Improvement of soft soils using reinforced sand over stone columns

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Abstract: In the present study, a series of laboratory model tests have been developed to study the behavior of unreinforced and geogrid-reinforced sand bed resting on stone columns. It has been observed that the soft clay is improved with stone columns. The diameter of stone columns has been taken as 50 mm, three stone columns have been used in the study with spacing of 75mm, while the footing is represented by a plate of 350x250x10mm for all the model tests carried out. Load was applied to the soil bed through the footing until the total settlement reached at least 5% of footing length. The influence of the thickness of unreinforced as well as geogrid-reinforced sand bed and the number of geogrid reinforcement on the performance of stone columns have also been investigated. The inclusion of geogrid layer within sand bed also increases the load carrying capacity and decreases the settlement of the soil. However multilayer reinforcement system is effective to transfer the stress from soil to stone columns. Significant improvement in load-carrying capacity of soft soil is observed due to the placement of sand bed over stone columns. Single layer reinforcement with stone columns is very effective to reduce the total settlement as there is considerable reduction in the total settlement due to stone column itself . The inclusion of reinforcement in the sand bed decreases significantly the depth of sand layer.

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1. Introduction

One of the techniques extensively used in soft soils is the use of stone columns. The use of stone columns can accelerate consolidation of the soft ground and consequently accelerate the strength gain of the surrounding soft soil. It has been used to increase the bearing capacity of soft soils and reduce the settlement of superstructures constructed upon.

In recent years, many studies have been carried out to understand the behavior of foundation reinforced by stone columns without considering the inclusion of geosynthetic reinforcement[1-5].Many researchers have studied the load-settlement behavior of single or multilayer geosynthetic-reinforced granular beds resting on soft soil without stone columns inclusions [6-15] .Most of the works reported in the literature are developed for foundations either reinforced by stone columns or geosynthetic layers. Limited studies have been done on the combined use of geosynthetic reinforcement and stone columns [16]. Han and Gabr [17] presented a numerical analysis of single layer geosynthetic-reinforced pile-supported earth platform over soft soil. Deb et al. [18] developed a lumped parameter model for single layer geosynthetic-reinforced granular fill-soft soil with stone columns. However, in the field multilayer geosynthetic reinforcements can be used along with stone columns. Thus, it is necessary to study the multilayer geosynthetic-reinforced granular fill resting over soft soil improved with stone columns. One of the techniques extensively used in soft soils is vibroreplacement, which consists of replacing some of the soft soil with crushed rock or gravel to form an array of stone columns beneath the foundation. Although the use of conventional stone columns in soft soil deposits was found to benefit foundations in many respects, Madhav and Miura, (19).The degree of improvement of a soft soil by stone columns is due to two factors. The first one is inclusion of a stiffer column material (such as crushed stones, gravel, sand) in the soft soil. This is largely reported in the literature [20- 25]. The second factor is the densification of the surrounding soft soil during the installation of the vibrocompacted stone column itself and the subsequent consolidation process occurring in the soft soil before the final loading of improved soil. The experimental work performed by Wattes et al. [26], and Vautrain [27] verifies that the installation of vibrocompacted stone columns leads to an improvement of the in situ soft soil characteristics and consequently, enhances the load displacement response of reinforced soil, Guetif, et al [28]. However, Greenwood [29] proposed an empirical method for estimating the reduction of settlement of reinforced soil taking into account the installation process of stone columns. In the present study, laboratory model tests have been conducted on three stone columns to study the effect of reinforcement and number of reinforced layers as well as unreinforced sand bed on settlement response. The maximum number of the reinforced layers and unreinforced sand bed has also been determined.

2 Materials

2.1Clayey soils

The properties of clay have been presented in table 1. Unconfined compressive strength (UCS) tests were carried out on clay samples. Water content of the clay was maintained at 25% throughout the series of tests. The bulk unit weight of the clay at 25% water content was determined to maintain identical unit weight in all the tests.

2.2 Sand

A commercially available graded sand were used to prepare the sand bed placed below the clay bed and over the stone column- improved soft clay. The average particle size of sand was ranging between 1-4mm . Crushed stone materials of size 2—8 mm were chosen to prepare the stone column, the particles were generally sub-angular. Sand &stone properties are represented in table2.

