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Evaluation of monotonic and cyclic behaviour of geotextile encased stone columns

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Abstract. Stone column installation is a convenient method for improvement of soft ground. In very soft clays, in order to increase the lateral confinement of the stone columns, encasing the columns with high stiffness and creep resistant geosynthetics has proved to be a successful solution. This paper presents the results of three dimensional finite element analyses for evaluating improvement in behaviour of ordinary stone columns (OSCs) installed in soft clay by geotextile encasement under monotonic and cyclic loading by a comprehensive parametric study. The parameters include length and stiffness of encasement, types of stone columns (floating and end bearing), frictional angle and elastic modulus of stone column's material and diameter of stone columns. The results indicate that increasing the stiffness of encasement clearly enhances cyclic behaviour of geotextile encased stone columns (GESCs) in terms of reduction in residual settlement. Performance of GESCs is less sensitive to internal friction angle and elasticity modulus of column's materials in comparison with OSCs. Also, encasing at the top portion of stone column up to triple the diameter of column is found to be adequate in improving its residual settlement and at all loading cycles, end bearing columns provide much higher resistance than floating columns.

Keywords: stone column; geotextile encasement; cyclic loading; residual settlement; lateral deformation; finite element analyses

1. Introduction

Stone columns, either by vibro replacement or vibro displacement methods, are one of the most common improvement techniques for foundation of embankments or structures on weak soils such as clays, silts and silty sands. The advantages of this method are decrease of settlement, accelerated consolidation settlement due to reduction in flow path lengths and simplicity of construction. The main principle in this method is replacing the soft soil with vertical columns of compacted aggregates which turn the in-situ soil into a compound material with higher shear strength and lower compressibility. The stone columns increase the load bearing capacity of soft soil by bulging and thereby inducing near passive pressure conditions in the surrounding soil (Greenwood 1970).

In recent decades, several numerical and experimental studies have been performed on the soils treated by stone column which resulted to improvement of bearing capacity of them (Bergado *et al*. 1990, Ambily and Gandhi 2004, 2007, Guetif *et al*. 2007, Jellali *et al*. 2007, Saroglou *et al*. 2009, Castro and Karstunen 2010, Maheshwari and Khatri 2010, Shivashankar 2011, Gnandji and Kalumba 2014, Sexton and McCabe 2015, Watts *et al*. 2015, Gniel *et al*. 2009, Guo *et al*. 2013, Guetif 2007, Han *et al*. 2001, Ardakani *et al*. 2014, Javanmard *et al*. 2013, Dinarvand *et al*. 2017).

Stone columns under compressive loads experience failure modes such as bulging (Hughes *et al*. 1975), general shear failure (Madhav and Vitkar 1978) and sliding (Aboshi *et al*. 1979). However, in very soft clays (c_u<15 kPa, were c_u is the undrained shear strength) most common failure mode for stone columns due to the lack of required lateral confining pressure is bulging. In order to increase the lateral confinement of the columns, and consequently their vertical bearing capacity in soft clays, encasing the columns with high stiffness and creep resistant geosynthetics has proved to be a successful solution in recent years.

In the last decade, numerous numerical and experimental studies have been performed on development of encased stone columns as a ground improvement technique in soft clays. However, most of these studies are related to performance of single encased stone column under static loading (e.g., Sharma *et al*. 2004, Alexiew *et al*. 2005, Murugesan and Rajagopal 2006, 2007, 2009, Smith and Filz 2007, Gniel and Bouzza 2009, Lo *et al*. 2010, Khabbazian *et al*. 2010, Demir *et al*. 2013, Rajesh and Jain 2015) and there are less experimental and numerical studies on cyclic behaviour of ordinary and encased stone columns available in the literature.

The results of experimental studies performed by Kolekar *et al*. (2011) on cyclic behaviour of marine clay treated with ordinary stone column showed that providing reinforced clay bed under cyclic loading which is lower than failure loads results in higher stiffness and strength of

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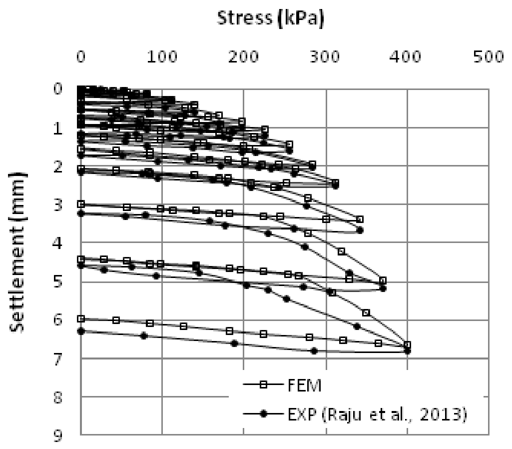

Fig. 1 Comparison of stress-settlement behaviour of GESC from experimental and FEM analyses

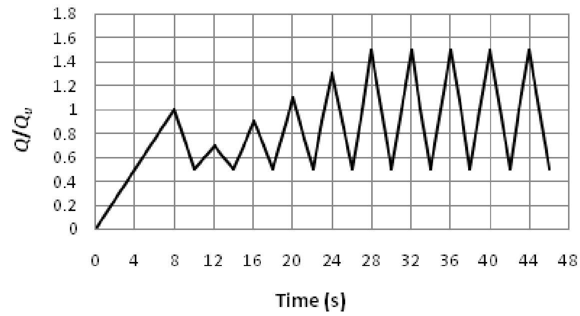

Fig. 2 Loading pattern

soil and leads to further enhancing the performance of treated soil.

