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Experimental and numerical investigation of geosynthetic encased stone columns using construction and demolition waste as an alternate filler material

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ABSTRACT: The construction of structures on weak and compressible soil deposits poses considerable difficulties for geotechnical engineers. Among various ground improvement techniques available, stone columns are extensively used to enhance bearing capacity, reduce settlement, improve slope stability, and mitigate liquefaction potential in seismic regions. However, the insufficient lateral confinement offered by the surrounding soil may reduce the effectiveness of stone columns in exceptionally soft soils. Encasing stone columns with geosynthetics provides an effective means of enhancing the confinement in such conditions. Traditional backfill materials such as crushed stone and gravel are facing depletion, prompting the need for sustainable alternatives. The present study investigates the potential use of construction and demolition waste (CDW) as a possible filler material for geosynthetic-encased stone columns. The study assesses the load-bearing capacity and settlement properties of weak clay bed reinforced with single stone columns of different diameters (50, 75 and 100 mm), utilising construction and demolition waste (CDW) and natural crushed stone aggregates (CSA) as filler materials. The results suggest that stone columns constructed using CDW exhibit comparable load-carrying capacity and settlement reduction to those constructed using CSA, regardless of whether they are encased or not. Furthermore, the performance of stone columns is improved and lateral bulging is reduced when the columns are encased with polypropylene geotextile, as opposed to when they are left uncased. The findings indicate that CDW-filled encased stone columns are a sustainable and effective ground improvement technique for construction on weak soil deposits.

KEYWORDS: Stone Column; Geosynthetic Encasement; Construction and Demolition Waste; Sustainability; Load-carrying capacity

1 INTRODUCTION

Stone columns are a cost-effective ground improvement technique to enhance the bearing capacity, minimize post-construction settlement and reduce liquefaction potential in weak and soft soil (Yoo & Abbas, 2019; Zhou et al., 2021; Fattahi et al., 2024). It will reduce the flow path of pore water and thus accelerate the drainage and consolidation of soil deposits (Castro et al., 2013). The improvement in bearing capacity is achieved through the lateral confinement provided by the surrounding soil, which restricts the radial bulging of the columns under load. However, sufficient lateral confinement may not be available if the stone columns are installed in very soft clayey soils having low undrained shear strength (Mohapatra et al, 2017; Mehrannia et al., 2018). In addition to this, loading columns in soft soil conditions results in loss of filler materials into the surrounding soil and intrusion of clay into the voids of the column, reducing its permeability and drainage efficiency (Dar & Shah, 2021). This issue can be addressed by encasing the stone columns with a geosynthetic material, which provides extra confinement and acts as a barrier between the column and the surrounding soil (Murugesan & Rajagopal, 2010; Dar & Shah, 2021; Abdelhamid, Ali & Abdelaziz, 2023).

Studies on soil reinforced with geosynthetic encased stone column (GESC) have found that the elastic modulus of the geosynthetic material plays an important role in improving the load-bearing capacity, as it will directly influence the hoop tension developed in the encasement, thereby increasing the additional confinement for the column (Murugesan & Rajagopal, 2010). GESC-reinforced soft clay was subjected to a series of centrifuge model tests, which showed that encasement improves the stress concentration ratio, and the improvements were more pronounced when stiffer geosynthetic materials were used (Chen et al., 2021). Unreinforced ordinary stone columns (OSCs) generally exhibit maximum bulging at a depth of 1.5 to 2 times their diameter from the surface. In order to maximise both cost and performance, research was done on partially encased stone columns (ESCs) with different lengths of encasement. Results showed that an encasement length of half the column height effectively reduced settlement by 34% while maintaining cost efficiency, confirming that full encasement is not always necessary for adequate confinement (Abdelbaset & Arafa, 2023). Thakur et al., (2021) examined the effectiveness of geotextile reinforcement of columns in two directions: vertically, by encasing the column throughout its length, and horizontally, by inserting circular geotextile discs into the column at 3 cm intervals. The vertical encasement improved bearing capacity by 76.7% and 81.9% for groups of three and four stone columns, which nearly matched the improvements from horizontal reinforcement of 77.4% and 83.6%, suggesting comparable performance. Horizontal reinforcement improves load transfer by mobilising interface friction during column bulging, whereas vertical encasement increases capacity by resisting hoop stresses.

