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Contribution of Stone Columns in Improving the Poor Ground Condition–A Review

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Abstract—*In this paper a short state-of-art on the stone column ground improvement technique on the basis of existing literature and standards is presented. For any geotechnical construction the primary requirement is for ground improvement. In today's construction industries land reclamation becomes popular now, therefore ground improvement is important requirement. Due to rapid infrastructure growth and scarcity of suitable land various ground improvement methods have been developed for making an unsuitable site as suitable for the construction. Stone column ground improvement method is one of the easiest, best and economical technique available for improving poor ground. In this method, a column of compacted dense granular material replaces the weak and unstable subsurface soils, therefore efficiently improving the strength parameters of soil like bearing capacity and also reducing the consolidation settlement. This methods offers sustainable and economical alternative to pilling and deep foundation. When stone column ground improvement technique is implemented, it aids in much stable solution to construction in weak cohesive soils. In this paper an attempt is made to discuss in detail about this technique to improve weak soil, its salient features, design parameters, major function and drawbacks. The stone column's behaviour is yet to be fully decided by analytical and numerical techniques, and predicting it's behaviour in cohesive soil brings specific challenges.*

Keywords*: Stone column, Ground Improvement, Weak soil, Geosynthetics.*

1. INTRODUCTION

For all around development of any country the civil engineering works are prime requirement. During the early phase of development , there was no crisis of suitable site for construction but now-a-day, due to rapid increase in infrastructure growth, particularly in metro cities, there is scarcity of suitable sites for the constructions. Therefore, one has to go for construction on poor ground conditions like soft clay, which cover large area all around Indian coast and some part in gangetic plains.

Although, pile foundation is one of the best solution of almost every such problems like poor ground condition, but due to its higher cost in construction, it is limited to rigid structure such as high rise buildings. For flexible structures which can tolerate some settlement, ground improvement techniques are considered to be economical. There are various available techniques for improvement of mechanical behaviour of soft soil foundation. Such as;

- Soil improvement without admixtures (i.e. soil replacement, preloading, sand drains, vertical drains)
- Soil improvement with admixtures or inclusions (i.e. stone columns, sand compaction piles)
- Soil improvement using stabilization with additives and grouting methods (i.e. chemical stabilization, Deep mixing, jet grouting)
- Soil improvement using thermal methods (i.e. Heating, Freezing)

Stone column is one of the most suitable technique and now used worldwide to increase the bearing capacity of soft soil and reduce the settlement of the superstructures constructed.

Ground improvement with stone column involve adding vertical column of granular materials (of higher stiffness than surrounding soft soil) into the ground to a suitable depth(up to 15m to 20m). Stone columns may be either end bearing or floating type. Former type is fully penetrated into the ground and drives its resistance against loading by its toe as well as skin friction. Whereas latter one is partially penetrated into the ground and drive its resistance against loading only due to its skin friction.

Types of Stone Column Construction

a) Vibro-Replacement (Wet Top Feed) (i.e. Vibroflotation)

- Stone column construction using water flush.
- Refers to the wet, top feed process in which jetting water is used to aid the penetration of the ground by the vibrator.
- Due to the jetting action, part of in-situ soil is washed to the surface. This soil is then replaced by the backfill material.

b) *Vibro-Replacement (Dry Top and Bottom Feed)*

- Stone column construction using compressed air and no water flush.
- Refers to the dry, top or bottom feed process almost no in-situ soil appears at the surface but is displaced by the backfill material.

c) Compacted Stone Column

- A continuous vertical dense column of interlocking aggregate grains, free of non granular inclusions.

d) Vibro-Concrete Columns
e) Vibro-Compaction

- Similar to Vibro Replacement, Except Stone is not added.

There are two beneficial effects that results from the presence of stone columns of granular material into the ground. First, the granular material being stiffer and higher in strength than the soft clay, it acts as piles transmitting the loads to a greater depth with load transfer occurring by a combination of skin resistance and end bearing(whether, it is fully or partially penetrated). Second, the granular material has high permeability as compared to surrounding soil hence it acts as vertical drains reducing the path length for consolidation of the soft clay under the foundation and hence speeding up the strengthening of soft soil.

