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Comparative Study on the Stone Column Prepared by Crushed Concrete Debris and Recycled Concrete Aggregate

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ABSTRACT

Using stone columns to support the structure constructed over weak soil strata is a widespread technique among engineers. The performance of a stone column (SC) mainly depends upon the soil in which it is installed, the material used to prepare it, the pattern, and its dimensions. This study evaluates the potential utilisation of crushed concrete debris (CCD) and recycled concrete aggregate (RCA) in the SC construction. For this purpose, a series of model tests on the square foundation supported by SC constructed in soft soil were conducted. The effect of the length of the column, the diameter of the column, and the number of columns prepared by two materials, CCD and RCA, are considered in this study. It is found that the SC prepared by RCA has a better load carrying capacity than the SC prepared by CCD. The improvement factor (IF) is determined based on the load-carrying capacity of SC made with RCA and CCD with respect to untreated soil. Test results have shown that the CCD and RCA both have the potential to be use as a construction material for SC.

Keywords: Stone column, Load-carrying capacity, Crushed concrete debris, Recycled concrete aggregate

INTRODUCTION

With the development and the growing population to fulfill the need for infrastructure, pressure on the land is increasing. It is now necessary to use even those lands which are unsuitable for construction. In such a situation, excessive settlement of structure and loss of global and local stability occurs. To avoid such problems, different ground improvement techniques are available (Priyadarshee A. et al., 2015, 2018, 2021; Thakur A. et al., 2021; Kumar, V. et al., 2023).

Stone columns are one of the most popular ground improvement techniques. Stone columns are prepared as vertical columns below the ground level with compacted and uncemented stone fragments, gravels, or sand. The partial replacement or lateral compaction of unsuitable or loose subsurface soils with a compacted vertical column of stone aggregate takes place during the construction of the stone column. The presence of the columns creates a composite material that is stiffer and stronger than the original soil. Due to this, a more significant part of the load is sustained by stone columns than soft clay. This leads to significant performance improvement of foundation beds (Zhang et al., 2020; Shehata H. et al., 2021). The stone column is used in the construction of different civil engineering-related structures like high-speed railway embankments in the Netherlands, aircraft factories in Germany (Black et al., 2007), under the foundation of the wastewater treatment plant in Santa Barbara, California (Mitchell and Timothi 1985) and other foundation projects (Shehata H. et al., 2021; Yoo C. and Abbas Q. 2020) have shown the beneficial performance.

Various studies conducted by researchers such as Dash and Bora (2013a), Thakur A. et al. (2021), Yoo C. and Abbas Q. (2020), Bazazzadegan, N. et al., (2024), have demonstrated, through diverse investigations, the substantial enhancement of load-bearing capacity and mitigation of settlement attributed to stone columns. Many of these inquiries into the efficacy of stone columns relied on model testing as a primary methodology. The stone column and soil system share the load from the foundation. Stone columns are relatively stiff, so their contribution to load sharing is more significant than that of soil (Ayadat et al., 2008) Hataf N. et al., 2020. Further, passive resistance mobilised during the dilation of stone columns due to lateral resistance also contributes to load-carrying capacity (Thorburn 1975). Besides the lateral stress, the internal resistance mobilised by the stone column also contributes significantly to the load-carrying capacity of the soil-column system (Hughes et al. 1975). From all the studies, the performance of stone columns depends upon the properties of the surrounding soil, the properties of the stone column, and the interaction between soil and stone column. Researchers like Das and Bora (2013a, b), Thakur A. et al., 2021, Verma et al., (2018), and others have shown that external reinforcement through the encasement of the stone columns can improve its load carrying capacity. The load-carrying capacity of stone columns can also be improved by internally strengthening the stone columns' materials. Different reinforcement or chemical treatments can be utilised for this purpose (Das M. et al., 2020; Rezaei M. et al., 2019; Sharma et al., 2007).

In studies like Black et al., (2007), Dash and Bora (2013), Nayak S. & Bhasi A. (2022), Bouziane A. et al., (2022) and others in which the performance of stone columns was investigated through the model test, stone columns were mainly prepared by natural aggregates alone or by prepared with natural aggregate encased externally. Researchers have also investigated the performance of stone columns stabilised internally. Researchers like Ayadat et al., (2008) have stabilised the stone column with rigid and plastic rods in the form of circular mesh. They have reported a significant improvement in the load-carrying capacity of the stone column. Concrete plugs, chemical grouts, and other materials were also used to enhance the internal load-carrying capacity of the stone column (Sharma et al., 2007). Due to their good interlocking and frictional resistance, natural aggregates or crushed stones are preferred for constructing stone columns. However, the need for alternative materials is increasing due to the increased cost of natural aggregates. Shahverdi M. and Haddad A. (2020), Lin et al., (2024), and other researchers have shown that recycled concrete aggregate (RCA) has the potential to be used in the construction of stone columns. Bhatia and Kumar (2019,2020) have investigated the performance of the crushed concrete debris (CCD) pile installed in fly ash fill. They have done model tests on a single floating pile and an end-bearing pile.

The use of recycled concrete demolition waste (RCDW) to enhance the load-carrying capacity of loose sand beneath circular footings using finite-element modeling and artificial neural networks (ANN) explored by Yadav, J. S. et al., (2024).

The impact of recycled construction and demolition waste (RCDW) layers of varying thickness and density on the load-bearing capacity of loose sand using plate load tests, finite element analysis (ABAQUS), and direct shear tests was investigated by Saini A. et. al., (2024). Results show that RCDW layers significantly improve bearing capacity and reduce settlement at optimal conditions. The pressure-settlement behavior of square footings on recycled concrete aggregate (RCA) layers over loose sand was evaluated by Soni H. et al., (2022). Results show that RCA layers enhance bearing capacity and reduce settlement significantly at optimal conditions.

The settlement behavior of sandy soils reinforced with ordinary, single-layer, and dual-layer geosynthetic-encased stone columns under cyclic load using PLAXIS-3D was investigated by Kumar N. & Kumar R. (2024). Results show that dual-layer encasement reduces settlement by 5.8%–11.2% compared to single-layer, which reduces settlement by 40.9%–47.8% compared to ordinary columns. Higher cyclic loading amplitudes and frequencies increase settlement, while stiffer geosynthetics further enhance performance. Findings aid in designing stable foundations for pavements, railroads, and offshore structures.

RCA requires some processing of debris concrete waste before use, while CCD can be utilised directly. This makes concrete debris more economical. However, further scope exists to understand the relative performance of RCA and CCD. Considering this, the present study investigates the performance of RCA and CCD as stone column material. The CCD is a waste material generated after the demolition of the concrete structure. Day by day, the amount of CCD debris is increasing due rapid infrastructure boom. The utilisation of such waste is essential to manage such waste. Using CCD directly or after processing in the construction of stone columns can be one of the helpful techniques in managing such waste. A series of model tests were conducted on a square footing supported by a stone column prepared by RCA and CCD. A comparative study was done to investigate the performance of CCD and RCA. The impact of the length of the column, the diameter of the column, and the number of columns on the performance of the stone column was also considered.

The internal resistance and overall performance of SC depend significantly on the grain shape and particle size distribution of RCA and CCD. RCA and CCD typically exhibit angular particle shapes due to their origin from demolished concrete structures. The angularity increases interparticle friction and enhances shear resistance, thereby improving the overall stability and load-bearing capacity of stone columns (Zhu, W. et al., 2022)

A well-graded particle size distribution ensures better compaction and reduced voids, which enhances the internal resistance of stone columns. Well-graded materials exhibit higher confinement effects, leading to improved load transfer efficiency. On the other hand, poorly graded materials may result in excessive settlement and reduced lateral support (Liang, P. et al., 2022).

