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Ground Improvement by Stone Columns - A Brief Review, Construction Technique and Basic Design Aspects

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Abstract
A stone column is a ground improvement technique used in geotechnical engineering to enhance the load-bearing capacity and drainage properties of weak or soft soils. These columns are formed by inserting compacted crushed stone or gravel into the ground, creating vertical reinforcement elements. The application of sites containing low-strength soil deposits is of great concern concerning the rapid increase in urbanization and industrialization. To overcome such difficulties in construction, ground improvement techniques are frequently practiced. The provision of the stone column is one of the well-known approaches to improve the weak soil properties. Moreover, the application of reinforced stone columns is chosen over the conventional method of stone columns to enhance the strength and durability parameters of weak soils to a greater extent.
This paper presents a review about the Stone Column, their Construction Technique and Basic Design Aspects. The paper also review the several theories exist from past to present which helps in understanding the enhancements by stone columns in boosting soft soils and loose cohesion less soils.

Keywords: *Stone column, Ground improvement, Geosynthetics, Soft soils, Cohesionless Soil, Routine Single Column Test.*

I. Introduction:

Stone columns are a widely used ground improvement technique that enhances the load-bearing capacity, stability, and drainage properties of weak soils. They are constructed by inserting crushed stone or gravel into the ground using vibro-replacement or vibro-displacement methods, creating stiff, vertically reinforced columns within the soil mass. Stone columns effectively reduce settlement, improve shear strength and accelerate consolidation by facilitating rapid drainage of excess pore water. Their applications span across various civil engineering projects, including foundation support for buildings, highways, and railway embankments, as well as liquefaction mitigation in earthquake-prone regions. Additionally, they are used in offshore and marine engineering to stabilize soft seabed soils for port infrastructure and wind farm foundations. The introduction of geosynthetics-encased stone columns has further expanded their use in extremely soft clays, ensuring greater lateral confinement and improved performance.

II. Brief Literature Review:

The role of stone columns in improving the bearing capacity of has been investigated by several researchers. Early studies regarding stone column were published by researchers such as Greenwood (1), Hughes et. al (2), Mckenna et. al (3), Alarifi Hamzh (4). In their researches, they reported the positive performance of the stone column in increasing bearing capacity and reducing settlement. Van Impe (5) discussed using geosynthetics to increase bearing capacity of stone columns. Samuel Thanaraj (6) used different materials like marbles, pebbles and concrete for stone column and observed increased bearing capacity. Sharad Kumar Soni (7) and M. Monisha (8) performed the settlement analysis of stone columns and observed decreased settlement when soil is improved with stone columns. The concept of encasing granular columns with geosynthetics to increase their capacity has been acknowledged by numerous researchers (9-12). Murugesan et al (10) explored the bearing capacity improvement of the stone column by geosynthetic rings using numerical analysis with finite element method. Their analysis showed that cylindrical reinforcement around the stone column increases its bearing capacity and rigidity and reduces bulging in compare to ordinary stone column.

III. Application/Functions of Stone Columns:

a) **Soil Stabilization** – Improves weak soils like clay, silt and loose sand by providing additional strength.
b) **Load-Bearing Capacity** – Increases the foundation's ability to support heavy structures by reducing settlement.
c) **Drainage Enhancement** – Acts as a vertical drain, accelerating the consolidation of soft, water-saturated soils.
d) **Liquefaction Mitigation** – Reduces the risk of soil liquefaction in earthquake-prone areas by increasing soil density.
e) **Reduction of Differential Settlement** – Helps distribute loads more evenly, preventing uneven settlement of structures.
f) **Eco-Friendly Alternative** – Reduces the need for deep foundations like piles, making it a cost-effective and environmentally friendly solution.

IV. Construction Techniques of Stone Column:

The construction methods for stone columns include the following. Each method is chosen based on soil conditions, project requirements and environmental factors.

4.1 Vibro-Replacement (Wet Method)

This method is used in soft, cohesive soils with high moisture content. A vibroflot (vibratory probe) is inserted into the ground using water jets. The soil is displaced and coarse aggregates (crushed stones or gravel) are fed into the cavity. The vibroflot compacts the stone column from bottom to top by vibrating and re-penetrating. Water helps in flushing out fine materials and assists in penetration. The top-feed method requires water for the installation, therefore, it is often referred to as a wet method.

