APPLICATION OF STONE COLUMN FOR GROUND IMPROVEMENT  
: A REVIEW  
Dhanshree Goyal¹, Satyajit Patel²

ABSTRACT

Stone column is one of the stabilizing solutions which is applicable to the areas containing soft compressible silts and clays and loose silty sands. The present paper gives a review about the stone column, the uses, construction methodology, application to different soils, important features influencing stone column, column design parameters like diameter, spacing, installation pattern, settlement etc. and also discusses the recent developments in the stone column technique.

Keywords: Ground Improvement, soil stability, stone columns, bearing capacity, settlement, consolidation, geo-synthetic encasement.

Introduction:
Stone columns are considered as one of the most versatile and cost effective ground improvement solution. Stone column is made by opening a vertical cylindrical hole in the soft clay bed and filling it with granular material compacted in stages so as to improve the strength and consolidation characteristics of soft clays. The methods for installation of stone column are: Vibro Compaction & Vibro Replacement. The objective of Vibro-compaction is to achieve densification of coarse grained soils ranging from fine sand to coarse gravel containing up to 15% silt. The Vibro Replacement method is widely used for stone column installation in cohesive soils & the unique characteristics of the technique is that it is able to treat an array of weak soils.

<table>
<thead>
<tr>
<th>Literature</th>
<th>Experimental Details</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shahu &amp; Reddy (2011)</td>
<td>• Soil: Clay $c_u = 7 – 9$ kPa.</td>
<td>The decrease in the settlement was much higher for the increase in the area ratio from 10-20% compared to that from 20-30%. The bending depends on the position of the column in the group. I.e. bending increases from the centre column to the peripheral &amp; to a corner column.</td>
</tr>
<tr>
<td></td>
<td>• Model Tank Dimensions: Diameter - 300mm</td>
<td></td>
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<tr>
<td></td>
<td>Depth- 600mm</td>
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<td></td>
<td>• Stone Column Data: Diameter:13mm &amp; 25mm</td>
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<td></td>
<td>Lengths:100mm&amp;150mm</td>
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<td></td>
<td>Area Ratio:10, 20 &amp; 30%</td>
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<td></td>
<td>No of columns:9, 13 &amp;21</td>
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</table>

¹ Application Of Stone Column For Ground Improvement_Dhanshree Goyal, Applied Mechanics Department, Teaching Assistant, Surat, India, dhanshree.goyal@yahoo.com  
² Application Of Stone Column For Ground Improvement_Satyajit Patel, Applied Mechanics Department, Assistant Professor, Surat, India, spatel@amd.svnit.ac.in
Rao & Madhira (2010)

- Stone Column Data:
  - Diameter: 800mm
  - Depth: 11 m
  - Spacing: 1.6m, 2.0m, & 2.5 m c/c

Results of 1.6m, 2.0m & 3.0m c/c spacing have shown an improvement of 100%, 25% and 3% resp. Effective spacing between SCs should be 2 to 3 times the column diameter.

Murugesan & Rajagopal (2008)

- Soil – CL
- Model Tank Dimensions:
  - Diameter - 210mm
  - Depth- 500mm
- Stone Column Data:
  - Material- granite chips
  - Column Diameter- 50,75 & 100 mm
- Geo-synthetics Used:
  - Woven, Non- woven, soft grid with fine mesh & soft grid with coarse mesh.

The ordinary SCs shown a clear catastrophic failure whereas the encased SCs shown the elastic behavior with no remarkable failure. The load carrying capacity increased by 3- 5 folds. The column encased with Woven geo-textile was stiffer than the non-woven and the soft grid. The capacity increased with the increment in the stiffness of encasement.

Ayadat et. al (2008)

- Soil– Kaolin Clay of
  - $q_u = 35$ KN/m$^2$
- Model Tank Dimensions:
  - Diameter – 390 mm
  - Depth- 520 mm
- Stone Column Data:
  - Material- Dry silica sand
  - Diameter: 23mm
  - Length- 470mm.
- Internal reinforcements:
  - 1% steel, 1% nylon, 1% aluminium and 2% steel

In the loose sand, bearing ratio increased to 42% for steel, 37% for nylon and 60% for aluminium rods; whereas for dense sand, the increase was slightly lower at 30, 25 and 50%, respectively. The load capacity was increased by 38, 54 and 75% for single, double and triple meshes, respectively.

