Performance of stone columns in unsaturated soils: Numerical evaluation

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Abstract. Stone columns are often designed using the conventional framework of saturated soils, ignoring the influence of in-situ unsaturated soil conditions. Such an approach contributes to unrealistic and, in certain scenarios, over-conservative designs. The key objective of this paper is to quantify the influence of matric suction on the confining support offered by the surrounding soil towards stone columns. In addition, how this approach can be implemented through a numerical technique is also presented and discussed. The numerical analysis suggests that the load-carrying capacity of stone columns increased with an increase in the matric suction in the boundary effect, and the transition zone. However, the contribution of matric suction towards load-carrying capacity starts reducing from the residual zone of saturation. Furthermore, the performance of stone columns in unsaturated soils is strongly associated with the area replacement ratio. 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

Geotechnical infrastructures are often constructed within the vadose zone, which is above the groundwater table, where the soils are typically unsaturated. The mechanical behavior of the soil in this unsaturated zone is intricately linked to the distribution of matric suction within the soil volume, resulting in distinct characteristics compared to fully saturated or dry soil conditions [1]. It has been estimated that a third of the earth's surface constitutes of arid or semi-arid regions, where there is more annual evaporation of water compared to infiltration, and hence soils are typically in a state of unsaturated condition [2]. Stone columns (also known as granular columns or granular piles) can be effectively used as a cost-effective ground improvement technique in such regions to reduce excessive settlements and enhance the load-carrying capacities of weak soil deposits [3-4]. The granular material used for the construction of stone columns are characterized by higher stiffness and strength. Such unique characteristics play a crucial role in resisting the applied stresses and contributing to the overall stability of the foundation. In addition to enhancing the mechanical properties (i.e., increase in shear strength and decrease in settlement) of the ground, stone columns were also found effective in reducing liquefaction potential and accelerating radial consolidation [5].

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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 [6-7] and soft compressible clays [8-9]. These studies are based on conventional soil mechanics assuming the groundwater table to be at the natural ground surface. However, changes in the degree of saturation are expected to cause significant changes in the shear strength and shear-induced volume change response of soils that influences the interaction between the soil layer and stone column. Due to this reason, a comprehensive understanding of the influence of saturated and unsaturated conditions is needed for an effective, economical, and stable design of stone columns. 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 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 and its associated matric suction (u_a - u_w) [10]. Due to the influence of matric suction (u_a - u_w), the soil in unsaturated state develops additional inter-particle forces. These forces develop bonds that contribute towards an enhanced shear strength. A typical non-linear variation in shear strength is expected through the soil-water characteristics curve (SWCC) as shown in Fig. 1 [11].

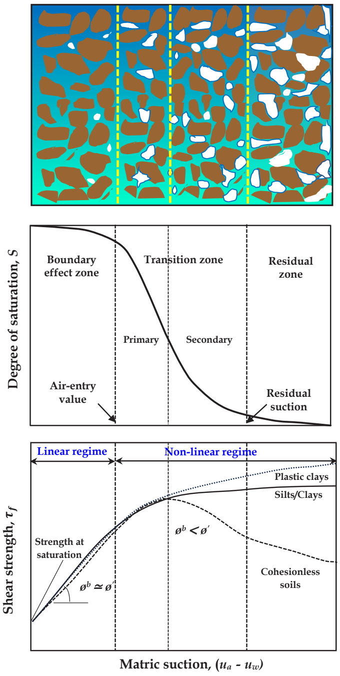

Fig. 1 SWCCs of different types of soils and the variation in shear strength with respect to matric suction in different zones

The rate of change of shear strength with respect to matric suction can be related to the change in the frictional angle $\o^b$. The angle $\o^b$ is equal to the friction angle $\o'$ when the matric suction is less than the air entry value (i.e., boundary effect zone). Therefore, the shear strength increases with an increase in matric suction within the boundary effect zone. The angle $\o^b$ is less than $\o'$ when matric suction is greater than the air-entry value but less than the residual suction value (i.e., transition zone). The relationship between the matric suction and the shear strength is non-linear within this zone. With further increase in matric suction beyond the residual suction (i.e., residual zone), the shear strength may increase or decrease or even remains constant based on the soil type [11]. These transformations in shear strength with changes in the degree of saturation influence the performance of stone columns and various design parameters such as diameter, length, pattern, and spacing between the stone columns. Conventional design approach based on principles of saturated soils could lead to an erroneous design with greater area replacement ratios, resulting in a conservative approach that excessively consumes construction materials. Such an approach may also lead to an excessive number of stone columns in the design. These design errors can be effectively overcome by extending the mechanics of unsaturated soils resulting in a more economical design. The objective of this research is to evaluate the effects of variation in shear strength associated with the changes in matric suction on the performance of stone columns using a systematic numerical study. Both saturated and unsaturated conditions were examined, including matric suctions corresponding to the three SWCC saturation zones. The stone column critical diameter based on the simulated area replacement ratios is determined as well as the influence of the area replacement ratio on the performance of stone columns is highlighted. The results from these investigations highlight the need for practicing engineers to apply the mechanics of unsaturated soils in designing stone columns for an efficient and cost-effective foundation, minimizing settlements and lateral bulging.

