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NUMERICAL EVALUATION OF SOFT CLAY SOIL IMPROVEMENT USING ENCASED STONE COLUMNS

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ABSTRACT

In this paper, the finite element method is used for investigating the performance of the stone column–weak soil systems under different conditions. Nowadays there are several techniques for soil improvement. Out of these techniques available is the using of encased stone columns which have been used to a large extent for several applications. To improve the behavior of stone column the geosynthetics is used for encasing the stone column as reinforcement material. The program ABAQUS is used in the analysis of the performance of the stone column– weak soil systems. The program implements the finite element method and allows prediction to be made of soil deformations considering Mohr–Coulomb failure criterion for nonlinear soil behavior. Under different conditions, a parametric study is undertaken to investigate the behavior of ordinary and encased stone columns. The effects of some special parameters were studied to show the improvement in soil bearing and settlement decrease for the stone column-soil system. These include the stone column dimensions, the stiffness of encasement and shear strength of the foundation soil.

1- INTRODUCTION

Stone columns technique is extensively used to improve poor ground performance. The main purposes of this technique are the total settlement reduction, soil bearing capacity increase, acceleration of the consolidation rate and also mitigation of the liquefaction potential of saturated loose deposits. 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 (Greenwood, 1970; Hughes et al., 1975; Guetif et al. 2007; and Wang, 2009).

Advance progress in the stone column technique is reinforcing the column using either reinforcement horizontal layers (Sharma, 1998; Sharma et al., 2004) or encasing the stone column by geosynthetics (Raithel and Kempfert, 2000; Raithel et al., 2002). The geosynthetic encasement will improve the load carrying capacity of stone columns due to the additional confinement from the geosynthetic. Many researchers investigated the encased stone column technique using both numerical and experimental studies Based on small-scale laboratory tests, Malarvizhi and Ilamparuthi (2004) reported the improved performance of geosynthetic-encased stone columns based on end bearing as well as floating columns.

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Ayadat and Hanna (2005) performed experimental investigation on the load carrying capacity and settlement of stone columns encased in geogrid textile material and concluded that the ultimate carrying capacity of a stone column increases with an increase in the stiffness of the geofabric material. A laboratory model test by McKelvey et al. (2004) addressed the load deformation characteristics of a small group of floating stone column beneath strip, pad and circular footings. Their results proved that bulging is more prominent in long columns while shorter columns tend to show significant punching behavior which agree with Barksdale & Bachus (1983).

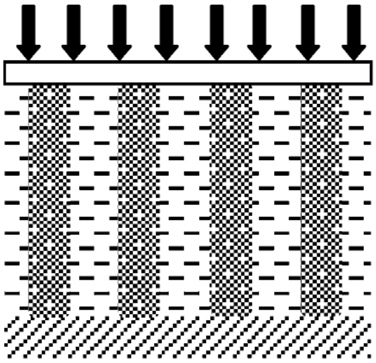
Through numerical and analytical models, Raithel and Kempfert (2000) and Raithel et al. (2002) studied the performance of geosynthetic-encased sand columns. Katti et al. (1993) proposed a theory for the improvement of soft ground using stone columns with geosynthetic encasement based on the particulate concept. It was found that the ultimate bearing capacity of reinforced stone column treated beds is three times that of the untreated beds. Lo and Mak, (2010) presented the findings of a series of numerical studies on the contribution of geosynthetic encasement in enhancing the performance of stone columns in very soft clay deposits. Huang and Han (2011) proved numerically that the behavior of geosynthetic reinforced embankments is time-dependent and it requires coupled hydraulic and mechanical modeling. Yoo (2010) presented results of a three-dimensional finite-element numerical model investigation into the performance of geosynthetic-encased stone columns installed in soft ground for embankment construction under different governing parameters of the system.

