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A Review of Soil Stabilization Using Stone Columns Technique

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ABSTRACT
Soft clay soils are in many coastal areas, these soils generally have high compressibility and don't provide required bearing capacity. Various techniques are used to improve these soils. The stone column technique has been successfully applied for the ground improvement. A stone columns technique 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 silty sand. Several research has been conducted on the behavior and performance of stone columns with various materials utilized as column filler replacing the normal aggregate. This paper will review extensively on previously conducted research on some of the materials used as stone column backfill materials, its suitability, and the effectiveness as a substitute for regular aggregates in soft soil improvement works. This paper also discusses the techniques and methods of construction of stone columns. The bearing capacity of stone columns, and a combination of both methods in reinforced and unreinforced modes are presented using scaled physical models. The effect of various diameters with various depths in ground also reviewed. Results show that using stone column improves bearing capacity of soft soils and decreasing settlement. Using geotextile as stone-column encasement increases the efficiency of stone columns significantly. Finally, some guidance and recommendations are provided on parameter selection for the study of stone columns.

Keywords: Stone Column, Soil Stabilization, Soil Improvement, Problematic Soil, Encasement, Geosynthetics, Bearing Capacity, Compressibility.

1. Introduction

All around the world, soft soils are typically found close to river estuaries and coastal regions. Near the northern and north-eastern shores of Egypt, the soft soils are located, where future investment projects are promised. The structures which constructed on these weak soils may cause collapses because of its low bearing capacity, excessive settlement characteristics during and for long time for construction, unstable slopes, and unstable excavations. However, there are various techniques that can be used to solve those problems, such as excavating and replacing the soft soils with suitable soils, using deep foundations, Stabilizing the soft soils with injected additives such as lime, geosynthetic or fibre reinforcement of the soft soil deposits, Preloading with or without vertical drains, vacuum preloading method, deep dynamic compaction, and ordinary or encased stone columns Hammad et al. (2014). The use of stone columns is an effective and reliable method for improving the properties of soft soil and solving such issues. It is considered to be both economical and environment-friendly method. In addition to the simplicity of construction, it is one of the advantages for using stone columns that researches had proved that the stone column has high performance in reducing consolidation and increasing bearing capacity Sharma et al. (2014a); Almeida et al. (2013); Dash et al. (2013b); Elsawy et al. (2013); Mohapatra et al. (2016); Murugesan et al. (2009); Yoo et al. (2010); Yoo (2012); Zhang et al. (2012)

2. Stone Columns

Stone columns are considered one of the best ground engineering methods for improving weak soils such as loose sands and soft clays. Stone columns consist of crushed coarse aggregates of various sizes filled in a cylindrical form in the ground. These columns typically have diameters between 0.6 and 1.0 m. Stone columns are used worldwide for increasing the bearing capacity of the weak soils and significantly decrease the settlement Abdel Hay et al. (2017). There are two types of stone columns: end bearing type and floating type as shown in Fig. 1.

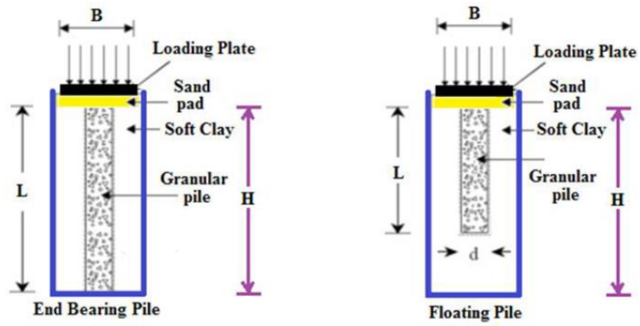

Figure 1: Types of stone columns.