2 Numerical Model

2.1 Modelling Considerations

Numerical analyses were carried out to evaluate the influence of matric suction variation and the associated shear strength changes in the surrounding soil on the performance of the stone column. The commercial software SIGMA/W was used, extending the elastic-perfectly plastic Mohr−Coulomb (MC) constitutive model. A uniform soil profile was assumed to extend up to 5 m depth under the natural ground level that extends 5 m horizontally as shown in Fig. 2(a). The model was restrained in the horizontal direction at the vertical ends and restrained in both directions at the bottom [12]. Effects of element size and boundary conditions were eliminated by considering fine mesh discretization. Only a half portion of the soil element is modelled as shown in Fig. 2(b), exploiting symmetry conditions. Analysis was carried out using a staged construction process and the pressure-settlement responses were generated using an incremental 100 kPa load. Uniform loading was applied on a surface simulating a 2m footing. The aggregates used for modelling stone column is a frictional material and was also modelled considering the Mohr-Coulomb yield criterion. A negligible cohesion value of 0.1 kPa was used to alleviate numerical errors. A comprehensive discussion on material modelling is presented in the subsequent sections.

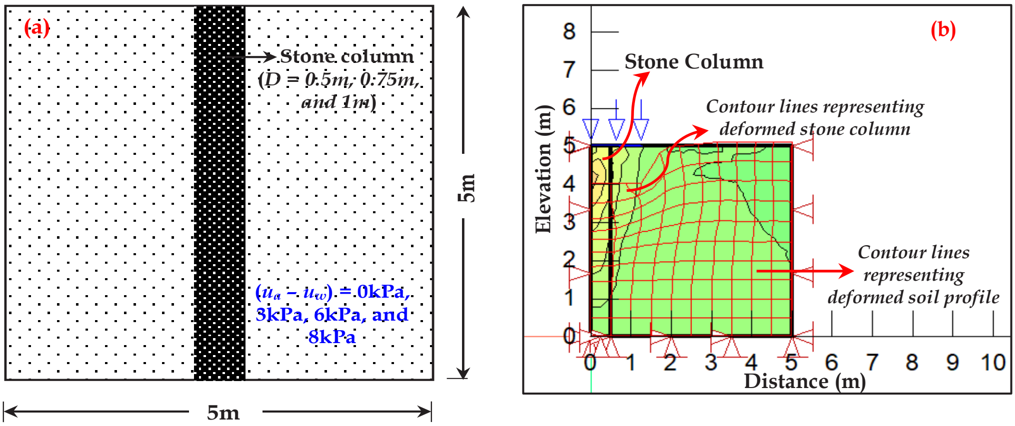

Fig. 2 (a) Schematic view of the model ground and stone column (b) Finite Element model

2.2 Material Properties

The Unimin 7030 sand was used to model the ground [13]. The soil is a poorly graded sand per the Unified Soil Classification System (USCS). The grain size distribution and SWCC of Unimin sand is shown in Fig. 3 and Fig. 4. The coarse aggregates with size ranging between 2 to 10mm was used for construction of stone column. The geotechnical properties of Unimin sand and aggregates used for construction of stone columns are summarized in Table 1. The non-linear variation in shear strength of unsaturated soils due to the influence of matric suction (u_a - u_w) was modelled using the SWCC and saturated shear strength parameters as given below [11],

$$\tau_{unsat} = c' + (\sigma_n - u_a)tan\o' + (u_a - u_w)\left[\frac{(S - S_r)}{(100 - S_r)}tan\o'\right] \tag{1}$$

where, τ_{unsat} is shear strength of unsaturated soil; $(\sigma_n - u_a)$ = net normal stress; S_r is residual degree of saturation; and c' and $\o'$ are effective shear strength parameters. Neglecting the influence of matric suction on the angle of internal friction, $\o'$ [11] the apparent cohesion c_a, can be evaluated using the equation below [14]

$$c_a = c' + (u_a - u_w)\left[\frac{(S - S_r)}{(100 - S_r)}tan\o'\right] \tag{2}$$

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].

