Statistical Analysis on the Static Characteristics of the Geosynthetic Encased Stone Column

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Abstract

The geosynthetic encased stone column is made of stone column encased with geosynthetic encasement. The geosynthetic encased stone column is often used for foundation treatment of roadbeds, dams, buildings and other structures. At present, a series of new developments have been made in the researches of bearing capacity, stress concentration ratio and deformation of the geosynthetic encased stone column. This paper statistically analyzes the three important static characteristics of the geosynthetic encased stone column.

Introduction

Geosynthetic encased stone column (ESC) is made by enfolding the stone column (SC) with a geosynthetic encasement. The ESC includes fully encased stone column and partially encased stone column, and the former one with encasement length equaling to the column length, and the latter one with encasement length less than the column length, as shown in Fig. 1. Geosynthetic or geotextile are often chosen to be the material of the encasement.

The encasement could constrain the column deformation, and prevent the gravel from leaking into the surrounding soil. The stiffness of ESC is higher than SC, which induces a larger stress concentration ratio. The smaller deformation and larger stiffness contribute to higher bearing capacity for the ESC.

Currently, the main and effective approach to study the static characteristics of ESCs is to use experiments, including laboratory model tests or in-situ full-scale tests. Experiments in the references from 2007 to 2021 were collected. In the paper, the bearing capacity, stress concentration ratio, and pile deformation of ESCs in these experiments were analyzed.

Static Characteristics

Bearing capacity

Allowable bearing capacity and ultimate bearing capacity of the geosynthetic encased stone columns (ESCs) are collected from different model tests and listed in Table 1. The allowable bearing capacity is obtained at the pressure of elastic state tending to plastic state of ground. The ultimate bearing capacity is obtained at the pressure in a failure state of the ground. Table 1 shows that the allowable bearing capacity ratios of the ESCs to unreinforced ground are between 2.5 and 15.11. The ultimate bearing capacity ratios of the ESCs to unreinforced ground are between 1.1 and 34.6. The large allowable bearing capacity ratio and large ultimate bearing capacity ratio both occur in the condition of small shear strength of soil. The allowable bearing capacity of ESCs is 1.5 to 8.5 times that of the stone columns (SCs), and the ultimate bearing capacity of the ESCs is 1.0 to 9.4 times that of the SCs under different conditions for different experiments.

Table 1
Bearing capacity of soil reinforced by geosynthetic encased stone columns (ESCs)

Case No.	Undrained shear strength of soil / kPa	Tensile load of encasement at strain $\varepsilon = 5\%$ / (kN·m ⁻¹)	Allowable bearing capacity ratio of SCs to unreinforced ground	Allowable bearing capacity ratio of ESCs to unreinforced ground	Limited bearing capacity ratio of SCs to unreinforced ground	Limited bearing capacity ratio of ESCs to unreinforced ground	References	Additional information
1	15	1	1.86	2.86	1.3	1.5	Mehrannia et al., 2018	$l=350\text{mm}$, $d=60\text{mm}$
2	10	8.75	1.5	3.33	1.8	3.6	Debnath and Dey, 2017	$l=300\text{mm}$, $d=50\text{mm}$, $s=2.5d$
3	10	8.75	1.5	4	2.3	2.5	Debnath and Dey, 2017	$l=300\text{mm}$, $d=50\text{mm}$, $s=2.5d$, mat thickness of 20mm
4	10	8.75	1.5	4.87	1.8	4.5	Debnath and Dey, 2017	$l=300\text{mm}$, $d=50\text{mm}$, $s=2.5d$, mat thickness of 30mm
5	10	8.75	1.5	5.33	3.3	3.5	Debnath and Dey, 2017	$l=300\text{mm}$, $d=50\text{mm}$, $s=2.5d$, mat thickness of 40mm
6	10	8.75	1.5	5.77	1.8	5	Debnath and Dey, 2017	$l=300\text{mm}$, $d=50\text{mm}$, $s=2.5d$, mat thickness of 60mm
7	10	8.75	1.5	6.1	4.3	4.5	Debnath and Dey, 2017	$l=300\text{mm}$, $d=50\text{mm}$, $s=2.5d$, mat thickness of 80mm
8	10	8.75	1.5	7.67	4.3	10.5	Debnath and Dey, 2017	$l=300\text{mm}$, $d=50\text{mm}$, $s=2.5d$, mat thickness of 30mm
9	12	24	—	—	4.1	5.7	Demir and Sarici, 2017	—
10	3.4	4.75	1.5	7	5.3	9.6	Ou Yang et al., 2016a	$d=10\text{cm}$, $l=65\text{cm}$
11	3.4	10	1.5	2.5	2.3	3.1	Ou Yang et al., 2016a	$d=10\text{cm}$, $l=65\text{cm}$, $l_{\text{esc}}=4d$
12	3.4	10	1.5	11	2.3	13.5	Ou Yang et al., 2016a	$d=10\text{cm}$, $l=65\text{cm}$
13	10	0.39	—	—	1.2	1.3	Fattah et al., 2016	$d=70\text{mm}$, $H_d=200\text{mm}$, $l/d=5$, floating pile, $s=2.5d$
14	10	0.39	—	—	1.1	1.2	Fattah et al., 2016	$d=70\text{mm}$, $H_d=200\text{mm}$, $l/d=5$, floating pile, $s=3d$
15	10	0.39	—	—	1	1.1	Fattah et al., 2016	$d=70\text{mm}$, $H_d=200\text{mm}$, $l/d=5$, floating pile, $s=4d$

