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Ground Improvement by Using Stone Column. (Case Study)

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Abstract:
Stone columns are a widely adopted ground improvement technique aimed at enhancing the load-bearing capacity of weak soils and mitigating the risk of liquefaction, particularly in low-plasticity soils like silt and clay. By reinforcing these soils with stone columns, their strength and tensile properties are significantly improved. The process of consolidation, facilitated by aggregates within the stone columns, accelerates the dissipation of pore water pressure, thereby enhancing soil stability. To further expedite the consolidation process, various admixtures and materials such as quarry dust and geosynthetics are incorporated into the stone columns. The inclusion of geosynthetic encasement around the stone columns notably improves their stress-settlement behavior, providing additional confinement and stability.
This study delves into the material properties, design characteristics, and installation techniques of stone columns. It encompasses a comprehensive experimental analysis of both single and grouped stone columns to assess their performance under different conditions. Field and laboratory tests, including shear strength assessments of soft clay and evaluations under various loading scenarios, were conducted to gauge the efficacy of the stone columns. Post-installation, field load tests were performed to verify the actual improvement in clay strength and to determine the enhanced bearing capacity. Additionally, a cost analysis of the ground improvement technique was undertaken to evaluate its economic feasibility.
Keywords: *Stone column, Soil improvement, Case study, Experiment*

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I. INTRODUCTION

Stone columns are a widely used ground improvement technique aimed at enhancing the bearing capacity of weak soils, minimizing settlement, and reducing potential earthquake-induced liquefaction damage. Also referred to as granular columns or granular piles, they are constructed through a process called vibro-replacement, which is one of the deep vibratory compaction methods. This technique improves loose or soft soils for construction purposes using specialized depth vibrators. The ground improvement process involves deep vibratory compaction along with the installation of stone columns using imported granular materials that meet the specifications outlined in BS EN 14731:2005.

Stone columns are widely employed to improve soil bearing capacity and to reduce the risk of liquefaction. Soils with low plasticity, such as silts and clays, are particularly susceptible to liquefaction; however, reinforcing them with stone columns can enhance both their strength and tensile properties. The dissipation of pore water pressure within stone columns is accelerated through a volume reduction process known as consolidation, aided by the presence of aggregates. To further speed up the consolidation process, various admixtures and materials such as quarry dust and geosynthetics can be incorporated into the stone columns. The primary aim of this study is to enhance the consolidation rate by integrating different materials into the stone columns depending on the soil type. Additionally, the stress-settlement performance of stone columns can be significantly improved by using geosynthetic encasement around them.

Case Study: Ground Improvement Using Stone Columns at JNPT, Mumbai

A station building project at Jawaharlal Nehru Port Trust (JNPT) in Mumbai involved the construction of structures comprising a ground floor and, if necessary, an additional first floor. The design utilized a reinforced concrete skeleton system supported by a raft foundation. The anticipated uniform load from the building was approximately 314 kPa, which significantly exceeded the allowable bearing capacity of the existing soil. This was primarily due to a subsurface layer of soft clay, which posed challenges related to excessive settlement and potential liquefaction.

To address these geotechnical concerns, stone columns were selected as the ground improvement technique. This method was chosen to enhance the bearing capacity of the soil and to mitigate settlement issues. The implementation of stone columns aimed to reinforce the weak soil strata, thereby providing a stable foundation for the proposed structures

II. Soil stratification

In the site total 5 Nos boreholes are carried out. From the study of the data, borehole BH 3 is considered as critical borehole. The stratification and design parameters based on borehole BH 3 are tabulated below.