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

where, 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 [15]. Eq. (2) and Eq. (3) were convenient to model the shear strength and modulus of elasticity of the unsaturated soil considering the influence of (u_a - u_w) [16].

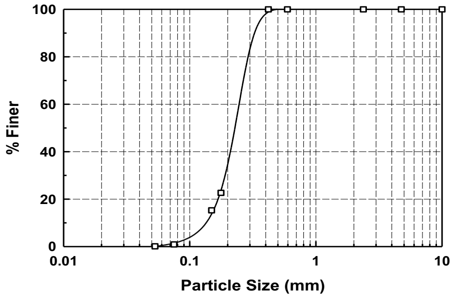

Fig. 3 Grain size distribution curve of the Unimin 7030 sand

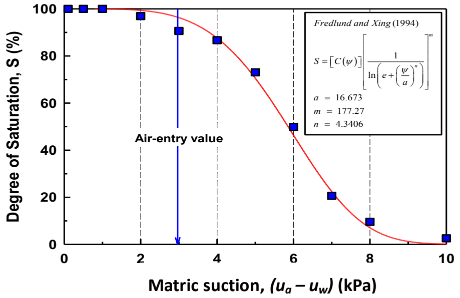

Fig 4. SWCC of the Unimin 7030 sand

2.3 Parametric Studies

The parametric variations include the matric suction of the soil and the diameter of the stone column. The model ground with GWT below the stone column is developed. The soil lies within the boundary effect zone where the degree of saturation ranges between 100% - 96% with matric suction ranging between 0 – 3kPa. Further, the soil lies in the transition zone where the degree of saturation is between 95% - 12% with matric suction ranging between 3.1 – 7.8kPa. The residual zone of saturation represents the degree of saturation below 12% with matric suction between 7.9 - 10kPa. Four different matric suction (u_a - u_w) values of the soil i.e., 0, 3kPa, 6kPa, and 8kPa were considered for the analysis, such that they represent information from different zones of saturation of SWCC for the rigorous interpretation of the results. A matric suction value of zero represents the saturated conditions of the soil. Whereas matric suction of 3kPa, 6kPa, and 8kPa fall in boundary effect, transition, and residual zones of saturation, respectively. End-bearing stone columns of diameters 0.5m, 0.75m, and 1m were modelled. The quantitative improvement in the stone column performance due to the contribution of matric suction is represented through settlement reduction factors δ, which is defined as a ratio of settlement of reinforced ground (s_z) to that of unreinforced ground (s_{zo}).

$$\delta = \frac{s_z}{s_{zo}} \tag{4}$$

In addition, detailed analyses were undertaken to determine the critical diameter of the stone column by varying the area replacement ratio A_r, which is defined as the ratio of area of stone column (A_{sc}) to that of area of unit cell (A_u) under consideration to determine their critical values.

$$A_r = \frac{A_{sc}}{A_u} \tag{5}$$

Table 1 Geotechnical properties of Unimin sand and coarse aggregates

Parameters	**Unimin sand 7030**	**Coarse aggregates**
Specific gravity, *G*	2.65	2.7
Grain size distribution (%)		
D_{10} *(mm)*	0.12	-
D_{30} *(mm)*	0.16	-
D_{50} *(mm)*	0.22	-
D_{60} *(mm)*	0.26	-
C_u	2.17	2.16
C_c	0.82	1.15
Unified soil classification symbol	SP	GP
Maximum dry unit weight, $\gamma_{d(max)}$, kN/m^3	16.80	16.6
Total unit weight, γ_{total}, kN/m^3	18.60	-
Saturated unit weight, γ_{sat}, kN/m^3	20.4	-
Angle of internal friction	35.3°	46°
Effective cohesion, *c'*	0	0
Modulus of elasticity (kPa)	10000	40000
Poisson's ratio	0.3	0.3