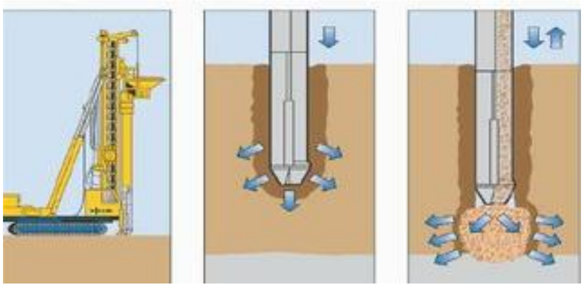
4.2 Vibro-Displacement (Dry Method)

This method is suitable for granular soils or soils with low moisture content. In this method a vibroflot penetrates the soil without the use of water jets. Stones are added progressively and compacted using the vibroflot. This method avoids excess water usage and usually uses air instead of water therefore, it is often referred to as a dry method.

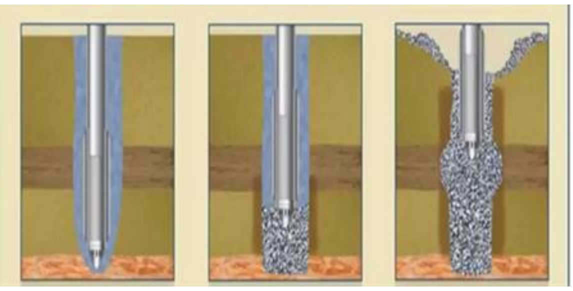
In both the methods (Wet or Dry), to construct the stone columns, a Probe is penetrated into the ground until the Probe reaches to the desired depth and then probe is moved up and down to flush out the hole. Then probe is withdrawn gradually by adding stone from the top to fill the hole in 0.6–1.2 m lifts and probe is repenetrated into the stone to compact/densify the stone radially into the surrounding soil until the predetermined amperage level is reached for each lift or the top elevation of the column is reached.

4.3 Rammed Stone Column (Dry Bottom Feed Method)

Rammed aggregate columns are installed by drilling a hole into the ground, backfilling it aggregates and ramming it. The method uses a displacement tool or mandrel to create a cavity in the ground. Crushed stone is fed through a bottom-feed system without the need for pre-excavation. The mandrel compacts the stone in layers as it is withdrawn. This method is suitable for low-strength and liquefiable soils.



Bottom Feed Process



Top feed process

V. Basic Design Parameters of Stone Column:

The basic design parameters of stone columns depends upon the
a) **Soil Type**: Clay, silt, loose sand etc.
b) **Shear Strength (Cu):** Typically, stone columns are used in soils with Cu < 50 kPa.
c) **Groundwater Level:** Affects drainage and consolidation.
d) **Loading Conditions:** Structural loads, embankment loads etc.

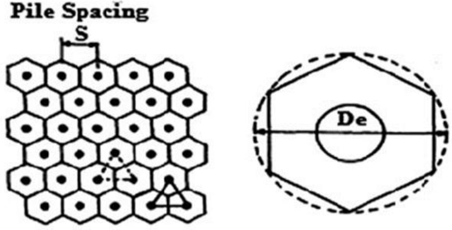
5.1 Stone Column Diameter, D

In vibro-flot method, the stone column diameter varies between 0.6 m in case of stiff clays to 1.1 m in very soft cohesive soils. The stone column diameter constructed by wet technique is bigger than that of a dry technique (13). Due to lateral displacement of stones during vibrations/ramming, the completed diameter of the hole is always greater than the initial diameter of the probe or the casing depending upon the soil type, its undrained shear strength, stone size, characteristics of the vibrating probe/rammer used and the construction method. The stone column diameter by using rammed process vary from 400 to 750 mm. The length of stone column, maximum and minimum densities of the stone effectively impact on the diameter of the stone column in the field (14).

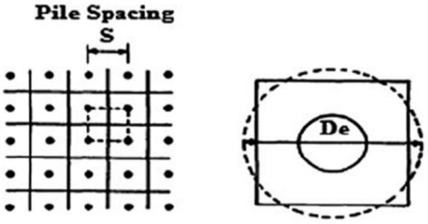
5.2 Pattern and Spacing

The square pattern or triangular pattern are possible installation patterns of stone column. But the most optimum and desirable installed shape is the triangular pattern since it gives the most dense and compacted packing of stone columns in a given area. The layouts of these two patterns are shown in Fig. 4.

