Geomechanics and Engineering, *Vol. 29, No. 6 (2022) 645-655*
https://doi.org/10.12989/gae.2022.29.6.645

Finite element analysis of granular column for various encasement conditions subjected to shear load

Akash Jaiswal* and Rakesh Kumar

Department of Civil Engineering MANIT, Bhopal,462003, India

(Received December 17, 2021, Revised April 12, 2022, Accepted May 3, 2022)

Abstract. Granular columns have recently found widespread use in underground construction. The behaviour of granular columns under vertical loads has been extensively studied, specifically in relation to vertical load capacity obtained by bulging of the column body, including the behaviour after encasement of material. Determining the shear strength of loose soils reinforced with granular columns has received less attention. After the observations of lateral deformation near the toe of the embankment, attempts have been made to strengthen the lateral strength of granular columns. The purpose of this research is to look into the effects of different encasement conditions on the lateral load capacity of granular columns. This was accomplished by three-dimensional finite element analysis with FEM software. Various normal pressures and two different encasement configurations, namely single layer encasement and double layer encasement, with differing tensile strengths, were used in this study to determine their effect on lateral resistance. The failure envelope for a single column planted in loose sand was used to analyse the findings for three different granular column diameters, as well as the impact of different encasement conditions. According to the findings, the inclusion of a Granular Column enhanced the shear strength and overall stiffness of the loose sand bed, and the encasement of the Granular Column helped in deriving higher lateral resistance.

Keywords: encasement; FEM; granular column; lateral load; numerical analysis

1. Introduction

The demand for land has increased significantly as a result of the rise of civilization and urbanization, in order to create better living and transportation circumstances. Houses, industrial structures, high-rise office skyscrapers, motorways, embankment rail lines, tunnels, shipyards, and earth dams have all witnessed substantial growth in recent years, and this trend is projected to continue. Construction sites with appropriate geotechnical features are becoming increasingly scarce, whereas sites that are unsuitable or less suitable are becoming abundant. Engineers have tackled bearing failure, total and differential settlements, ground heave, instability (including sliding, flipping, and slope failure), seepage, erosion, and liquefaction. Granular columns, which inject stronger granular material into the ground, appear to be a cost-effective and environmentally friendly way to deal with severe settlement of weak ground (Barksdale and Bachus 1983, Alamgir *et al*. 1996). The granular inserted material also shortens the drainage channel and accelerates the consolidation process. (Han and Ye 1992). The placing of granular columns is one of the most prevalent methods of improving soil and improving subsurface soil conditions.

Granular columns provide greater slope stability, higher bearing capacity and shear strength, and reduced settlement and consolidation time, to name a few advantages.

The granular column-reinforced ground functions as a composite system with higher strength and stiffness than the basic soil bed (Alamgir *et al.* 1996, Murugesan and Rajagopal 2010, Madhav *et al.* 2009, Tan *et al.* 2021), however the improvement factor also depends on the lateral strength of the treated soil (Fattah *et al.* 2011). Granular columns are frequently engineered to withstand the vertical loads generated by the structures built on top of them. The bulging of the circumference of the column allows it to distribute longitudinal load, which aids in enhancing the ground's stiffness (Bergado *et al.* 1988, Hughes *et al.* 1974). The intervening soil may not provide enough bulging resistance or lateral confinement in very loose soils. At the limiting settlement, it is unlikely that the granular column will be able to deliver the required load bearing capacity. Several studies, including analytical and numerical investigations (Hosseinpour *et al.* 2014, Ghazavi and Nazari 2013, Zhang *et al.* 2013, Chen *et al.* 2015, Castro 2017) as well as experimental (Deb *et al.* 2011, Vekli *et al.* 2012, Nazariafshar and Aslani 2020, Mehrannia *et al.* 2018), have been conducted to determine the vertical bearing capacity and according to these studies, the most important parameters that determine the bearing capacity of granular columns are the area replacement ratio, material friction angle, and granular column length.

It was necessary to strengthen the circumferential bulging resistance of the granular column in order to enhance the capacity of the ground. Effect of Encased Granular Columns supporting an embankment on a soft deposit were also analysed numerically and experimentally (Almeida *et al.* 2013, Hosseinpour *et al.* 2015) as well as on trial embankment (Almeida *et al.* 2014), results indicates

---

*Corresponding author, Research Scholar
E-mail: akashcivilengg777@gmail.com

http://www.techno-press.org/?journal=gae&subpage=7

ISSN: 2005-307X (Print), 2092-6219 (Online)

that because of the encasement, the columns were able to withstand higher vertical stresses. The bearing stresses in a vertically loaded column enclosed in various geosynthetics were found to be significantly increased when the column was loaded vertically (Murugesan and Rajagopal 2009, 2010, Yoo and Kim 2009, Lo *et al.* 2010, Khabbazian *et al.* 2010, Pulko *et al.* 2011, Ali *et al.* 2012, 2014, Dash and Bora 2013, Hasan and Samadhiya 2017), in case of end bearing as well as floating columns (Fattah at al. 2016). Furthermore, due to the interlocking and frictional effects of horizontal layers with granular column aggregates, the use of horizontal layers of geosynthetics can increase bearing capacity while simultaneously reducing lateral bulging. (Prasd and Satyanarayana 2016, Hasan and Samadhiya 2016, Shamsi 2019). Limited investigations have been carried out to determine the shear strength of granular columns, on the other hand.

The shear collapse of granular columns when exposed to horizontal stresses has received little attention in the literature. Murugesan and Rajagopal (2009) investigated the behaviour of granular columns under horizontal loads, which was done through plane strain experimental tests for encased columns. It was discovered that the encasing of granular material improved the shear capacity of the columns, which was reported by the authors. Abusharar and Han (2011) discussed that the most common failure mechanism for sand compaction and Granular Columns has been found as shear failure. Khabbazian *et al.* (2015) concluded that the Granular Columns that are located beneath the edge of the embankment are more prone to failure than the other Granular Columns. Mohapatra *et al.* (2016) performed large shear box tests on granular columns at various normal pressures. Variations in strength were noted for three plan configurations with various column diameters and encasements. Shear strength increased as the area replacement ratio increased. The stiffness of the encased granular column along the shear plane increases shear strength, whereas at larger displacements, the mobilisation of tensile force increases shear strength. They have identified two sub-types of shear failure according to the behaviour of the encasement. Aslani *et al.* (2019) also found that the soil-Granular Column system is stiffer than the soft clay layer, and that this stiffness changes with area replacement ratios.

Cengiz *et al.* (2019) used a 1-g physical model to investigate the behavior of the unit cell while it was subjected to both static and cyclic horizontal stresses. For this purpose, the Unit Cell Shear Device (UCSD), a novel multi-sectional shear box apparatus, has been developed specifically for this purpose, allowing for the modelling of the unit cell portion that is close to the slip circle. Because of the encasement, the granular column at the toe of the embankment has increased shear strength for both static and cyclic lateral loading. Nazariafshar and Aslani (2020) also performed experimental tests in a large shear box test setup for clay as the bed material, strengthened by the granular columns, to determine the values of stress concentration ratios at different arrangements of granular columns. The results indicated that as the diameter of the granular column increased, the stress concentration ratio decreased and a square arrangement of granular columns has the largest stress concentration ratio and the lowest for the case when a single granular column is used. Recently, Aghili *et al.* (2021) conducted an experimental study using a large-scale cyclic direct shear test to investigate the impact of the granular column on the cyclic shear parameters of clay strengthened by granular column. Granular Column enhanced the cyclic shear resistance of the treated clay model as compared to untreated clay, and the maximum shear stress of the treated clay model improved as the granular column diameter and relative density increased.

