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3-Dimensional Numerical Evaluation of Geosynthetic Encased Stone Columns in Unsaturated Soils

Mohammed Shakeel Abid[1*], *G Venkata* Ramana[2], *Sai K* Vanapalli[3], *and Kasinathan* Muthukkumaran[4]

[1]Department of Civil Engineering, Kakatiya l Institute of Technology & Science, Warangal, India
[2]Department of Civil Engineering, National Institute of Technology, Warangal, India
[3]Department of Civil Engineering, University of Ottawa, 161 Louis-Pasteur St., Ottawa, Ontario, Canada
[4]Department of Civil Engineering, National Institute of Technology, Tiruchirappalli, India

Abstract. Geosynthetic encased stone columns are often designed using the conventional framework of saturated soils ignoring the influence of in-situ unsaturated soil conditions. This article evaluates the performance of stone columns with and without geosynthetic encasement extending the mechanics of unsaturated soils. The focus of numerical simulations was directed towards understanding the influence of matric suction on the confining support offered by the surrounding soil to stone columns with and without geosynthetic encasement. Investigations were extended considering the stiffness and the length of the geosynthetic encasement. The numerical studies suggest the load-carrying capacity of stone column increased with an increase in the matric suction in the boundary effect and the primary transition zone. However, the contribution of matric suction towards load-carrying capacity starts reducing from the secondary transition zone. The information on boundary effect and transition zones can be derived from the soil-water characteristic curve, which is a relationship between the water content and soil suction. In addition, the effect of stiffness and length of encasing material in unsaturated soils was found to be in contrast with saturated soils. The results of the study are promising towards developing procedures that can be used in the rational design of stone columns in unsaturated soils.

1 Introduction

Stone columns have been extensively used as a cost-effective ground improvement technique to reduce excessive settlements and enhance the load-carrying capacities of weak soil deposits in recent decades [1-4]. Apart from enhancing the mechanical characteristics of the ground, stone columns were also found effective in reducing liquefaction potential and accelerating radial consolidation [5]. Extensive research through experimental and numerical studies has been carried out by various researchers towards evaluating the performance of stone columns in a wide variety of soils ranging from loose sands [1,6] and soft compressible clays [7;8] extending the principles of conventional saturated soils. However, stone columns are constructed either in part or fully in the vadose zone, which lies above the natural groundwater level where the soil is typically unsaturated. Moreover, the maximum deformations in stone columns are expected near the ground surface within the vadose zone. Therefore, the application of principles of unsaturated soils considering the contribution of matric suction is required for the rational design of stone columns.

The effective lateral confining support offered by the surrounding soil is the key factor responsible for enhancing the strength and stiffness of the stone column. The lateral confining support from the surrounding soil is predominantly dependent upon its shear strength which is sensitive to the degree of saturation that is strongly related to the matric suction (u_a - u_w) [9].

* Corresponding author: msa.ce@kitsw.ac.in

In addition, these changes in shear strength alter shear-induced volume changes influencing the performance of stone columns. Therefore, 3-Dimensional numerical studies were carried out to evaluate the effect of matric suction on lateral confining support offered by the surrounding unsaturated soil. In addition, the influence of variation in stiffness and length of geosynthetic encasement on the performance of geosynthetic encased stone columns in saturated and unsaturated soils is also investigated. The results obtained were helpful in deciding the critical stiffness and length of geosynthetic encasement for stone columns in unsaturated soils.

2 Numerical Model

2.1 Modelling Considerations

Finite element analyses were performed using the commercial software Plaxis [10] to study the behavior of the stone column with and without encasement in unsaturated soils. The soil and stone columns were modelled as continuum elements using the elastic-perfectly plastic Mohr–Coulomb (MC) constitutive model. The geosynthetic encasement was modelled as an element that has only normal stiffness (i.e., it only has translational degrees of freedom at their nodes and can only sustain tensile stresses) [11]. Fixed boundary conditions were used at the bottom of the model and roller vertical boundaries were assumed in the lateral direction. A good connection between the soil and geosynthetic was ensured using interface elements. The R_{inter} adopted in the study is 0.67, which is within the range of 0.45 to 0.8 (Brinkgreve et al. 2006). The soil profile was assumed to be uniform extending up to 8m in depth and 12m in the lateral direction. In the present study, an end-bearing stone column of diameter 1m along with a surface footing of size 2m in diameter was used to apply loading. A quarter portion of the soil element was modelled exploiting the symmetry conditions as shown in Fig. 1. Analysis was carried out as a staged construction process assuming the incremental load of 100kPa to generate the pressure-settlement responses. Effects of element size and boundary conditions were eliminated by considering fine mesh discretization.