Conclusions
Stone columns solution is the cost-effective approach for treating the difficult soils. Stone columns act as a vertical drain and reduce the time for primary consolidation. Many research works have been carried out to study & understand the behavior of columns & highlighted various parameters influencing the overall performance. When the stone columns are installed in very soft deposits, Geo-synthetics are used for encasement of stone columns, so as to provide adequate confinement & for improved performance.

References:
APPLICATION OF STONE COLUMN FOR GROUND IMPROVEMENT

Dhanshree Goyal, Teaching Assistant, SVNIT, dhanshree.goyal@yahoo.com
Satyajit Patel, Assistant Professor, SVNIT, spatel@amd.svnit.ac.in

ABSTRACT: The infrastructure growth in urban and metropolitan areas has resulted in a dramatic rise in land prices and lack of suitable sites for development. Construction works in soft grounds often encounter problems originating from weak engineering properties of soft soils such as low bearing capacity, excessive settlements and ground movements, large lateral flow, and slope instability. A range of ground improvement techniques have developed that allows the sites with poor or marginal ground conditions to be developed both safely and economically. The solutions for ground improvement mainly depends on the type of the soil present on the site, ground conditions, design loads, size of the treatment area and site location. Stone column is one of the stabilizing methods which are applicable to the areas containing soft compressible silts and clays and loose silty sands. The present paper gives a review about the stone column, the uses, construction methodology, application to different soils, important features influencing stone column, column design parameters like diameter, spacing, settlement, installation pattern, etc. and also discusses the recent developments in the stone column technique.

INTRODUCTION
Ground Improvement is the modification of foundation soils to provide better performance under loading conditions. Various ground improvement techniques such as Stone Columns, Vacuum Pre-Consolidation, Soil Cement Columns, Pre-Consolidation using Pre-fabricated Vertical Drains, Lime treatment etc. have been utilized in order to improve the soil properties artificially.

Among these methods, stone columns are considered as one of the most versatile and cost effective technique. They have been extensively used over the past decades in numerous ground improvement and foundation projects and are gaining acceptance as they are applicable to an array of soil conditions and soil strengths. The overall performance of stone column is controlled by the lateral support provided by the surrounding soils, which typically increases with depth. The basic principle of these column type techniques such as stone columns, grout injected stone column, geo-textile encased sand columns, and etc is to relieve the load on the soft soils [19].

Stone column is made by opening up of a hole in the soft clay bed and subsequently filling it up with granular material compacted in stages so as to improve the strength and consolidation characteristics of soft clays. Stone Columns were first used in 1830 by French military engineers to support heavy foundations of the ironworks. Stone Columns were forgotten until 1930s when they were rediscovered as the by-product of the Vibro-flotation technique for compacting granular soils [16]. Guetif et. al [15] reported that the improvement of a soft soil by stone columns is mainly by three factors. The first is inclusion of a stiffer column material such as crushed stones, gravel etc in the soft soil. The second is the densification of the surrounding soft soil during the installation of stone column & third is the acting as vertical drains.

STONE COLUMN USES
- Applicable to wide range of soils.
- Supports the embankments, liquid storage tanks, raft foundations & other low rise structures.
- Increases the soil bearing capacity & shear strength of soils.
- Reduces the settlements in soils due to inclusion of stronger granular material
- Increases the resistance to Liquefaction by reducing the pore water pressure.
- The material component being granular with high permeability, stone column accelerates the consolidation of weak soils & shortens the drainage path.
- Improve the slope stability of embankments.
- Increases the friction angle & the shear modulus.

