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Research Article

Evaluating the Effectiveness of Nonwoven Geotextile-Encased Cinder Gravel Column in Improving Load-Bearing and Deformation Characteristics of Soft Clay

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Application of vertically installed columnar materials made of natural gravels or crushed aggregate is one of the commonly implemented practices to improve the performance of soft clay grounds under footing load. Alternative materials like cinder gravel also plays a reinforcing role when blended with soft clay. However, information on the precise extent to which a vertically installed cinder gravel column is effective in improving the properties of a clay foundation and its potential response to the permanently applied footing load has not been well documented in the literature. Hence, the current study specifically aimed at evaluating the effectiveness of geotextile-encased cinder gravel column in improving deformation and bearing capacity of soft clay ground. The experimental model which considered installation of a single geotextile-encased cinder gravel column into soft clay was considered. A cylindrical steel container was used in designing the experimental test. The container was filled with clay soil and the cinder gravel column was vertically installed through a replacement method. Finding of the study revealed that ultimate load-bearing capacity of the soft clay foundation after being reinforced with conventional cinder gravel was 1.85 times that of the untreated soft clay soil. The load-carrying capacity of the clay soil decreased with increment in diameter of the column whereas it is directly related to the volume replacement ratio. With regard to directional improvement, the vertical reinforcement performs better than the horizontal geotextile strips in cinder gravel column from bearing capacity improvement view point. In lessening settlement, however, application of horizontal geotextile discs at spacing ranging between half- and full-column diameter overweighs performance of the vertical encasement. In summary, application of geotextile encasement to the top 75% of the clay thickness is sufficient to come up with optimum improvement in bearing capacity and encasing the entire thickness is not necessarily required.

1. Introduction

Ground improvement techniques applied are tools used to lessen problems related to soft ground's unsuitability for engineering structures [1–5]. Soft clay is typically known for having low stiffness, usually an unconfined compressive strength of less than 50 kPa [6–9]. Granular columns have a significant practical role in the treatment of soft ground like clay with the intention of mitigating the engineering performance of weak soil [10–16]. Granular columns can be made of different materials, such as shredded bricks, crushed waste stone, crushed old concrete, crushed aggregate, and natural gravel [17]. Among the many ground improvement techniques adopted, granular columns are usually applied in relatively deep soil strata [18, 19]. The construction of a granular column consists of the partial replacement or lateral compaction of soft soil, typically penetrating the weak strata in a compact vertical column of stones [20]. Inclusion of columns in soft soil results in the formation of a composite material that is stiffer than the original soil. It literally improves load-bearing capacity and shear resistance. Total settlement reduction and facilitation of consolidation rate are also beneficial effects of columnar improvement methods in soft soils [21–23]. The Ethiopian Rift Valley is known for its large coverage of volcanic materials like pumice, scoria, and cinder [24]. Damtew [25] and Newill and Aklilu [26] reported that cinder is one of abundantly found in volcanic prone areas of the Ethiopian Rift. From an application point of view, cinder gravel is widely used for the improvement of weak subgrade materials and as replacement material for production of light-weight concrete. However, its application and use as columnar reinforcement for weak grounds like clay have not been well practiced.

Many studies have been conducted to investigate the performance of using columnar materials (stone, lime, and sand columns) in improving the bearing capacity and deformation characteristics of soft clay foundations. Jia-Jun [27] in the study on settlement behavior of soft clay soil reinforced with stone column, investigated the critical influence of stone column on performance of clay soil. Finding of the study revealed that application of stone column to half depth of soft clay soil increased its load-carrying capacity by two folds. It was also reported that an increment in the area replacement ratio led to a significant reduction in the permanent vertical deformation of the clay soil. The study conducted by Fahmi and Kolosov [28] indicated that the encased stone column performs better than the plain column provided without any vertical encasement. Thanaraj [29] conducted a series of laboratory-based experimental models to compare the performance of a geogrid-encased stone column with a marble waste column and a pebble column. Finding of the study indicated that the problem of column bulging as a result of loading was and controlled overcome by the geogrid encasement. It was also stated that the marble column contributed better than the stone column and pebble column in lessening the vertical deformation of the poor soil. Kumar Soni [30], in the experimental study targeted at evaluating the performance of jute geotextile-reinforced stone columns, reported that the systematic application of stone columns to soft clay improved Californian bearing ratio of the clay soil. The works of Simon Magnusson [31] and Wood [32] suggested that stone column lengthening does not significantly contribute to settlement reduction in soft clay ground. Contrarily, Znamenskii [33] reported that the length of columnar objects directly affects the volume replacement ratio, and hence, its influence on the deformation performance of soft soils should not be understated.

In summary, the existing works on stabilizing soft clay foundations by using columnar materials are still limited to the following aspects: (i) No precisely documented information exists regarding the employment of cinder gravel columns for soft clay improvement, and the study objects give emphasis to the performance of stone, sand, and lime column. (ii) Though the effect of vertical encasing has been extensively studied, none of the existing studies incorporated the pertinent potential of horizontally situated geotextile discs in improving the properties of clay foundations. (iii) In many cases, the type of geosynthetic material used as an encasement is geogrid, and the reinforcing capacity of geotextile materials was hardly dealt with. (iv) The potential effect of the combination of the vertical and horizontal geotextile reinforcements has not been addressed.

Therefore, this paper explores the performance of a cinder gravel column in a soft clay foundation from the perspectives of bearing capacity and deformation. An investigation on the improvement potential of horizontally situated geotextile discs is incorporated. Comparative analysis is also carried out between the responses of horizontal geotextile strips and the vertical encasements to the applied footing load. The effects of variation of the parameters such as encasement length, horizontal disc spacing, and cinder column diameter are studied.

2. Methods and Materials

2.1. Material Characterization

2.1.1. Clay Soil. The clay soil used in the study was sampled from clay-dominated areas in the Jimma Institute of Technology, Ethiopia. The soil sample was taken from a depth of 2.5 m below the ground surface. The collected sample was spread out on a plastic sheet for about a month in order to let the soil get dry. The dry soil was crushed and sieved through a 10 mm sieve to prepare a soft clay soil bed. Wet sieve analysis and hydrometer analysis were carried out per ASTMD1140 (ASTM, 2017c) for coarse grains and ASTM D7928 (ASTM, 2017b) for fine grains. The other physical properties of the soil sample were determined according to ASTM standards, as depicted in Table 1.

2.1.2. Cinder Gravel. The cinder gravel material was collected from outskirts of Adama city which is one the areas situated in Ethiopian Rift Valley. In order to investigate the critical effects of variation in cinder gravel diameter, three different dimensions (30 mm, 40 mm, and 50 mm) were considered. There is no clearly established standard for the preparation of a cinder gravel column with respect to particle size, gradation, and density. The optimal size of the particles is hence chosen from a practical perspective in order to ensure simple column filling and a good degree of compaction [34]. Stone aggregates with particle sizes ranging between 2 and 10 mm were used as stone column material by many researchers [20, 35–38]. The usage of this particular particle size range is based on the fact that in practice, stone columns with diameters (D_c) ranging between 0.6 and 1.0 m are often built using crushed aggregates/gravels of size (d) = 25–50 mm. As a result, for many practical purposes or prototypes, a D_c/d ratio in the range of 12–40 is commonly recommended [39]. Other than stone aggregate, granular columns have been done by using sand [40]. For this study, cinder gravel particle sizes ranging from 0.075 mm to 4.75 mm were used and the particle size distribution is shown in Figure 1.

The coarse aggregate of scoria has a lower specific gravity than the fine aggregate scoria gravel, implying that fine scoria has more degree of compaction than coarser scoria [41]. The conducted gradation test revealed that the D_{10}, D_{30},

Table 1: Physical properties of the soft clay soil.

SN	Soil index properties	Values
1	Natural moisture content	61.5 ± 1
2	Liquid limit (%)	85.20
3	Plastic limit (PL) (%)	35.50
4	Plasticity index (PI) (%)	49.70
5	Activity	0.78
6	Specific gravity (Gs)	2.68
7	Classification (USCS)	CH, fat clay
8	Dry unit weight (kN/m^3)	10.20
9	Bulk unit weight of clay bed (kN/m^3)	16.47
10	Cohesion (kN/m^2)	38.50

Figure 1: Sample of cinder gravel used for the experimental model.

and D_{60} values are 0.464, 1.167, and 2.331 mm, respectively. The coefficient of uniformity and coefficient of curvature is equal to 4.03 and 1.26, respectively. Physical properties of the materials used in the study including properties of scoria summarized in Table 2 were obtained via conducting intensive laboratory tests. Scoria by its nature is known for its open voids, cavities, and air-trapped vacuums (bubbled voids) as it is volcanic material. Using scoria gravel directly for determination of its shear strength parameters gives rise to misleading results. Hence, the compacted and compressed state of the material (at 70% relative density) has to be used in order to obtain its real shear strength parameters. The 70% relative density is roughly equivalent to 95% proctor. Hence, the internal friction of the scoria material was determined at 70% relative density. The friction angle obtained at 70% relative density is a friction angle at which the material reaches its maximum compressive volume change up on exertion of external stress.

X-ray diffraction (XRD) test was conducted to determine its chemical properties (Figure 2 and Table 3). To determine the mineralogical phases present in the cinder gravel samples, XRD analyses were carried out. Representative oven-dried cinder gravel samples were crushed until a powder passes the No. 200 (0.075 mm opening) sieve. The powder samples were step-scanned from 10° to 75° (2θ) with 1 second time step and under continuous scanning speed. Testing and analysis were conducted by setting voltage of 30 kV with 25 mA and the scanning time for XRD test was 0.02°/sec. As indicated by the chemical analysis, silicon dioxide (53.7%) was the most dominant chemical found in the cinder material, followed by aluminum oxide and ferric oxide, 14.8% and 10.1%, respectively.