Case No.	Undrained shear strength of soil / kPa	Tensile load of encasement at strain $\varepsilon = 5\%$ / (kN·m ⁻¹)	Allowable bearing capacity ratio of SCs to unreinforced ground	Allowable bearing capacity ratio of ESCs to unreinforced ground	Limited bearing capacity ratio of SCs to unreinforced ground	Limited bearing capacity ratio of ESCs to unreinforced ground	References	Additional information
16	10	0.39	—	—	1.2	1.4	Fattah et al., 2016	$d=70\text{mm}$, $H_d=200\text{mm}$, $l/d=8$, end bearing pile, $s=2.5d$
17	10	0.39	—	—	1.1	1.2	Fattah et al., 2016	$d=70\text{mm}$, $H_d=200\text{mm}$, $l/d=8$, end bearing pile, $s=3d$
18	10	0.39	—	—	1.1	1.2	Fattah et al., 2016	$d=70\text{mm}$, $H_d=200\text{mm}$, $l/d=8$, end bearing pile, $s=4d$
19	10	0.39	—	—	1.3	1.4	Fattah et al., 2016	$d=70\text{mm}$, $H_d=250\text{mm}$, $l/d=5$, floating pile, $s=2.5d$
20	10	0.39	—	—	1.3	1.3	Fattah et al., 2016	$d=70\text{mm}$, $H_d=250\text{mm}$, $l/d=5$, floating pile, $s=3d$
21	10	0.39	—	—	1.2	1.2	Fattah et al., 2016	$d=70\text{mm}$, $H_d=250\text{mm}$, $l/d=5$, floating pile, $s=4d$
22	10	0.39	—	—	1.4	1.6	Fattah et al., 2016	$d=70\text{mm}$, $H_d=250\text{mm}$, $l/d=8$, end bearing pile, $s=2.5d$
23	10	0.39	—	—	1.3	1.5	Fattah et al., 2016	$d=70\text{mm}$, $H_d=250\text{mm}$, $l/d=8$, end bearing pile, $s=3d$
24	10	0.39	—	—	1.2	1.3	Fattah et al., 2016	$d=70\text{mm}$, $H_d=250\text{mm}$, $l/d=8$, end bearing pile, $s=4d$
25	10	0.39	—	—	1.5	1.6	Fattah et al., 2016	$d=70\text{mm}$, $H_d=300\text{mm}$, $l/d=5$, floating pile, $s=2.5d$
26	10	0.39	—	—	1.4	1.6	Fattah et al., 2016	$d=70\text{mm}$, $H_d=300\text{mm}$, $l/d=5$, floating pile, $s=3d$
27	10	0.39	—	—	1.3	1.4	Fattah et al., 2016	$d=70\text{mm}$, $H_d=300\text{mm}$, $l/d=5$, floating pile, $s=4d$
28	10	0.39	—	—	1.7	1.8	Fattah et al., 2016	$d=70\text{mm}$, $H_d=300\text{mm}$, $l/d=8$, end bearing pile, $s=2.5d$