At optimal water content, SC constructed using RCA and CCD achieves better compaction, resulting in higher stiffness, improved load carrying capacity, and reduced settlement of stone columns. Increased moisture reduces interparticle friction, decreasing stiffness and load-carrying capacity; also, excess moisture prevents proper interlocking and compaction of RCA and CCD in stone columns. Additionally, moisture beyond the optimum level can cause bulking, where water films around fine particles create a false sense of volume expansion, weakening the structural integrity of stone columns. Moisture content significantly influences the compaction characteristics of recycled aggregates and their behavior under load. optimum moisture content enhances the performance of granular materials in ground improvement applications, preventing settlement issues and ensuring better shear strength (Shah, S. K. H., et al., 2021).

DETAILS OF EXPERIMENTS

Test Materials

The soil used in this study to prepare the clay bed was Kaolin clay obtained from the locally available markets. The specific gravity of clay was found to be 2.71. Liquid limit, plastic limit, and plasticity index of soil were found to be 41%, 20%, and 21%, respectively. Most of the particles of kaolin clay were fine-grained. Soil is classified as CL (clay with low plasticity) according to the Unified Soil Classification System (USCS, ASTM D 2487, 2006) soil is classified as CL (clay with low plasticity). Maximum dry density (MDD) and optimum moisture content (OMC) were found to be 18.1 kN/m^3 and 17.5%, respectively, from the standard proctor test results.

Two materials were used to construct stone columns (SC): recycled concrete aggregates (RCA) and crushed concrete debris (CCD). The RCA was obtained after the mortar was removed from the surface of the aggregate from the CCD. The size of the RCA was between 2 mm and 10 mm. CCD was obtained from the crushed concrete without processing. In CCD, aggregates were covered with mortar. Before utilising it to prepare the stone column, it was sieved through 10 mm and retained on a 2 mm sieve. The specific gravity of RCA was found to be 2.69. RCA's maximum and minimum dry density were 16.78 kN/m^3 and 14.1 kN/m^{3,} respectively. The specific gravity of CCD was found to be 2.55. The maximum and minimum dry density of CCD were found to be 13.5 kN/m^3 and 16.1 kN/m^{3,} respectively. While preparing the stone columns with the help of RCA and CCD, materials were placed at 70% relative density. The angle of friction at 70% relative density for RCA and CCD were found to be 46^o and 42^{o,} respectively.

Sand used in this study was obtained from the locally available market. The purpose of the sand was to use it as a cushion over the soil-column bed. The specific gravity, maximum dry density, and minimum dry density were 2.65, 13.92 kN/m^{3,} and 16.8 kN/m^{3,} respectively. The sand was also compacted at 70% relative density, and the friction angle at this relative density was 37^o.

Planning of experiments

In the present study, a series of model tests were performed to simulate the situation where a soft clay deposit is present and a stone column is constructed to improve the load-carrying capacity. To evaluate the performance stone column prepared by CCD and RCA, three series of tests were performed. Details of the tests are presented in Table 1. The series ‘A’ was conducted on the foundation supported by soil without a stone column. The tests in Series ‘B’ and ‘C’ were conducted on soil with uncased stone columns (USC) prepared by CCD and RCA, respectively. In all series of tests, the impact of diameter of stone column (D), length of stone column (L) and number of stone column (N) on the performance of SC were evaluated. Considering this, D/B was varied as 0.3 and 0.5; N was varied as 1, 6, 7, 12 and 13, and L/B were varied as 1, 2 and 3. The SC used in this study was a floating type.

Table 1: Details of the test series

Test series	Foundation Support	Constant parameter	Variable parameter
A	Soil alone (UR)	-	-
B	Soil + SC of CCD (USCCCD)	D/B=0.3	N= 1, 6, 7, 12, 13 L/B= 1, 2, 3
		D/B=0.5	N= 1, 6, 7, 12, 13 L/B= 1, 2, 3
C	Soil + SC of RCA (USCRCA)	D/B=0.3	N= 1, 6, 7, 12, 13 L/B= 1, 2, 3
		D/B=0.5	N= 1, 6, 7, 12, 13 L/B= 1, 2, 3

Details of test setup

All the model tests were conducted in steel tanks measuring 500 mm x 500 mm x 600 mm. Load on the soil was applied through a square plate measuring 100 mm x 100 mm x 10 mm. The schematic diagram of the test setup is presented in Fig. 1. The load on the plate was applied through a hydraulic jack. The settlement of the plate was measured by a dial gauge, which was placed over the plate and the top surface of the soil. Model tests were conducted on the different numbers of SC, i.e. 1, 6, 7, 12 and 13. For this purpose, different configurations of the SC were adopted. Fig. 2 shows the arrangement of SC used during the model test. According to "IS 15284-1 (2003)” the most commonly used arrangements such as triangular grid which provides uniform stress distribution and is recommended for better load-carrying performance and square grid which is mostly adopted for ease of construction but may result in slightly non-uniform stress transfer.

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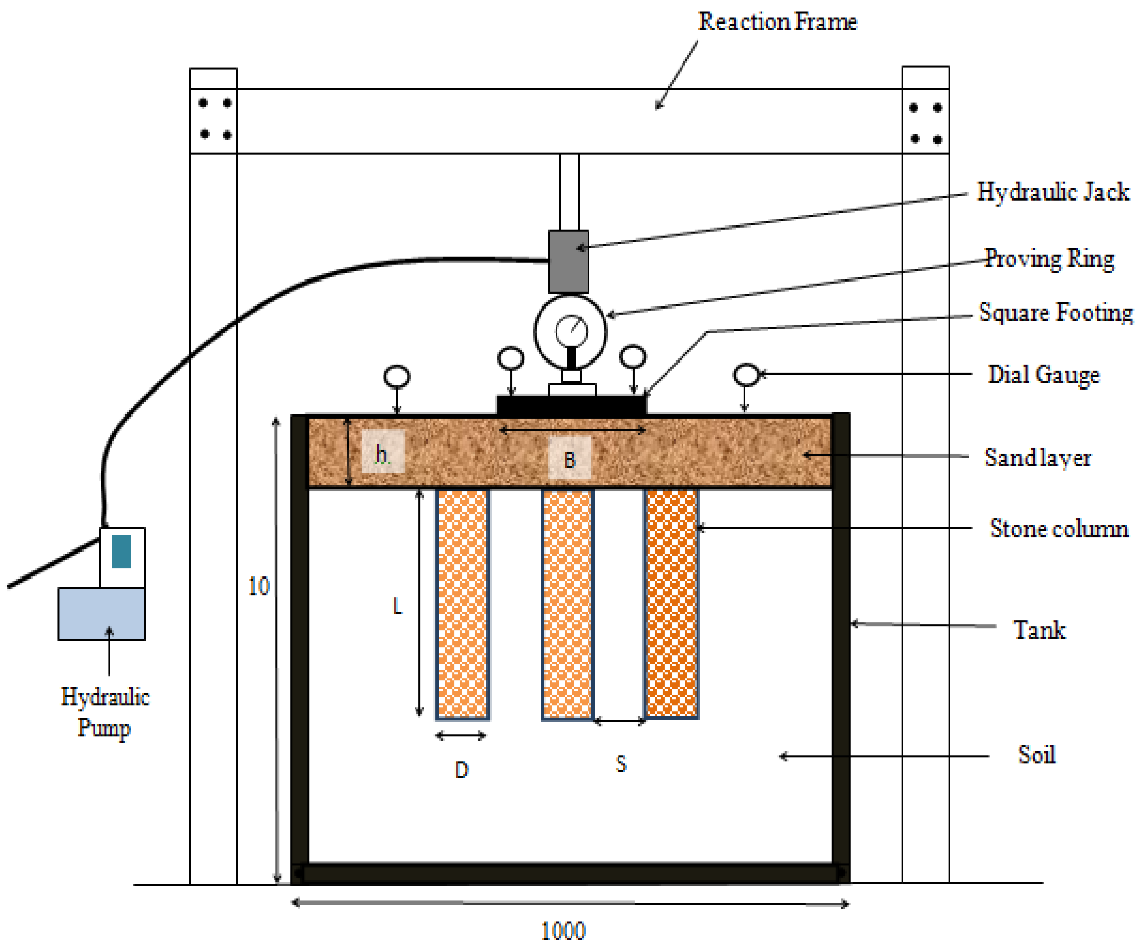