Ali et. al., (2012) studied experimentally various stone column depths, floating and end bearing types with and without encasement and the results showed that using the encasement is the best way for fully penetrated columns. In end bearing stone columns, geogrid showed the best results as compared to geotextile for encasement. Ali K et. al., (2014) investigated the effect of end bearing and floating for single and group of stone columns with and without encasement and due to various methods of encasement. The results showed that the end bearing columns geogrid was the ideal method for enhancement soil properties. Javad et. Al., (2022) studied experimentally the construction method effect on stone columns performance. Spoorthi et. Al., (2018) investigated the effect of soft soil strength with and without stone column, with stone column reinforcement, and the optimum of stone column spacing, and the results showed that the reinforcement increased the strength and stiffness of the stone column, thus enabling quicker and economical installation. Ghazavi et. al., (2018) studied experimentally for various types for stone columns encasement of 60, 80 and 100 mm diameters and 60 mm diameter in stone column groups. The results showed that significantly increasing in bearing capacity while lateral bulging reduces by interlocking and frictional effects with infill aggregates. Niroum et. al., (2011) studied the performance of using stone column encasement for increasing bearing capacity of soft clay soil. The results showed that using reinforced stone column enhancing soil engineering properties. Mokhtari et. al., (2012) studied the effect on stone column in soft clay soil and the results showed that stone column was observed significantly effect on isolated and raft footings. Mani et. al., (2013) studied the effect of using stone column in coastal region to enhance the soil engineering properties such as bearing capacity and settlement. Castro (2017) investigated the effect of encased stone column in a group considering the influence of column length and arrangement and the results showed that encased stone columns played an important rol e in improving soil engineering performance(Castro 2017). Babu et. al., (2013) reviewed the details of a stone column construction and their analysis.

2. Methods of Stone Columns Construction

Stone columns have been installed using various methods over the years as shown in Fig. 2. In construction stone columns, unsuitable subsurface soils are partially replaced with a compacted vertical stone column that typically completely penetrates the weak layers of soils. The most common methods of installation stone columns have been proposed in the following:

1- **Replacement method** involves replacing in-situ soil with stone column materials. A vibratory probe (vibroflot), accompanied by a water jet, is used to create the holes for the columns. This technique is suitable when the ground water level is high, and the in-situ soil is relatively soft.

2- **Displacement method** is utilized when the water table is low and the in-situ soil is firm. It involves using a vibratory probe, which uses compressed air, to displace the natural soil laterally.

3- **Case-borehole or rammed columns method** is also used. In this method, the piles are constructed by ramming the granular materials in the prebored holes in stages using heavy falling weight (Ambily and Gandhi et al. 2007a; Dheerendra Babu et al. 2013; McCabe, Nimmons, and Egan et al. 2009; Mokhtari and Kalantari 2012; Nazariafshar et al. 2022a).

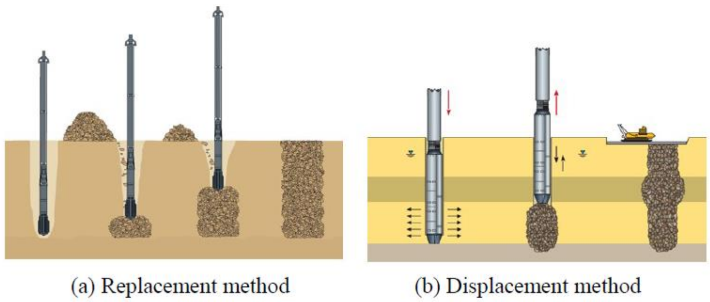

Figure 2: Installation techniques methods of stone columns (Hammad et al. 2014).

Table I shows the most important references for laboratory studies of weak soils reinforced with Encased stone columns which illustrates the replacement method as the most used method in installation stone columns. It is also clear that little research has been conducted on the displacement method.

Table 1
Existing investigational study findings (modified after Pandey et al. (2022)).

Researchers	Type of study	Installation method
Erfan et al. (Naderi, Asakereh, and Dehghani 2018a)	Laboratory	Replacement
Javad et al. (Nazariafshar et al. 2022a)	Laboratory	Replacement & Displacement
Ambily et al.(Ambily and Gandhi 2007a)	Laboratory	Replacement
Ghazavi et al. (Ghazavi and Nazari Afshar 2013a)	Laboratory	Replacement
Gniel and Bouazza (Gniel and Bouazza 2009)	Laboratory	Replacement
Das and Bora (Dash and Bora 2013a)	Laboratory	Replacement
Gu et al. (Gu et al. 2016)	Laboratory	Replacement
Hong et al. (Hong, Wu, and Yu 2016)	Laboratory	Replacement
Miranda et al. (Miranda et al. 2016)	Laboratory	Replacement
Sivakumar et al. (Sivakumar et al. 2004)	Laboratory	Replacement
Yoo and Lee (Yoo and Lee 2012)	Laboratory	Replacement
Gniel and Bouazza (Gniel and Bouazza 2010)	Field	Replacement
Black et al. (Black et al. 2007)	Laboratory	Displacement
Murugesan and Rajagopal (Murugesan and Rajagopal 2006)	Laboratory	Displacement
Murugesan and Rajagopal (Murugesan and Rajagopal 2009)	Laboratory	Displacement
Sharma et al. (Sharma, Kumar, and Nagendra 2004a)	Field	Replacement

3. Basic Design Parameters

3.1. Stone column diameter

The construction of stone columns in soft soil has basic considerations. The softer the soil, the bigger is stone column diameter installed. The diameter of the stone column varies between 0.6 m in stiff clays to 1.1 m in very soft clay. Laboratory, stone column diameters ranging from 20mm to 200mm have been used by researchers (Baviskar et al. 2018; Pandey et al. 2022).

