A Review article on Construction, Parametric Study and Settlement Behavior of Stone Column

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Abstract

The various geotechnical construction technique is being primarily used of the ground improvement. The current advancement of industrial and urban growth and also the need for the wider access to the land have resulted in the development of various soil improvement methods. Stone column happens to be one among the best possible available methods for the improvement of soft/weak soil. This paper tries to indicate the review of the ground improvement by one of the existing method of stone column from the already present literature and standards. In this method, the soft soil is being enforced with a column of stone which is installed in the system. The high permeability of the stone column's material portion not only increases the soil's load carrying capability, but also decreases soil settlement, up to a certain extent and thus minimizes the settlement to occur after the construction. In order to reach this goal, various essential characteristics of stone columns have been considered in relation to design parameters.

Keywords: Ground improvement; Stone column; Soft clay; Settlement.

1. INTRODUCTION

Variety of geotechnical methods of construction are being utilized to enhance the performance of weak/soft clay. The key driving force behind the use of ground improvement techniques is the continuing advancement in urban and industrial development, as well as the increasing demand for buildings on soft clay soil. Hereby, the need arrived for the performance of land reclamation to use such type of lands. Thereby, it has been discovered possible to use the ground improvement strategies to upgrade such unproductive lands.

The soft type of soil is usually spread over vast areas that generally have lower bearing capacity, high compressibility, lower permeability and inadequate strength.[1],[2]. The flocculated structure of cohesive soil making them unstable, and further gets compressed while subjected to increasing overburden pressure. Compressive soils can be strengthened using a number of strategies, including compaction piles, displacement type and replacement type; vacuum pre-consolidation, the use of prefabricated vertical drains, and soil reinforcement [3]. The factors on which the solutions required for ground improvement majorly depends are the soil type at the site, prevailing ground conditions, size of the site and treatment area, location of the site, design loads[1].

At various site with weak ground criteria, instead of replacing the weaker soils by piled foundations, the economical approach is by improving its bearing capacity. These ground improvement techniques are found cost effective as it uses almost 50% of that cost as of a piling strategy [4]. Stone column are said to be one among the most environment friendly and cost-effective methods which are installed in weak soil deposits to improve its problems. This method helps in reducing the excessive and differential settlement and can also help in accelerating the consolidation process[5][6]. In this process, a small portion of non-suitable subsurface soils, are removed and restored with that of a stone column which is compacted which often permeates with the soft layers[6]. Due to the material component of the stone column and its high permeability, it does not only upgrade the bearing capacity of that of weak soil but also helps in reduction of the settlement to a certain extent and thereby minimizes the post construction settlement behavior. In fact, this column of stones also work as a vertical drains which makes the consolidation process rapid[7]. Moreover,
compacting the granular materials while installing it and then replacing it with the weaker soils which is a stronger materials and thereby increase the unit weight of soil significantly[1].

The major objective of this paper focuses on analyzing the various possible methods of construction of stone column prevailing recently, detailed study of the various design parameters involved, studying its performance mechanism along with its uses, analyzing the settlement behavior and also its failure mechanism. This paper also deals with the current advancement in this field, mainly with the encasement of the stone column.

2. CONSTRUCTION METHODS OF STONE COLUMN

The construction method for a stone column depends upon the availability and applicability of the equipment. For creating a column of desired strength, granular matter be it stone or a sand must be compacted to desired level[7]. The following section, hereby, briefly explains the basic construction principal according to the available literature.

2.1 Vibro-Replacement Method

This type of construction and installation of a stone column is being highly preferred in the cohesive soils. A vibro-flot which is a mechanical unit of vibration is being used to make a hole at the site and then granular material is compacted inside the hole. As Fig 1 suggests that the construction of stone column could be done either of the wet process or that by a dry process depending upon that of accessibility of the equipment and the condition of the ground. Faster speed and better depth of execution are the major advantages of this method[8].

