International Journal of Engineering Technology Science and Research
IJETSR
www.ijetsr.com
ISSN 2394 – 3386
Volume 2, Special Issue
September 2015

Performance of Different Types of Stone Columns in Soil Stabilization – A Review

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ABSTRACT

Stone columns are extensively used to improve the bearing capacity of poor ground and reduce the settlement of structures built on them. A stone column is one of the soil stabilization methods that is used to increase strength, decrease the compressibility of soft and loose fine graded soils, accelerate a consolidation effect and reduce the liquefaction potential of soils. They are mainly used for stabilization soft soil such as soft clays, silts and silt-sands. It is believed that this method was used first in France in 1830s. This method is in wide range of use especially in Europe since 1950s. The columns consist of compacted gravel or crushed stone arranged by a vibrator. This article presents a review of previous studies on the performance of improving the bearing capacity of various types of soils, with different material and other parameters.

Key words : stone column, bearing capacity, settlement, stabilization, soft soil

INTRODUCTION

The Engineering structures constructed on thick deposits of soft soil strata have problems of low bearing capacity, excessive total and differential settlement, lateral spreading etc. To mitigate such problems, different ground improvement techniques are available namely; vertical drains, lime/cement column, stone (granular) column etc. in view of their proven performance, short time schedule, durability, constructability and low costs. Stone column technique seems to be very suitable and favourable ground improvement technique for deep soft soil improvement. Further to prevent excessive bulging, squeezing of stone into soft soil, stone column can be encased with suitable geosynthetic. Another advantage of encasement is having high load carrying capacity and lesser settlement of composite foundation. This paper presents the current state of the geosynthetic encased stone column as a ground improvement technique. A review is provided aiming to: (a) identify key considerations for the general use of encased stone columns, (b) provide insights for design and construction, (c) compile the latest research developments.. The paper identifies areas where more research is needed and includes recommendations for future research and development.

Load carrying capacity of a stone column is attributed to frictional properties of the stone mass, cohesion and frictional properties of soils surrounding the column, flexibility or rigidity characteristics of the foundation transmitting stresses to the improved ground and the magnitude of lateral pressure developed in the surrounding soil mass and acting on the sides of the stone column due to interaction between various elements in the system. The stone column derives its axial capacity from the passive earth pressure developed due to the bulging effect of the column and increased resistance to lateral deformation under superimposed surcharge load. The theory of load transfer, estimation of ultimate bearing capacity and prediction of settlement of stone columns was first proposed by several researchers (Malarvizhi, 2004).

Guetif et al., 2007, reported based on improvement of a soft soil by stone columns is due to three factors. The first one is inclusion of a stiffer column material (such as crushed stones, gravel, and others) in the soft soil. The second factor is the densification of the surrounding soft soil during the installation of stone column. The third factor is the acting as vertical drains. So, the insertion of stone columns into weak soils is not just a replacement operation and stone column can changes in both the material properties and the state of stresses in the treated soil mass (Ghanti & Kashliwal, 2008).

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RIVIEW OF LITERATURES

Literatures on various studies on the behaviour of stone columns have been studied. Studies have been conducted on various parameters especially on the following two categories:

1. Behaviour of stone column in various types of soils
2. Behaviour of stone columns with geogrid encasements
3. Consolidation of stone column with various material
4. Performance analysis of reinforced stone columns by numerical modelling

1. Behaviour of stone column in various types of soils

[1] Pradip Das and Dr.Sujit Kumar Pal [2013] conducted a study of the behaviour of stone column in local soft and loose layered soil. They had an investigation on the utilization of stone column to improve the load capacity of sandy silt soil with clay in naturally consolidated state.Load tests also conducted through the compression testing machine are performed on single un-encased stone column in sandy silt soil with clay.The stone column treated soil can carry more load than untreated soil. The load carrying capacity of treated soil increase with the increase in diameter of stone column.When column area is loaded, failure of bulging occurs within the entire column area. The encased stone column in layered soil also decreases with the increasing diameter of stone column. The load carrying capacity of treated layered soil decreases with the increasing of diameter of stone column.

[2] K. V. Sudheer, et al [2011] made an experiment on the behaviour of compaction sand pile and stone column in fine sand with clay. Laboratory tests were carried out on compaction sand piles as well as stone columns of size 25mm diameter installed in the reconstituted saturated soil. The mini plate load tests were conducted and the load settlement behaviours were observed.It is found that when the clay content is increased up to 20% the percentage of improvement is increased. From the results it can be concluded that even with small percentage of clay present in the loose fine sand sample, ground improvement by stone column is highly preferable than compaction sand pile.

