Geosynthetic Encased Stone Columns under Unsaturated Soft Soil Conditions

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Abstract: The design of geosynthetic encased stone columns often relies on the conventional framework of saturated soil mechanics, neglecting the influence of in-situ unsaturated soil conditions. Such an approach results in unrealistic or overly conservative designs. For this purpose, this study evaluates the performance of stone columns with and without geosynthetic encasement under unsaturated soil conditions, focusing on the role of matric suction in the surrounding soil. A series of laboratory plate load tests were conducted to examine the mechanical behavior and load-carrying capacity of geosynthetic encased stone columns in saturated and unsaturated soils. The results indicate that matric suction in the surrounding soil significantly enhances the load-carrying capacity of stone columns. Geosynthetic encasement further improves performance by reducing radial deformation and promoting uniform stress distribution and effective load transfer. These improvements result in greater load-carrying capacity and structural stability of stone columns, particularly under varying unsaturated soil conditions. In summary, this study provides valuable insights into the interaction between unsaturated soils and geosynthetic encasement, offering a rational framework for designing stone columns in geotechnical applications where unsaturated soil behavior is critical.

1. Introduction

The performance of ground improvement techniques in unsaturated soil conditions has gained significant attention due to the unique mechanical behavior of such soils. Complex interactions between soil particles, water, and air, influenced by varying matric suction, play a crucial role in determining load-bearing capacity and deformation characteristics [1,2]. Among various ground improvement techniques, geosynthetic encased stone columns have been widely used to enhance carrying capacity, reduce settlement, and improve stability of marginal soils in recent decades [3]. However, conventional design methodologies for stone columns predominantly rely on the framework of saturated soil mechanics, neglecting the influence of capillary stress or matric suction, $(u_a - u_w)$ in the surrounding unsaturated soils. The matric suction has a considerable impact on hydro-mechanical behavior and related soil-geosynthetic-column interaction characteristics. The settlements in the soil reinforced with geosynthetic encased stone columns are sensitive to the changes in the groundwater table and associated capillary stresses. Therefore, the influence of matric suction on the mechanical behavior of geosynthetic encased stone columns is to be considered for proposing rational and reasonable design procedures for the geosynthetic encased stone columns [4-6]. Thus, this study aims to bridge this gap by exploring the performance of geosynthetic encased stone columns under unsaturated conditions.

A comprehensive understanding of the soil-geosynthetic-column interface mechanism in both saturated and unsaturated soils is essential for accurately interpreting the mechanical behavior of geosynthetic encased stone columns. Existing design codes and guidelines, predominantly based on saturated soil mechanics, are widely employed in the design of these columns. However, in many practical scenarios, geosynthetic encased stone columns extend either partially or entirely into unsaturated soils, as groundwater tables in several regions are located at considerable depths. This condition is frequently encountered in semi-arid and arid regions worldwide. In the unsaturated zone, capillary stresses or matric suction contribute to an increase in shear strength and stiffness, which is not accounted for in conventional saturated soil mechanics. Consequently, applying these principles to analyze or design geosynthetic encased stone columns in unsaturated soils may lead to erroneous estimates of their load-carrying capacity. Matric suction significantly influences stress distribution and load transfer mechanisms, altering the performance of stone columns with or without geosynthetic encasement [7,8]. To address these limitations, this study systematically evaluates the behavior of stone columns under unsaturated soil conditions, with and without geosynthetic encasement. Laboratory plate load tests were conducted to quantify their load-carrying capacity and deformation characteristics in both saturated and unsaturated conditions. This research provides key insights into the combined effects of matric suction and geosynthetic encasement on stone column performance, supporting the development of a more comprehensive design framework. These findings are particularly relevant for optimizing geosynthetic-encased stone columns in unsaturated soil conditions, improving their efficiency and reliability across varying moisture conditions.