Fig. 1. Schematic diagram of the test setup

Chummer (1972) and Das and Bora 2013 have shown that the failure surface below the foundation extends up to 2-2.5 times the width of the footing from the centre of the foundation. Considering this, in the present study size tank is enough to avoid the interference of the wall of the tank on the failure wedge. The maximum length of SC used in this study was three times the width of footing, i.e. about 270 mm. With respect to the length of SC, the depth of the tank was sufficient. The behavior of single and multiple stone columns in clay, demonstrating how increasing the number of columns enhances load-bearing capacity, was studied by Balaam & Booker (1981).

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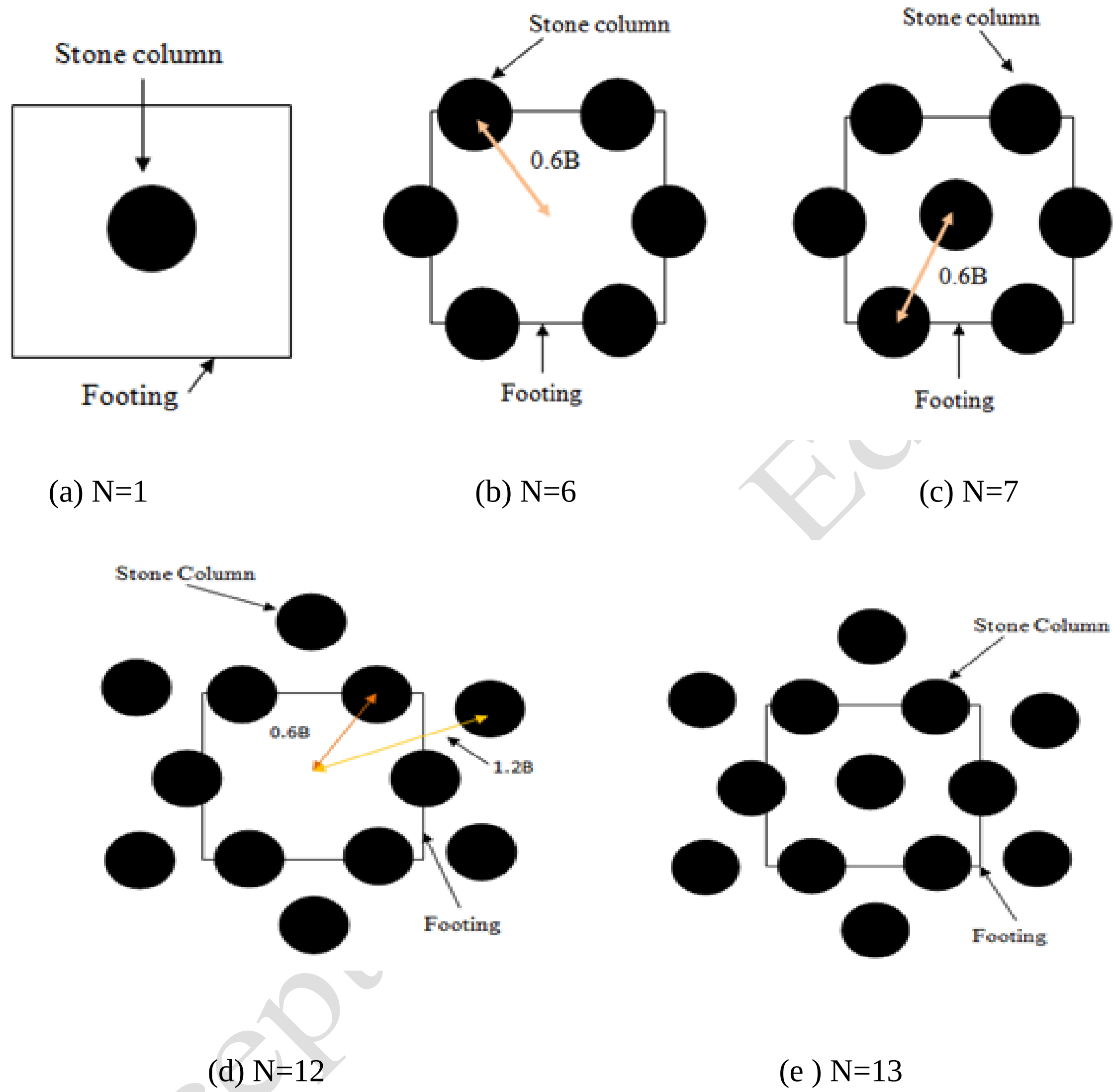

Fig. 2. Configuration of the stone column considered in the study

Preparation of test bed

The present study mainly prepared two types of test beds: the first type was prepared with soil alone, and the second type was prepared with soil and USC. In all cases, the first soil was prepared. For this purpose, desired amount of water was added and properly mixed with pulverised soil. For preparing the test bed with soil alone, marking in the tank was done, and soil was placed in layers and compacted with a uniform effort to achieve the desired density. For the preparation of the test bed with USC, the first soil bed was prepared similarly. After preparation of the soil bed, SC was installed by replacement method. In this method hollow pipe was used. First, this pipe was inserted in the soil till the desired depth, and the inside soil was scooped out. After this, CCD or RCA were placed inside and compacted to achieve the desired density.

Test Procedure

In all the tests after the preparation of the soil bed, a square plate was placed at the centre of the tank then it was attached with a proving ring and jack. To measure the settlement of the plate, dial gauges were attached to the plate. After the arrangement of the jack, proving the jack and dial gauge, the load was applied, and the corresponding settlement was measured. The load applied was measured by proving the ring. The load was applied until maximum settlement reached about 30%.

RESULTS AND DISCUSSION

The following section presents and discusses the results obtained from the model tests. The impact of SC prepared by CCD and RCA is presented as SC is a pressure-settlement response. Settlement here is represented in terms of S/B ratio, i.e. settlement to width footing ratio. The impact of SC length, diameter, and number is also discussed. The impact of SC on the foundation's settlement is presented in terms of the settlement reduction factor (SRF). The expression for SRF corresponding to any stress level can be written as follows.

$$SRF = \frac{S_u - (S_r)_{SC}}{S_u} X\ 100 \qquad \ldots (1)$$

Where S_u is a settlement of UR clay bed $(S_r)_{sc}$ is the settlement of SC reinforced clay bed.

