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Numerical Analysis of a 3D Unit Cell Model for Soft Soil Reinforced with Different Granular Columns

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ABSTRACT

Recycled aggregates have been increasingly considered in recent years, owing to the limited supply of natural aggregates coupled with the corresponding carbon footprint. Recycled aggregates are aggregates prepared from construction and demolition waste. Their use aims to reduce energy consumption and contributes to reducing waste harmful to the environment. This study is based on a number of numerical tests using the finite element method of PLAXIS 3D software with the elastic-perfectly plastic behavior model and the Mohr flow criterion for all materials. A unit cell model of soft soil treated with three types of granular columns was loaded to failure: ordinary stone columns (OSCs), sand-fiber mix (SFM) and recycled aggregate porous concrete pile (RAPP). An extensive parametric study was conducted to investigate the effect of column type, friction angle, elasticity modulus, column length and geotextile effective stiffness on the behavior of soft soils. The results of numerical tests indicated that the bearing capacity of the recycled aggregate columns is three times greater than that of columns of natural aggregates. The findings of this research are given in the form of load-settlement graphs, which made it possible to release recommendations to carry out works using this technique.

KEYWORDS: Soft soil, Granular column, Numerical analysis, Unit cell, Bearing capacity, PLAXIS 3D software.

INTRODUCTION

Currently, the reinforcement by a stone column is one of the techniques used to reduce the settlement and increase the bearing capacity of soft soil. The technique concept is to change 10-40% of the weak soil with a cylinder containing compacted granular material (Boumekik et al., 2021). Ordinary Stone Columns (OSCs) are constructed in soft soil to reduce settlement, as well as to improve and increase the bearing capacity (Han and Ye, 2001). Many researchers have attempted to study the behavior of sand-fiber mix (SFM) or geogrids through numerical or experimental methods (Ambily and Gandhi, 2007; Hasanzadeh and Shooshpasha, 2017; Malarvizhi and Ilamparuthi, 2008). Recycled aggregate porous concrete pile (RAPP) is a pre-cast concrete pile that is designed to be installed in a manner that minimizes disturbance to the surrounding ground. On the other hand, OSCs are constructed by inserting large stones or gravel into the soil using vibration or other equipment, which may cause additional soil compaction. SFM is a geosynthetic matt with stones or other fill material tightly packed in its cells to form a mattress-like structure that is placed over the soft soil. RAPP is designed in a way that allows it to enhance both the stability and drainage of the soil in which it is installed. In comparison, OSCs generate vertical drainage pathways through the void spaces among the granular material used to form them. The SFM aims to facilitate lateral drainage flow, as well as to prevent the buildup of excess pore water pressure in soft soils. RAPP has a relatively higher compressive strength compared to OSC and SFM. Experimental and numerical study of RAPP to replace natural granular columns such as traditional columns (Kim et al., 2012)

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found that RAPP had a higher bearing capacity than traditional columns. The ultimate bearing capacity of the reinforced soils and the failure of vertically loaded stone columns depend on the geometric and physical properties of the surrounding soils and stone columns (Kang et al., 2023). Miranda and Da Costa (2016) found that the vertical bearing capacity of columns increased with increasing geotextile stiffness. The stiffness of geogrids used in stone columns had a significant impact on their bearing capacity (Ambily and Gandhi, 2007), while Malarvizhi and Ilamparuthi (2008) found that the stiffness of geogrids had a more significant impact on the bearing capacity of soft-clay columns. Moreover, previous studies have also investigated the geotextiles' impact on bearing capacity. The use of geotextiles significantly improved the bearing capacity and stiffness (Dilbas, 2021). Several studies have emphasized the widespread use of natural aggregates in strengthening soft soils by granular columns (Hadri et al., 2021; Malarvizhi and Ilamparuthi, 2008), while recycled aggregates have been less studied as this recyclable material is still under study and research (Alabi and Mahachi, 2020; Kim et al., 2012).

In this study, the adopted (FEM) model was validated with experimental and numerical data from Basu (2009) and Hasan and Samadhiya (2016) and showed good agreement. Then, an intense parametric study was carried out to determine the sensitivity of targeted results with regard to the main parameters' variations; namely, the amelioration that was realized in comparison response of (OSC, SFM and RAPP) was first investigated and the effects of reinforcement material, friction angle, encasement stiffness and length of granular column were then studied. This research work is presented as a contribution in the form of a numerical model that studies the behavior the RAPP instead of OSC and SFM, noting that RAPP is a relatively new material used in reinforced particle columns.