Soil Stratification	Level (RL)		SPT N
	From	To	
Silt with Sand (low plasticity)	0.00	10.50	10-21
Silt with Sand (low plasticity)	10.50	12.40	31-33
Highly Weathered Rock (Sand Stone)	12.40	31.50	>100
Average Depth of the treatment required (m) (From RL 265.000)	9.00 m from Working Platform level		

Existing soil properties:
STRATUM 1- Silt with Sand (Low Plasticity)

Following are the properties of the stratum-

Sr. No.	Parameter	Symbol	Unit	Value
1	Liquid Limit (LL)	wl	%	NP
2	Plastic limit (PL)	wp	%	NP
3	Average SPT N Value	N		15
4	Cohesion (C)	c	kN/m2	0
5	Friction angle- local shear	ϕ	Degree	25
6	Modulus of Elasticity, (Es=300(N+6))**	E	kN/m2	6300
7	Poison's ratio	μ		0.35
8	Coefficient of Volume compressibility**(1/Es)	mvc	m2/kN	0.0001587

*: Assumed
**: Refer Table 5-6, "Foundation Analysis and Design" by J E Bowles, 5th edition

AGGREGATE MATERIAL PROPERTIES USED FOR THE STONE COLUMN

Sr. No.	Parameter	Symbol	Unit	Value
1	Liquid Limit (LL)	wl	%	NP
2	Plastic limit (PL)	wp	%	NP
3	Friction angle	ϕ	Degree	45
4	Modulus of Elasticity,	Es	kN/m2	200000
5	Coefficient of Volume compressibility**(1/Es)	mvc	m2/kN	0.0000050

Existing Soil Conditions
Initially the suitability of the soil to rest the foundation shall be checked by calculating -

- Bearing Capacity of the virgin soil
- Settlement due to the pressure equal to bearing capacity; and;
- Settlement due to proposed loading conditions

2.1 Calculation of SBC & Settlement - Before Treatment.
As per IS 6403, the ultimate bearing capacity for soil has been calculated. The square raft is considered for size 6.0m x 6.0m, Depth of footing below ground level is 1.5m and other properties are mentioned above table. Factor of safety considered as 3. Local shear failure criteria have considered for calculation as per friction angle (25 degree).
As per IS 6403, the safe bearing capacity of existing soil before treatment has been calculated as 119 kN/sqm.

2.1.1 Settlement Calculations
Settlements comprises of -
1. Immediate Settlements, and;
2. Consolidation Settlements

As in this case the strata are Silty Sand - cohesionless soil the settlements will be immediate settlements. Consolidation settlements shall be neglected in this type of strata.
SPT observed at depth 1.50 m below ground level,
As soil is cohesive in nature and non-plastic silt is observed, the observed SPT values has been corrected as per IS 2131.
As per IS 8009 part I, the settlement of existing soil before treatment has been calculated for 119 kN/sqm is 48.0mm. But as per structural requirement, design pressure is required 314 kN/sqm. Hence the settlement of existing soil before treatment has been calculated for 314 kN/sqm is 126.0mm.
The calculated settlement of untreated soil will be 126mm. Hence ground improvement is required. For this case, stone column recommended for soil improvement.

2.1.2 Design of Ground Improvement Using Stone Columns

Design Calculations
The design is based on the following codes and standards -
Design Standards
IS 15284 - Part 1: Design and Construction for Ground Improvement Guidelines – Stone Columns
From the available data, the required parameters for design of stone column are summarized in Table above. Design requirement of stone column given below,
Applied Pressure Intensity, P at GL :314.00 kN/sqm
Allowable Post Construction Settlement :75mm as per IS 1904
Finished Diameter of Stone Column, ds :0.9m
Grid Pattern : Triangular
If area ratio requirement is specified, find spacing from area ratio, else calculate the capacity of column. Then equating the applied pressure and the load capacity of column, determine the spacing
Area of Stone column stone columns, Ast, is, ($0.785 * d^2$) :0.63585
Proposed grid pattern of stone columns is :Triangular
Effective Area of Stone column Ae, is ($0.785 * De^2$) :0.86546 S
Area ratio = (Ast / Effective influence area of Stone column) :$0.735/S^2$

Now, there are three steps to calculate spacing of stone column. The Yield capacity of Stone Column is the summation of –
a) Resistance offered by surrounding soil against bulging (passive resistance of surrounding soil)
b) Bearing support provided by the soil in between the Stone Columns
c) Increase in Resistance due to surcharge effect.