2. APPLICATION OF STONE COLUMNS

Stone column acts as vertical drains and thus speeding up the process of consolidation, replaces the soft soil by a stronger material and initiate compaction of soil during the process of installation thereby increasing the unit weight. Stone columns also mitigate the potential for liquefaction and damage by preventing build up high pore pressure by providing drainage path.

Advantages

Weak soil, having low shear strength and high compressibility to support structure constructed over it, require strengthening to be capable of carrying loads from structure. Stone columns are best suited for such problematic soil, because it;

- Reduces the total and differential settlement.
- Minimise the liquefaction potential of cohesionless soil.
- Increases the stiffness of composite ground.
- Improve the bearing capacity of the weak soil.
- Improve the drainage conditions and accelerate consolidation.
- Control the deformation and also environmental friendly.

The stress-settlement behaviour of stone column may be further improved by providing geosynthetics reinforcement either as encasement or horizontal strips.

3. LITERATURE REVIEW

Due to rapid urbanisation the ground improvement is becoming popular now-a-days. Stone column ground improvement is one of the best, economical and easily available method to improve the weak soil like clay, silt etc. Various research works have been done till now to determine the contribution of stone columns in weak soil.

FHWA has recommend the use of stone column technique in soft soil with undrained shear strength (c_u) between 15 and 50 kPa. In such cases, the stone column drive load carrying capacity by mobilization of lateral earth pressure from the surrounding soft soil against bulging.

However, in very soft soils the lateral confinement offered by the surrounding soil is not adequate and the stone column may not develop the required load carrying capacity. In such cases, the load carrying of stone columns has been increased by reinforcing the stone columns with geosynthetics.

Hasan and Samadhiya (2017) performed laboratory tests as well as numerical analysis and found that the ultimate load intensity of encased floating and end bearing columns was more or less equal for the shear strength of clay higher than 8kPa. The ultimate load intensity of end bearing column was increasing linearly with increase in the stiffness of geotextile and for end bearing columns with horizontal strips the ultimate load intensity was increasing with the reduction in vertical spacing of geogrid strips. The bulging of columns was controlled by geosyhnthetic reinforcement provided.

Frikha et al.(2015) conducted an experimental investigation to study the mechanical properties of remoulded Tunis soft soil reinforced by a group of sand columns, and states that the distribution of load bearing capacity tends to improve due to interaction between a group of columns and soft clay.

Geosynthetic encasement provides lateral confinement to the columns against bulging by mobilisation of hoop stresses and horizontal circular discs provide the same improvement by friction mobilisation. Former one is a more effective way to provide lateral confinement to the columns compared to the latter, maximum improvement in the bearing capacity is obtained for encased columns for both floating and end-bearing. The failure stress of composite ground improves greater for end-bearing columns as compared with floating columns for both encased and horizontal circular discs-reinforced columns. In the case of floating columns, the geotextile encasement performed better than those with geogrid encasement. Geogrid encasement has a better option than a geotextile encasement for the case of end-bearing columns. Both geotextile and geogrid is found to be equally effective as horizontal circular discs for both floating and end-bearing stone columns [**Ali et al.(2014)**]

Dash and Bora (2013) carried out experimental works and found that with the provision of stone column-geocell mattress combined, the bearing capacity of soft clay bed has increased significantly with respect to plain clay bed. The load carrying capacity increases with increase in length of stone columns until 5 times the diameter of stone column, for the geocell-stone column reinforced foundation bed. Similarly, as the spacing of stone columns reduced below 2.5 times the diameter of stone column, did not attract much of additional performance in the composite system. Besides, with height of geocells increasing beyond 1.1 times the diameter of footing, the performance improvement was found to be reduced.

The failure stress of ground improved with floating stone columns with length greater than 9 times the column diameter has almost the same as that of ground improved with end-bearing stone columns. Whether floating or end-bearing, long unreinforced stone columns always fail by bulging, whereas short floating columns (unreinforced or reinforced) always fail in punching. The increment in the failure stress of composite ground due to encasement or horizontal strips has negligible for short floating columns. Whether a column floating or end-bearing, encasement over the full column length has higher failure stress than encasement over the top half or quarter of the column length [**Ali et al. (2012)].**

Based on the experimental results of laboratory model tests on unreinforced and geogrid-reinforced sand bed resting on single end bearing stone column-improved soft clay **Deb et al. (2011)** states that, the presence of stone column in soft clay improves the load carrying capacity and decreases the settlement. The placement of sand bed further increase the load-carrying capacity and decrease the settlement of the stone column improved soil. The inclusion of geogrid as reinforcing element in the sand bed significantly improve the load-carrying capacity and reduce the settlement of the soil. Decrease in bulge diameter and increase in depth of bulge has 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 has been observed due to application of geogrid.

