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Comparative analysis on effectiveness of crushed aggregate and scoria gravel as columnar reinforcement material under raft foundation

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ABSTRACT

Scoria gravel is widely used as stabilizer material in road construction and concrete works. However, limited information regarding its performance as columnar stabilizing material has been reported. This study hence explores suitability of scoria gravel as columnar stabilizing material in compressible soils. Besides, comparative analysis to evaluate effectiveness of crushed aggregate columns (CAC) and scoria gravel columns (SGC) in improving deformation characteristics of clay ground was carried out by using finite element based numerical analysis. Compressible massive clay reinforced with CAC and SGC under building load was modeled to simulate the settlement attributes of the foundation material. The conducted numerical model considered both the floating and end bearing gravel columns. Finding of the study revealed that provision of floating SGC performs better than the crushed aggregate stone column in lessening vertical deformation of the clay foundation. However, the floating SGC did not result in significant improvement in lessening lateral deformation in comparison with group of CAC. Hence, application of granular piles as columnar reinforcing material in purely clay soil is not as effective as SGC from settlement reduction view point. Contrarily, the bridging effect of end bearing crushed aggregate pile is more pronounced than that of scoria gravel as the column material directly gets contact with stiff substratum. It can also be inferred from finding of the study that application of granular pile group suits well compressible grounds where stiffer strata is situated immediately at column tip.

1. Introduction

Application of columnar reinforcement in compressible soil is one of the widely used and proved effective stabilization methods [1–4]. Vertically installed columnar materials made of lime and crushed aggregate are commonly practiced so as to lessen excessive deformation and improve load carrying capacity of compressible grounds [5–9]. What makes columnar stabilization preferable over other soil stabilization techniques in many cases is that it is implemented without imposing exaggerated disturbance to soil composition and stratification [10]. It has also paramount importance in significantly reducing cost of excavation and haul [8,11].

Many studies have been conducted on suitability analysis of columnar stabilization methods and documented that granular pile also called stone pile is proved effective material in improving deformation and load bearing performance of clay ground. In relation to this, Kwa SF et al. [7,8] stated that application of stone column is an efficient method of improving the strength properties of soft soils and reducing soil vertical deformation as well. It also provides cost effective and sustainable alternative comparatively with piling and deep foundation solutions. Besides, the application of soft ground improvement by using stone column technique aids in minimizing excessive ground deformation and hence in areas of massive compressible layers it can suitably and easily be implemented. Amith KS, Murthy VR and Beena KS [3,12] indicated that stone column has widely been accepted improvement technique to support load of building structures and embankments built over large area. Finding of the study concluded that use of stone column has proved to be an economical and technically viable ground improvement technique especially for light weight structures. According to Karkush MO et al. [13–16], performance of columnar members depends on type of soil where stone pile is installed. The significance of stone pile in reducing settlement in highly compressible soil is by far less than that of relatively stiffer grounds. In relation to this [2], pointed out that loose sandy clay with an average sensitivity value of less than 4, gains considerable degree of improvement in settlement reduction upon its reinforcement with stone pile. Jorge C and Tabchouche S et al. [10,18] stated that the design and provision of stone column is apparently influenced by the formation and property of the weak ground which is

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subjected to changes in density and stiffness upon installation of columns. Stone column practically is used for reinforcing clay soils up to a depth of 15 m. With a depth of greater than 15 m however it has been proved inefficient in comparison to the deep foundations like pile. Installation of stone column beyond the stated depth requires some operational requirements like casing in order to provide stable excavation [8,20]. Stone column can be floating or end bearing type which is based on the method of load transfer and the nature of soil found near the bottom tip of the columns. The later type is preferred in many cases over the former one due to its better performance in improving bearing capacity and reducing vertical deformation [19,21]. Furthermore, Haleh M et al. [22] reported that the dimension parameters (spacing, diameter and length) are the foremost influencers of suitability and practice of using columnar materials in weak soil. It was accordingly proposed that stone pile group performs well for center-to-center spacing ranging from 2.5 to 3.5 times column diameter. Similarly, the settlement characteristics and load carrying capacity of weak foundations reinforced with granular pile highly depends on installation pattern, installation method, deformation tolerances and end bearing reaction of the columns [6,23–26].

None of the previously conducted studies reported on applicability and suitability of vertically installed scoria material in reducing deformation of expansive soils under building load. Even though application of crushed aggregate stone column is proved effective in improving bearing capacity and deformation of clay ground, no clear record has been documented regarding suitability of the scoria column. In addition, no comparative analysis has been carried out on performance of scoria and stone pile as columnar reinforcing materials. In the current study, the potential performance of scoria gravel column and crushed aggregate stone column is evaluated from settlement reduction perspective. Finite element method is adopted to numerically model the soft ground and vertically installed columns under building load. Lastly, comparative analysis on suitability and effectiveness of both materials in lessening lateral and vertical deformation is carried out and elaborated as well.

2. Methods and materials

2.1. Characterization of the materials used

The numerical model employed in the current study considered three different materials having their own properties. These include expansive clay soil, crushed aggregate stone pile and volcanic tuff (scoria gravel). A compressible clay ground was considered as naturally existing foundation of the light weight building structure. The massive clay stratum extending over significant depth was subjected to columnar stabilization to improve its deformation characteristics. Clay sample for the purpose of material characterization was collected from outskirt of Jimma city, Ethiopia. Clay soils unless modified with materials having better engineering performances, leads to precarious ground deformation up on application of superimposed loads [17,28]. Not all compressible soils are suitable for implementation of stone column. Especially, the extremely expansive soils and soft clay are not convenient to bring about satisfactory improvement in bearing capacity and settlement reduction [17]. The soil mass considered in current study is clay with insignificant content of sand.

Crushed basalt aggregate was used as vertically installed stone columns. Stone column material in many practical cases is made of crushed and natural aggregate [29]. Pebble gravel with good stiffness can also be used as stone column material. Stone columns are commonly provided in group and can be floating or end bearing type [30]. The applicability and suitability of materials as columnar reinforcing material is basically affected by density and frictional resistance, gradation and permeability of the material [31]. Apart from lessening the compressibility of loose soils, columnar materials also perpetuate the consolidation rate by reducing radial path of drainage which is imperative in reducing the liquefaction potential of soils [29]. Employment of columnar reinforcement also improves the load bearing capacity and compressibility of soft soils [27,28,68–70].

Scoria is the second alternative material considered as columnar material in this study. The samples of scoria material used in the numerical model was collected from vicinity of Adama city, Ethiopia which is one of the areas predominantly covered by volcanic ash originated materials. Scoria is light weight material well known for its high permeability and non-plastic characteristics [32,33]. Hence, its application in clay soils is deemed to improve the drainage property and frictional resistance [34,75–77].

In some cases, sand material is provided on top of the reinforced clay soil just below mat foundation. Even though the primarily purpose of having sand drain is to make the loading area leveled and uniform, it also plays drainage role [35,36].

Soil layer relatively stiffer than the clay mass was used as bearing strata so that the end bearing scenario develops in transferring the imposed external load. For the end bearing columns, bottom tip of the column materials directly rests on the stiffer layer that load bearing capacity of the columns is mainly derived from the developed end bearing reaction [35]. The layer is made of coarse soil grains with considerable amount of finer particles situated below the top compressible clay layer. In the current numerical model, the stiff layer was considered for the analysis of end bearing columns only. Some of the physical properties of the materials are summarized in Table 1. Similarly, particle size distribution of the considered materials is illustrated in Fig. 1. As illustrated in Fig. 1, the clay soil considered in the current study has insignificant content of sand fraction which accounts about 4.67%. Likewise, clay fractions constitute 55.14% of the sample.

Table 1
Physical properties of the materials required.

