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Circular Raft Footings Strengthened by Stone Columns under Static Loads

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***Abstract*—**Stone columns have been widely employed to improve the load-settlement characteristics of soft soils. The results of two small scale displacement control loading tests on stone columns were used in order to validate numerical finite element simulations. Additionally, a series of numerical calculations of static loading have been performed on strengthened raft footing to investigate the effects of using stone columns on bearing capacity of footings. The bearing capacity of single and group of stone columns under static loading compares with unimproved ground.

***Keywords*—**Circular raft footing, numerical analysis, validation, vertically encased stone column.

I. Introduction

IN geotechnical engineering, the construction of structures such as a storage tanks, warehouse, etc., on soft soils usually involves excessive settlement and stability problems. Among various soil improvement techniques commonly employed in the field, stone columns are an effective solution to keep (differential) settlements within acceptable limits and to guarantee the bearing capacity of foundations on soft soils [1]. Also it gives the advantage of accelerated consolidation settlements due to reduction in flow path lengths and the simplicity of its construction method [2].

During the last four decades, the stone column has been utilized worldwide and proved successful results. Several modifications have been proposed to increase the efficiency of this technique such as addition of additives, use of special patterns of reinforcements, encasing the stone columns with geonet or geogrid to provide extra confinement that enhances the bearing capacity and reduces the settlement drastically without compromising its effect as a drain [3].

Although widely used, the interaction between soil and the columns is not well understood, in particular when the columns do not reach a firm stratum but "float" in the soft soil layer [1]. Therefore, to investigate the behavior of stone column numerical studies were undertaken to further understand the interaction between the geogrid, column material and surrounding soil. Gniel and Bouazza [4] numerically simulated small scale laboratory tests in order to investigate the interaction between the geogrid, column material and surrounding soil. Kirsch [5] simulated some field experiments in order to examine various parameters such as area ratio, improvement factor and influence of column length. Ghazavi and Nazari Afshar [6] conducted numerical analysis to study scale effects on small stone columns tested in the laboratory.

This paper presents the results of numerical study carefully calibrated with laboratory measurements to investigate the load carrying mechanism of groups of stone columns in soft soil under static loading.

II. Axisymmetric Finite Element Model

In the present paper, a series of numerical calculations have been performed to investigate the behavior of floating stone columns in soft clay under static loading. First, an axisymmetric finite element analysis was done on ordinary and encased isolated stone column in laboratory scale to validate by some experimental tests from Ghazavi and Nazari afshar [6] using PLAXIS software. Additionally, analyses were carried out in prototype scale by validated model under static loading in order to evaluate the effects of stone column groups on the bearing capacity of footings subjected to such loading.

A. Validation of Model

Results of selected experimental tests conducted by [6] were used to validate the numerical model used in this study. Experimental test set up consists of a large box with plan dimension of 1.2 m × 1.2 m and 0.9 m height. This tank has a rigid loading frame for installing loading system and provides space for soft soil and stone column materials. Clay, crushed stone and geosynthetics properties used in the tests and simulations are listed in Table I.

TABLE I
PROPERTIES OF MATERIALS USED IN THE EXPERIMENTS AND SIMULATIONS [6]

Parameters	Properties		
	Clay	Stone	Geotextile
Modulus of elasticity (kPa)	600	40000	-
Poisson s ratio (μ)	0.47	0.3	-
Cohesion (kPa)	15	0	-
Internal friction angle (φ)	0	46	-
Secantm stiffness (kN/m)	-	-	35

Fig. 1 shows schematic of soil container modeled in the numerical simulations. The Mohr-coulomb failure criterion was employed to model clay and stone column material behavior. Also, a linear elastic criterion was assumed for geosynthetic material [6]. In consistent with the displacement control loading system used in the experimental tests,

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numerical analyses were performed by applying constant displacement increments as constant velocity. Rigid steel plate has been used for applying displacement increments as shown in Fig. 1. Boundary conditions of full fixity at the base and horizontal fixity at perimeter wall are considered in the FEM model.

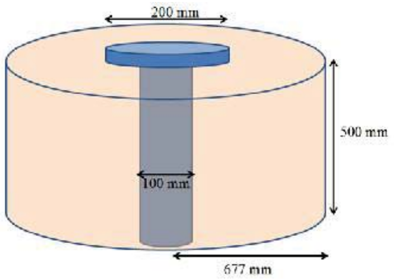

Fig. 1 Schematic of single stone column and soil container used in numerical analyses

The results of two experiments were used as benchmarks for validation of the numerical model. The benchmark tests were selected to represent both unreinforced and vertical encased stone column (VESC). Table II provides a summary of the important specifications of the benchmark experiments. Ordinary stone column finite element mesh and depicted points for evaluating stresses under footing and on the stone column are presented in Fig. 2.