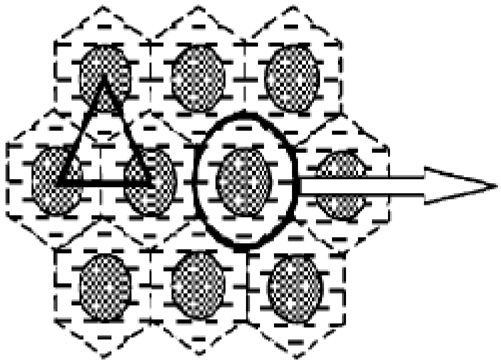
This paper is meant to numerically examine the performance of stone column–weak soil systems. The unit cell idealization was adopted and the model was analyzed with an axi-symmetric finite element analysis using commercial finite element program ABAQUS/Standared. Key parameters relevant to the design of stone column–weak soil systems, such as column dimensions, column length/diameter ratio, reinforcement ratio, geosynthetic encasement stiffness, and shear strength of the foundation soil were highlighted.

2- BASIC CONSIDERATIONS

2.1- Unit Cell Concept

Unit-cell idealization was used to abridge the behaviour of columns group beneath a uniformly loaded area. This area is simplified to a single column installed at the centre of a cylinder of clay representing the column's zone of influence. This concept is illustrated in Figure (1) and described in detail by Barksdale and Bachus (1983). Based on the unit cell concept, various analytical and numerical solutions have already been developed by many researchers for understanding the load transfer mechanism of soft soil reinforced with stone column, e.g., Han et al.(2000 & 2002), Ambily et al. (2007), Malarvizhi et al. (2008), Wang (2009), Lo et al. (2010), Murgasen et al. (2010), and Shien and Siew (2011).


(a): a uniformly loaded area on ground with stone columns


(b): The column influence zone

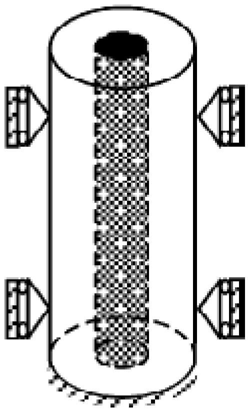

(c): The cell idealisation

Figure (1): The Unit-Cell Concept

For the purposes of the design and analysis, a cylindrical unit cell is considered, consisting of stone column and soil from the influence area as shown in Figure (1, c). The influence areas for stone columns installed in square and triangular plan patterns are calculated from that of an equivalent square or hexagonal area, respectively. The radius of the circular influence area is related to the centre to centre spacing ‘s’ between the stone columns 0.525s for triangular patterns as stated in Barron (1948).

In the unit cell concept the reinforcement ratio (area replacement ratio A_r) is a significant design factor which is defined as the ratio of stone column area to total unit cell area (Bergado et al., 1996):

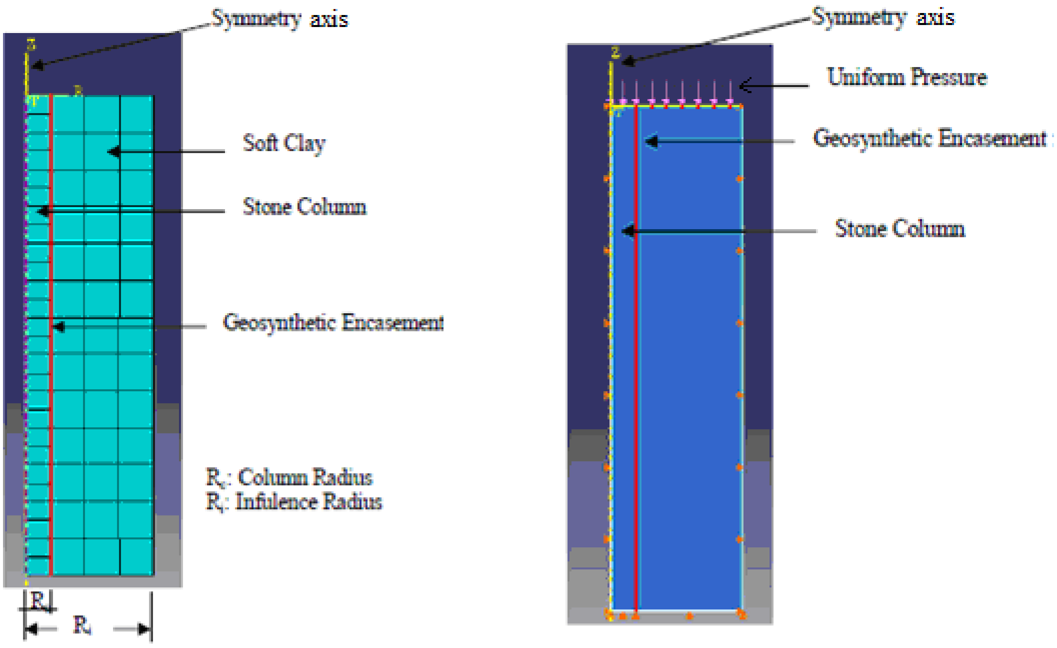
$$\mathbf{A_r = A_c/(A_c+A_s)} \qquad \text{Equn. (1)}$$