To maintain same unit weight of sand in each test, the required weight of sand in each layer was calculated based on bulk unit weight. The sand was poured in two layers. Each layer was compacted with steel hammer to achieve the required thickness .The same procedure was used for stone columns, but the stone was poured in five layers.

2.3. Geogrid

Biaxial geogrid was used as a reinforcement layer. The properties of geogrid reinforcement have been presented in Table 3.

Table 1. Engineering properties of clayey soil

Property	Soil
Classification	CL
Colour	Brown
Liquid limit%	45
Plastic limit%	20
Plasticity index%	25
Optimum moisture content%	18.0
Maximum dry unit weight	17 KN/m³
Specific gravity	2.63
Bulk unit weight at 25%water content	19.2KN/m³

3 Testing Program

3.1. Experimental Setup

To prepare the soil bed, a rectangular tank of 1000 mm x 250 mm size and 500 mm high was used in all the tests. , a thin-walled aluminum tube measuring 50 mm in outside diameter was pushed slowly through the clay sample to a depth of 35cm. Centrality was achieved by using a guide attached to the top of the cylinder. The sample within the tube was retrieved, creating a cylindrical cavity of 50 mm diameter at the centre of the clay. Three cylindrical cavities were achieved representing the stone columns with 50mm diameter &spacing 75mm. The stone column was installed up to 35cm depth in clay bed. Compaction were used to the clay, stones and sand to achieve the required density of the materials. Steel plate of 350x100 mm and thickness 10 mm was used as footing to apply the load. Dial gauges were used for measuring the settlement of footing during the application of load. The diameter of stone columns was chosen to be 50 mm each, in all the tests and the depth of clay bed was maintained at 350 mm ; below the clay bed, a 50mm sand bed was at the bottom of the container. The first test was carried out on clay bed without any improvement techniques and the load-settlement behavior was investigated. Other tests were carried out on soft soil improved by stone column alone and on soft soil improved by stone column along with unreinforced and geogrid-reinforced sand bed. Plate. 1. shows the schematic diagram of the test setup. Summary of the tests conducted has been presented in fig 2, 3, 4, 5, and 6.

Table 2. Properties of sand &stone

Parameters	Values	
	Sand	stone
Specific gravity	2,7	2.67
Maximum dry unit weight	19.2 KN/m³	17.5KN/m³
Bulk unit weight at 65% relative density	17.9 KN/m³	16.1KN/m³

Table 3. Properties of grogrid

Parameter	Value
Aperture size	135x135mm
Thickness	1.omm
Weight	285gm/m²
Strain at failure	3.5%
Elastic axial stiffness at 1% strain	300 KN/m
Maximum tensile strength	8.5 K N/m

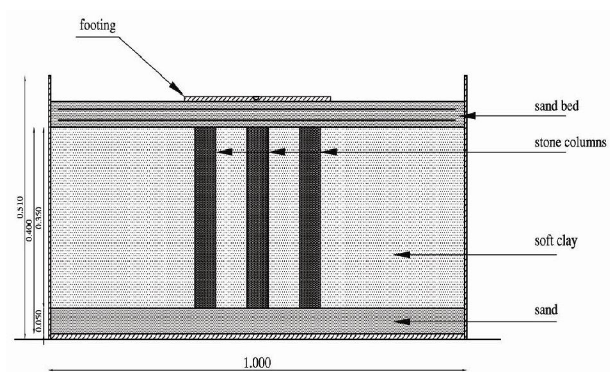

Plate. 1 schematic diagram of the apparatus

3.2. Preparation of Clay Bed

In all the tests, identical technique was to prepare the clay bed. To maintain similar properties throughout the tests, clay bed was prepared at 25% water content in all the cases. The bulk unit weight at 25% water content was found as 19.2 kN/m3. To maintain same unit weight of clay in each test, the container was filled in five equal layers of 70 mm thickness and the required weight of clay in each layer was calculated. Each layer was compacted with steel hammer to achieve the required thickness.