**METHODS OF CONSTRUCTION**

Methods of construction of stone column depend on equipment availability & applicability. The correct selection of stone column construction method & the proper quality control are keys to successful improvement of soft soils. Various methods for installation of stone column are:

**Vibro Compaction Method**

The objective of Vibro-compaction is to achieve densification of coarse grained soils ranging from fine sand to coarse gravel containing up to 15% silt. The effectiveness of the process is based on the fact that vibration allows soil particles to rearrange themselves into positions giving rise to their optimum density. A vibrating poker device consisting of a cylindrical steel shell with an interior electric or hydraulic motor carries out the Vibro-Flotation by piercing in the soil up to the specified depth. The movement of the ground through the vibrating poker introduces high friction angle in the construction of columns; hence, the compacted soil gains a greater average strength and compaction than the untreated ground. The hole created by the poker is then filled with inert crushed stone or gravel and is compacted in stages from the base of the hole upwards. The combined water jetting and horizontal vibratory action of the vibroflot acts to compact the loose soils into a denser condition and significantly improve the bearing capacity of the treated ground. The effect of vibrations on cohesive soils such as clays and silts is negligible & cannot treat certain soils such as clays, pure silts, and mixed deposits of silts. To overcome this problem, Vibro Replacement method was introduced.

(Volume size distribution showing applicability of Vibro-Compaction and Vibro-replacement)

**Vibro-Replacement Method**

Vibro-Replacement method was first developed in 1956. This method is widely used for stone column installation in cohesive soils in which density is not enhanced by vibrations. The unique characteristics of the technique is that it is able to treat a wide range of weak soils ranging from loose silty sands, soft marine clays, ultra soft soils, peaty clays & garbage fills. The design of vibro-replacement is based on loading conditions, soil parameters, properties of granular material & intended performance criteria [27]. The main advantage of this method is better depth & speed of execution. The different types of installation methods available under this category are classified as:

a) Wet Top Feed
b) Dry Top Feed
c) Dry Bottom Feed

**Wet Top Feed**

Wet top feed method is used for medium to deep treatment below water table & for treatment of softer cohesive soils whose un-drained shear strength ranges from 15-50 kPa [6]. In this method, water forces through the head of a vibrator bit already mounted on the end of a drilling rig [21]. Desired depth is achieved through the combined effect of vibration & high pressure water jets. On reaching the desired treatment depth, stone backfill of 12-75 mm size is added & densified by means of electrically or hydraulically actuated vibrator
located near the bottom of the probe. The main disadvantage of this method is that it raises the issues of water supply and disposal.

**Dry Top Feed**
Wet top feed method is similar to wet top feed & uses controlled air flush to aid the construction. Since, dry top feed does not use jetting & flushing water; it is much cleaner than the wet technique.

**Dry Bottom Feed**
Dry bottom feed has now largely replaced Wet top feed method since its development in late 1970s. This method is mainly used for treatment of soft cohesive deposits [23]. It is ideal for locations with limited access to water & also suitable in congested areas. This method can successfully treat grounds with un-drained shear well below 15-20 kPa. Penetration to required depth occurs through the combination of vibrations & downward force of the machine [21]. Stones are then fed through a bin from the top of the machine that moves down to the bottom of the vibrator head.

**IMPORTANT FEATURES OF STONE COLUMN TREATMENT**

**Influence of Soil Type**
Subsurface soils whose un-drained shear strength range from 7 to 50 kPa or loose sandy soils including silty or clayey sands represents a potential class of soils requiring improvement by stone columns. Subsurface conditions for which stone columns are in general not suited include sensitive clays and silts (sensitivity≥4) which lose strength when vibrated.

**Influence of Construction Methodology**
The disturbance caused to the soil mass due to a particular method of constructing the stone columns significantly affects the overall behavior of the composite ground. The availability of equipment, speed of construction and the depth of treatment would normally influence the choice of construction technique.

**Treatment Depth**
The treatment depth with stone column for a given soil profile should be so determined that the stone columns extend through the most significant compressible strata that contribute to the settlement of the foundation. Average depth of stone column accomplished in India may be around 15m, although with equipment modification, higher depths beyond 20m may be possible.

**Area of Treatment**
Stone columns work most effectively when used for large area stabilization of the soil mass. Their application in small groups beneath building foundations is limited and is not being used. Thus, large loaded areas which apply uniform loading on foundation soils, such as beneath embankments, tank farms and fills represent a major area of application.