[3] B. Galy et al [2012] done a research on the Influence of the vibro-stone column reinforcement on the seismic bearing capacity of a surface shallow footing. A new approach to estimating the bearing capacity of reinforced soils under seismic conditions is proposed. It is based on limit equilibrium theory, pseudo-static and pseudo-dynamic concepts and a specialized method for estimating reinforced soil properties. The parametric study presented indicates that a 1.5B treatment width on each side of the footing is sufficient to increase the original bearing capacity by 25 to 50% (depending on the Area ratio) in the case of a "partial improvement" scenario is presented here.

[4] Kumar Rakeshand Jain P.K. [2012] made a research on Prospect of using granular piles for improvement of expansive soil. The load settlement behaviour of the soil was determined for different size of the granular pile. Geo-grid encased granular piles were also installed in the soil. The bearing capacity of the stone column increases by introducing circumferential geo- grid reinforcement. And as the depth of circumferential reinforcement increases settlement decreases and the bearing capacity increases.Further reduction in settlements is noticed with the increasing depth of geo grid-encasement. On full depth encasing, reduction in total settlements of up to 79.13% is noticed.The tests also reveal that the larger diameters of ordinary stone columns can be replaced by smaller diameters of geo grid-encased stone column.

[5] BehzadKalantari and Bandar Abbas [2012] made a review on Soft soil stabilization using stone columns. The installation methods, design and failure modes of stone columns were taken and concluded with the following: The use of stone column in soft clays has been found to provide moderate increase in load carrying capacity accompanied by significant reduction in settlement. Being granular and freely drained material, consolidation settlement is accelerated and post construction settlement is minimized. Stone columns may have particular application in soft soils such as N.C clay, silt and peat, they are generally inserted on volume displacement basis excavating a hole with specified diameter and desired depth.

[6] Ali et al. [2010] Behaviour of reinforced stone columns in soft soils. Laboratory model tests have been carried out on floating and fully penetrating single piles with and without geotextile to find out the effect of encasement, l/d ratio and diameter of column on bearing capacity. Since stone columns having lengths more than six times their diameter do not contribute much to bearing capacity therefore, floating columns should be preferred in situations where hard strata is at a depth more than this length. As far as possible, columns of smaller diameter should be provided because these are stronger than large diameter columns. The columns should be wrapped around with some geosynthetic material, by doing so the bearing capacity of improved ground is increased by manifolds. Since bulging of stone columns takes place only in upper portion due to lack of lateral pressure, hence providing geosynthetic in that portion may also be equally beneficial.



Diameter = 70 mm	Diameter = 50 mm	Diameter = 40 mm
Length = 400 mm	Length = 300 mm	Length =240 mm

[7] SudipBasack, et al [2011] -to analyse the response of stone column reinforced soft soil under embankment loading, adopting the free strain approach and considering arching, clogging and smear effects. A design methodology associated with a series of charts and curves for various clogging and smear zone parameters has been suggested by the authors.Utilizing them, a typical design example for stone column reinforcement in a soft clay deposit has been presented. Considering the characteristics of stone column reinforced soft clay, a numerical solution based on unit cell theory was developed by the authors for computing the rate of consolidation, stress distribution, settlement and degree of post-consolidation ground improvement achieved. The free strain hypothesis is adopted for analysis which appears to be more realistic for embankment loading when the arching effect and clogging are taken into account. The comparison of the numerical results with the available solutions and field data indicates acceptable agreement which justifies the validity of the model.

[8]A.P. Ambily& S.R. Gandhi, (2004), have done a research on Experimental and Theoretical Evaluation of Stone Column In Soft Clay. This ground improvement technique has been successfully applied for the foundations of structures like oil storage tanks, earthen embankments, raft foundations etc. where large settlement is possible. Experimental studies were carried out to evaluate the behaviour of stone column by varying spacing, shear strength of soft clay, moisture content etc. the observations given below: When column area alone is loaded, the failure by bulging of column with maximum bulging at 0.5 to 1 times the column diameter below the top. The load settlement behaviour when entire area is loaded is almost linear and it is possible to arrive at the stiffness of the improved ground. The stiffness obtained from model test compares well with that obtained from the finite element analysis compared to the load settlement for s/d of 2 and 3, s/d of 4 is not having any significant improvement.