3.3. Column Construction

A replacement technique was considered the most easily repeated method for column installation in very soft soils. After preparing the clay bed of 350 mm over a sand bed 50mm thickness at the bottom of the container, three cylindrical holes of diameter 50 mm &spacing of 75mm were dug at the centre of the clay bed by steel pipe of 50 mm diameter and a depth of 350mm. The unit weight of stones was determined and using the known volume of the hole, the total weight of stone required to fill up the hole was determined. Total weight of stone material was divided into five equal layers to fill up the hole. Each layer of stone was poured and compacted with steel bar in such a manner that the finished height of each layer of stone column was 70 mm.

3.4. Preparation of Sand Bed

The weight of sand required to form a certain thickness of the bed for the lower and upper bed was determined by using the known unit weight of sand. For different thicknesses of sand, the required weight of sand was calculated and preparation of bed was carried out in layers. Each layer was compacted with a hammer with equal efforts of compaction to achieve the required depth of sand bed.

3.5. Testing Procedure

Loading was applied through a footing resting on the prepared soil bed and resistance offered by test bed with or without stone column was measured with the help of proving ring. Load was applied in equal increments and each increment of the load was maintained until negligible change in the settlement was observed. The settlement due to increment of each equal interval of loading step was observed through three mechanical dial gauges having least count of 0.02 mm fixed on the footing. Loading was applied until the total settlement of the footing attained was at least 5% of footing length.

4. Results and Discussions

4.1. Thickness of Sand Bed

To determine the optimum thickness of unreinforced sand bed, the thickness of sand bed was varied from 20mm to 80mm.The load carrying capacity at 175mm settlement has been calculated. From Fig. 1, it has been observed that the placement of sand bed over stone column-improved soft clay increases the load- carrying capacity of the improved soil . As compared to unimproved clay bed, an improvement of 75% in load- carrying capacity has been observed when the clay bed is improved with stone column only. As compared to unimproved clay bed, 100,126,140,167&180% improvement in load-carrying capacity has been observed when unreinforced sand bed of 20,40,50,60&80mm is placed over stone column-improved soft clay respectively. Fig. 1 shows the load settlement characteristics of the unreinforced sand bed of different thicknesses placed over stone column-improved clay.For 20,40,50,60&80 mm sand bed thickness, a loading intensity of 0.6 kN, as compared to unimproved soil, the settlement has been reduced by 63%, 69.2%,80%,87% and 90.7% respectively. For 1.0KN the settlement has been reduced by 60%, 74.8%,80%,85.6% and 88% respectively. The increase of sand bed thickness increases the load-carrying capacity also the settlement reduction increases up to a thickness of 60mm whereas beyond this value the reduction of settlement decreases and the increase of thickness is insignificant.

The thickness of sand bed was taken 60mm in the study .The reinforced geogrids was taken 1,2,3 &4 layers.

Fig. 2 shows the load-settlement characteristics of the geogrid reinforced sand bed of 1,2,3&4 reinforced layers placed over stone column-improved clay. The improvement in load-carrying capacity at 175 mm settlement is 180%&200% when unreinforced and geogrid reinforced sand bed with optimum number of layers has been placed over stone column improved soft clay respectively.

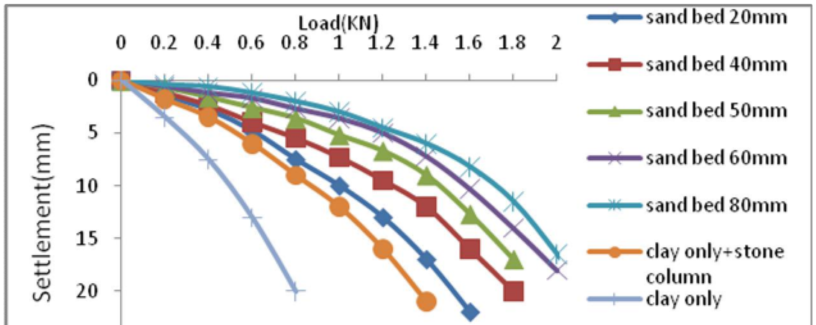

Fig.1. Load settlement characteristics of unreinforced sand bed of different thicknesses