Where:

A_r = the reinforcement ratio
A_c = area of stone column cross-section
A_s = area of soil in unit cell surrounding the column

3- FINITE ELEMENT MODELING

Finite element analyses were performed using the program ABAQUS/standard (2009). The geosynthetic encasement was modeled as an isotropic linear elastic material using 3-node triangular membrane elements with tensile stiffness of different values according to mentioned ones in Table (2) and a Poisson’s ratio of 0.3. While elastic-perfectly plastic Mohr-Coulomb model for undrained condition has been assumed to model the behavior of the foundation soil and stone column materials. The material properties used in the analyses were based on the material properties that Mohammed and Qutaiba (2009) had used in their analyses as for surrounding soft soil Cu = 20 kPa. Foundation soil and stone column were modeled using 4-node bilinear axisymmetric quadrilateral, elements. The Finite element model discretization is shown in Figure (2). In this investigation the case of triangular plan patterns of stone columns is considered with column diameter of 1m and the influence radius is 2.625 m. A 500kPa pressure was applied in 100kPa increments.



(a) axisymmetric model mesh

(b) loads and boundary conditions

Figure (2): Finite Element Model Discretization

4- RESULTS AND ANALYSIS

4.1- Effect of stone column encasement

In order to evaluate the effect of encasement of the stone columns, the lateral deformations and settlement are assessed of 1m diameter uncased and encased columns. The lateral deformations of the two columns obtained from the proposed models are presented in Figure (3).

As it can be seen from the results, encasing the columns results in stiffer columns due to the confinement effect provided by the encasement. The lateral deformation of the mentioned columns decreases by up to (40%). It is clear that the lateral stresses are higher in the encased column as compared to the corresponding lateral stresses in uncased one. The increase in confining pressure can be seen over the full height of the stone column, which leads to mobilisation of higher vertical load capacity in the encased columns.

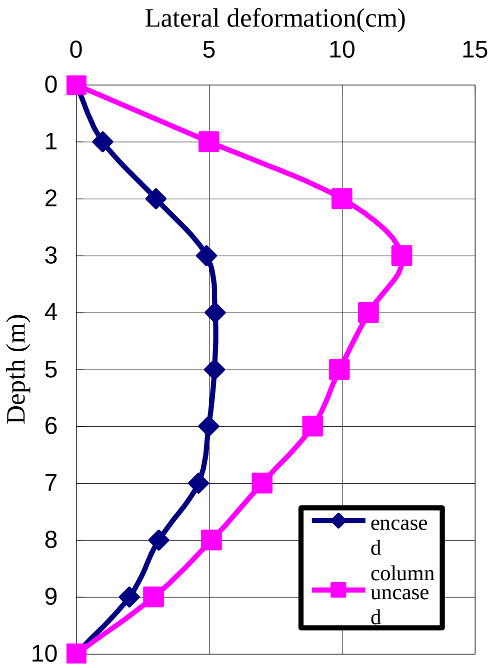


Figure (3): Effect of encasement on the lateral deformation of 1 m diameter column

4.2- Ratio of column length to column diameter (L/D)

The reinforcement ratio as well as the length of stone column of encased stone column technique plays an effective influence on improving the strength of soft clay treated by stone column. In this investigation, a parametric study has been performed over a range of (L/D) and (A_r) values as stated in Table (1). This study is based on the bearing improvement ratio I_r= ($q_{treated}/q_{untreated}$).