Spacing and diameter of stone columns have significant impact on the settlement. A large diameter and small spacing of stone columns reduce the settlement (15). The spacing of stone columns is generally determined by the design load, the degree of improvement required for providing a satisfactory foundation, specific stone column factors, soil tolerance, construction site circumstances and the process of installing. However, the column spacing may broadly range from 2 to 3 times of the diameter of stone column. For large projects, it is desirable to carry out field trials to determine the most optimum spacing of stone columns.



(a) Triangular arrangement of Stone columns



(b) Square arrangement of Stone columns

Figure 2: Layouts of Stone Columns

5.3 Equivalent Diameter

The tributory area of the soil surrounding stone column forms regular hexagon around the column. It may be closely approximated by an equivalent circular area having the same total area (see Fig. 2). The equivalent circle has an effective diameter (De) which is given by following equation:

De = 1.05 S for an equilateral Triangular pattern, and
= 1.13 S for a square pattern
Where,
S = Spacing of the stone columns.

The resulting equivalent cylinder of composite ground with diameter, De enclosing the tributory soil and one stone column is known as the unit cell.

5.4 Replacement Ratio

The area of the stone column after compaction (As) to the total area within the unit cell (A) where D and De are diameter of stone and triangular pattern respectively (16) (Fig. 2). is called as Replacement Ratio a_s. It quantify the volume of soil substituted by the stone column. The area replacement ratio ($a_{s)}$ is given by.

a_s = As / A
Where,

As = Area of Stone Column
A = Total area within cell

It is recommended that to improve bearing capacity of treated ground significantly by stone column, the area replacement ratio shall be more than 0.25 or greater (17).

5.5 Stress Concentration Factor

Stress concentration occurs on the stone column because it is considerably stiffer than the surrounding soil. From equilibrium considerations, the stress in the stiffer stone columns should be greater than the stress in the surrounding soil. The Stress Concentration factor, 'n' due to externally applied load σ is defined as the ratio of average stress in the stone column, σ_s to the stress, σ_g in the soil within the unit cell,

$$n= (\sigma_s)/ (\sigma_g)$$

The value of Stress Concentration factor (n) generally lies between 2.5 and 5 at the ground surface. The stress concentration factor (n) increases with time of consolidation and decreases along the length of the stone column.

VI. Failure Mechanisms of Stone Columns

Failure mechanism of a Single Stone Column loaded over its area significantly depends upon the length of the column. For columns having length greater than its critical length (that is about 4 times the column diameter) and irrespective whether it is end bearing or floating, it fails by bulging (Figure 3). However, column shorter than the critical length are likely to fail in general shear if it is end bearing on a rigid base (Figure 3) and in end bearing if it is a floating column as shown in Figure 3.

Wherever interlayering of sand and clay occurs (Figure 4), and if the sand layer is thick enough as compared to the size of the loaded area, the general compaction achieved by the action of the installation of the stone columns may provide adequate rigidity to effectively disperse the applied stresses thereby controlling the settlement of the weak layer. However, effective reduction in settlement may be brought about by carrying out the treatment of stone columns through the compressible layer. When clay is present in the form of lenses and if the ratio of the thickness of the lense to the stone column diameter is less than or equal to 1, the settlement due to presence of lenses maybe insignificant.