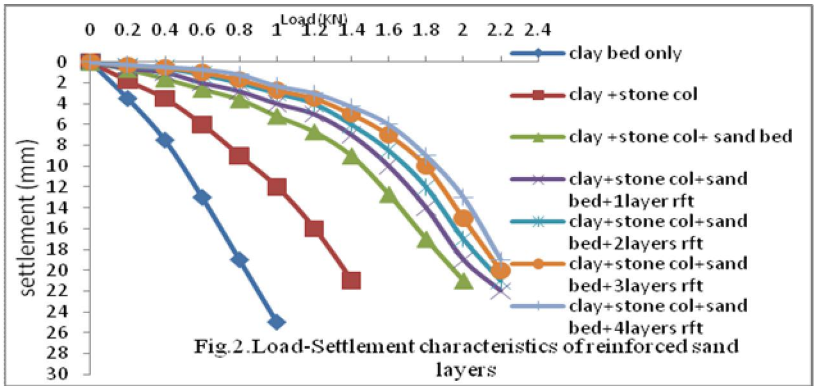

Fig.2. Load-Settlement characteristics of reinforced sand layers

4.2. Number of Geogrid-Reinforced Sand Bed

It has been observed that as the number reinforcement layer increase, the reduction in settlement increase. To determine the optimum number of the geogrid-reinforced sand bed, 1, 2, 3, and 4 layers of geogrids were used. Results obtained when using three layers of reinforcement are nearly close to those obtained with four layers.

A loading intensity of 0.2 kN, as compared to unimproved sand bed, the settlement has been reduced by 15.3%, 43.2%,57% respectively .For 0.6 kN, as compared to unimproved sand bed, the settlement has been reduced by 23%, 53.8%,61.5% respectively. For 1.0KN the settlement has been reduced by 31%, 43%,47% respectively.

The presence of reinforcement layers in sand bed increases the load-carrying capacity also the settlement reduction increases with the increase of number of geogrid layers up to a value of 3 layers, whereas beyond this value the reduction of settlement is insignificant. At low sand bed thickness, large deflection has occurred in the geogrid reinforcement directly underneath the footing. The large deflection of the geogrid reinforcement would mobilize the membrane action and induce more mobilized tension in the geogrid layer. The vertical component of the tensile force acting in the geogrid reinforcement partially counterbalances the superimposed load exerted by the overlying soil. As a result, the vertical stress is reduced in the zone below the reinforcement due to combined action of mobilized tension in the reinforcement and membrane action in its curvature [31- 34] (Burd, ; Lee et al.; Basudhar et al., Deb et al,) However, when the sand bed reinforcement layers increases, a major portion of the shear failure zone of the soil is developed above the reinforcement layer and the deflection of the reinforcement also decreases. This led to reduction in the utilization of membrane action and less mobilized tension in the geogrid has been induced [32](Lee et al.). This phenomenon reduces the effectiveness of the geogrid layer causing reduction in bearing capacity. Thus, the stone column under geogrid-reinforced sand bed produces less bearing capacity than that under geogrid-reinforced sand bed. Studies show that as the thickness of the reinforced sand bed is equal to or greater

than the optimum thickness of the unreinforced sand bed, the bearing capacity of unreinforced and reinforced sand bed is almost same [32](Lee et al). This is due to the fact that as the thickness of the reinforced sand bed increases, the deflection of the reinforcement decreases and the effectiveness of the reinforcement also decreases. When the thickness of the reinforced sand bed is equal to or greater than the optimum thickness of the unreinforced sand bed the effectiveness of the reinforcement is almost insignificant. Thus, the geogrid-reinforced sand bed with 60 mm thickness will almost same bearing capacity as compared to that under an unreinforced sand bed with 80mm thickness. The improvement in load-carrying capacity, as compared to unimproved soft clay, at 175 mm settlement is 180% and 200% when unreinforced and geogrid-reinforced sand beds with optimum thickness have been placed over stone column-improved soft clay, respectively. [32] Lee et al. reported similar observation based on numerical and model studies of strip footing resting on reinforced- granular fill-soft soil system without stone column inclusions. Due to presence of stiffer stone column in the soft clay, lower optimum thickness of the sand bed has been required as compared to the optimum thickness under without stone column condition to get the maximum improvement in load-carrying capacity of improved ground. However, from the present study and the results reported by [32]Lee et al., it has been observed that the ratio of optimum thickness of the unreinforced to geogrid- reinforced sand bed is almost similar for both the cases under with and without stone columns [34](Deb et al).