Table (1): Series values for the parametric study

Influence Factor	Range of values
The reinforcement ratio (A_r)	0.1,0.15,0.2,0.25,0.3,0.35
length to column diameter ratio (L/D)	2,3,4,5,6,7,8,9,10,11,12,13,14,15

Figures (4) to (9) shows the relation between L/D and the bearing improvement ratio (Ir) for the values mentioned in Table (1) for both uncased stone columns and encased stone column. These figures show that for uncased stone column, the strength of column increases with the increase in the length of stone column. The efficient (L/D) ratio of stone column is mostly found to be (L/D) = 8 for all reinforcement ratios. Beyond this value of (L/D), there is no effect on the (Ir) value.

It can also be seen that for encased stone column, the bearing improvement ratio increases with the increase of (L/D) even when (L/D) ratio becomes more than 8 for all area replacement ratios. This means that in case of encased stone column, there is no limitation on the effective (L/D) ratio.

The strength of stone column increases with using geosynthetic encasement compared with uncased stone columns and the increasing in bearing improving ratio (Ir) is considered with the ratio (L/D) increase. In Figures (4-6), it is clear that there is not any bearing improvement until the value of the ratio (L/D) = 3. Actually the efficient improvement is starting from (L/D) = 7 for (Ar) = 0.1 and 0.15, while the increasing in the (Ir) value for (Ar) ≥ 0.25 is starting from (L/D) = 8.

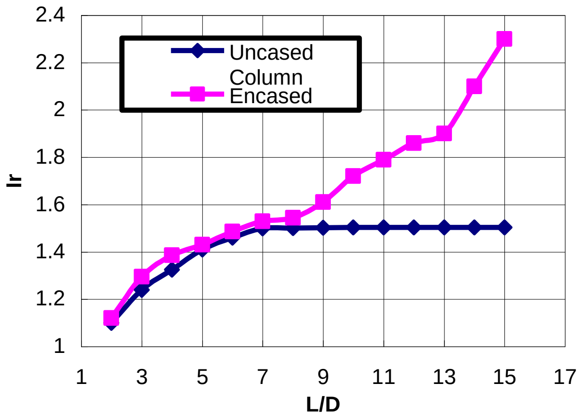
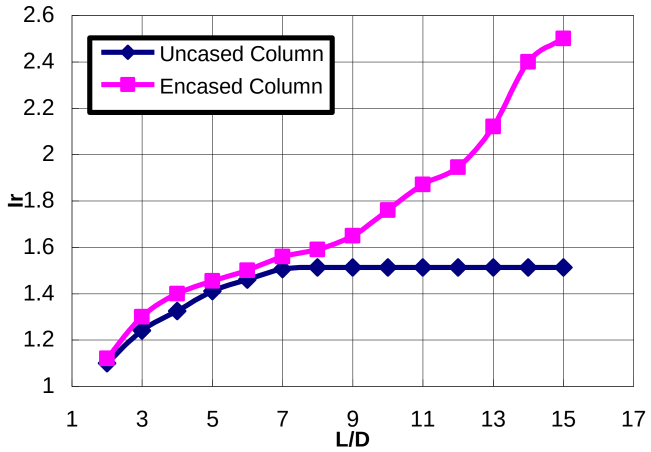