NUMERICAL MODELING

Presentation of the Finite Element Model (FEM)

A series of numerical analyses were carried out using the PLAXIS 3D finite element analysis software as indicated in the literature (Rajan and Krishnamurthy, 2022; Shooshpasha et al., 2013) to simulate the three types of granular columns to reinforce soft soil. Fig. 1 shows the numerical model and mesh configurations used in the analysis. Cylindrical unit cell model can be simplified as a 3D model, where the vertical axis passes through the center of the column. Due to geometry limitation in PLAXIS, some studies (Ambily and Gandhi, 2007; Hasan and Samadhiya, 2016) used a square unit cell equivalent to a cylindrical unit cell. In this study, a square unit cell model was created. Basu (2009) formed a stone column of 7.5-cm diameter and 60-cm length in the center of a rectangular tank (size 262.5×262.5×600 mm) of weak clay and loaded with a circular plate 7.5 cm in diameter perpendicular to the center. In this study, simulations of short-term load tests on granular columns were carried out. Assuming that the load applied to the plate is solid, the vertical load is defined as a pre-scribed displacement. Vertical displacements were allowed at the lateral border, but at the bottom borders of the unit cell, vertical and horizontal displacements were constrained. The left, right and bottom boundaries are treated as impermeable. Pore pressures are set to zero above the ground-water level. Coarse mesh may provide sufficiently accurate results for preliminary analyses or design studies (bearing capacity, vertical and lateral deformation curves). Characteristics and sizes of mesh in this model are: soil elements' number 7893, node number 11374 and average element size 2.29e-3 m.

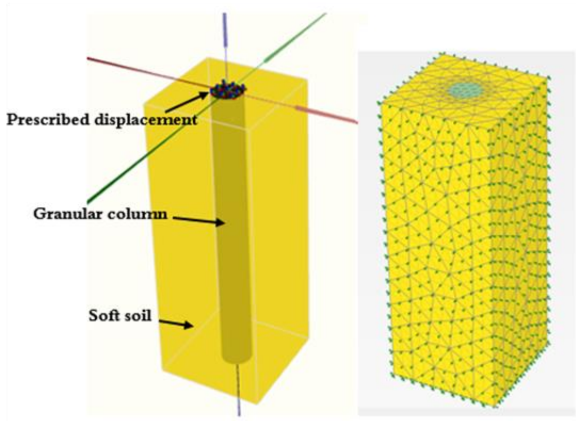

Figure (1): Numerical model with the finite-element mesh

Validation of Numerical Model

Load-settlement curves were compared with laboratory and numerical curves obtained (Fig. 2). The model is validated by the simulation of load settlement behavior of soft soil reinforced by a single SFM column, based on small case model test performed in the laboratory by Basu (2009). Hasan and Samadhiya (2016) also worked on this model numerically and verified it with the same curves. Validation results were good, as the difference in the experimental model (Basu, 2009) is approximately 7.97% and in the numerical model (Hasan and Samadhiya, 2016) is 4.01%.

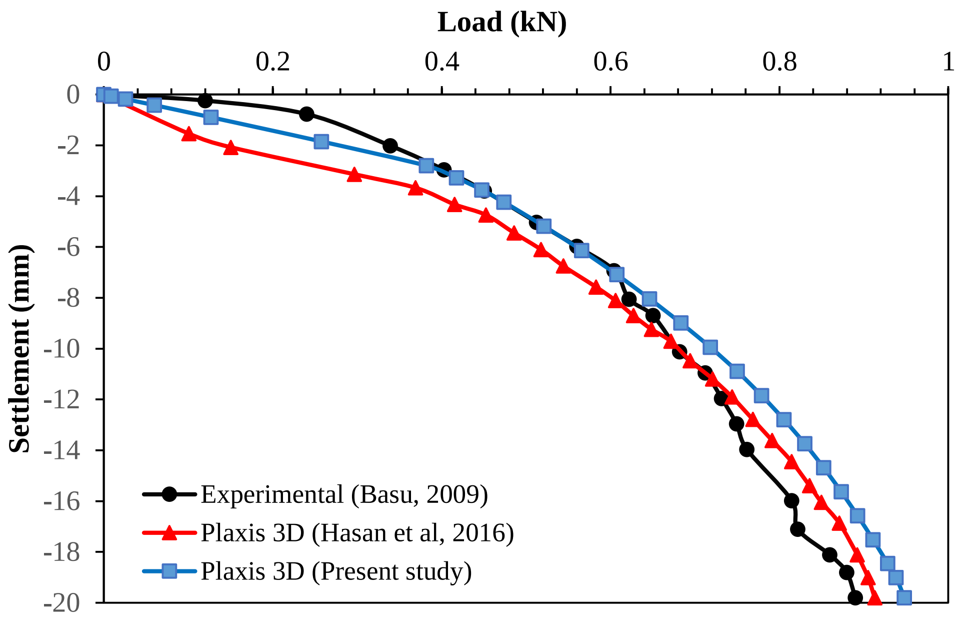

Figure (2): Numerical validation through results (Basu, 2009; Hasan and Samadhiya, 2016)

Materials' Properties

Based on the experimental and numerical studies of (Basu, 2009; Kim et al., 2012; Labed and Mellas, 2016), the soil mechanical properties for the studied numerical model were obtained. After checking the experimental model of Basu (2009) where weak clay and SFM were used, this model was relied upon to follow the evolution of soil behavior by replacing the reinforcement soil SFM with OSC (Labed and Mellas, 2016) and RAPP (Kim et al., 2012). The linear elastic perfectly plastic Mohr-Coulomb model was adopted for soils of four types, which was also adopted by many authors, who used it in soft soil reinforced with stone columns (Ambily and Gandhi, 2007; Ghazavi and Nazari Afshar, 2013). This model is characterized by volumetric weight, Poisson's coefficient, Young's modulus, internal friction angle of soils, dilation angle and cohesion. The values of the parameters are presented in Table 1.