2. Experimental Program and Material Properties

2.1 Testing Program

Stone columns are widely used in soft clay soils to improve load-carrying capacity, reduce compressibility, and enhance shear strength, mitigating settlement and stability issues [9]. However, the mechanical behavior of soft clays is highly influenced by compaction state, governed by factors like compaction effort and initial water content, which affect pore structure and matric suction [10]. To investigate these effects, a series of model plate load tests were conducted on geosynthetic-encased stone columns under saturated and unsaturated conditions. Four water content conditions were considered: saturated, dry of optimum (11% water content, γ_d = 18.14 kN/m^3), optimum (12.5% water content, γ_d = 19 kN/m^3), and wet of optimum (15% water content, γ_d = 18.27 kN/m^3). These tests assessed how variations in matric suction influence soil stiffness, load transfer, and settlement behavior. Findings from this study provide critical insights into optimizing stone column design in unsaturated soft clays, particularly in environments where soil moisture conditions fluctuate.

2.2 Test setup

Model plate load tests were conducted to evaluate the behavior of stone columns with and without geosynthetic encasement under saturated and unsaturated conditions. The testing apparatus included a 10-ton hydraulic jack mounted on a load frame for controlled loading. The model ground and stone columns were constructed in a 350 mm inner diameter, 500 mm high mild steel cylindrical tank, providing a confined testing environment. The load application was monitored using a pre-calibrated proving ring, while displacements were recorded with a high-precision dial gauge. Stone columns with a 75 mm diameter were modeled, maintaining a 25% area replacement ratio and an L/D ratio of 6, following standard design parameters [11]. This setup enabled a systematic evaluation of stone column performance across different soil saturation states, ensuring repeatability and accuracy in capturing soil-column interactions under controlled laboratory conditions. A schematic of the test arrangement is shown in Fig. 1.

2.3 Material properties

The soft clay used to construct the model ground was classified as the clay with low plasticity (CL) according to the Unified Soil Classification System (USCS). The maximum dry unit weight of the clay, determined following BIS 1980, was 19 kN/m^3 at an optimum water content of 12.6%. These properties provided the foundational parameters for preparing the clay bed for experimental study. The stone columns were formed using locally sourced crushed-stone aggregates with a particle size range of 2 mm to 10 mm. Angular aggregates were chosen to enhance interlocking and strength characteristics. Large direct shear tests, conducted with a shear box measuring 310 mm × 310 mm × 310 mm, determined the angle of internal friction (ϕ') of the stone aggregates to be 40°. The grain-size distribution curves for both the soft clay and crushed stone aggregates are shown in Fig. 2, illustrating their suitability for the intended application. Furthermore, the soil-water characteristic curves (SWCC) of the soft clay at varying initial water contents and unit weights were determined using the contact filter paper method (ASTM D5298-10, 2010). The SWCC results, fitted with the van Genuchten (1980) model, are presented in Fig. 3. These curves provide critical insights into the matric suction behavior of the clay under different conditions, which plays a vital role in influencing the performance of stone columns in unsaturated soils. Moreover, non-woven geotextiles were used for encasing the stone columns due to their advantageous strength and drainage properties. The geotextile tubes were prepared with a 20 mm longitudinal overlap, bonded with epoxy adhesive, as described by Abid et al. [11]. Wide-width tensile tests (ASTM D4595, 2001) revealed that the tensile strength of the geotextile with a longitudinal joint was approximately 50% of the original material. The geotechnical properties of the materials used in the study are summarized in Table 1.