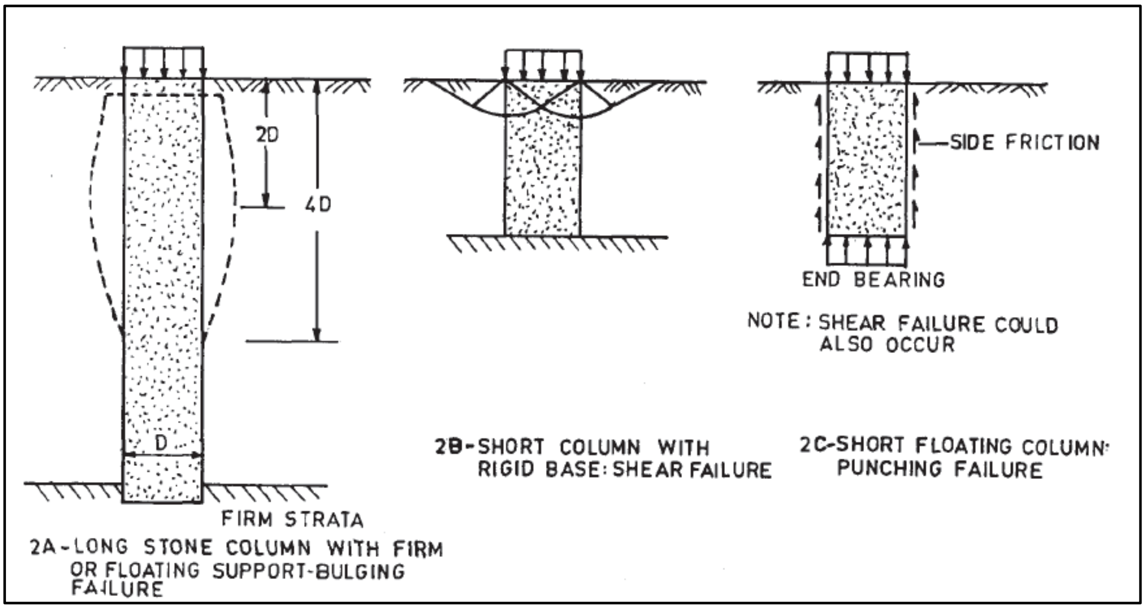


Figure 3: Failure Mechanism of Single Stone Column Homogenous Soft Soil

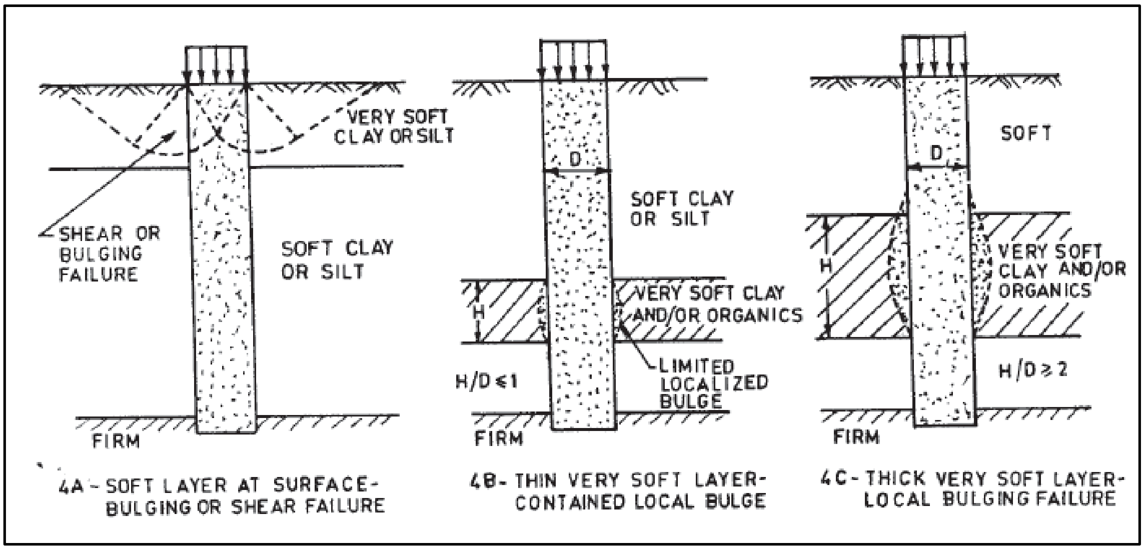


Figure 4: Failure Mechanism of Single Stone Column in Non Homogenous Cohesive Soil

In mixed soils, the failure of stone columns should be checked both for predominently sandy soils as well as the clayey soil.

VII. Conclusions:

Stone columns are widely used for ground improvement in geotechnical engineering, particularly in weak or compressible soils. By installing compacted columns of crushed stone or gravel into the ground, they enhance soil strength, increase load-bearing capacity, and reduce settlement. These columns also improve drainage by facilitating water flow, which helps in mitigating liquefaction risks in seismic-prone areas. Based on the outcomes of past studies with physical modeling, mathematical analysis and full-scale testing, various parameters that influence overall performance of the stone column like column length, strength of the column material, area replacement ratio, column spacing, strength of the column material, and installation method have been discussed. Common applications of the stone columns include supporting embankments, roads, railways, and foundations for buildings and industrial structures. Their cost-effectiveness, efficiency, and eco-friendliness make them a preferred solution for stabilizing soft soils and ensuring long-term ground performance.

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