Settlement Behaviour of Very Soft Soil Reinforced with Stone Columns

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Abstract: Construction on soft soils has always been a problem to geotechnical engineers. A review of the literature reveals that many techniques and methods have been developed to work with such soils. The technique of soft soil improvement by the installation of stone columns has become popular in recent past and has proven its application to many construction situations in soft soils. Construction of stone columns provides a new composite ground consisting of stiff stone column-soil matrix. Stone column reinforcement in the soft ground increases the bearing capacity and improves the settlement characteristics. They can be used to accelerate the rate of consolidation of soft soil deposits through a well-understood mechanism. They act as vertical drains that provide a shorter drainage path for excess pore water pressure to dissipate rapidly.

In the present investigation, an attempt has been made to study the settlement characteristics of soft soil reinforced with the stone column. The main objective of the study was to investigate the settlement-time behaviour of the stone column in very soft soil having undrained shear strength (c_u) ≈ 5 kPa under different bearing pressures and to verify the results of the experimental results with the analytical theory on consolidation rate of composite ground. A Compactive effort is applied during the construction of stone column and its average value is equal to 21.98 kJ/m^3. The settlement of the reinforced soft soil bed is reduced by 25.8% when reinforced with stone column diameter of 76.2 mm.

Keywords: Soft soil; Stone column; Settlement characteristics; Consolidation rate

1 Introduction

In the recent past, various techniques of ground improvement have been developed and applied due to the shortage of suitable construction site. Ability to enhance both soft clays and granular soils, by specific solutions suitable to meet any particular settlement or bearing capacity requirements resulted in wide acceptance of stone columns and established it as most widely used form of ground improvement technique (McCabe et al 2009; Black et al. 2006). Its applications are widely published in literature which is used to treat various ground conditions successfully, including non-cohesive deposits (Slocombe et al. 2000), soft clays (Cooper and Rose 1999; Egan et al. 2008), reclaimed land sites (Renton-Rose et al. 2000) and fill grounds (Watts et al. 2000).

Studies on stone columns is carried out extensively and contributed immensely to understanding its strength and settlement behaviour (Balaam and Booker 1981; Barksdale and Bachus 1983; Charles & Watts, 1983; Mitchell and Huber 1985; Bell 2004; Murugesan and Rajagopal 2010; Shahu and Reddy 2011; Rangeard et al. 2016; and Chandrawanshi et al. 2017).

Stone columns constructed by vibro compaction were employed in grounds with predominantly cohesionless soils, which densify sunder the effect of horizontal/vertical vibrations imparted by the poker. Stone columns in cohesive soils are constructed by vibro replacement method, which includes the formation of a cylindrical void in the cohesive ground with the help of poker, backfilled by well-graded crushed stone aggregates. The laboratory testing programs differ with different researchers and still evolving to capture the load bearing-settlement phenomenon of reinforced clay bed. Rangeard et al. (2016) carried out a study on sand column constructed in soft clay under constant consolidation pressure to assess the influence of compaction effort with low replacement ratio and concluded that the settlement reduction is observed significantly with higher compaction efforts.

Current research adopts an experimental laboratory programme on small scale models for studying the effectiveness of stone columns constructed by vibro replacement technique (adopted with modification) in reducing settlements, formed in reconstituted soil with well-defined properties. Stone columns with varying replacement ratio and uniform compactive effort (applied to the stone aggregates during construction) were investigated.

2 Material Used

Kaolin clay is used to prepare soft ground for experimentation and stone aggregates were used to construct the stone column.

2.1 Kaolin Clay

Kaolin or China clay is a form of industrial mineral with the chemical composition of $Al_2.Si_{2.}O_{5.}(OH)_4$. It has low shrinkage and swelling capacity, is inert and easy to mix and therefore is a well established material used in the laboratory modeling. Use of kaolin for experiments ensures reproduction of samples with repeatable properties. Kaolin was used as fine soil. Its basic properties are listed below in Table.1.

2.2 Stone Aggregates

The stone aggregates of crushed basalt rock were used to form the stone columns. The stone aggregates were washed and sieved to obtain particles between 1.25 mm and 4.75 mm. Properties are shown in Table. 2. Practically in the field, stone columns are constructed in diameters (*d*) between 0.6 m to 1.2 m depending on the prevalent soil conditions (Ranjan 1989).