Previous research has revealed that shear failure of granular columns is a significant factor to consider when designing granular columns. This research focuses on the finite element-based analysis of granular column material in loose sand under direct shear load. For the stabilization of sandy soil, methods like vibro-compaction can also be used, but for very fine sand materials, having a granular column act as a vertical drain, which helps with the dissipation of excess pore water pressures during a possible liquefaction event Chenari *et al.* (2019). As the 2D asymmetrical model takes advantage of the symmetry, but occasionally the intrinsic mechanism, such as the continuous shearing plane observed in the 3D model, cannot be adequately replicated by the axisymmetrical model (Ng and Tan 2015), also the 3D unit cell analysis is more rigorous than the 2d analysis, the differences between the two methodologies may be minor (Hosseinpour *et al.* 2019), studies encourage the use of three-dimensional analysis. PLAXIS 3D was utilized as a tool for developing FEM models that were validated by earlier research. The numerical model employed in this work was validated using data from experimental experiments performed by Nazariafshar and Aslani (2020) and Mohapatra *et al.* (2016). Afterwards, many combinations of normal load and various encasements of varying tensile strength were investigated in order to comprehend their effects on granular columns subjected to lateral loads.

2. Validation of FEM modelling

2.1 Validation-I

Clay was employed as the bed material in the studies done by Nazariafshar and Aslani (2020) and two other materials, including crushed gravel and fine-grained sand, were used as the granular column materials. To do physical modelling and experiments, they used a large direct shear machine and installed a granular column using the replacement method, by use of open-ended steel pipes hold the column in place. All of these tests for single column were numerically modelled in current study and the findings obtained through FEM modelling were compared. Three diameters of 124.5, 145, and 169 mm of granular column in the center of the large shear box test were considered individually for each of the column materials (Sand and Gravel), these columns are referred as Ordinary Granular Columns (OGC) since they are not encased. Characteristics of each of material properties used can be referred from Nazariafshar and Aslani (2020). All combinations were assessed at standard pressures of 30, 45, 60, and 75 (kPa).

Table 1 Model properties for FEM model (Validation -I)

Parameters	Column Material	Clay Bed
Young's modulus, E (kPa)	44000	4600
Undrained shear strength, cu(kPa)	11	21
Angle of internal friction, φ (°)	35	6
Poisson's ratio, μ	0.28	0.36
Dilation angle, ψ (°)	5	0

Table 2 Model properties for FEM model (Validation -II)

Parameters	Column Material	Sand Bed
Young's modulus, E (kPa)	50000	12000
Undrained shear strength, cu (kPa)	1	1
Angle of internal friction, φ (°)	41	31
Poisson's ratio, μ	0.28	0.30
Dilation angle, ψ (°)	11	1

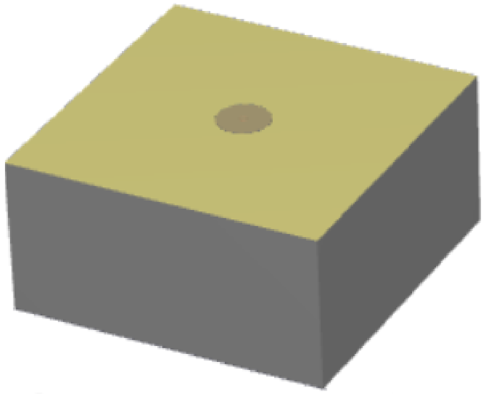


Fig. 1 Schematic diagram of soil bed and single column modelled

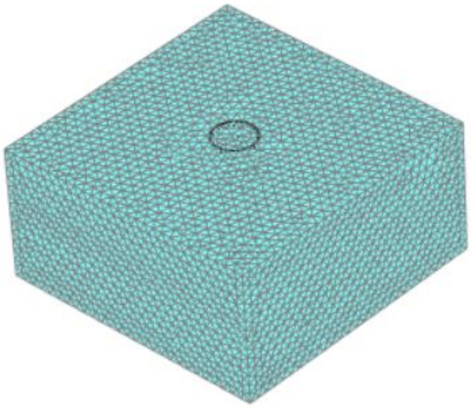


Fig. 2 Generated mesh of the model with ordinary granular column (OGC)

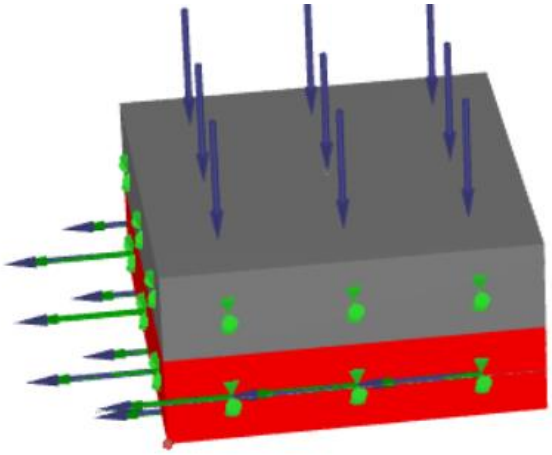


Fig. 3 Model with applied normal and horizontal load

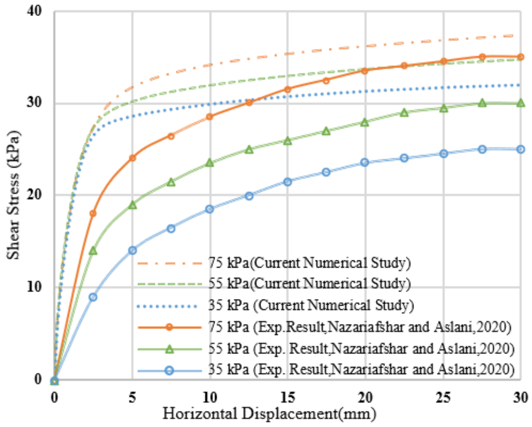


Fig. 4 Shear stress vs. horizontal displacement at different normal pressure for 145mm diameter granular column

The linear elastic perfectly plastic Mohr Coulomb failure criteria were used to simulate the behavior of clay as bed material and stone aggregates as column material in the validation-I. Mohr Coulomb model is applicable in analysis of embankments and shallow foundations, several researchers (Pulko *et al.* 2011, Ghazavi and Nazari 2013, Hosseinpour *et al.* 2015, Hasan and Samadhiya 2017, Chenari *et al.* 2019) have also utilized this model for comparable studies on granular columns. The input parameters for model (E, c, φ, and ψ) may be easily derived from relevant laboratory experiments (Table 1). To simulate the large shear box test, plates were created. The boundary conditions were set up so that the shear box's upper half is stationary and restricted in all directions, while the lower half can only move horizontally and is restricted in the other two. The model construction of a large shear box filled with sand bed and a granular column with a length of 152.4mm was built with the creation of an interface at the periphery with reduced strength properties compared to the material, as shown in Fig. 1. Mesh generation was completed after the essential and required characteristics were assigned; the resulting mesh is displayed in Fig. 2.