Shivashankar, et al., (2010) Conducted a series of laboratory plate load tests carried out in unit cell tanks and suggested a new method of reinforcing the stone columns with vertical nails installed along the circumference of the stone column to improve the performance of these columns. Stone column reinforced with vertical circumferential nails over a depth thrice the diameter (3D) exhibits much higher stiffness and ultimate load capacity than unreinforced stone column for all the diameters studied. Further the confinement needed only where bulging takes place also, the nails were found to be more effective for smaller area ratios.

On the basis of investigation of geogrid encasement on stone columns (Isolated and Group) **Gniel and Bouazza (2009)** suggested that, the constrained conditions provided by unit-cell loading provided additional lateral confinement to the encased columns, preventing radial column failure and enabling encasement mesh to be loaded to tensile capacity. Isolated columns failed by radial expansion below the level of encasement. Increasing the length of encasement acted to increase stiffness and steadily reduced the vertical strain. Whereas, for isolated columns, it acted to increase the column capacity, while the strain at failure remained quite consistent. A large increase in capacity was observed for the fully encased column. Radial column bulging significantly occurred directly below the base of encasement. This bulging occurred along the full length of non-encased section in case of partially encased group columns. This bulging was confined to a length of about 2 column diameters for the partially encased isolated columns.

Isaac and Girish (2009) studied the influence of column material in the performance of stone column through laboratory experiments on fully penetrating model stone columns installed in clay. Five reinforcement materials were studied: stones, gravel, river sand, sea sand and quarry dust. Load versus settlement response was determined and found that, among the different stone column materials used, river and sea sand were no significant difference in the load deformation behaviour of soil. Gravel was more effective than the sand. Quarry dust was effective in load deformation characteristics of soil and also a economically available material. The spacing of the column also played an important role in affecting the load deformation characteristics stones. The Load carrying capacity was increasing as spacing between the columns was decreasing. **Shlash et al. (2009)** considered the group efficiency of 24 model stone columns installed in soft clay. The group consist of 2, 3 and 4 columns. The tests were conducted on stone columns with length to diameter ratio (L/D) of 6 and 8. The results illustrated that the group efficiency decreases with increasing the number of stone columns, also the stone columns with L/D of 8 provided higher efficiency than those with L/D of 6.

When column area alone is loaded, the failure take place by bulging with maximum bulging at a depth of about 0.5 times the diameter of stone column. As the spacing between columns increases, the axial capacity of the column decreases and settlement increases up to a spacing to diameter ratio (s/d) 3, beyond which the change is negligible. The ratio of limiting axial stress on column to corresponding shear strength of surrounding clay is found to be constant for any given s/d and angle of internal friction of stones, and independent of the shear strength of the surrounding clay **[Ambily and Gandhi (2007)].**

Al-Qyssi (2001) conducted model tests to improve the behaviour of stone columns by using different patterns of reinforcement consisting of two and three discs connected to a central shaft. Different parameters were studied i.e. spacing between stone columns, effect of shape of footing, effect of area replacement ratio, and the number of stone columns. It was found that circular footing demonstrates a higher bearing ratio at failure followed by the square then by the rectangular model footings. The bearing ratio increases with increasing spacing from 2D to 2.5D and 3D c/c (D is the stone column diameter) for all the three shapes of model footing. The area replacement ratios showed an insignificant influence on the efficiencies of the single stone column.

It is concluded from the previous studies that there is no general relationship for predicting the baring capacity of single and group of stone columns that take into account several factors affecting the stone column behaviour are L/D ratio, spacing between columns, use of different geosynthetics for reinforcement and the number of columns in a group.