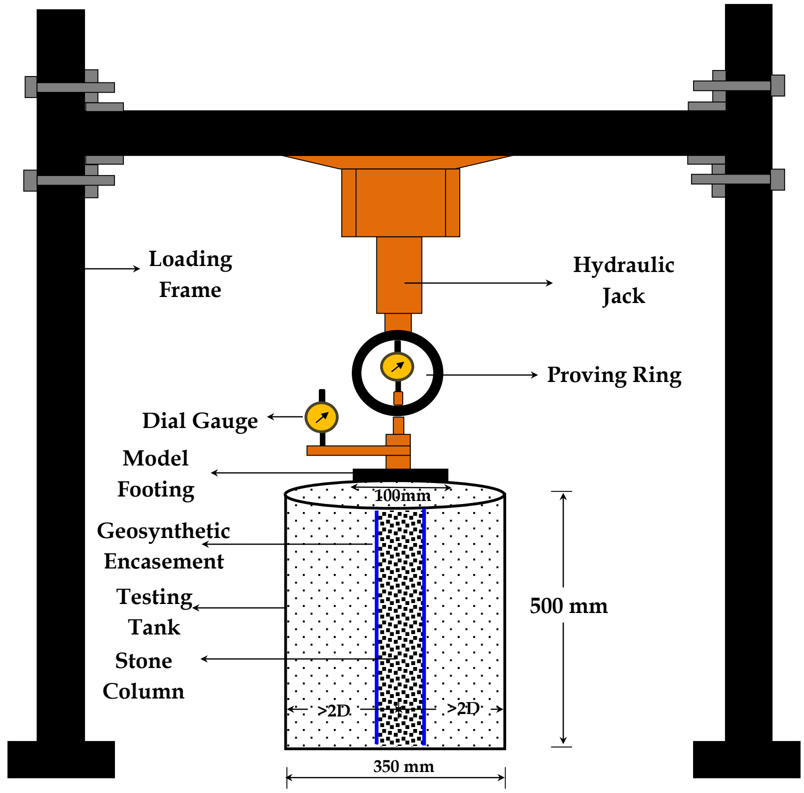

Figure 1: Schematic view of experimental setup.

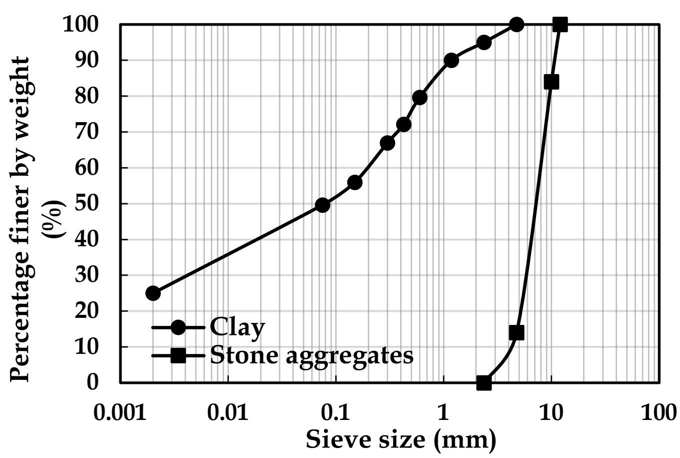

Fig. 2 Grain size distribution curve of both soil and crushed stone aggregates

2.4 Model testing and construction methodology

A methodical approach was used to prepare the model ground and construct the stone columns within the testing tank, ensuring accurate simulation of in-situ conditions. The soft clay was first thoroughly mixed with the required amount of water to achieve the desired moisture content. The prepared soil was then placed into the test tank in 100 mm thick layers. Each layer was compacted uniformly using a rectangular rammer weighing 10 kg with a drop height of 300 mm to achieve the target unit weight. The achieved unit weight and moisture content of the soil were verified by extracting samples using cylindrical molds (50 mm diameter, 100 mm height) from different locations in the test tank. These tests confirmed uniformity in unit weight and moisture content with ±2% coefficient of variation.

The stone columns were constructed using the replacement method to avoid any significant disturbance to the surrounding soil. A casing pipe made of steel, with an outer diameter of 75 mm and a length sufficient to match the required depth, was used to construct the stone columns. The casing pipe was lubricated on both inner and outer surfaces with a layer of grease to facilitate easy penetration and extraction. It was driven vertically into the soil to the desired depth without causing notable disturbance to the surrounding soil. The soil within the casing pipe was carefully removed using helical augers slightly smaller than the diameter of the pipe. For geosynthetic-encased stone columns, the geotextile was wrapped around a cylindrical wooden block of slightly smaller diameter than the casing pipe. This assembly was inserted into the pipe and then carefully withdrawn, leaving the geotextile in place to act as an encasement. The stone aggregates required for the column were weighed and added in five equal layers to the casing pipe. Each layer was compacted using a steel tamping rod (10 mm in diameter) under 25 blows at a drop height of 200 mm. During the placement of each subsequent layer, the casing pipe was lifted slowly, maintaining an overlap of 25 mm with the previously compacted layer to minimize disturbance to the surrounding soil [12]. This process was repeated until the stone column reached the required height. After the column was prepared, axial load was applied to the test plate at a constant displacement rate of 1 mm/min until a total displacement of 50 mm was achieved. The corresponding load–displacement responses were recorded to evaluate the performance of the stone columns.