Table 2: Physical properties of cinder gravel material.

SN	Index properties	Value
1	Average densest dry unit weight (kN/m^3)	13.6
2	Average loosest dry unit weight (kN/m^3)	11.74
3	Gradation type	Well graded
4	Specific gravity (SSD)	2.5
5	Water absorption capacity (%)	0.5
6	Cohesion (kN/m^2)	0.06
7	Angle of internal friction (°) at 70% of relative density	40.5

Wet sieve analysis and hydrometer analysis were carried out per ASTMD1140 (ASTM, 2017c) for coarse grain and ASTM D7928 (ASTM, 2017b) for fine grain. Figure 3 represents the gradation and particle size distribution of both the soft clay and cinder gravel. The percentages of gravel, sand, silt, and clay in soil is 0.27%, 3.87%, 63.63%, and 32.27%, respectively. The clay soil has unconfined compressive strength of less than 50 kPa, and hence, it is categorized as soft clay type.

2.1.3. Nonwoven Geotextile. In practical cases, geotextiles are used for encasement to enhance the performance of column materials with respect to load-carrying capacity [42, 43]. The geotextile used in the current study is of the UV-stabilized nonwoven type and is made of virgin polypropylene polymer. The major functions of geotextiles are separation, filtration, drainage, reinforcement, and membrane protection [38, 44]. Filtration, separation, reinforcement, and erosion control are the main purposes of nonwoven geotextiles [45, 46]. The use of nonwoven geotextile as horizontal and vertical reinforcement has also been reported in wide range of literature. In relation to this, the type of geotextile material used in the current study has been proved to be effective in transportation, environmental, hydraulic, and civil engineering applications [47–50]. In relation to this, nonwoven geotextile material specifically was applied for encasement purpose in the study. The encasement plays pertinent roles in further mitigating the bearing capacity of the soft soil treated with cinder gravel column. Geotextiles are commonly made of petroleum byproducts such as polymer, polyethylene, and polypropylenes. They are known for their important engineering properties such as tensile strength, burst and puncture strength, modulus of elasticity, permeability, resistances to wear, tears, and abrasion and adverse environmental conditions [5, 51]. Introduction of horizontal strips of geotextile in compressible soil enhances the tensile strength of the soil. Basically, the strength gain in soil due to the introduction of horizontal strips of geotextile is attained by three mechanisms. First, lateral restraint develops via the interfacial friction between geotextiles and soil grains. Second, a potential bearing surface failure plane develops an alternate, higher shear-strength surface. Thirdly, the strips provide a membrane-type of support to bear the external loads

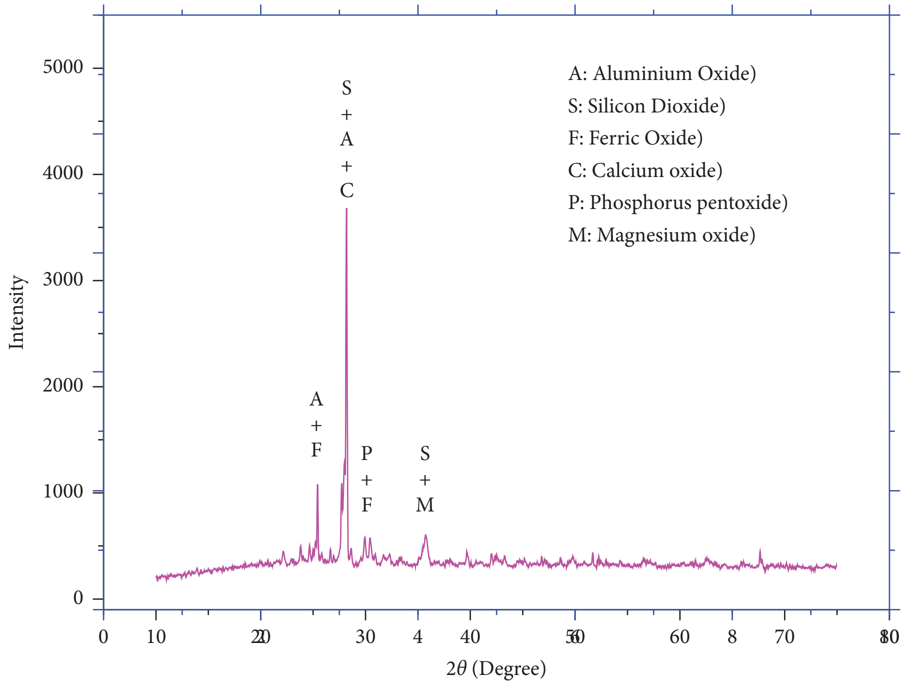

Figure 2: X-ray diffraction patterns for the cinder gravel material.

Table 3: Chemical compositions of the cinder gravel material.

SN	Chemical compositions	Chemical formulas	Weight (%)
1	Silicon dioxide	SiO_2	53.7
2	Aluminum oxide	Al_2O_3	14.8
3	Ferric oxide	Fe_2O_3	10.1
4	Calcium oxide	CaO	5.1
5	Phosphorus pent oxide	P_2O_5	4
6	Magnesium oxide	MgO	3.7
7	Potassium oxide	K_2O	2.3
8	Titanium oxide	TiO_2	2
9	Disodium oxide	Na_2O	1.8
10	Barium oxide	BaO	1.2
11	Strontium oxide	SrO	1
12	Manganese oxide	MnO	0.7

[13, 51]. Furthermore, the horizontal strips of geotextiles act as a reinforcing element to the soft clay helping to provide a stronger structural material. The strips are capable of transferring their strength to the soil being reinforced. Geotextiles effectively allow water to easily pass through while filtering out fine materials that can weaken the soil. By doing so, geotextiles perform well in enhancing the reinforcement role which in turn enhances the frictional resistance of the soft clay [52–54]. The physical and mechanical properties of the geotextile material are summarized in Table 4. Properties of the nonwoven geotextile were adapted from manufacturing standards and specifications of the local manufacturer named "GEOSYNTHETICS INDUSTRIAL WORKS PLC" headquartered in Addis Ababa, Ethiopia. Figure 4 represents the geogrid material required for vertical and horizontal reinforcement.

2.2. The Experimental Design

2.2.1. Test Setup. The existing reality and current practices demonstrate that there are no specifically well-established design guidelines for column materials [55]. The model tests were carried out by using a 4 mm tick cylindrical test tank made of stainless steel with a diameter of 420 mm and a height of 300 mm. Malarvizhi and Ilamparuthi [56] stated that the failure zone is spread over a radial span of approximately 1.5 times the diameter of the periphery. The tank was selected in such a way that the corresponding stress could remain minimal at the border. The container is sufficiently rigid and exhibited no lateral deformation during preparation of the cinder gravel bed and during the overall test process. The empty steel tank was manually graduated to a 50 mm vertical interval to monitor the fill stages and deformation of the clay material (Figure 5).

2.2.2. Preparation of the Soft Clay Bed. Air-dried clay was pulverized and checked for initial moisture content before being used in each test clay bed. As required, more water was added and thoroughly mixed to create a uniform paste, resulting in a moisture content of 61.5% (equal to the moisture content of the site) and the clay soil had unconfined compressive strength of 38.5 kPa). The clay bed was prepared in a medium test tank and placed in 6 layers, each 50 mm thick. Before filling the tank with the clay soil, the inner box face-walls were coated with a thin layer of grease to reduce the friction between the clay and the tank wall. Hence, the grease coat has no effect on smearing and hydraulic conductivity of the interface between the cinder

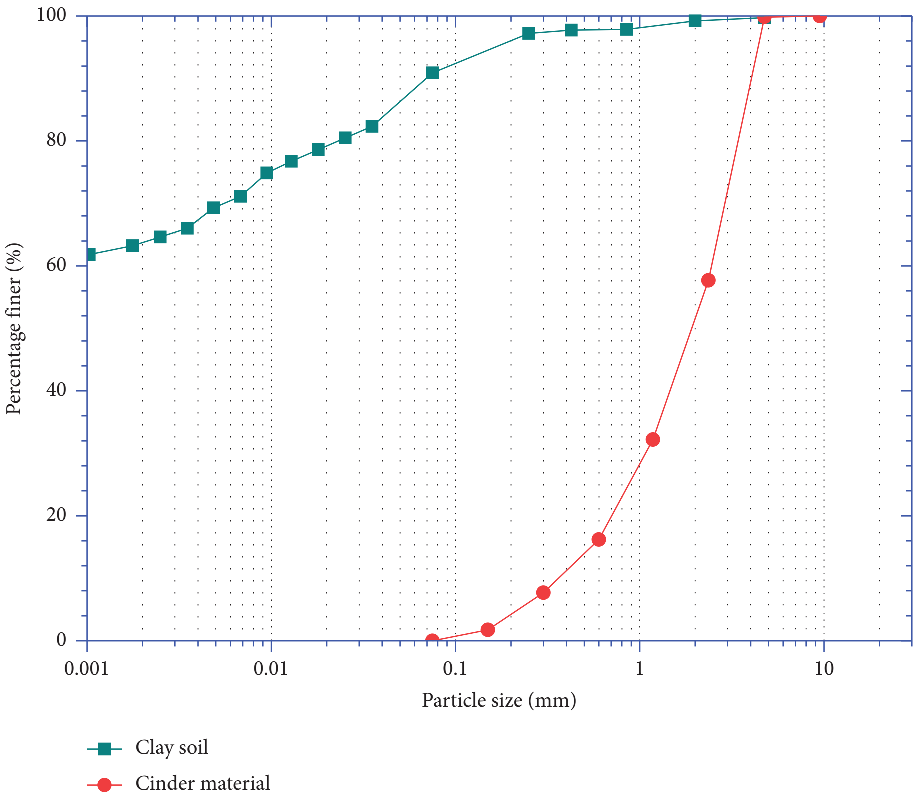

Figure 3: Particle size distribution of the clay and cinder gravel used.