In the calculation, Q1, Q2 and Q3 parameters are calculated as per above mentioned three steps.

Resistance offered by surrounding soil, Q1= 104.035 kN
Safe Load carried by surrounding soil, $Q2= 103.042* S^2 - 75.705$ kN
Increase in resistance due to surcharge effect, Q3= 1313.10 kN
Hence, Q= Q1 + Q2 + Q3
$Q = 104.03 + 103.04 * S^2 - 75.70 + 1313.10$ (kN)
$Q = 1341.43 + 103.04 *S^2$
Now, Applied Pressure Intensity, P = 314 kN/sqm
Area covered by each stone column, $Ae = 0.866*S^2$ (sqm)
Applied Load = $314.00 * 0.866 * S^2$
Hence, equating the applied load and load capacity of each column, find out the spacing, 's'

$$1341.43 + 103.04 * s^2 = 314.00 * 0.866 * s^2$$
$$1341.43 + 103.04 * s^2 = 271.89 * s^2$$
$$1341.43 = 168.85 * s^2$$
$$s^2 = 7.944$$
$$s = 2.82 \text{ (m)}$$
$$\text{say } s = 2.80 \text{ (m)}$$

Summary		
Diameter of stone column	In Meter	0.90
Grid pattern		Triangular
Spacing	In Meter	2.8

The Pressure applied to the proposed raft footing (67 m x 150 m) is 314 kN/m² for permissible settlements of 75 mm.

Based on the available data, the bearing capacity and settlements were worked out. The analysis derives the following results –

Bearing capacity of virgin soil based on shear criteria, q	119.00 kN/m²
Settlements due to the pressure applied equal to q	48 mm
Settlements due to th eproposed loading conditions ie 314 kN/m²	126 mm

The bearing capacity of the virgin soil is very much less than the applied pressures and also the settlements due to the applied pressures exceeds the permissible limit. This necessitates the Ground Improvement. Considering the soil type and proposed loading Ground Improvement is proposed by use of Stone Columns.

The following is the summary of Ground Improvement using stone column

Stone columns design for the applied pressure, p	314.00 kN/m²
Finished dia of stone columns, d	0.90 m
Length of stone columns, L	9.00 m
Spacing of Stone Columns, s	2.30 m
Grid Pattern of Stone Columns	Triangular Grid
Area Ratio, as	0.14
Stress Concentration ratio, n	7.00
Settlement of treated Ground	63 mm

The settlement after treatment is less than the permissible settlement of 75 mm.

III. Installation of Stone Columns

Vibro stone columns, also known as vibro-replacement, are a ground improvement technique used to enhance the load-bearing capacity and reduce settlement in weak or compressible soils. This method involves the insertion of compacted stone columns into the ground, thereby reinforcing the soil and improving its mechanical properties.

3.1 The installation of vibro stone columns typically follows these steps:

1. Insertion of Vibratory Probe: A specialized vibratory probe, known as a vibroflot, is inserted into the ground to the desired depth. The probe's vibrations displace the surrounding soil, creating a cavity.

2.Stone Placement: Crushed stone or aggregate is introduced into the cavity, either from the top (top-feed method) or through a pipe attached to the probe (**bottom-feed method**).

3.Compaction: The probe is withdrawn in stages, and the stone is compacted in layers using the probe's vibrations. This process densifies the stone column and the adjacent soil, enhancing overall ground stability.

This method not only replaces weaker soil with stronger material but also densifies the surrounding soil due to the vibrations, leading to improved load distribution and reduced settlement.

Finished Diameter, The diameter of vibro stone columns can vary based on soil conditions, equipment used, and design requirements. Typically, finished diameters range from 600 mm to 900 mm. A finished diameter of 900 mm is common in many applications, providing a balance between load-bearing capacity and installation efficiency.