**Termination**
End bearing is not a specific requirement for stone columns. However, they should extend through the soft compressible strata.
DESIGN PARAMETERS

Stone Column Diameter (D)
Installation of stone column in soft cohesive soils is basically a self compensating process. The softer the soil, the bigger is the diameter of the stone column formed. The completed diameter of the hole is always greater than the initial diameter of the probe, depending on the soil type, un-drained shear strength, stone size, characteristics of vibrating probe used & the construction method [17]. The diameter of the stone column formed by wet technique is always more than that constructed by dry method [14]. Diameter of column installed by vibroflot varies between 0.6m in case of stiff clays to 1.1m in very soft cohesive soils.

For the purposes of settlement & stability analysis, it is convenient to associate the tributary area of soil surrounding each stone column. The tributary area may be closely approximated by an equivalent circular area having the same total area having an effective diameter expressed as:

\[ D_e = 1.05 \times S \] (for equilateral triangular pattern)
\[ D_e = 1.13 \times S \] (for a square pattern)

The resulting equivalent cylinder of composite ground with diameter \( D_e \) enclosing the tributary soil & one stone column is known as the Unit Cell.

Pattern
Stone Column should be installed preferably in an equilateral triangular pattern which provides the densest packing, although a square pattern may also be used [17].

Column Spacing
The design of stone column should be site specific & no precise guidelines can be given on the maximum & minimum column spacing. The spacing of stone column is generally determined by the design load, degree of improvement required for providing a satisfactory foundation, specific stone column factors, soil tolerances, construction site circumstances & the process of installing. Reference stated the potential experiences shows that closer spacing is preferred under isolated footing than beneath large rafts. However, the column spacing may broadly range from 2 to 3 times the diameter of the column depending upon the site conditions, loading pattern, installation technique, design load, soil tolerances [17]. It is desirable to perform the field trials for large projects in order to determine the most optimum spacing of stone column taking into consideration the required bearing capacity of the soil & permissible settlement of the foundation. Rao [28] presented a case study for determination of optimum spacing of stone column by conducting pre- and post installation standard penetration tests .They found that preferred effective spacing between stone columns should be between 2-3 times the column diameters, as too close spacing is not feasible from construction point of view. The columns arranged with spacing more than 3 times the diameter of the column does not give any significant improvement [3]. Dash [9] found that the optimum spacing giving maximum improvement is 2.5 times the diameter of stone column. Laboratory test [11]were carried out to study the influence of spacing of the column on the load-deformation characteristics. It was reported that increases as the spacing decreases the effectiveness increases.

Replacement Ratio (\( a_s \))
The volume of soil replaced by stone column has an important effect upon the performance of improved ground. To quantify the amount of soil replacement by the stone, the term replacement ratio is used which is the ratio of area of stone column after compaction (\( A_c \)) to the total area within the Unit cell (\( A \)). It may also be expressed as: \( a_s = 0.907(D/S)^2 \), where the constant 0.907 is a function of pattern used, which is commonly employed for equilateral triangular pattern. Increasing the area ratio, improves the overall performance of granular pile reinforced ground [29]. For an improved bearing capacity for stone column treated ground, \( a_s \) of 0.25 or greater is required [36].
Stress Concentration Factor (n)

When the stone column reinforced ground is loaded, concentration of stress occurs in the stone column, and an accompanying reduction in stress occurs in the surrounding less stiff soil. The stress concentration factor ‘n’ is defined as the ratio of the stress in the stone column (σ_s) to the stress in the surrounding cohesive soil (σ_c). The magnitude of stress concentration factor depends on the relative stiffness of the stone column & surrounding soil. Shahu et. al [29] reported ‘n’ value increases with the increase in area ratio. Reports concluded that for end bearing stone column, the ‘n’ value is more than that of floating type. The value of ‘n’ generally lies between 2.5 – 5 at ground surface[17]. The stress in the clay & stone using the stress concentration factor can be calculated by the following equations:

\[
\sigma_c = \frac{\mu_c}{1 + (n-1) \mu_s} \sigma
\]

\[
\sigma_s = \frac{\mu_s}{1 + (n-1) \mu_s} \sigma
\]

where \( \mu_c \) & \( \mu_s \) are the ratio of stresses in the clay & stone respectively, to the average stress \( \sigma \) over the tributary area. These above equations which give the stress due to applied loading in the stone column & the surrounding soil are extremely useful in both settlement & stability analysis [5].