Table 4: Some physical and mechanical properties of geotextile material.

SN	Tested property	Values
1	Grab tensile strength (N)	450
2	Elongation (%)	65
3	Californian bearing ratio (CBR) puncture strength (N)	1400
4	Trapezoid tear strength (N)	190
5	Index puncture strength (N)	300
6	Permeability (m/s)	$100 * 10^{-3}$
7	Permittivity @ water 20°C (S^{-1})	2.1
8	Apparent opening size (microns)	175
9	Thickness under 2 kPa (mm)	1.5
10	Mass per unit area (g/m^2)	120
11	Oxidation resistance (% day)	90/14
12	Ultraviolet protection (% hr)	70/500
13	Chemical resistance	Excellent
14	Microbiological resistance	Excellent
15	Roll width (cm)	590
16	Roll length (m)	100

column and the surrounding soil. Additionally, to reduce friction between the soil and the steel tank, the inner surface of the tank was entirely covered by using thin plastic sheets and the overlapping parts of the sheets were covered by using a duct tape (Figure 6).

Shear strength of the clay is significantly affected by its water content. So, it is necessary to conduct all experiments without varying the water content to possibly compare the performance of the cinder gravel column with and without geotextile. To maintain similar properties throughout the tests, the clay bed was prepared with 61.5% of moisture content and 16.5 kN/m^3 unit weight in all cases. A water content that corresponds to the unconfined compression strength result of the site was considered. The clay was thoroughly mixed by hand to obtain a uniform and consistent paste. Soft clay bed construction was carried out using a unit weight-control approach. Apart from the in-situ density and moisture content, the specimens were tested for shear strength as well. Unconfined compressive strength (UCS) tests were undertaken on two tanks filled with clay beds in order to check the similarity and consistency of the UCS of the clay material obtained from the field. The test specimens have diameters of 38 mm and heights of 76 mm. The samples' UCS value varies between 37.18 and 38.5 kPa. However, it is difficult to conduct UCS test using UCS machine on all test beds since it takes up a large area and leads to deformation of the soil bed. The UCS tests were hence performed on all clay beds using a pocket penetrometer, and the obtained results range from 45 to 46 kPa. As compiled in many literature studies, pocket vane shear tests were utilized to conduct UCS on soft clay beds. Pocket penetrometers can also be used to test the UCS of remolded soft clay beds [42, 57, 58].

The unconfined compressive strength tests of the soft soil bed were conducted around the periphery of the test tank. Care was taken to ensure that no significant air voids were left out in the clay bed. The operation was repeated until the


(a) (b)

Figure 4: (a) Geotextile for VECGC (vertically encased cinder gravel column), and (b) geotextile disc for HRCGC (horizontally reinforced cinder gravel column).

(a) (b) (c)

Figure 5: Preparation of test tank: (a) marking test tank at 5 cm vertical spacing to control compaction, (b) marked test tank, and (c) greasing and covering inner surface of the test tank with plastic sheet.

soil bed achieved its final height. After the soft soil bed was prepared, the bed was covered carefully with a plastic plate and moist cloth and kept for two days to maintain uniform moisture throughout the clay fill. In all soil bed preparation experiments, the same approach was applied.

2.2.3. Construction of Cinder Gravel Column (CGC). The cinder gravel column was constructed using a replacement method. To access the full-limiting axial stress, the diameter of the pile is to be taken as at least one-fourth of the depth of the column [59–61]. The location where to install the cinder gravel column in the test container was properly marked to let the centroid of the column coincide with the axis application of the applied axial load. A casing pipe having an outer diameter equal to the diameter of the cinder gravel column was used to install the cinder gravel column. For the current study, steel pipes with outer diameters of 50 mm, 40 mm, and 30 mm and thicknesses of 2 mm were used. The length of the cinder gravel column constructed was 300 mm as an end bearing, and also the floated cinder gravel columns for lengths of 25%, 50%, and 75% of the total thickness of the clay bed were studied. Grease was slightly applied on both the inner and outer surfaces of the pipe for easy penetration and withdrawal without causing any significant disturbance to the surrounding soil. The steel pipe was inserted using strain-controlled compression loading in a Wykeham Ferrance loading frame (Figure 7).

The soil was scooped out from the tube using a special auger. The pipe was withdrawn and twisted slowly during

(a) (b) (c) (d)

Figure 6: Preparation of soft clay bed: (a) mixing air-dried clay soil, (b) placing and controlling during filling test tank with clay paste, (c) tightening with a plastic sheet to keep the moisture content of the clay bed, and (d) covering with a wet cloth for 48 hours.

(a) (b) (c) (d) (e) (f)

Figure 7: (a) Greasing open-ended pipe, (b) inserting open-ended pipe into clay bed, (c) scooping out soil in the pipe, (d) twisting pipe to withdraw, (e) pouring cinder gravel to the prepared hole for cinder gravel column, and (f) compaction of cinder gravel column in to layers.

the lifting process. This is to prevent the intrusion of the surrounding clay soil into the cinder gravel column or neck formation in the geotextile in the case of ECGC (encased cinder gravel column) due to the lateral thrust of the surrounding clay. The cinder gravel was moisturized with 5% water content to keep it free from absorbing water from the surrounding clay soil during the construction. The construction of a cinder gravel column was done by filling to a height of $D_c/2$ (half of the diameter of the cinder column) and continuing until the hole was filled, exactly as described by Rezaei [62]. To reach a compacted height of 25 mm, cinder gravel was charged into the hole in layers with a calculated quantity of 70 gram. The cinder gravel was compacted using a 2 kg weight and a 20 mm rod metal width. The cinder gravel was compacted with 2 kg and 20 mm width of rod metal and the free-falling height is 100 mm, with 15 blows dropped to each layer to fulfill the density of 12.98 kN/m^3 (equal to 70% of the relative density to ensure that it does not create any disturbance to the surrounding soft clay by bulging laterally [63].

The techniques for constructing reinforced cinder gravel columns were the same as for CGC (cinder gravel column) with the exception that a geotextile was placed before the cinder gravel or a circular disc geotextile was placed horizontally at the appropriate interval. Similarly, cinder gravel columns reinforced with horizontal strips were constructed by pushing down the circular strips to the desired positions with the help of 20 mm-diameter metal rods. After the installation of the column, the top surface of the container was covered with a plastic sheet and kept for two days as the curing period to ensure uniform moisture. Any form of displaced soil on the surface was removed and trimmed to make the surface leveled. In the case of reinforced cinder gravel columns, any protruding geotextile was cut and made level with the surrounding clay surface to allow even distribution of the plate load. Figure 8 represents the installation of the vertical geotextile encasement in the clay soil.

In a practical case, it is undeniable that it is very challenging to suitably construct granular columns in soft clay with high moisture content. During installation phase of the cinder column material, first the soil mass where the column is to be provided would be removed by using boring machines down to the required depth. The installation process is carried out by using a systematically designed steel tube whose bottom end is closed to avoid the intrusion of water into the tube. The pipe mold is used to attain the needed geometry and shape of the cinder column. Besides, it provides lateral support to the exposed face of the excavated hole. The cinder material is then poured into the steel tube and compacted, and the horizontal strips are provided at the needed interval. After completing the pouring and compaction process, the tube is removed by opening its bottom tip. In this process, the construction of cinder columns in highly saturated clay soil can be implemented.

Apart from the alternatives stated above, another possibility may be using the drainage method. In order to overcome the challenging workability issues related to drainage, draining mechanisms such as preloading can possibly be implemented. Before the placement of the actual structural load, surcharge in the form of preloading is used for the prior intention of facilitating the water dissipation rate from the clay mass. Therefore, the construction process can be executed without facing any further hardship.

2.2.4. Experimental Test Procedure of the Cinder Gravel Column. According to Malarvizhi and Ilamparuthi [56], the loading plate diameter in the test tank should be 2 to 2.3 times the diameter of the single column. Barksdale and Bachus [64] claimed that a stone loaded with a rigid plate over an area wider than its diameter has a higher ultimate load-carrying capacity than a column of stone loaded exactly over its top surface (plate diameter is equal to that of the stone column). A circular steel plate with a diameter of 100 mm, 80 mm, and 60 mm was used for cinder gravel columns with diameters of 50 mm, 40 mm, and 30 mm. As stated by the authors in [52, 65], the failure zone is spread over a radial span of approximately 1.5 times the diameter of the column. The dimension (diameter) of the test tank (container) was selected in such a way that the corresponding stress could remain minimal around the container face. Yada and Ramjiram et al. [7, 13] reported that there is no well-established rule devised to scale the diameter of granular columns for the purpose of experimental design, even though it has been pointed out that the test tank has to be at least 1.5 times the diameter of granular columns. In the practical construction scene, stone columns usually have a diameter ranging from 0.5 to 0.75 m. Therefore, in this study, the diameters and lengths of the cinder gravel column were varied only for the purpose of conducting a parametric study, and the dimensions were increased with the concept of an arithmetic series such that their common difference is 10 mm. The diameters were varied without worrying about boundary effects since the effect of proximity to a boundary applies to all considered dimensions. The diameter of the footing size used for the present study was about two times the diameter of a single cinder gravel column. The load was applied through a proving ring with a constant displacement rate of 1 mm/min. With regard to the size of the circular plate, some literature recommends that the minimum diameter of the test tanks has to be at least 5 times the diameter of the circular footing. In fact, it is impossible to completely avoid the adverse impact of boundary effects in almost all of the experimental-based models. However, the considered dimensions of the test tank ought to be large enough [5]. Since the loading was so fast, it was essentially an undrained condition, which simulates loading as soon as construction of the considered structure is completed [2]. Loading was considered for settlements up to 25% of the foundation diameter. The loading has to be applied until the settlement exceeds 10% of the foundation diameter [59]. Figure 9 represents the pocket penetrometer test and layout of the loading frame considered in the experimental model.