TABLE II
SPECIFICATION OF EXPERIMENTS USED FOR VALIDATION [6]

Benchmark experiment	Properties of stone column		
	Diameter (mm)	Length (m)	Geotextile
Ordinary stone column (OSC)	100	0.5	-
VESC	100	0.5	√

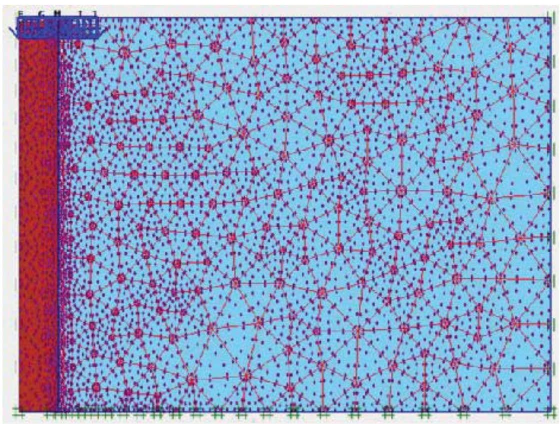

Fig. 2 OSC finite element mesh

The results of numerical analysis simulating experiment 1 and 2 are presented in Fig. 3 which compares the load-settlement curves. This figure shows that the numerical simulations results are in good agreement with experiments. As stated before, OSCs in very soft soils may not endure considerable loads due to low lateral confinement. So, numerical results confirm that using geotextile as an encasement lead to increase in bearing capacity about 40%, the same as experiments conducted by [6].

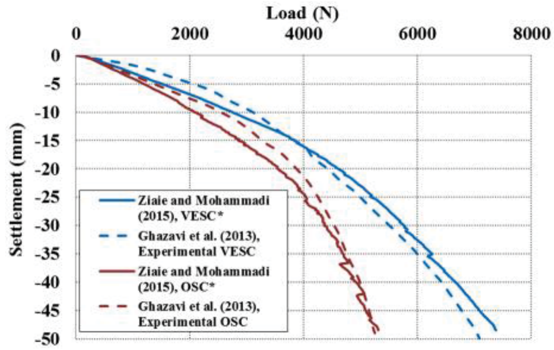

Fig. 3 Comparison of numerical and experimental results of settlement versus load for both benchmark experiments: VESC, OSC

The results of numerical simulation for benchmark experiments are depicted in Fig. 4 for variation of lateral displacement of stone column over normalized depth (Y/L, Y indicates level of points from the top of stone column and L is stone column total length). The figure shows that the maximum bulging of stone columns in benchmarks OSC and VESC are respectively around 6 mm and 4.5 mm. Comparison of these two curves indicates that the maximum bulging decreases by using encapsulated stone column with geotextile and simultaneously, referring to Fig. 3, increases stone column load capacity around 40%.

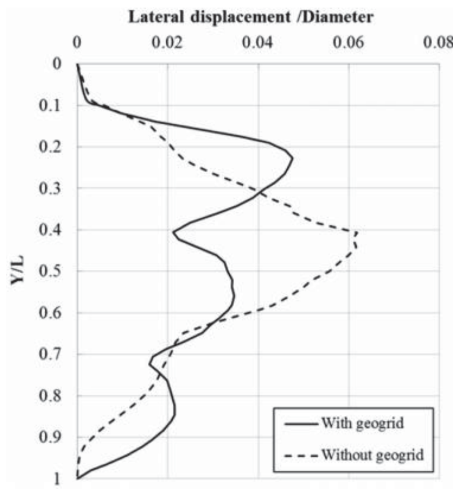

Fig. 4 Normalized lateral displacement of stone column versus normal depth

B. Description of Prototype Model

More numerical analyses of single and group of reinforced stone columns have been performed in prototype scale in order to evaluate the influences of the stone column in improving the bearing capacity of foundations under static loading. The results of single and group stone columns subjected to static displacement-control (by applying low constant velocity) are compared with the results of circular foundation without improvement.

Specifications of different analyses comprising load type and geometry of improvement layout as well as material properties of soil, stone column and geotextile are brought in Tables III and IV respectively.

Fig. 5 shows the schematic of an axisymmetric single stone column in cylindrical container.

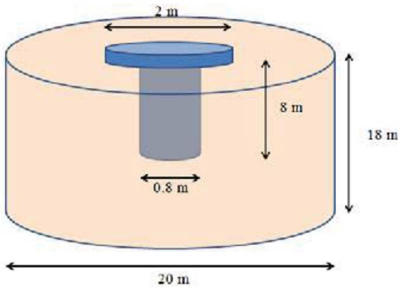

Fig. 5 Schematic model of single stone column used in the numerical modeling

Fig. 6 shows the deformed mesh and bulging occurred due to static loading. Deformed mesh is depicted in Fig. 6 shows the bulging that occurred on single stone column.