In summary, vibro stone columns are an effective solution for ground improvement, particularly in areas with soft or compressible soils. Their installation enhances the structural integrity of foundations and mitigates potential settlement issues.

3.2 Equipment Details

1. Vibrofloat Setup: A free-hanging vibrofloat along with necessary accessories is used.

2. Lifting Machinery: A crawler-mounted crane with a minimum lifting capacity of 50 tons is required.

3.Additional Equipment: Pelverpack and Penning make vibrofloat with hopper and tremie pipe attachments suitable for the desired depth. A loader, JCB, or excavator is used for transferring aggregates into the hopper.

3.3Materials Used

1. Aggregates: Well-graded stones or aggregates ranging in size from 75 mm down to 4.75 mm are utilized for stone column construction.

IV. Methodology for Stone Column Installation

4.1. Site Preparation

1.The designated area is cleared of any vegetation or obstructions.
2.All service lines within the treatment zone are identified before work begins and are either protected, rerouted, or removed as necessary.
3.Overhead utilities that could hinder machinery operations are removed.
4.If needed, a working platform made of compacted borrow material is built to facilitate safe and effective movement of construction equipment over soft clay surfaces.

4.2. Point Marking

1.Using benchmarks and boundary reference coordinates, stone column installation points are accurately marked on the ground.
2.Each stone column location is assigned a unique identification number, corresponding to layout drawings.

3.Spacing between columns follows the approved design specifications.
4.Marking is verified through surveying techniques, ensuring alignment with the established benchmarks.

5.Each installation point is clearly identified on the ground using lime powder or stakes.

4.3. Machinery Setup

1.A vibroflot, consisting of a hydraulically driven eccentric mass within a strong steel casing, is suspended from the crawler crane.
2.The vibroflot includes follower tubes and a hopper for feeding aggregates.
3. It operates using a diesel-powered generator producing high centrifugal force for soil penetration.

4. Its tapered nose assists in penetrating the ground, while vertical fins prevent rotation during operation.

5.Adequate quantities of well-graded aggregates (sizes from 75 mm to 4.75 mm) are stockpiled close to each installation point for easy access during the stone column formation.

4.4. Boring:

After the assembly, the power pack is started and the vibroflot is lowered into the ground. The desired depth is achieved by the combined action of water from the tip and the vibratory action of the vibroflot. After reaching the desired depth, if required the vibroflot is surged up and down at a time to create an open annulus around the vibroflot.

4.5.Compaction Process

Aggregates are transported from the stockpile to the installation site using loaders. The aggregate is then introduced directly into the borehole. The vibroflot is activated to apply vibrations, which drive the aggregate laterally, forming a column of the desired diameter. The vibroflot is slightly raised and lowered to ensure thorough compaction of the aggregate at its tip. An increase in rig pressure by approximately 10 to 20 bar indicates adequate compaction. This process is repeated in lifts of 1.0 to 1.5 meters until the stone column reaches the ground surface.

V. After the stone column installation, the stone column load test is carried out to check the settlement of the stone column.

5.1 Equipment's Required

1.Loading platform of required Capacity having plate girder & reaction anchor system or kentledge system.
2.Hydraulic Jack of required capacity with calibrated load measuring device, such as pressure gauge will be used.
3.Settlement Recording Device: Four number of dial gauges with 50 mm travel, capable of measuring settlement to an accuracy of 0.01 mm.
4.Hydraulic pump with pressure gauge with 1000 kg/cm2 range and 5 kg/cm2 least count.
5.Stop Watch
6.Measuring Tape: 5m/15m
7. Plates with diameters of 3.36 m, 2.52 m, 1.50 m, and 1.00 m, with a minimum thickness of 25 mm, are used for 900 mm diameter columns in a three-column group test..
8. Plates with diameters of 1.94m, 1.50 m, 1.00 m, and 0.50 m, with a minimum thickness of 25 mm, are used for 900 mm diameter columns in a three-column group test.