The loading plate shall be mounted concentrically above the CGC. The settlement and load of the footing during the loading were measured by using LVDT (linear variable differential transformer). The thickness of the loading plate

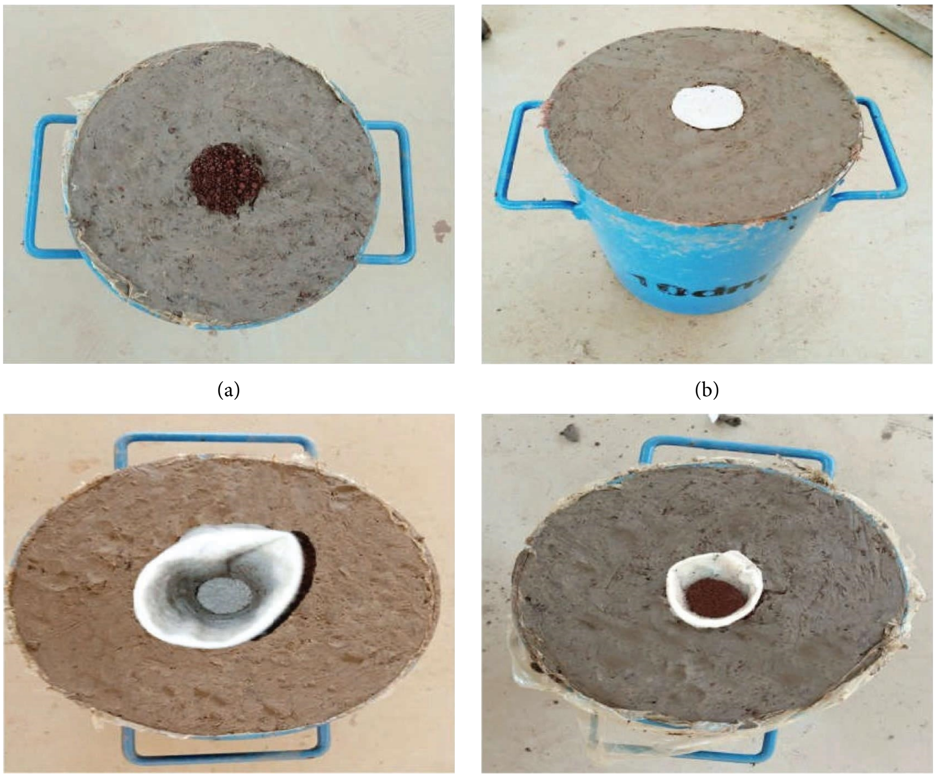
(a) (b) (c) (d)

Figure 8: (a) Unreinforced CGC, (b) HRCGC, (c) HVRCGC (horizontal-vertical reinforced cinder gravel column), and (d) VECGC.

was 10 mm selected in such a way that it is sufficiently rigid. Soil samples for moisture content were also collected from different depths of clay bed after loading accomplished, and it was found to be almost uniform with ±1% variation.

2.2.5. Feasibility Test. Pilot tests were conducted to refine the procedure for material mixing, compaction of soil layers, the viability of soil auguring, and the construction of a CGC without collapse. So, the potential for complications was identified before actual experiments were carried out. How much water is necessary to reach 61.5% of the water content and how the water content uniformity of the tank is to be maintained were assessed before the actual test was performed. It also ensured an estimation of the viability of compaction of the cinder gravel, the number of blows to use, and the compaction effort needed to attain the required relative density of CGC.

3. Results and Discussions

3.1. The Influence of Diameter of Cinder Gravel Column on Bearing Capacity and Deformation. To investigate the effects of column diameter, three different diameters (30 mm, 40 mm, and 50 mm) were used. Figure 10 represents the essential effects of cinder column diameter variation on both vertical deformation and the ultimate bearing capacity of the clay foundation. By changing the diameter of the column, the change in ultimate bearing capacity was observed. The proposed footing size was twice the diameter of the CGC, and the area of the column was 25% of the footing area. The experimental analysis result revealed that as the diameter of the cinder gravel column decreases, load-carrying capacity of the improved soft clay soil increases. For the CCGC (conventional cinder gravel column) with a diameter of 40 mm and 30 mm, the percentage increment in bearing capacity over the 50 mm diameter is 24.3% and 54.1%, respectively.

Ali [42] examined the effect of column diameter for an area ratio of 25% on the bearing capacity of the improved soft soil (Cu = 6-7 kPa) with an unreinforced stone column and found that as the column diameter decreased from 50 mm to 30 mm, the bearing capacity of the ground improved by about 42%. However, Verma [20] in the study on the investigation of the effect of stone column diameter on bearing capacity concludes that an increase in column diameter from 32 mm to 50 mm improved the ultimate bearing capacity of clay soil by 52% for a group of five columns. By keeping the size of the plate footing and other parameters constant, a decrease in the diameter of the granular column can significantly enhance the bearing capacity of soft soil (Figure 11).

3.2. Effect of Length of the Reinforcing Cinder Gravel Column. Lengths of CGC equivalent to 25%, 50%, 75%, and 100% of the total length of the clay bed (l) were considered to investigate the effect of variation in length of CGC on the

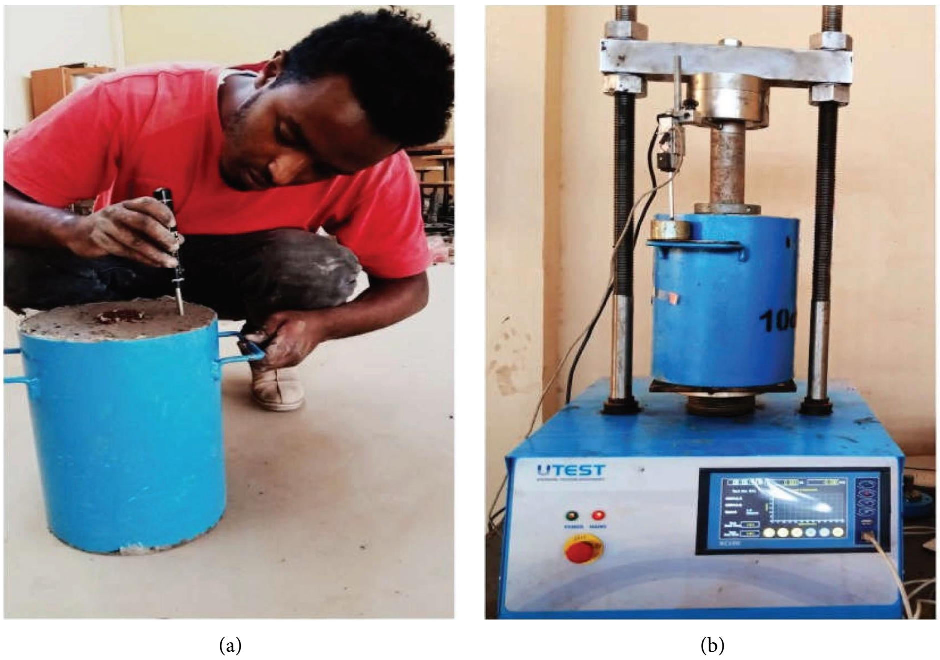

Figure 9: (a) UCS test using pocket penetrometer, and (b) the overall test model subjected to footing load.

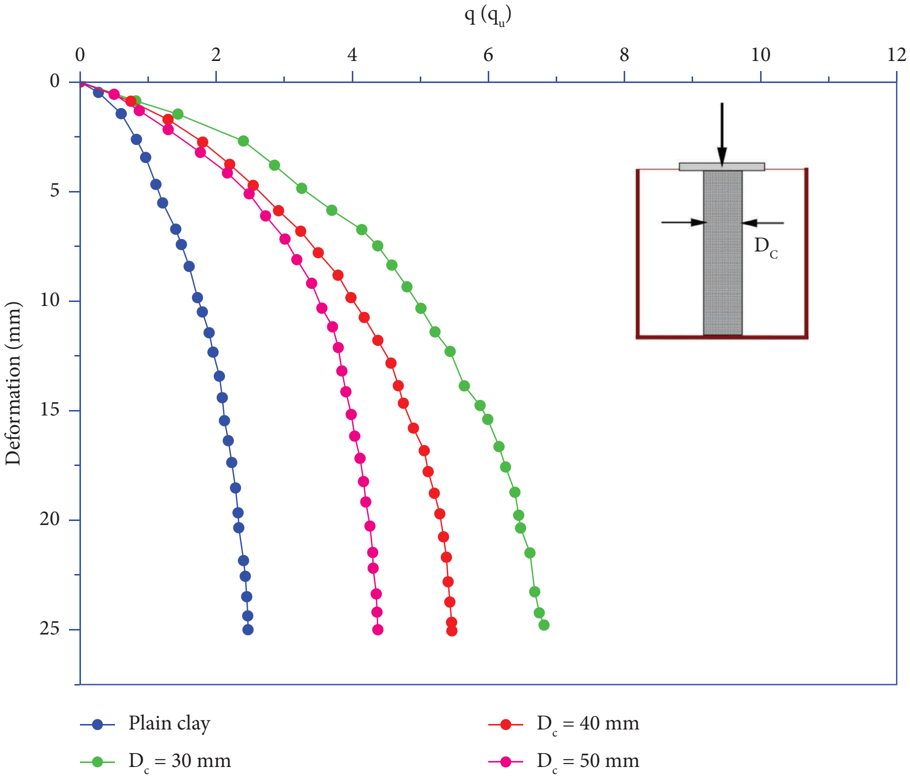

Figure 10: q/q_u (ratio of applied vertical stress and unconfined compressive strength) versus settlement (S) curve for various diameters of cinder gravel column.