Table 1: Geotechnical properties of materials used in the study.

Soil		**Crushed stone aggregates**		**Geotextile**	
Parameters	**Quantity**	**Parameters**	**Quantity**	**Parameters**	**Quantity**
Liquid limit	48.78%	Maximum dry unit weight	16 kN/m^3	Ultimate tensile strength	
Plastic limit	21.51%	Specific gravity	2.80	Machine direction	12 kN/m
Plasticity index (%)	27.27	Void ratio	1.17	Cross-machine direction	10.5 kN/m
Unified soil classification symbol	CL	D_{10}, D_{30}, D_{50}, and D_{60}	4.5, 6, 7 and 8 mm	Thickness	2.0 mm
Dry unit weight	18.57 kN/m^3	C_u and C_c	1.77 and 1	Mass per unit area	250 g/m^2
Bulk unit weight	21 kN/m^3	Gradation symbol as per USCS	GP	Ultimate elongation	>50%
Specific gravity	2.68	Angle of internal friction	40°	Punching strength from CBR plunger test	1700 N
Void ratio	0.44				

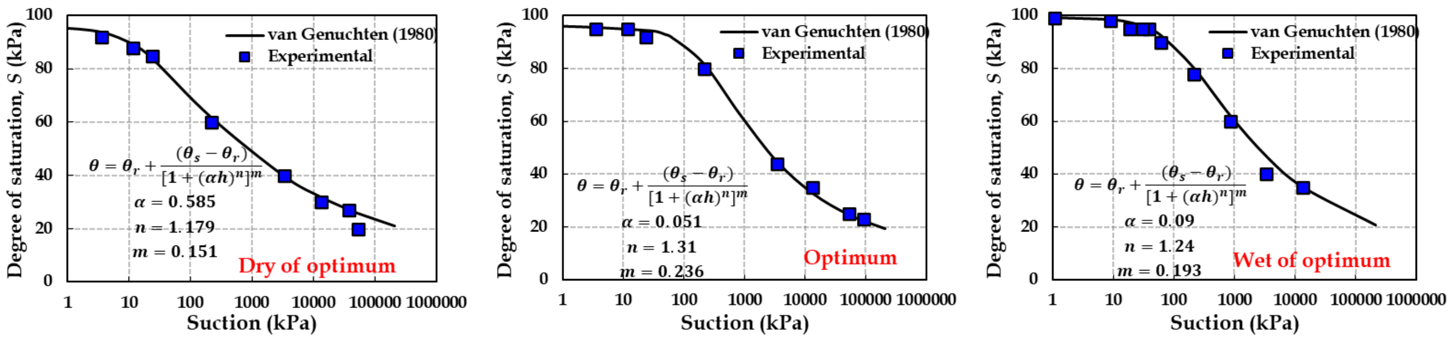

Figure 3: Soil-water characteristics curves (SWCC) at different unit weights.