Properties/ Parameters	Clay soil	Crushed aggregate	Scoria	Stiff strata	Sand
Moisture Content (%)	30.63	–	–	24.17	–
Liquid limit, LL (%)	67.58	–	–	42.45	–
Plastic limit, PL (%)	37.24	–	–	31.33	–
Plasticity index, PI (%)	30.34	–	–	11.12	–
Activity, A	0.64	–	–	–	–
Specific gravity, G_s	2.67	2.78	2.56	2.70	2.70
Bulk unit weight, γ (kN/m^3)	17.34	23.14	15.86	19.76	18.60
Permeability, K (m/s)	$4.6*10^{-7}$	$3.2*10^{-1}$	$2*10^{-1}$	$1.3*10^{-4}$	$1*10^{-2}$
Unconfined Compressive Strength (kPa)	39.52	–	–	–	–
Young's modulus, E (MPa)	6.50	135.00	41	75.00	30.00
Compression index, C_c	1.32	–	–	–	–
Aggregate Crushing Value, ACV (%)	–	16.31	54.31	–	–
Aggregate Impact Value, AIV (%)	–	8.76	36.63	–	–
Los Angeles Abrasion, LAA (%)	–	21.31	46.17	–	–
Water Absorption (%)	–	2.11	6.86	–	–
Cohesion, C (kPa)	41.08	0.00	0.00	18.14	0.00
Friction angle, Ø (°)	0.00	41.00	39.00	30.00	36.00
Dilation Angle, Ψ (°)	0.00	11.00	9.00	0.00	6.00

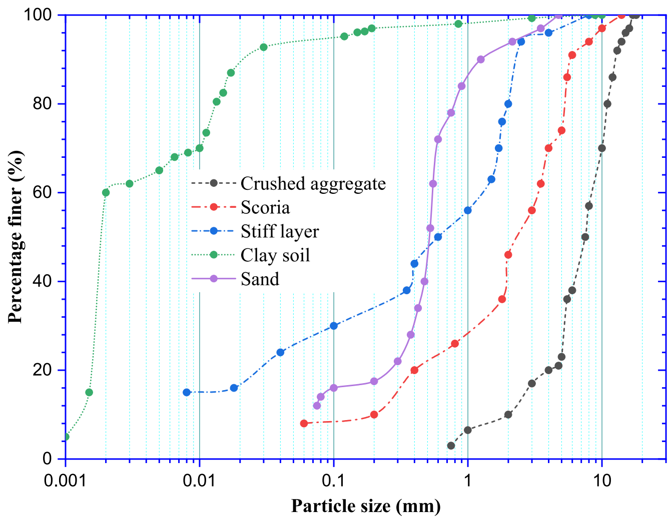


Fig. 1. Particle size distribution of crushed aggregate, scoria, stiff layer and clay.

2.2. The numerical analysis

2.2.1. Definition of the problem of interest

In the current study, massive clay soil reinforced with vertically installed granular piles and scoria columns was numerically modeled to simulate the deformation attributes of the compressible clay. The 3D version of Plaxis software was used to execute the finite element based simulation. The problem of interest also includes a building load supported by a mat foundation provided without removing any part of the clay mass through the conventional excavation. The considered finite element model took into account two different case scenarios. The two cases differ from one another with the method of load transfer. The first scenario is the case in which the columnar materials do not get contact with hard strata (stiff layer). Hence, the columns are considered as floating members in clay mass and fundamentally drive their load bearing capacity from frictional resistance developed between column surface and the surrounding clay mass [35,37]. It is typically the case in which stiff soil strata is situated at large depth from the ground surface. The second scenario considered the condition where bottom tip of the columnar members directly rest on hard strata. The external load hence is directly transferred to the stiff layer situated below the clay mass. Hence, the columnar members are considered as end bearing type as their load carrying capacity is mainly driven from the column end reaction [37,48]. The dimension parameters of elements of the numerical model are illustrated in Table 2 and all dimensions are in meter (m).

2.2.2. Dimensions and geometry of the model

The problem of interest considered in the study has a number of material layers. The dimensions of the model domain, the characteristics of the stone columns, and the size of the foundation were chosen based on the current building practices, as reported in the literature [38–41, 66]. In the case of floating columns, the model geometry is made of a single layer of material (the 27 m thick clayey layer). Similarly, the model for the end bearing case is made of 12 m and 15 m thick soft clay and stiff strata respectively. Load of the building resting on 10 m by 20 m reinforced concrete mat is also part of the numerical model. The building load is directly transferred to the clay mass via the 0.3 m thick mat foundation provided on top of the horizontal sand drain. Stone column in many practical cases is installed at center-to-center spacing ranging from 1 m to 2.5 m [42]. José LM et al. [43] stated that the typical stone column grid spacing ranges from 1.5 to 2.5 m with an average of 2 m. The grid spacing is influenced by the geotechnical characteristics of the soil and loads applied. According to Shivashankar R et al. and Afshar JN et al. [17,37], columnar soil stabilization technique by using stone column is viably applied up to a depth of 15 m from the ground surface. With regard to column diameter, the most commonly used diameters of stone pile fall in the range of 0.3 m and 1 m [43]. Selection of column diameter depends on a number of factors such as the equipment used for installation and its suitability to the soil, characteristics of the soil strata and amount of energy used during installation (vertical force and running time). For a group of stone columns provided over large area, columns with varying diameters and lengths can be used based on the resistance of the soil layers penetrated [44]. The dimensions required as in put for the numerical modeling are hence adapted from technical literatures. Accordingly, 0.4 m, 1.5 m and 12 m magnitude of dimension parameters were used for diameter, spacing and length of columnar materials respectively. To make the comparative analysis viable and logical, the dimension parameters of the columnar materials were intentionally considered uniform in magnitude. Geometry of the model is depicted in Fig. 2.

Geometrically, stone piles are modeled with different simulation shapes. The widely employed model geometries are unit cell, axis symmetric, plane strain, Equivalent homogeneous soil and three-dimensional models. However, the 3D model is the most effective geometry for accuracy of deformation and bearing capacity of soil mass [37]. The three-dimensional model also may assume two different forms, the full three dimensional and three-dimensional rows or slice of columns. Selection of the proper and friendly model geometry for simulation of columnar reinforcing materials highly depends on and affected by the specific purpose for which the soil stabilization is intended to be applied [45]. In the current study hence, the full three-dimensional geometry was employed to simulate properties of the vertically reinforced soft clay under building load.

2.2.3. The numerical analysis processes

The numerical model conducted is believed to be analogous to the real construction process of columnar materials in thick clay mass. The processes executed in a real-life construction and installation of the columnar materials was painstakingly incorporated irrespective of time duration it takes for each activity to be completed. Since design of the study calls for load deformation analysis, no time dependent consolidation analysis has been carried out. The overall processes of numerical modeling possess the following steps. First, the clay mass having the specified thickness was modeled so as to determine the initial in situ properties of the weak soil. In this step, both cases (floating and end bearing) were separately simulated in the complete absence of any type of loading. Secondly, the clay mass under building load was modeled without installation of vertical columns. In this stage, the sole massive

Table 2
Dimension parameters of the model layers and columnar materials.

Scenario 1 (End bearing columns)					Scenario 2 (Floating columns)				
Materials	Thickness	Diameter	Length	Spacing	Materials	Thickness	Diameter	Length	Spacing
Clay soil	12.00	–	–	–	Clay soil	22.00	–	–	–
Stone pile	–	0.40	12.00	1.50	Stone pile	–	0.40	12.00	1.50
Scoria Column	–	0.40	12.00	1.50	Scoria Column	–	0.40	12.00	1.50
Stiff strata	10.00	–	–	–	Mat	0.3	–	–	–
Mat	0.3	–	–	–	–	–	–	–	–

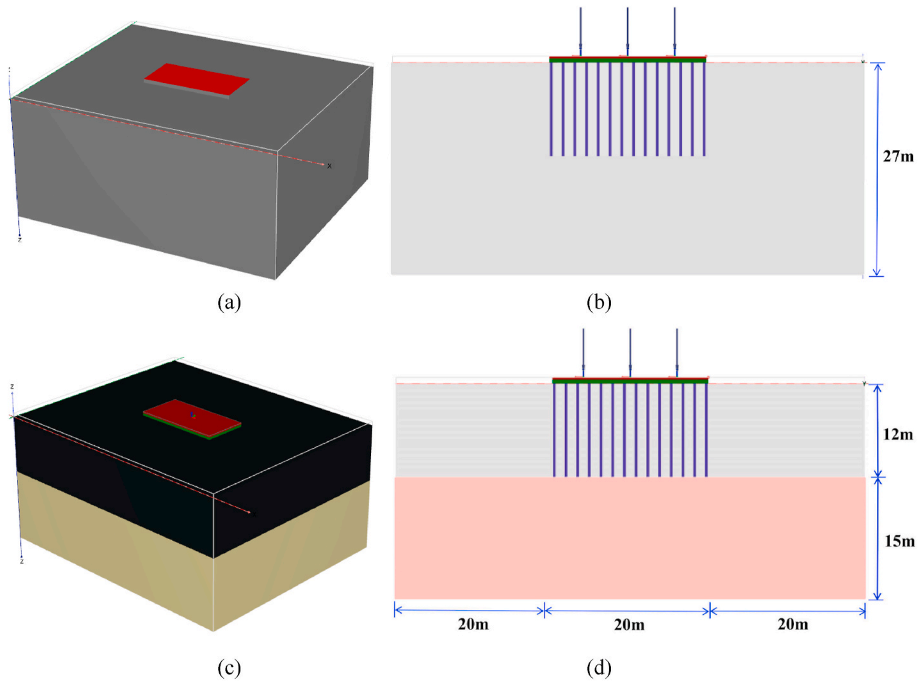


Fig. 2. Dimensions of the model: a and b) the case of floating columns, c and d) the case of end bearing columns.

compressible soil was directly subjected to external load. Thirdly, the clay mass reinforced with a group of scoria gravel columns and stone pile was separately modeled for the floating case. In this modeling phase hence the effect of building load and the floating columnar members on deformation characteristics of the massive clay was simulated. In addition to vertical deformation, the horizontal deformation of the massive clay was simulated. Lastly, the same simulation was carried out for the end bearing columns so that the critical effect of the floating and end bearing columns can be compared.