Table 1. Properties of kaolin clay

Property	Value
Specific Gravity	2.62
Clay Content, %	27
Silt Content, %	73
Liquid Limit, w_L, %	27
Plastic Limit, w_P, %	18
Plasticity Index, *P.I.* , %	9
Classification (IS:1498-1970)	CL
Optimum moisture content, *O.M.C.* , %	14.25
Maximum dry unit weight, $\gamma_{d\,max}$, kN/m^3	18.85

Suitable stones aggregates of varying size (*s*) 2-75 mm are used, so that the ratio *d*/*s* falls in the range of 8 and 550 (IS: 15284 Part 1). In the present research, the dimensions of the stone aggregates are reduced in the same proportion to accurately model the behaviour of stone columns installed in the field i.e. *d*/*s* ratio lies in between 5.3 - 60.7.

Table 2. Physical properties of stone aggregates

Property	Value
Specific Gravity	2.72
D_{10}, mm	1.45
D_{30}, mm	1.9
D_{60}, mm	2.6
C_U	1.793
C_C	0.957
Percentage fines (≤ 0.075 mm), %	0
Classification (IS:1498-2007)	SP
Minimum dry unit weight, γ_{min}, kN/m^3	14.43
Maximum dry unit weight, γ_{max}, kN/m^3	17.86
Minimum size of aggregates, mm	1.18
Maximum size of aggregates, mm	4.75

3 Experimental Programme

Details of experimental programme are provided in Table 3. A cylindrical test tank having internal diameter of 150 mm and height 230 mm is used to prepare soft clay bed of uniform properties. The soft clay bed was prepared by consolidating kaolin slurry, prepared at a water content of 1.5 times the liquid limit, then applying a pressure of 60 kPa. The laboratory small scale model tests were carried out on this soft clay bed in unreinforced and reinforced condition. Reinforcement is provided by constructing single stone column of varying diameters from 25.4 mm to 76.2 mm. Replacement ratios corresponding to five different diameters of stone columns were 2.86, 6.45, 11.46, 17.92 and 25.81 % respectively.

Table 3. Details of experimental programme

Test series	Test description	Applied pressure	Method of construction of stone column	Compa -ctive effort	Stone column diameter (mm)	Tests
TS-1	Soft soil bed (c_u = 5 kPa)	100,150 and 200 kPa	-	-	-	3
TS-2	Reinforced soft soil bed (c_u = 5 kPa, with stone column)	150 kPa	RP	E	25.4, 38.1, 50.8, 63.5, 76.2	5
					Total tests	8

RP = Replacement method
E = Compactive effort of 21.98 kJ/m^3 used while constructing stone columns

4 Preparation of Clay Bed

The kaolin was mixed with water equal to 1.5 times of liquid limit, then mixed with the help of mechanical mixer and then kept in a sealed plastic bag for 4 hours to obtain homogeneous properties. After this period the soil was filled into the test mould. The bottom of the test mould is porous and before putting the kaolin sample filter paper was applied. This prevents the expulsion of kaolin from tiny holes and properly seals the soil. Filter paper is put between the porous plate and the sample from the top also. And then kaolin is subjected to a consolidation pressure of 60 kPa for 24 hours. Kaolin is stabilized under the sustained pressure and its settlement is less than 0.01 mm/min after 12 hours. Schematic representation of getting soft soil bed, type 1 i.e. of c_u= 5 kPa is shown in the Fig. 1.

Table 4. Physical properties of soft soil bed

Test bed type	Applied pressure (kPa)	Time duration (hrs)	Soft soil bed's undrained shear strength (c_u, kPa)
Type-1	60	24	5

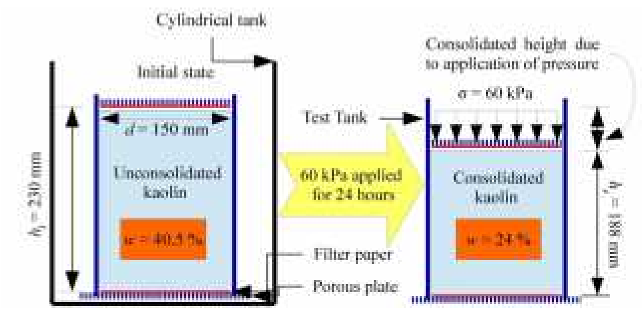

Fig. 1 Preparation of consolidated soft soil bed

5 Construction of Stone Column

A purpose of this study is to understand the settlement characteristics of the reinforced soft clay. The stone columns can be constructed by two methods viz. replacement and displacement method with varying compactive efforts applied during its construction. In replacement method, soft clay was extruded out and replaced with stone aggregates which were compacted further with compactive effort. Whereas in displacement method the poker displaces the soil and intrudes, the tubular cavity is filled with stone aggregates and compactive effort is applied for achieving higher density. Displacement method gives a true representation of actual field installation technique, as it displaces the treated soil (Egan et al. 2008), but the technique was difficult to simulate in the laboratory with reduced scale models. In our experimental study, the stone columns were constructed by the displacement method. In the displacement method, the hollow pipe with cone was pushed into the centre of the test bed. It displaces the soil and cylindrical cavity is formed, which was then filled with stone aggregates.