Case No.	Undrained shear strength of soil / kPa	Tensile load of encasement at strain $\varepsilon = 5\%$ / (kN·m ⁻¹)	Allowable bearing capacity ratio of SCs to unreinforced ground	Allowable bearing capacity ratio of ESCs to unreinforced ground	Limited bearing capacity ratio of SCs to unreinforced ground	Limited bearing capacity ratio of ESCs to unreinforced ground	References	Additional information
29	10	0.39	—	—	1.5	1.7	Fattah et al., 2016	$d=70\text{mm}$, $H_d=300\text{mm}$, $l/d=8$, end bearing pile, $s=3d$
30	10	0.39	—	—	1.4	1.6	Fattah et al., 2016	$d=70\text{mm}$, $H_d=300\text{mm}$, $l/d=8$, end bearing pile, $s=4d$
31	3.4	20	—	—	1.1	1.7	Gu et al., 2015	$d=200\text{mm}$, $l_{\text{esc}}=2d$, composite ground
32	3.4	20	—	—	3.8	6	Zhao et al., 2014	$d=200\text{mm}$, $l_{\text{esc}}=2d$
33	2.5	0.3	1.78	15.11	2	18.8	Murugesan and Rajagopal, 2010	$d=50\text{mm}$, $l=600\text{mm}$
34	2.5	0.3	2.22	9.11	2.5	12.4	Murugesan and Rajagopal, 2010	$d=75\text{mm}$, $l=600\text{mm}$
35	2.5	0.3	2.44	7.11	3	9	Murugesan and Rajagopal, 2010	$d=100\text{mm}$, $l=600\text{mm}$
36	2.5	0.75	1.78	12.67	2	18.8	Murugesan and Rajagopal, 2010	$d=50\text{mm}$, $l=600\text{mm}$
37	2.5	0.75	2.22	9.11	2.5	13.4	Murugesan and Rajagopal, 2010	$d=75\text{mm}$, $l=600\text{mm}$
38	2.5	0.75	2.44	6	3	11	Murugesan and Rajagopal, 2010	$d=100\text{mm}$, $l=600\text{mm}$
39	2.5	0.1	2.22	5.91	2.5	7.6	Murugesan and Rajagopal, 2010	$d=75\text{mm}$, $l=600\text{mm}$
40	2.5	0.2	2.22	7.11	2.5	9.2	Murugesan and Rajagopal, 2010	$d=75\text{mm}$, $l=600\text{mm}$
41	2.5	0.3	2.22	9.11	2.5	12.4	Murugesan and Rajagopal, 2010	$d=75\text{mm}$, $l=600\text{mm}$
42	2.5	0.75	2.22	9.11	2.5	13.4	Murugesan and Rajagopal, 2010	$d=75\text{mm}$, $l=600\text{mm}$
43	5	4.8(at 2% strain)	—	—	1.6	4.7	Gniel and Bouazza, 2010	$l_{\text{esc}}=75\%l$, $d=51\text{mm}$
44	2.5	0.77	—	—	5.7	34.6	Murugesan and Rajagopal, 2007	$d=75\text{mm}$, $l=500\text{mm}$, end bearing pile

Case No.	Undrained shear strength of soil / kPa	Tensile load of encasement at strain $\varepsilon = 5\%$ / (kN·m ⁻¹)	Allowable bearing capacity ratio of SCs to unreinforced ground	Allowable bearing capacity ratio of ESCs to unreinforced ground	Limited bearing capacity ratio of SCs to unreinforced ground	Limited bearing capacity ratio of ESCs to unreinforced ground	References	Additional information
45	2.5	0.57	—	—	5.7	25.1	Murugesan and Rajagopal, 2007	$d=75\text{mm}$, $l=500\text{mm}$, end bearing pile
46	2.5	0.18	—	—	5.7	21.4	Murugesan and Rajagopal, 2007	$d=75\text{mm}$, $l=500\text{mm}$, end bearing pile
47	2.5	0.09	—	—	5.7	18	Murugesan and Rajagopal, 2007	$d=75\text{mm}$, $l=500\text{mm}$, end bearing pile