4.3. Thickness of reinforced sand bed

Fig. 3. shows the load-settlement characteristics of the geogrid reinforced sand bed of different thicknesses placed over stone column-improved clay . To determine the optimum thickness of the geogrid-reinforced sand bed, 3 layers of geogrid reinforcement was chosen with 20,40,50,60,80mm of sand bed. It has been observed that as the thickness of reinforced sand bed increases the load-carrying capacity increases up to a depth of 60mm whereas beyond this value ,the increase of the thickness of the sand bed is insignificant. When the thickness of the reinforced sand bed is equal to or greater than the optimum thickness of the unreinforced sand bed the effectiveness of the reinforcement is almost insignificant (Lee et al.,).The improvement in load-carrying capacity, as compared to unimproved soft clay over stone column and geogrid-reinforced sand beds which have been placed over stone column-improved soft clay at 17.5 mm settlement with thickness of sand bed 20mm is 35.7% and 138% respectively, for 40mm thickness, 50% and 163% respectively, for 50mm thickness, 57.5% and 175% respectively, for 60mm thickness, 64.5% and 188% respectively, for 80mm thickness, 71.4% and 200% respectively.

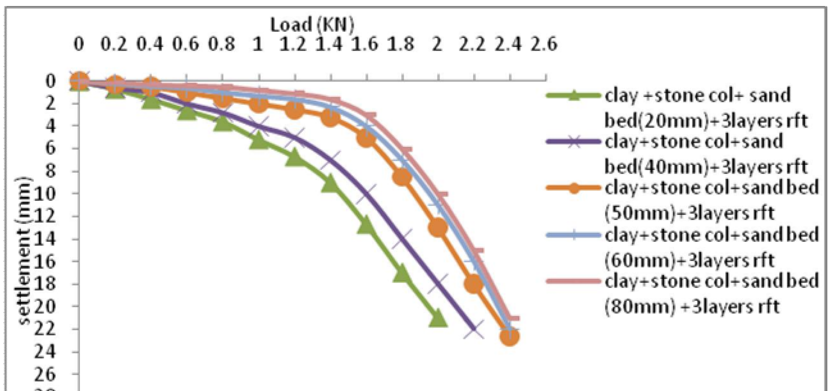

Fig.3. Load-Settlement characteristics of reinforced sand layers for different thicknesses

4.4. Length of geogrid

Fig. 4. shows the load-settlement characteristics of sand bed reinforced by geogrid reinforcement of various lengths. From the load- settlement characteristics, it has been observed that for a particular settlement, the load-carrying capacity increases as the length of the geogrid increases up to twice the length of the footing, whereas beyond this value the increase of length is insignificant. The length of geogrid used was 1L,1.5 L,2 L,2.5 L, while the sand bed was 60mm. Thus, the optimal extent of the reinforcement is twice the length of the footing; and, beyond this length any additional reinforcement is ineffective.

However, in the present study, the model container has been taken as sufficiently large to reduce the boundary effects. To reduce the scaling effects, the dimensions of the various components have been chosen proportionally with the prototype dimensions. In the present experimental study, small aperture size and thin model geogrid with relatively low stiffness has been used to avoid the size effect in the model experimental results. However, in case of field application comparatively large aperture size and thicker geogrids with higher stiffness are usually used. Thus, the chosen model geogrid properties used in the present experiments are suitable to achieve the same performance results as compared to full-scale geogrid. Thus, the results of the present laboratory model study are useful to investigate the behavior of the unreinforced and geogrid-reinforced sand bed resting over stone column-improved soft clay.