Table 1. Material properties

Property	Clay	SFM	OSC	RAPP
Previous studies	(Basu, 2009)	(Basu, 2009)	(Labed and Mellas, 2016)	(Kim et al., 2012)
Elasticity Modulus, E (kPa)	250	6700	40000	16400
Friction Angle φ (°)	0	34.47	38.00	32.70
Cohesion (kPa)	16.00	15.55	1.00	727.90
Poisson's Ratio (μ)	0.30	0.30	0.30	0.30
Dry Unit Weight (kN/m^3)	14.90	18.00	17.00	18.46

RESULTS AND DISCUSSION

Bearing Capacity and Lateral/Vertical Deformation Behavior of Soils

Numerical analyses of the unit cell simulation were carried out on the proposed granular column of three soils and the optimization of behavior is determined based on a reduction in settlement, vertical and lateral deformation of the column. Improvement in the characteristics of each soil in bearing capacity was noticed. It is directly proportional to the vertical and horizontal displacements. Only bearing-capacity curves were dealt with for their importance in this research. It was mentioned earlier that the vertical loading is applied in the form of a pre-scribed displacement; therefore, 20 mm was determined as a constant value of displacement for all models. It was sufficient to determine the bearing capacity and to show the differences between the soil types. Fig. 3 shows the FEM results in relation to the load settlement behavior of all soils used; therefore, it was revealed that RAPP gave excellent results compared to OSC and SFM. Thus, it was found that the bearing capacity increased by 88.53%, 117.77% and 770.25% for the OSC, SFM and RAPP columns, respectively, as compared to untreated soil (US). Furthermore, it was noted that RAPP gave high results compared to OSC and SFM, with the values reaching 299.62% and 361.60% respectively, while the comparison between OSC and SFM was almost identical between them by the value of 15.51%. The difference between RAPP and other techniques (Fig.3) can be attributed to several factors, such as materials used, construction method and technique effectiveness. Lateral deformation of the column occurs when the vertical load is greater than the confined internal stress. When the depth increases, internal confining stress increases. So, we note that a lateral deformation is formed in the top of the column. Surrounding soil gives some additional lateral support to limit column expansion. Distribution of mesh deformation through a depth of 0.6 m (Fig. 4a), to illustrate the effect of lateral bulge and how important the reinforcing soil used is in reducing it, when the column is of SFM, bulge in the critical zone is slightly smaller than in the case of OSC by an estimated 19.05%. While RAPP achieved a more effective result compared to SFM and OSC, the swelling value was smaller by 282.88% and 221.62%, respectively (Fig. 4b). The value of β (vertical distance between the column surface and the maximum value of lateral displacement U_x) was almost convergent at a value of 4.52×10^{-2} m for OSC and 4.75×10^{-2} m for SFM, while RAPP achieved nearly twice the result with a value of 8.27×10^{-2} m. Comparing the lateral deformation curve in Fig. 4 with the vertical load-settlement curve in Fig. 3, it turned out that the deeper the distance β, the greater the endurance and the less the lateral bulge. In Fig. 4b, the maximum lateral deformation of RAPP is shown to be 0.001 mm, indicating that there is no lateral deformation or movement. This can be attributed to several factors, including the high cohesion factor of material and careful installation and alignment of piles. The high cohesion factor of the RAPP, which is 727.9 kPa according to the information provided, indicates that the material has a high degree of internal strength and resistance to shear forces. This means that RAPP is able to maintain its shape and stability even under external loads or forces that would cause weaker materials to deform or fail. Overall, the combination of high cohesion factor of RAPP, careful installation and pile alignment contributes to very small deformation of RAPP (Fig. 4b). To validate the investigations of bearing capacity and lateral deformation, vertical-deformation curves were added as a function of time during one day. The results presented in the vertical-deformation curves gave preference to RAPP at the expense of OSC and SFM, where the comparison ratio of improvement between RAPP and SFM was 247% and between RAPP with OSC 438% (Fig. 5).

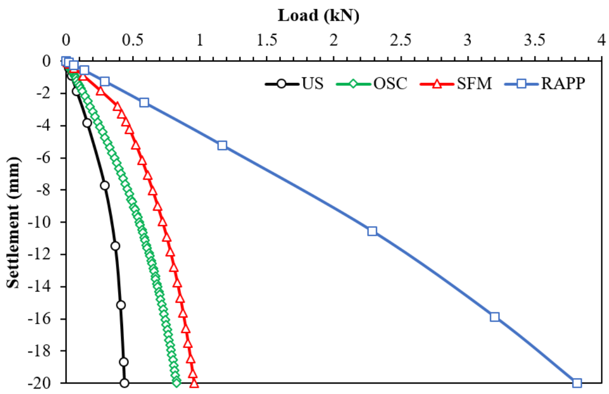

Figure (3): Vertical load-settlement behavior of soils

Parametric Study

Each parameter is isolated and examined separately to determine the effects of the model. The values of soil materials and geometric parameters used for the analysis are displayed in Table 2. They are selected according to the typical range adopted in the latest studies (Basu, 2009; Boumekik et al., 2021). The results are presented as the load-displacement curves and the parameters analyzed are the friction angle, Young's modulus, the column length and the encasement stiffness of the geotextile.