Figure (4): Bearing improvement at A_r = 0.1



Figure(5): Bearing improvement at Ar = 0.15

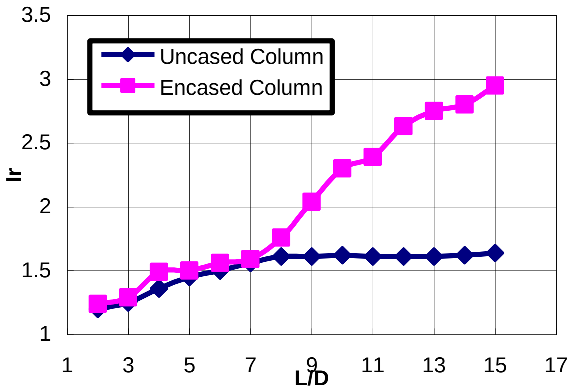


Figure (6): Bearing improvement at Ar = 0.2

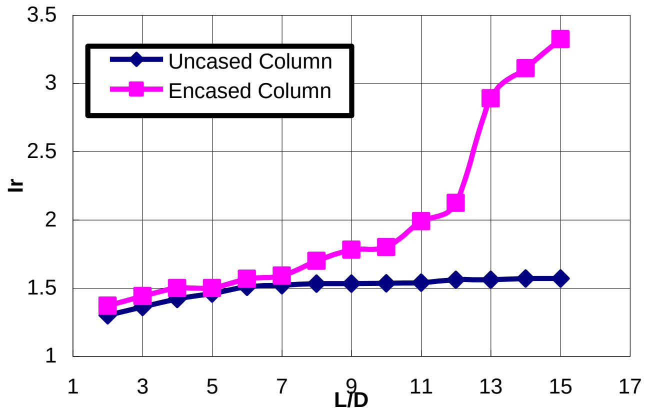


Figure (7): Bearing improvement at Ar = 0.25

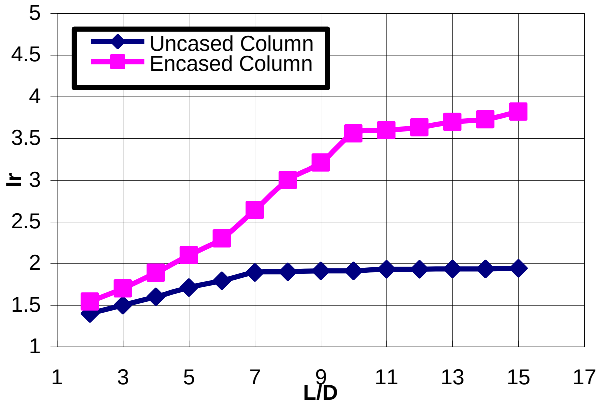


Figure (8): Bearing improvement at Ar = 0.3

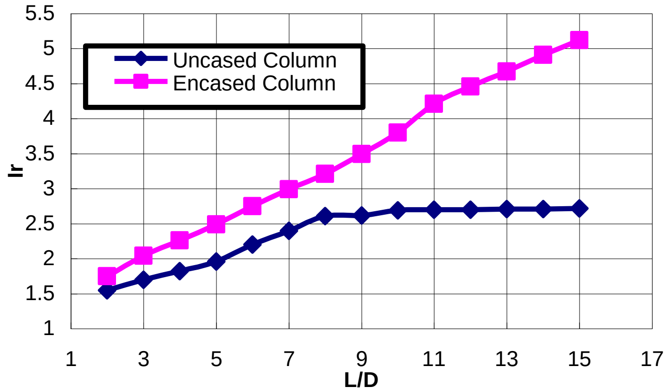


Figure (9): Bearing improvement at Ar = 0.35

4.3 - Effect of encasement stiffness

The effect of the geosynthetic tensile stiffness used for encasement on the behavior of the stone column was numerically studied by changing the stiffness range of geosynthetic over a wide range of values up to 10,000 kN/m. the ranges used in the numerical investigations as shown in Table (2). All other parameters were kept constant. Some recent geosynthetic products made of high firmness polyester materials have tensile strengths of the order of 10,000 kN/m, as reported by Murugesan and Rajagopal (2006).

Figure (10) shows the pressure settlement behavior of 1m diameter stone column encased with geosynthetic of different stiffness values.