Raju *et al*. (2013) investigated the behaviour of ordinary and geosynthetic encased stone columns to improve the characteristics of black cotton soil by conducting a number of cyclic plate load tests. It is found that as compared to untreated black cotton soil alone, the coefficient of elastic uniform compression (c_u) increases with inclusion of stone columns and further increase in c_u is resulted by encasing stone columns with geosynthetic due to increased lateral stiffness.

Due to the lack of studies about behaviour of geotextile encased stone columns (GESCs) under cyclic loading, this paper aims to present 3D finite element (FE) analyses that simulate the monotonic and cyclic response of single GESC in soft clay by using ABAQUS software. Also, to compare the performance of the GESC with ordinary stone column (OSC), parallel analyses were performed on stone columns without encasement. Parametric analyses are also done to evaluate the effect of different parameters such as tensile stiffness and length of the encasement, frictional angle and elastic modulus of stone column's material, types of stone columns (floating and end bearing) and diameter of stone columns on the cyclic behaviour of stone columns.

2. Numerical analyses

2.1 Verification

In this paper, all of the numerical analyses were carried out in three-dimensional space using the finite element program of ABAQUS. A cyclic plate load test performed by Raju *et al*. (2013) on a single floating encased stone column with length to diameter ratio of 8 (G+SSC L/D=8) simulated with same characteristics to validate finite element method (FEM) used in this paper. The model consisted of a 30 mm diameter geotextile encased stone column with depth of 240 mm placed in a cylindrical clayey soil mass of 300 mm diameter and 300 mm height subjected to vertical cyclic load through a square bearing plate with thickness of 10 mm and size of 150 mm×150 mm at constant loading increments up to around 400 kPa.

For modeling the behaviour of stone column the Mohr-Coulomb plasticity model was used with linearly elastic perfectly plastic behaviour and the soft soil was modeled as a modified Cam Clay material which its parameters are correspond to those presented by Raju *et al*. (2013) and Basack *et al*. (2015). The geotextile was modeled as membrane elements and assumed to be an isotropic linear elastic material available in ABAQUS, with parameters described by Raju *et al*. (2013), Basack *et al*. (2015).

The stress-settlement response of geotextile encased stone column (GESC) under cyclic loading from FE analysis compared to experimental results obtained by Raju *et al*. (2013) is shown in Fig. 1. As can be seen, there is a good conformity between the results of experimental and FE analyses, in spite of a slight disparity due to the material homogeneity assumed by numerical analysis and inability of numerical modelling to provide the actual interaction between stone column and geotextile.

2.2 Modelling single OSC and GESC under Monotonic and cyclic loading

In second phase of this study the bearing capacity (Q_u) of OSC and GESC was determined. For this purpose, 80 cm diameter single ordinary and encased stone columns with 10 m length were placed in a soft clay layer with 12 m thickness and were subjected to ramped monotonic vertical loading up to 200 and 400 kPa, respectively. After assessing Q_u for OSC and GESC, the stone columns were subjected to ramped monotonic stress up to Q_u and unloaded to $0.5Q_u$. Afterward; cyclic loading with loading amplitude varies from 0 to Q_u at $0.2Q_u$ increments applied to stone columns. The considered loading pattern was shown in Fig. 2.

The stone column was modeled using a linear elastic-perfectly plastic model with Mohr-Coulomb failure criterion. Mohr-Coulomb parameters used in the numerical analyses are similar to the typical values used in previous studies (e.g., Guetif *et al*. 2007, Ambily and Gandhi 2007) and are presented in Table 1.

The soft clay was modeled as a modified Cam Clay material and its parameters are corresponded with those obtained from experimental tests on soft Bangkok clay by Balasubramaniam and Chaudry (1978). As reported by Balasubramaniam and Chaudry (1978), this soft soil is normally consolidated clay with OCR close to 1.0. The parameters used in the Cam Clay model include the slope of

Table 1 Material Properties used in numerical models

Material	Model	γ (kN/m^3)	c (kPa)	φ (°)	Ψ (°)	E (MPa)	Poisson's ratio	κ	λ	M	e
Stone	Mohr-Coulomb	16.7	10	40	10	60	0.30				
Soft soil	Cam Clay	14.5					0.2	0.09	0.51	1.00	2.00
Geotextile	Linear elastic					600	0.3				