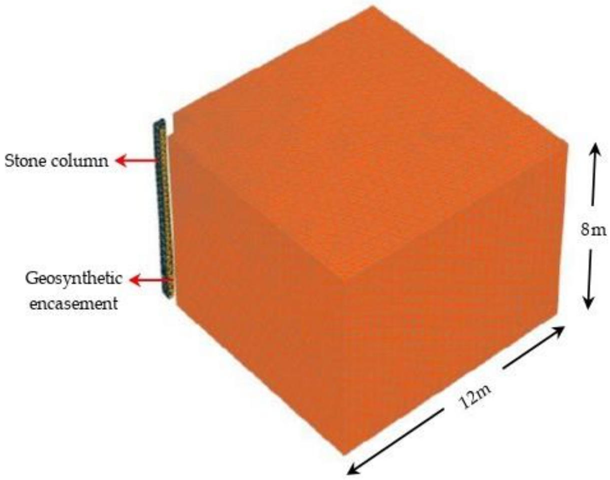

Fig. 1 3-Dimensional finite element model

2.2 Parametric Studies

The parametric variations include matric suction ($u_a - u_w$) of the soil, stiffness of the geosynthetic (J_g) modelled for encasing the stone column, and length of the geosynthetic encasement. The model ground with GWT below the stone column is developed. Six different matric suction ($u_a - u_w$) values of the soil i.e., 0, 2.5kPa, 3.5kPa, 5kPa, 7.5kPa, and 9kPa were considered for the analysis. These matric suction values were chosen such that representative information from different zones of saturation of SWCC could be gathered for the rigorous interpretation of the results. A matric suction of ‘0’ and ‘9kPa’ represents saturated and close to dry conditions of the soil. Whereas matric suction of 2.5kPa, 3.5kPa, 5kPa, and 7.5kPa pertains to boundary effect, primary transition, secondary transition, and residual zones of saturation. The quantitative and qualitative improvement in the performance of stone column due to the contribution of matric suction is represented through pressure-settlement responses and confining pressure developed around the stone column. In addition, detailed analyses were undertaken to study the behavior of stone column with and without encasement by varying the stiffness and length of encasement to determine their critical values.

A non-woven geotextile with three different stiffness values i.e., 500kN/m, 2500kN/m, and 5000kN/m [12] were used for analyses. Analysis was continued by varying the encasement length along the depth of stone column (L) i.e., *0.25L, 0.5L, 0.75L,* and *L*. The improved performance was quantified based on the reduction in settlement of the stone column using a non-dimensional parameter known as settlement reduction factor (β) which is the ratio of settlement of soil reinforced with stone columns to that of unreinforced soil.

2.3 Material Properties

The geotechnical properties of clean dry sand collected from the riverbed of the Godavari River from India was used to model the ground. The soil is classified as poorly graded sand as per the Unified Soil Classification System (USCS). The aggregates used for modelling stone column are a frictional material with a minute cohesion value of 0.1kPa to alleviate numerical errors. The geotechnical properties of the sand and aggregates are represented in Table 1. The grain size distribution curve and SWCC determined using a tensiometer are shown in Fig. 2.

Table 1. Geotechnical properties of soil and aggregates

Parameters	Soil	Coarse aggregates
Specific gravity, *G*	2.60	2.80
Grain size distribution (%)		
Gravel	0.40	100
Sand	99	0
Fines	0.60	0
Unified soil classification symbol	SP	GP
Maximum dry unit weight, $\gamma_{d(max)}$, kN/m^3	18.84	16
Minimum dry unit weight, $\gamma_{d(min)}$, kN/m^3	14.94	13
Dry unit weight, (kN/m^3)	15.42	-
Void ratio	0.686	-
Angle of internal friction (°)	32.61	40
Modulus of elasticity (kPa)	2371	40000
Poisson’s ratio	0.35	0.3