Backfill for Stone Columns

Crushed stone & gravel for the column backfill shall be clean, hard, un-weathered, and stone free from organics, trash or other deleterious materials. The individual stones should be chemically inert, hard & resistant to breakage [17]. Well graded stones of 75-2 mm size shall be used. It may be noted that stones of uniform size may permit the penetration of clay into the large sized voids thereby jeopardizing the capacity of the column &/or its function as a vertical drain. In case of bottom feed method, maximum size of aggregates should be restricted to 40 mm to avoid the blockages in the machine [6]. The grading should be designed to ensure good drainage & mobilization of the column strength after a relatively small settlement.

Brown (1977) has defined a suitability number for vibro-flotation backfills, which is given as:

Brown’s Suitability Number = \[1.7 \left( \frac{3}{D_{50}} + \frac{1}{D_{20}} + \frac{1}{D_{10}} \right)\]

Where \( D_{50}, D_{20}, D_{10} \) are in mm at 50, 20, 10% passing by weight.

Corresponding Suitability Numbers & backfill ratings are given in Table.

<table>
<thead>
<tr>
<th>Suitability Number</th>
<th>0-10</th>
<th>10-20</th>
<th>20-30</th>
<th>30-50</th>
<th>&gt;50</th>
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<tbody>
<tr>
<td>Rating</td>
<td>Excellent</td>
<td>Good</td>
<td>Fair</td>
<td>Poor</td>
<td>Unsuitable</td>
</tr>
</tbody>
</table>

To select the efficient backfill type, three criteria of availability, suitability & economy should be considered. Laboratory tests [11] were performed to study the influence of column material in stone column performance. In the study, it was observed that stones were the effective column material compared to materials like gravel, quarry dust, river sand & sea sand.

Granular Blanket

Irrespective of the method used to construct the stone column, the granular blanket should be laid over the top of the stone column, consisting of the clean medium to coarse sand compacted in layers to a relative density of 75 to 80 % [17]. It acts as a drainage layer & also to distribute stresses coming from the superstructure [25]. Shivashankar et. al [6] reported that for lower values of area replacement (≤0.25), provision of adequate thickness of granular pad is highly beneficial in improving the performance of reinforced ground. Minimum thickness of the compacted sand blanket should be 0.5m.This blanket should be exposed to atmosphere at its periphery for pore water pressure distribution [16]. The granular bed has a significant effect on the overall performance of the reinforced ground. Madhav [22] investigated the effect of granular pad on the response of the treated ground. The granular pad laid on the top, distribute the applied loads over larger areas which in turn tend
to confine the granular pile over greater depth & induce a stiffer response from them. Experimental study [2] shows that in the case of rigid loading, stress concentration factor(n) decreases with the increase in t_{sand}/d upto a value of 0.75, beyond which the effect is negligible & in case of flexible loading, n increase with the increase in t_{sand}/d upto a value of 1.0. The granular bed can further be reinforced with geo-grid to enhance the load carrying capacity & reduce the settlement of stone column improved soft clay. Thus, while analyzing the results of granular column reinforced ground, the contribution from the granular pad should not be ignored.

Critical Column Length (L_c)
Researchers suggest that the critical length defines the overall stone column failure mechanism. The critical column length is the shortest column which can carry the ultimate load regardless of settlement. Hughes [16] reported the critical length as 4.1 times the column diameter for optimum load carrying capacity. Columns longer than the critical length did not show much increase in load carrying capacity; however, it may be required to control the settlements [24, 6]. Dash [9] reported that the optimum length of stone column for maximum performance is about 5 times the column diameter.