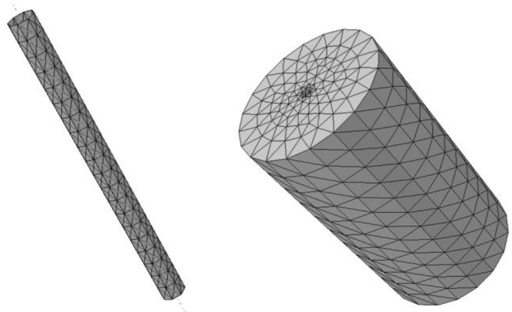

Fig. 3 Typical finite element mesh used in the analyses

swelling line (κ), the slope of virgin consolidation line (λ), the void ratio at unit pressure (e), the slope of critical state line (M), and Poisson's ratio. These parameters are tabulated in Table 1.

According to the studies of Alexiew *et al*. (2005), the most common range of tensile stiffness (J) of encasement is between 2000 kN/m and 4000 kN/m. Therefore, a tensile stiffness of 3000 kN/m was used in the analyses. Assuming the thickness of the encasement equal to 5 mm in all models, the elastic modulus (E) can be calculated from Eq. 1 (Alexiew *et al*. 2005).

$$J = E \times t \tag{1}$$

where t is the thickness of the geotextile element used to represent the geotextile and J is the secant tensile stiffness of it which is defined as the ratio of tensile force per unit width to the average strain in the geotextile. Assuming that the hoop tension force developed in the encasement is much smaller than the tensile capacity of geotextile, the creep effects of geotextile were not considered in this study.

The nonwoven geotextile was assumed to be an isotropically linear elastic material that its parameters are presented in Table 1. It should be noted that stone column-geotextile interface was assumed to be full strength. This is because of an undulating in interface due to the installation of stone column (Lo *et al*. 2010).

Also, the initial stress conditions were applied to model through K_0 procedure which is available in ABAQUS program. In order to applying K_0 stress conditions on model the saturated unit weight of soft Bangkok clay considered to be 14.5 kN/m^3 (Sunitsakul *et al*. 2010).

As shown in Fig. 3, the finite element mesh used in the numerical simulations was developed using 6-node linear triangular prism elements for modeling stone column and soft clay and 3-node triangular membrane for encasement.

3. Results and discussions

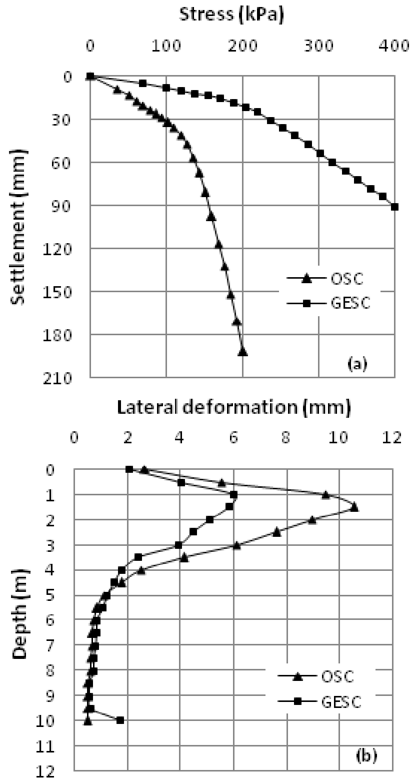

Fig. 4 Behaviour of single floating OSC and GESC under monotonic loading

3.1 Effect of encasing on monotonic and cyclic behaviour of single stone column

Fig. 4 shows the stress-settlement behavior at 25 mm settlement and variation of lateral bulging in depth at 100 mm settlement for single floating stone column. As it can be seen in Fig. 4(a), encasing the stone columns resulted to considerable reduction in settlement and increase of bearing capacity up to around 75% due to the excess confinement provided by the encasement. Also, as shown, the bearing capacity Q_u for OSC and GESC is equal to 120 and 210 kPa, respectively.

It is clearly seen from Fig. 4(b) that geotextile encasement makes stone columns stiffer and consequently under a constant load the hoop tension force mobilized in the encasement and the lateral confinement stress calculated from Eq. 2 (Rajagopal *et al*. 1999, Latha *et al*. 2006, Murugesan and Rajagopal 2006) increase significantly. Therefore, the lateral bulging of single GESC decreases up to around 57% of the same value for single OSC.

$$\Delta\sigma_3 = \frac{2M}{d_0}\left[\frac{1-\sqrt{1-\varepsilon_a}}{1-\varepsilon_a}\right] \tag{2}$$

where $\Delta\sigma_3$ is increase in confining pressure, ε_a is axial strain, M is secant stiffness of the geosynthetic and d_0 is diameter of the stone column.