Fig. 7 shows the normalized lateral displacement of single stone column versus normal depth. The maximum lateral displacement is expected to occur in level where the confined pressure is not enough to provide lateral pressure for stone column, it means near the surface. On the other hand, the presence of the connection between the raft footing and stone column improved the rigidity of the top soil zone and imposed the maximum bulging not to occur near the surface and push it downward. As can be seen in the figure the maximum bulging has happened in Y=0.3L from the top of the stone column. The results of load-settlement curves of both unimproved soil and improved soil by single stone column are shown in Fig. 8. The comparison of two curves shows that using single stone column under footing increases bearing capacity about 60%. The value of bearing capacity is defined by the load corresponding to 7.5 cm settlement of the footing [7].

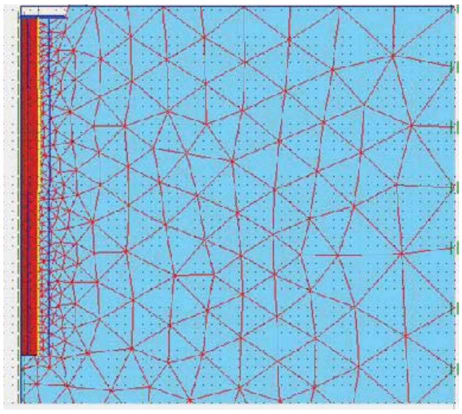

Fig. 6 Deformed mesh and bulging of stone column under static loading

TABLE III
SPECIFICATION OF PERFORMED ANALYSES

Test	Applied load	Properties of stone column				Steel plate diameter (m)
		Diameter (m)	Length (m)	Number of columns	Spacing	
Single stone column	static	0.8	8	1	-	2
Group stone columns	static	0.8	8	7	2.5D	6
Unimproved ground	static	-	-	-	-	6

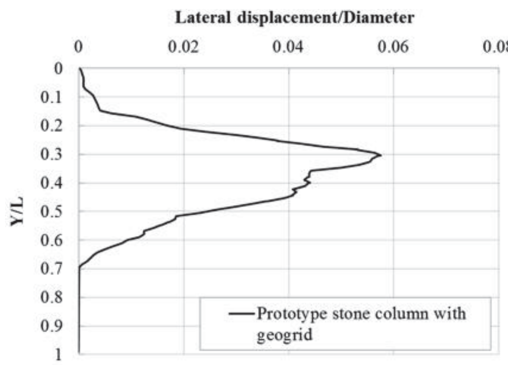

Fig. 7 Normalized lateral displacement of single stone column versus normal depth

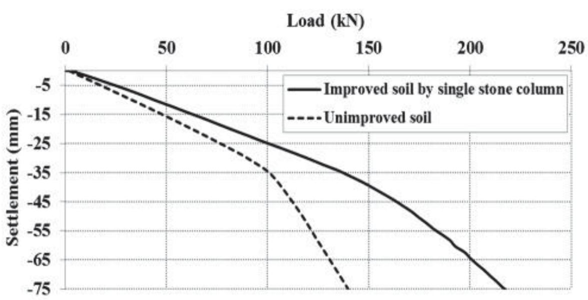

Fig. 8 Comparison of bearing load by depth for unimproved soil and improved soil with single stone column

In order to simulate the 3D problem of the group of stone columns in an axisymmetric analysis, the groups of stone columns were simplified by a ring of stone column having an equivalent thickness as can be seen in Fig. 9 [8]-[10], [6]. The thickness of this ring is determined such that the area of the ring becomes equal to the summation of cross sections of all 6 periphery stone columns. Vertical reinforcement considered in both internal and external sides of the equivalent ring. Since real areas of reinforcement around periphery columns are more than two vertical sides of the ring, reducing the secant stiffness of geotextile used for equivalent ring is considered in numerical analyses.

TABLE IV
MATERIAL PROPERTIES OF PROTOTYPE MODEL ANALYSES

Parameters	Properties		
	Clay	Stone	Geotextile
Modulus of elasticity (kPa)	2000	80000	-
Poisson s ratio (μ)	0.47	0.3	-
Cohesion (kPa)	15	0	-
Internal friction angle (φ)	0	40	-
Secant stiffness (kN/m)	-	-	35

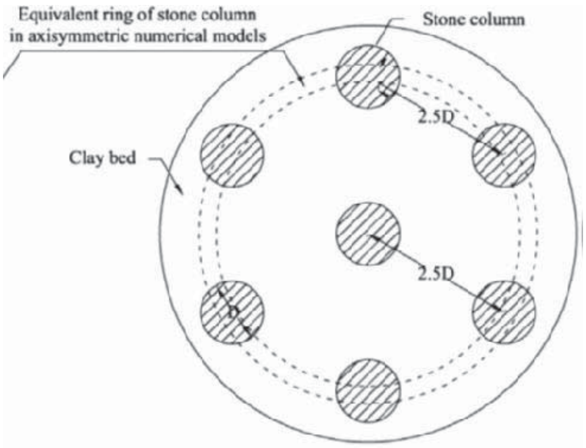

Fig. 9 Group stone column arrangement for analysis [6]

Fig. 10 represents the deformed mesh and bulging that occurred in central and periphery columns.