3 Results and Discussions

3.1 Contribution of matric suction

The variation in settlement reduction factors, δ, with varying matric suction in the surrounding soil is shown in Fig. 5. It is clear from Fig. 5 that the settlement reduction factor of soil reinforced with the stone column is predominantly dependent on the shear strength of the surrounding soil, which is sensitive to the degree of saturation and its associated matric suction. Higher settlement reduction factors were observed when the surrounding soil was in a saturated condition. In other words, a limited amount of improvement was observed when stone columns were installed in saturated soils, which is due to insufficient lateral confining support offered by the surrounding soil. The rate of change in settlement reduction factor with respect to different suction zones (i.e., boundary effect, transition, and residual zones) is not constant. The settlement reduction factor reduced by 51% when the soil transformed from a saturated state to an unsaturated state with matric suction pertaining to boundary effect zone. The reduction in settlement reduction factor continued until the transition zone, which is due to an enhanced soil-water-air interphase mechanism leading to greater lateral confinement support from the surrounding unsaturated soil. With further increase in matric suction from the transition zone to the residual zone of saturation the settlement reduction factor increased, illustrating a decrease in the water menisci area in contact with soil, causing a reduction in lateral confining support. As expected, lower settlements are obtained for larger diameter stone columns. Fig. 5 shows that there is a critical column diameter (D_{cr}), beyond which the settlement reduction is limited.

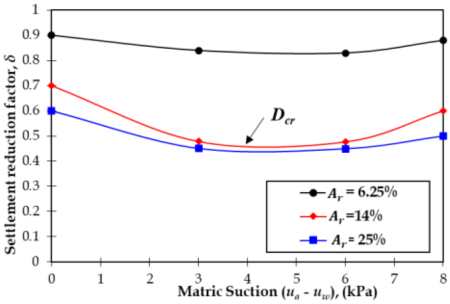

Fig. 5 Variation of the settlement reduction factor δ, with matric suction in the surrounding soil for different area replacement ratios

3.2 Area replacement ratio

The area replacement ratio is generally considered as a key parameter in designing stone columns [9]. Stone columns of three different diameters, i.e., 0.5 m, 0.75 m, and 1 m with the corresponding area replacement ratio of 6.25%, 14% and 25% were analysed. The settlement reduction factor reduced with an increase in the diameter of stone columns in both saturated and unsaturated conditions illustrating an improvement in the reinforced ground. The improvement in settlement reduction was 47% when diameter increased from 0.5 m to 0.75 m. Whereas, with an increase in diameter from 0.75 m to 1 m an additional improvement of only 4% was observed. This implies increase in diameter of stone column beyond the optimum value could lead to a conservative design with limited reduction in settlements. Furthermore, the critical diameter of stone column (D_{cr}) in unsaturated soils is smaller when compared to that of the saturated soils.

A common mode of bulging failure was observed in all the cases. Fig. 6 represents the lateral bulging in stone columns of different area replacement ratios in soil with varying matric suctions. The reduction characteristics of lateral bulging across different zones of the

SWCC were comparable to the settlement reduction factors. The lateral displacements were reduced to the maximum extent when the matric suction in the surrounding soil was in boundary effect and transition zones. The lateral bulging reduced by 76% with the transformation of the surrounding soil from a saturated state to an unsaturated state. The lateral bulging extended up to a depth equal to the diameter of the stone column when the surrounding soil was in an unsaturated state, whereas the lateral bulging extended until a depth corresponding to 2.5 times the diameter of the stone column for saturated soils. The increase in shear strength of the soil with increase in matric suction has contributed a greater lateral confining support to the stone column, which resisted the lateral deformations. With further increase in matric suction from transition zone to residual zone of saturation the surrounding soil offered limited resistance to lateral bulging which is due to the reduction in the shear strength of the surrounding unsaturated soil.