5.2 Test Procedure :Load Test Procedure for Stone Columns-

1.The kentledge system is designed to apply a load 1.3 times greater than the maximum test load.

2.Settlement measurements are taken using four dial gauges, positioned at opposite ends of the footing, with a sensitivity of 0.02 mm or better.
3.For initial tests, load-settlement observations are carried out up to 1.5 times the design load for both single column and three-column group tests.
4.For routine tests, observations are made up to 1.1 times the design load.
5.Loading is applied in increments, each equivalent to 20% of the design load. Each load increment is maintained until the settlement rate falls to 0.05 mm per hour or lower, at which point the next load increment is applied.
6.Settlement readings are recorded at time intervals of 1 min, 2 min, 4 min, 8 min, 16 min, 30 min, 1 hr, 2 hrs, 3 hrs, and 4 hrs, and continued until the settlement rate criteria are satisfied.
7.After reaching the maximum test load, the load is maintained for a minimum of 12 hours.
8.The unloading process is carried out in five equal stages, allowing enough time at each stage for the settlement to stabilize.
9.A graph is then plotted with the applied load on the X-axis and the corresponding settlement on the Y-axis.

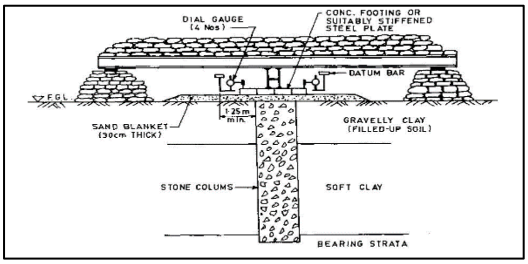

Fig. 1- Test setup

Interpretation of the Test Data

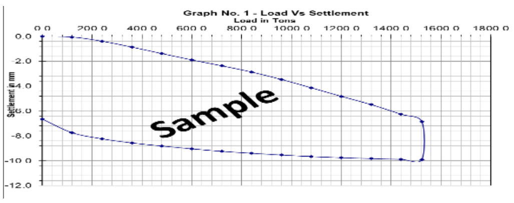

Fig. 2- Load vs settlement curve

5.3 Acceptance Criteria :
The stone column load test is deemed acceptable if the observed settlements do not exceed the following limits under the design load:
1. Single Column Test: Maximum settlement should not surpass 10 to 12 mm.
2. Three-Column Group Test: Maximum settlement should not exceed 25 to 30 mm.
These thresholds ensure that the stone columns provide adequate support and maintain structural integrity under the anticipated loading conditions.

VI. CONCLUSIONS

After the whole scenario, it is observed that the stone column requirement is much needed in soft sub soil condition. Actual ground study, stone column recommendation, design of stone column, stone column installation and stone column load test were carried out in my observation. In this process following points are observed,
1. Effect of Friction Angle and Column Diameter:

The bearing capacity of stone columns increases with a higher internal friction angle of the stone material and a larger column diameter. These factors enhance the shear strength and load-bearing capability of the columns .

2. Impact of Spacing (S/D Ratio):Increasing the center-to-center spacing between stone columns (S) relative to their diameter (D) beyond a ratio of 3 (S/D > 3) leads to a decrease in load-bearing capacity. However, this reduction becomes negligible beyond this spacing, indicating an optimal range for column placement .

3. Performance in Soft Cohesive Soils:

Stone columns are particularly effective in improving the bearing capacity and reducing settlement in soft cohesive soils. Their installation facilitates faster consolidation and enhances the overall stability of the ground .

4. Simplified Estimation Methods:Analytical methods have been developed to estimate the safe bearing capacity of stone columns. These methods consider parameters such as friction angle, column diameter, and spacing, providing a practical approach for design and assessment .

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