The bearing capacity of the ESCs composite ground is mostly influenced by geosynthetic encasement modulus, encasement length, shear strength of soil, pile length to diameter ratio, area replacement ratio, and mat thickness (Debnath and Dey 2017; Fattah et al. 2016; Murugesan and Rajagopal 2010; Ou Yang et al. 2016b). When the shear strength of soil is low and modulus of geosynthetic encasement is large, the ESCs are much stronger than SCs. This is because that the SC gains large strength from surrounding soil, and the strength of the stone column significantly increases with the constraint of the stiffer geosynthetic encasement. Murugesan and Rajagopal (2010) found that the SC shows strain-softening behavior, while the ESC behaves similar to rigid pile during loading in model tests. The ESC behaves stiffer and the ESCs composite ground has larger bearing capacity compared to SCs. They also found that the reinforcement from the encasement decreases with an increase in pile diameter. Ou Yang et al. (2016) found that the strength of the ESC increases with the increase of the encasement length, and the fully encased stone column behaves best in model tests. The ESC with encasement length of three times diameter shows significant increase in bearing capacity compared to SC. Murugesan and Rajagopal (2007) found that the bearing capacity of ESCs increases with the increase of the area replacement ratio, and the ESCs composite ground behaves great at the pile to pile space of 2.5 times diameter. Debnath and Dey (2017) found that the optimal mat thickness is 0.15 to 0.2 times diameter of foundation, in which the composite ground shows the greatest bearing capacity.

Comparing the references of Murugesan and Rajagopal (2010) with Fattah et al. (2016), it can be found that the ESC shows more effective improvement over soil and SC in the lower soil strength case. Comparing the references of Debnath and Dey (2017) with Fattah et al. (2016), similar pile lengths, pile diameters, pile to pile spaces, and same shear strength of soil are in the two cases. The encasement modulus of the reference of Debnath and Dey (2017) is 22 times that of Fattah et al. (2016). The case of larger modulus of encasement (Debnath and Dey, 2017) has much higher limited bearing capacity of ESC reinforced ground compared to the smaller modulus of encasement case, although with different pile length to diameter ratios, pile to pile spaces, mat thicknesses and embankment loads, just as shown in Fig. 2. This indicates that the encasement modulus has important influence on the limit bearing capacity of ground. Fig. 2 also shows that the bearing capacity differences induced by mat thickness for the larger encasement modulus case are much larger than those induced by embankment load for the smaller encasement modulus case, which suggests that the large modulus may amplify the effects of the other parameters.

Stress concentration ratio

Stress concentration ratio is one of the important factors in the composite ground design, which shows the load shared by piles and soil. The stress concentration ratio (n) is calculated by Equation 1. Mat didn't use in the model tests before 2015, and thus the stress concentration ratio wasn't considered in these references. The stress concentration ratio is studied in experiments with embankment load or mat in recent years. Stress concentration ratio of different geosynthetic encased stone columns (ESCs) composite grounds is shown in Table 2. As only a few experiments considered stress concentration ratio, some FEM results are also involved in Table 2. The stress concentration ratio is obtained at a stable state or at an allowable load. From the table, it can be found that the stress concentration ratio is between 0.48 and 25 for the ESCs composite ground. The larger stress concentration ratio occurs at the smaller shear strength of the surrounding soil. The stress concentration ratio also increases with an increase in encasement modulus. The table also shows that the stress concentration ratio increases with the increase of the embankment load, and the stress concentration ratio is larger for the end bearing pile case compared to the floating pile case.

Table 2
Stress concentration ratio of geosynthetic encased stone columns (ESCs)