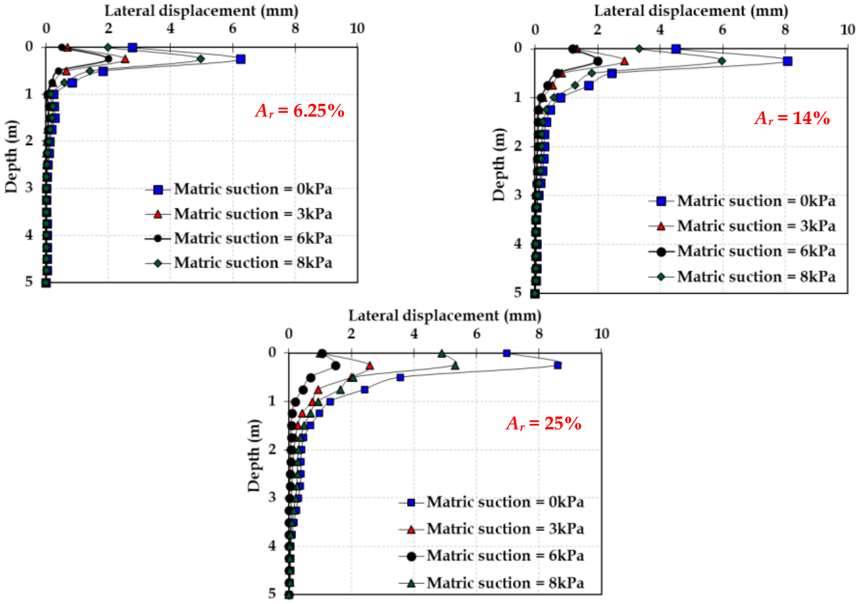

Fig. 6 Lateral displacement in stone columns of different diameters

3.3 Influence of matric suction on displacements

The displacement contours of the soil and stone columns in both saturated and unsaturated conditions are summarized in Fig. 7 – 9. A reduction in displacements was observed from saturated to unsaturated conditions. Displacements were higher near the ground surface, which reduced with the depth representing a reduction in stresses along the depth of the soil. As the matric suction in the surrounding soil increases, the lateral bulging of the stone column reduces, thereby reducing the stresses propagating into the column. However, the contribution of the matric suction in the surrounding soil to the stability of the stone column reduces with progressive saturation. Displacements were minimum in boundary effect zone and transition zones when compared to the residual zone of saturation. Moreover, the displacement magnitude was observed to be inversely proportional to the diameter of stone column up to critical diameter of stone column and the decrease was limited when diameter surpassed critical diameter value.

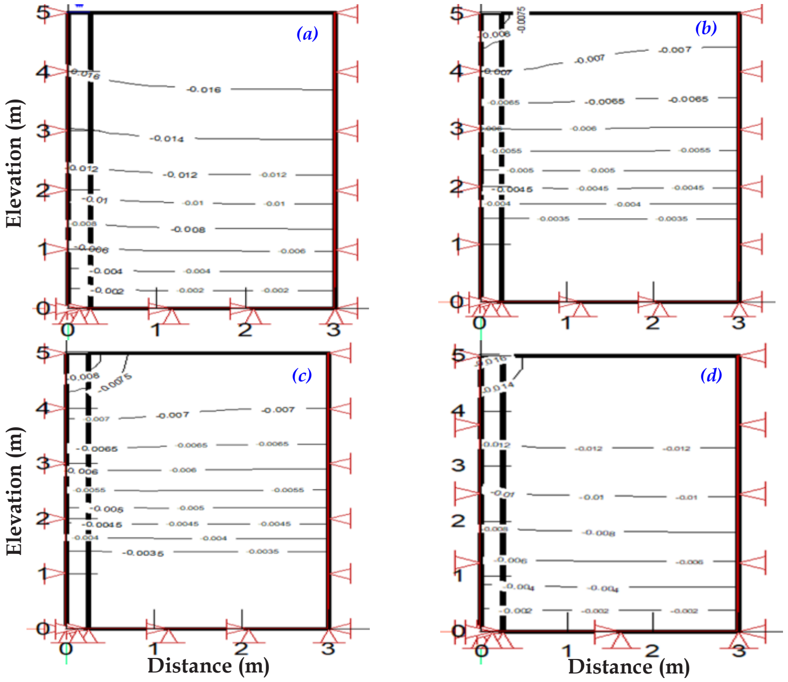

Fig. 7 Displacement contours of stone column with 0.5m diameter a) $(u_a - u_w) = 0$; b) $(u_a - u_w) = 3$kPa; c) $(u_a - u_w) = 6$kPa; d) $(u_a - u_w) = 8$kPa