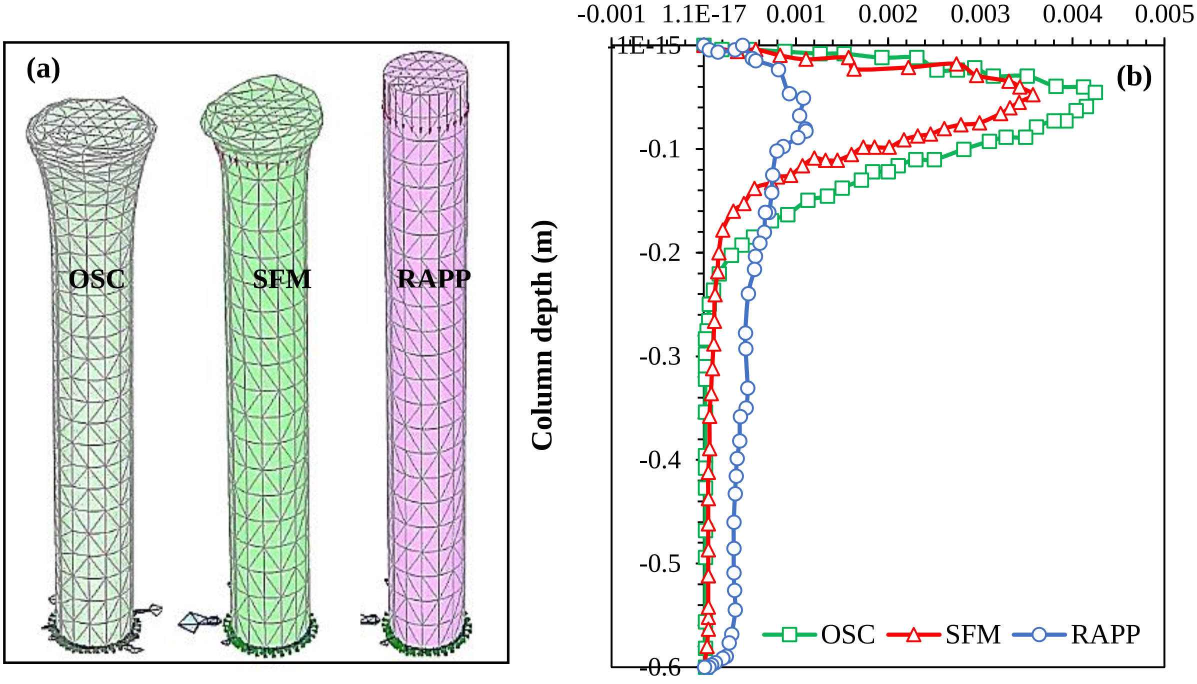

Figure (4): (a) Deformation of finite-element mesh in the columns and (b) Lateral deformation of columns

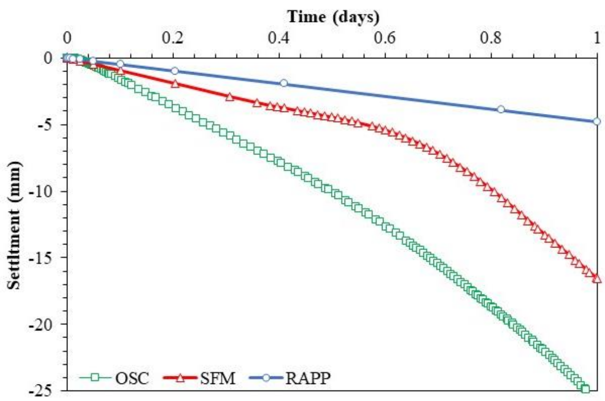

Figure (5): Vertical deformation of columns as a function of time

Effect of Encasement Length

When looking for the strengthening of weak soils with stone columns, one often resorts to the study of change in column length or more specifically to the study of floating columns. These studies mostly summarize the search for the ideal length of the corresponding column for optimal bearing capacity. Thus, the evolution of the change in the column depth from 0 to 0.6 m was studied while studying the importance of each soil in further improving the bearing capacity. Fig. 6 shows the load-settlement curves of three numerical models that vary by column type ((a) OSC, (b) SFM and (c) RAPP). The ideal length for OSC and SFM was 0.2 m. That is, the maximum value of bearing capacity was achieved at a total length with a value of 0.827 kN for OSC and 0.955 kN for SFM. RAPP reaches above these values by only 1.05 kN with a length of 0.1 m. RAPP gives excellent results, especially as the reinforcement depth is great, where the percentage increase between each of the two consecutive lengths was estimated at values ranging from 16% to 54%. As a result, it can be said that RAPP achieved better results than SFM by 6.63 times and OSC by 8.88 times, in the percentage of increase in bearing capacity at the total length of the column.