Impact of the number of SC

Figs. 3 and 4 illustrate the variation in bearing pressure with settlement for different lengths of SC having D/B=0.3 and L/B=2. Fig. 3 presents the pressure-settlement response of SC prepared by CCD, and Fig. 4 depicts the same for SCs prepared by RCA. Data for unreinforced soil are also included in these figures for comparative analysis. The bearing pressure at various settlement levels increases with the number of SCs. Individual SCs, composed of materials stronger than soil alone, create a relatively stiffer structure when combined with soil. This combination enhances the load-carrying capacity of the soil due to the construction of SCs. As shown in Fig. 3, even the installation of a single SC significantly improves bearing pressure at different settlement levels. For instance, at a settlement level of 25% (S/B = 25%), the bearing pressure improvement is approximately 23% with a single SC. As the number of SCs increases, the area replacement ratio, which indicates the area covered by SCs relative to the total ground area, also increases. This results in a corresponding increase in the stiffened ground area, further enhancing load-carrying capacity. Fig. 3 reveals that bearing pressure improves by approximately 1.75 times and 2.45 times when the number of SCs increases to 6 and 12, respectively. With six SCs, each SC is installed such that the centre of the SC is 0.6B from the centre of the footing, ensuring most of the SC is beneath the footing.

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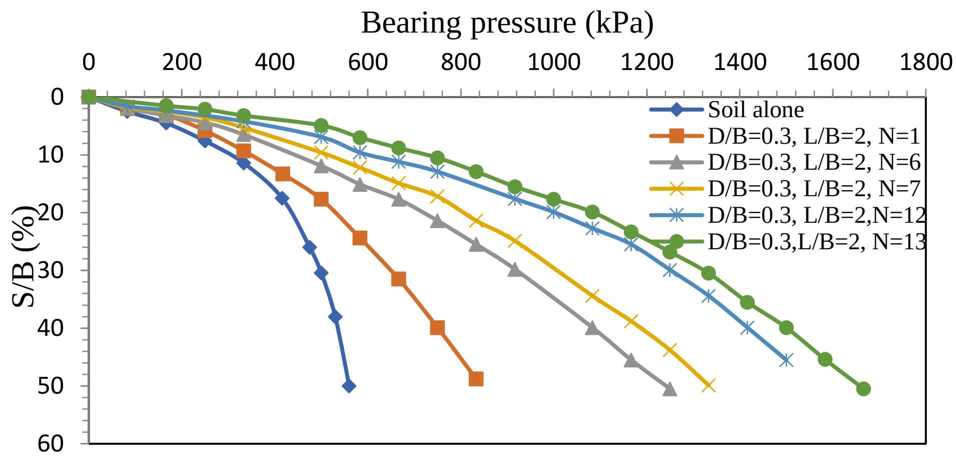


Fig. 3. Load deformation behavior of stone column prepared by CCD with varying number (D/B=0.3, L/B=2)

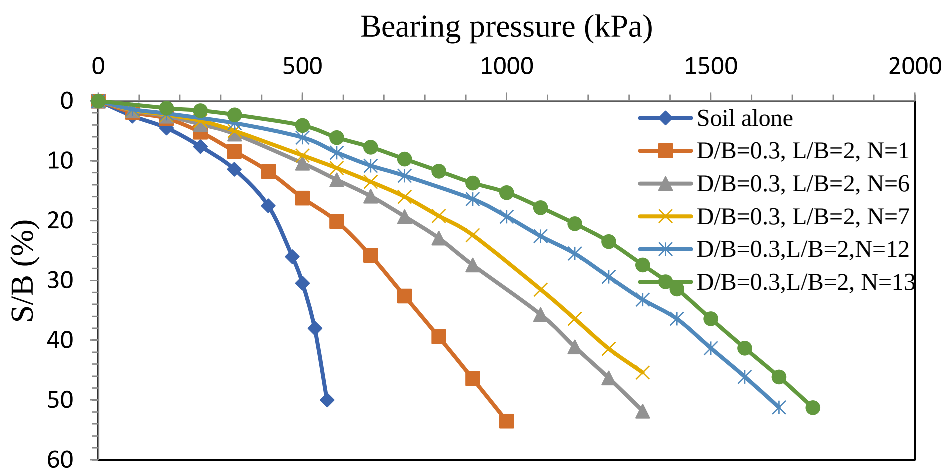
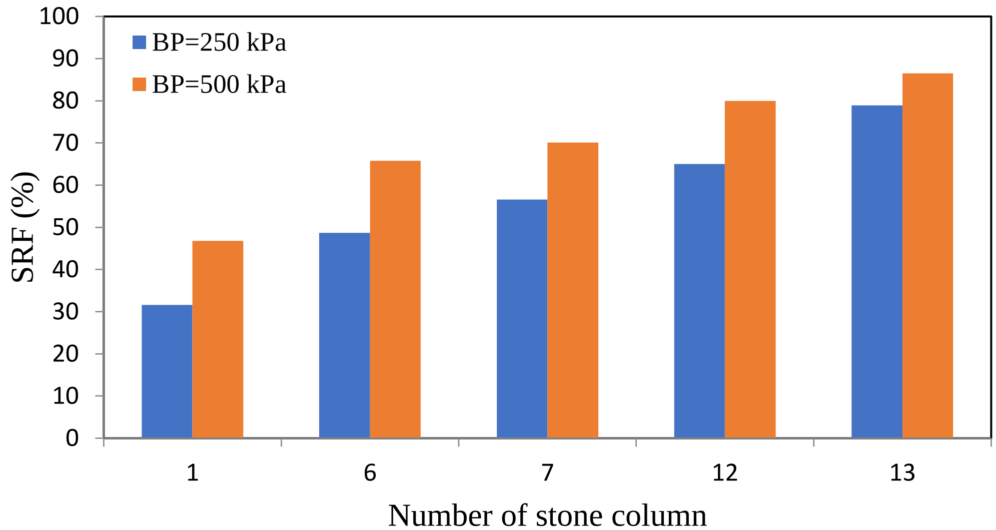


Fig. 4. Load deformation behavior of stone column prepare by RCA with varying numbers (D/B=0.3, L/B= 2)

However, when twelve SCs are installed, an additional six SCs are placed 1.2B from the centre of the footing. Such configurations, where the number of SCs increases, enhance load-carrying capacity by distributing the load of the footing and increasing confinement. It is also noted that bearing pressure further increases when an SC is installed at the centre of the footing, as seen in cases with N=7 and N=13. A similar trend of increased load-carrying capacity with the number of SCs is observed with SCs prepared from RCA, as shown in Fig. 4.

The installation of SC reduces the foundation's settlement. To evaluate SC's potential to reduce settlement, the SRF mentioned above was evaluated. Fig. 5 shows the impact of the number of SC prepared by CCD and RCA on the SRF.

Two different stress levels, 250 kPa and 500 kPa, were considered to evaluate the SRF. It can be observed that the SRF increases with an increase in the number of SC. It was noted that settlement was reduced by more than 80% when the number of SC increased to thirteen for SC prepared by CCD and RCA. Due to higher stiffness, the Soil-SC system can sustain more loads at any deformation level. In other words, the Soil-SC system gets less deformation at any stress level. The stiffness of the soil-SC system increases with an increase in the number of SC. It can be further observed that the SRF is more at higher stress levels, i.e. at 500kPa, than at lower stress levels, i.e. at 250 kPa.



