Performance of encased single stone column in layered soil

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Abstract. Stone columns were found to be effective, economical and widely-used ground improvement technique in soft grounds. It is important to understand the behavior of stone columns when they are installed in layered soils. This paper presents results from a series of small scale laboratory model tests carried out in unit cell tank to investigate the behavior of floating and end bearing stone columns in layered soils with and without encasement, consisting of loose sand overlying a soft soil. Tests were conducted with loading only the stone column area to estimate the limiting axial capacity of stone column. Laboratory tests were carried out on a column of 10 cm diameter surrounded by layered soil. Test results indicated that the bearing capacity of layered soil has been improved in all cases of stone column applications. The non-encased floating stone columns gave better results than non-encased end bearing stone column. The inclusion of geotextile encasement resulted in further improvement of layered soil and the encased floating stone column had superior bearing capacity improvement.

1. Introduction

Stone columns have been used in many difficult foundation sites throughout the world to increase the bearing capacity and the rate of consolidation, to reduce the total and differential settlements, and to improve slope stability of embankments and also to improve the resistance to liquefaction [1].

It is well established that stone columns derive their bearing capacity from the lateral confining pressure from the surrounding soils [2-4]. When stone columns are installed in very soft soils or in layered soils where the top layer is very soft, they may not derive significant bearing capacity owing to low lateral confinement, which leads to excessive bulging. Improvement in the bearing capacity of the stone column can be achieved by the encasement of the stone column in geotextiles [5]. Increased confinement of the stone column reduces lateral bulging, thereby increasing the bearing capacity of the stone column [6-7].

Previous studies investigated the performance of stone columns in the settlement and bearing capacity of soft soils [1, 8-9]. There have been very limited studies performed on the behavior of stone columns in layered soils [10-11]. However, in reality, foundations are usually set in layered soils and understanding the behavior of stone columns in layered soils is very important for civil engineers [11]. In the literature, the condition of layered soils was mostly considered to be a soft soil overlying a very soft soil, each of varying thicknesses [10-11]. However, the performance of stone columns in loose sand overlaying soft soil was not considered. In the present study, the performance of stone columns in...
layered soil consisting of loose sand overlaying soft soil was studied in a small-scale laboratory model test tank with the single stone column at the center and the layered soil surrounding it.

For the enhancement of weak soils where the depth of the hard layers lies at deeper layers, the choice of floating stone columns may be one of the best options [12]. Literature review points out that most of the conducted researches on the behavior of stone columns were at most on the condition of end bearing stone columns [13-14]. There are very limited studies conducted on the vertical stress-settlement behavior of floating stone columns [13-14]. Hence, in the present study, small scale laboratory model tests have been conducted to examine the performance of both floating and end bearing stone columns with and without geotextile encasement in layered soil.

2. Experimental investigation

2.1 Materials used

A clayey silty soil was used in the present study, which was taken from Famagusta, North Cyprus. The specific gravity of this soil was found to be 2.65. The liquid limit, plastic limit and plasticity index of the soil were found to be 58%, 30% and 28%, respectively. As per the Unified Soil Classification System (USCS), the soil was classified as silt with high plasticity (MH). To analyze the worst soil condition in the laboratory, soil specimens at different water contents were prepared and unconfined compressive strength, UCS tests were performed on those specimens. The variation of UCS with increasing water content values was shown in Figure 1. The values in Figure 1 indicated that the water content corresponding to 33 kPa was found to be 33%. According to Das [15], the consistency of the soil at 33 kPa was described to be soft. Throughout the study, the water content of the soil in the model test tank was preserved at 33%. The bulk density of the soil at the same water content was 1.81 g/cm3.

A sandy soil which was used in the study was taken from the Bedis Beach in Famagusta, North Cyprus. The average particle size of the sand material (D50) was 0.22 mm. The sand used has a coefficient of uniformity (Cu) of 1.29 and a coefficient of curvature (Cc) of 1.06 and was classified as poorly graded sand (SP) as per Unified Soil Classification System (USCS). The specific gravity, maximum dry density (ρdmax) and minimum dry density (ρdmin) of the sand were found to be 2.65, 1.55 g/cm3 and 1.46 g/cm3, respectively. The friction angle of the sand was found to be 31°.

The stone columns formed were of 10 cm diameter and constructed by crushed stone aggregate with particle size varying in the range of 1mm to 5mm. The average particle size of the aggregate material (D50) was 3.0 mm. The crushed stone aggregate used has a coefficient of uniformity (Cu) of 1.67 and a coefficient of curvature (Cc) of 0.99 and was classified as poorly graded sand (SP) as per Unified Soil Classification System (USCS). The specific gravity, maximum dry density (ρdmax) and minimum dry density (ρdmin) of the aggregate were found to be 2.48, 1.61 g/cm3 and 1.49 g/cm3, respectively. The friction angle of the aggregate at 70% relative density was found to be 45° and the corresponding density was 1.57 g/cm3. The grain size distribution of soft soil, sand and the crushed stone aggregate used in this experimental investigation were depicted in Figure 2.
Figure 1. Unconfined compressive strength (UCS) of soil with changing water content.