Table 2. Material properties' values used for parametric research

Category		Description / Range				Base values
Encasement stiffness (J), (kN/m)		0	4.5	6	8.5	0
Encasement length (m)		0.1	0.2	0.3	0.4	0.6
		0.5	full encasement			
Friction angle (φ°)	OSC	35	38	40	45	38
	SFM	30	34.47	40	45	34.70
	RAPP	32.70	35	40	45	32.70
Young's modulus (E), (kPa)	OSC	30000	40000	50000	60000	40000
	SFM	6700	8000	10000	12000	6700
	RAPP	12000	14000	16400	18000	16400

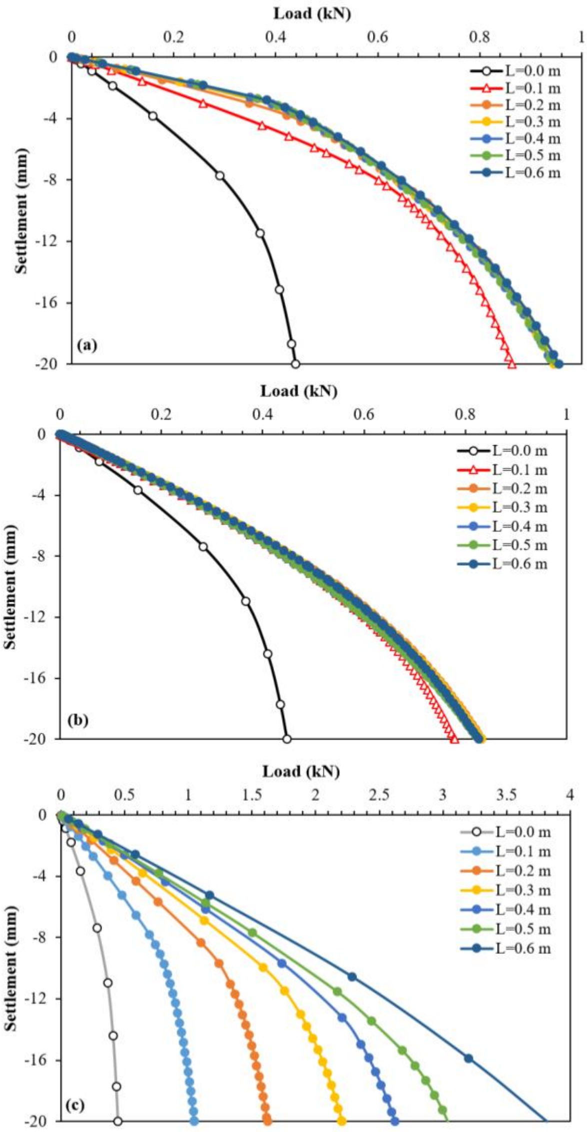

Figure (6): Effect of encasement length on vertical-load intensity settlement behavior of columns: (a) OSC, (b) SFM and (c) RAPP

Effect of Geotextile Encasement Stiffness

Geotextiles were modeled using the PLAXIS 3D code which behaves as an isotropic, linear elastic material without failure limitations. The boundary conditions of the unit cell only allow deformations along the vertical direction (Fig. 1). Vertical and horizontal displacements at the base of the unit cell were restrained. Using the geotextile element requires the specification of mechanical and geometric characteristics. Therefore, geotextile properties were determined in PLAXIS 3D software using the following parameters: elastic, isotropic material type and tensile stiffness (J), knowing that the geotextile was confined laterally along the column. Tensile strength of geosynthetic material has been reduced in accordance with the scaling law proposed by Hasan and Samadhiya (2016). Moreover, several researchers (Ghazavi and Nazari Afshar, 2013; Gniel and Bouazza, 2009) employed geosynthetic materials with tensile strengths ranging from 1.5 kN/m to 20 kN/m. Geotextiles with tensile strengths of 8.96 kN/m were used in the laboratory study. Based on the parametric study, it was noted that there is a distinct effect and an excellent scientific value when using geotextile with each type of column. The findings showed that geotextile encasement with stiffness (J) improved bearing capacity, according to the curves given in Fig. 7. Previously, it was found that the reinforcement with SFM is slightly better than with OSC, on the contrary when adding the geotextile to the column; the latter gave better results than SFM (Figs. 7a and 7b). For OSC, as compared with a stone column devoid of geotextile encasement (J = 0.0 kN/m), the bearing capacity is improved by 38.34%, 45.94% and 57.47% when the column is surrounded in geotextile with stiffness of J = 4.5, 6 and 8.5 kN/m, respectively. Moreover, for OSC at the same value of stiffness (J), bearing capacity was 22.32%, 26.55% and 32.93%, respectively. More importantly, it was clear that RAPP achieved better results than with OSC and SFM even if the RAPP was without geotextile encasement. However, it should be mentioned that RAPP with encasement has achieved a maximum approximate value at J = 4.5 kN/m estimated at 12.00% in comparison to a column devoid of geotextile encasement (Fig.7c).