STONE COLUMN BEHAVIOUR
Effect of Stone Column Installation:
The insertion of stone columns into the weak soils by vibro installation technique accompanied with vibrations and horizontal displacement of the soil, believed to cause positive changes in both material properties and the state of the stresses in the treated soil mass. Kirsch [20] analyzed the improvement by an isolated stone column & group column due to the installation effects and reported that the column group improves the soil by 5% to 15% due to global installation effect & individual stone column leads to about 40% improvement compared to an untreated ground. Alamgir [1] reported that the standard penetration resistance of soft ground has been increased significantly after a stone column installation. N-value ranges from 2-7 for natural ground but it increased to 5-12 in the reinforced soft ground. Immediately after column installation, high excess pore pressure develops in the surrounding soft clay. Studies [15] reported that after the primary consolidation takes place, the total dissipation of excess pore pressure causes the significant increase in the effective mean and radial stresses. Field tests [8] were carried out to have a better understanding of the installation effects of stone columns. The densification of the in-situ soil surrounding the stone column decreases with the distance away from it. Weber [35] studied the smear zone & densification zone around the stone column where the smear zone was described as a strongly sheared and remolded zone.

Failure Mechanism of Stone Columns
Failure mechanism of a single stone column loaded over its area significantly depends on the length of the column [17]. Hughes [16] found that about 4 diameter lengths of the column were significantly strained, at failure. He examined the mechanism of stone column failure. The ultimate strength of an isolated column loaded at its top is governed primarily by the maximum lateral reaction of the soil around the bulging zone. If the length diameter ratio is less than 4, then columns would fail in end bearing before bulging. Stone column transmits some load to the soil by shear stresses & by end bearing. The major load transfer mechanism (except short column) is lateral bulging into the surrounding soil. Ambily [3] studied the behavior of single column & group of seven columns by performing the laboratory tests and compared with the numerical results obtained from FEM analysis. Model tests [30] were carried to study the behavior of column group & reported that the bending of column depends on its position in the group. The bending increases as one move away from the centre column & peripheral column bends more than the one that lies inside the group. Shivshankar [32] investigated the performance of stone column installed in the layered soils. The maximum bulging was observed at a depth of one times the column diameter from the top & the total length of stone column subjected to bulging was observed to be 2-3 times the column diameter. Entire bulging was noticed mostly in the weak layer zone only. McKelvey [24] reported that the punching was prominent in short columns whereas bulging was
significant in long columns. The bottom region did not appear to have undergone significant deformation. Researchers used X-Ray techniques successfully to monitor the deformation of an isolated column & surrounding soil. But the method is expensive & raises various health & safety issues when used in laboratory conditions. Cylindrical Cavity Expansion Theory (CCET) has been used to model the bulging behavior of granular columns leading to the prediction of bearing capacity & settlement performance.

Failure mechanism of single stone column in a homogenous soft layer

Failure mechanism of single stone column in a non-homogenous soft layer

**RECENT DEVELOPMENTS**

**Encased Stone Column**
Stone columns derive their load carrying capacity from the lateral confining pressure from the surrounding soils. When the columns are installed in very soft deposits, they may not derive necessary load capacity due to low lateral confinement. In such situations, they need to be provided with additional confinement for its improved performance. The concept of encasing the stone columns by wrapping with Geo-textile was first proposed by Van Impe in the year 1985. Murugesan [26] performed laboratory experiments on stone columns with & without encasement. The geo-synthetic encasement increases the load carrying capacity of individual stone column up to 3-5 times depending upon the stiffness of the geo-synthetics used. Pressure-settlement response of GESC generally shows linear behavior not indicating any catastrophic failure unlike the conventional one. Tandel [18] reported that the stress-settlement response of stone column group can be improved by reinforcing them with suitable geo-synthetics. The soft clay beds improved by stone column-geo-cell sand mattress increases the bearing capacity by 10 folds [9]. Results indicated that such provision leads to the increase in the stiffness of the foundation bed & subsequently to a large scale reduction in footing settlement. Deb [10] studied the behavior of multilayer geo-synthetic reinforced granular fill over the stone column-reinforced soft soil & found them effective in transferring the stress from the soil to the column. Ayadat & Hanna [4] conducted tests on the geo-fabric encapsulated stone column to investigate its performance in a collapsible soil.