(a) Stone column prepared by CCD

(b) Stone column prepared by RCA

Fig. 5. Effect of the number of SC on the SRF (D/B= 0.3, L/B=2) (a) prepared by CCD (b) prepared by RCA

Impact of length of SC

Fig. 6 and Fig. 7 depict the bearing pressure versus settlement response of a footing supported by soil reinforced by SC having different lengths, i.e. L/B = 1, 2 and 3. It can be observed that with the increase in the length of the SC, bearing pressure increases. At the settlement level of 25%, when the length of SC changes from L/B=1 to 3, about 1.3 times improvement in the bearing pressure takes place. An increment in the length of SC improves the interaction between soil and SC due to an increment in the surface area. Due to this, skin friction improved with an increase in the length. This increment in the resistance becomes the reason for the improvement in the load-carrying capacity of the soil-SC system.

Further, let's compare the performance of the soil-SC system with soil alone. It can be noted that the performance of SC with L/B =1 improves the bearing pressure about 1.4 times, while SC having L/B =2 improves the bearing pressure about 1.56 times at S/B=25%. It shows that after a certain length of SC, the contribution of length starts decreasing. Similar findings are reported by other researchers, such as Dash and Bora (2013 a, b). The contribution of length in load-carrying capacity is identical in both cases when SC was prepared by CCD or RCA (Fig. 6 and Fig. 7).

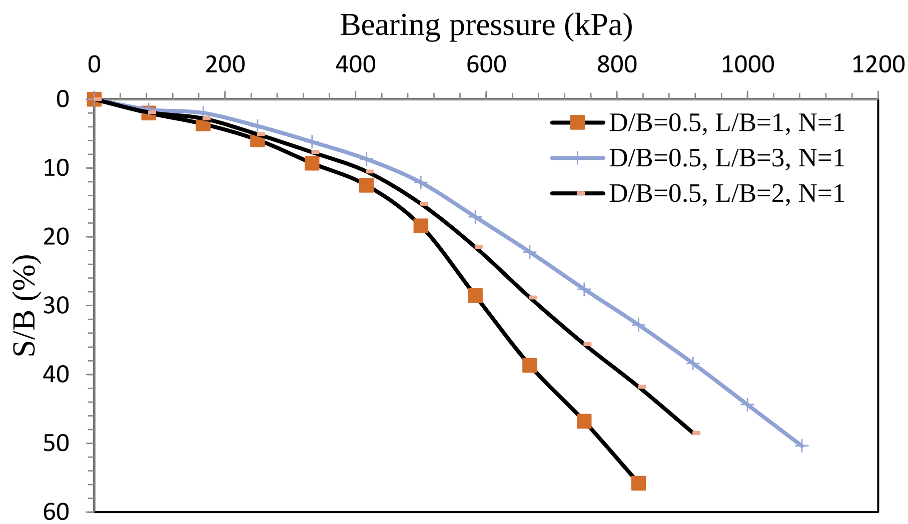


Fig. 6. Load deformation behavior of stone column prepared by CCD having different length (D/B=0.5, N=1)

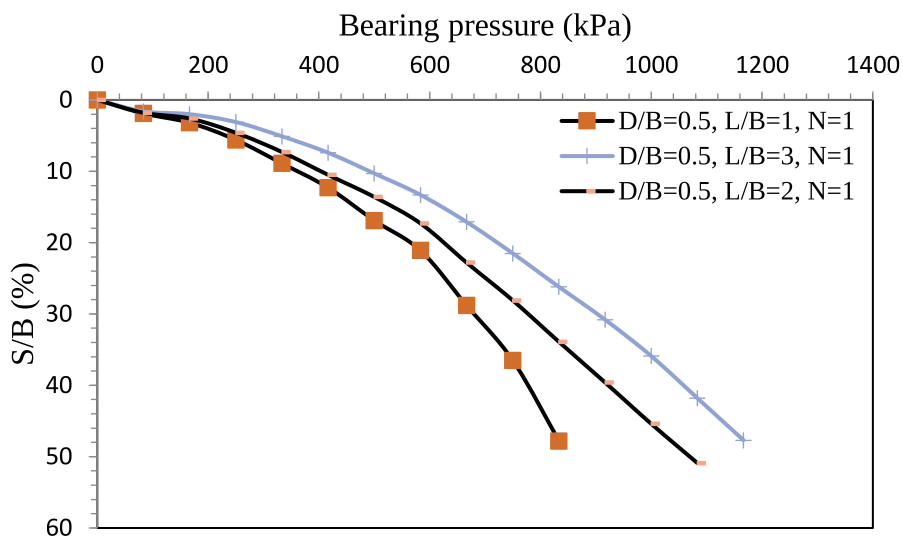


Fig. 7. Load deformation behavior of stone column prepared by RCA having different length (D/B=0.5, N=1)

Fig. 8 illustrates the variation of the Settlement Reduction Factor (SRF) with the length of the stone column (SC) for both crushed concrete debris (CCD) and recycled concrete aggregate (RCA). The data clearly indicate that SRF increases with the length of the SC, demonstrating the positive impact of longer SCs on reducing settlement. As the length of the SC increases, the resistance against settlement also increases. Consequently, at any given bearing pressure, the settlement decreases. For instance, at a bearing pressure of 500 kPa, the SRF is approximately 44% for L/B=1. However, this increases to about 55% and 66% for L/B=2 and L/B=3, respectively. This trend confirms that the length of the SC significantly influences settlement reduction, though the marginal benefits decrease beyond a certain length.

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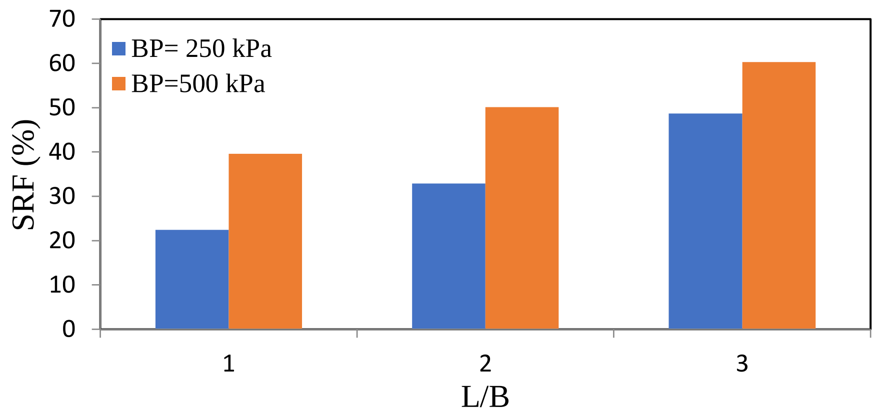
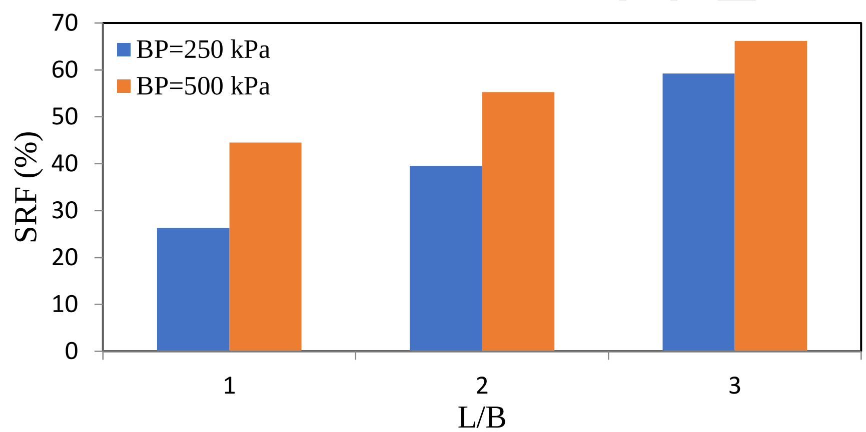


(a) Stone column prepared by CCD



(b) Stone column prepared by RCA

Fig. 8. Variation of SRF with L/B (D/B= 0.5, N=1) (a) prepared by CCD, (b) prepared by RCA

Impact of the diameter of SC

Figures 9 and 10 depict the variation of bearing pressure with varying diameters of SC at different settlement levels for both types of SC prepared by CCD and RCA. It can be observed that when the D/B of SC increases, the bearing pressure of SC increases. Such improvement in the load-carrying capacity can be noted for all the configurations of SC, i.e. for N=1, 6 and 12. The resistance by the SC against the footing load is mobilized by the surface friction resistance and bearing pressure at the end of SC. When the diameter of SC increases, then the surface area and bottom area also increase. Due to such increment in both areas, frictional and end resistance increase.