4. BASIC DESIGN PARAMETERS

Although there is no any direct design concept for construction of stone column, but based on past experience of expert engineers of same fields followings basic design parameters should be considered while constructing stone columns in soft soil ground.

a) Stone column diameter, D.

Approximate diameter of the stone column in the field may be determined from the known compacted volume of material required to fill the hole of known length and maximum and minimum densities of the stone.

b) *Pattern*

Stone columns should be installed preferably in an equilateral triangular pattern which gives the most dense packing although a square pattern may also be used. A typical layout of the patterns are shown in Fig.1.

c) *Spacing*

The column spacing may broadly range from 2 to 3 times the diameter, depending upon the site conditions, loading pattern, column factors, the installation technique, settlement tolerances, etc.

d) Equivalent Diameter

The tributary area of the soil surrounding each stone column forms regular hexagon around the column. It may be closely approximated by an equivalent circular area having the same total area. 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 D_c enclosing the tributory soil and one stone column is known as the unit cell.

e) Replacement Ratio (a_s)

For purpose of settlement and stability analysis, the composite ground representing an infinitely wide loaded area may be modeled as a unit cell comprising the stone column and the surrounding tributary soil. To quantify the amount of soil replaced by the stone, the term replacement ratio(a_s) is used.

Replacement ratio (a_s) is given by:

$$a_s = \frac{A_c}{A} = \frac{A_c}{A_c+A_g}$$

where

A_c = area of the stone column,

A_g = area of ground surrounding the column, and

A = total area within the unit cell.

The area replacement ratio may also be expressed as follows:

$a_s = 0.907\,(D/S)^2$ & $0.783\,(D/S)^2$

where the constant 0.907 and 0.783 are function of the pattern used which, i.e. triangular and square respectively.

f) Stress Concentration Factor (n)

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, is defined as the ratio of average stress in the stone column (σ_s) to the stress (σ_g) in

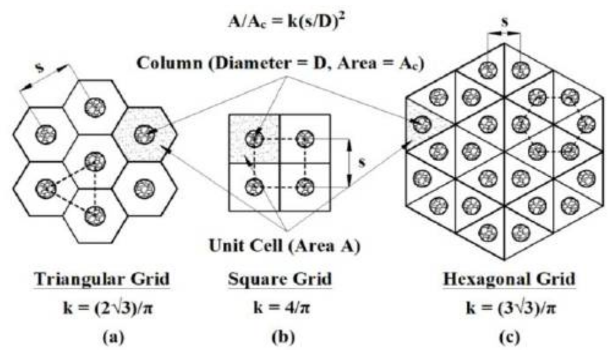


Fig. 1: Different installation pattern of stone column the soil within the unit cell,

$$n = \frac{\sigma_s}{\sigma_g}$$

The value of n generally lie between 2.5 and 5 at the ground surface.

g) Critical Column Length

McKelvey et al.(2004) stated that the stone column bulging was more distinguished in the upper portion of the column. It was found also that the depthh of bulging can be considered to be approximately four times the diameter of the column. **Shadi. S. Najjar et al. (2010)** provided that the critical column length is the shortest column which can carry the ultimate load regardless of settlement. The outcomes of the experimental investigation indicated that the critical column length is roughly six times the diameter

h) Backfill for Stone Column

Crushed stone or gravel for the column backfill shall be clean, hard, unweathered stone free from organics, trash or other deleterious materials. To select the efficient backfill type, three criteria of availability, suitability and economy should be considered. A mixture of crushed stone and sand may also used in suitable proportional.

The design of stone column is still empirical, based on past experience and needs field trials before execution. No well-defined guidelines or codes are available.

5. FAILURE MECHNISMS

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 (i.e. about four times the column diameter) and irrespective of whether it is end bearing or floating, it fails by bulging (see Fig.2A). However, column shorter than the critical length are likely to fail in general shear if it end bearing on a rigid base (see Fig.2B) and in end bearing if it is a floating column as shown in Fig.2C. In practice, however a stone column is usually loaded over an area greater than its own (see Fig.3) in which case it experiences significantly less bulging leading to greater ultimate load capacity and reduced settlements since the load is carried by both the stone column and surrounding soil.

Wherever interlayring of sand and clay occurs and if the sand layer is thick enough as compared to the size of loaded area, the general compaction achieved by the action 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 one, the settlement due to presence of lenses may be insignificant.