3.2. Stone column spacing

The stone columns design should be based on the needs of the site, and there is no specific value to determine the minimum and maximum stone columns spacing. However, the stone columns spacing vary from 2 to 3 times the stone column diameter depends on several different factors, such as the site conditions, loading pattern, column factors, the installation method and settlement tolerances. Researchers showed that the optimum stone columns spacing giving maximum performance improvement is 2.5 times diameter (Dash and Bora 2013b). For large projects, it is preferable to conduct field experiments to calculate the optimum of stone columns spacing, considering the soil bearing capacity and the foundation settlement (Baviskar et al. 2018; Dheerendra Babu et al. 2013; Rao et al. 2011; Suriya et al. 2017).

3.3. Filler Materials of Stone Columns

Filler materials of stone columns require important specifications to enable to reinforce the weak soil and thus strengthen it. Filler materials consider an important parameter in designing stone columns. Natural aggregates have been utilized in construction projects for a long time. But at present, the world is moving towards sustainable construction and reusing recyclable materials if possible. In addition, it is getting harder to find sand and gravel from natural sources. Consequently, considering sustainable options as alternatives is the best solution. There are three important factors when choosing filler materials, such as availability, suitability, and economy. Researchers are studying the possibility of using sustainable and recycled materials and their effect on improving weak soil properties (Ghazavi et al. 2013a; M. A. Mohamad Ismail et al. 2011; Siva Gowri Prasad et al. 2016; Zahmatkesh et al. 2010). It was agreed by many researchers who evaluated the effectiveness of filler materials and found their positive effect significantly in improving soil properties(George et al. 2016; Nazaruddin et al. 2013; Palaniappan et al. 2013; Prasad et al. 2015). The column material size is chosen based on the ratio of the column diameter (D) to the column material size (d). The range of D/d value lies in 4.72–62.5(Malarvizhi et al. 2006; Pandey et al. 2022; Wood et al. 2000). Table II shows various types of stone column filler materials that were used by to stabilize the soil.

Table 2
Previous Studies for Various Types of Filler Materials of Stone Columns

Researcher	**Filler materials**
Ambily et al. (2007b) *Kousik et al.* (2009) *Ghazavi et al.* (2013b)	Crushed stone aggregates
Naderi et al. (2018b)	Gravel (2-10mm)
Spoorthi et al.(2018)	Coarse aggregate (Well-graded aggregates)
Hataf et al. (2020)	Aggregates with 3 different sizes
Javad et al. (2022b)	Gravel
Andreou et al. (2008)	-Sand -gravel
Dipty Sarin Isaac (2008)	-clay - quarry dust -sea sand -river sand -gravel -stones
Vidhyalakshmi et al. (2009)	Fly ash aggregate
Pivarc, (2011)	Crushed stones (gravel)

Balan et al.(2015)	-gravel -quarry dust
Shakri et al. (2014)	PFA
Hassan et al. (2016)	crushed polypropylene
Akhitha, (2017)	Tyre chips

3.4. Area replacement ratio

Area replacement ratio is defined as the ratio of area of the stone pile (A_p) to the total area within the unit cell (A):

$$A_r = \frac{A_P}{A} \qquad (1)$$

Where.

A_r= area replacement ratio

A=area of the stone pile

A_p=the total area within the unit cell

An area replacement ratio of 0.25 or higher is needed for treated ground for stone columns in order to significantly improve in bearing capacity (Dheerendra Babu et al. 2013; Wood et al. 2000).

3.5. Critical Column Length

The length of the columns is an important parameter in designing stone column. It could be more economical to add columns rather than increasing length (Miranda et al. 2021). There are several proposals for the critical length of the columns the available information could be confusing as detailed in the next section.

Dash et. Al., (2013) showed that the optimum length of stone columns giving maximum performance improvement is 5 times diameter. Researchers showed that for control of bulging failure mode a minimum L/D=4 (length to diameter of the stone column equal to 4) is required (Ghazavi et al. 2013b; Naderi et al. 2018b) Others recommended to consider a L/D ratio of greater than 5, to ensure punching shear will not happen (Nazariafshar et al. 2022b).