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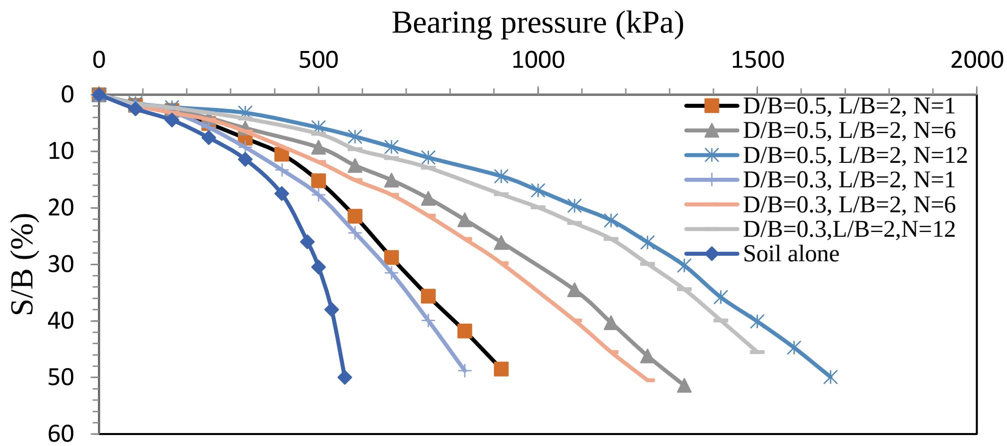

Fig. 9. Load deformation behavior of stone column prepared by CCD having different diameter (L/B=2)

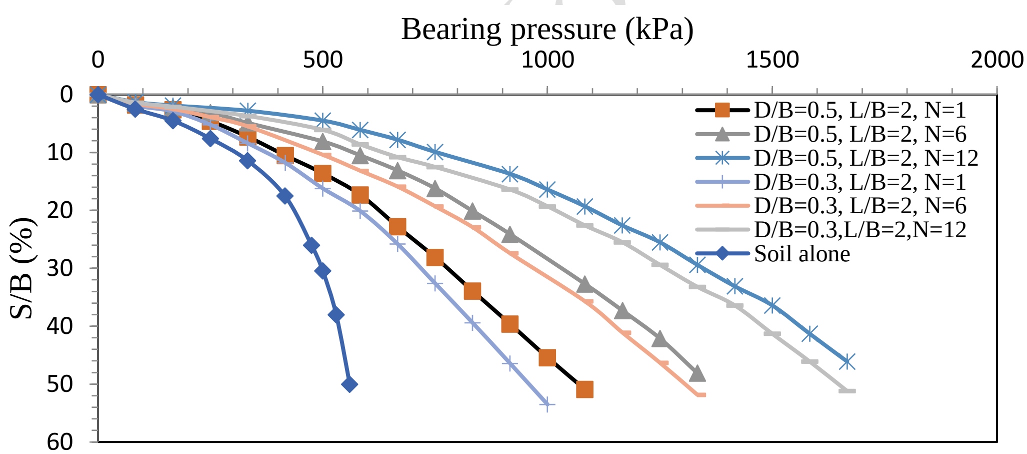

Fig. 10. Load deformation behavior of stone column prepared by RCA having different diameter (L/B=2)

Fig. 11 illustrates the impact of diameter on the settlement for the SC prepared by CCD and RCA. It can be observed that the settlement of the SC decreases with an increase in the diameter of the SC. For all the configurations of the SC, a similar trend was found. The area replacement ratio increases with an increase in the diameter of the SC. Due to this, the stiffness of the soil-SC structure increases. In the case of D/B =0.3, SFR was reached up to 72%, while it can reach up to 82%.

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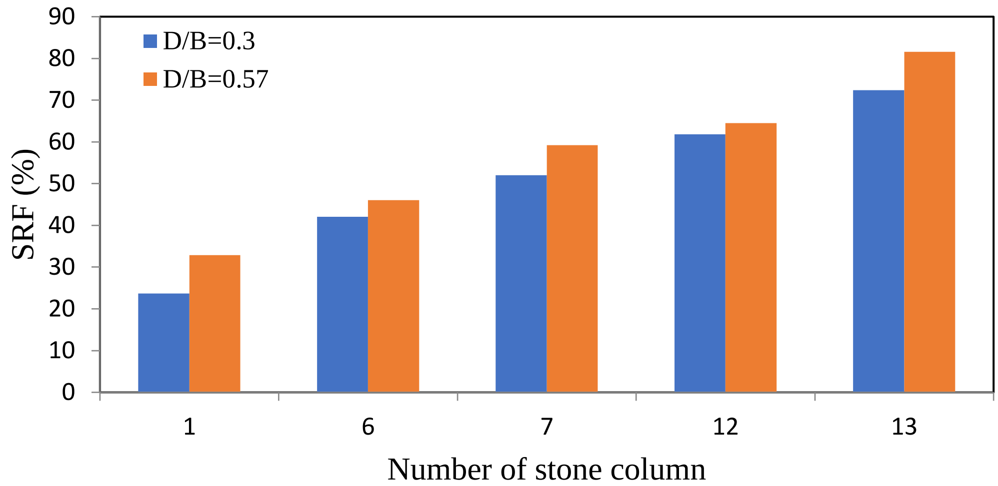
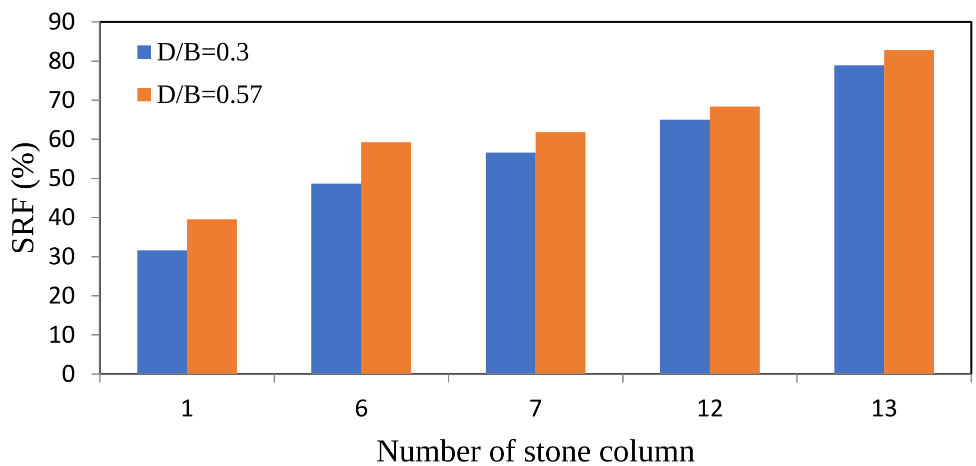