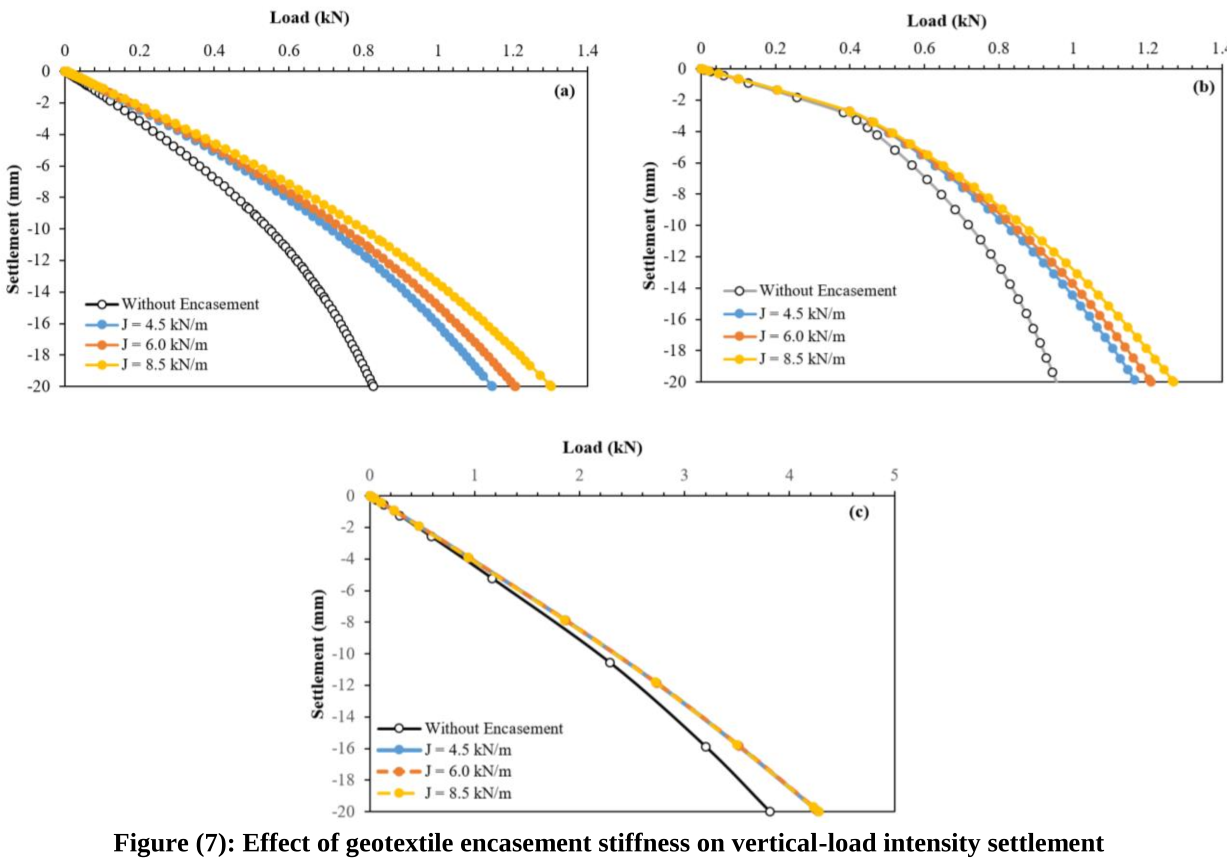

Figure (7): Effect of geotextile encasement stiffness on vertical-load intensity settlement behavior of columns: (a) OSC, (b) SFM and (c) RAPP