ultimate strength of the cinder gravel column and clay soil as well (Figure 12). As column length (y) increases, soil replacement will increase with cinder gravel, thereby increasing bearing capacity. The resulting increments in ultimate bearing capacity of soft clay treated with CGC for the 25%, 50%, 75%, and 100% column length increment were 24%, 50%, 78%, and 85%, respectively. With the length of the cinder gravel column getting longer, the performance

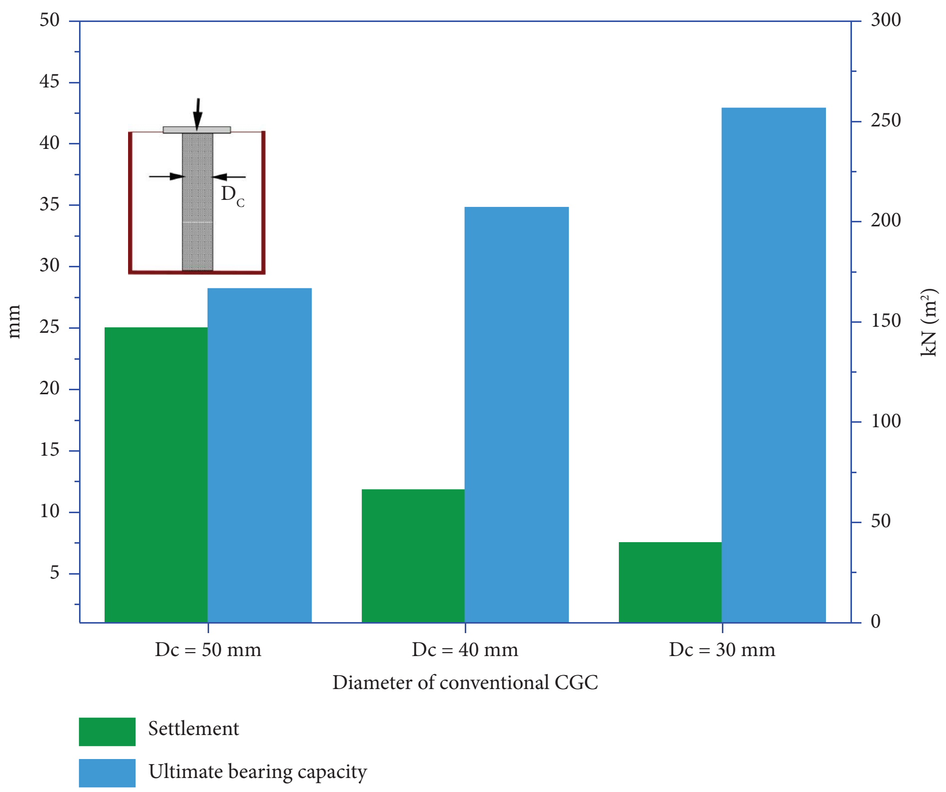

Figure 11: Effect of column diameter on ultimate bearing capacity- settlement relationship for improved soft clay soil.

enhancement also gets improved. With regard to column length, the findings of Ali [42] have a similar pattern to the findings of the current work. However, the increment rate in the bearing capacity began falling immediately as the column length exceeded 75% of the total clay thickness, and no significant improvement was observed afterwards. Various researchers recommended critical column length to be used for soft clay improvement. Accordingly, Fattah [66], Ambily and Gandhi [36], and Mohanty and Samanta [61] pointed out that a column length ranging between 4 and 6 times the diameter of the column is preferred to achieve optimal improvement, above which no substantial improvement in load-bearing capacity is expected. As depicted in Figure 13, the settlement of footing decreases as the ultimate bearing capacity increases for 90 kPa footing load.

3.3. Effect of the Vertical Encasement Length on Ultimate Bearing Capacity of Soft Clay. The nonwoven geotextile encasement with various lengths (25%, 50%, 75%, and 100% of the total thickness of the clay bed) was considered to examine the critical effects of encasement length on the ultimate strength of the cinder gravel column. A gradual increment in encasement length by 25%, 50%, 75%, and 100% of the total height of the clay bed resulted in a rise in the ultimate bearing capacity of soft clay treated with CGC by 40%, 69%, 86%, and 91%, respectively, over that of a conventional cinder gravel column. As indicated in Figure 15, an enlargement of the encasement length mitigated the ultimate strength of the cinder gravel column by far. In relation to this, as encasement length increases, the ultimate strength increases. However, the increment was at a decreasing rate. Similarly, the findings of Ali [42] demonstrated that as the length of the encasement increases, so does the carrying capacity of the floating stone column. Chamling [67], in the study on the behavior of encasing stone columns for undrained shear strength of soil, concluded that for clay soil with low undrained shear strength, the bearing capacity apparently gets improved with enlargement in the length of geotextile encasement, even though at a decreasing rate. Besides, it was also pointed out that the encasement length contributes much to the mitigation of column stiffness. The influence of the reinforcement length in sand columns with a diameter of 50 mm and 75 mm was examined by Kumar [68], who found that the load-carrying capability of a reinforced sand column decreased with a reduction in the length of the geotextile reinforcement. However, the fall in geotextile encasement length from 100% to 50% of the soil thickness resulted in no significant impact on the loading capacity. Figure 14 shows the q/c_u versus s/D_f curve for various encasement depths.

Furthermore, Bonab [69] in the study on the examination of the effects of encasement length for three different nonwoven geotextile lengths concluded that extending the nonwoven geotextile length from half to the full length of the soil thickness improved the bearing capacity by 11.1% and 7.5% for column diameters of 80 mm and 100 mm, respectively. Similarly, increasing the encasement length from half to the full length of CGC increases the bearing capacity by 12.9% in the current study.

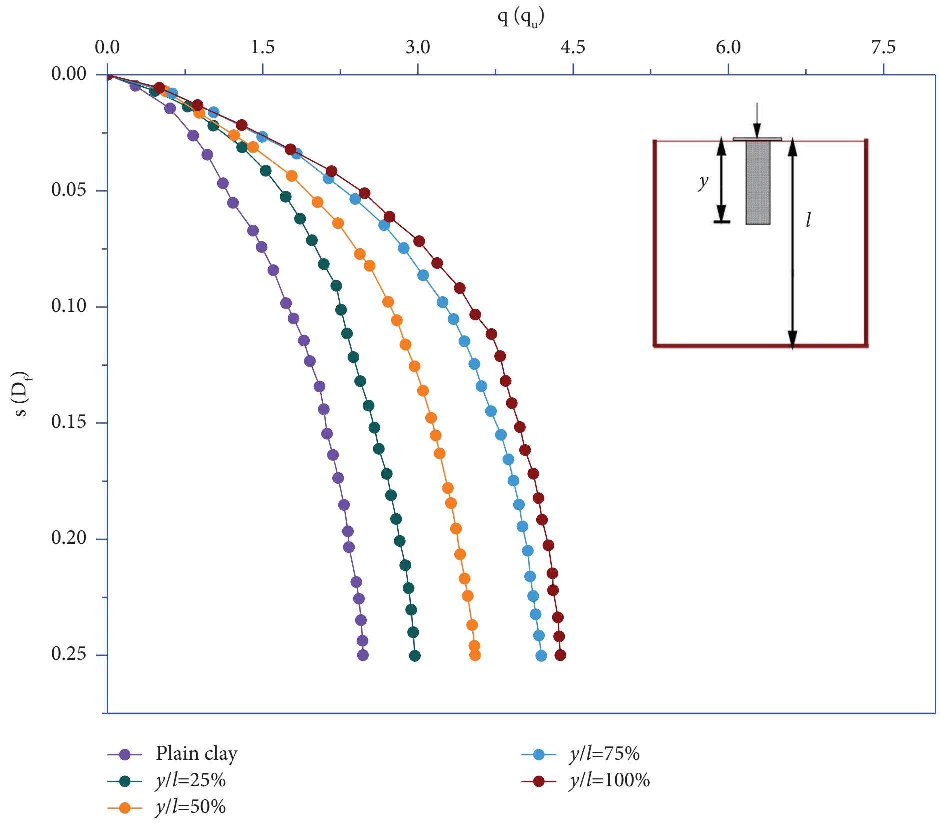

FIGURE 12: q/q_u versus S/D_f (ratio of settlement and footing diameter, D_f) curve for different lengths of cinder gravel column.