(a) Stone column prepared by CCD



(b) Stone column prepared by RCA

Fig. 11. Variation of SRF with number of SC (L/B= 02, BP=250 kPa) (a) prepared by CCD, (b) prepared by RCA

Impact of material used in the construction of SC

Figs. 12, 13, and 14 show the impact of the material used in the construction of SC on the load-carrying capacity of soil reinforced by SC having N= 1, 7, and 13. SC prepared by both of the materials can perform satisfactorily way. It can be observed that in all the cases, the bearing pressure of SC was higher when it was prepared with the RCA than CCD. CCD contains aggregate and mortar, while RCA is treated material. Because of this, the angle of internal friction of CCD is lesser than that of the RCA. This makes RCA a better material in terms of interlocking and friction. When load through footing is transferred to the SC then the deformation in the SC takes place. The SC prepared by the materials having a greater internal angle of friction can resist such deformation in a better way. Because of this, RCA performs relatively better than CCD.

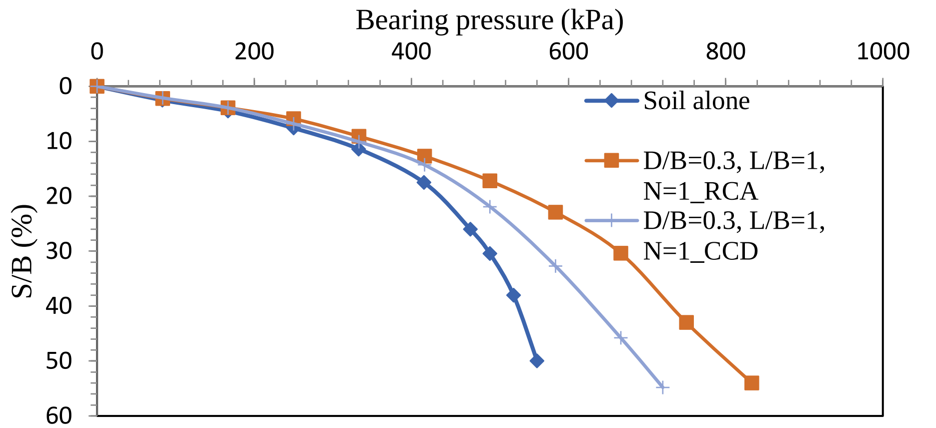


Fig. 12. Load deformation behavior of stone column prepared by CCD (D/B=0.3, N=1, L/B=1)

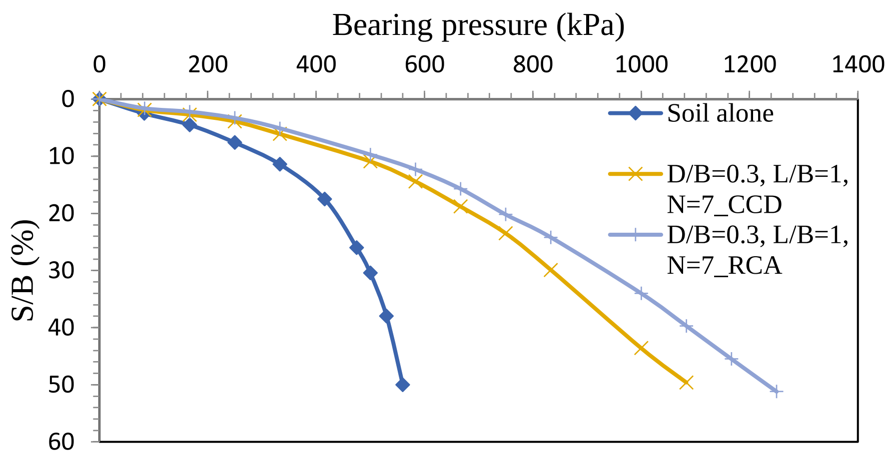


Fig. 13. Load deformation behavior of stone column prepared by RCA (D/B=0.3, N=7, L/B=1)

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Fig. 15 shows the impact of RCA and CCD made SC on the foundation's settlement at the bearing pressure of 250 kPa and 500 kPa. It can be observed that the improvement in the SFR takes place in the range of 1.12- 2.2 times. In all the conditions settlement of the foundation is smaller in the case of RCA. Due to higher internal resistance in the case of RCA, the SC prepared by it is stiffer than the SC prepared by CCD. Due to this, at applied load settlement was reduced when RCA was used in the construction of SC.

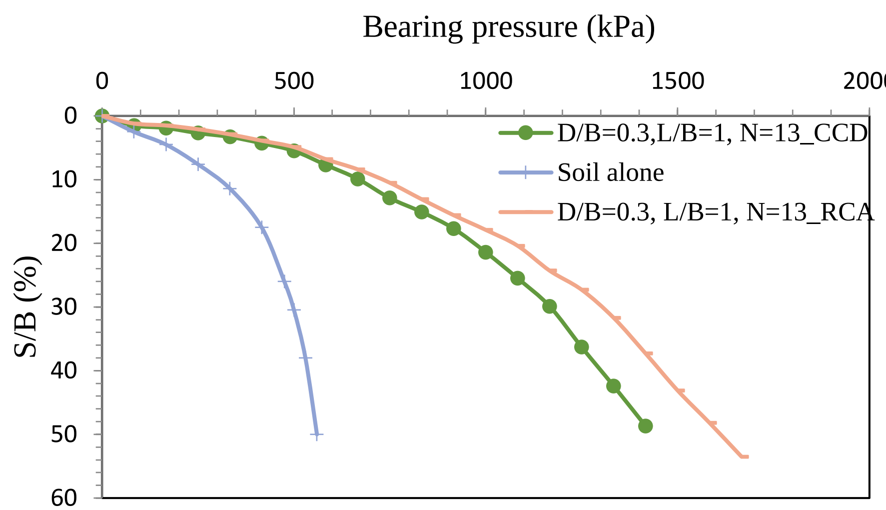
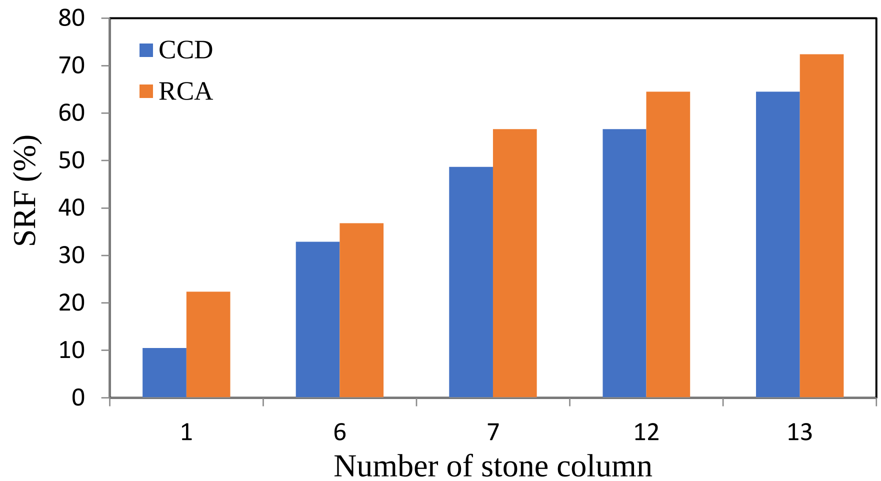
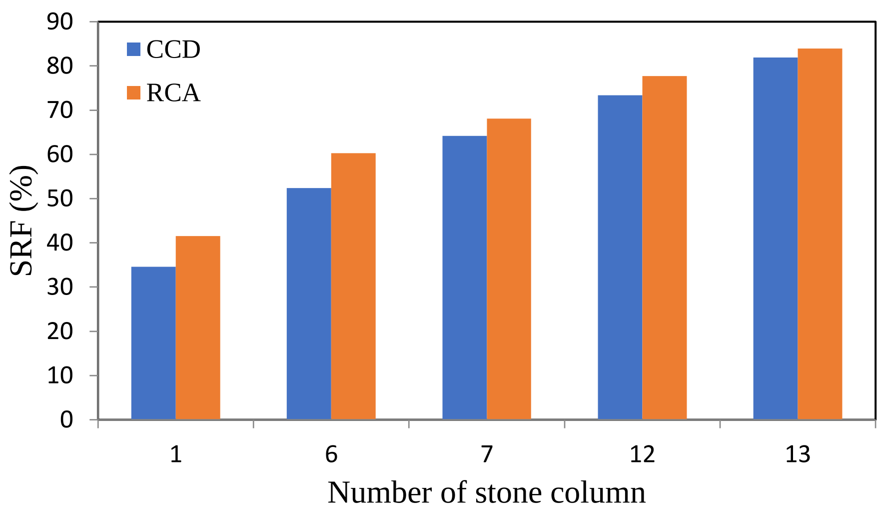