Construction and demolition waste (CDW) is produced in enormous quantities globally as a result of building and infrastructure projects, demolition, and renovations brought on by rapid urbanisation. Integrating circular economy principles and sustainable practices into CDW management can facilitate the transition toward achieving the 3R (Reduce, Reuse, Recycle) strategy in waste management (Islam et al., 2024). The scarcity of natural aggregates, such as crushed stone, for the construction of stone columns has led engineers to investigate alternative filler materials. CDW has been shown to be a potential sustainable alternative for natural aggregates for the construction of stone columns in soil reinforcing applications. Saxena et al. (2024) evaluated the performance of stone columns made with natural aggregates versus concrete debris using unsoaked California Bearing Ratio (CBR) tests on unit cell models. According to the findings, GESC using concrete waste produced a CBR value that was 1.8 times more than that of OSCs for natural aggregate. A Plaxis 3D numerical study of 36 CDW-GESC units revealed that they served as vertical drains, assisting in the dissipation of surplus hydrostatic pressure in soft soil. The results indicated that approximately 65% of the total settlement occurred during the construction phase itself (Anita et al, 2023). This study aims to experimentally assess the feasibility of substituting natural aggregates with CDW in the construction of GESCs of varying diameters through large-scale laboratory testing, and to numerically validate the findings using Plaxis 3D finite element analysis.

2 EXPERIMENTAL INVESTIGATIONS

2.1 *Materials*

Black cotton soil (BCS) was gathered from the Nalgonda region of Telangana state in India to replicate the worst-case scenario of a soil deposit with poor undrained shear strength. It was allowed to air dry in an open area and then pulverised in a mechanical soil crusher before being used for constructing the clay bed. The feasibility of using construction and demolition waste (CDW) for the construction of stone columns was assessed by comparing the performance of natural crushed stone aggregate (CSA) and CDW as filler materials. The construction and demolition waste sourced from the Jeedimetla recycling facility in Telangana predominantly consists of recycled concrete aggregates (RCA). The fundamental properties of these materials are given in Table 1. Table 2 summarises the properties of non-woven polypropylene geotextile used for encasement, which includes the results of the measurements of its seam strength and tensile strength, which were conducted in compliance with ASTM D4884-96 (1996) and ASTM D4595-09 (2009).

Table 1. Properties of BCS, CSA and CDW

Parameter	BCS	CSA	CDW
Specific gravity	2.59	2.67	2.37
USCS classification	CH	GP	GP
Liquid limit (%)	65.5	-	-
Plasticity index (%)	42	-	-
Maximum dry density (kN/m^3)	15	-	-
Optimum moisture content (%)	24	-	-
Bulk density at 70% relative density (kN/m^3)	-	14.86	13.87
Angle of internal friction (°)	-	43	46.5

Table 2. Properties of geotextile

Parameter	Value
Thickness (mm)	1.5
Mass (g/m^2)	150
Ultimate tensile strength (kN)	4
Elongation at break (%)	85
Seam strength (kN)	3.5
Initial elastic modulus (kN/m)	20

2.2 *Construction of clay bed and stone columns*

The tests were carried out in a fabricated steel tank measuring 1.2 m of length and width in plan and 1 m in depth. The clay bed was prepared to achieve an undrained shear strength of 15 kPa, with the corresponding water content of 38.6% determined through laboratory vane shear tests. The required soil mass for a bulk unit weight of 18.5 kN/m³ was premeasured, mixed with the calculated water quantity, and compacted inside the tank in five 100 mm layers to achieve the target depth and density. Loading tests were carried out on unreinforced clay beds and single column reinforced beds with different diameters (50mm, 75mm and 100mm) of ordinary (OSC) and geosynthetic encased stone columns (GESC). Krishnan and GuhaRay (2025) have evaluated the behaviour of OSCs, and the results were used in this study to compare the performance of geosynthetic encasement. The installation of stone columns was carried out using oil-lubricated, thin-walled steel pipes for easy insertion and removal. A helical auger was used to remove the encased clay after the pipes were driven to their maximum depth with the least amount of soil disturbance possible. After carefully withdrawing the pipe, aggregates (2–10 mm) in the required quantity for each column diameter were placed into the hole and compacted in 100 mm layers to a relative density of 70%. In the case of GESCs, a stitched non-woven polypropylene encasement was provided around the steel pipe before pushing into the clay. For the comparison of the performance, both CDW (CDW-GESC) and CSA (CSA-GESC) were used for the construction of stone columns separately.