3. Results and Discussions

3.1 Shear strength response to matric suction and compaction conditions

Unconfined compression tests were performed on soil specimens in accordance with IS 1991 to investigate the influence of varying initial degrees of saturation and unit weights on the matric suction and shear strength characteristics of the soil. Cylindrical specimens with a diameter of 38 mm and height of 76 mm were prepared at different unit weights by adjusting the initial water content. The relationship between undrained shear strength and matric suction for the soil samples is illustrated in Fig. 4. The shear strength of the soil is significantly influenced by several parameters, including matric suction, degree of saturation, and unit weight, which collectively govern the mechanical behavior of the soil. From the experimental results, it was observed that shear strength increases with increasing unit weight, especially when comparing dry of optimum conditions (γ_d = 18.14 kN/m^3) to optimum conditions (γ_d = 19 kN/m^3). This enhancement in shear strength can be attributed to the increase in matric suction that occurs with higher unit weights. In the case of specimens compacted at dry of optimum moisture content, the soil matrix contained relatively lower amounts of water in the pores at a given matric suction, compared to those compacted at optimum and wet of optimum moisture contents. Moreover, the soil's rapid desaturation due to inter-aggregate interactions under dry of optimum conditions contributes to the observed behavior. Increasing the dry unit weight leads to a reduction in the void ratio, thus reducing the available pore space within the soil matrix. As a result, capillary forces increase, which in turn elevates the matric suction, due to the smaller pore sizes that develop with compaction. Conversely, when the initial degree of saturation increases from optimum (w = 12.5%) to wet of optimum (w = 15%) conditions, the increased water content within the soil pores results in higher matric suction. This phenomenon arises due to the increase in the contact area between aggregates, which becomes wet under higher moisture conditions. The enhanced water retention within the soil particles leads to stronger bonding and cohesion, thereby improving the shear strength. The increase in matric suction, driven by both the higher water content and the reduced pore size, compensates for the negative impact of reduced dry unit weight on shear strength. Consequently, the shear strength increases overall.

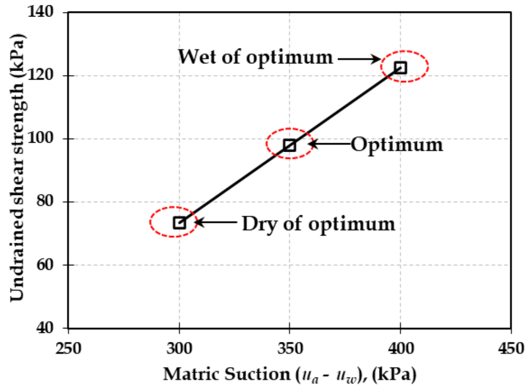

Figure 4: Influence of matric suction on the undrained shear strength of the soil.

3.2 Pressure-settlement behavior and load-carrying capacity

The pressure-settlement behavior of stone columns, both with and without geosynthetic encasement, was analyzed under varying saturation conditions, as shown in Fig. 5. In saturated conditions, the unreinforced soil exhibited a near-vertical pressure-settlement curve, with failure occurring at a limited footing settlement of approximately 4%. This response indicates a rapid and significant loss of load-carrying capacity, primarily due to the inability of soil to sustain additional load, resulting in excessive settlement and failure through punching. The limited capacity of the saturated soil to redistribute stress leads to sudden failure. In contrast, the pressure-settlement behavior of both unreinforced and soil reinforced with stone columns under unsaturated conditions displayed notable differences. When the soil was compacted to different degrees of saturation (dry of optimum, optimum, and wet of optimum), failure did not occur until higher settlements were reached. The presence of air within the soil matrix reduces pore water volume, thereby increasing the effective stress in the soil. This enhances stability due to a combination of increased interparticle contact, capillary forces, and improved soil structure in the unsaturated state. Additionally, the air-filled voids facilitated better particle-to-particle contact, resulting in a denser and more stable soil structure.

In saturated conditions, the stone columns exhibited a stiffer pressure-settlement curve compared to the unreinforced soil. This behavior is attributed to the effective transfer of applied stress to the stone columns, which function as primary load-bearing elements rather than the surrounding soft soil. Under unsaturated conditions, a non-linear suction hardening effect was evident, where increased matric suction resulted in enhanced confining support for the stone columns. This effect became more pronounced with higher degrees of saturation and matric suction. The ultimate load-carrying capacity of both the unreinforced and reinforced systems was determined using the double tangent method proposed by Vesic [13]. The results indicated that load-carrying capacity increased with higher matric suction, which correlated with greater initial degrees of saturation. This highlights the role of matric suction in the ability of soil to confine and support the stone columns. Initially, the load-carrying capacity of the reinforced soil was enhanced due to the stiffening effect of the stone columns, driven by the interlocking of compacted aggregates. However, as the stone columns deformed under load, the interlocking between the aggregates weakened due to dilation, leading to a reduction in stiffness and strength. Despite this, once a critical deformation threshold was reached, shear resistance in the surrounding soil mobilized, thereby increasing the overall load-carrying capacity. The increase in matric suction in the surrounding unsaturated soil further amplified this improvement. In soils with lower matric suction (dry of optimum conditions), confining support was minimal. However, as matric suction increased (from optimum to wet of optimum conditions), the confining support improved, contributing to greater stability and load-carrying capacity in the reinforced system. Matric suction, therefore, serves as a key stress-state variable, enhancing the confining support from the surrounding soil and improving the overall stability of the system.