Fig. 14. Load deformation behavior of stone column prepared by RCA (D/B=0.3, N=13, L/B=1)



(a) BP = 250 kPa



(b) BP= 500 kPa

Fig. 15. Variation of SRF of SC prepared by different materials (D/B=0.5, L/B=1) (a) BP= 250 kPa (b) BP= 500 kPa

Although RCA seems better than CCD as construction material for the SC, it requires processing, which may increase the cost of construction with the help of it.

However, both of the construction materials have the potential to be utilised in the construction of the SC. Depending upon the economical requirement and suitability for structural requirements RCA or CCD may be chosen in the construction of SC.

Improvement Factor:

The Improvement Factor (IF) is determined in terms of load-carrying capacity of SC prepared by RCA and CCD with respect to UR soil under different settlement as given formula, eq (2):

At initial settlement, RCA-based SCs exhibit a higher IF in load-carrying capacity compared to CCD-based SCs. This is primarily due to the coarser nature of RCA, which provides better interlocking and load distribution at the early loading. On the other hand, CCD contains finer particles, which result in more initial compression and a lower load-bearing capacity.

$$I_f = \frac{Load\ carrying\ of\ SC - Load\ carrying\ of\ Soil\ alone}{Load\ carrying\ of\ Soil\ alone} \times 100 \qquad (2)$$

However, as the settlement increases beyond 15 mm, the IF for both RCA and CCD stone columns becomes nearly equal, as observed in the figure 16 & 17. This phenomenon occurs because the fine particles in CCD gradually fill the voids within the column structure, leading to a denser matrix that enhances load transfer. As a result, after approximately 15 mm of settlement, CCD-based SCs exhibit a comparable load-bearing performance to RCA-based SCs. The IF of the SC prepared using CCD is 166% at 30 mm settlement for N = 13, D/B = 0.3, and L/B = 2, while the SC prepared using RCA achieves IF of 176% under the same conditions.

This behavior aligns with previous research; finer materials within granular columns undergo densification over time, leading to improved long-term stability and load distribution. The filling of voids with crushed particles enhances the performance of stone columns, particularly in later settlement stages (Siahaan, F., et al., 2018).

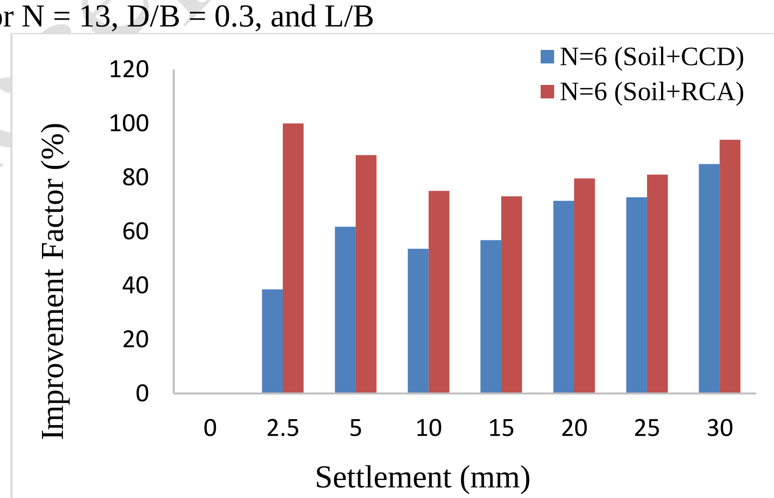


Fig. 16. Comparison of improvement factor (%) of SC prepared by CCD and RCA (D/B=0.3, L/B=2)

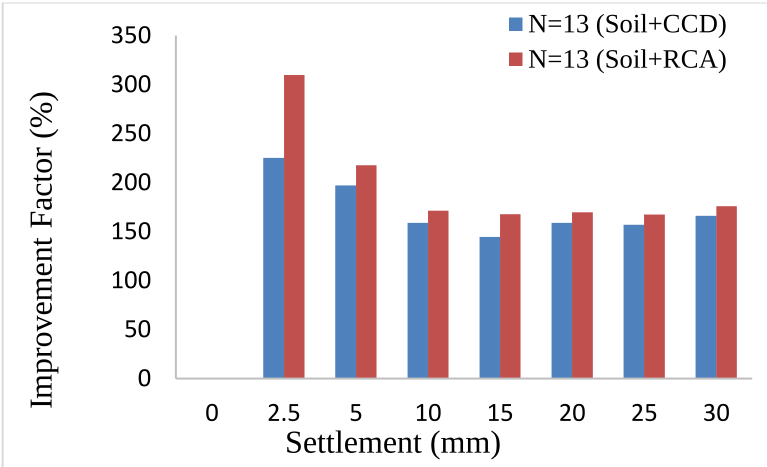


Fig. 17. Comparison of improvement factor (%) of SC prepared by CCD and RCA (D/B=0.3, L/B=2)

CONCLUSIONS

- This paper analyses and discusses the results obtained from the model test. The results confirm that the performance of the SC prepared by RCA and CCD both have the potential to improve the soil's load-carrying capacity. Based on these findings, the following important conclusions can be drawn.
- The load-carrying capacity increases with the increase in the number of SC made of CCD or RCA due to an increase in the stiffness of the soil-SC structure, which can improve load-carrying capacity by more than 2.5 times. It also decreases settlement significantly.
- The length of the SC improves the load-bearing capacity of the soil-SC system and reduces settlement by incrementing the soil-SC interaction.
- The increment in the diameter of the SC improves load-carrying capacity and reduces settlement through an increment in surface interaction and end resistance.
- SC prepared by CCD and RCA both have the potential to improve the soil's load-carrying capacity. However, RCA's performance was found to be better due to the internal resistance.
- The improvement factor (IF) of the SC prepared using CCD is 166% at 30 mm settlement for N=13, D/B = 0.3, L/B = 2, while the IF of the SC prepared using RCA is 176% under the same specifications.

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