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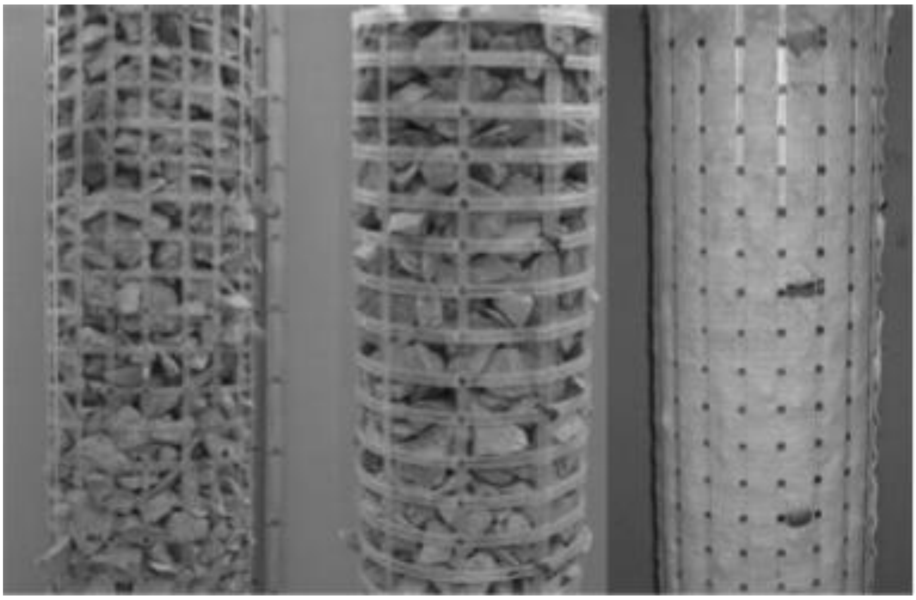
2. Behaviour of geogrid encasements



[1] Ahmet Demir, et al [2013] made an experimental study on behaviour of geosynthetic reinforced stone columns on unreinforced and reinforced soft clay. Firstly, unreinforced tests was carried out and then reinforced with only stone column and geogrid encasement stone column were investigated. Some properties such as, diameter of stone column and encasement effect on improvement of soft clay were also observed. They have concluded with the following findings:Stone column improves bearing capacity of clay bed and decreases settlement.Smaller diameter stone column has lower bearing capacity than larger diameter stone column. Geogrid encasement increases bearing capacity of stone column because bulging behaviour of stone column decrease.Sand embankment increases bearing capacity of stone column slightly but it is not a significant improvement.

[2] Tendal Y.K, et al [2012] A review is Provided Reinforced granular column for deep soil stabilization aiming to identify key considerations for the general use of encased stone columns, To provide insights for design and construction, To compile the latest research developments. Case histories of field applications and observed field performance. Geosynthetic encased stone column reduces settlement almost half that of untreated ground The ultimate bearing capacity of reinforced stone column and stone column treated beds are about three times and two times that of the untreated bed. While theoretical analyses and model testing results indicate that geosynthetic encased stone column methods can be efficient for soft soil improvement, well-documented case histories of successful utilization are rather limited. There remains a great need for well-documented data sets of field performance scenarios. The paper identifies areas where more research is needed and includes recommendations for future research and development.

[3] HamedNiroumand et al [2011] in their research on Soil improvement by reinforced stone columns based on experimental work made a review on ground improvement for using reinforced stone columns in geotechnical engineering projects. There was a special focus on how to performance and evaluate ground improvement using reinforced stone column for special purposes. The previous results indicated the reinforced stone columns significantly increase the bearing capacity and tension of the soil. Based on previous results, critical values were discussed and recommended. The inclusion of horizontal meshes increased the load carrying capacity of granular columns. The performance increased with increasing mesh numbers. It was also found that ductile materials in the plate forms were the best reinforcement arrangement for the granular columns. The geosynthetic encasement prevents the contamination of stone column and thus will not reduce the friction between the stone aggregates and clay bed.

3. Consolidation of stone column with various material

[1] H.A Mahamed Ismail, et al [2011] has done research on Consolidation of sand and aggregate as stone column material. A unit cell is used to study the consolidation under distribution load for aggregate and sand column. An axisymmetric consolidation model using PLAXIS software simulation is used to compare the increasing rate of consolidation for both materials. The concluded with:Stone column installation in soft clays may improve the soil characteristic. The consolidation process can be expedited when installing the stone column. Sand column is the suitable material to be used as stone column in accelerating the consolidation rate.