All of the numerical analyses for the situations in question were carried out with a horizontal movement of a maximum of 30 mm. The normal load delivered to the top of the soil bed and the shear force applied to the lower halve of the big shear box test are depicted in Fig. 3. When gravel

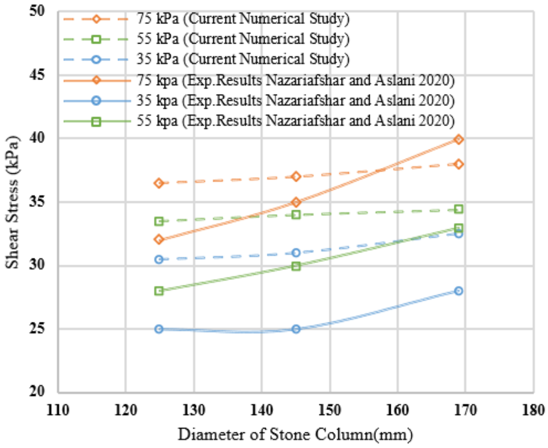


Fig. 5 Variation of shear stress with diamater for granular pile

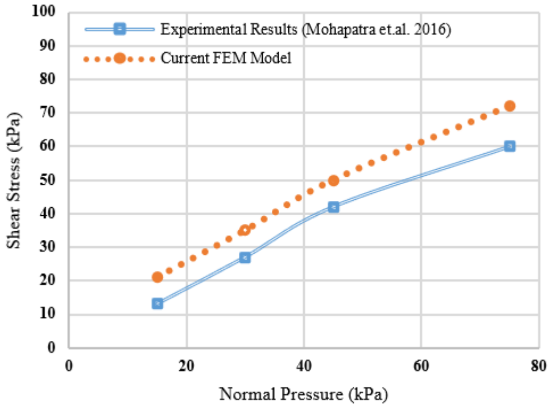


Fig. 6 Comparision of shear stress value at 20 mm horizontal displacement for various normal pressure

was utilized as a column material, the shear stress fluctuation with horizontal displacement is shown in Fig. 4 for the case when granular column diameter is 145 mm installed in clay bed at different normal pressures which shows that results of the numerical study are in line with the results of the experimental investigation that was taken into consideration.

As shown in Fig. 4, the numerical model shear values at lower displacements are slightly higher than the experimental shear values at maximum displacement. The shear stress values at 30 mm displacement change by no more than 5kPa. Result of numerical study shows the shear stress values for all normal stress conditions are approximately the same for lower horizontal displacement values, but differ and increase for higher horizontal displacement values. The A constant normal pressure and a variation in shear stress with diameter are depicted in Fig.5. The results of the current numerical study agree well with the results of the previous experimental study.

2.2Validation –II

Mohapatra *et al.* (2016) used sand as the bed material aggregates as the granular column materials. For physical modeling and experiments,a large direct shear apparatus was used.In the current work 100 mm diamatere ordinary single column installed in sand bed was modelled in PLAXIS 3D keeping all the conditions same as indicated researcher's work.The modelling part is performed in similar manner as discussed above for validation-I. The material properties utilized in FEM modeling are summarized in Table 2.

Table 3 Model properties for FEM model

Parameters	Column Material	Sand Bed
Young's modulus, E (kPa)	48000	12000
Undrained shear strength, cu (kPa)	1	1
Angle of internal friction, φ (°)	41	31
Poisson's ratio, μ	0.3	0.3
Dilation angle, ψ (°)	11	1

The numerical model shear values at smaller displacements of 20 mm are nearly same as the experimental shear values as demonstrated in Fig. 6. The shear stress values found in the experimental investigation of Mohapatra *et al.* (2016) are in good agreement with the present numerical study under all normal pressure conditions of 15, 30, 45, and 75 (kPa), However, the results of current numerical study are slightly higher than the experimental results, as these shear stress levels are at a lower horizontal displacement of 20 mm and the FEM model exhibits linear elastic behavior at lower displacement values.

3. Material properties

In small-scale laboratory studies, slight disturbances in the setup can cause results to deviate; the problem is solved by Numerical Analysis. The numerical model studies on the lateral load capacity of granular columns were carried out using a PLAXIS 3D, which simulated a large direct shear box having a plan size of 305 mm x 305 mm and a depth of 150 mm. All the tests were performed under dry conditions.

When creating the sand bed in the numerical modelling, it was important to make sure that the maximum portion of sand particles was assigned in the range of 2 μm -50 μm when creating the PLAXIS material property, to ensure that the generated soil bed falls within the vibro replacement category, as discussed by Chenari *et al.* (2019). Testing for critical state was carried out in the laboratory on the friction angle of sand as well as crushed granular aggregates employed in the formation of the granular columns. A total of three distinct diameters of granular columns were used in the numerical analysis, with diameters of 50 mm,75 mm and 100 mm. Table 3 shows the physical characteristics of the material that was employed in this study. Approximately 5% of the material was allocated to particle sizes between 2 μm and > 50 μm in order to maintain the coarseness of the particles in the final product.

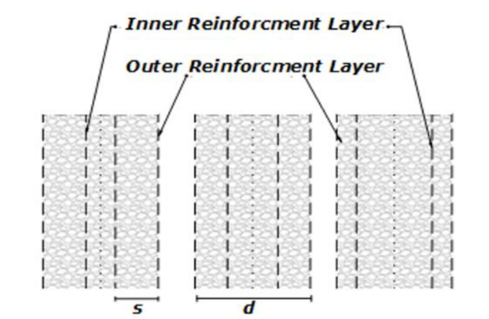


Fig. 7 Cross Sectional view of different encasement areas in DLE

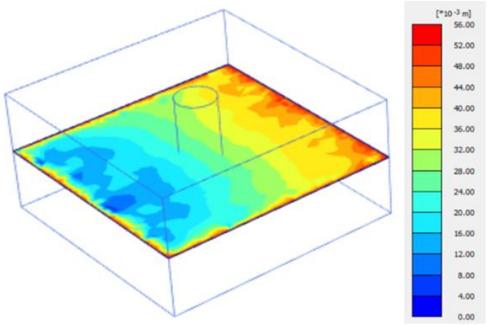


Fig. 9 Displacment shading on shear plane

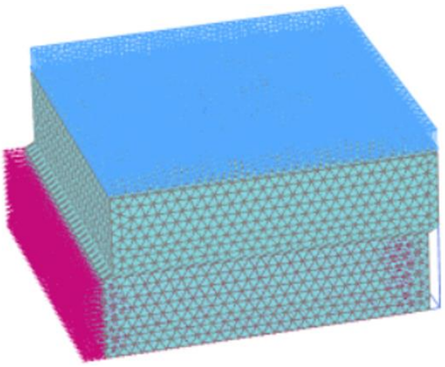
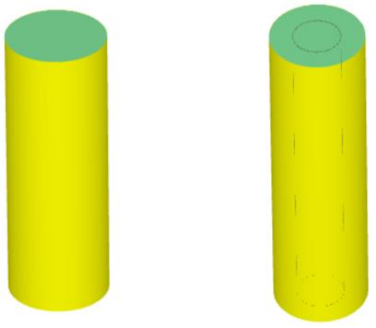