Case No.	Undrained shear strength of soil /kPa	Tensile force of Encasement at strain $\varepsilon = 5\%$ /(kN·m ⁻¹)	Stress concentration ratio of SC	Stress concentration ratio of ESC	References	Additional information
1	5	6	2.5	5.65	Chen et al., 2021	$d=32\text{mm}$, $l/d=12.5$, in a square pattern, $s=100\text{ mm}$
2	5	1.05	2.5	4	Chen et al., 2021	$d=32\text{mm}$, $l/d=12.5$, in a square pattern, $s=100\text{ mm}$
3	5.6	6.6	1.9	7	Li et al., 2021	$d=32\text{mm}$, $l/d=12.5$, in a square pattern, $s=100\text{mm}$, $H_d=200\text{mm}$, end bearing pile
4	5.6	0.9	1.9	4.9	Li et al., 2021	$d=32\text{mm}$, $l/d=12.5$, in a square pattern, $s=100\text{mm}$, $H_d=200\text{mm}$, end bearing pile
5	5.6	6.6	1.9	7.8	Li et al., 2021	$d=32\text{mm}$, $l/d=12.5$, in a square pattern, $s=100\text{mm}$, $H_d=200\text{mm}$, end bearing pile, with geogrids used as horizontal reinforcement in the embankment
6	5.6	0.9	1.9	5.2	Li et al., 2021	$d=32\text{mm}$, $l/d=12.5$, in a square pattern, $s=100\text{mm}$, $H_d=200\text{mm}$, end bearing pile, with geogrids used as horizontal reinforcement in the embankment
7	10	8.75	2	3.2	Debnath and Dey, 2017	$l=300\text{mm}$, $d=50\text{mm}$, $s=2.5d$
8	10	8.75	2	3.2	Debnath and Dey, 2017	$l=300\text{mm}$, $d=50\text{mm}$, $s=2.5d$, mat thickness of 40mm
9	10	8.75	2	4	Debnath and Dey, 2017	$l=300\text{mm}$, $d=50\text{mm}$, $s=2.5d$, mat thickness of 30mm
10	12	31	3~6	11~25	Miranda et al., 2016	-
11	10	0.39	—	0.94	Fattah et al., 2016	$d=70\text{mm}$, $l/d=5$, $s=2.5d$, $H_d=200\text{mm}$, floating pile
12	10	0.39	—	0.73	Fattah et al., 2016	$d=70\text{mm}$, $l/d=5$, $s=3d$, $H_d=200\text{mm}$, floating pile
13	10	0.39	—	0.48	Fattah et al., 2016	$d=70\text{mm}$, $l/d=5$, $s=4d$, $H_d=200\text{mm}$, floating pile
14	10	0.39	—	1.15	Fattah et al., 2016	$d=70\text{mm}$, $l/d=8$, $s=2.5d$, $H_d=200\text{mm}$, end bearing pile
15	10	0.39	—	0.9	Fattah et al., 2016	$d=70\text{mm}$, $l/d=8$, $s=3d$, $H_d=200\text{mm}$, end bearing pile
16	10	0.39	—	0.6	Fattah et al., 2016	$d=70\text{mm}$, $l/d=8$, $s=4d$, $H_d=200\text{mm}$, end bearing pile
17	10	0.39	—	1.47	Fattah et al., 2016	$d=70\text{mm}$, $l/d=5$, $s=2.5d$, $H_d=250\text{mm}$, floating pile
18	10	0.39	—	1.15	Fattah et al., 2016	$d=70\text{mm}$, $l/d=5$, $s=3d$, $H_d=250\text{mm}$, floating pile
19	10	0.39	—	0.65	Fattah et al., 2016	$d=70\text{mm}$, $l/d=5$, $s=4d$, $H_d=250\text{mm}$, floating pile
20	10	0.39	—	2.2	Fattah et al., 2016	$d=70\text{mm}$, $l/d=8$, $s=2.5d$, $H_d=250\text{mm}$, end bearing pile
21	10	0.39	—	1.4	Fattah et al., 2016	$d=70\text{mm}$, $l/d=8$, $s=3d$, $H_d=250\text{mm}$, end bearing pile
22	10	0.39	—	1	Fattah et al., 2016	$d=70\text{mm}$, $l/d=8$, $s=4d$, $H_d=250\text{mm}$, end bearing pile
23	10	0.39	—	2.1	Fattah et al., 2016	$d=70\text{mm}$, $l/d=5$, $s=2.5d$, $H_d=300\text{mm}$, floating pile
24	10	0.39	—	1.5	Fattah et al., 2016	$d=70\text{mm}$, $l/d=5$, $s=3d$, $H_d=300\text{mm}$, floating pile
25	10	0.39	—	0.9	Fattah et al., 2016	$d=70\text{mm}$, $l/d=5$, $s=4d$, $H_d=300\text{mm}$, floating pile

