایش مربع مواجه می‌شود. نتایج همچنین نشان می‌دهد که عملکرد HRSCs در شرایط خاکی درجا بسیار بهتر از OSCs بود.

کلمات کلیدی: HRSCs، OSCs، پایه رافت، FEM، ستون‌های سنگی.