The Hardening Soil (HS) material model was used to simulate the properties and deformation characteristics of the soft clay, stone pile and scoria gravel column. Mohr- Coulomb is the most widely applied constitutive model to simulate soil behavior especially in problems involving linear interfaces [46]. Even though it is easy to work with, it basically lacks particular aspects of soil behavior such as difference in stiffness between virgin-loading and unloading–reloading. The more advanced and versatile material models like Hardening Soil take into account the shortcomings commonly observed in the Mohr- Coulomb [16,47,78,79]. The Soft Soil (SS) model accounts for creep whose effect is categorically ignored in the conventional Mohr- Coulomb constitutive model. However, the Hardening Soil (HS) model is still more complex material model that was priory developed to overcome some of the limitations of the SS model, especially with regard to the over consolidated regions [16,65]. The HS model is a constitutive model formulated based on Vermeer's double hardening soil model that both the shear and compression hardening of soft soil are considered [49]. Its shear yield surface assumes hyperbolic shape and an elliptic cap yield surface in the P-Q plane. The model is suitably used for simulating soils of different types and properties [50,64].

In using Plaxis for vast number of geotechnical problems, especially in complexity concerning soil stratigraphy and external structures considered, it is so difficult to make clear comparison between 15-noded and 6-noded finite element calculations [46]. However, it is technically apparent that fine meshes are recommended to be used near imposed external loads and structures. At these critical boundaries hence strong mesh refinement is required when using the 6-noded element than the 15-noded element. This implies that regions subjected to stress boundary conditions are the typical locations where the 6-noded element is less effective [51]. According to Pan W et al. and Liu GR et al. [52,53], the 15-noded elements are better in calculation time and accuracy of results at analyzing failure conditions for ultimate limit state whereas the 6-noded element suffice in working load conditions. In the current study hence a 15-noded element method was used for the calculations and iterations executed in the finite element model. The material parameters used in the numerical model is summarized in Table 3. Physical properties of the materials were obtained via conducting intensive laboratory tests. Almost all of the parameters were directly obtained via laboratory based experimental investigations. Some others were indirectly generated from these parameters by using established empirical relationships.

2.2.4. Boundary conditions and interfaces

In solving geotechnical problems of different nature, various boundary conditions are applied some of which are but not limited to load, displacement, stress and hydraulic boundaries. Numerical Boundary conditions are expected to be analogous to the physical boundary conditions. In some complex domains however, it remains difficult to exactly illustrate every feature of physical boundary conditions by using numerical models [54]. In the current study, both displacement and stress boundary conditions were considered. The problem domain was subjected to both horizontal and vertical fixities from the bottom. Besides, the vertical sides of the geometry were fixed against lateral displacement. The only stress boundary condition considered in the model is a building load which is transferred to the clay via the rigid reinforced concrete mat. The intensity of stress imposed by the building load is considered to be 140kpa.

The most challenging thing in determining dimension of the numerical models is proximity of the fixed boundaries to the main area of interest in the model. Closeness of the fixed boundaries to the area of interest (loaded area) adversely influences accuracy of the calculation. It limits the number of iterations and density of mesh expected to be generated which in turn impairs result of the calculations. Considerable distance should exist between exterior boundaries of the model and the loaded area (area of interest) [55,67]. In the current study hence the model dimensions were determined taking into account the influence of proximity. The generated deformed mesh of the model is illustrated in

Table 3
Input parameters used for the numerical model.

Properties/ Parameters	Unit	Clay	Crushed aggregate	Scoria	Stiff Strata
Initial void ratio, e_o		0.60	0.63	0.62	0.57
Unit weight	kN/ m^3	16.78	22.34	16.67	17.31
Over-consolidation ratio, OCR		1	-	-	-
Lateral earth pressure coefficient at rest, K_o		1	0.223	0.211	0.156
Natural moisture content	%	32.63	–	–	26.47
Stiffness modulus for unloading/ reloading, E_{ur}	MPa	16.43	200.06	134.59	90.06
Stiffness modulus for primary loading, E_{50}	MPa	1.86	66.15	36.70	18.61
Oedometric modulus, E_{oed}	MPa	6.27	94.48	52.92	31.75
Permeability in X direction, K_x (m/s)		$4.51*10^{-7}$	$3.32*10^{-1}$	$2.62*10^{-1}$	$3.76*10^{-4}$
Permeability in Y direction, K_y (m/s)		$4.51*10^{-7}$	$3.32*10^{-1}$	$2.62*10^{-1}$	$3.76*10^{-4}$
Vertical Permeability, K_v	m/s	$4.3*10^{-7}$	$3*10^{-1}$	$1.8*10^{-1}$	$4.6*10^{-4}$
Compression index, C_c		1.32	–	–	–
Modified Compression Index, λ*		0.187	–	–	–
Modified Swelling Index, κ*		0.038	–	–	–
Stress level dependency of stiffness, M		0.5	0.5	0.5	0.5
Strength reduction factor, R_{int} Rint		1	1	1	1
Cohesion, C	kPa	42.21	0.00	0.00	23.17
Friction angle, Ø (°)	o	0.00	41.00	38.00	24.45
Dilation Angle, Ψ (°)	o	0.00	11.00	8.00	0.00

Fig. 3.

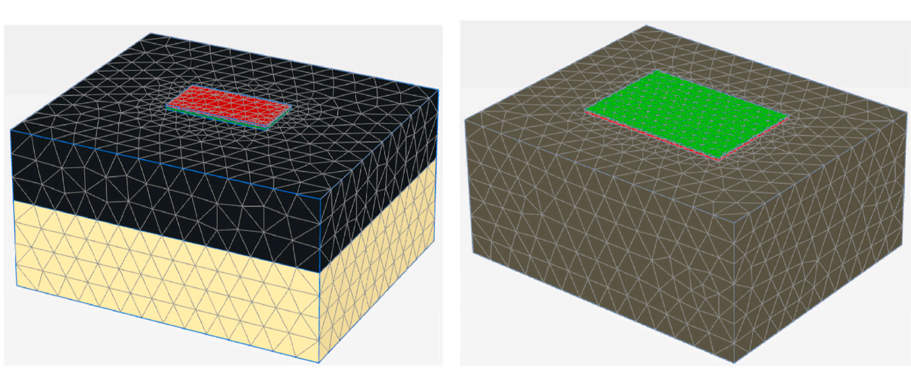
The effect of the boundary position was evaluated by comparing the magnitude of mean effective stresses and normalized vertical displacements at three different points P, Q and R which are situated at depth of 2 m, 6 m and 10 m respectively below center of the loaded area. In the process of fixing a suitable model dimension experiencing minimal boundary effect, **Equations 1 and 2** were used to calculate the normalized error for vertical deformation and mean effective stress respectively. The gradual fall in magnitude of these two parameters is considered as good indicator of convergence of the model iteration [71]. Convergence of the deformation and stress with increasing boundary distance revealed that locating the lateral boundaries at a distance between 0.65 and 1 times larger dimension of the loaded area (B = 20 m) from edge of the area was found to be sufficient to avoid influences of boundaries on the analysis results (Tables 4 and 5). It is clear that lessening the bottom boundary of the model has a minimal effect on settlement and mean effective stress. Hence, the boundaries were conservatively positioned at distances of B from edge of the loaded area.

$$\text{Normalized error for vertical dispalcement } (u_z)(\%) = \frac{(u_z, 1 - u_z, 2)}{u_z, 1} * 100 \tag{1}$$

$$\text{Normalized error for mean effective stress } (p')(\%) = \frac{(p'_z, 1 - p'_z, 2)}{p'_z, 1} * 100 \tag{2}$$

where u_z, 1 – u_z, 2 and p'_z, 1 – p'_z, 2 are the differences between vertical deformations.

In finite element analysis, mesh density is one of the critical issues need to be carefully dealt with as it is associated with accuracy of calculation [56,64]. In fact, smaller mesh size results in more elements in the model which leads to prolonged run times and more accurate results. Considering large number of meshes with smaller size increases the processing time required to generate the calculation results [57]. Applying meshes having smaller sizes alleviates the problem of divergence in results of the analysis. As mesh size decrease, the attributes such as maximum deformation converges towards the calculated value [58]. However, the analysis run time rises exponentially which in turn provides diminishing marginal returns in terms of calculation accuracy. Calculation accuracy hence depends on degree of refinement of the mesh [59]. For accuracy of calculation not only size of meshes matter but also geometry of the meshes has its own impact. For the three-dimensional model, there are four mesh elements commonly used which include tetrahedral, bricks, prisms and pyramids whereas triangular and quadrilateral elements are used in the two-dimensional model [58]. Medium mesh size was considered for the model with refinement to very fine mesh around the columns to enhance the accuracy level. Rigid interface was assumed between the granular columns and the surrounding clay



(a) (b)

Fig. 3. The deformed meshes of the model, a) End bearing case, b) Floating case.