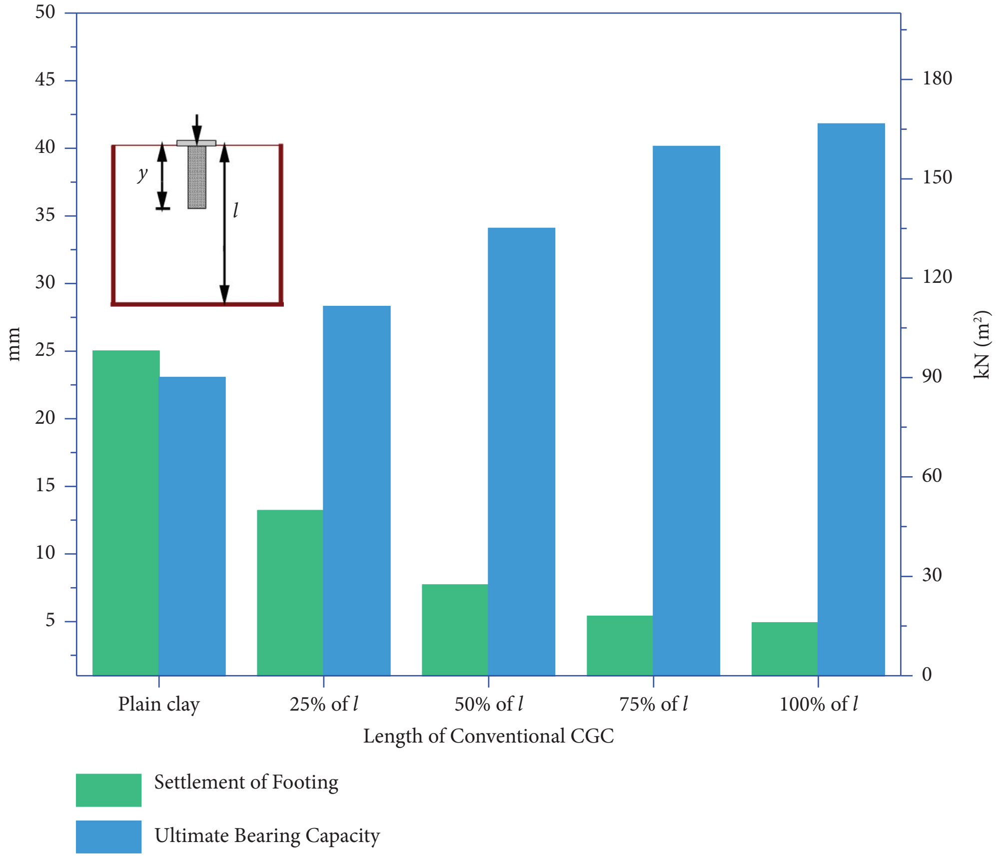

FIGURE 13: Effect of length of cinder gravel column on ultimate bearing capacity–settlement relationship for improved soft soil.

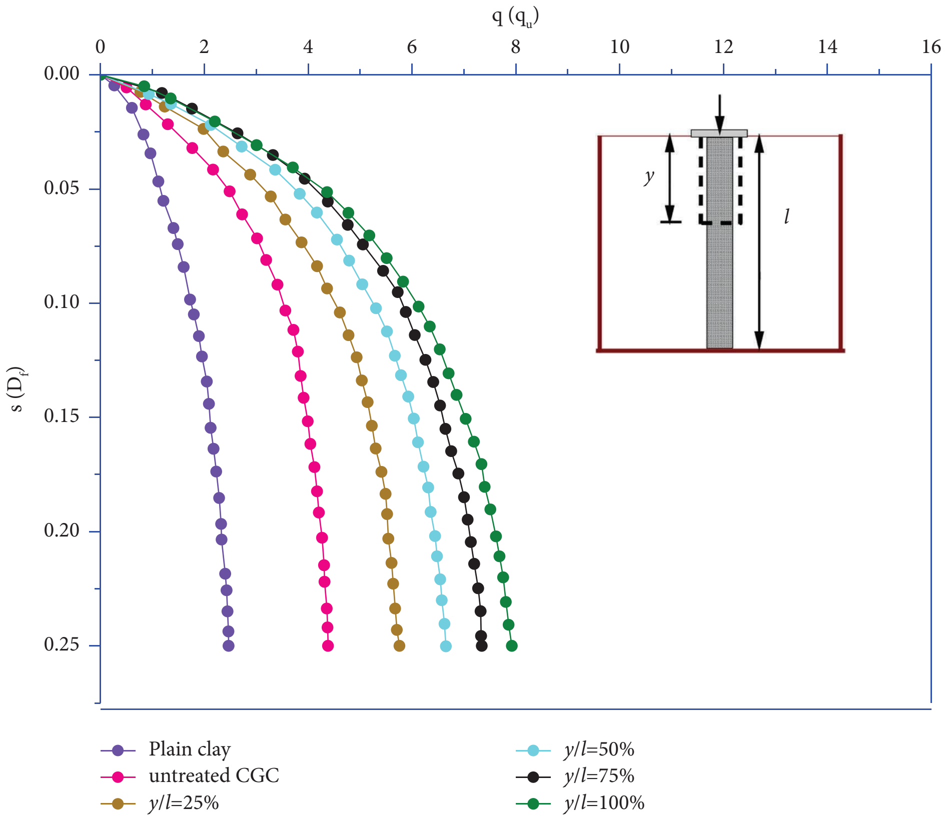

Figure 14: q/q_u versus s/D_f curve for various encasement lengths.

The experimental analysis revealed that in almost all columns installed without geotextile encasement, bulging failure of the column material occurs at a depth of D_c to $3D_c$ from the top of the columns by the time of loading. However, the bulging problem was overcome by the provision of encasement. The encasement confines the column material together, and no significant lateral deformation was observed due to the loading. Hence, the role of encasement in mitigating stiffness, density, and overall performance of the column material is so visible. The percentage of reduction in bearing capacity when lowering the length of encasement from 100% to 75% of the soft clay thickness is 2.57%, which is insignificant in its effect. It has an implication that variation of encasement dimension within the stated range did not show considerable improvement in load-carrying capacity. Hence, encasing 75% of the total length of the clay bed is sufficient from the point of view of improving bearing capacity, and it is also more cost effective than encasing the entire thickness of the clay soil. Similarly, the findings of Bonab [69] and Kumar [68] revealed that no significant reduction in load-bearing capability was observed by reducing the reinforcement length from 100% to 50% and eventually recommended that reinforcing the clay soil with encasement up to half of its thickness is more cost effective than encasing the entire depth. As illustrated on Figure 15, the settlement of footing decreases as the ultimate bearing capacity increases for 194 kPa footing load.

3.4. Effect of HRCGC on Ultimate Bearing Capacity and Settlement of Soft Clay.

To investigate the influence of horizontally situated geotextile, horizontal strips were provided at different intervals throughout the height of the cinder column. Effects of the spacing variation was investigated by using two different spacing having a magnitude equal to the column diameter (D_c) and half of the column diameter ($D_c/2$). Figure 16 represents the q/q_u versus s/D_f curve for various numbers of horizontal circular strips. Accordingly, the improvement rate in the resulting ultimate load-carrying capacity for strip spacing of D_c and $D_c/2$ was 40.5% and 62%, respectively. The experimental result revealed that horizontal placement of geotextile strips significantly augmented the stiffness of the cinder column and bearing capacity of the clay foundation. In the absence of vertical encasement, the lateral deformation of the cinder material was by far greater than the resulting vertical deformation, which implies that the potential contribution of the horizontal strips is primarily to reduce settlement in soft ground foundations.

The findings of the current study regarding the effects of horizontal strip provision are in good agreement with the work of Bonab [69], in which significant enhancements in the bearing capacity and stiffness properties of the clay foundation were achieved. Furthermore, strengthening the stone column with horizontally placed geotextile strips at very close intervals augmented the carrying capacity of the clay foundation. A gradual reduction in the strip spacing by

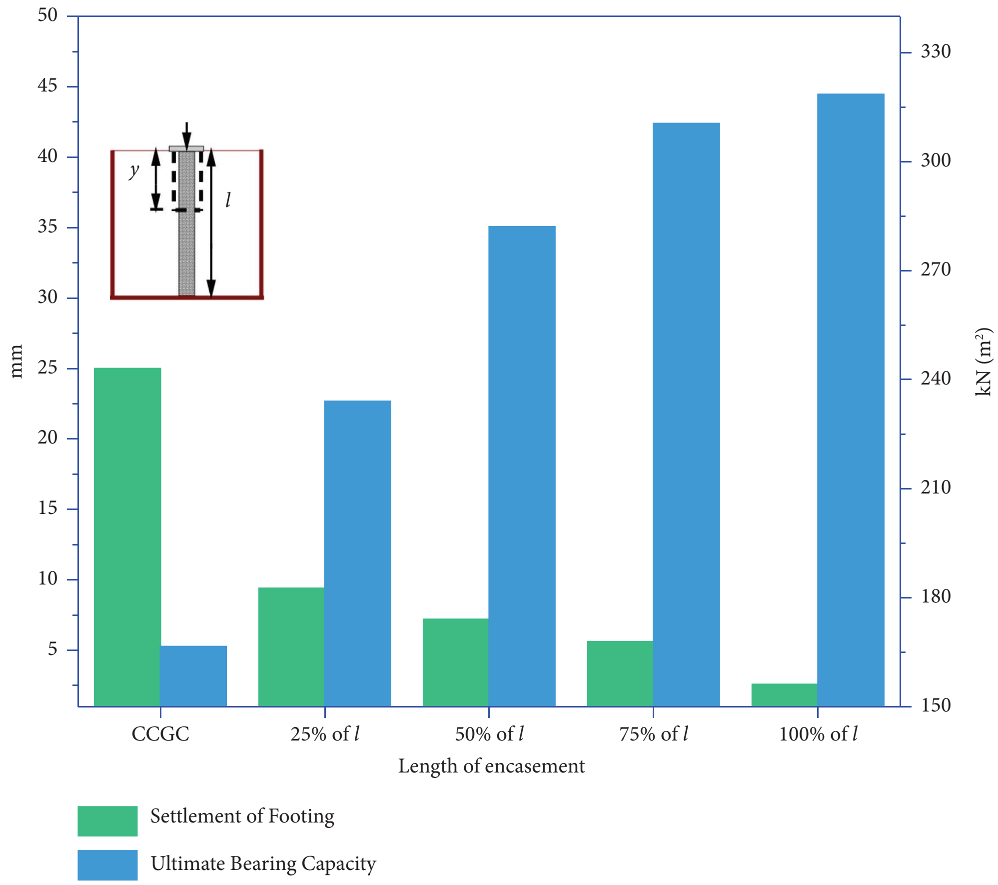

Figure 15: Effect of encasement length on ultimate bearing capacity–settlement relationship for improved soft soil.