2.2 Vibro-Composer Method

This type is mostly used to sustain the weak clay soils mostly in those regions where there is a high level of groundwater. The diameter of column of around 600-800mm can be constructed without any difficulty with this method. The casing pipe is penetrated to the required depth for the granular compactions using a vertical vibratory hammer which is heavy and placed at the very top of the pipe. The pipe used for casting is continuously extracted and the driven back partially into the soil with the help of vibratory hammer which starts around the bottom (Fig 2). This procedure of penetration is done continuously till a fully complete penetration of compacted granular pile is erected[7][9].

2.3 Rammed Columns or Cased Borehole Method

Here, the pre-bored holes are being filled with compacted granular materials in several stages, by a heavy weight that is dropping which ranges between 15 to 20 kN when viewed from a height that of around 1.0-1.5 m which can be depicted in Fig 3. This type of method is costly and works in a very slow manner once the depth of the soil layer is greater than 12-15 m[7][9].

Fig. 1. Vibro-replacement technique -wet process and dry process [7].
3. PERFORMANCE MECHANISM

The design load usually varies between 20 to 50 tons for stone column. And around 15 to 35 % of the loose and weak soil is being substituted by a stronger material like sand/stone. There was relatively major difference found between the shear strength of soil replaced with that of a stone column to that of native soil. This presence of a stiffer material lower down the overall compressibility, a larger shear strength. The stone is being experienced by a vertical stress applied around the surface at the ground level and the soft soil starts moving downward. As a result of the column's higher stiffness as compared to the surrounding soil results in the concentration of stress in the stone column. Due to the axial load, a large bulge takes place at around 2-3 meters under the surface. This bulge results in the extra confinement for the column due to the increased stresses. As contrast to that of the stone column in groups, more bulging is seen to occur in a single stone column[9][10].

4. USES OF STONE COLUMN

The method of stone column has usually been found effective and helpful in (1) improving embankment and natural slope stability (2) enhancing the bearing capacity (3) Lowering down the total and differential settlement (4) lowering down the risk of sand liquefaction (5) taking the settlement time rate upward. Stone columns are used to strengthen characteristics of the soil and help the structures that are constructed on top of fully soft to barely firm cohesive soils, also in loose silty soil/sands with fine aggregates being greater than 15 percent[9]. All around the globe, this method of stone column is being utilized in embankment support, highway development, abutments of bridges, railroads and various other structures. Specifically, in Europe, stone columns are extensively used to provide support to the structures such as tanks, buildings and warehouse instead that of embankments. In Japan, it is being used to support fills, tanks, embankments and also structures. Stone columns can also be very handy in controlling the liquefaction potential of a cohesion less soil which surrounds a proposed or existing foundation or is supporting embankments, abutment and even below shallow foundations in earthquake prone zones and even stabilizing the existing slopes[9].

5. BASIC DESIGN PARAMETERS

A. Stone column Diameter, \( D \)

The diameter created for the hole is always larger than the casing diameter as vibration or ramming must causes lateral displacement. In the method of vibro-flot, the stone column diameter varies from 0.6m in the stiff clays case to that of 1.1m in most soft cohesive sample of soil. The stone column’s diameter created by the wet method is
larger to that made by dry method[11]. While using the rammed process, the diameter of the stone column is between 400 to 750 mm. The diameter of the column is being impacted by the maximum and minimum densities of the stone and also that of length of the column[7].

B. Pattern and Spacing

The most possible pattern for installing the stone column is a square pattern, but the most effective, desirable and optimum shape for the installation is triangular type of pattern because it provides one among most compacted along with dense pack of the stones in the column in a given specific area. The proper layout of the triangular and square patterns is shown in Fig 4.

It is to be noted that, diameter(d_c) and spacing (S_c) highly impact the value of settlement. Bigger the value of diameter with a lower amount of spacing considerably reduces the settlement[12]. Design load, amount of improvement helps in determining the spacing of stone column to provide desired foundation, a reliable stone column factors, soil tolerance, process of installation and site circumstances for construction. Reference [7] state that according to a practical validation, shows, closer spacing is required in isolated footing as compared to larger rafts. Generally, the spacing might vary between two or three times to that of stone column’s diameter.