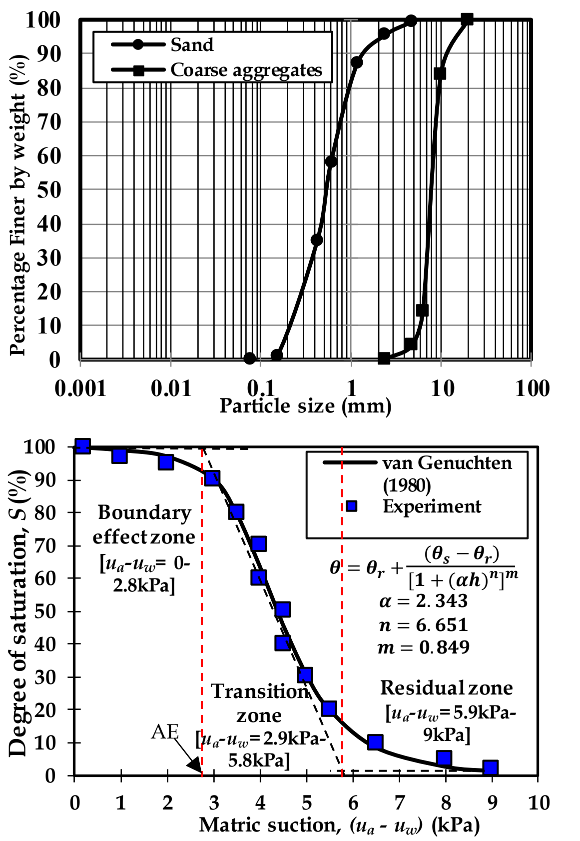

Fig. 2 a) Grain size distribution of sand and coarse aggregates
b) SWCC of Godavari River sand

The non-linear variation in shear strength of unsaturated soils due to the influence of (u_a - u_w) was modelled using the SWCC and saturated shear strength parameters as given below [13].

$$\tau_{unsat} = c' + (\sigma_n - u_a)tan\phi' + (u_a - u_w)\left[\frac{(\theta - \theta_r)}{(\theta_s - \theta_r)}tan\phi'\right] \quad (1)$$

where, τ_{unsat} is shear strength of unsaturated soil; $(\sigma_n - u_a)$ = net normal stress; c' and ϕ' are effective shear strength parameters.

Neglecting the influence of matric suction on the angle of internal friction, ϕ' the apparent cohesion c_a, can be evaluated using the equation below [14]

$$c_a = c' + (u_a - u_w)\left[\frac{(\theta - \theta_r)}{(\theta_s - \theta_r)}tan\phi'\right] \quad (2)$$

In addition, the variation in modulus of elasticity of unsaturated soil due to the influence of (u_a - u_w) can be determined by using the semi-empirical model proposed by [15]

$$E_{unsat} = E_{sat}\left[1 + \alpha\frac{(u_a - u_w)}{(P_a/101.3)}S_r^{\beta}\right] \quad (3)$$

E_{unsat} is the modulus of elasticity of unsaturated soil, P_a = atmospheric pressure (i.e., 101.3 kPa); α and β are the fitting parameters with a value of 0.5 and 1 for non-plastic soils [16]. Eq. (2) and Eq. (3) were convenient to model the shear strength and modulus of elasticity of the unsaturated soils taking into account of the influence of matric suction.