[2] Jajatikesharinaik [2013], in his research on Load carrying capacity of stone columns embedded in compacted pond ash, attempted to assess the suitability of reinforcing technique by stone columns to improve the load carrying capacity of pond ash deposits through several laboratory model tests. The shear parameters of the compacted pond ash samples reinforced with stone columns of varying area ratios and length ratios are evaluated from triaxial compression test. In addition to this, stone columns having different area ratios and length ratios are introduced in compacted pond ash beds and the bearing capacity of the composite system is evaluated through a series of footing loading tests. Due to the confinement and sample prepared at higher compactive effort attributed to the closer packing of particles, resulting in the increased interlocking among particles. A closer packing is also responsible in increasing the cohesion component and angle of internal friction in the sample.so that the unit cohesion was increased from 0.106 kg/cm2 to 0.239 kg/cm2 and angle of internal friction was increased from 19.870 to 37.40. The UCS tests among all area ratio and their respected length ratio of reinforced stone columns as increasing of area ratio of reinforced pond ash the stress value has decreased with the decreased of strain.

[3] S.N. Malarvizhi and K. Ilamparuthi [2010] have done a research on Load versus settlement of clay bed stabilized with stone &reinforced stone columns. Load tests were performed on soft clay bed stabilized with single stone column and reinforced stone column having various slenderness ratios and using different type of encasing material. Encasing the stone column with geogrids resulted in an increase of load carrying capacity irrespective of whether the column is end-bearing or floating. In case of floating columns the l/d ratio has less influence on the capacity of column for the lengths studied in this investigation.The ultimate load capacity of the reinforced column increases with the stiffness of the reinforcement. The ultimate bearing capacity of reinforced stone column and stone column treated beds are three times and two times that of the untreated bed.The encased stone column is stiffer than stone columns, thereby reducing the load on clay, consequently reducing the settlement.

[4] Castro J.et al[2013]- made a research on Foundations of embankments using encased stone columns. This paper presents a closed-form solution to study soft soil improvement, both reduction of settlement and consolidation time, by means of encased stone columns. An end-bearing column and its surrounding soil, is modelled in axial symmetry under a rigid and constant load. Soil is assumed as elastic but plastic strains are considered in the column. Parametric studies of the settlement reduction and stress concentration show the efficiency of encasing the columns, which is mainly ruled by the encasement stiffness compared to that of the soil. Therefore, encasing stone columns is recommended in very soft soils and the encasement should be stiff enough. Besides, the settlement reduction decreases with the applied load.

4. Performance analysis of reinforced stone columns by numerical modelling

[1] DiptySarin Isaac Girish M.S. [2009], Suitability of different materials for stone column construction . The influence of column material in the performance of stone column is studied through laboratory experiments on model stone columns installed in clay. The unreinforced soil under the same loading condition was analysed. It was found that stones are the most effective stone column material. Quarry dust, though a waste product is effective in improving the load deformation characteristics of the soil used. Experimental study on behaviour of group of three columns and seven columns was also conducted. A finite element analysis using 15-noded triangular elements with the software package PLAXIS was also carried out. Among the different stone column materials used, stones are found to be more effective from single column test and group column test.

Quarry dust, though a waste product is effective in improving the load deformation characteristics of the soil used and its performance is comparable with that of sand. Hence quarry dust can be economically and effectively used for stone column construction as it is cheap and easily available. Stress-settlement response is predicted by the finite element method and found matching with experimental results.

[2] Tendel YK, et al [2012], conducted research on Suitability of different materials for stone column construction. Five reinforcement materials were studied: stones, gravel, river sand, sea sand and quarry dust. Load versus settlement response was determined. The unreinforced soil under the same loading condition was analysed. It was found that stones are the most effective stone column material. Quarry dust, though a waste product is effective in improving the load deformation characteristics of the soil used. Experimental study on behaviour of group of three columns and seven columns was also conducted. A finite element analysis using 15-noded triangular elements with the software package PLAXIS was also carried out. Among the different stone column materials used, stones are found to be more effective from single column test and group column test. River sand is more effective than sea sand. Gravel is more effective than sand in general, though river sand behaves similar to gravel in some cases. Stress-settlement response is predicted by the finite element method and found matching with experimental results.