50% resulted in 22.5% reduction in the permanent vertical deformation. There is a significant increase in the ultimate strength of a cinder gravel column with an increase in the number of horizontal circular strips and an improvement in proximity. Similarly, findings of the current study revealed that the VECGC performed better than the HRCGC with regard to bearing capacity improvement. In mitigating ultimate bearing capacity and settlement of the clay soil, both VECGC and HRCGC play a significant role. However, the degree of improvement observed in the ultimate bearing capacity is higher when using VECGC. In relation to this, the performance of HRCGC in reducing the permanent vertical deformation of clay soil was quite better than applying the vertically installed encasement. In relation to this, Thakur et al. [50] concluded that horizontally reinforced stone columns provide better ground improvement in comparison with encased stone columns. Moreover, Thakur et al. [16, 22] reported that the bearing capacity of soft clay for vertically encased and horizontally reinforced groups of columns is almost similar, with horizontally reinforced columns depicting slightly higher bearing capacity. Figure 17 illustrates that the settlement of the footing gets diminished with an increment in bearing capacity for the 166.5 kPa applied footing load.

3.5. Effect of VHRCGC on Load-Bearing Capacity and Deformation of Soft Clay. The combined effect of vertical and horizontal reinforcement of the cinder gravel column on soft clay bearing capacity and vertical deformation was investigated. Figure 18 shows the q/q_u versus s/D_f curve for vertical-horizontal reinforcement of cinder gravel columns. Various numbers of horizontal strips were provided in the encased cinder gravel column for the full-length encasement, with the strip spacing ranging from the half column diameter to the full column diameter. The increment in ultimate bearing capacity of soft soil treated with horizontal-vertical geotextile reinforcement for the spacing of D_c and $D_c/2$ is about 116% and 143%, respectively. The obtained percentage improvement in the combination of vertical and horizontal reinforcement is greater than that of the plain cinder gravel column by more than seven folds. Experimental tests were also carried out by placing the horizontal strips only along half the length of the column and the vertical encasing around the remaining length of the column. Therefore, top half of the column length was reinforced with the horizontal strips, whereas the bottom half was encased. The experimental result then indicated that 51.3% and 63.4% improvement in ultimate bearing capacity was obtained that is almost half of the combined

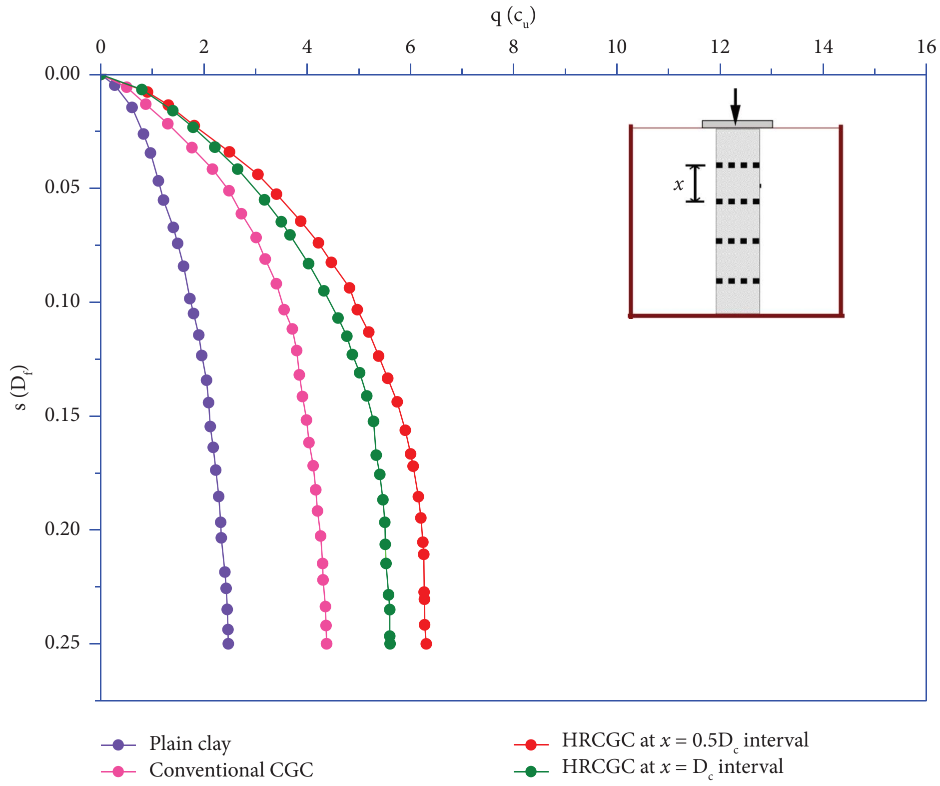

FIGURE 16: q/q_u versus s/D_f curve for CGC having horizontal reinforcement at various depths.

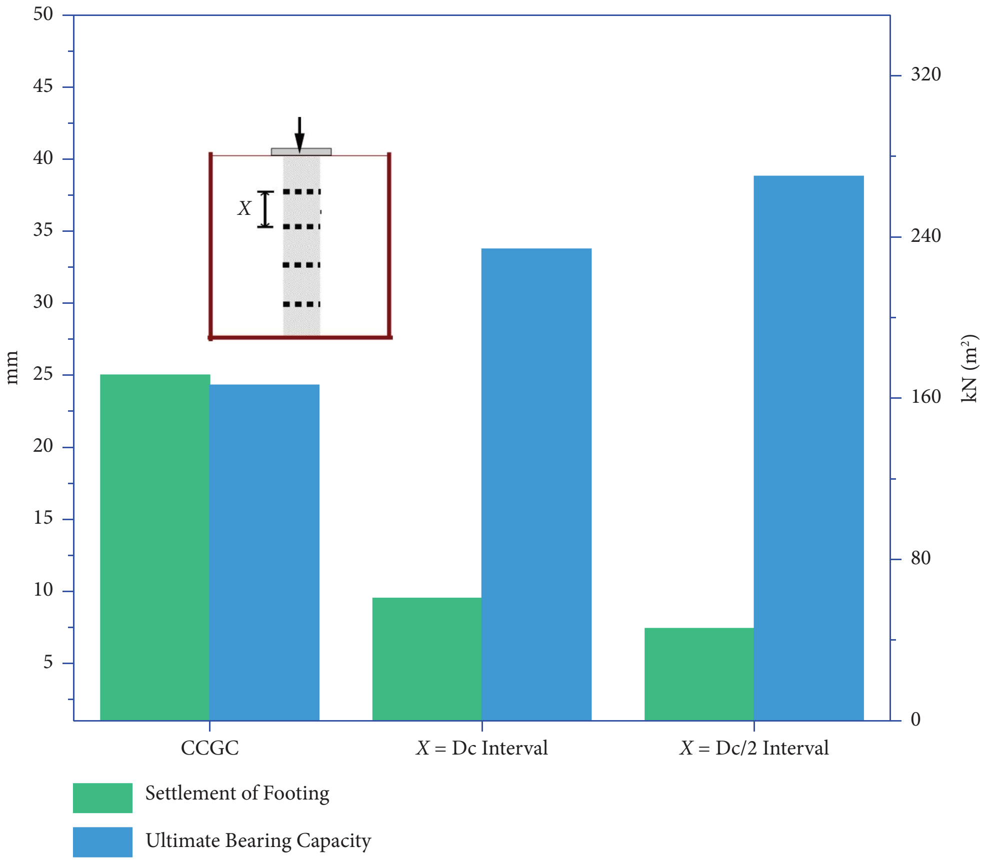

FIGURE 17: Effect of spacing (x) of horizontal reinforcement on the ultimate bearing capacity-settlement relationship for improved soft soil.

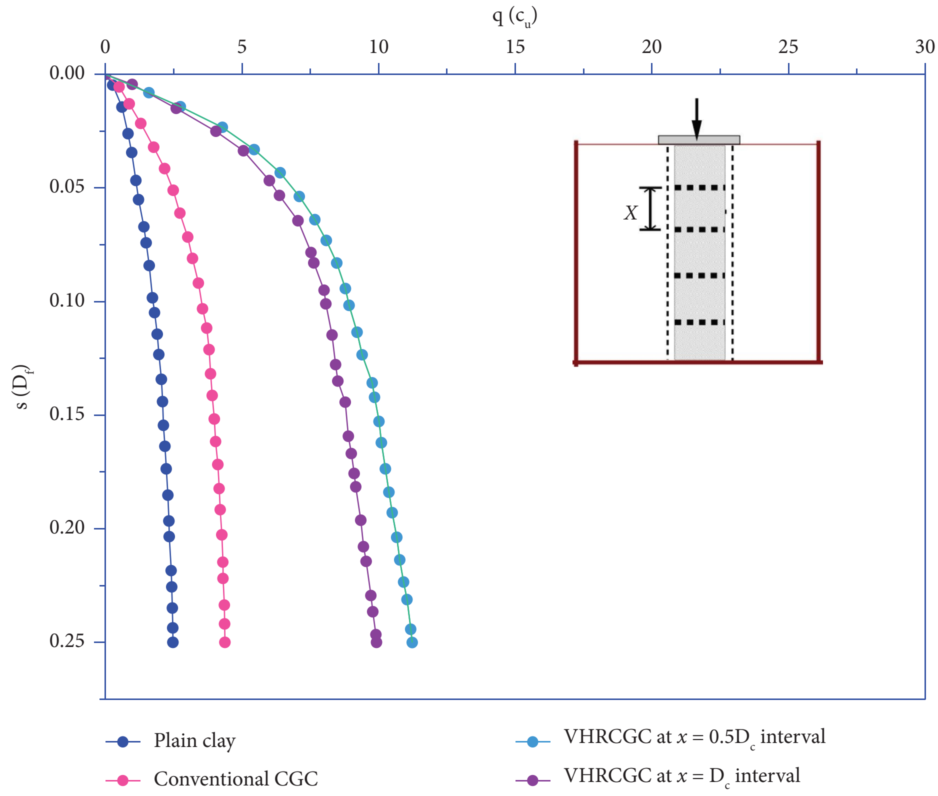

FIGURE 18: q/q_u versus s/D_f curve for ECGC having horizontal reinforcement at various depths.