Fig. 5 shows the settlement behaviour of single floating OSC and GESC under loading pattern shown in Fig. 2. As shown in Fig. 5, for both single floating OSC and GESC, with the progress of testing and increasing the number of

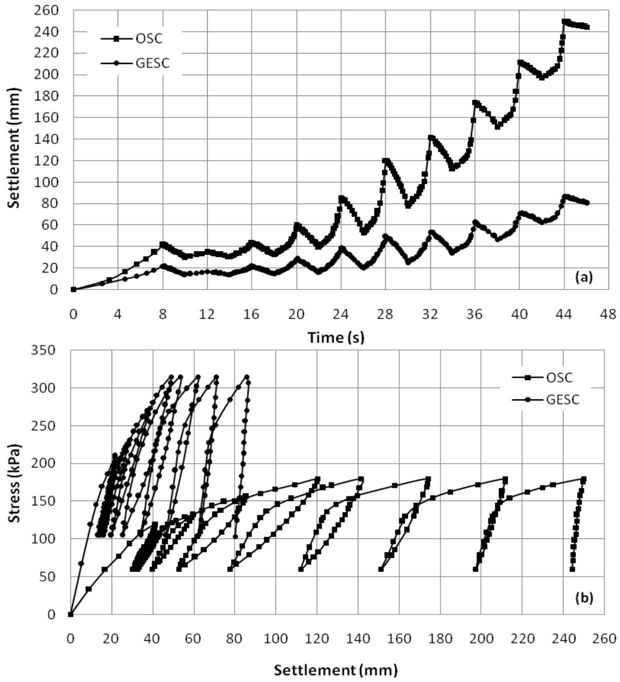

Fig. 5 Variation of (a) settlement vs. time and (b) stress vs. settlement for single floating OSC and GESC under considered loading pattern

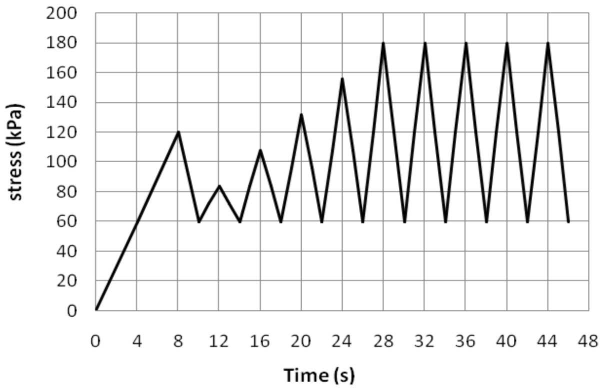

Fig. 6 Loading pattern considered in parametric analyses

loading cycles, the residual settlement at the end of each loading cycle increases, especially, for OSC after 3rd loading cycle in which the applied load reaches to around the bearing capacity of OSC. The rate of this increase in residual settlement for single OSC is higher than same for single GESC, because of excess confinement provided by geotextile layer around GESC.

3.2 Parametric analyses

As described previously, parametric analyses are also done to evaluate the effect of different parameters such as tensile stiffness and length of the encasement, frictional angle and elastic modulus of stone column's material, types (floating and end bearing) and diameter of stone columns on the cyclic behaviour of single OSC and GESC under loading pattern as indicated in Fig. 6. The results of these analyses in terms of normalized residual settlements at the end of each loading cycle (the ratio of residual settlement at

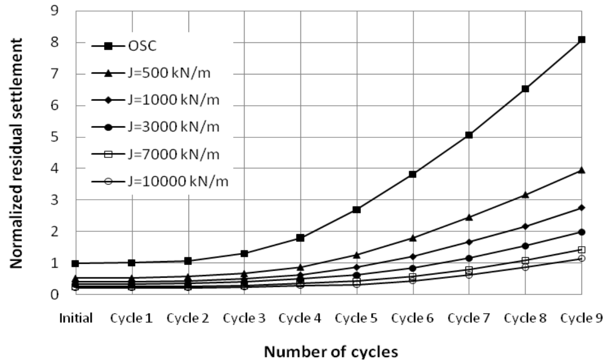

Fig. 7 Variation of normalized residual settlement of single floating OSC and GESC with different geotextile tensile stiffness

the end of each cycle to initial residual settlement at the time of 10 s for 80 cm diameter floating OSC which is equal to 30.23 mm) and lateral deformation corresponded to peak load of each loading cycle were compared together.

3.3 Influence of geotextile stiffness on encasement effect

In this paper, the effect of tensile stiffness of geotextile encasement on the performance of stone column was investigated by varying it over range of 500 to 10000 kN/m, while all other parameters were kept constant. The variation of normalized residual settlement of single floating full length encased GESC with different geotextile stiffness and single floating OSC are shown in Fig. 7. It is clearly seen from Fig. 7 that the increase of geotextile stiffness makes stone columns significantly stiffer and consequently, the hoop tension force mobilized in the encasement and the lateral confining stress calculated from Eq. (2) increase. As an example, at 9th loading cycle, increase of encasement tensile stiffness (J) up to 10000 kN/m causes to reduction in residual settlement of the GESC up to around 14.2% of the same value for OSC.