Table (2): Encasement stiffness values

Encasement Legend	Uncased Column	Geo 1	Geo 2	Geo 3	Geo 4	Geo 5
Encasement Stiffness Value (kN/m)	0	250	1000	2500	5000	10000

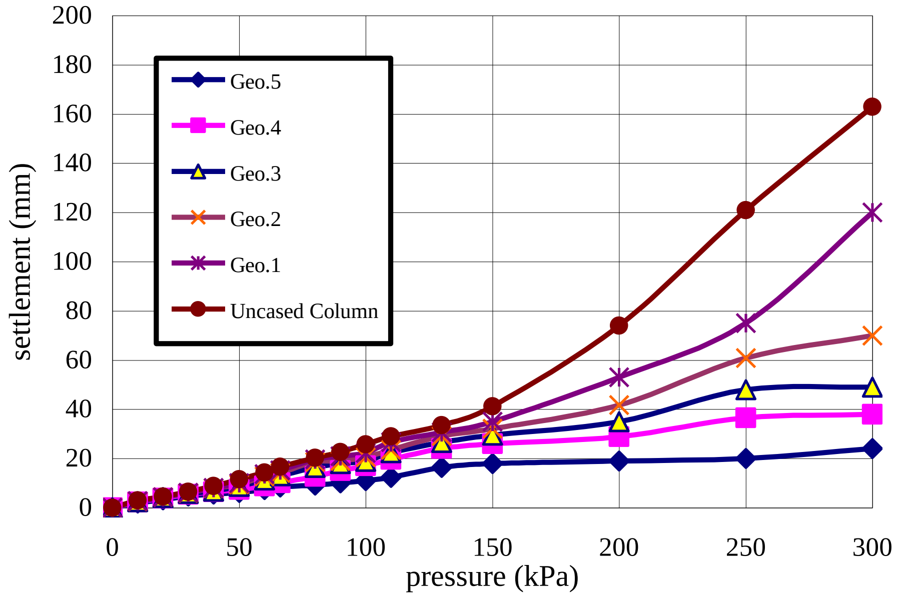


Figure (10): Effect of encasement stiffness on the settlement of 1 m diameter column

Figure (10) shows the pressure settlement behavior of 1m diameter stone column encased with geosynthetic of different stiffness values. It is obvious that the larger value of encasement stiffness, the smaller value of settlement for the same column diameter. It is clearly seen from Figure (10) that increasing stiffness of geosynthetic encasement results in smaller values of stone columns settlements.

The increasing of the stiffness of the geosynthetic encasement of stone columns makes the stone columns stiffer. This result in significantly increase in the ring tension force mobilized in the encasement and therefore the lateral confinement provided by it. Consequently increasing of encasement stiffness, results in a significant improvement of the performance of the encasement stone columns. The improved performance due to the encasement can be attributed to the improvement of overall stiffness of the columns due to larger confining stresses assembled in the column.

4.4- Effect of diameter of the stone column

In order to evaluate the effect of encasement stiffness on the settlement performance, the reduction percent in settlement of encased stone columns related to the uncased column was precious to be investigated. This investigation was performed for different column diameters (1m, 0.75m and 0.5 m) by applying pressure loading only on the stone column surface, while keeping the influence radius constant at 2.625 m. The stiffness values of encasements varied according to the values stated in Table (2) under a specific pressure of 300 kPa. The pressure–settlement diagrams for the different cases are presented in Figure (11). As it gave the same trend, only diagrams for diameters 1 and 0.75 m with encasement stiffness of uncased, 250, and 1000 kN/m cases are presented in Figure (11).