3 Results and Discussions

3.1 Behavior of geosynthetic encased stone columns in unsaturated soils

The pressure settlement responses of stone columns with and without geosynthetic encasement in saturated and unsaturated soils is shown in Fig. 3. The pressure typically increases with an increase in the settlement until it reaches a peak value P_{max} and then drops or fluctuates slightly with further settlement. The pressure-settlement response of saturated soil reinforced with stone column was observed to be nearly vertical illustrating a clear failure at a limited footing settlement of 25mm. The pressure increased until a settlement of 35mm when the stone column was encased with geosynthetic followed by failure after attaining peak settlement. The increase in the carrying capacity was around 2.5-fold upon encasing stone column with geosynthetic in saturated conditions. In case of unsaturated soils, pressure increased monotonically without any sign of failure. This observation was consistent with the increase in matric suction. A significant increase in pressure was observed with an increase in matric suction into boundary effect zone. The increase in pressure continued with further increase in matric suction beyond the boundary effect zone (i.e., in the primary transition zone). However, a decrease in pressure was observed with a further increase in matric suction. The wetted contact area of the unsaturated soil interface of the stone column is affected by matric suction, which is considered as a stress-state variable that operates independently. [17]. Increase in matric suction beyond primary transition zone caused a reduction in the soil-water-air interphase leading to a decrease in contribution of matric suction on lateral confinement. The variation of ultimate carrying capacity of stone column with and without encasement in saturated and unsaturated conditions is summarized in Fig. 4. The carrying capacity of conventional stone column (CSC) increased by 17-fold from saturated to unsaturated conditions. Increase in carrying capacity was about 10-fold for the geosynthetic encased stone column (GESC) in unsaturated soils. A significant enhancement in carrying capacity was observed when stone column was encased with geosynthetics in saturated soils. However, increase in carrying capacity of stone columns in unsaturated soils with geosynthetics was limited. The requisite confinement to resist the applied pressure was offered by the surrounding unsaturated soil leaving the additional confining support offered by geosynthetic encasement immobilized. Geosynthetic encasement offered an adequate enhancement in carrying capacity when matric suction was pertinent to residual zone of saturation and close to dry conditions. However, enhancement in carrying capacity for matric suction representing boundary effect zone, primary, and secondary transition zones are insignificant. The lateral confining pressure developed along the stone column in saturated and unsaturated soils is illustrated through Fig. 5. The confining pressure is directly proportional to the shear strength of the soil. The confining pressure leads to an increase in the effective stress, which contributes to the shear strength of the soil.

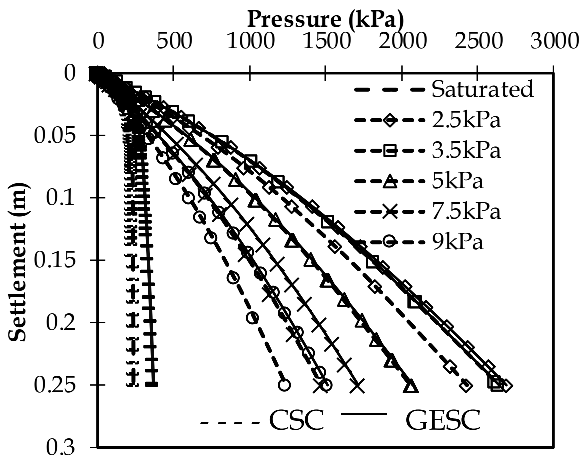

Fig. 3 Pressure settlement response of conventional and geosynthetic encased stone columns

The lateral confining pressure offered by the soil and interfaces illustrated the nonlinear influence of matric suction on the shear strength along the soil-water characteristic curve (SWCC). Mobilization of confining pressures is higher up to a depth of two times the diameter of the stone column below the ground surface. The increase in confining pressure extended over the full height of the geosynthetic encased stone column, which leads to the mobilization of higher carrying capacities in the saturated soils.

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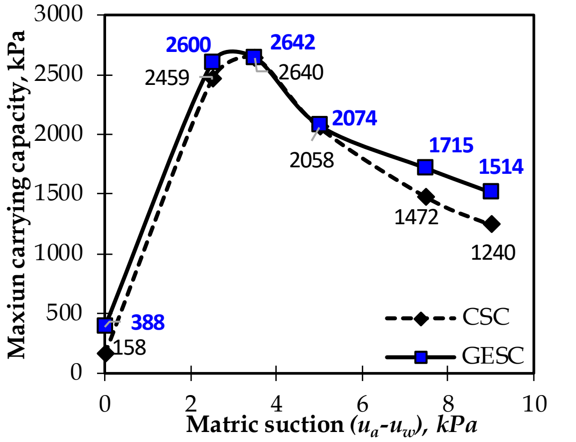

Fig. 4 Variation in carrying capacity of stone column with and without encasement

Significant confining support due to the contribution of matric suction can be observed when the soil is unsaturated. Geosynthetic encasement in unsaturated soil accounted for disruption of the air-water menisci along the soil-geotextile-column interface leading to a net decrease in water content. Such a behavior can be attributed to the development of capillary breaks causing a reduction in the shear strength of the unsaturated soil interface. This phenomenon restrained the development of additional lateral confinement around the geosynthetic encased stone columns in unsaturated soils.