Table 4
Influence of the lateral boundary distance on vertical deformation.

Boundary distance (m)	Vertical displacement, u_z (mm)			Normalized u_z error (%)			Mean effective stress, p' (kPa)			Normalized p' error (%)		
	P	Q	R	P	Q	R	P	Q	R	P	Q	R
0.5 B = 10	54	27.2	17	0.56	1.84	1.76	26	32	46	0.77	0.62	0.65
0.75 B = 15 m	53.7	26.7	16.7	0.93	0.75	2.40	25.8	31.8	45.7	1.94	1.26	2.63
1 B = 20	53.2	26.5	16.3	0.38	0.75	1.23	25.3	31.4	44.5	1.98	0.96	2.02
1.25 B = 25 m	53	26.3	16.1				24.8	31.1	43.6			

Table 5
Influence of the bottom boundary distance on vertical deformation.

Boundary distance (m)	Vertical displacement, u_z (mm)			Normalized u_z error (%)			Mean effective stress, p' (kPa)			Normalized p' error (%)		
	P	Q	R	P	Q	R	P	Q	R	P	Q	R
0.5 B = 10	56	27.7	17.8	0.71	1.81	4.49	27.8	32.7	47.6	1.44	1.22	1.05
0.75 B = 15 m	55.6	27.2	17	0.72	1.47	2.94	27.4	32.3	47.1	2.19	0.93	0.42
1 B = 20	55.2	26.8	16.5	0.72	1.49	4.85	26.8	32	46.9	2.99	1.88	1.28
1.25 B = 25 m	54.8	26.4	15.7				26	31.4	46.3			

soil. It is expected that reducing the interface factor will increase settlement of columns due to slipping between the column material and the clay [36].

2.2.5. Installation patterns of columns

The practical installation of stone column can be executed in square, triangular arrangement, mix of the two or hexagonal patterns [10,48,60,61]. In the case of structures with uniformly distributed loads, stone columns are usually laid out in a regular grid of square or triangular fashion [37]. From the perspective of speeding up radial drainage and reinforcing performance however the triangular arrangement was found to be relatively preferable than the square arrangement [61]. In the current study, the triangular installation pattern was used for the finite element model. Stone column is also installed with provision of geogrid encasement. Geogrid is usually used to lessen lateral deformation of the soil mass and hence improve lateral stability [62]. In the current study however the effect of encasement has not been considered. The gravel columns are provided without any lateral encasement. Hence, larger lateral deformation is expected than the encased one [63]. The geogrid encased stone columns experience much higher load bearing capacity and undergo lesser compressions and lateral bulging as compared to conventional stone columns provided without encasement [37].

3. Results and discussions

3.1. Deformation response of the clay ground reinforced with floating columns

Change in vertical deformation of the clay mass with depth before and after installation of floating columns is presented in Fig. 4. Settlement of the clay mass goes rising as the depth of embedment decreases that the region near the surface deforms relatively higher than the deeper portion of the clay. Introduction of the columnar materials (granular pile and scoria gravel column) considerably reduced the resulting vertical deformation of the clay mass subjected to superimposed building load. The floating group of scoria column improved the vertical deformation by an average of 11.12%, 28.38% and 39.41% for depths range of 0.5 m–3 m, 4 m–7 m and 8 m–15 m respectively. A noticeable difference was observed between the degree of improvement achieved by crushed aggregate column and scoria gravel column (SGC). The resulting magnitude of vertical deformation when using floating crushed aggregate column (CAC) remains greater than that of the floating scoria column at all indicated depths. For instance, at a depth of 6 m from the surface, 33.65% improvement in magnitude of settlement was witnessed for SGC whereas only 14.64% reduction was obtained

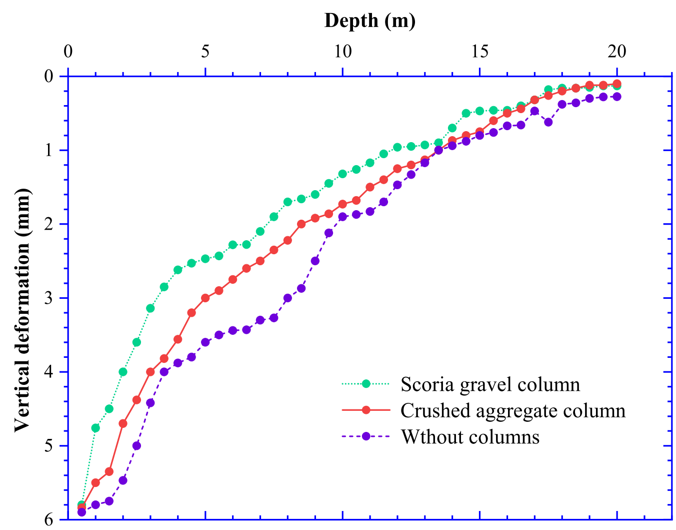


Fig. 4. Vertical deformation Vs depth curve (With and without floating columnar materials).

due to provision of CAC. This could be due to higher weight and density of crushed aggregate material than scoria gravel which may contribute to vertical displacement of the compressible clay. The scoria however is light in weight and hence it contributes less to development of vertical stress. The pattern of variation in settlement with depth has good agreement with the work of Nima RA [9] in which it has been stated that the magnitude of settlement decreases with increase in embedment depth and offset from the center.

The magnitude of vertical deformation also varies with variation in the distance from center of the column group. Comparatively larger ground subsidence was witnessed along center line of the column group. Fig. 5 illustrates the settlement versus offset curve at a depth of 6 m from the surface. As offset from midpoint of the loaded area increases, the resulting ground subsidence lowers in magnitude. Intensity of the imposed external stress (building load) lessens as the lateral distance from the loaded area increases. Hence, less magnitude of vertical deformation is apparently expected at farther offsets [9]. Accordingly, magnitude of the vertical deformation falls by 12.51% and 17.56% in average per unit distance from the centerline for floating CAC and SGC respectively. In this specific case, the vertical deformation observed when the clay soil is reinforced with CAC is yet larger than that of SGC. Haresh DG and Mittal DL [8] pointed out that high density materials

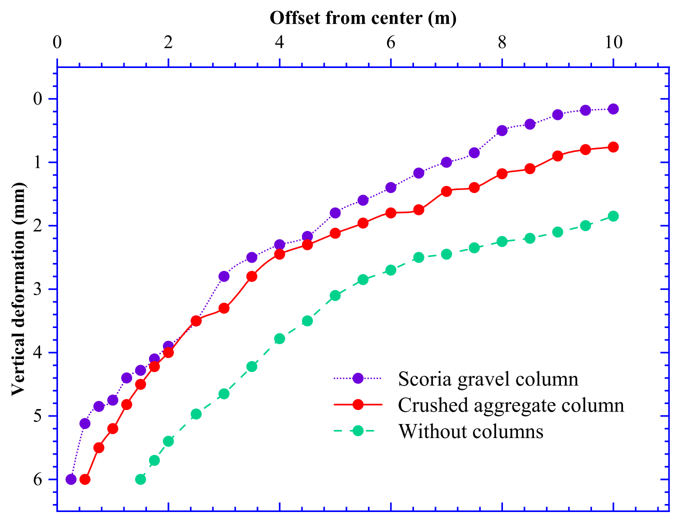


Fig. 5. Vertical deformation Vs distance curve for floating columns (at a depth of 5 m).

contribute to the effective vertical stress in addition to their reinforcement role.

Lateral deformation of the reinforced and non-reinforced clay mass at various depths along the centerline of the loaded area was illustrated in Fig. 6. As a result of densification and grain rearrangement upon exertion of the surface load, displacement of the clay mass in horizontal direction takes place. The deformation was noticeable in magnitude around center of the column group. Even though the superimposed building load is expected to be evenly distributed over the entire loaded area via the bridging effect of the rigid mat, the pressure intensity remains greater at the center. As illustrated in Fig. 6, the reinforced weak clay was laterally displaced relatively by larger magnitude near the surface than at high depths. At a depth of 10 m for instance, the clay soil deforms by 0.4 m in the absence of columnar materials. After reinforced with provision of floating crushed aggregate and scoria gravel column however lateral displacement of 0.32 m and 0.36 m were witnessed. Below the depth of 8 m, the rate of variation in magnitude of lateral deformation remained insignificant. In relation to this, maximum deformation was encountered at a depth of 5 m from the surface. Not only positive displacement but also negative displacement was also observed for depth ranging from 0.5 m to 1.5 m. The deformation sharply rose up to a depth of 5 m where the maximum value was obtained whereas it gradually collapses until it becomes almost constant for the region found below 12 m depth of embedment. At all considered offsets, the performance of floating scoria gravel column is visibly less than that of the crushed aggregate column in reducing lateral deformation of the weak clay mass. For instance, the clay mass in the presence of floating CAC under goes 21.87% less deformation than in the presence of SGC at a depth of 5 m. Unlike in the case of vertical deformation, the capacity of SGC in reducing lateral displacement is by far less than CAC.