C. Replacement Ratio

Area replacement ratio is being used to express the amount of the volume substituted which is defined as a_s (Eq. 1). It’s being expressed in the form of ratio of the area of that of stone column taken after doing the compaction (A_s) to that of total area comprised within a unit cell (A), and here D and D_e are taken as the diameter of the stone column and effective diameter of that unit cell[13] (Fig. 4 and Fig. 5). It is highly advised to have an area replacement ratio of 0.25 or more in a way to significantly enhance the bearing capacity of the treated soil[14].

\[
a_s = \frac{A_s}{A} \tag{1}
\]

(a) Triangular Pattern

(b) Square Pattern

Fig. 4. General stone-column installation methods and patterns and also the equivalent diameters: (a) triangular pattern; (b) square pattern [9].

Fig. 5. The stone column is concentric to the outer boundary of that of a given unit cell [9].
D. Stress Concentration Factor

Majorly after applying load on the ground which is being reinforced by stone column, concentration of the stress happens in the stone column, which also results in reducing the stress occurring around that of surrounding soil which are generally soft in nature. Concentration Factor which is denoted by \( n \) is the ratio of the stress occurring in that of the stone column (\( \sigma_c \)) to that of stress occurs in the cohesive sample of soil surrounding it (\( \sigma_s \)). In general, this value ranges between 2-6[9]. The different equation which is required to calculate the stresses in stone column by the help of stress concentration factor \( n \) are given as:

\[
\begin{align*}
\sigma &= \sigma_c \alpha_s + \sigma_s (1 - \alpha_s) \quad (3) \\
\sigma_c &= \frac{\sigma}{1 + (n-1) \alpha_s} = \mu_c \sigma \quad (4) \\
\sigma_s &= n \sigma / [1 + (n-1) \alpha_s] = \mu_s \sigma \quad (5)
\end{align*}
\]

where \( \mu_c \) and \( \mu_s \) are dependent with respect to that of stress concentration factor and replacement ratio. The above-mentioned equations were found very much useful in both stability and settlement analysis [9]. Along with the consolidation time, stress concentration factor increases along with the area replacement ratio. Along with the total length of that column, stress concentration factor reduces which also decreases with increase of the applied load [9].

6. FAILURE MECHANISM

Length of the column is one of the major factors on which the failure mechanism related to a single column that is being loaded over its total area mostly depends upon. Columns which have their length more than its critical length which is supposed to be around four times that of the size i.e., diameter of the column mostly fail in bulging, without considering the fact whether it being an end bearing type or it being a floating type (Fig. 6 a). However, there are columns which are shorter than its critical length, which are mostly supposed to fail about the type of general shear failure if it’s an end bearing one on a rigid base (Fig. 6 b) and fails in end bearing if it’s a floating type (Fig. 6 c). This failure mechanism is applicable generally to the type of stone columns which are generally being installed in a type which are homogenous soil layers. It might be possible in the practical sense where there might be isolated zones consisting of very weak cohesive soils which might end up resulting in the bulging at shallow and also deep depths which is quite significant and thereby this should be considered wherever necessary [18].

![Fig. 6 Failure mechanism of a Single column in a homogenous soft layer [18].](image-url)
SETTLEMENT ANALYSIS

Settlement analysis of any untreated ground can be obtained as per IS 8009. Reduced stress method may be used to determine the settlement for the ground that is treated. This is mainly based upon the area replacement ratio $\alpha$, also stress concentration factor $n$. With this we can determine the settlement for the ground that is treated and also the reduction factor $\beta$ can be found out [15].

In accordance with the relative stiffness that of materials, cross-sectional area of the columns ($A_s$), also the amount of spacing, and the applied stress $\sigma_s$ is being distributed between the columns and the present surrounding weaker soils. This sharing of the applied stress among the column and also the local soil can be given and expressed in accordance to that of stress concentration ratio, $n$, which is given as [18]:

$$n = \frac{\sigma_s}{\sigma_g}$$  \hspace{1cm} (6)

where,
\begin{align*}
\sigma_s &= \text{vertical stress applied in compacted columns and} \\
\sigma_g &= \text{vertical stress applied in surrounding ground}
\end{align*}