Table 5. Compaction specifications for making stone column by the effort, *E*

Diameter of Stone Column (mm)	**Compacted Height (mm)**	**No. of Blows per layer**	**Drop Height (mm)**	**Compactive Effort (kJ/m^3)**
25.4	50	1	100	23.21
38.1	25	1	100	20.62
50.8	25	2	100	23.20
63.5	25	3	100	22.28
76.2	25	4	100	20.62
Weight of ramming rod = 0.6 kg			*Average*	*21.98*

6 Experimental Results

In test series TS-1, the soft soil of undrained strength 5.0 kPa were subjected to sustained bearing pressures of 150 kPa and their final settlement was noted. The test variable was area replacement ratio of the construction of stone columns. The settlement recorded with the stone column reinforced test beds are compared with the unreinforced bed.

It is noted that the installation of the stone column reduces the settlement. To quantify this reduction in settlement, a dimensionless parameter, settlement reduction ratio (S.R.R.) is introduced. It is defined as:

$$S.R.R. = \left[\frac{h_{scb} - h_{rcb}}{h_{scb}}\right] \times 100$$

Where, h_{scb} = settlement of the soft soil bed for a given bearing pressure, and h_{rcb} = settlement of the soft soil bed reinforced with stone column under the same bearing pressure.

Larger the value of S.R.R. better is the improvement in the stone column reinforced soft soil ground. In this chapter, the test results of various tests series are presented and discussed.

6.1 Test Series TS-1: Settlement Characteristics of Soft Soil Beds

As given in Table 3, in Test series TS-1, the soft soil beds of kaolin having undrained shear strength c_u = 5 kPa were prepared. These beds were then subjected to three different bearing pressures (i.e. 100, 150 and 200 kPa). Settlement values were recorded with time and the final thickness of the test bed was considered when the settlement rate reduces to less than 0.1mm/hr. Different tests of test series TS-1 has been numbered as C1 – C3. The test results of test series TS-1 are given in Table 6.

Table 6. Settlement of soft soil beds under different bearing pressure

Test Number	Undrained Shear Strength (kPa)	Bearing Pressure (kPa)	Initial height of the soft soil bed (mm)	Final height of the soft soil bed (mm)	Settlement (mm)
C1	5.0	100	188	179.29	8.71
C2	5.0	150	188	178.19	9.81
C3	5.0	200	188	177.49	10.51

Settlement vs. time graphs for soft soil bed (c_u= 5 kPa) under three bearing pressures (100, 150 and 200 kPa) was plotted and shown in Fig. 2.

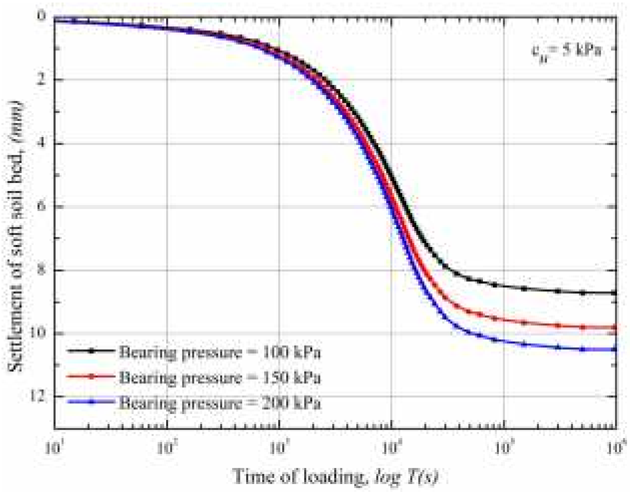

Fig. 2 Settlement vs. time of loading for different bearing pressures (c_u=5 kPa)

6.2 Test Series TS-2: Settlement Characteristics of Reinforced Soft Soil Beds

The test Series, TS-2 was conducted on soft soil of undrained shear strength (c_u) of 5 kPa reinforced with stone columns of various area replacement ratio (a_s) constructed by replacement method. All the tests beds were subjected to constant bearing pressure of 150 kPa. Table. 7 provided the details of the stone columns constructed by replacement method with different compactive efforts.