Fig. 7 demonstrates the horizontal deformation vs horizontal offset curve at depth of 6 m from the surface. Like the vertical deformation, the magnitude of lateral displacement at various offsets from the middle point lowers as offset from center of the loaded area increase that relatively large deformation happens near the center. The numerical analysis revealed that a maximum deformation of 5.1 mm and 4.81 mm was encountered near center of loaded area when the clay is reinforced with SGC and CAC respectively. However, the clay mass deforms by a maximum of 5.65 mm in the absence of any columnar reinforcement. With increase in horizontal offset by 2 m, the horizontal deformation falls by an average of 18.33% for floating SGC whereas the lateral displacement gets reduced by 26.22% for CAC. In relation to this, at a lateral offset of 7 m from the center, the encountered displacement was 19.46% higher than that of the CAC. It can hence be inferred that the performance of CAC in reducing lateral displacement is better than the SGC. It was indicated that an average difference of 13.51% in degree of improvement is observed between CAC and SGC per 1 m offset from the center. The experimental study conducted by Shivashankar R et al. [74] on behavior of stone columns in layered soil has good similitude in deformation pattern with the current study. Finding of the study revealed that the maximum lateral deformation occurs at 1/6 of the column length.

3.2. Deformation response of the clay ground reinforced with end bearing columns

In Fig. 8 variation of settlement with embedment depth was illustrated. In similar manner with the floating columns, settlement of the reinforced and non-reinforced clay mass decreases with increase in embedment depth. However, the clay soil settles less when end bearing CAC is in place than SGC. At almost all indicated depths, the magnitude of settlement with presence of end bearing CAC remained greater. When CAC directly rests on hard strata, the aggregate material deforms less due to high density of the material. The CAC hence plays a bridging role between the stiff layer and the mat foundation. In this case a significant amount of the imposed external load is supported by the aggregate made

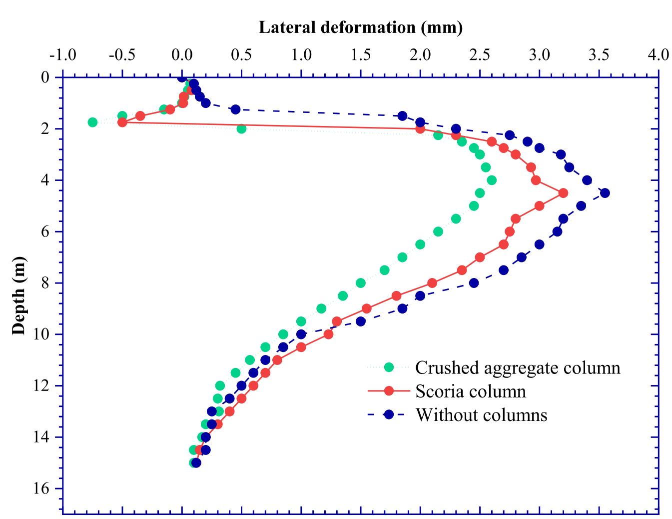


Fig. 6. Horizontal deformation Vs depth curve for floating columns (at center of the stone column group).

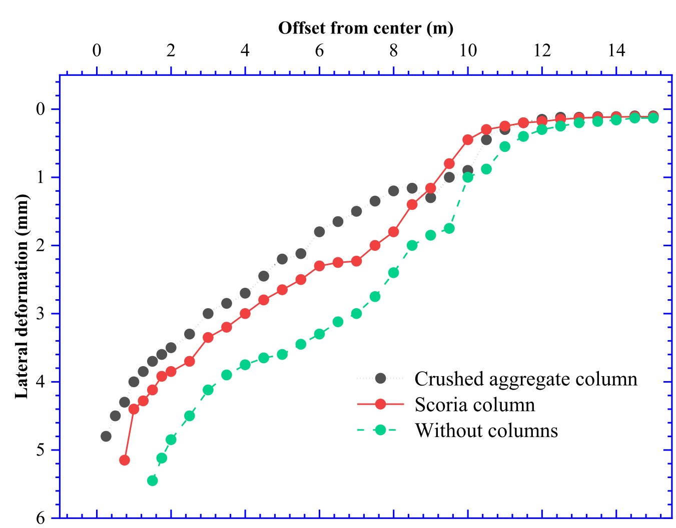


Fig. 7. Horizontal deformation Vs distance for floating columns (at a depth of 5 m below the surface).

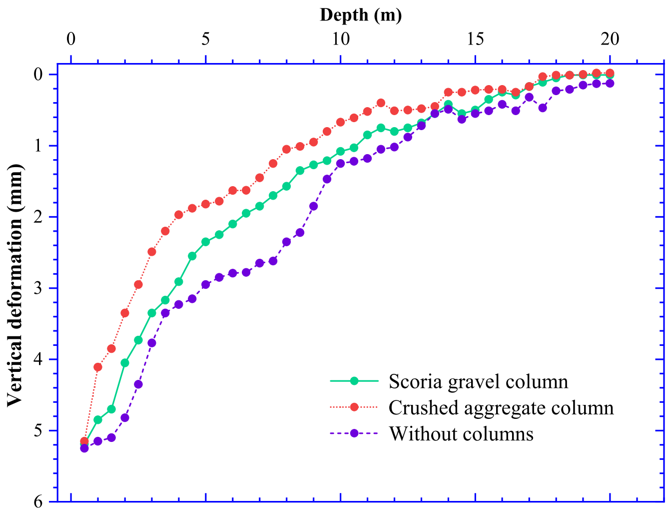


Fig. 8. Vertical deformation Vs depth curve (with and without end bearing columns).

columns. However, in the case of scoria material, larger deformation is observed due to less density and stiffness of scoria material. As a result, scoria column is more compressed than the crushed basalt aggregate column. When CAC is considered, vertical deformation of 1.96 mm and 0.4 mm is witnessed at depths of 4 m and 11 m respectively. With installation of SGC however the ground settles by 2.53 mm and 0.83 mm respectively at the stated depths. In the presence of end bearing SGC, the settlement magnitude near the surface is 405.26% higher than at bottom tip of the column group. Similarly, soil zone situated at the bottom tip settles 300% higher than the one observed near the surface in the absence of any columnar reinforcement. Hence, in reducing vertical deformation, the end bearing CAC performs better than the end bearing SGC.

The deformation of the soft clay along vertical direction with and without end bearing vertical columns was illustrated in Fig. 9. The numerical simulation revealed that both granular columns (CAC and SGC) lessened settlement of the clay deposit subjected to external loading. The settlement sharply falls as lateral distance from the centerline increase. However, the clay mass settles more when it is reinforced with SGC than CAC at all offsets from center line of the column group. The floating SGC performs better than the CAC in controlling the downward compressibility of clay material. Despite its noticeable role in floating case, the end bearing SGC group is more compressed than the CAC under the considered building load.

Lateral deformation of the clay deposit at varying depths along center line of the end bearing column group is presented in Fig. 10. Like in the case of floating columns, the end bearing crushed aggregate columns reduces the resulting lateral displacement than the end bearing scoria gravel column group. Especially around a depth of 4 m where maximum lateral deformation take place, significant marginal difference was observed between magnitudes of deformation in the presence of CAC and SGC. When the clay is reinforced with provision of CAC, maximum deformation of 2.3 mm is witnessed at a depth of 4 m whereas the deformation magnitude rises to 2.96 mm with introduction of SGC. As indicated by Azhani Z and Ramli N [29], bulging problem in stone column occurs at an approximate depth of 2.5–3 times the diameter of column, measured from the surface. In the current study, the depth where maximum lateral deformation took place is within a range of 0.2 and 0.4 times column length from the surface.

Lateral displacement of the clay mass reinforced with end bearing column group at a depth of 6 m was illustrated was investigated (Fig. 11). Pronounced difference in magnitude of the lateral deformation is observed between the clay treated with CAC and the untreated one. At a horizontal offset of 5 m from center line, the clay soil deforms by 1.75 mm, 2.16 mm and 3 mm with CAC, SGC and without columns respectively. The clay soil in absence of vertical columns deformed 71.43% higher than when it is reinforced with CAC at the stated offset. In addition, the group of end bearing crushed aggregate columns performs better than the scoria gravel columns in lessening lateral deformation of the clayey foundation. The analysis result has good similitude with findings of Zeynep C [1] in which effect of end bearing columns on settlement of soft soil was studied.