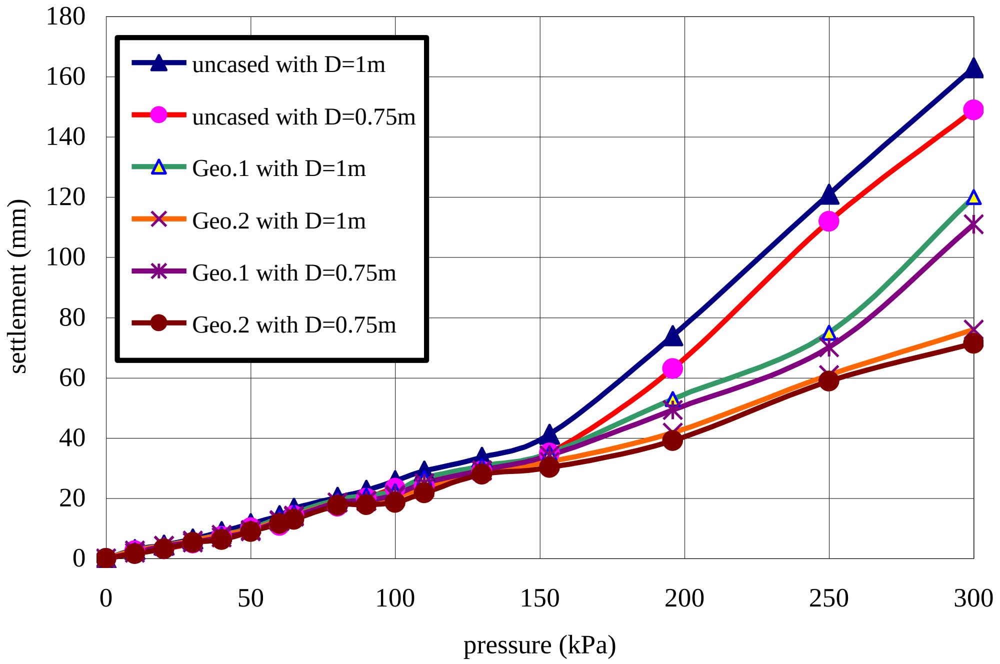


Figure (11): Effect of encasement stiffness on the settlement of different diameter columns

The performance of encased stone columns of smaller diameters is better than that of bigger diameter stone columns because of mobilization of higher confining stresses in larger stone column. The higher confining stresses in the column leads to higher stiffness of smaller diameter encased columns. The reason for this is the development of larger additional confining stresses in smaller diameter encased columns. The same can also be observed in the results presented in Figure (12) which shows the settlement reduction percent of encased stone columns of different diameters (1m, 0.75m and 0.5 m).

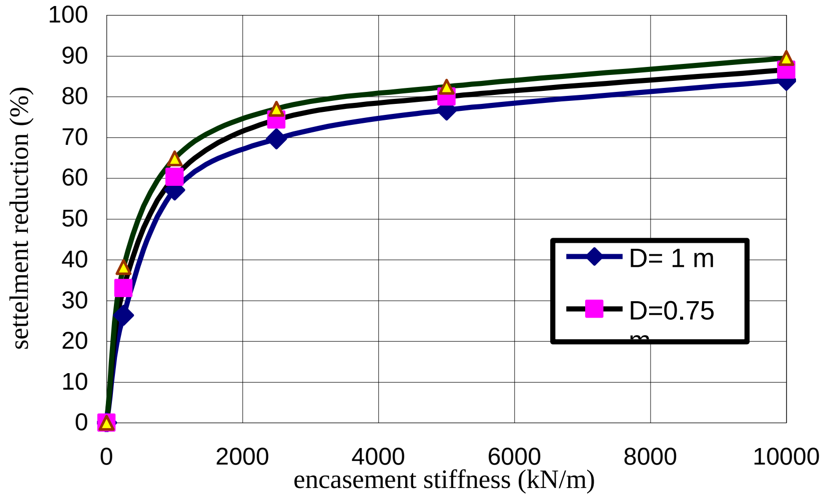


Figure (12): Effect of encasement stiffness on settlement reduction with different column diameters

4.5- Effect of shear strength of the foundation soil

The effect of the strength of foundation soil was numerically investigated by performing analyses for two cohesive strength values of 10 and 20 kPa. The analyses were performed for a column diameter of 1m, and encasement stiffness cases of uncased column, 250 and 5000 kN/m as stated in Table (2). The pressure–settlement performance is monitored as shown in Figure (13).