Fig. 8 Isomatric view with load and displacement



(a) (b)

Fig. 10 Encasements provided in FEM model (a) SLE and (b) DLE

4. Encasement conditions

Encasement was provided in two ways for the study; Single Layered Encasement (SLE) and Dual Layered Encasement (DLE). In single layer encasement, the layer of encasement is placed at the periphery of the column, which encases the entire granular column (previously used). Whereas in Dual Layered Encasement, two layers of encasement are used, the first one is the same as placed in SLE (at the periphery), which is constant for all the DLE samples. The second layer of encasement is placed inside the granular column body, i.e., at a distance of 0.5d from the axis of the granular column, as shown in Fig. 7, which creates a spacing of 0.5d between the two layers of encasement. For this study, four distinct types of encasements (ET1, ET2, ET3, and ET) were used. The model encasements ET1, ET2, ET3, and ET4 have stiffnesses of 35, 70, 175, and 350 kN/m, respectively. To understand the influence of various encasement parameters, such as ultimate tensile strength, on the shear strength of the column body, the strength of the second, third, and fourth encasements were kept at 2,5 and 10 times that of the first. For SLE, these are indicated by SLE1, SLE2, SLE3 and SLE4.In the instance of DLE, only ET1 was used to determine whether two layers of lower tensile strength or one layer of higher stiffness were more effective.

5. FEM Modelling by PLAXIS-3D-

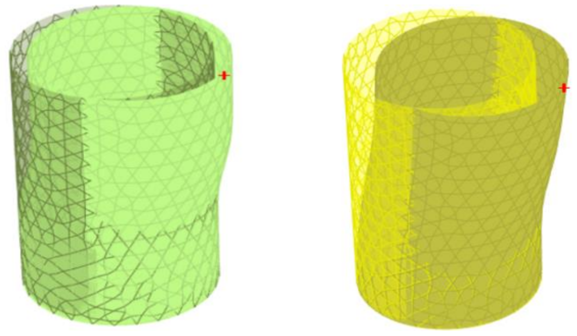
The large Shear box test arrangement was simulated in the PLAXIS-3D software using10 noded elements. Plate elements were used to create two sections, one with the upper half limited in all three directions and the lower half free in only one. Within the available space in the box, a sand soil bed with dimensions of 305x305 mm cross-sectional area and 150mm in height was produced. At the center of the box, a granular column with the requisite diameter was produced, interacting with the property R_{iner} given at the periphery of column for regular granular columns (OSC). Geogrid was assigned to encased granular columns (ESC), with the required tensile strength. Mesh was carried out with a medium coarseness. A predefined displacement of 50mm was applied to the lower part of the shear box in stages (Fig. 8). Numerical analysis was performed on four different normal pressures for each case of OSC or ESC (at 30, 45, 60, and 75 kPa).

The upper half of the shear box was subjected to a predetermined displacement of 50 mm related to lower half, which was performed in stages. Each of the cases of OSC or ESC was subjected to a four distinct normal pressures. (at 30, 45, 60, and 75 kPa) for numerical analysis.Encased granular column includes 5 types i.e., SLE,SLE70,SLE175,SLE350 and DLE. Fig 10 represents the provided single and Double layered encasement conditions in the different models.

6. Results and discussion

6.1 Failure mechanism

The column without the encasement was visibly sheared along with the granular column, according to the results of



(a) (b)

Fig. 11 Deformed granular colum body at 50 mm horizontal displacment (a)OGC and (b) Encased Granular Column

this numerical analysis. Fig. 11(a) illustrates this failure. There was no bending in any of the encasement situations, indicating that the encasement material did not break where it was sheared, as illustrated in Fig. 11(b). This type of encasement behavior is critical because it prevents the ground from failing when a section of the ground is subjected to more lateral stress than the rest of the ground. Experiments show that in models with encased column material, shear strength is influenced by the modulus and strength of the geosynthetic encasement. This is true for models with encased column material. Experiments by Mohapatra (2016) *et al.* revealed that there are two forms of shear failure: Type-1 and Type-2, and the current study supports this.

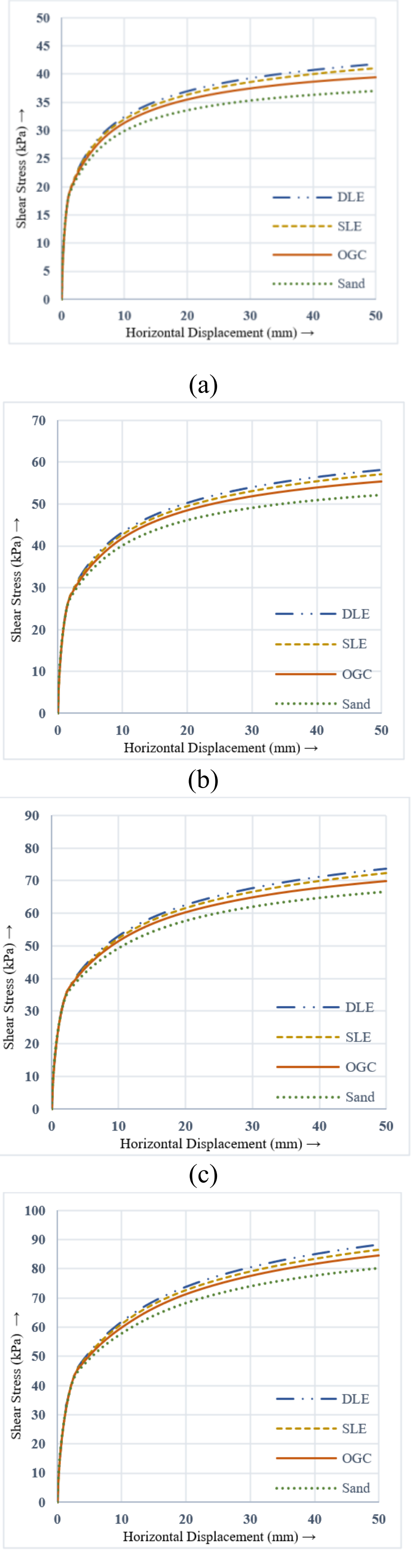
Under typical pressures of 30,45,60,75 kPa, the shear strength of the soil was measured at 50 mm displacement and was found to be 37,52,66,80 kPa. The shear strengths for the 100 mm granular column diameter cases were found to be 37,52,66,80 kPa. When a larger diameter column was used, a higher percentage of change was seen overall (Figs. 12-14). Shear stresses are observed to increase when sand is reinforced with OGCs due to the combined soil-granular column system's increased shear resistance. The granular column and the soil around it work together as a composite material, resulting in increased shear resistance. Higher shear resistances are mobilized for all column diameters of 50 mm, 75 mm, and 100 mm as the percentage area occupied by the granular column in the plane of shear increases, a behavior that is blatantly clear.

6.2 Effect of normal pressure

For the tests, four different normal pressures were utilized in the testing, with the findings varying from one another. The OGC was placed in the center of the soil bed, which increased shear strength by 8–30% depending on the diameter of the granular column used. (Figs. 12-14). For a range of area replacement ratios and normal pressure values, raising normal pressure increases shear strength by 4 to 46%, according to Nazariafshar and Aslani (2020).