3.2 Influence of stiffness of geosynthetic

The influence of the tensile stiffness of the geosynthetic used for encasement on the performance of the stone column was investigated by varying the stiffness of geosynthetic. The improved performance due to the increase in stiffness of encasing geosynthetic was quantified using the settlement reduction factor, β, and the critical stiffness of encasing geosynthetic material is determined as shown in Fig. 6.

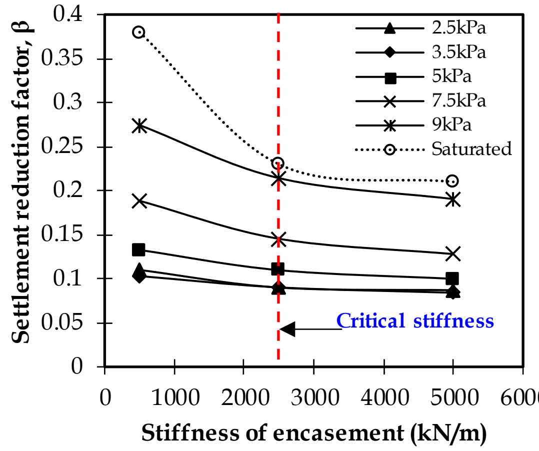

Fig. 6 Variation of settlement reduction factor with stiffness of encasing geosynthetic for different suction values

Critical stiffness of the encasing material can be defined as that stiffness where further enhancement in the stiffness of the encasing geosynthetic provides a negligible improvement in the performance of reinforced ground. Three different encasement stiffness (i.e., 500kN/m, 2500kN/m and 5000kN/m) were used to determine critical stiffness of encasement in saturated and unsaturated soils. The settlement reduction factor reduced with increase in stiffness of encasing geosynthetic.

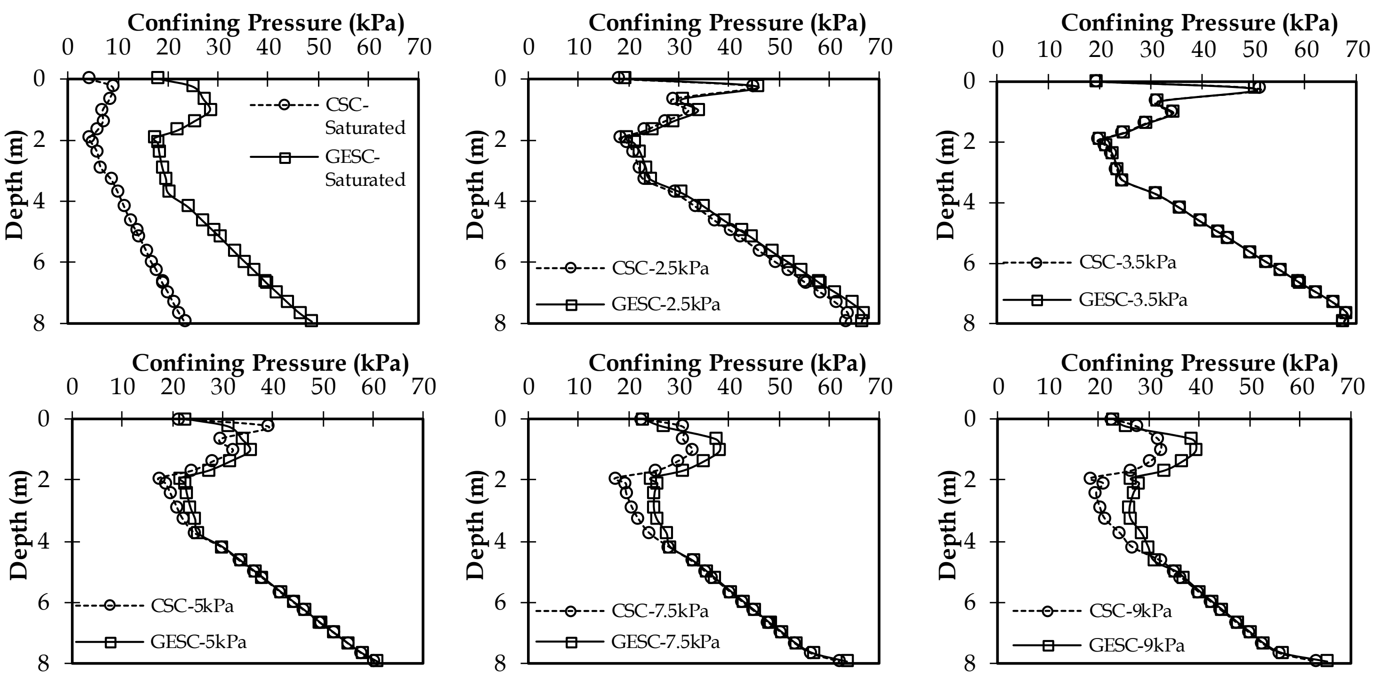

Fig. 5 Variation in confining pressure along the depth of stone column for saturated and unsaturated condition