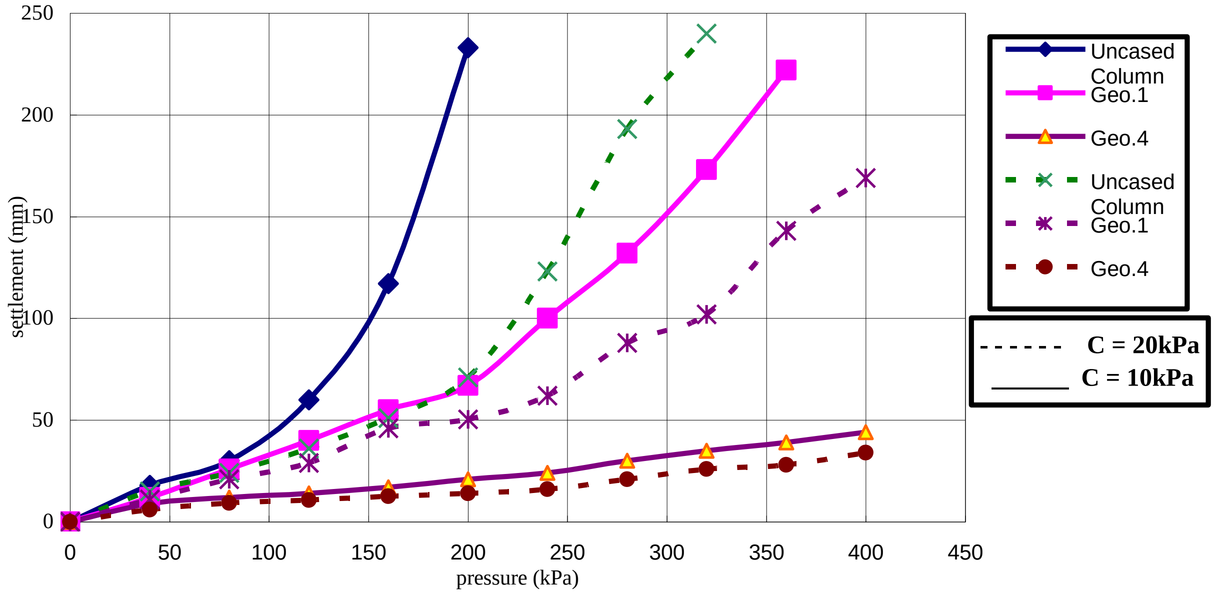


Figure (13): Effect of soil shear strength

It has been noticed that the load capacity of uncased column is totally dependent on the shear strength of the foundation clay soil. On the other hand, the effect of the strength of foundation soil on the capacity of the encased stone columns decreases with the increase of the geosynthetic stiffness.

It can be also noticed that when the encasement stiffness is increased to 5000 kN/m, the pressure–settlement performance of encased column is almost independent of the shear strength of the surrounding foundation clay soil. With the increase of the encasement stiffness, the stresses transmitted into the foundation soil will be reduced. As the encasement stiffness increases, the soil support to the stability of the encased stone column decreases. This observable fact makes the encased columns capacity almost independent of the strength of the foundation soil for very stiff encasement.

5- CONCLUSIONS

Based on the finite element analysis and the results obtained, the following conclusions are made:

- Encasing the columns results in stiffer columns due to the confinement effect provided by the encasement. The increase in confining pressure leads to mobilisation of higher vertical load capacity in the encased columns.
- The improved performance due to the encasement can be certified to the improvement of overall stiffness of the columns due to larger confining stresses assembled in the column.
- The performance of encased stone columns of smaller diameters is better than that of bigger diameter stone columns because of mobilization of higher confining stresses in larger stone column. The higher confining stresses in the column leads to higher stiffness of smaller diameter encased columns.
- The efficient column length to column diameter ratio (L/D) of stone column is generally found to be 8 for all reinforcement ratios mentioned. Beyond this value of L/D, there is no effect on the bearing improvement value.
- The load capacity of uncased column is totally dependent on the shear strength of the foundation clay soil while increasing the geosynthetic stiffness result in decreasing in the effect of the strength of foundation soil on the capacity of the encased stone columns

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