4. Granular blancket(Bed)

A granular layer with 0.3 m thickness or more is carried out on the top of the ground of stone column for drainage purposes and to distribute the stresses coming from superstructures (Dheerendra Babu et al. 2013). Bulging and subsequent failure of granular pile occur near the top of the granular pile because of high-stress concentration in that region.

Many researchers investigated the effect of the presence of sand bad and its thickness on the efficiency of stone columns to improve soil properties and they showed that the existence of sand bed decreases the stone columns bulging, and the reduction is more significant with the inclusion of geogrid layer in the sand bed2006; Deb 2008; Deb et al. 2007; Deb et al. 2008; Dheerendra Babu et al. 2013).

5. Failure Mechanisms

Stone columns may fail through different failure mechanisms if the necessary precautions are not taken. Single stone column or stone columns group, loading condition, column length (i.e., floating or end bearing), the strength of the surrounding soil, column material, and the encasement are the parameters defining the failure modes of stone columns(Pandey et al. 2022).

In homogeneous soil, when a stone column with end bearing is loaded over its diameter, it fails in bulging for (L/d >3) and occurs local shear failure for (L/d<3) (show in Fig. 3b). So, reinforced stone column with geosynthetic which limits lateral spreading and compression decrease the bulging (show in Fig. 3c) (Hong et al. 2016; Murugesan et al. 2009; Pandey et al. 2020; Pandey et al. 2022). With increasing the stiffness of encasement, the bulging can be reduced. Consequently, when the reinforcement is partially for the stone columns, the bulging appears in the other part (show in Fig. 3d) (Ali et al. 2014b; Dash et al. 2013a; Gniel et al. 2009; Gu et al. 2016; Pandey et al. 2022). Failure modes of stone column groups depends on the loading type and lateral spreading (show in Fig. 3e) (Pandey et al. 2022). While in non-homogeneous soil collapse occurs in the weakest soil layer(Pandey et al. 2022; Wood et al. 2000). The encasement failure, either mesh failure or failure of the bonded zone, is another predominant failure occurring due to an increase in the hoops stress beyond its ultimate strength (show in Fig. 3f)(Dheerendra Babu et al. 2013; Pandey et al. 2022).

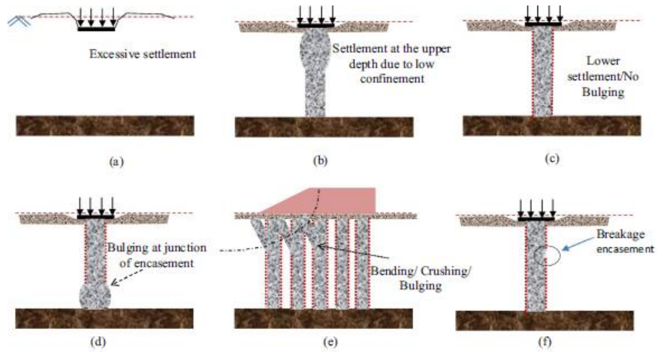

Figure 3: Schematic representation of some of the failure modes for different composite ground Pandey (2022).

6. Encased Stone Columns

Encasement of Stone columns as shown in Fig. 4 are widely used to improve the engineering properties of weak soils such as increasing bearing capacity and decreasing settlement.

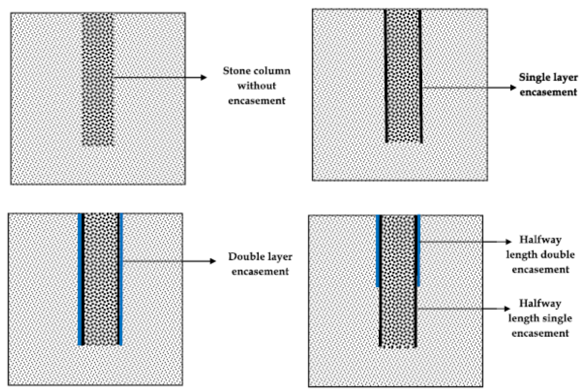

Figure 4: Schematic representation of encased stone columns (Rathod, Abid, and Vanapalli 2021)

There are two installation method to encase stone columns, either by replacement or displacement methods as previously explained (Pandey et al. 2022). Geosynthetic materials are used as a type of the stone column encasement. Geosynthetic encasement can be used to extend the use of stone columns for extremely soft soil condition(Dheerendra Babu et al. 2013). This encasement gives the stone column more confinement and has a number of benefits, including enhanced stiffness of the column, prevention of stone loss into the surrounding soft clay, preservation of the drainage and frictional properties of the stone aggregates, etc(Alexiew et al. 2005; Dheerendra Babu et al. 2013; Gniel et al. 2009; Kempfert et al. 2006; Murugesan et al. 2006, 2007; Prisco et al. 2006). There are two different methods of encased stone columns as horizontal encasement and vertical encasement. Stone columns can be reinforced horizontally with geosynthetic materials to reduce the bulging and increase the load-carrying capacity(Sharma et al. 2004b; Wu et al. 2009) as shown in Fig. 5.