Also, as shown in Fig. 7, by increase of tensile stiffness (J) the rate of reduction in residual settlement of GESC decreases. For example, at 9th loading cycle, with increasing the encasement tensile stiffness (J) from 500 to 1000 kN/m and 7000 to 10000 kN/m, the amount of reduction in residual settlement of the GESC are around 30.3% and 19.7%, respectively. While, reduction in residual settlement of OSC encased by nonwoven geotextile with tensile stiffness of 500 kN/m is 51%. This is because of this fact that, performance of geotextile encasement in reduction of residual settlement is due to less confinement around stone column. Therefore, at high tensile stiffness (J), because of high confinement provided by geotextile encasement with lesser stiffness (J), the rate of reduction in residual settlement by increase of geotextile stiffness decreases.

3.3.1 The effect of diameter of stone columns

The effect of diameter on the behaviour of floating ordinary and encased stone columns was investigated by performing analyses stone columns with diameters of 60, 80, 100 and 120 cm. The analyses were performed for

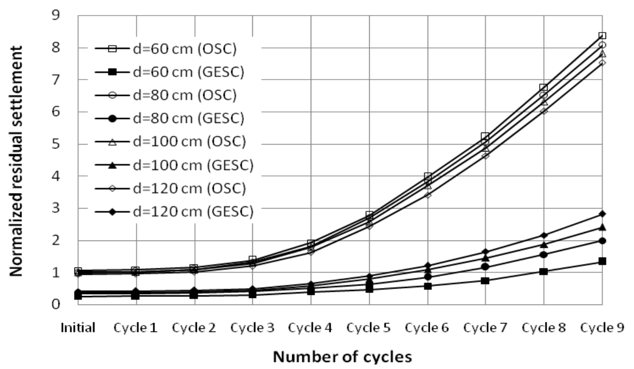

Fig. 8 Variation of normalized residual settlement of single floating OSC and GESC with different diameters

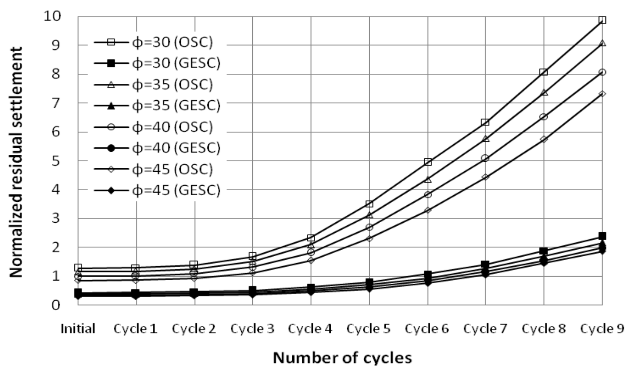

Fig. 9 Variation of normalized residual settlement of single floating OSC and GESC with different internal friction angle

geotextile stiffness of 3000 kN/m and obtained results are presented in Fig. 8. It can be seen in Fig. 8 that at all loading cycles, increase of diameter causes a little decrease in residual settlement of OSCs. Reversely, in case of encased stone columns, the performance of GESC with smallest diameter is superior to that of larger diameter columns and decrease of column diameter caused to considerable reduction in residual settlement of GESC. Also, from Fig. 8, encasing stone columns with smaller diameters has better performance in decreasing the residual settlement than same for larger diameters. As an example, at 9th loading cycle, the reduction in residual settlement for stone columns with 60 and 120 cm diameter by encasing with geotextile are 84.2% and 62.6%, respectively. It is because of development of larger additional confining stresses in smaller diameter encased columns as discussed earlier. Due to Eq. (2), as column diameter (d_0) is in denominator, larger confining pressures are generated for lesser diameter columns. In other words, as the increase in confining pressure ($\Delta\sigma_3$) is provided by lateral deformation of stone column, therefore, for OSCs with larger diameter in which less lateral deformation is developed, less $\Delta\sigma_3$ is provided by encasement which causes to larger residual settlement compared to stone column with smaller diameter.

3.3.2 The effect of internal friction angle of the stone column's material

The effect of internal friction angle of stone column's material (φ_s) in the range of 30° to 45° on the cyclic performance of single floating OSC and GESC in terms of variation of normalized residual settlement has been plotted in Fig. 9. It is obvious from the figure that increase of φ_s makes the stone column stiffer and consequently, the peak and residual settlements of stone columns decrease. Also, at all loading cycles, the reduction in residual settlement caused by increase of φ_s for OSC is more than that for GESC. For example, at 9th loading cycle, by increase of φ_s from 30° to 45°, residual settlement of single OSC and GESC decreases up to around 25.9% and 21.4%, respectively. The reason for this behaviour is that the effect of stone column friction angle in reduction of residual settlement is significantly less than the effect of encasing stone column.