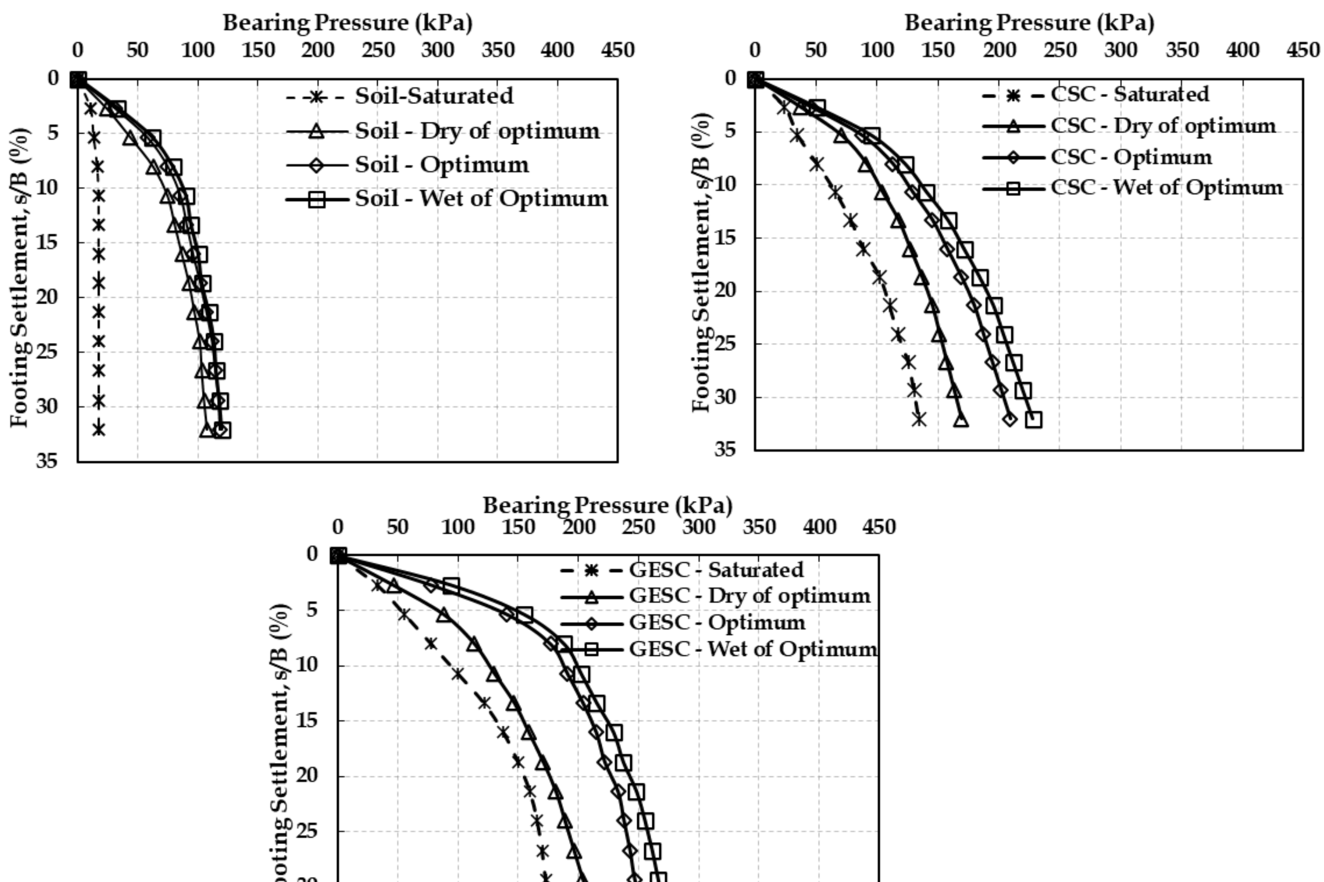

Figure 5: Pressure -settlement responses a) unreinforced soil b) soil reinforced with conventional stone column c) soil reinforced with geosynthetic encased stone column in saturated and unsaturated conditions.