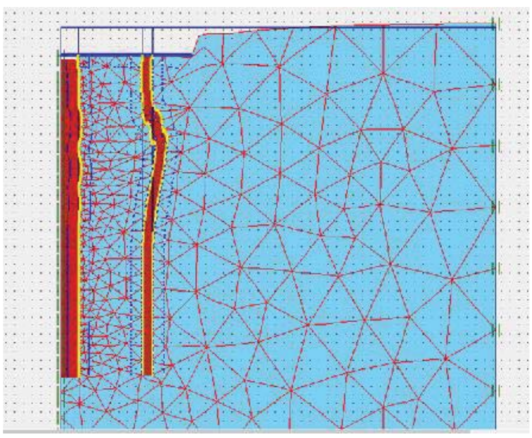

Fig. 10 Deformed mesh for group analysis of stone column in static loading

Fig. 11 compares the lateral displacement of central and periphery stone columns versus normalized depth. The curves indicate that bulging occurred in central stone column at upper levels and lateral displacement occurred in periphery columns. It can be concluded that in group stone columns the considerable deformation is bulging for central column and lateral deformation for periphery columns.

The numerical results of statically loaded footing placed on both improved and unimproved soil have been depicted in Fig. 12. The curves show about 100% increase in bearing load by using 7 stone column groups under the footing. The value of bearing capacity is defined by the load corresponding to 7.5 cm settlement of the footing [7].

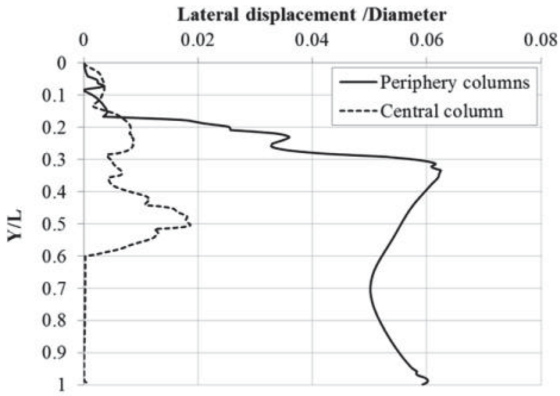

Fig. 11 Variation of lateral displacement of central and periphery stone columns versus normalized depth

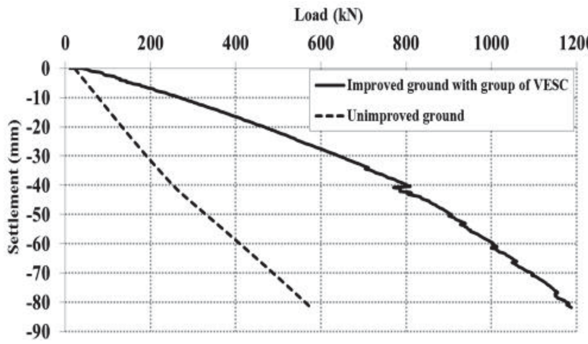

Fig. 12 Comparison of the load-settlement static curves of unimproved ground and improved ground with group of VESCs

III. CONCLUSION

Effects of single and group of stone column as strengthening elements of weak soft soils were evaluated using finite element method. Two small scale tests on single stone column were simulated numerically in order to verify the accuracy of the modelling and the assumptions. Numerical results confirm that using geotextile as an encasement lead to increase in bearing capacity about 40%, the same as experiments conducted by [6]. Comparison of variation of lateral displacement of stone column over normalized depth indicates that the maximum bulging decreases by using encapsulated stone column with geotextile and simultaneously, increases stone column load capacity around

40%. After validation of numerical modelling, full scale models of single and group of stone columns were subjected to static gradual displacement load. Results show that maximum lateral displacement of the stone column occurred in Y=0.3L from the top of the stone column. This is due to the low confined pressure at higher levels that cannot provide enough lateral pressure for the stone column. On the other hand, the connection zone between column and footing imposes the maximum lateral displacement not to happen at top. Also, group analysis of stone column in static loading shows that in group stone columns the considerable deformation is bulging for central column and lateral deformation for periphery columns.

The obtained results were compared with the results of raft foundation without the stone columns. The results show that single and group of stone columns under footing increases static bearing capacity of footing about 60% and 100% at 7.5 cm settlement, respectively.

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