3.3. Validation of the results

Validation of the finite-element based numerical model was validated with existing numerical models conducted by Dogan T and Kahyaoglu MR [72] and Debbabi IE et al. [73]. Dogan T and Kahyaoglu MR [72] studied the deformation behavior of encased group of stone columns supporting embankments for three column diameters (0.6 m, 1 m and 1.4 m). The considered column groups are 10 m long and situated at an interval of 1.5 m. Similarly, Debbabi IE et al. [73] modeled a group of ordinary and encased stone columns to improve deformation and load bearing performance of thick clay mass under embankment load. The columns with 10 m length and spacing of 2.5 m were used. In Fig. 12,

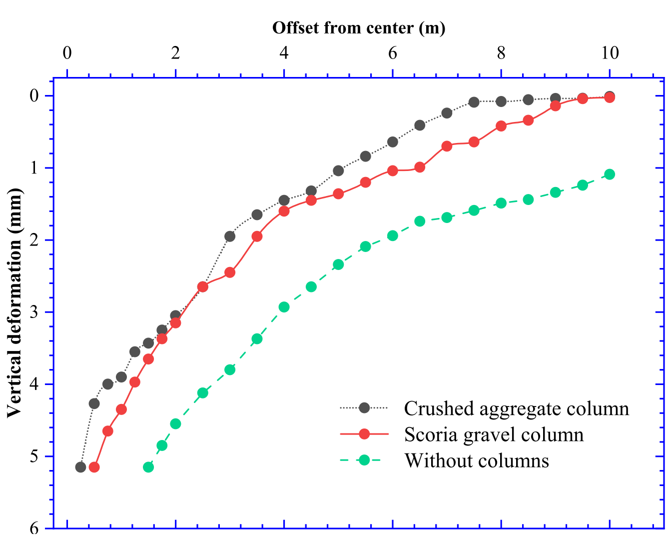


Fig. 9. Vertical deformation Vs distance curve for end bearing columns (at a depth of 5 m).

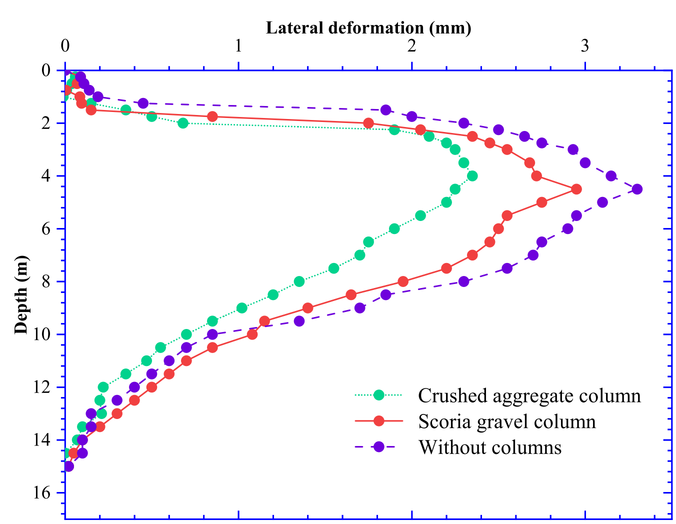


Fig. 10. Horizontal deformation Vs depth curve for the end bearing case (at center of the column group).

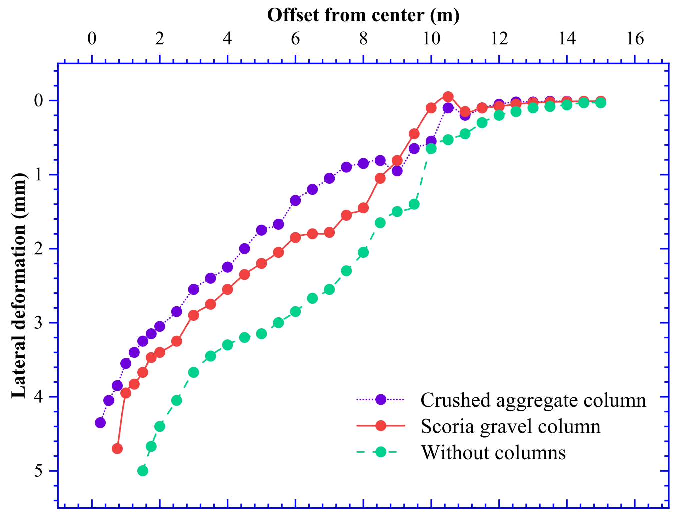


Fig. 11. Horizontal deformation Vs distance curve for end bearing columns (at a depth of 5 m).

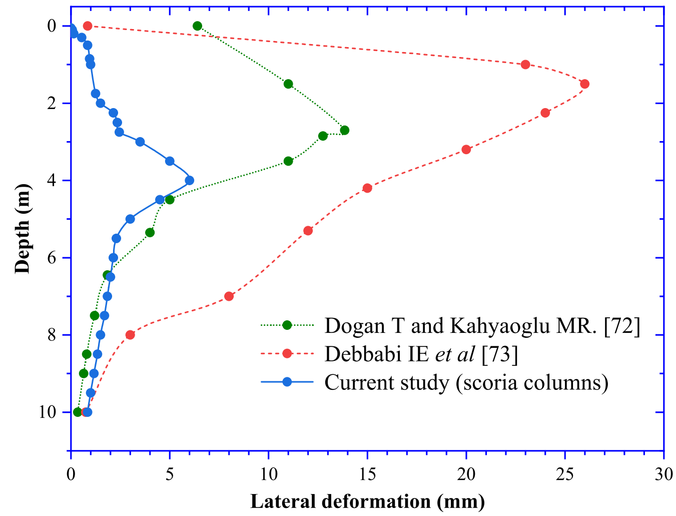


Fig. 12. Comparison of finding of the current study with previous studies.

response of the stone column reinforced clay to lateral deformation at various depths of the clay is illustrated for purpose of comparison. The resulting deformation pattern is in good agreement with finding of the current study. The maximum bulging (lateral deformation) in the three cases (including the current study) takes place at about 1/3 of the column length from the surface.

4. Conclusion

In the current study a comparative analysis between performances of CAC and SGC in lessening deformation of clayey soil was carried out. Based on findings of the work, the following conclusions are drawn;

- In the floating case, the scoria column reinforced soil settles less than the crushed aggregate reinforced one at all depths and horizontal distances from mid-point of the column group. This implies that inclusion of lightweight columnar materials in highly sensitive clay for soil reinforcement results in development of less vertical stress which contributes less to the resulting vertical deformation. Furthermore, deformation of the clay ground in the presence of floating SGC drops by 33.34%, 35% and 47.5% at depths of 5 m, 10 m and 15 m respectively as a result of inclusion of floating SGC. On the other hand, ground settlement of 16.67%, 10% and 37.5% at were witnessed at the stated depths due to inclusion of floating CAC.
- From the perspective of reducing horizontal deformation, the performance of crushed aggregate columns was by far better than the group of scoria gravel columns. The clay soil undergoes greater lateral deformation in the presence of scoria columns than the crushed aggregate columns.
- The end bearing scoria columns undergoes relatively greater deformation both in vertical and horizontal directions than the floating columns. For the crushed aggregate columns however the clay soil experienced greater deformation in the lateral direction when the floating case is considered. Hence, end bearing scoria columns obviously improves deformation performance of clay soil but it was found more effective than the CAC in the floating case. In relation to this, vertical deformation of the clay ground is reduced by 40%, 41.67% and 55.56% at depths of 5 m, 10 m and 15 m respectively due to inclusion of end bearing CAC. In the presence of SGC however, the settlement magnitude at the stated depths is found to be higher than that of CAC by 33.34%, 36.36% and 60% respectively.
- The deformation (both vertical and lateral) profile diminishes with increasing lateral distance from center line of the loaded area both for CAC and SGC.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] C. Zeynep, Experimental study on stress concentration factors in single and groups of end-bearing and floating stone columns. Master thesis, Middle East Technical University, https://etd.lib.metu.edu.tr/upload/12617342/index.pdf, 2014.
[2] K. Mani, K. Nigee, A study on ground improvement using stone column technique, International Journal of Innovative Research in Science, Engineering and Technology 2 (11) (2013). http://www.ijirset.com/upload/2013/november/73_A%20STUDY.pdf.
[3] K.S. Amith, V.R. Murthy, Numerical analysis of stone columns in soft clay with geotextile encasement and lime stabilization, Soil Dynamics and Earthquake Geotechnical Engineering (2019), https://doi.org/10.1007/978-981-13-0562-7_19.
[4] M. Fathi, A. Abdrabbo, A. Naema, Behaviour of single pile in consolidating soil, Alex. Eng. J. 54 (2015) 481–495, https://doi.org/10.1016/j.aej.2015.05.016.
[5] S.L. Shivangi, R. Bahadur, Suitability analysis of stone column materials with PLAXIS, Eng. Technol. Appl. Sci. Res. 12 (2) (2022) 8421–8425.
[6] S. Samaila, M.Y. Nor Zurairahetty, A. Kamarudin, M.S. Khairun Nissa, Numerical simulation with hardening soil model parameters of marine clay obtained from conventional tests, SN Appl. Sci. 3 (156) (2021). https://link.springer.com/article/10.1007/s42452-020-04115-w.
[7] S.F. Kwa, E.S. Kososov, Y.F. Mohammed, Behavior of different materials for stone column construction, J. Eng. Appl. Sci. 14 (4) (2019) 1162–1168.
[8] D.G. Haresh, D.L. Mittal, Ground improvement by using stone columns, Journal of Emerging Technologies and Innovative Research 2 (11) (2015).
[9] R.A. Nima, Numerical Analysis of Soft Clay Reinforced with Stone Columns, Master's thesis. Eastern Mediterranean University, Gazimağusa, North Cyprus, 2012.
[10] C. Jorge, Modeling stone columns, Materials 10 (2017) 782, https://doi.org/10.3390/ma10070782.
[11] J. Castro, M. Karstunen, N. Sivasithamparam, Influence of stone column installation on settlement reduction, Comput. Geotech. 59 (2014) 87–97.
[12] K.S. Beena, Ground improvement using stone column, in: International Conference on Recent Advances in Geotechnical Earth Quake Engineering Soil Dynamics, California, San Diego, 2010. https://scholarsmine.mst.edu/cgi/viewcontent.cgi?article=2920&context=icrageesd.
[13] M.O. Karkush, A. Jabbar, Improvement of soft soil using linear distributed floating stone columns under foundation subjected to static and cyclic loading, Civil