As normal pressure increases in the soil treated with granular columns, the soil gains shear strength. When compared to OGC, the inclusion of an encased granular column at the center enhances shear resistance by approximately 50%. The stiffness of a granular column enhances the ultimate shear strength of the column structure.

In Figs. 12-14, the influence of normal pressure on the shear resistance of soil treated with single and double-layered encased granular columns is depicted. Its confinement allows it to mobilise greater shear strength during significant displacement stages.



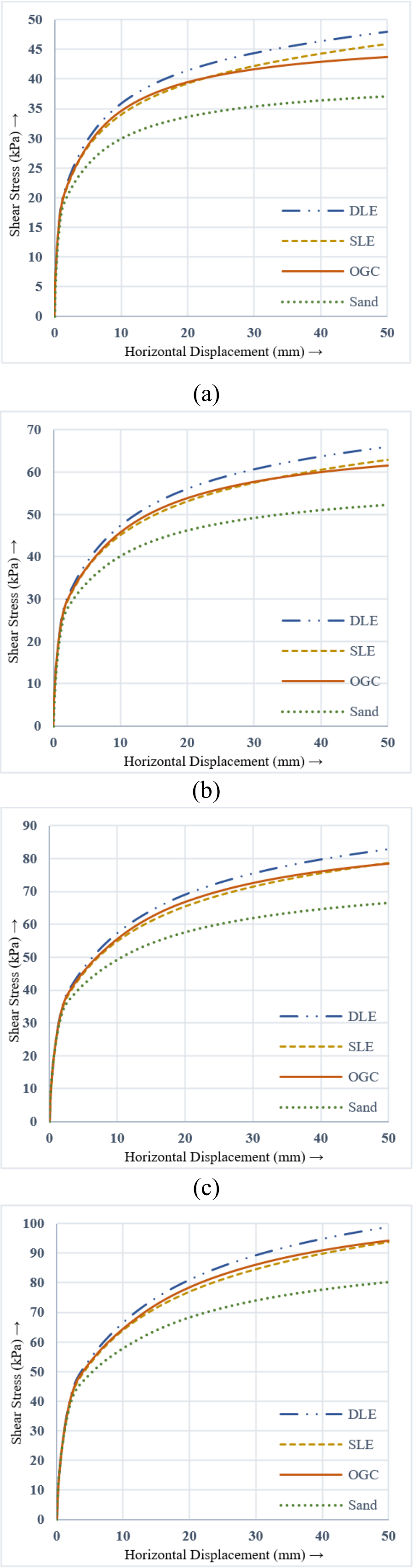
(a)

(b)

(c)

(d)

Fig. 12 Shear stress vs. horizontal displacement of 50 mm diameter installed granular column at various normal pressure (kPa)(a)-30, (b)-45, (c)-60 and (d)-75



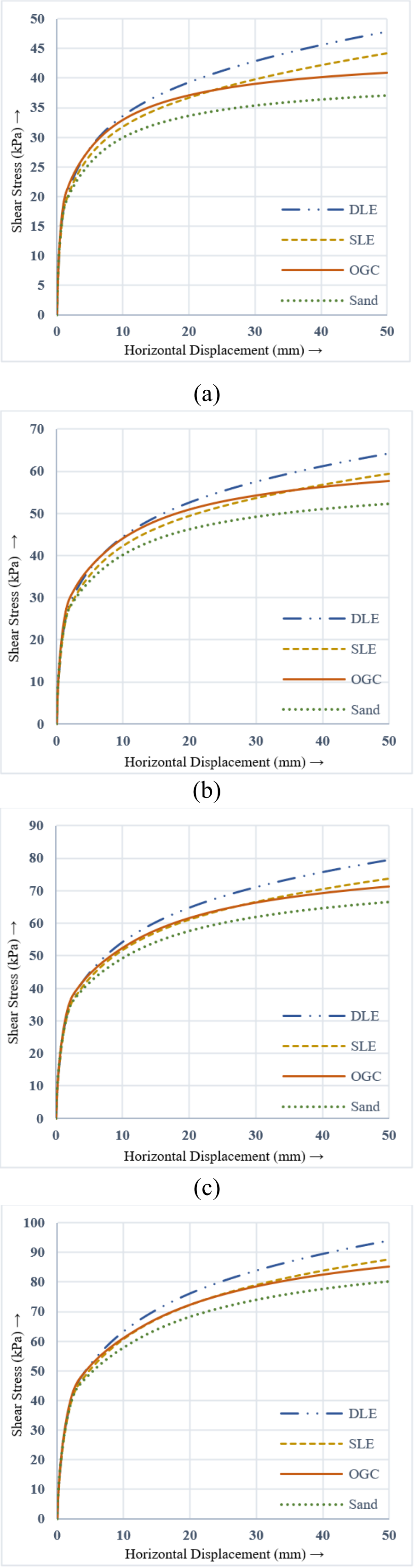
(a)

(b)

(c)

(d)

Fig. 13 Shear stress vs. horizontal displacement of 75 mm diameter installed granular column at various normal pressure (kPa) (a)-30, (b)-45, (c)-60 and (d)-75



(a)

(b)

(c)

(d)

Fig. 14 Shear stress vs. horizontal displacement of 100 mm diameter installed granular column at various normal pressure (kPa) (a)-30, (b)-45, (c)-60 and (d)-75