Table 7. Dimensions of stone columns, TS-2 (c_u = 5 kPa, RP, E)

Method of Construction of Stone Column	Test No.	Initial Diameter of Stone Column (mm)	Compactive Effort Applied (kJ/m^3)		Final Diameter of Stone Column (mm)
RP	T1	25.4	E (21.98)	23.21	26.1
	T2	38.1		20.62	39.0
	T3	50.8		23.20	51.9
	T4	63.5		22.28	64.9
	T5	76.2		20.62	77.8

Fig. 3 shows the settlement time graph for the 5 different tests of Test series, TS-2. The settlement reduction ratio (S.R.R.) for the different tests conducted in Test series, TS-2 are given in Table. 8. Settlement vs. time values obtained from analytical method is plotted and compared with the experimentally obtained graph for stone column diameter of 26.1 mm as mentioned in Table. 8.

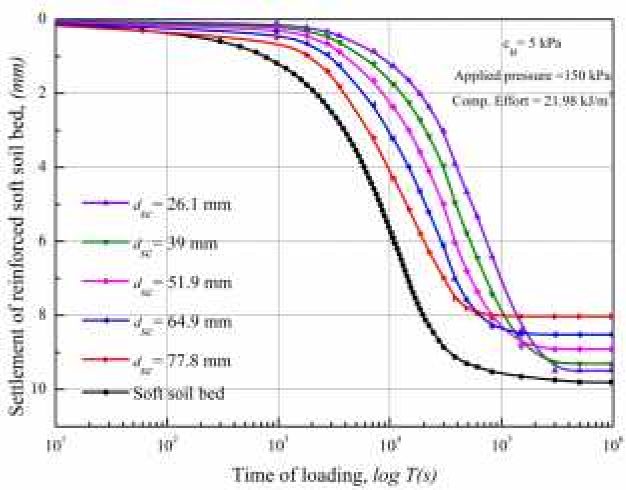

Fig. 3 Settlement vs. time of loading for R.S.S. (c_u=5 kPa, RP, E, 150 kPa)

Table. 8 Settlement reduction ratio, (c_u = 5 kPa, RP, 150 kPa, E)

Method of Construction of Stone Column	Test No.	Initial Diameter of Stone Column (mm)	Final Diameter of Stone Column (mm)	Compactive Effort Applied (kJ/m^3)	Settlement of Soft Soil Bed (mm)	Settlement Reduction Ratio, S.R.R. (%)
RP	T1	25.4	26.1	E (21.98)	9.49	3.32
	T2	38.1	39		9.31	5.16
	T3	50.8	51.9		8.92	9.18
	T4	63.5	64.9		8.52	13.26
	T5	76.2	77.8		8.03	18.26

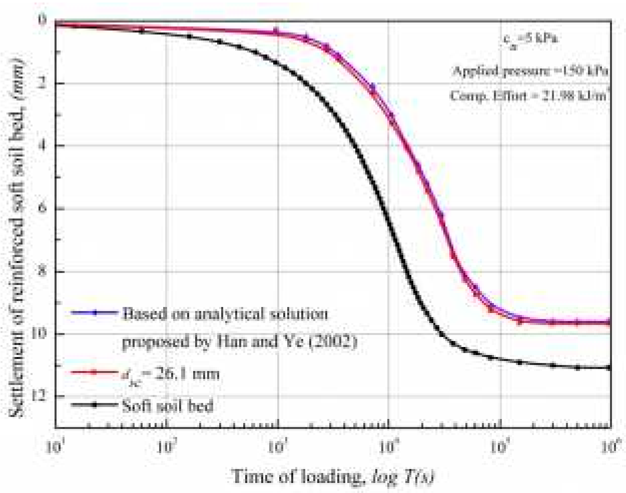

Fig. 4 Comparison done for S.C. of 26.1 mm (c_u=5 kPa, RP, 150 kPa, E)

7. Conclusions

The research work conducted reports the settlement performance of a soft clay bed reinforced with the stone columns with different diameters constructed by constant compactive effort. Following conclusions were drawn:

1. The settlement values of a reinforced soft soil bed under a bearing pressure is dependent on the replacement ratio of stone column. More is the diameter of stone column more is replacement ratio and smaller the settlement of the reinforced soft soil bed.
2. Final diameter of stone column is enlarged due to application of compactive effort applied. The finalized diameter of 76.2 mm become 77.2 mm due to applied compactive effort.
3. Settlement of the reinforced soft soil bed can effectively controlled using larger stone columns. Reduction in settlement (i.e. SRR) is more for larger diameter of stone column.

4. Due to compactive effort applied during the construction of stone column the adjoining soft soil structure is disturbed. This zone is named as smear zone. Permeability of the soft soil is modified and its value is reduced in this zone. The analytical relation used for the comparison accounts for the reduced permeability in the smear zone and is showing good agreement with the experimental results.
5. Least settlement of the reinforced soft soil bed is achieved for the highest replacement ratio of stone column diameter of 76.2 mm that corresponds to 25.8%.

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