3.3 Effect of geosynthetic encasement in unsaturated soils

Fig. 6 illustrates the variation in ultimate load-carrying capacity of both unreinforced and reinforced soil under saturated and unsaturated conditions, emphasizing the combined effects of matric suction and geosynthetic encasement on the performance of stone column.

The results indicate that while geosynthetic encasement significantly enhances the carrying capacity of stone columns in saturated soils, its impact in unsaturated conditions is further amplified by the presence of matric suction in the surrounding soil. In saturated conditions, the geosynthetic encasement primarily contributes to additional confinement, leading to an increase in load-carrying capacity by 4-fold compared to that of unreinforced soil. This enhancement is attributed to the ability of geosynthetic encasement to provide lateral support, reducing column bulging and improving stiffness, which in turn enhances load transfer [14]. However, in unsaturated soils, an increase in carrying capacity of 6-fold is observed due to the integrated effect of geosynthetic encasement and matric suction. The surrounding unsaturated soil inherently offers confinement through capillary forces, increasing the apparent cohesion and thereby improving stress distribution within the soil-column system [15]. As matric suction increases from dry-of-optimum to wet-of-optimum conditions, the confinement effect intensifies, leading to a nonlinear increase in the load-carrying capacity, as evident from the trend in Fig. 6.

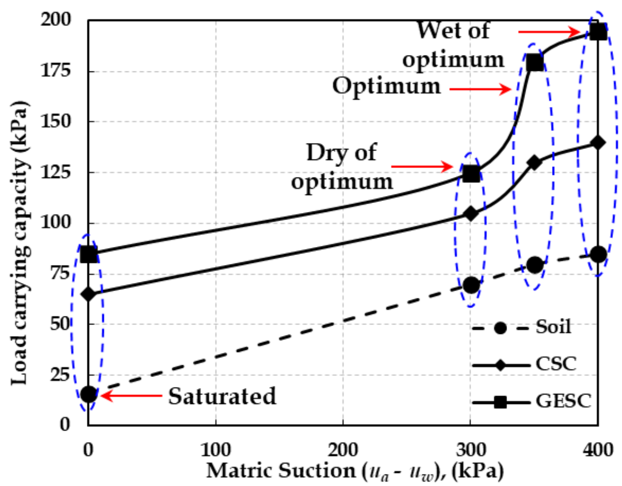

Figure 6: Variation in ultimate load-carrying capacity of unreinforced and reinforced soil in saturated and unsaturated conditions

4. Conclusions

This study systematically examined the influence of initial degree of saturation, unit weight, and matric suction on the shear strength and load-carrying behavior of soil reinforced with stone columns, with and without geosynthetic encasement. The findings reveal that matric suction significantly contributes to improving the effective stress within the soil matrix, thereby enhancing the soil-column interaction and improving the load-carrying capacity of the system.

Experimental results from unconfined compression tests indicate that shear strength is significantly influenced by matric suction, unit weight, and degree of saturation. The pressure-settlement response of stone columns revealed that in saturated conditions, unreinforced soil experienced rapid failure, whereas with inclusion of stone columns an improved stiffness and load distribution was observed. In unsaturated conditions, matric suction induced a nonlinear suction-hardening effect, enhancing confining support and stability. The combined effect of geosynthetic encasement and matric suction in unsaturated conditions resulted in a sixfold increase in load-carrying capacity, with capillary forces and apparent cohesion significantly enhancing structural performance. Overall, the study emphasizes the importance of considering unsaturated soil mechanics for the rational design of stone columns, particularly in environments where soil moisture content varies. The findings provide essential insights into optimizing the design and implementation of geosynthetic encased stone columns in practice. However, to fully validate the findings and assess the practical feasibility of geosynthetic encased stone columns, further research, including large-scale field tests, is recommended to better understand their long-term behavior and limitations.

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