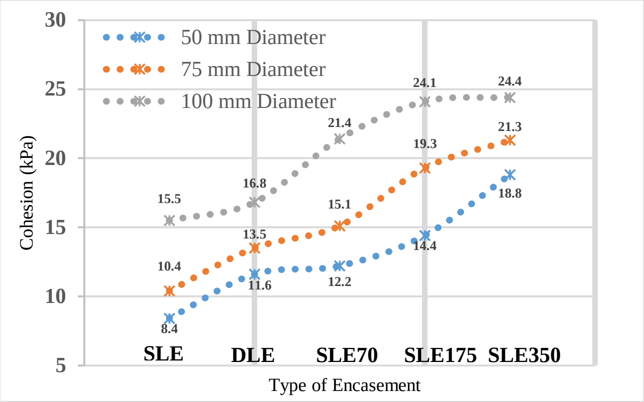


Fig. 15 Comparison of cohesion value for different encasement condition

6.3 Parameters of shear-

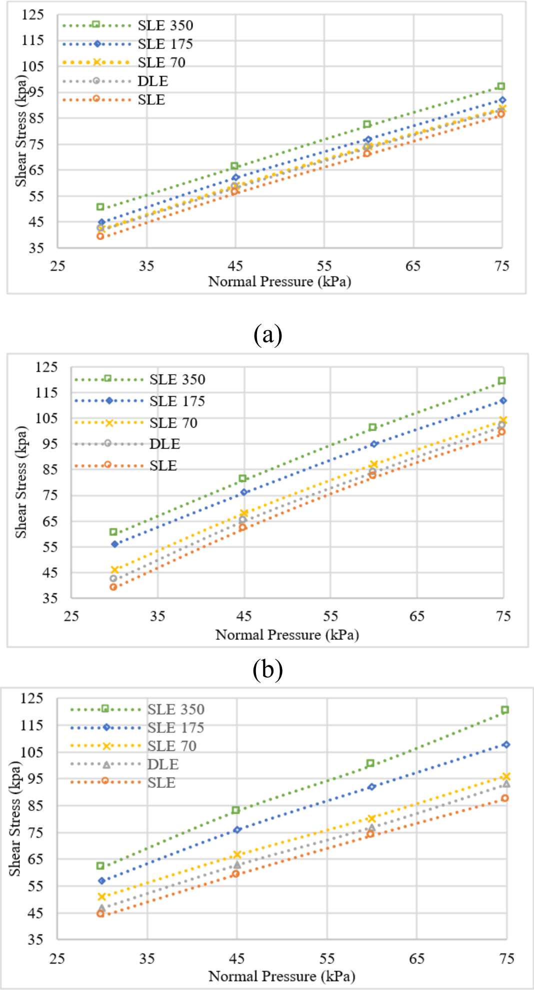
Fig. 15 shows the apparent cohesion for various encasements condition of Granular Column at 50 mm displacement. The Mohr-Coulomb failure envelopes were used to obtain the value of Cohesion for each case. Apparent Cohesion for the composite setup of SLE, DLE, SLE70, SLE175, and SLE350 is 8.4, 11.6, 11.6, 14.4, and 18.8 kPa for the Granular Column of 50 mm in diameter. Due to the confinement of granular columns, geosynthetic confinement enhances apparent cohesiveness, implying an increase in shear strength. Due to tensile stresses in the encasement generated by shear displacement, significant apparent cohesiveness was mobilized at higher strains.

Shear strength is increased within the granular columns as a result of this. When a 50 mm column diameter was employed, it was discovered that the cohesion of the composite body for SLE350 was 2.23 times greater than the cohesion of the SLE values. The effect of geosynthetic confinement was shown to be quite significant at lower area replacement levels, but it steadily diminished as the diameter of the column increased in diameter. The apparent cohesiveness displayed by dry granular soils is a result of the specific soil deformations that occur in large shear box tests but are missing in small shear box tests, which is due to the particular soil deformations that occur in large shear box tests (Liu 2006, Bareither *et al*. 2008).

6.4 Effect of encasement

The shear stress versus horizontal displacement curves for large shear tests were performed under different normal loads. Even at a smaller displacement value of 5 mm, the mobilised shear stress in sand, OSC, SLE column, and DLE column was virtually equal in all cases for the usual load scenario of 30 kPa (save for the DLE column). As the displacement grew, it was discovered that the increase in mobilised shear was greater in OSC, SLE, and DLE when the displacement was connected to the sand bed.

As opposed to the DLE system, which has two layers of encasement, the SLE system has only one. When compared to the shear strength mobilised at bigger displacements, SLE has a smaller shear strength mobilised. For all examples with a displacement of 10 mm, the mobilised shear was larger for smaller diameter cases. The minimal proportion for 100 mm cases was found to be 68%, and for 50 mm cases it was found to be 70%. A finite element model was constructed and tested on encased granular columns using various geosynthetic encasement materials, including SLE, SLE70, and SLE175.



(a)

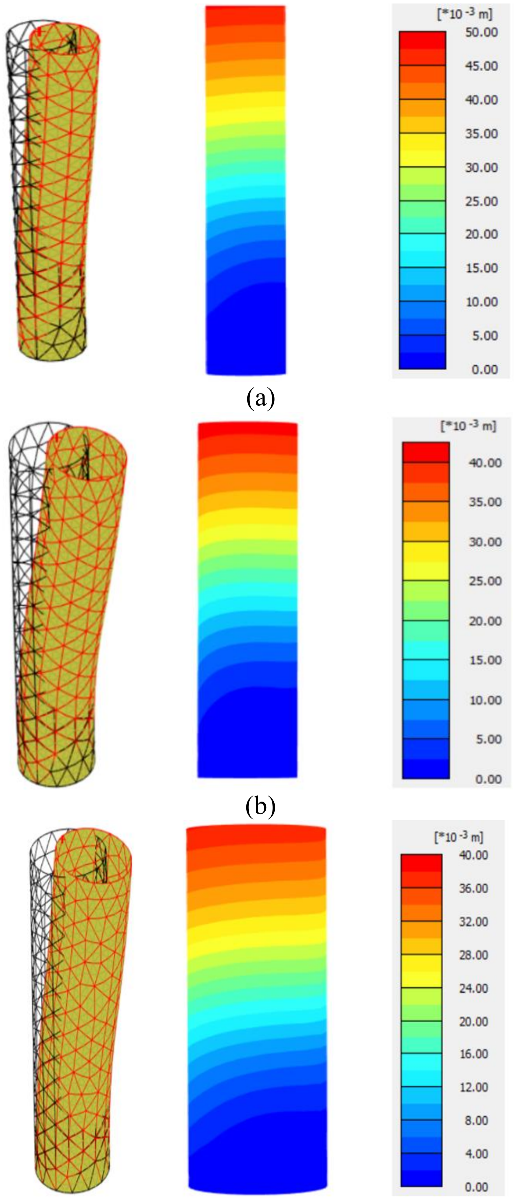
(b)

(c)

Fig. 16 normal pressure vs shear stress for different diameters of granular column (a) 50 mm diametere, (b) 75 mm diameter and (c) 100 mm diameter

The shear strength of a 50, 75, and 100 mm diameter installed column increases with normal pressures of 30, 45, 60, and 75 kPa as illustrated in Fig. 16. When the horizontal displacement is 50 mm, the shear strength increases due to material changes. The encasement has a higher modulus of elasticity than the surrounding material. As shown above, a higher modulus encasement promotes the mobilisation of more shear strength. SLE has a lower modulus than SLE70, SLE175 and SLE350, therefore it can deform more than the aggregate for a given shear stress.

For normal pressures of 30, 45, and 75 kPa for the 50 mm diameter case, the SLE350 shear stress is 1.28, 1.79, 1.55, and 1.12 times larger than the SLE. The ratios are 1.40, 1.38, 1.55, and 2.57 for a 100 mm column diameter. It



(a)

(b)

(c)

Fig. 17 Horizontal displacement for inner layer of DLE for different diameters of granular column (a) 50 mm diametere, (b) 75 mm diameter and (c) 100 mm diameter

implies that the higher modulus of elasticity of granular columns increases shear stress. Normal stress levels are increased above a threshold, but the amplification is less than at lower normal stress levels. A higher modulus of elasticity of the encasement leads to greater improvement when the diameter (i.e., a larger area replacement ratio) of the granular column is larger.

In DLE, the granular column body is encased in two layers of encasements (one around the periphery and one within the granular column body, i.e., inner layer of Encasement). In the case of a 50 mm column, both show an advantage over OGC. In 75 mm and 100 mm diameter columns, DLE columns are stronger than SLE columns but not as strong as SLE70 columns. The shear mobilisation for DLE is the average of SLE and SLE70. In other words, one thick encasement at the edge is more effective than two layers with half the strength distributed throughout.

The horizontal displacement in the inner layer of encasement in DLE varies with diameter. Fig. 17 depicts the horizontal displacement in the inner layer of the encasement in DLE when a granular column is subjected to a lateral force at 30 kPa. In the large shear box test, the inner layer of encasement of a granular column of 50 mm diameter shows a 50 mm displacement, but at 75mm and 100 mm diameters, the displacement is 40 mm and 32 mm, respectively, indicating a higher stiffness of the combined system of sand bed reinforced by granular column of higher diameter. The outer layer of encasement mobilises more strain than the inner layer for 50 mm, 75 mm, and 100 mm column diameters. The inner layer of DLE encasement will provide later stage strength to the granular column body.