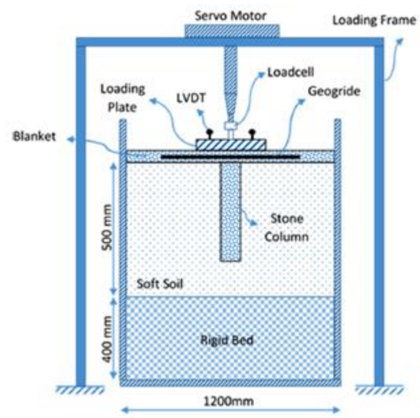

Figure 5: Schematic diagram of test setup of horizontal encased blanket (Mehrannia, 2018)

Number of studies have been conducted to examine the behaviour of reinforced stone columns (Ambily et al. 2007b; Black et al. 2007; Bouassida et al. 2009; Elshazly, Hafez et al. 2007; Murali Krishna et al. 2007; Wood et al. 2000). Yoo (2012) performed field tests to investigate the effect of settlement and load carrying capacity on geogrid-encased stone column. The results show that significantly improvement for encased stone columns. Gu et. al., (2016) performed laboratory tests on various encased stone column lengths (Gu et al. 2016). The results show that the effective encased stone column length was at three to four times column diameter based on the consideration of performance and effective cost. Hasan and Samadhiya., (2017) investigated laboratory the performance of encasement on stone columns in very soft clay soil. Results show the improvement of using geosynthetic encased stone columns on soil engineering properties. Schnaid et. al., (2017) conducted a numerically case study about bridge abutment on geotextile-encased columns in soft clay soil. The performance was significantly improved by reducing the horizontal earth pressure up to 50%. Chen et. al., (2018) investigated laboratory triaxial and uniaxial tests on unreinforced and reinforced stone columns. The significant performance of encased stone columns is achieved. Dash and Bora., (2013) investigated laboratory tests on the performance of geosynthetic encased stone column in soft clay soil. The results show the improvement of encased stone columns that reduces bulging. Miranda and Da Costa., (2016) performed laboratory tests on encased stone columns to enhance soft clay soil. The results show the improvement of using encased stone columns compared with unreinforced stone columns. Miranda et. al., (2017) conducted series tests in laboratory to investigate the effect of using encased stone columns with different material on soil properties. The results show the significant enhancement of using geotextile as a material of encased stone columns on soil engineering properties. Castro., (2017) conducted analytical study to investigate the effect of using reinforced stone columns beneath a rigid footing. The results show the improvement of using fully encased stone columns on soft soil(Castro 2017). Naderi. et. al., (2018) performed laboratory tests and numerical modelling to investigate the effect of existence and location of stone column on bearing capacity of strip footing near soft clay slope. Results show that reinforcing clay slope with stone column in all situations leads to increase in bearing capacity of strip footing.

7. Conclusion

Stone columns technique is one of the best methods to improve weak soil such as very soft and soft clays, and loose silty sands. Studies for the design of stone columns are still ongoing, and experience plays an important role in finding the best design. Specific conclusions based on the critical review of the available literature on stone columns are as follows:

- Stone columns in soft clay soils are normally installed by replacement method or displacement method. In environmentally sensitive areas, Stone columns are often constructed using replacement method and not much experimentation has been done with displacement method.
- Previous studies have highlighted on some different factors that affect the performance of stone columns such method of installation, column diameter, column length, column spacing, area replacement ratio and filler material of stone columns.

- Laboratory tests should be performed under drained conditions, particularly with drainage being permitted from the top of the columns.
- using geosynthetic encased stone columns showed improvement in strength and stiffness of soft clay soil and decreasing bulging of columns.
- Decrease in bulge diameter and increase in depth of bulge have been observed due to placement of sand bed over stone column-improved soft clay. Further decrease in maximum bulge diameter and increase in depth of bulge have been observed due to application of geogrid.

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