[3] J. PIVARČ [2011] in their paper 'Stone columns – determination of the soil improvement factor dealt with Priebe`s theory (1976) on the design of an improvement factor, which is one of the most used analytical methods and also describes the numerical and laboratory models of stone columns. The improvement factors calculated from numerical and laboratory models were compared with the improvement factors resulting from Priebe´s theory. A comparison of all three approaches to estimate the soil improvement factor by the stone columns with Priebe´s original diagram. The agreement between the improvement factor calculated by Priebe`s method, the FE method and obtained from the laboratory experiments appear satisfactory. All the models in this study were prepared by the vibro- replacement method, which means that soil was removed out from the hole and not compacted to the sides such as in the vibro-displacement method.

[4] Yashwant A. et al [2013] Studied on behaviour of stone columns subjected to cyclic loading. Studies were conducted in the laboratory to understand the behaviour of stone column reinforced ground when subjected to moving loads, which are cyclic in nature. The clay bed was prepared using slurry consolidation method, and behaviour of 100 mm diameter stone column has been studied. The frequency of the vibration in the study is chosen as 0.1 Hz and 1.0 Hz, which is the observed range for moving loads. There is 4 times increase in the strength of clay bed when reinforced with stone column.At lower frequencies higher settlements were observed.Lower frequencies result in higher vertical stiffness ratio.

[5] Mahmoud Ghazavi.K and Toosi N [2011] have made an analysis of stone columns reinforced weak soil under harmonic vibrations The stone column is divided to series of lumped masses connected by springs and dashpots. The springs simulate the axial stiffness of the column material and the dashpots reflect the material damping properties of the stone column material. The reaction of the surrounding soil is taken into account by attaching some springs and dashpots. The former simulates the dynamic soil stiffness and the latter simulates the geometric damping due to wave propagation within the surrounding soil. In soil-stone column system, the stiffness and damping related to change of a0 is respectively 9.1 and 6.6 times greater than that of soil-concrete pile system. In soil-stone column system, the stiffness and damping related to change in slenderness ratio is respectively 9 and 7 times greater than that of soil-concrete pile system. The effect of frequency on variation of stiffness and damping of stone columns is more than that slenderness ratio.

[6] Mahmoud Ghazavi and Samira Ebrahimi [2010] Analysis of stone Reinforced weak soil under harmonic vibrations. An element stone column is considered and reaction of the soil on loading the column is modelled using a one-dimensional simulation. The governing differential equation of the stone column- soil element is derived. For this purpose, the stone column is divided to series of lumped masses connected by springs and dashpots. The springs simulate the axial stiffness of the column material and the dashpots reflect the material damping properties of the stone column material. Columns reinforced weak soil under harmonic vibrations. With increasing mechanical properties of stone column and its length, the vibration amplitude decreases. For small Vs/Vc, a stone column has better operation than concrete pile.The effect of dimensionless frequency

variation on stone column amplitude is negligible. In soil-stone column system, the stiffness and damping related to change of a0 is respectively 9.1 and 6.6 times greater than that of soil-concrete pile system. In soil-stone column system, the stiffness and damping related to change in slenderness ratio is respectively 9 and 7 times greater than that of soil-concrete pile system. The effect of frequency on variation of stiffness and damping of stone columns is more than that slenderness ratio.

[7] AminatonMarto, et al [2013] in their study on Performance analysis of reinforced stone columns using finite element method, Settlement and bearing capacity of stone columns and geogrid encased stone columns in terms of various diameters were selected as criteria for judgment and comparison of the behaviour of the ordinary and geogrid encased stone columns.The load capacity of the stone column can be increased by the increase of the diameter of the column and for a specific settlement the stone column with bigger diameter can afford higher load than the smaller diameter stone column.The load capacity and stiffness of the stone column can be increased by all-round encasement by geogrid. By geogrid encasement, it is found that the stone columns are confined and the lateral bulging is minimized. The elastic modulus of the geogrid encasement plays an important role in enhancing the capacity and stiffness of the encased columns. The magnitude of loads transferred into the encased stone columns can be increased by using stiffer encasement this is due to the confining pressures generated in the stone columns are higher for stiffer encasements.

[8] Zahmatkesh& A. J. Choobbasti [2010] Researched on Settlement evaluation of soft clay reinforced by stone columns, considering this paper investigates the performance of stone columns in soft clay. Finite element analyses were carried out to evaluate settlement of soft clay reinforced with stone columns using 15-noded triangular elements using Plaxis software. A drained analysis was carried out using Mohr-Coulomb's criterion for soft clay, stones, and sand. Variation of stress in soft soil after installation of column with distance from column is significantly reduced. The load settlement behaviour of model with an entire area loaded is almost linear and it is possible to find the stiffness of improved ground. Effect of the strain on the SRR is small due to vertical stress versus settlement relation is almost linear. Floating stone columns in high area replacement percent, because of used frictional material significantly reduce settlement.