Moreover, as demonstrated in the preceding explanation, the installation of OGCs contributes to the improvement of shear resistance; Additionally, encased stone columns are more resistant to lateral stress than OGCs. A weak ground with the potential to collapse under shear pressure can be addressed by the placement of stone columns on the ground. Beneath the embankments in particular, Chen *et al.* (2015) demonstrate that the outer columns face larger shear loads when compared to the columns situated at the centerline of the embankment. Because less shear strength is required at the centerline, OGCs can be used there, while an encased stone column beneath the embankment can provide the higher shear resistance required at the outer line, but only if the vertical load resistance is sufficient within the acceptable settlement at the designed diameter and spacing. Furthermore, if additional vertical resistance is necessary, Encased stone columns can be utilized at the center line and checked for acceptable shear resistance, Dual Layered encasement can be used at the corner columns.

7. Conclusions

Granular columns that have been subjected to lateral loading are the primary focus of this study. Analysing the behavior of encased granular columns and plain granular columns was done using FEM modelling software. According to the results of our calculations, when OGC and enclosed columns are used in conjunction with normal pressures, granular columns can sustain more lateral loads than they would otherwise be able to. In light of the facts, we come to the following conclusions.

Granular material in an OGC shows an evident shear failure, however the encasement of a granular column does not show any rupture, only bending occurs in the contained granular column.

- The granular material in OGC displays an evident shear failure; but, in the case of an encased stone column, the encasement shows no rupture and simply bends. Increases in the diameter of the stone column resulted in a moderate gain in shear strength, but increases in the diameter of the encased column resulted in a considerable improvement in shear strength

- Soil-stone column system has a higher stiffness than a loose sand bed, and the stiffness varies depending on the amount of the bed that has been replaced by the granular columns.
- The encasement layer mobilizing tensile forces, increasing lateral load capability. With a higher modulus of elasticity, the encasement can mobilize lateral resistance up to more than 150%.
- The DLE granular column exhibits a 1.6-1.8 times greater mobilization of strength at lower displacement values when compared to other granular columns. The effects of DLE are more pronounced in cases with smaller diameters and less pronounced in situations with a high area replacement ratio.
- Placing granular columns improves the shear strength of soil. The higher area of replacement of the granular column has lesser effect on apparent cohesion, but the lower area of replacement increases apparent cohesiveness significantly.

References

Abusharar, S.W. and Han, J. (2011), "Two-dimensional deep-seated slope stability analysis of embankments over stone column improved soft clay", *Eng. Geol.*, **120**, 103-110. https://doi.org/10.1016/j.enggeo.2011.04.002.

Aghili, E., Hosseinpour, I., Chenari, R.J. and Ahmadi, H. (2021), "Behavior of granular column-improved clay under cyclic shear loading", *Transportation Geotech.,* **31**, 100654. https://doi.org/10.1016/j.trgeo.2021.100654.

Alamgir, M., Miura, N. and Pooorooshasb Madhav, M.R. (1996), "Deformation analysis of soft ground reinforced by columnarinclusions", *Comput. Geotech.*, **18**(4), 267-290. https://doi.org/10.1016/0266-352X (95)00034-8.

Ali, K., Shahu, J.T. and Sharma, K.G. (2012), "Model tests on geosynthetic-reinforced stone columns: a comparative study", *Geosynth. Int.*, **19**(4), 292-305. https://doi.org/10.1680/gein.12.00016.

Ali, K., Shahu, J.T. and Sharma, K.G. (2014), "Model tests on single and groups of stone columns with different geosynthetic reinforcement arrangement", *Geosynth. Int.*, **21**(2), 103-118. https://doi.org/10.1680/gein.14.00002.

Almeida, M.S., Hosseinpour, I., Riccio, M. and Alexiew, D. (2015), "Behavior of geotextile-encased granular columns supporting test embankment on soft deposit", *J. Geotech. Geoenviron. Eng.*, **141**(3), 04014116. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001256.

Almeida, M.S.S., Hosseinpour, I. and Riccio, M. (2013), "Performance of a geosynthetic-encased column (GEC) in soft ground: numerical and analytical studies", *Geosynthetics Int.*, **20**(4), 252-262. https://doi.org/10.1680/gein.13.00015.

Ambily, A.P. and Gandhi, S.R. (2007), "Behavior of stone columns based on experimental and FEM analysis", *J. Geotechgeoenviron. Eng. ASCE*, **133**(4), 405-415. https://doi.org/10.1061/(ASCE)1090-0241(2007)133:4(405).

Aslani, M., Nazariafshar, J. and Ganjian, N. (2019), "Experimental study on shear strength of cohesive soils reinforced with stone columns", *Geotech. Geol. Eng.*, **37**(3), 2165-2188. https://doi.org/10.1007/s10706-018-0752-z.

Ayadat, T., Hanna, A.M. and Hamitouche, A. (2008), "Soil improvement by internally reinforced stone column", *Ground Improv.*, **161**(2), 55-63. https://doi.org/10.1680/grim.2008.161.2.55.

Barksdale, R.D. and Bachus, R.C. (1983), "Design and construction of stone columns", Vol.1. Report No. FHWA/ RD-83/026, National technical information service, Springfield, Virginia.

Bergado, D.T. and Panichayatum, Sampaco, C.L. (1988), "Reinforcement of soft bangkok clay using granular piles", *Proceedings of the international symposium on theory and practice of earth reinforcement*, Kyushu, Japan.

Bowles, J. (1997), "*Foundation Analysis and Design 5th Ed*", The McGraw-Hill Companies, Inc., New York, 308.

Castro, J. and Sagaseta, C. (2011) "Deformation and consolidation around encased stone columns", *Geotext. Geomembranes*, **29**(3), 268-276. https://doi.org/10.1016/j.geotexmem.2010.12.001.

Cengiz, C., Kilic, I.E. and Guler, E. (2019), "On the shear failure mode of granular column embedded unit cells subjected to static and cyclic shear loads", *Geotext. Geomembranes*, **47,** 193-202. https://doi.org/10.1016/j.geotexmem.2018.12.011.

Chen, J.F., Li, L.Y., Xue, J.F. and Feng, S.Z. (2015), "Failure mechanism of geosynthetic encased stone columns in soft soils under embankment", *Geotext. Geomembranes*, **43**(5), 424-431. https://doi.org/10.1016/j.geotexmem.2015.04.016.

Dash, S.K. and Bora, M.C. (2013), "Influence of geosynthetic encasement on the performance of stone columns floating in soft clay", *Can Geotech. J.*, **50**(7), 754-765. https://doi.org/10.1139/cgj-2012-0437.

Deb, K., Samadhiya, N.K. and Namdeo, J.B. (2010), "Laboratory model studies on unreinforced and geogrid-reinforced sand bed over stone column-improved soft clay", *Geotext. Geomembranes*, **29**(2), 190-196. https://doi.org/10.1016/j.geotexmem.2010.06.004.

Fattah, M.Y., Shlash, K.T. and Al-Waily, M.J.M. (2011), "Stress concentration ratio of model stone columns in soft clays", *Geotech. Test. J.*, **34**(1), 1. https://doi.org/10.1520/GTJ103060.