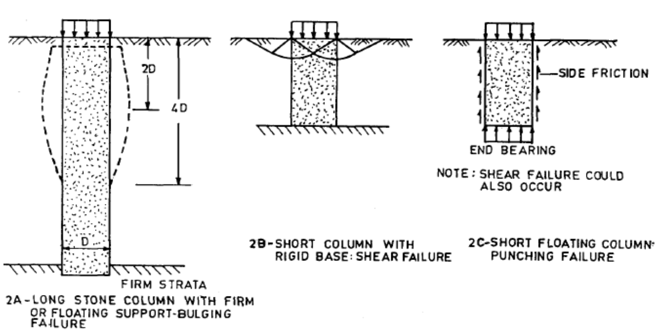
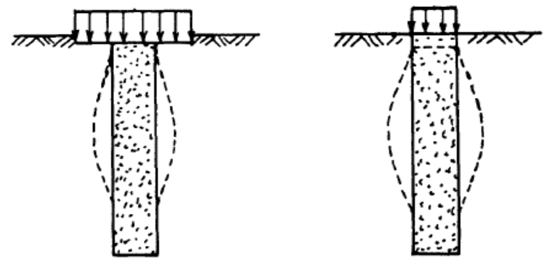


Fig. 2: Failure mechanisms of a single stone column in a homogenous soft layer (Courtesy IS 15284 Part 1 : 2003)



(a) (b)

Fig. 3: Different type loadings applied on stone columns,(a) column + surrounding area and (b) Only column area loaded. (Courtesy IS 15284 Part 1 : 2003)

In mixed soils, the failure of stone columns should be checked both for predominantly sandy soils as well as the clayey soil, the governing value being lower of the two calculated values.

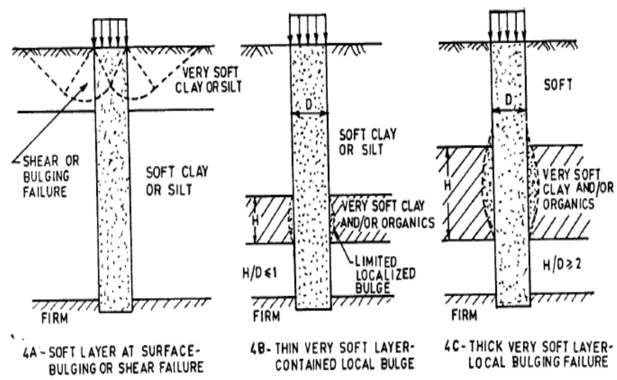


Fig. 4: Stone column failure mechanisms in non-homogenous cohesive soil (Courtesy IS 15284 Part 1 : 2003)

6. CONCLUSION

Stone columns play a main role in the area of ground improvement. Stone columns are the best and economical ground improvement technique in the areas consisting weak soil such as soft silt and clay. Based on the available literatures and critical reviews on stone columns, some conclusions are made bellow:

- In areas with cohesive soils, the stone columns generally constructed by ramming or vibro replacement method either wet process or dry process.
- Stone columns act as a cost efficient method of ground improvement offer considerable contract program savings over other ground improvement techniques.
- In this method, the portion of the soils that are weak and unsuitable are replaced with compacted dense aggregate columns which are stiffer and stronger than the unimproved native soil. It often completely penetrates into the weak layers, and an increase in bearing capacity will occur.

- Beside of these, the stone columns act as drains and significantly reduce the time for primary consolidation to occur as well as total settlements and liquefaction potential.
- Based on the outcomes of past studies with physical modeling, mathematical analysis and full-scale testing, various parameters that influence overall performance of the technique have been highlighted, these are column length, strength of the column material, area replacement ratio, column spacing, and installation method.

7. LIMITATIONS

- Stone column when used in sensitive clays (sensitivity is $\geq$ 4) have certain limitation. There is increase in the settlement of bed because of the absence of lateral restrain.
- The clay particles get clogged around the stone column thereby reducing radial drainage.
- Such type of clay also loses strength when vibrated.

To overcome these limitations and to improve the efficiency of the stone column with respect to the strength and the compressibility stone columns are encased (reinforced) using geosynthetics.

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