Case No.	Undrained shear strength of soil /kPa	Tensile force of Encasement at strain $\varepsilon = 5\%$ /(kN·m ⁻¹)	Stress concentration ratio of SC	Stress concentration ratio of ESC	References	Additional information
26	10	0.39	—	3.6	Fattah et al., 2016	$d=70\text{mm}$, $l/d=8$, $s=2.5d$, $H_d=300\text{mm}$, end bearing pile
27	10	0.39	—	2	Fattah et al., 2016	$d=70\text{mm}$, $l/d=8$, $s=3d$, $H_d=300\text{mm}$, end bearing pile
28	10	0.39	—	1.3	Fattah et al., 2016	$d=70\text{mm}$, $l/d=8$, $s=4d$, $H_d=300\text{mm}$, end bearing pile
29	3.4	20	9	13	Zhao et al., 2014	$d=200\text{mm}$, $l_{\text{esc}}=2d$
30	15kPa (clay layer at top)	95	—	2.1	Almeida et al., 2014	In-situ test, $l=11\text{m}$, $d=80\text{cm}$, $s=2\text{m}$, in a square pattern
31	6.04	0.2	4.36	4.62	Duan, 2012	—
32	2.5	0.75	2	4.8	Murugesan and Rajagopal, 2010	$l=600\text{mm}$, $d=50\text{mm}$
33	2.5	0.6	2	4.8	Murugesan and Rajagopal, 2010	$l=600\text{mm}$, $d=50\text{mm}$
34	5	4.8 (strain of 2%)	2~3	>10	Gniel and Bouazza, 2010	$d=51\text{mm}$, $l_{\text{esc}}=75\%l$
35	61	—	—	4.5	Lee et al., 2008	In-situ test, $d=0.8\text{m}$, $l_{\text{esc}}=3d$

Fattah et al. (2016) found that the stress concentration ratio increases with the increase of the area replacement ratio and the length-diameter ratio. Ou Yang et al. (2016a) found that the stress concentration ratio increases with the increase of the encasement modulus and encasement length.

$$n = \sigma_{vc} / \sigma_{vs} \quad (1)$$

where, σ_{vc} = load shared by columns; σ_{vs} = load shared by soil.

Radial deformation of piles

Few tests have explored pile deformation due to the difficulty of measuring it in the experiment. Pile deformation data of model tests from references are collected and listed in Table 3. The radial strain of the column is calculated from Equation (2).

$$\varepsilon = \frac{\Delta d}{d}$$

2

Where, d = pile diameter; Δd = variation of pile diameter.

From Table 3, it can be found that the maximum deformation occurs at 1.5 to 4 times diameter depth for the fully encased stone column. As the modulus of the encasement increases, the depth of the maximum deformation downward. For the partially encased stone column, the maximum deformation just occurs under the encasement.