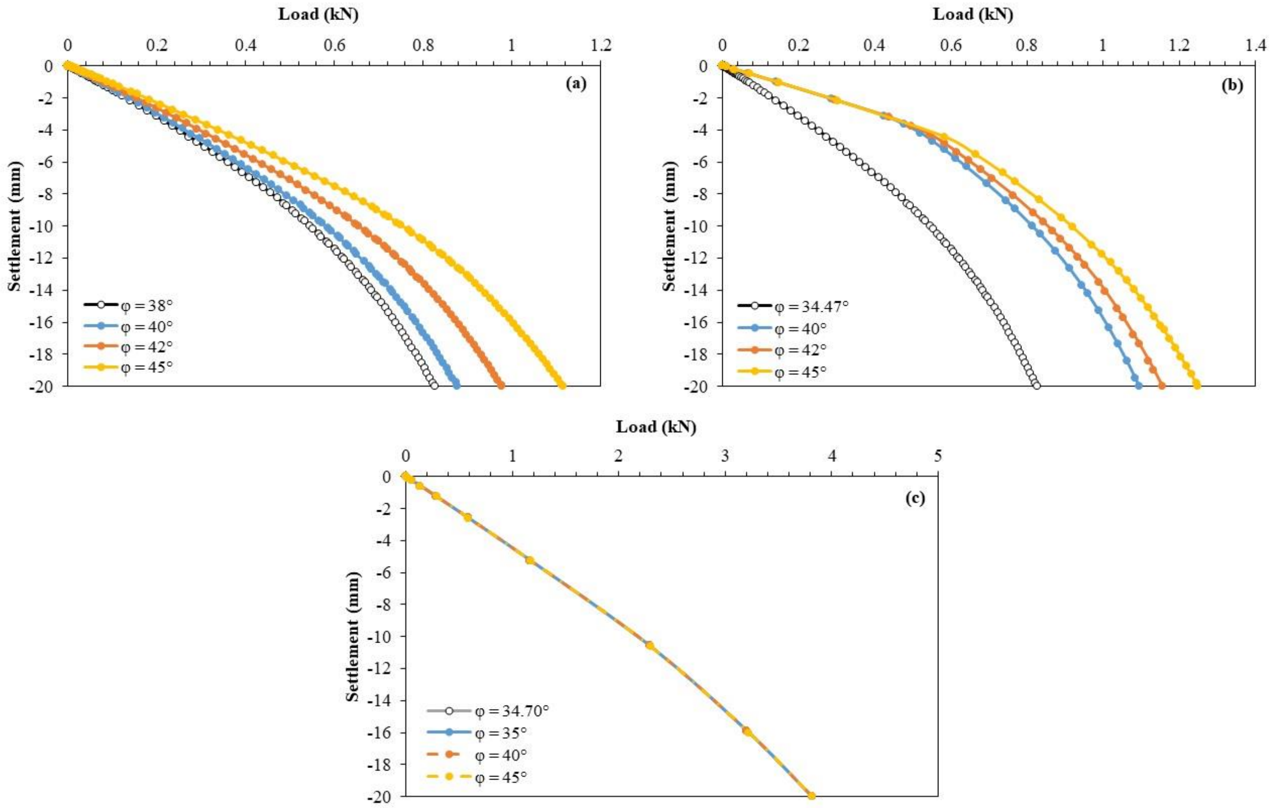

Figure (8): Effect of friction angle on vertical-load intensity settlement behavior of columns: (a) OSC, (b) SFM and (c) RAPP

Friction Angle Effect of Reinforcement Materials

Analyses were conducted with a series of four friction angles for each column type, OSC (38, 40, 42 and 45°), SFM (34.47, 40, 42 and 45°) and RAPP (32.7, 35, 40 and 45°). Fig. 8 shows the curves of columns loading as a function of settlement for various friction angles. It can be observed that the more the bearing capacity, the greater the friction angle value. The difference between the bearing capacity of angle 38° and that of 40° in OSC is estimated to be 6.26%, between (38° and 42°) is 18.36% and between (38° and 45°) is 35.12% (Fig. 8a). In contrast, SFM achieved better results than OSC, where the ratio of difference between angles in the bearing capacity was as follows: between (34.47° and 40°) is 32.64%, between (34.47° and 42°) is 39.72% and between (34.47° and 45°) is 51.64% (Fig. 8b). This shows that the friction angle (in OSC and SFM) has an important role in improving the bearing capacity. In Fig. 8c, the curves of the loading of RAPP columns as a function of settlement for different friction angles (35°, 40° and 45°) are shown. It can be observed that all the lines overlap with each other, indicating that the bearing capacity of RAPP columns is not affected by changes in the friction angle. This is because RAPP has a high cohesion factor of 727.9 kPa, which means that the material is able to resist shear forces without relying on friction between particles. Cohesion is a measure of internal strength that arises from the attractive forces between particles. In contrast, friction is a measure of the resistance to movement between particles that arises from the contact forces between them. Since RAPP has a high cohesion factor, it is less dependent on the friction angle of the material for its bearing capacity. Fig. 8c indicates that when RAPP is used as a column material, the friction angle may not be a major consideration in the design process.

Young's Module Effect of Reinforcement Materials

Elasticity module range for OSC is from 30 to 60 MPa, for SFM from 6.7 to 12 MPa and for RAPP from 12 to 18 MPa. These values are used to highlight the effectiveness and effect of Young's modulus (E) in improving the bearing capacity of soil. In Fig. 9a, it can be observed that all the lines overlap with each other, indicating that the bearing capacity of OSC columns is not significantly affected by changes in E. This result may be due to the fact that the range of E for OSC is relatively narrow and therefore, the increase in stiffness from one value to another was not significant enough to have a noticeable impact on the bearing capacity. OSC material properties may also contribute to the insensitivity of bearing capacity to changes in E. Scaling down E can help reduce the complexity of the model. It is important to note that while the results in Fig. 9a suggest that E has little impact on the bearing capacity of OSC columns, other factors, such as the friction angle and the density of the material, are still important considerations in the design of OSC columns. Increase in E of SFM gave a slight effect of 1% (Fig. 9b). The data in Fig.9c showed that the change in the value of E for RAPP gave a good effect in increasing the bearing capacity. Bearing capacity increases as the value of the elasticity modulus increases, where the percentage difference between the modules of bearing capacity is: (12000; 14000 kPa) 10.06%, (14000; 16400 kPa) 10.77% and (16400; 18000 kPa) 6.34%. As a result, RAPP stiffness plays an important role in soil improvement.