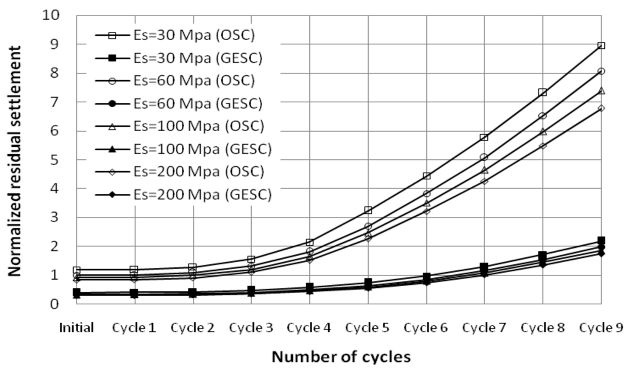

Fig. 10 Variation of normalized residual settlement of single floating OSC and GESC with different elastic modulus

3.3.3 The effect of elastic modulus of the stone column's material

The elastic modulus of stone column's material (E_s) was varied between 30 MPa to 200 MPa and its effect on cyclic performance of single OSC and GESC has been investigated and the results are presented in Fig. 10.

As shown in Fig. 10, at all loading cycles, increasing elastic modulus of stone column's material leads to decrease of residual settlement of both single OSC and GESC. On the other hand, this decrease is more for OSC than for GESC. In the case of OSC, it can be said that increase of E_s makes stone column material more elastic and consequently, the peak and residual settlements of OSC decreases. While, for GESC, reduction of E_s proportional to encasement stiffness increases the hoop tension force induced in encasement. Whereas, the horizontal stress difference ($\Delta\sigma_{h,diff}$) which is the difference between horizontal stress in the stone column ($\Delta\sigma_{h,c}$) and sum of horizontal stresses provided by the encasement ($\Delta\sigma_{h,geo}$) and the soft soil ($\Delta\sigma_{h,s}$) is another parameter which has an effect on the soft clay and leads to horizontal deformation until a corresponding additional earth pressure is mobilized in the soft soil layer to bring the horizontal stresses in equilibrium directly (Kempfert 2006). In GESC, by reduction of E_s which leads to increase of both $\Delta\sigma_{h,geo}$ and $\Delta\sigma_{h,s}$, because of less confinement stresses provided by the soft clay, $\Delta\sigma_{h,diff}$ and residual settlement of GESC slightly increase.

3.3.4 The effect of encasement length

Fig. 11 shows the variation of residual settlement for

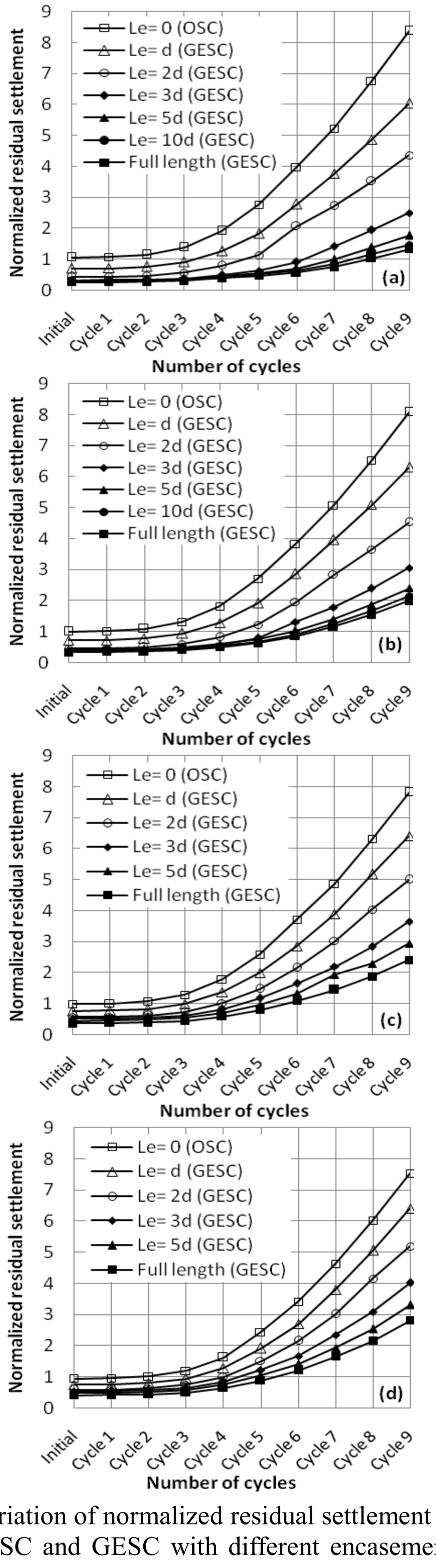

Fig. 11 Variation of normalized residual settlement of single floating OSC and GESC with different encasement length and diameter of (a) 60, (b) 80, (c) 100 and (d) 120 cm