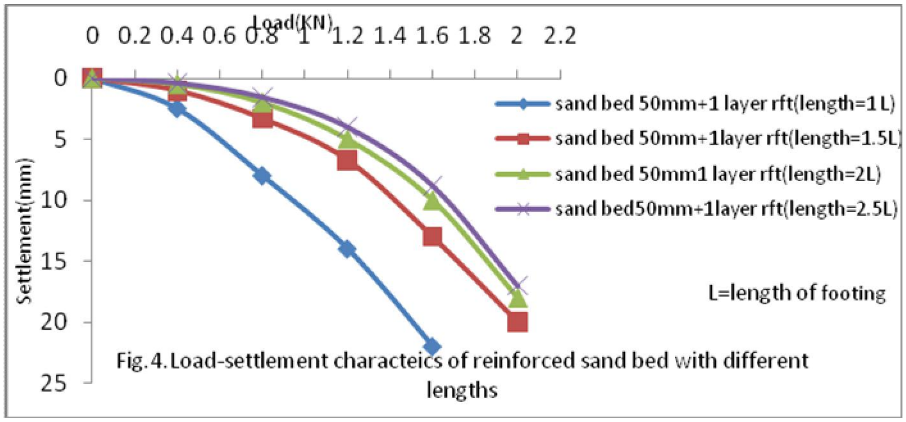

Fig.4.Load-settlement characteics of reinforced sand bed with different lengths

4.5. Load-settlement characteristics

Fig. 5. shows the load-settlement characteristics of the unimproved clay bed, clay bed improved by stone column alone and clay bed improved by stone column along with 60 mm thick unreinforced and geogrid-reinforced sand bed. The number of the geogrid layer has been taken as 1,2, & 3layers. The improvement in load-carrying capacities under different conditions has been computed at 175 mm settlement,5% of the footing length. From Fig. 5, it has been observed that the placement of sand bed over stone column-improved soft clay increases the load- carrying capacity of the improved soil and the use of geogrid layer within the sand bed is effective in further increment of the same. As compared to unimproved clay bed, an improvement of 75% in load- carrying capacity has been observed when the clay bed is improved with stone column only. As compared to unimproved clay bed, 140% improvement in load-carrying capacity has been observed when unreinforced sand bed is placed over stone column-improved soft clay and for reinforced sand bed the improvement is 150,175,200% for 1,2, & 3 reinforcement layers respectively. For a loading intensity of 0.5 kN, as compared to unimproved soil, the settlement has been reduced by 41.6%, 67%,83.3%,86.2% and 91.6% when the soil is improved by only stone column, by stone column along with unreinforced and geogrid-reinforced sand bed1,2,3 layers respectively. For a loading intensity of 1.0 kN, as compared to the presence of stone columns, unreinforced sand bed, reinforced sand bed with 1,2,3 layers, the reduction is 35.7%, 57.1% , 71.4%,78.5&85.7% respectively in settlement has been observed ; whereas for a loading intensity of 1.5 kN, the reduction in settlement is 29.1%,50%,62.5%,67% &79.2% respectively. Thus, it can be said that the geogrid reinforcement is more effective for higher loading intensity than for lower loading intensity. Similar behavior has been observed by Deb et al. [30] in the developed model for geosynthetic-reinforced granular fill-soft soil system with stone columns.