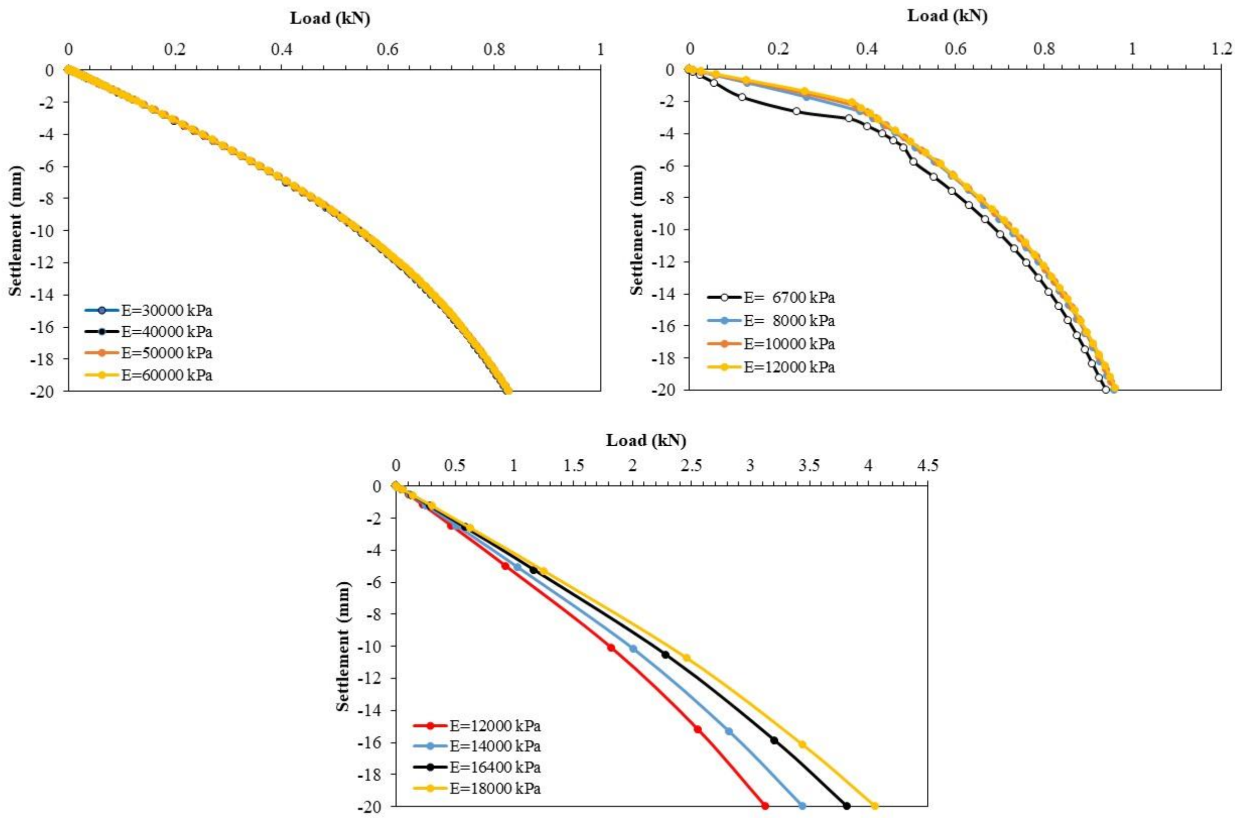

Figure (9): Effect of Young's modulus on vertical-load intensity settlement behavior of columns: (a) OSC, (b) SFM and (c) RAPP

CONCLUSIONS

The main conclusions can be stated as follows:

RAPP showed good behavior in improving bearing capacity, vertical and lateral displacement, as it was about 7 times greater in SFM and 9 times greater in OSC.

RAPP gives good results whenever the depth of reinforcement increases, while the increase in SFM and OSC stops at 0.2 m as the ideal length, noting that RAPP achieved better than these results at only 0.1-m length.

The increase in the tensile strength of geotextile encasement of granular columns leads to an increase in the column stiffness, where it turns out that the reinforcement with SFM is slightly better than with OSC initially, but when geotextiles were added to the column, OSC gave better results than SFM. More importantly, RAPP obviously achieved better results than OSC and SFM even if RAPP was without geotextiles.

As the internal friction angle of column material increases, so does the bearing capacity. This demonstrates that the granular column's friction angle (OSC, SFM) has a crucial influence on improving bearing capacity. On the contrary, RAPP was not affected by the change in the values of friction angle.

Increasing Young's modulus in OSC and SFM had no significant effect on bearing capacity, while in RAPP, it had the opposite effect and brought good improvements. RAPP generally obtained the best performance.

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