Also, if $A_g$ is the plan area of the given soil for the columns then [18]:

$$\left( A_s + A_g \right) \sigma = A_s \sigma_s + A_g \sigma_g$$  \hspace{1cm} (7)

The area replacement ratio is the replacement of soil along with the stones which can expressed as [18]:

$$\alpha_s = \frac{A_s}{A_s + A_g}$$  \hspace{1cm} (8)

The sharing of the load which is being applied between the surrounding soil and the column of stones can be estimated as [18]:

$$\sigma_g = \frac{\sigma}{1+(n-1)\alpha_s} = \mu_g \sigma$$  \hspace{1cm} (9)

$$\sigma_g = \frac{n \sigma}{1+m-1\alpha_s} = \mu_s \sigma$$  \hspace{1cm} (10)
Consolidation settlement that of the composite treated soil $S_t$ is represented as \[18\]:

$$S_t = m_v \sigma_g H$$

where,

$m_v$ = modulus of volume decrease of soil, and

$H$ = thickness of soil which is being treated

From one dimensional consolidation theory, settlement of a non-reinforced ground is given as \[18\]:

$$S = m_v \sigma H$$

Settlement Reduction Ratio $\beta$ is given as \[18\]:

$$\beta = \frac{\text{Settlement of a treated soil} S_t}{\text{Settlement of untreated soil} S}$$

$$\beta = \frac{S_t}{S} = \frac{1}{1+(n-1)\alpha_x}$$

8. ORDINARY AND ENCASED STONE COLUMNS

The stone column reinforced ground generally behaves as composites which have higher strength and stiffness. But due to very soft clay which have very low undrained shear strength, there is highly any sufficient lateral confinement. Due to this low lateral support, it might result in lateral bulging at a shallow depth and result in shear failure in the granular columns. Clogging of the column may also result in reduction of the discharge capacity of the column[15]. The encasement can be done either as vertical encasement or horizontal encasement. Horizontal Reinforced Stone Columns(HRSCs) have less lateral bulging than Ordinary Stone Columns(OSCs) because of the additional support offered by frictional and interlocking interactions between the geosynthetic material and the stone column aggregates[16]. When subjected to cyclic loading, the findings show that under cyclic loading, the overall advantage of the encasement to the stone column's output is greater than under static loading. When the column is subjected to cyclic loading, the degree of load transfer to the column is shown to be lower than when the column is subjected to static loading, resulting in 25% decrease of stress concentration ratio. When subjected to lower frequency and/or smaller amplitude loading, the encasement is found to be more effective in improving the stone column efficiency[17].

9. SUMMARY AND CONCLUSION

In ground improvement field, one of the significant methods is stone column. In areas with soft compressible clays and silts, as well as loose silty sands, stone columns are the strongest and also the most applicable ground improvement technique. In places where there is a lot of sand, stone columns are considered to be the best and most practical ground improvement methods.

Based on the literature studies and various critical reviews on the stone columns, the following conclusion can be made:

Stone columns are usually installed by vibro-replacement or ramming methods, which can either be wet or dry, in areas with cohesive soils. In contrast to other ground improvement methods, stone column is considered as a cost-effective type of ground improvement methods that provides substantial contract programme savings. The poor and unsuitable parts of the soil are changed with dense aggregate which are compacted while being used in columns that are stiff and also strong when compared to the unimproved local soil during the process. Mostly it is found to be penetrating completely into the soft layers, resulting in an improvement in the bearing capacity. Aside from that, the stone columns serve as a type of drains, reducing the time it takes for primary consolidation, as also that of total settlements and risk of liquefaction. Various elements that affect overall efficiency of this method have been made clear based on the findings of previous studies along with the mathematical analysis, physical simulation, and complete
research. Column length, column material strength, area replacement ratio, column spacing, column material strength, and installation method are the variables to consider. Also, the failure mechanism along with that of settlement analysis by reduced stress method have been studied.

To that extent, the findings show that the untreated soil without stone column settles twice as much as the strengthened soil with stone column. Furthermore, the lowest settlement occurs for the triangle pattern with increasing diameter and the decreasing spacing.

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