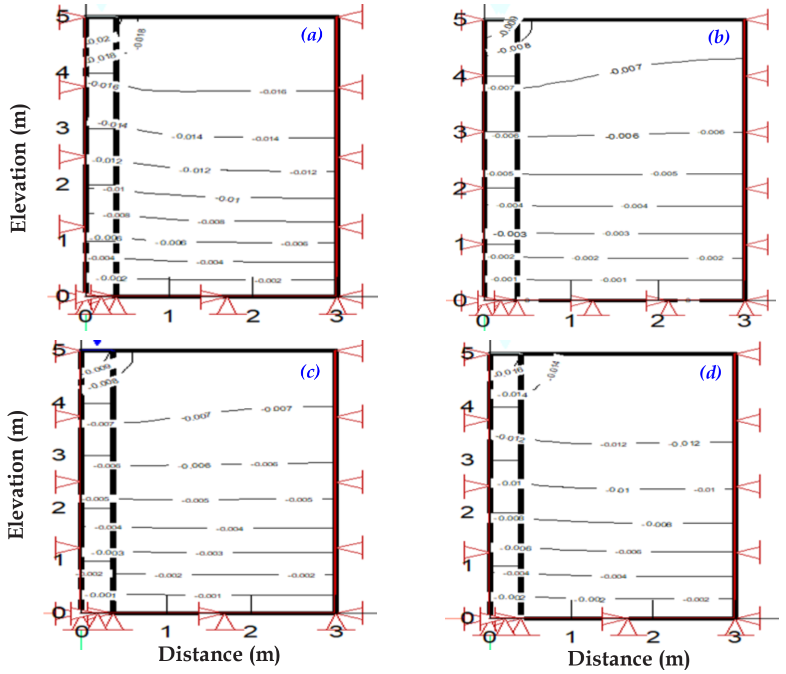

Fig. 8 Displacement contours of stone column with 0.75m diameter a) $(u_a - u_w) = 0$ b) $(u_a - u_w) = 3$kPa c) $(u_a - u_w) = 6$kPa d) $(u_a - u_w) = 8$kPa

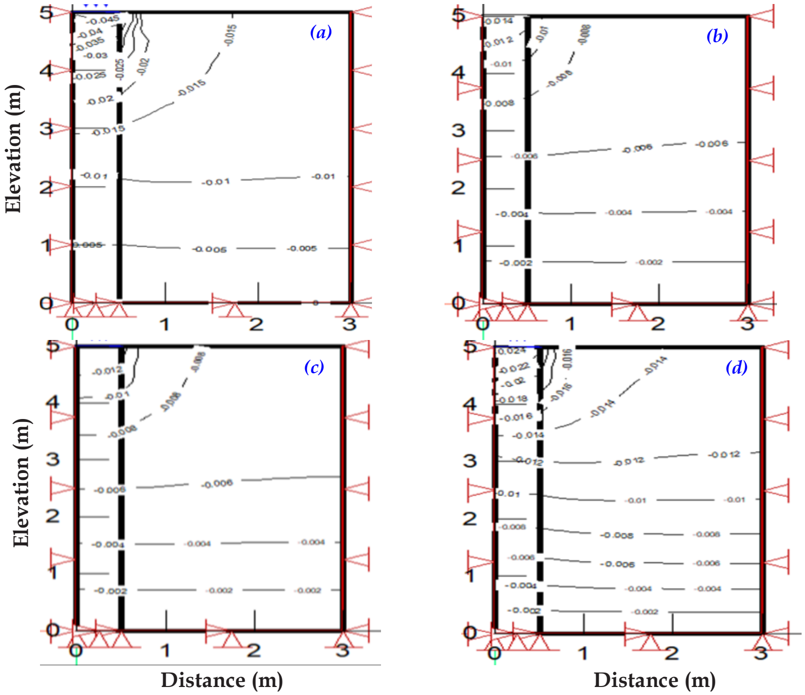

Fig. 9 Displacement contours of stone column with 1m diameter a) $(u_a - u_w) = 0$ b) $(u_a - u_w) = 3$kPa c) $(u_a - u_w) = 6$kPa d) $(u_a - u_w) = 8$kPa

4 Conclusions

The contribution of matric suction on the performance of the stone columns with varying area replacement ratios were studied through finite element analysis and comparisons were drawn for both saturated and unsaturated conditions. The mechanical behavior of the soil reinforced with the stone column is represented in terms of settlement reduction factor δ, displacement contours, and bulging deformation profiles. The following conclusions can be drawn from the findings of the present study.

The enhancement in the mechanical behavior of reinforced ground is strongly associated with the changes in shear strength caused by modifications in matric suction. Reduction in settlement factors, displacement contours, and bulging deformations were illustrated when soil translated from saturated condition to unsaturated condition, representing an improvement in the mechanical behavior of reinforced ground. The maximum enhancement in performance of stone column was witnessed when matric suction was within boundary effect and transition zones due to the improved soil-water-air interphase mechanism. Limited improvement was observed with further increase in matric suction, corresponding to the residual zone of saturation. Additionally, the improvement due to inclusion of stone column increased with increase in area replacement ratio until the diameter of the stone column reached a critical diameter value. The summarized results highlight the importance of considering the mechanics of unsaturated soils for the rational design of stone columns. Nevertheless, more research studies using full-scale field testing are required to fully comprehend their capabilities and constraints.

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