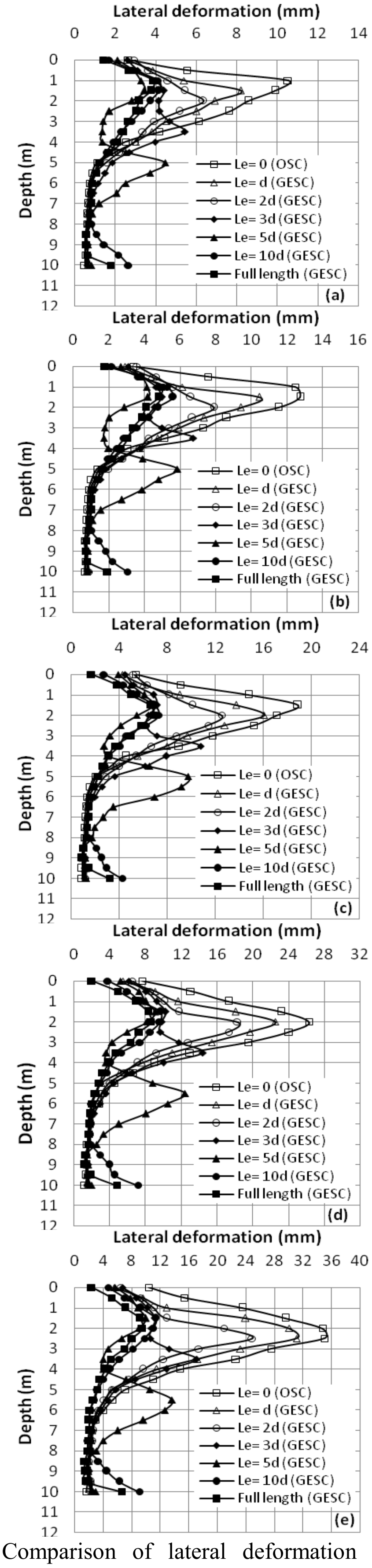

Fig. 12 Comparison of lateral deformation of 80 cm diameter single floating OSC and GESC with different encasement length at (a) 1st, (b) 2nd, (c) 3rd, (d) 4th, (e) 5th and (f) 7th loading cycle

different diameters of single floating OSC and GESC with different encasement length (L_e). Also, in order to better understand, the lateral deformation of 80 cm diameter OSC and GESC with different length of encasement corresponded to peak load of each loading cycle investigated and plotted in Fig. 12.

Due to Fig. 12, it is observed that for all stone diameters

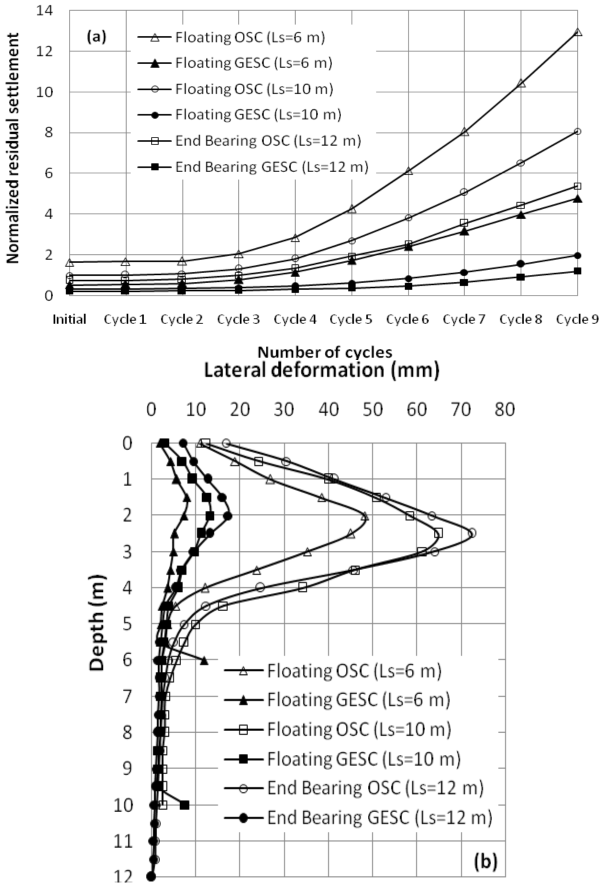

Fig. 13 Variation of (a) normalized residual settlement and (b) lateral deformation at 9th loading cycle of 80 cm diameter single floating and end bearing OSC and GESC

(d) under cyclic loading the encasement beyond a depth equal to triple the diameter of the column doesn't lead to further improvement in performance. It shows that encasing at the top portion of the stone column is adequate for improved performance.

As shown in Figs. 11 and 12(a) to 12(c), the maximum bulging of OSC at initial loading cycles (from initial conditions to 3rd loading cycle in which the peak of applied load reaches to around bearing capacity of OSC) will be predominant up to a depth of 1.5-2 times of the diameter of stone column from the ground surface. Hence, at these loading cycles, the encasement lengths which are covered this range of depth (i.e., L_e=2d) have more efficiency on reduction in lateral deformation and consequently residual settlement. While, at higher loading cycles (from 4th loading cycle to 9th cycle), as can be seen in Figs. 12(d) to 12(f), the position of maximum lateral deformation of OSC moved to depth of 2-3 times of the OSC diameter. Therefore, encasing OSC at a depth up to triple the diameter of the column (i.e., L_e=3d) causes more reduction in lateral deformation and residual settlement of OSC in comparison with higher depth of encasing. As an example, at 9th loading cycle, the reduction in residual settlement of 80 cm diameter single floating OSC by encasing at the depth of 3d and full length of stone column are 64.1% and 75.3%, respectively.