Engineering Journal 5 (3) (2019) 702, https://doi.org/10.28991/cej-2019-03091280.
[14] A.P. Ambily, S.R. Gandhi, Behavior of stone columns based on experimental and FEM analysis, J. Geotech. Geoenviron. Eng. 133 (4) (2007) 405–415, https://doi.org/10.1061/(ASCE)1090-0241.
[15] J. Castro, C. Sagaseta, Consolidation and deformation around stone columns: numerical evaluation of analytical solutions, Comput. Geotech. 38 (3) (2011) 354–362, https://doi.org/10.1016/j.compgeo.2010.12.006.
[16] K. Minna, A. Amardeep, BEST SOIL:Soft Soil Modelling and Parameter Determination, Chalmers University of Technology Gothenburg, Sweden, 2017.
[17] R. Shivashankar, M.D. Babu, S. Nayak, R. Manjunath, Stone columns with vertical circumferential nails: laboratory model study, Geotech. Geol. Eng. 28 (5) (2010) 695–706.
[18] S. Tabchouche, M. Bouassida, M. Mellas, Behavior of foundation on end bearing stone columns group reinforced soil, Geotechnical Engineering Journal of the SEAGS & AGSSEA 5 (4) (2019).
[19] R. SivaSankara, M. Chittaranjan, R.C. Ravi Kumar, K. Kowshik, Performance evaluation of stone column installed soft ground - a parametric study with numerical investigation, Int. J. Innovative Technol. Explor. Eng. 8 (2S) (2018).
[20] Y.F. Mohammed, S.Z. Bushra, A.H. Hanan, An Experimental analysis of embankment on stone columns, J. Eng. 20 (7) (2014).
[21] Y.F. Mohammed, A.A. Mohammed, S.A. Ahmed, Estimation of bearing capacity of floating group of stone columns, Engineering Science and Technology, an International Journal 20 (2017), https://doi.org/10.1016/j.jestch.2017.03.005.
[22] M. Haleh, H.B. Masoud, K.A. Ali, Numerical investigation of stone columns system for liquefaction and settlement diminution potential, International Journal of Geo-Engineering 8 (11) (2017), https://doi.org/10.1186/s40703-017-0047-x.
[23] F. Kirsch, Vibro stone column installation and its effect on ground improvement, Numerical Modelling of Construction Processes in Geotechnical Engineering for Urban Environment. Taylor & Francis 115–124 (2006).
[24] Z. Guetif, M. Bouassida, J.M. Debats, Improved soft clay characteristics due to stone column installation, Comput. Geotech. 34 (2007) 104–111.
[25] J. Castro, M. Karstunen, Numerical simulations of stone column installation, Can. Geotech. J. 47 (2010) 1127–1138.
[26] K.S. Watts, D. Johnson, L.A. Wood, A. Saadi, An instrumented trial of vibro ground treatment supporting strip foundations in a variable fill, Geotechnique 50 (2000) 699–708.
[27] S.I. Ai-Azzo, Treatment of expansive clayey soil in AL-Wahda district at Mosul city with crushed lime stone, Iraqi Journal of Earth Sciences 9 (2) (2009) 1–10.
[28] A.P. Mukesh, H.S. Patel, A Review on effects of stabilizing agents for stabilization of weak soil, Civ. Environ. Res. 2 (6) (2012). https://www.iiste.org/Journals/index.php/CER/article/viewFile/2432/2455.
[29] Z. Azhani, N. Ramli, Sustainable materials used as stone column filler: a short review, IOP Conf. Ser. Mater. Sci. Eng. 342 (2018), https://doi.org/10.1088/1757-899X/342/1/012001.
[30] V.V. Znamenskii, O.M. Hegazy, D.A. Sayed, The 3D numerical model of the stone column in soft clay soils, J. Phys. Conf. 1928 (2021), 012011, https://doi.org/10.1088/1742-6596/1928/1/012011.
[31] E. Fathi, R. Mohtasham, Numerical analysis of the reinforced stone column by geosynthetic on stability of embankment, Proceedings of the World Congress on Civil, Structural, and Environmental Engineering (CSEE'16) Prague, Czech Republic (2016), https://doi.org/10.11159/icgre16.112.
[32] J. Crucho, L. Picado-Santos, F. Silva, Cement treated volcanic scoria for low traffic road pavements in the Azores archipelago, Materials 14 (20) (2021) 6080, https://doi.org/10.3390/ma14206080.
[33] I.M. Aho, S.J. Uungwa, Engineering properties of scoria concrete as a construction material, Global J. Eng. Res. 14 (2015) 59–63, https://doi.org/10.4314/gjer.v14i1.7.
[34] I. Gratchev, C. Surarak, B. Balasubramaniam, E. Oh, Consolidation of Soft Soil by Means of Vertical Drains: Field and Laboratory Observations. 11th Australia New Zealand Conference on Geomechanics (ANZ 2012), 2012, https://doi.org/10.13140/2.1.2146.1760.
[35] K. Mahdi, J. Anwar, Improvement of soft soil using linear distributed floating stone columns under foundation subjected to static and cyclic loading, Civil Engineering Journal 5 (3) (2019), https://doi.org/10.28991/cej-2019-03091280.
[36] B.N. Adamu, Settlement analysis of pipe culvert situated in soft clay treated with prefabricated drains, Adv. Civ. Eng. (2022), https://doi.org/10.1155/2022/9569077.
[37] J.N. Afshar, M. Ghazavi, K. Hemmati, Analytical method for seismic bearing capacity of stone-column reinforced shallow foundations, International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics 7 (2010). https://scholarsmine.mst.edu/icrageesd/05icrageesd/session05/7.
[38] A.M. Hanna, M. Etezad, T. Ayadat, Mode of failure of a group of stone columns in soft soil, Int. J. GeoMech. 13 (1) (2013) 87–96, https://doi.org/10.1061/(ASCE)GM.1943-5622.0000175.
[39] J. Chai, J.P. Carter, Modelling soft clay behavior, in: Deformation Analysis in Soft Ground Improvement, Springer Netherlands, Dordrecht, 2011, pp. 7–55, https://doi.org/10.1007/978-94-007-1721-3_2, 18.
[40] V. Raju, J. Daramalinggam, Modern geotechnical practices, in: K. Ilamparuthi, R. Robinson (Eds.), Geotechnical Design and Practice. Developments in Geotechnical Engineering, Springer, Singapore, 2019, https://doi.org/10.1007/978-981-13-0505-4_4.
[41] M.Y. Fattah, B.S. Zabar, H.A. Hassan, Experimental analysis of embankment on ordinary and encased stone columns, Int. J. GeoMech. 16 (4) (2016), 04015102, https://doi.org/10.1061/(ASCE)GM.1943-5622.0000579.
[42] A. Maulana, A. Meilani, The Effectiveness of stone column spacing in reducing the potential of liquefaction, INERSIA 17 (2) (2021), https://doi.org/10.21831/inersia.v17i2.44413.
[43] L.M. José, S. Harish, R.D. John, Performance prediction of stone-column-supported foundations, Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering (2006), https://doi.org/10.3233/978-1-61499-656-9-1327.
[44] A.S. Mahmood, W. Qiyao, Numerical study on bearing capacity and bulging of the composite stone column, Open Civ. Eng. J. 15 (2021) 13–28, https://doi.org/10.2174/1874149502115010013.
[45] J.A. Black, V. Sivakumar, A. Bell, The settlement performance of stone column foundations, Geotechnique 61 (11) (2011) 909–922, https://doi.org/10.1680/geot.9.P.014.
[46] K. Mats, in: Plaxis 2D Comparison of Mohr-Coulomb and Soft Soil Material Models. Master Thesis, Luleå University of Technology, 2013.
[47] A.E. Santos, DEM Study of a Single Stone Column in a Clayey Stratum, Graduate Theses and Dissertation, 2017. https://scholarworks.uark.edu/etd/2617.
[48] P. Tai, Application of stone columns in foundations of transportation infrastructure, PhD thesis, School of Civil, Mining and Environmental Engineering, University of Wollongong (2017). https://ro.uow.edu.au/theses1/289.
[49] F. Yanbin, H. Siyue, Z. Sizhan, Y. Yong, Parameter analysis on hardening soil model of soft soil for foundation pits based on shear rates in Shenzhen Bay, China, Adv. Mater. Sci. Eng. (2020), https://doi.org/10.1155/2020/7810918.
[50] P.A. Vermeer, A double hardening model for sand, Geotechnique 28 (4) (1978) 413–433.
[51] Y. Liang, B.A. Izzuddin, Locking-free 6-noded triangular shell elements based on hierarchic optimization, Finite Elem. Anal. Des. (2022) 204, https://doi.org/10.1016/j.finel.2022.103741.
[52] W. Pan, W.A. Wheel, Y. Qin, A Six-node Triangle finite volume method for solids with a rotational degree of freedom incompressible material, Comput. Struct. 88 (23–24) (2010) 1506–1511, https://doi.org/10.1016/j.compstruc.2010.08.001.
[53] G.R. Liu, T. Nguyen-Thoi, H. Nguyen-Xuan, K.Y. Lam, A node-based smoothed finite element method (NS-FEM) for upper bound solutions to solid mechanics problems, Comput. Struct. 87 (2009) 14–26, https://doi.org/10.1016/j.compstruc.2008.09.003.
[54] F. Tornabene, S. Brischetto, N. Fantuzzi, M. Bacciocchi, Boundary conditions in 2D numerical and 3D exact models for cylindrical bending analysis of functionally graded structures, Shock Vib. (2016), https://doi.org/10.1155/2016/2373862, 2016.
[55] R.H. Muhammad, Numerical analysis of shallow foundations with varying loading and soil conditions, Buildings 12 (2022) 693, https://doi.org/10.3390/buildings12050693.
[56] V. Kokalanov, Numerical Simulation for Absorbing Boundary Conditions, Ruhr University Bochum, 2008.
[57] L. Yucheng, G. Gary, Effects of mesh density on finite element analysis, SAE Technical Paper 2013-01-1375, https://doi.org/10.4271/2013-01-1375, 2013.
[58] S. Kurra, P.R. Srinivasa, Effect of mesh parameters in finite element simulation of single point incremental sheet forming process, Procedia Materials Science 6 (2014) 376–382.
[59] D. Nasasira, K.S. Amit, Effect of mesh size on soil-structure interaction in finite element analysis, Int. J. Eng. Res. Technol. 9 (6) (2020).
[60] Y.F. Mohammed, A.A. Mohammed, S.A. Ahmed, Estimation of bearing capacity of floating group of stone columns, Engineering Science and Technology 20 (2017) 1166–1172, https://doi.org/10.1016/j.jestch.2017.03.005.
[61] G.S. Brian, A.M. Bryan, K. Minna, S. Nallathamby, Stone column settlement performance in structured anisotropic clays: the influence of creep, J. Rock Mech. Geotech. Eng. 8 (2016), https://doi.org/10.1016/j.jrmge.2016.05.004.
[62] F. Eiman, M. Reza, Numerical analysis of the reinforced stone column by geosynthetic on stability of embankment, Proceedings of the World Congress on Civil, Structural, and Environmental Engineering (CSEE'16) (2016), https://doi.org/10.11159/icgre16.112. Prague, Czech Republic.
[63] A. Zukri, R. Nazir, Numerical modeling techniques of soft soil improvement via stone columns: a brief review, IOP Confrence Series: Mater. Sci. Eng. 342 (2018), https://doi.org/10.1088/1757-899X/342/1/012002.
[64] T. Schanz, A. Vermeer, P. Bonnier, The hardening soil model: formulation and verification, in: Beyond 2000 Computional Geotechnics-10 Years, PLAXIS, Amsterdam, Netherlands, 1999, p. 281p.
[65] N. Noura, B. Khadija, O. Latifa, B. Lahcen, Numerical Simulations of Ground Improvement Using Stone Columns in Bouregreg Valley. Sustainable Civil Infrastructures, Springer, Cham, 2018, https://doi.org/10.1007/978-3-319-63889-8_6.
[66] M. Mehdi, K. Hossein, The use of stone columns to reduce the settlement of swelling soil using numerical modeling, Journal of Civil Engineering and Materials Application 1 (2) (2017) 45–60, https://doi.org/10.15412/J.JCEMA.12010203.
[67] T. Damtew, k Meaza, B. Adamu, Deformation analysis of cement modified soft clay soil using Finite Element Method (FEM), Heliyon 8 (2022), https://doi.org/10.1016/j.heliyon.2022.e09613, 2022.
[68] A.B. Negesa, Assessing the causes of time overrun in building and roadconstruction projects: the Case of Addis Ababa City, Ethiopia, J. Eng. 2022 (2022) 1–14, https://doi.org/10.1155/2022/8479064, 2022.
[69] A. Beyene, Y. Tesfaye, D. Tsige, A. Sorsa, T. Wedajo, N. Tesema, et al., Experimental study on potential suitability of natural lime and waste ceramic dust in modifying properties of highly plastic clay, Heliyon 8 (10) (2022), e10993, https://doi.org/10.1016/j.heliyon.2022.e10993.