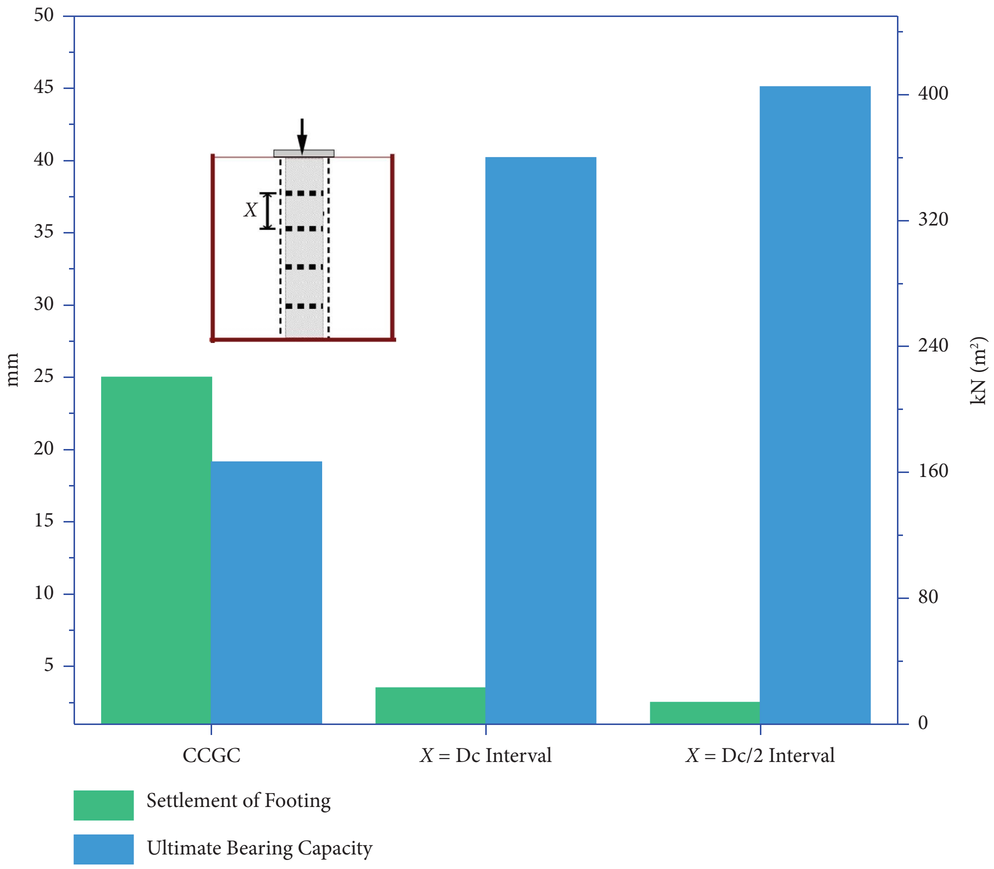

FIGURE 19: Effect of vertical-horizontal reinforcement on the ultimate bearing capacity-settlement relationship for improved soft soil.

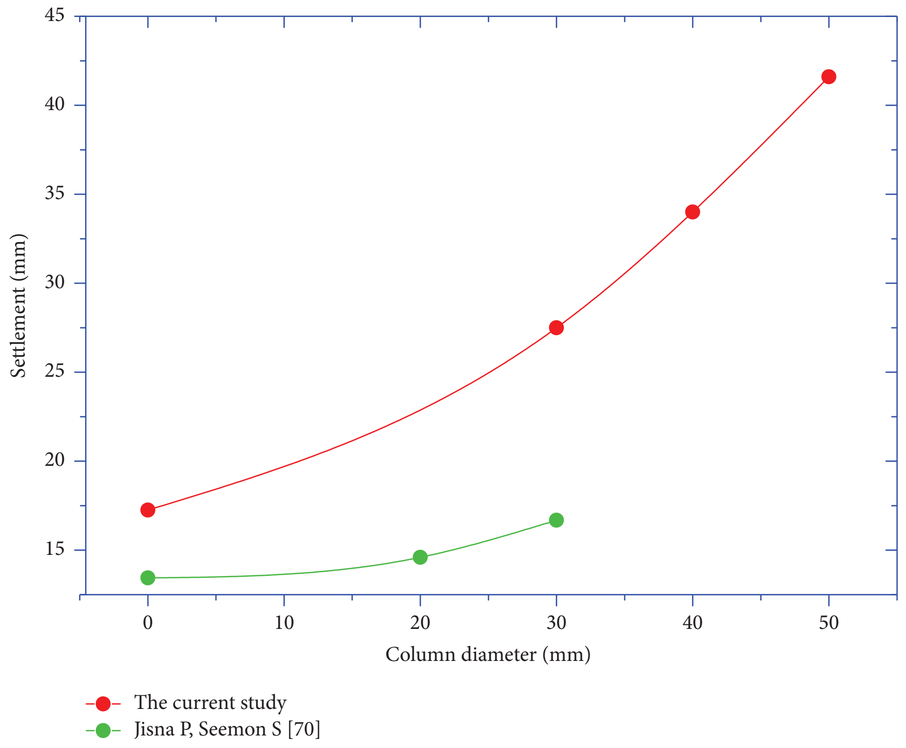

Figure 20: Comparison of settlement finding of the study with Jisna and Seemon [71].

effect of horizontal and vertical reinforcement over the entire column length. Bonab [69] and Ali [42] in the experimental study on soft clay improvement with stone columns reported a similar improvement tendency in the current study. Besides, the study concluded that the improvement potential of VHRCGC is very significant, especially from the perspective of bearing capacity. Figure 19 shows a decrement in settlement of the footing with a rise in the values of the ultimate bearing capacity for the 166.5 kPa footing load.

3.6. Validation of the Results. Results of the current experimental model was validated and compared with findings of Ambily and Gandhi [36], Mohanty and Samanta [70], and Jisna and Seemon [71]. As illustrated in Figure 20, a comparison between the work of Jisna and Seemon [71] and the current study was made for the magnitude of settlement. The resulting settlement of the clay soil in absence of stone column is 13.4 mm and 17.25 mm for Jisna and Seemon [71] and the current study, respectively. Even though the magnitude of settlement in the current study remains higher for all considered diameters, the variation trend and pattern in vertical settlement is in good agreement with Jisna and Seemon [71].

Every dimension of the model remaining the same, the following summarized settlement results were observed upon application of a stress of 166.5 kPa. As indicated in Table 5, the magnitude of vertical deformation in the current study is relatively higher than that of Ambily and Gandhi [36] and Mohanty and Samanta [70] by 10% and 15.84%, respectively.

Table 5: Comparison of findings of the current work with existing literature for applied stress of 166.5 kPa.

Stress (kPa)	Settlement (mm)	Author
166.5	27.5	The current study
166.5	25	Ambily and Gandhi [36]
166.5	23.74	Mohanty and Samanta [70]

4. Conclusions

Application of cinder gravel column to soft clay as columnar reinforcement essentially performed well in modifying the strength and deformation characteristics of clay soil. Installation of cinder gravel column in soft clay foundation improved the load-bearing capacity and significantly lessened the deformation. More specifically,

(i) Bearing capacity of the soft clay reinforced with conventional cinder gravel (in the absence of any vertical and horizontal encasement) was found to be 1.85 times more than that of the untreated clay. The conducted experimental model also revealed that the positive influence of directional application of geo textile material on soft clay is very visible. Provision of geotextile encasement around periphery of the cinder column contributed much to increment in bearing capacity and stiffness of the column material and decrement in both vertical and horizontal deformation of the clay soil.

(ii) The encasement length of the column material positively affects bearing resistance and the resulting permanent deformation under footing load. The gradual increase in length of encasement up to 75% of the clay thickness gives rise to a gradual increase in bearing capacity at a decreasing rate. However, for the percentage increment of geotextile encasement ranging between 75% and 100% of the clay soil thickness, no considerable variation in bearing capacity values was observed.

(iii) The percentage reduction in bearing capacity when lowering the length of encasement from full-diameter to three-fourths of the cinder column diameter is 2.57%, which is insignificant in its effect. Hence, from the point of view of improving bearing strength, 75% encasement length is the ideal dimension recommended to come up with an optimum and economical improvement. It is hence the largest economical and the smallest safe dimension found to be used in reinforcing soft clay with columnar cinder gravel material. Besides, the experimental study revealed that cinder gravel column of smaller diameter performs better than the wide columns in reducing vertical deformation for and improving ultimate bearing capacity, which is obviously in contrary to findings of some of previous studies.

(iv) Not only the vertical encasement but also the provision of horizontal geotextile discs play critical roles in enhancing the properties of soft clay. Better bearing strength improvement was achieved with vertical encasement than with the placement of horizontal geotextile discs in the cinder column, whereas the horizontally situated discs performed better in lessening the vertical deformation. However, the largest improvement is achieved with critical combination of vertical and horizontal geotextile application. Accordingly, for the horizontally situated geotextile discs at a spacing of D_c and $D_c/2$, the load-bearing capacity of the clay foundation was improved by 116% and 143%, respectively, which is by far greater than the improvement obtained when using plain cinder gravel by seven folds.

Data Availability

The data required to support the findings of the study were included in the article.

Conflicts of Interest

The authors have no conflicts of interest regarding the publication of this paper.

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