Fattah, M.Y., Zabar, B.S. and Hassan, H.A. (2016), "Experimental analysis of embankment on ordinary and encased stone columns", *Int. J. Geomech.*, **16**(4), 04015102. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000579.

Ghazavi, M. and Nazari Afshar, J. (2013), "Bearing capacity of geosynthetic encased stone columns", *Geotext. Geomembranes*, **38**, 26-36. https://doi.org/10.1007/s13369-013-0709-8.

Han, J. and Ye, S.L. (1992), "Settlement analysis of buildings on the soft clays stabilized by stone columns", *Proceedings of The International Conference On Soil Improvement and Pile Foundations*, Nanjing, China.

Hasan M. and Samadhiya N.K. (2016), "Influence of combined vertical and horizontal reinforcement on granular piles in soft clays", *Proceedings of the Indian Geotechnial Conference IGC2016, IIT Madras*, Chennai, India, December.

Hasan, M. and Samadhiya, N.K. (2017), "Performance of geosynthetic-reinforced granular piles in soft clays: Model tests and numerical analysis", *Comput. Geotech.*, **87**, 178-187. https://doi.org/10.1016/j.compgeo.2017.02.016.

Hosseinpour, I., Almeida, M.S.S. and Riccio, M. (2015), "Full-scale load test and finite-element analysis of soft ground improved by geotextile-encased granular columns", *Geosynthetics Int.*, **22**(6), 428-438. https://doi.org/10.1680/jgein.15.00023.

Hosseinpour, I., Riccio, M. and Almeida, M.S.S. (2014), "Numerical evaluation of a granular column reinforced by geosynthetics using encasement and laminated disks", *Geotext. Geomembranes*, **42**(4), 363-373. https://doi.org/10.1016/j.geotexmem.2014.06.002.

Hosseinpour, I., Soriano, C. and Almeida, M.S. (2019), "A comparative study for the performance of encased granular columns", *J. Rock Mech. Geotech. Eng.*, **11**(2), 379-388. https://doi.org/10.1016/j.jrmge.2018.12.002

Hughes, J.M.O. and Withers, N.J. (1974), "Reinforcing of soft cohesive soils with granular columns", *Ground Eng.*, 7(3), 42-49.

Jamshidi Chenari, R., Karimpour Fard, M., Jamshidi Chenari, M., and Shamsi Sosahab, J. (2017), "Physical and numerical modeling of stone column behavior in loose sand", *Int. J. Civil Eng.*, **17**(2), 231-244. https://doi.org/10.1007/s40999-017-0223-6.

Khabbazian, M., Kaliakin V.N. and Meehan, C.L. (2010), "Numerical study of the effect of geosynthetic encasement on the behaviour of granular columns", *Geosynthetics Int.*, **17**(3), 132-143. https://doi.org/10.1680/gein.2010.17.3.132.

Khabbazian, M., Kaliakin, V.N. and Meehan, C.L. (2015), "Column supported embankments with geosynthetic encased columns: validity of the unit cell concept", *Geotech. Geol. Eng.*, **33**, 425-442. https://doi.org/10.1007/s10706-014-9826-8.

Lo, S.R., Zhang, R. and Mak, J. (2010), "Geosynthetic-encased stone columns in soft clay: a numerical study", *Geotext. Geomembranes*, **28**(3), 292-302. https://doi.org/10.1016/j.geotexmem.2009.09.015.

Madhav, M.R., Sharma, J.K. and Sivakumar, V. (2009), "Settlement of and load distribution in a granular piled raft", *Geomech. Eng.*, **1**(1), 97-112. https://doi.org/10.12989/gae.2009.1.1.097.

Mohapatra, S.R. and Rajagopal, K. (2017), "Undrained stability analysis of embankments supported on geosynthetic encased granular columns", *Geosynth. Int.*, **24**, 465-479. https://doi.org/ 10.1016/j.geotexmem.2016.01.002.

Mohapatra, S.R., Rajagopal, K. and Sharma, J. (2016), "Direct shear tests on geosynthetic-encased granular columns", *Geotext. Geomembranes*, **44**, 396-405. https://doi.org/ 10.1016/j.geotexmem.2016.01.002.

Mohapatra, S.R., Rajagopal, K. and Sharma, J. (2017), "3 Dimensional numerical modeling of geosynthetic-encased granular columns", *Geotext. Geomembranes*, **45**, 131-141. https://doi.org/ 10.1016/j.geotexmem.2017.01.004.

Murugesan, S. and Rajagopal, K. (2009), "Shear load tests on stone columns with and without geosynthetic encasement", *Geotech. Test. J.*, **32**(1). https://doi.org/10.1520/gtj101219.

Murugesan, S. and Rajagopal, K. (2010), "Studies on the behavior of single and group of geosynthetic encased stone columns", *J. Geotech. Geoenviron. Eng.*, **136**, 129-139. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000187

Nazariafshar J. and Aslani, M. (2020), "Effect of stress concentration ratio on shear strength of soft soils improved with stone columns", *Iran J. Sci. Technol. T. Civil Eng.*, **45**(1-4), 1-20. http://doi.org/10.1007/s40996-020-00391-z.

Ng, K.S. and Tan, S.A. (2015), "Stress transfer mechanism in 2D and 3D unit cell models for stone column improved ground", *Int. J. Geosynth. Ground Eng.*, **1**(3). https://doi.org/10.1007/s40891-014-0003-1.

Prasad, S.S.G. and Satyanarayana, P.V.V. (2016), "Improvement of soft soil performance using stone columns improved with circular geogrid discs", *Indian J. Sci. Technol.*, **9**(30), 1-6. https://doi.org/10.17485/ijst/2016/v9i30/99186.

Pulko, B., Majes, B. and Logar, J. (2011), "Geosynthetic-encased stone columns: analytical calculation model", *Geotext. Geomembranes*, **29**(1), 29-39. https://doi.org/10.1016/j.geotexmem.2010.06.005.

Shamsi, M., Ghanbari, A. and Nazariafshar, J. (2019), "Behavior of sand columns reinforced by vertical geotextile encasement and horizontal geotextile layers", *Geomech. Eng.*, **19**(4), 329-342. https://doi.org/10.12989/gae.2019.19.4.329.

Tan, X., Feng, L., Hu, Z. and Abbas, S.M. (2021), "The equivalent shear strength properties of the composite soil reinforced by stone columns: an FDM-DEM-coupled numerical evaluation", *Environ. Earth Sci.*, **80**(4), 1-12. https://doi.org/10.1007/s12665-021-09412-0.

Vekli, M., Aytekin, M., İkizler, B. and Calik, U. (2012), "Experimental and numerical investigation of slope stabilization by stone columns", *Nat. Hazards*, **64**(1), 797-820. https://doi.org/10.1007/s11069-012-0272-8.

Yoo, C. and Kim, S.B. (2009), "Numerical modeling of geosynthetic-encased granular column-reinforced ground", *Geosynth. Int.*, **16**(3), 116-126. https://doi.org/ /10.1680/gein.2009.16.3.116.

Zhang, L. and Zhao, M.H. (2015), "Deformation analysis of geotextile-encased stone columns", *Int. J. Geomech.*, **15**(3), 1-10. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000389.

CC