[9] BahadorReihani&Masouddehghani [2010] have done the modelling of ground improvement with stone columns. An analysis was carried out using the commercially available finite-element program PLAXIS, to compare the load settlement behaviour with the model test. A parametric study was carried out to investigate the behaviour of standard and encased floating stone columns in different conditions. Different parameters were studied to show their effect on the bearing improvement and settlement reduction of the stone column. The bearing improvement ratio and the settlement reduction ratio are increased with decrease in undrained shear strength of the surrounding soil for all end bearing soil undrained shear strengths. With increasing the friction angle of clayey soil, the bearing capacity of stone columns increase. With increasing the modulus of elasticity of stone columns materials, the bearing capacity of stone columns increases.

[10] S.N. Malarvizhi and K. Ilamparuthi [2010] in their study on Mechanism of geogrid encased stone column, conducted Model tests in the laboratory on stone columns and encased stone columns and they were simulated numerically using PLAXIS FE code and results were compared with experimental results. The results of numerical analysis are analysed to establish the mechanism by which stone column and encased stone column derive their resistance. They have concluded that The stone column derives its resistance by its bulging over a length of 4d to 6d under the load with maximum bulging at the depth around 2d. The column material offers passive resistance against bulging. This passive resistance coefficient was found to be close to the passive resistance of column material. This response is seen irrespective of the end condition of the column. The magnitude of bulging of encased stone column for a given settlement is far less than the stone column despite all the conditions being the same for both except encasement. The significant reduction in the radial bulging is due to the stiffness of the encasement.

[11] Zahmatkesh& A. J. Choobbasti [2010] Researched on Settlement evaluation of soft clay reinforced by stone columns, considering this paper investigates the performance of stone columns in soft clay. Finite element analyses were carried out to evaluate settlement of soft clay reinforced with stone columns using 15-noded triangular elements using Plaxis software. A drained analysis was carried out using Mohr-Coulomb's

criterion for soft clay, stones, and sand. Variation of stress in soft soil after installation of column with distance from column is significantly reduced. The load settlement behaviour of model with an entire area loaded is almost linear and it is possible to find the stiffness of improved ground. Effect of the strain on the SRR is small due to vertical stress versus settlement relation is almost linear. Floating stone columns in high area replacement percent, because of used frictional material significantly reduce settlement.

[12] BahadorReihani&Masouddehghani [2010] have done the modelling of ground improvement with stone columns. An analysis was carried out using the commercially available finite-element program PLAXIS, to compare the load settlement behaviour with the model test. A parametric study was carried out to investigate the behaviour of standard and encased floating stone columns in different conditions. Different parameters were studied to show their effect on the bearing improvement and settlement reduction of the stone column. The bearing improvement ratio and the settlement reduction ratio are increased with decrease in undrained shear strength of the surrounding soil for all end bearing soil undrained shear strengths. With increasing the friction angle of clayey soil, the bearing capacity of stone columns increase. With increasing the modulus of elasticity of stone columns materials, the bearing capacity of stone columns increases.

[13] Murugesan & Rajagopal [2010] made a research on Experimental and numerical investigations on the behaviour of geosynthetic encased stone columns to analyse the performance of geosynthetic encased stone columns in very soft soils. The stone columns, particularly installed in very soft soils, may not be able to resist these shear movements because of the low confinement offered by the surrounding soil. The shear load capacity of such stone columns can be significantly improved by encasing the individual stone columns with suitable geosynthetic. The encasement confines the aggregate and makes the stone column act like a semi rigid pile; thus leading to increased shear stiffness of the column.

Conclusions:

From the review of above mentioned literatures, it has been observed that

1. The performance of encased stone column of smaller diameters is superior to that of larger diameter stone columns for the same encasement because of mobilization of higher confining stresses in smaller diameter stone columns.
2. The ultimate load capacity of the reinforced column increases with the stiffness of the reinforcement.
3. Geosynthetic encased stone column reduces settlement almost half that of untreated ground.
4. The ultimate bearing capacity of reinforced stone column and stone column treated beds are about three times and two times that of the untreated bed.
5. While theoretical analyses and model testing results indicate that geosynthetic encased stone column methods can be efficient for soft soil improvement, well-documented case histories of successful utilization are rather limited. There remains a great need for well-documented data sets of field performance scenarios.

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