The stone columns thus formed were subjected to loading through a steel loading plate of appropriate diameter and 30 mm thickness positioned on top of the column. A hydraulic jack with a 20 kN capacity that was fixed to a rigid loading frame was used to apply vertical loading until a 50 mm settlement was achieved. An appropriate load cell was used to measure the applied load, and two linear variable differential transformers (LVDTs) positioned diametrically opposite each other on the plate were used to record settlement. Figure 1 shows the sewn encasement inserted into the hole and the GESC constructed in the clay bed.

Figure 1. Sewn encasement placed in the hole with aggregate poured inside

3 FINITE ELEMENT ANALYSIS

The load-settlement characteristics of BCS reinforced with GESC were numerically investigated using Plaxis 3D. The Mohr–Coulomb criterion was used in the numerical study to simulate the linear elastic–perfectly plastic behaviour of the soil, CSA, and CDW, whereas rigid circular footing and geotextile were modelled as elastic materials. Before the test loads were applied, initial gravitational loads were considered. The material properties, such as Poisson's ratio and Young's modulus, were taken from well-established research (Anita et al, 2023). The complete set of input parameters for the simulation is detailed in Table 3.

Table 3. Properties of materials considered for numerical modelling

Parameter	BCS	CSA	CDW
Unsaturated unit weight (kN/m^3)	13.41	16.62	14
Saturated unit weight (kN/m^3)	18.58	18	15
Elastic modulus, E (kN/m^2)	2000	80,000	63,000
Poisson's ratio, μ	0.45	0.3	0.3
Cohesion, C (kPa)	15	1.06	1.1
Angle of internal friction, Φ (°)	1	43	46.5

4 RESULTS AND DISCUSSIONS

4.1 *Load-settlement behaviour of GESC*

This study examines the feasibility of using GESC in improving the load-settlement behaviour of BCS by employing CSA and CDW as filler materials. Figures 2 and 3 show the experimental and numerical results of the tests carried out on three diameters (50, 75 and 100 mm) of GESC constructed using both types of infill materials individually. It shows a positive correlation between the ultimate load and the diameter of the column, irrespective of the filler material. The ultimate load-carrying capacity of BCS was improved from 220 N to 3200 N and 2500 N for CSA-GESC and CDW-GESC, respectively. This can be attributed to the increased stiffness resulting from the larger replacement area of the bigger diameter column, along with the additional confinement provided by the hoop tension developed in the encasement. As observed from both graphs, GESCs do not show a clear peak load and strain softening after reaching the ultimate load, as indicated by the absence of a sudden drop in the curves. However, Krishnan and GuhaRay (2025) observed a clear drop in the graph and strain softening for single OSC as a result of the bulging failure.

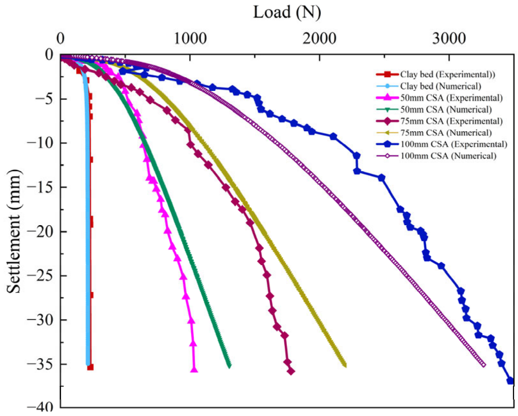

Figure 2. Load-settlement behaviour of CSA-GESC

As observed in Figures 2 and 3, the ultimate loads of CSA and CDW-filled GESC are comparable for all diameters, with a slight reduction in the performance of CDW-GESC. For a 100 mm diameter GESC, the ultimate loads observed were 3200 N for CSA and 2400 N for CDW. The CDW used in the current study exhibited a very high angle of internal friction and density, which contributed to its performance as a higher-grade filler material. The better angle of internal friction of CDW has provided sufficient interlock between the particles of GESC, making CDW a suitable filler, regardless of its source as a recycled material. It will not only minimise the environmental impact but also result in cost-effective ground improvement by reducing the costs associated with material procurement and landfill fees for disposing of CDW.

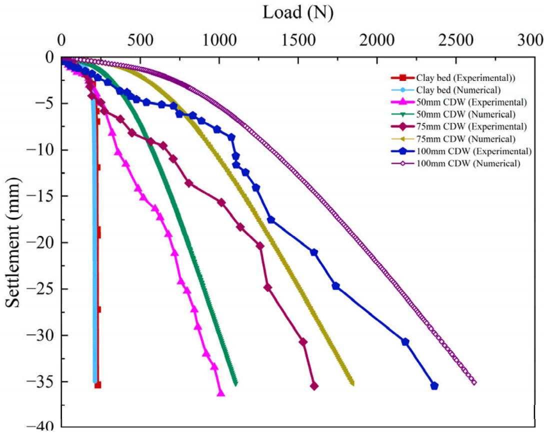

Figure 3. Load-settlement behaviour of CDW-GESC

A comparison of the load-settlement behaviour of GESC derived from both experimental and finite element analysis yielded comparable results, as shown in the above Figures. This shows the reliability of the 3D Plaxis model for predicting the behaviour of the stone column for different parametric studies.