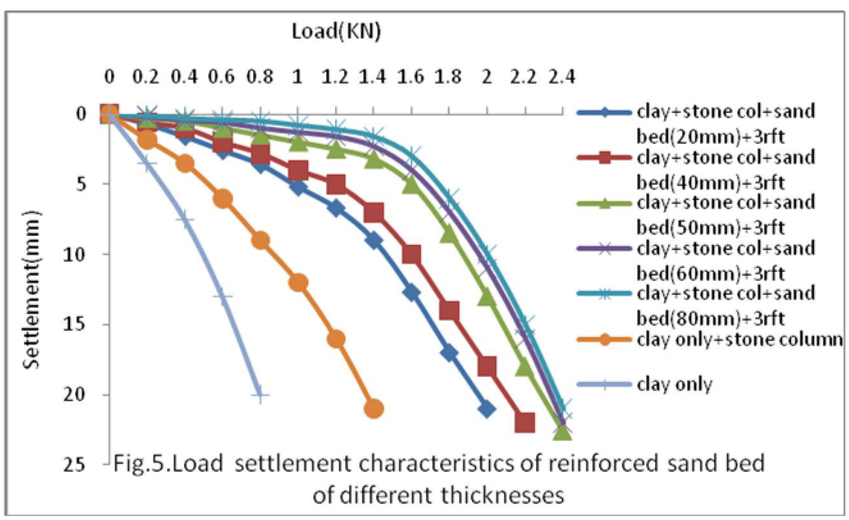

Fig.5.Load settlement characteristics of reinforced sand bed of different thicknesses

Conclusions

Based on the experimental results the following conclusions can be drawn:

I. The presence of stone columns in soft clay improves the load- carrying capacity and decreases the settlement of the soft soil. The placement of sand bed further increases the load-carrying capacity and decreases the settlement of the stone column-improved soil. The inclusion of geogrid as reinforcing element in the sand bed significantly improves the load-carrying capacity and reduces the settlement of the soil. As compared to unimproved soft clay, 75%, 140 % and 200% improvement in load- carrying capacity have been observed (at settlement equal to 5% of the footing length) when soft clay is improved by stone column alone, by placing of unreinforced and geogrid-reinforced sand bed of optimum thickness over stone column, respectively.

2. The optimum thickness of unreinforced sand bed placed over the stone column- improved soft clay is 1.6 times the optimum thickness of the geogrid-reinforced sand bed. The optimum thickness of unreinforced and geogrid-reinforced sand bed is 0.23 and 0.143 times the length of the footing, respectively.

3- It has been observed from the load- settlement characteristics that for a particular settlement, the load-carrying capacity increases as the length of the geogrid increases up to twice the length of the footing, whereas beyond this value the increase of length is insignificant.

4- The presence of reinforcement layers in sand bed increases the load-carrying capacity also the settlement reduction increases with the increase of number of geogrid layers up to a value of 3 layers, whereas beyond this value the reduction of settlement decreases.

5-, It has been observed that the placement of sand bed over stone columns-improved soft clay increases the load- carrying capacity of the improved soil and the use of geogrid layer within the sand bed is effective.

6-The sand bed layer below stone columns is effective to prevent any deformation to the stone columns due to loading of footing. The chosen model of the stone column properties used in the present experiments are suitable to achieve the same performance results as compared to full-scale stone columns.

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References

1. Balaam NP, Booker JR. Analysis of rigid raft supported by granular piles. Tnt J Numer Anal Methods Geomech 198 l;5:379-403.
2. Alamgir M, Miura N, Poorooshasb RB. Madhav MR. Deformation analysis of soft ground reinforced by columnar inclusions. Comput Geotech 1996; 18(4): 26790
3. Poorooshasb RB. Meyerhof GO. Analysis of behavior of stone columns and lime columns. Comput Geotech 1997;20(1):47 70.
4. Lee JS. Pande ON. Analysis of stone-column reinforced foundations. Tnt J NumerAnal Methods Geomech 1998;12(12):1001 20.
5. Shahu JT, Madhav MR, Hayashi S. Analysis of soft ground- granular pile - Granular mat system. Comput Geotech 2000;27(1): 45 62.
6. Madhav MR. Poorooshasb HB. A new model for geosyntheticreinforced soil.Comput Geotech 1988; 6(4):277 90.
7. Poorooshasb RB. Analysis of geosynthetic reinforced soil using a simple transform function. Comput Geotech 1989;8(4):289 309.
8. Ghosh C, Madhav MR. Settlement response of a reinforced shallow earth bed. Geotext Geomembranes 1994;13(9):643 56.
9. Shukla SK, Chandra S. The effect of prestressing on the settlement characteristics of geosynthetic-reinforced soil. Geotext Geomembranes 1994:13(8):531- 43.
10. Shukla 5K. Chandra S. Modeling of geosynthetic-reinforced engineered granular fill on soft soil. Geosynth Tnt 1995;2(3): 603- 17.
11. Yin JR. Modeling geosynthetic-reinforced granular fills over soft soil.Geosynth Tnt 1997;4(2): 165 85.
12. Nogami T, Yong TY. Load- settlement analysis of geosynthetic reinforced soil &with a simplified model. Soils Found 2003;43(3):33—42.
13. Maheshwari P. Basudhar PK, Chandra S. Analysis of beams on reinforced granular beds. Geosynth Tnt 2004;ll(6):470 80.
14. Deb K. Chandra 5, Basudhar PK. Settlement response of a multilayer geosynthetic- reinforced granular fill-soft soil system. Geosynth Tnt 2005;12(6):288 98.
15. Deb K. Chandra 5, Basudhar PK. Nonlinear analysis of multilayer extensible geosynthetic-reinforced granular bed on soft soil. Geotech Geol Eng: Tnt J 2007;25(1):11 23.
16. Gniel .J, Bouazza. A Improvement of soft soils using geogrid encased stone columns , Geotextiles &Geomembranes,27,(208),p167-175.
17. Han J. Gabr MA. Numerical analysis of geosynthetic- reinforced and pile- supported earth platform over soft soil. J Geotech Environ Eng, ASCE 2002; 128(1):44 53.