Figure 2. Particle size distribution of soft soil, sand and crushed stone aggregates used in the study.
In this study, non-woven geotextile was used as an encasing material in the stone columns. The geotextile material had a tensile strength of 7 kN/m. The properties of the non-woven geotextile utilized in this study were illustrated in Table 1.

| Test                                | Standard   | Value | Unit    |
|-------------------------------------|------------|-------|---------|
| Weight                              | EN ISO 9864| 500   | gr/m²   |
| Thickness (2kPa)                    | EN ISO 9863-1| 2.7   | mm      |
| Tensile strength (longitudinal - transverse) | EN ISO 10319| 7     | kN/m    |
| Break extension (longitudinal-cross) | EN ISO 10319| min. 60 | %      |
| Static puncture                     | EN ISO 12236| 2040  | N       |
| Dynamic puncture                    | EN ISO 13433| 10.04 | mm      |
| Water permeability, VH50            | EN ISO 11058| 0.034 | l/s* m² |
| Visible pore size, O90              | EN ISO 12956| 0.070 | mm      |

2.2 Experimental setup
Two types of stone columns were considered in the study: floating stone column with L = 50 cm and end bearing stone column with L = 75 cm (at the base of model test tank). All stone column diameters were 1 cm. A steel rod of 2 cm diameter was used for the compaction of stone column material to reach the required density. The load was applied through a 10 cm diameter steel circular plate and 38 mm thickness. Two linear variable differential transformers, LVDT were used to measure the settlement of the loading plate. A circular steel test tank of 40 cm diameter and 80 cm high was used in the present study. The layered soil in the model test tank consisted of 35 cm soft soil bed at the tank bottom and 35 cm of loose sand was placed on top of it.

The soft soil was placed in the test tank and the soil was consolidated with an in-situ overburden pressure. Then, the sand layer was laid over the consolidated soil layer. For the placement density of the sand layer, minimum dry density of 1.46 g/cm³ was used.

2.3 Details of test series
Three series of model tests were carried out on unreinforced layered soil, non-encased stone columns and encased stone columns. After the preparation of the soil specimens in the test tank, the vertical load was applied over the area of the stone column by a constant rate of 1.2 mm/min up to 30 mm vertical settlement of the footing. The loading period was maintained short to simulate the undrained condition during construction.

3. Results and discussion

3.1 Vertical stress-settlement behavior of stone column
In the present study, in order to reach the clear ultimate load in the load-settlement curves of stone columns, the loading of the stone column was continued until 30 mm settlement and the vertical stress corresponding to this settlement value was considered to be the ultimate vertical stress of the stone column. The behavior of non-encased and encased floating and end bearing stone columns in layered soil were studied with 10 cm diameter stone columns.

3.1.1 Behavior of non-encased and encased floating stone columns
Figure 3 presents the vertical stress-settlement curves of single stone column with and without encasement. The figure indicated that the ultimate vertical stress of the non-encased floating stone
column resulted in a significant amendment of layered soil bearing capacity. The ultimate vertical stress value of non-encased floating stone column reached 124 kPa at 30 mm settlement, while the ultimate vertical stress value of encased floating stone column increased further and reached 240 kPa at 30 mm settlement. In case of encased floating stone column, the increase in the bearing capacity of the soil was due to the radial elongation of the geotextile under applied loads; this was achieved by the tensile strength and stiffness of the geotextile material [8].

3.1.2 Behavior of non-encased and encased end bearing stone columns
From Figure 3, it can be seen that the non-encased end bearing stone column resulted in a considerable improvement in the ultimate vertical stress of soil. The ultimate vertical stress reached 114 kPa at 30 mm settlement. The encased end bearing stone column exhibited little improvement to the bearing capacity of soil and the ultimate vertical stress value of the encased end bearing stone column reached 150 kPa at 30 mm settlement.

3.1.3 Behavior of floating and end bearing stone columns
Figure 3 indicated that the non-encased floating stone column with shorter length (L/d=5) gave better improvement to the bearing capacity of soil than the non-encased end bearing stone column with longer length (L/d=7.5). In soft soils, an increase in the L/d ratio of stone column within the range of 6-10 increases the ultimate vertical stress of the stone columns [23-24]. In the case of non-encased floating and end bearing stone columns in layered soil, an increase in L/d ratio resulted in a reduction in the ultimate vertical stress. Thus, the findings in layered soil were contradicting the findings obtained for soft soil.

From Figure 3, it can be seen that the encased floating stone column (L=50 cm) resulted in a significant improvement in the ultimate vertical stress of soil compared to encased end bearing stone column (L=75 cm). The reason for this behavior was that for shorter encased stone column, the stone column was densified in a shorter time then the time required for the elongation of geotextile started and the soil-column interface shear resistance contributed to the bearing capacity of the stone column. While, in longer encased stone column, the densification of stone column material took longer time to transfer the load along the stone column length. Due to the limited elongation of the geotextile, soil-column interface shear resistance was not attained and thus, the geotextile did not contribute to the increase the bearing capacity of the stone column.
4. Conclusions
Based on the small-scale laboratory model test results, the following conclusions can be drawn from the study:
1. The ultimate vertical stress and settlement were improved in all cases of stone column applications in layered soil.
2. The encased floating stone column gave the maximum performance in the improvement of bearing capacity among all stone column applications.
3. The non-encased floating stone column gave better results of improving bearing capacity of soil than the non-encased end bearing stone column. The geotextile encasement of stone columns gave further improvement to the bearing capacity of the soil.

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