In the case of GESCs with $3d \leq L_e < 10d$, two bulging location are visible. The first bulging location is the same for bulging of OSCs, but with lower values, because of excess confinement provided by encasement. The second bulging which has higher value than the first bulging occurs in the portion of GESCs with no encasement, because of severe reduction in the confinement.

As a result, only the top portion of the stone column (up to depth of triple the diameter of the column) needs more lateral confinement in order to improve its cyclic performance. Especially, for very long stone columns, it may not be necessary to provide encasement for whole of height.

3.3.5 The effect of length of stone column

For perusing the effect of embedded length (L_s) or type of stone column (floating and end bearing), analyses were performed on 80 cm diameter floating (with length of 6 and 10 m) and end bearing (with length of 12 m) OSC and GESC, and the results in terms of variation of residual settlement and lateral deformation at 9th loading cycle have been presented in Fig. 13.

It is revealed from Fig. 13(a) that for both OSC and GESC, end bearing column provides much higher resistance than floating column. As an example, at 9th loading cycle, The residual settlement for floating OSC and GESC with length of 6 m (L_s/H ratio of 0.5, in which H is depth of soft clay layer) are 2.4 and 3.9 times of the same for end bearing OSC and GESC with length of 12 m (L_s/H ratio of 1.0), respectively. It can be said that, the residual settlement of top surface of floating stone column is sum of residual settlement in stone column and soft clay underlying it, in which the portion of residual settlement in underlying soft clay is much more than for stone column. While, in the case of end bearing OSC and GESC the residual settlement of underlying soft soil is zero and consequently the residual settlement of top surface of stone column decreases significantly.

Also, due to Fig. 13(a), the reduction in residual settlement of top surface of floating OSC by encasing it with geotextile is less than for end bearing OSC. As described above, for floating OSC the portion of residual settlement in underlying soft clay is more than that for stone column and as known, geotextile encasement decreases only the residual settlement of stone column. Therefore, decrease of residual settlement of top surface of floating OSC by geotextile encasement is less than for end bearing OSC in which the portion of residual settlement of only stone column is 100%.

It is obvious in Fig. 13(b) that, lateral deformation for end bearing OSC and GESC is more than that for floating stone columns. The reason for this behaviour is that, for end bearing stone columns, whole of applied load is endured by stone column and consequently the lateral deformation of stone column increases in comparison with floating stone columns. Also, as shown in Figs. 12 and 13(b), unlike end bearing GESC, the lateral deformation at the end of floating GESCs is not zero and lateral deformation increases significantly at this point. This is because of the sharp decline in confinement due to end of encasement which is resulted to increase of lateral deformation.

4. Conclusions

In this paper, the effect of different parameters on the cyclic performance of geotextile encased stone columns by 3D numerical models was studied. Based on the results obtained from this study, the following conclusions are:

(1) At monotonic loading conditions, encasing the stone columns with nonwoven geotextile resulted to considerable reduction in settlement and increase of bearing capacity.

(2) For both single floating and end bearing OSC and GESC, the residual settlement at the end of each cycle increases, but the rate of this increase in residual settlement for single OSC is higher than same for single GESC.

(3) The increase of geotextile tensile stiffness (J) makes stone columns significantly stiffer and consequently the rate of reduction in residual settlement of floating GESC decreases.

(4) At all loading cycles, increase of stone columns diameter causes a little reduction in residual settlement of floating OSC. However, in case of floating GESCs, decrease of column diameter caused to considerable reduction in residual settlement.

(5) At all loading cycles, increase of internal friction angle causes decrease of peak and residual settlement of floating stone columns which is more for OSC in comparison with GESC.

(6) At all loading cycles, by increase of elastic modulus of the stone column's material residual settlement of both floating OSC and GESC decreases. While, the reduction in residual settlement for OSC by increase of E_s is higher than for GESC.

(7) The maximum bulging of OSC at initial loading cycles will be predominant up to a depth of 1.5-2 times of the diameter of stone column from the ground surface, but, at higher loading cycles the position of maximum lateral deformation of OSC moved to depth of 2-3 times of the OSC diameter. Therefore, encasing stone columns beyond a depth equal to triple the diameter of the column does not lead to further improvement in cyclic performance.

(8) At all loading cycles, end bearing column provides much higher resistance than floating column and geotextile encasing for end bearing OSC has better performance in reduction of residual settlement in comparison with floating OSC.

(9) Lateral deformation for end bearing OSC and GESC is more than that for floating stone columns.

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