18. Deb K. Basudhar PK, Chandra S. Generalized model for geosynthetic reinforced granular fill-soft soil with stone columns. mt J Geomech ASCE 2007z7(4):266 76.
19. Madhav and Miura, 1994; Priebe, 1995; Muir-Wood et al., 2000);
20. Balaam NP. Booker JR. Analysis of rigid rafts supported by granular piles.Tnt J Numer anal Moth Geomech 198 1;5(4):379 403.
21. DTU 13.2 (Documents Techniques Unifies). Colonnes ballastCes; 1992, Chapitre VIII.
22. Priebe H. The design of vibro replacement. Ground Eng 1995:31 7.
23. Poorooshasb HR Meyerhof GG. Analysis of behaviour of stone columns and lime columns. Comput Geotech 1997;20(1):47 70.
24. Bouassida M. GuetifZ, de Buhan P. Dormieux L. Estimation par une approche Variationnelle du tassement d'un sol renforcé par colonnes. Rexue Française de GCotech 2003;102:21 9.
25. Dhouib A, Blondeau F. Colonnes ballastées. Edition Presses de l'Ccole nationale des ponts et chausses,Paris;2005
26. Wattes KS. Johnson D, Wood LA, Saadi A. An instrumented trial of vibro ground treatment supporting strip foundations in a variable fill. Geotechnique 2000;50(6):699-708.
27. Vautrain J.Comportementetdimensionnement des colonnes ballastCes. Revue Française de GCotech 1980;11:59,73
28. Guetif .Z.,Bouassida M , Debats. J.M. Improved soft clay characteristics due to stone column installation.Computers&Geotechnics,34(2007),p10 4-111
29. Greenwood DA. Mechanical improvement of soils below ground surface. In: Proceedings of the conference on ground engineering. Institution of Civil Engineers 1970, London. paper II. p. 11 22.
30. Deb. K, Chandra. S,. Basudhar P.K Response of multilayer geosynthetic- reinforced bed resting on soft soil with stone columns,Computers &Geotechnics 35(2008),p323-330
31. Burd, H.J., 1995. Analysis of membrane in reinforced unpaved roads. Canadian Geotechnical Journal32, 946—956.
32. Lee, 1CM., Manjunath, V.R., Dewaikar, D.M., 1999. Numerical and model studies of strip footing supported by a reinforced granular fill-soft soil system. Canadian Geotechnical Journal36, 793—806.
33. Basudhar, RIC, Dixit, RM., Gharpure, A., Deb, IC, 2008. Finite element analysis of geotextile-reinforced sand-bed subjected to strip loading. Geotextiles and Geomembranes 26, 91—99.
34. Deb. K, Kumar. N , Babasaheb.J. Laboratory model studies on unreinforced and geogrid-reinforced sand bed over stone column-improved soft clay, Geotextiles &Geomembranes, 2011, p190-196.

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