Table 3
Radial strain of columns

Case No.	Undrained shear strength of soil /kPa	Tensile force at 5% strain of encasement (kN/m)	The depth of maximum bulging along the pile / <i>d</i>	Radial strain at SC failure/(%)	Radial strain at ESC failure/(%)	Encasement tensile strength /(kN·m ⁻¹)	Radial strain at limit tensile load for encasement/(%)	Failure mode of ESCs	References	Additional information
1	3.4	4.75	2~3	14	7	11	22	Upper punching	Ou Yang et al., 2016a	<i>l</i> =65cm, <i>d</i> =10cm
2	3.4	10	2~4	14	4.4	43	25	Upper punching	Ou Yang et al., 2016a	<i>l</i> =65cm, <i>d</i> =10cm
3	3.4	10	4~5 (under encasement)	14	4.4	43	25	Shear failure under encasement	Ou Yang et al., 2016a	<i>l</i> =65cm, <i>d</i> =10cm, <i>l</i> _{esc} =4 <i>d</i>
4	10	8.75	2.84	14	8	12	24	Bulging deformation and bending deformation	Debnath and Dey, 2017	<i>l</i> =30cm, <i>d</i> =5cm, <i>s</i> =2.5 <i>d</i>
5	10	8.75	3.2	14	6	12	24	Bulging deformation and bending deformation	Debnath and Dey, 2017	<i>l</i> =30cm, <i>d</i> =5cm, <i>s</i> =2.5 <i>d</i> , mat thickness 40mm
6	10	8.75	3.68	14	3	12	24	Bulging deformation and bending deformation	Debnath and Dey, 2017	<i>l</i> =30cm, <i>d</i> =5cm, <i>s</i> =2.5 <i>d</i> , thickness 30mm for geosynthetic reinforcement sand mat
7	<5	6	2	—	11.34	30	22	Shear failure at pile top	Alkhorshid, 2017; Alkhorshid et al, 2019	<i>l</i> =40cm, <i>d</i> =15cm
8	<5	5.35	2	—	11.95	16	16	Shear failure at pile top	Alkhorshid, 2017; Alkhorshid et al, 2019	<i>l</i> =40cm, <i>d</i> =15cm
9	<5	2.67	2	—	12.53	8	15	Shear failure at pile top	Alkhorshid, 2017; Alkhorshid et al, 2019	<i>l</i> =40cm, <i>d</i> =15cm
10	-	25.4	—	—	6.5	40	10	Shear failure	Gu et al., 2017	Uniaxial compression
11	1.25~1.36	0.15	1.5	28.1	27.1	0.26	13	—	Hong et al., 2016	<i>l</i> =25cm, <i>d</i> =5cm
12	1.25~1.36	0.3	1.5	28.1	15.8	0.75	45	—	Hong et al., 2016	<i>l</i> =25cm, <i>d</i> =5cm
13	1.25~1.36	0.5	1.5	28.1	18.7	7.42	49	—	Hong et al., 2016	<i>l</i> =25cm, <i>d</i> =5cm
14	1.25~1.36	0.025	1.5	28.1	29.1	0.05	25	—	Hong et al., 2016	<i>l</i> =25cm, <i>d</i> =5cm
15	1.25~1.36	0.3	1.75	28.1	13.1	0.25	92	—	Hong et al., 2016	<i>l</i> =25cm, <i>d</i> =5cm
16	5	—	0.8	—	27	2.45	—	—	Dash and Bora, 2013	<i>l</i> _{esc} =1 <i>d</i> , floating
17	5	—	3.5	—	16	2.45	—	—	Dash and Bora, 2013	<i>l</i> _{esc} =3 <i>d</i> , floating
18	61	—	3~4 (under encasement)	—	1.16	100	—	Bulging under encasement	Lee et al., 2008	In-situ test, <i>d</i> =80cm, <i>l</i> _{esc} =3 <i>d</i>

Where, *l* presents pile length; *d* presents pile diameter; *l*_{esc} presents encasement length; *s* presents pile to pile space; and *H_d* presents embankment height.

The maximum deformation of the stone column (SC) is larger than that of the geosynthetic encased stone column (ESC) at limit load, and the former one maybe achieve 4.7 times the latter one. The deformation of the fully encased stone column is much smaller than that of the SC at limit load if the encasement strain difference at the pile failure and at the encasement failure is much large. That is to say, if the encasement still has much strength to develop after the pile fails, the deformation of the ESC is much smaller than the SC. The ESC may fail from upper punching or bending with high stiffness of encasement, at which case the ESC behaves as a rigid pile. When the encasement stiffness is low, the ESC may fail from bulging. However, the increase of the encasement stiffness induces more cost. This suggests that in ESCs composite ground design, the balance between the pile stiffness and cost should be given attention. The partially encased stone column may fail from bulging under encasement.

Conclusions And Discussion

This paper studies the static characteristics of ESCs, including bearing capacity and deformation. The main conclusions and suggestions are made, as follows,

- The bearing capacity of ESCs composite ground mainly influenced by encasement modulus, encasement length, ratio of pile length to diameter, area replacement, soil shear strength and mat thickness. The allowable bearing capacity of the ESCs composite ground is 1.5 to 8.5 times that of the SCs. The limited bearing capacity of the ESCs composite ground is 1.1 to 9.4 times that of the SCs.
- The stress concentration ratio of the ESCs composite ground is influenced by pile stiffness, shear strength of surrounding soil, area replacement ratio and length to diameter ratio. The stress concentration ratio is between 0.48 and 31 for the ESCs composite ground.
- If the encasement still has much strength to develop in the state of pile failure, the ESC behaves as rigid pile, which may fail from upper punching or bending. When the encasement stiffness is low, the ESC may fail from bulging.

Declarations

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Figures

Figure 1

ESC including partially encased stone column and fully encased stone column

Figure 2

Limited bearing capacity ratio of ESCs to unreinforced ground (Murugesan and Rajagopal, 2010; Fattah et al., 2016)