(Encased Stone Columns)

**Internally Reinforced Stone Column:**
The stone columns, when reinforced internally using concrete plugs, chemical grouting or by adding internal inclusions like plastic fibers, etc. leads to the stiffening of the column and increases the lateral stress in the surrounding soil, and accordingly its bearing capacity. Ayadat [5] conducted laboratory tests on sand columns internally reinforced with horizontal wire meshes
made of plastic, steel and aluminium materials and investigated its effect. The performance increases with the increasing of mesh numbers. Also ductile materials like aluminium in the form of plates gave the best results as reinforcement. Black et. al [7] investigated the performance of stone column jacketed with a tubular wire, bridging reinforcement with a metal rod & concrete plug. Shivashankar [31] investigated the performance of stone column reinforced with vertical circumferential nails installed in the soft soils. It was reported that with the increase in number of nails, the improvement increases.

**Settlement Analysis**
The ability to meet absolute (probably more important differential) settlement criteria is normally the governing factor for vibro-replacement design in the soft clay & therefore researchers concentrate most on the settlement performance ahead of bearing capacity. Settlement performance is expressed in the form of settlement improvement factor (n) defined as

\[ n = \frac{S_{untreated}}{S_{treated}} \]

Where \( S_{untreated} \) is the settlement in absence of stone column treatment
\( S_{treated} \) is the corresponding settlement with stone column treatment

It was observed that larger group of columns give stiffer response since more columns work as a group & the group achieves a lesser degree of deformation. Such enhanced rigidity of column group is due to increased confining action. Consolidation Settlement of the composite treated soil is given by \( S = m_v \sigma_v H \)
where \( m_v = \) Co-efficient of volume change
\( \sigma_v = \) Vertical stress in the surrounding soil &
\( H = \) Thickness of the treated soil

**Rate of Consolidation**
Field observation suggests that stone columns accelerate the rate of consolidation of soft clays. Raju et. al [21] reported a 6 fold increase in consolidation rate compared with unimproved ground. McCabe et. al [23] found that the post installation consolidation completes much faster in the case of stone column compared to that of piles, thereby, providing a further indication of the drainage benefit that the column offers. At the end of primary consolidation, there is an increase in the effective mean stress in the reinforced soil as compared to those taking place in soft clay due to higher Young’s Modulus of column material [15]. In a cohesive soil reinforced with stone columns, pore water moves towards the column in a curved path having both vertical and radial components of flow. The average degree of primary consolidation could be handled by considering the vertical and radial consolidation effects separately as expressed by the following equation:

\[ U = 1 - (1 - U_z) (1 - U_r) \]

Where, \( U \) is the average degree of consolidation considering both vertical and radial flow
\( U_z \) is the average degree of consolidation considering vertical flow
\( U_r \) is the average degree of consolidation considering radial flow.

**Conclusions**
Specific conclusions based on the critical review of the available literature on stone columns are as follows:

1. Stone columns solution is the cost-effective approach for treating the difficult soils. They can be constructed by either by Vibro compaction or Vibro Replacement method. The dry bottom feed method is the preferred approach for constructing columns in soft soils whose \( c_u \) is below 5 kPa. In environmentally sensitive areas, columns are frequently constructed by the dry process rather than the wet one.
2. Literatures suggest that un-drained shear strength can be increased permanently with stone column construction, provided construction standards are adequate. Lateral effective stresses increases around column because of the installation process.
3. Stone columns act as a vertical drain and reduce the time for primary consolidation. They decrease the pore pressure during an Earthquake & hence, can help in mitigating the liquefaction potential.
4. Many studies have been carried out to study & understand the behavior of columns &
highlighted various parameters influencing the overall performance.
5. The stone column bearing capacity increases with increasing the friction angle of the stone material and the stone column diameter.
6. When the stone columns are installed in very soft deposits, they may not derive sufficient load capacity due to low lateral confinement. To overcome this problem, geo-synthetics are used for encasement of stone columns, so as to provide adequate confinement & for improved performance.

REFERENCES:
17. IS: 15284-2003 Indian standard code of practice for design and construction for ground improvement-guidelines.