[70] Y.T. Boru, A.B. Negesa, G. Scaringi, W. Puła, Settlement analysis of a sandy clay soil reinforced with stone columns, Studia Geotechnica Mech. (2022) 1–10, https://doi.org/10.2478/sgem-2022-0020, 2022.
[71] A. Grizi, W. Al-Ani, D. Wanatowski, Numerical analysis of the settlement behavior of soft soil improved with stone columns, Appl. Sci. 12 (2022) 5293, https://doi.org/10.3390/app12115293.
[72] T. Dogan, M.R. Kahyaoglu, Numerical study on the deformation behavior of geosynthetic-encased stone columns supporting embankments, Tek. Dergi 697 (2022) 12617–12634, https://doi.org/10.18400/tekderg.949826.
[73] I.E. Debbabi, R.M. Saddek, A.S.A. Rashid, A.S. Muhammed, Numerical modeling of encased stone columns supporting embankments on sabkha soil, Civil Engineering Journal 6 (8) (2020), https://doi.org/10.28991/cej-2020-03091569.
[74] R. Shivashankar, R.M.D. Dheerendra Babu, S. Nayak, V. Rajathkumar, Experimental studies on behaviour of stone columns in layered soils, Geotech. Geol. Eng. 29 (2011) 749–757, https://doi.org/10.1007/s10706-011-9414-0.
[75] M.G. Hailemariam, T.M. Damtew, B.N. Adamu, Consolidation attributes and deformation response of soft clay reinforced with vertical scoria drains under road embankment, Adv. Mater. Sci. Eng. (2023) 1–15, https://doi.org/10.1155/2023/2623062, 2023.
[76] M.A. Getnet, T.M. Damtew, W.M. Teyba, B.N. Adamu, Combined performance of polyethylene terephthalate waste plastic polymer and crumb rubber in modifying properties of hot mix asphalt, Adv. Mater. Sci. Eng. (2023) 1–14, https://doi.org/10.1155/2023/6320490, 2023.
[77] K.T. Narob, T.M. Damtew, T.B. Habte, B.N. Adamu, Evaluating the effectiveness of nonwoven geotextile-encased cinder gravel column in improving load-bearing and deformation characteristics of soft clay, Adv. Mater. Sci. Eng. (2023) 1–20, https://doi.org/10.1155/2023/1753757, 2023.
[78] A. Beyene, H. Merka, D. Tsige, Suitability analysis of vertically installed scoria gravel drains for enhancing consolidation performance of clayey ground, Results in Engineering 17 (2023), https://doi.org/10.1016/j.rineng.2023.100975.
[79] A. Beyene, N. Tesema, F. Fufa, D. Tsige, Geophysical and numerical stability analysis of landslide incident, Heliyon 9 (3) (2023), https://doi.org/10.1016/j.heliyon.2023.e13852.