A significant reduction in settlement reduction factor was observed when stiffness of geosynthetic increased from 500kN/m to 2500kN/m. However, reduction in settlement reduction factor, β was limited when the stiffness of encasing geosynthetic material increased from 2500kN/m to 5000kN/m demonstrating immobilization of additional stiffness of encasing material. Therefore, a stiffness of 2500kN/m can be defined as a critical stiffness value for geosynthetic encasement. In addition, the settlement reduction factors exhibited effective mobilization of stiffness of geosynthetic encasement in saturated, residual, and dry conditions. However, stiffness of geosynthetic material was not fully mobilized in boundary effect and transition zones irrespective of the stiffness value. The results are supported by the plastic deformations developed in geosynthetic encased stone columns with varying stiffness in saturated and unsaturated conditions (Fig. 7). The deformation in vertical and lateral directions illustrates the transfer of pressure along the depth of the stone column and on the surrounding soil, respectively. The deformations were relatively higher in the lateral direction rather than in the vertical direction for saturated soils, highlighting the softening behavior of soil. Such a behavior can be associated with aggregates losing their ability to interlock due to excessive bulging and continuing to deform until reaching residual strength conditions. The plastic deformations were relatively higher in the vertical direction irrespective of stiffness of geosynthetic in unsaturated soils illustrating transfer of pressure along the depth of stone column. Such a behavior exhibits insignificance of the concept of critical stiffness in unsaturated soils. However, geosynthetics or natural textiles with limited stiffness can be used for cost-associated benefits to encase stone columns and avoid excessive displacement of aggregates.

3.3 Influence of encasement length

The encasement length for stone column was varied along the depth of stone column (i.e., *0.25L, 0.5L, 0.75L,* and *L*) and the critical length of encasement in saturated and unsaturated soils is determined by quantifying settlement reduction factors. The critical length of encasement is defined as that length of encasement, where a further increase in encasement length doesn't offer any additional improvement in performance. The variation in settlement reduction factor for different encasements length of stone columns is shown in Fig. 8. The settlement reduction factor reduced with increase in encasement length of stone column in saturated soils, exhibiting the incompetence of surrounding saturated soil to offer requisite lateral confinement. Such a behavior is consistent with the experimental studies of Dash and Bora, 2013 [17], where the carrying capacity for an end-bearing stone column increased with increasing encasement length. Significant reduction in settlements were observed upon increasing the encasement length up to 0.5 times the length of stone column, for matric suction pertaining to residual and dry conditions. However, the reduction in settlement reduction factors were insignificant for stone columns in boundary effect and transition zones. The concept of critical length of encasement has a limited significance for stone columns in unsaturated soils. However, the critical length of encasement can be assumed to be approximately around 0.5 times the length of stone columns in unsaturated soils.