4.2 *Effect of encasement*

Krishnan and GuhaRay (2025) have carried out large-scale laboratory tests on a single OSC and determined the effect of replacing CSA with CDW. Figure 4 shows the improvement achieved by encasing different diameters of stone columns for both types of filler materials. For all diameters of columns, a slight reduction in ultimate load was observed for CDW compared to CSA, irrespective of the encasement, and this can be attributed to its nature of being a waste material having higher crushability. However, the stiffness of the reinforced soil increased to even 3-fold for 100 mm CSA-GESC and 2.3-fold for 100 mm CDW-GESC compared to the corresponding OSCs. When the GESCs were vertically loaded, they would try to bulge and create hoop tension in the encasement in the circumferential direction. This would have provided additional confinement to the aggregates along with the lateral stress from the surrounding soil, which resulted in a stiffer reinforced soil-column system.

The numerical simulation yielded a typical deformed mesh of OSC and GESC after testing, as illustrated in Figures 5 and 6, respectively. As observed in the previous studies, the single OSC failed by bulging at an approximate depth of 'b', where 'b' lies between d and 2d ('d' is the diameter of SC). However, there was no prevalent bulging observed in the encased stone column, which is consistent with the discussions above.

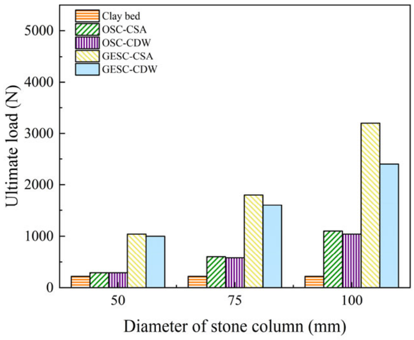

Figure 4. Comparative Performance of single OSC and GESC with CSA and CDW as filler

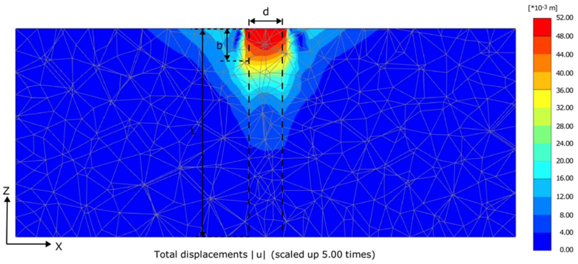

Figure 5. Deformed mesh of single OSC after loading

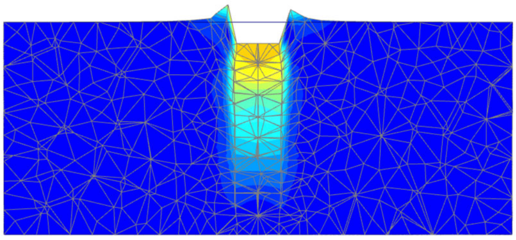

Figure 6. Deformed mesh of single GESC after loading

5 CONCLUSIONS

In this study, large-scale experimental tests and numerical analysis were carried out on a single GESC to investigate the feasibility of utilizing CDW for its construction. Based on these analyses, the following concluding remarks can be made

- The ultimate load-carrying capacity of soft soil can be improved by reinforcing it with OSCs. However, the stiffness and performance of reinforced soil further increase by encasing the column with suitable geotextile material.
- OSC exhibits larger lateral bulging with a clear ultimate load and strain softening after achieving that load. However, GESC exhibits negligible bulging with reduced strain softening.
- GESC have better lateral confinement due to the hoop tension developed in the circumferential direction of the encasement, which resulted in its efficient use in very soft soil having low undrained shear strength.
- GESC made with CDW exhibited only a slight decrease in ultimate load compared to those made with CSA, indicating CDW's promise as a sustainable filler material. Nevertheless, the performance of CDW-GESC is influenced by the material's quality, highlighting the need for a comprehensive parametric study to account for CDW from various sources. In addition to that, the long-term durability of stone columns constructed using CDW must be thoroughly analysed to ensure structural reliability under service load.

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