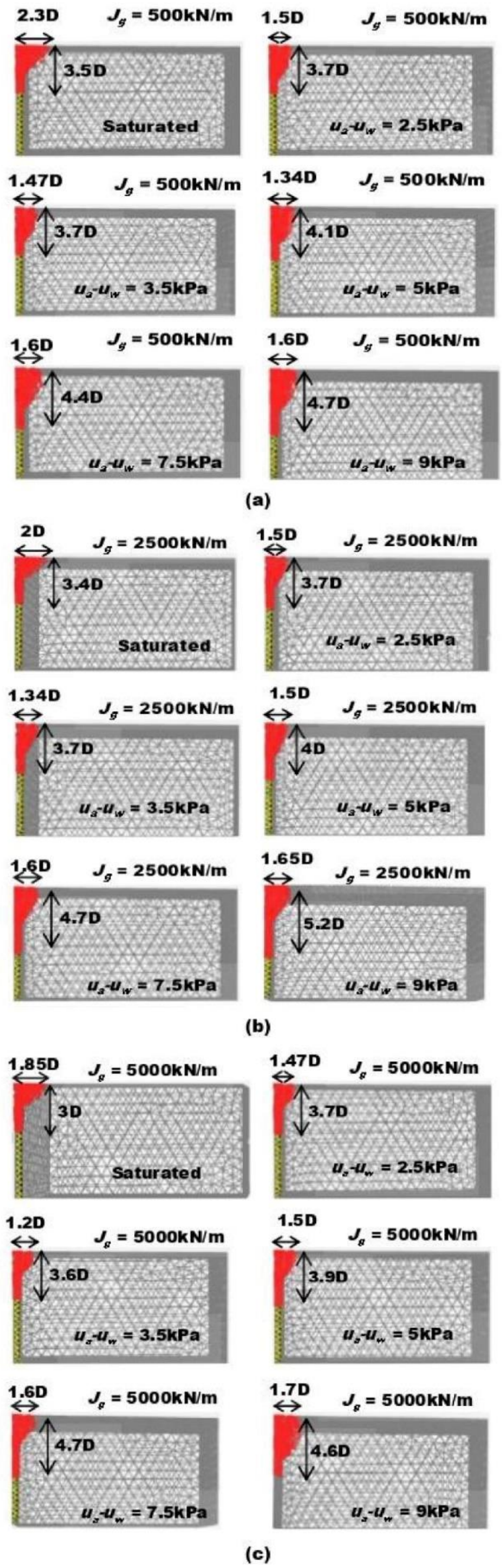

Fig. 7 Plastic deformation in stone columns encased with geosynthetic with different stiffness values a) J_g= 500kN/m b) J_g= 2500kN/m c) J_g= 5000kN/m

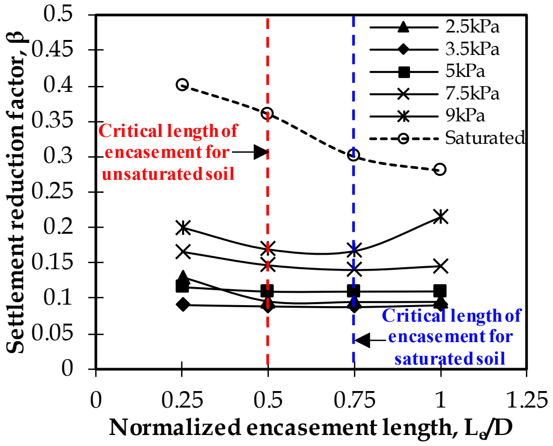

Fig. 8 Variation of settlement reduction factor with encasement length for different matric suction values

4. Conclusions

Comprehensive numerical studies were carried out to evaluate the behavior of geosynthetic encased stone columns in saturated and unsaturated soils extending the conventional Mohr−Coulomb (MC) constitutive model using Plaxis 3-dimensional numerical software. The effect of matric suction on stiffness and length of encasement was considered to define the critical stiffness of encasement and critical length of the encasement. The findings from the numerical studies are succinctly highlighted below:

The performance of stone columns with and without encasement is predominantly dependent upon the degree of saturation of the surrounding soil and its associated matric suction. Matric suction extensively contributed to lateral confining support offered by the surrounding soil which enhanced the carrying capacity of the stone columns. The enhancement in carrying capacity was higher in boundary effect and transition zones due to the influence of water menisci area in contact. An increase in matric suction decreased the water menisci contact area in residual zone and dry conditions causing reduction in the carrying capacity of stone column. Additional confinement through geosynthetic encasement was required for stone columns in saturated and dry soils. Encasing stone columns with geosynthetics in unsaturated soils didn't enhance the performance of the stone column as there was no significant increase in the stiffness of the geosynthetic. Increase in stiffness and length of geosynthetic encasement enhanced the performance of stone column in saturated soil until critical stiffness values of 2500kN/m and 0.75L respectively. The critical stiffness and critical length of encasement have limited importance while designing stone columns in unsaturated soils. However, geosynthetics with limited stiffness can be used for encasing stone columns throughout their depth to avoid excessive displacement and formation of an enlarged base.

The summarized results highlight the importance of considering the mechanics of unsaturated soils into account for the rational design of geosynthetic encased stone columns. Nevertheless, more research studies using full-scale field testing are required to fully comprehend their capabilities and constraints.

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